Seismic Exploration of Small Bodies

Final Report
Grant: NNX15AL87G

NNH16ZOA001N-16NIAC-A1

NASA Innovative Advanced Concepts (NIAC) Phase I
National Aeronautics and Space Administration
Washington DC 20546-0001

Submitted by:
Jeffrey Plescia
The Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel MD 20723-6099
240 228 6871
jeffrey.plescia@jhuapl.edu

October 1, 2016

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Summary

As a result of the Phase I study, we have demonstrated that a mission to a small body (asteroid, comet) whose objective is to conduct a seismic experiment to understand the interior structure, can be accomplished with small (<200 kg) spacecraft launched on a small launch vehicle (Athena IIc).

We modeled the seismic response of a small body and calculated that the energy necessary to propagate through the body and be detected by a seismometer. These calculations provide guidance as to the type of energy source that is required. A simple energy source similar to a NASA standard initiator (NSI) can be used, although a single NSI is insufficient. An NSI is an explosive pyrotechnic that is used to sever connections on spacecraft. Use of such an energy source has illustrated two additional areas of study - anchoring of the source and sensor to the surface and understanding the efficiency of energy propagation from the source into the surface.

The spacecraft has the ability to carry and deploy a series of source/sensors to conduct the experiment by placing them on the surface. We identified a suite of candidate near-Earth asteroids as targets and used one 1991VG as the target to calculate the mission trajectory and ΔV requirements. Spacecraft and launch vehicle performance are launch that any of the candidates could be reached with appropriate mass and launch margins.

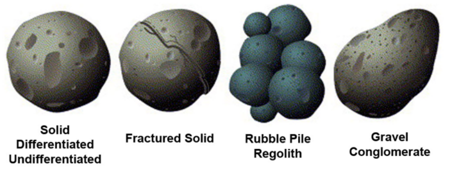
Sources and sensors are deployed from arm attached to the spacecraft. The spacecraft maneuvers next to the target body and presses the sensor against the surface and releases it. After emplacing all of the surface packages, the sensors are monitored for a period of time to measure the seismic noise. Finally, the active seismic experiment is conducted.

The work conducted during Phase I demonstrates that a small mission can be designed to conduct an active seismic experiment on a small near-Earth body. While other targets may require more performance, the basic architecture is viable for any target.

We have identified a number of specific technical areas that require more detailed study. Those areas are largely focused on the detailed analysis and design of the source mechanism and anchoring it to the surface. Such topics will be part of a Phase II proposal.

1.0 Background

The scientific objective that was the impetus for the Phase I study was the need to understand the interior structure of small bodies (asteroids and comets). Understanding the interior structure is critical to understanding the formation and evolution of these bodies as well as understanding the threat they might pose to the Earth.



Walker et al (2006)

F*igure 1. Models of possible small body structure, ranging from homogenous solid to coalesced rubble.*

Asteroid and comets represent the dregs of the accretionary processes, left over pieces of matter that didn't manage to get together a quorum to build a planet or were not around at the right time. Thus, they represent an inventory of the original accretionary matter. In some cases, small bodies remained more or less static until something bigger ran into them and shattered them to pieces (Figure 1). Sometimes the pieces collected to form a rubble pile (e.g., Itokawa). Sometimes the body was large enough that it was just fractured rather than shattered. In a few cases, the body was large enough to evolve beyond its original state (e.g., Ceres, Vesta). Understanding these processes provides insight into how thing accrete.

Small bodies whose orbit crosses that of the Earth are potential hazards by impacting the Earth. If the body is small enough or weak enough, it may simply burn up in the atmosphere. If it is strong enough, it will make it to the surface and become a general nuisance. It has been suggested that it might be possible to deflect a hazardous body if its orbit could be nudged at the right time. In all of these cases, understanding the interior structures is critical to understanding whether the body is a threat and if it can be moved.

The only to understand the detailed structure of the interior of a large body is conduct active and passive seismic experiments. Such experiments were conducted on the Moon during Apollo and provide data to understand the shallow regolith as well as the deep interior. If one wished to understand the interior of a comet or asteroid, a seismological approach is the only way. Seismic studies of other planetary bodies has involved large complicated instrumentation. The Apollo seismometers were emplaced by the Apollo astronauts and for the Mars InSight mission, an entire spacecraft is devoted to deploying a single seismic station. A few smaller scale experiments have been conducted - Vikings I and II (Anderson et al., 1977) and the Deep Space 2 / Mars Microprobe (Smrekar et al., 1999; Gavit and Powell, 1996) - but these were not successful. Most recent studies of seismology missions have assumed that the sensor would be emplaced with a penetrator, however these studies have shown that such a deployment is complicated, particularly in light of the standard approach to a seismometer - a mass and a spring. These instruments must be leveled in order to work complicating the deployment.

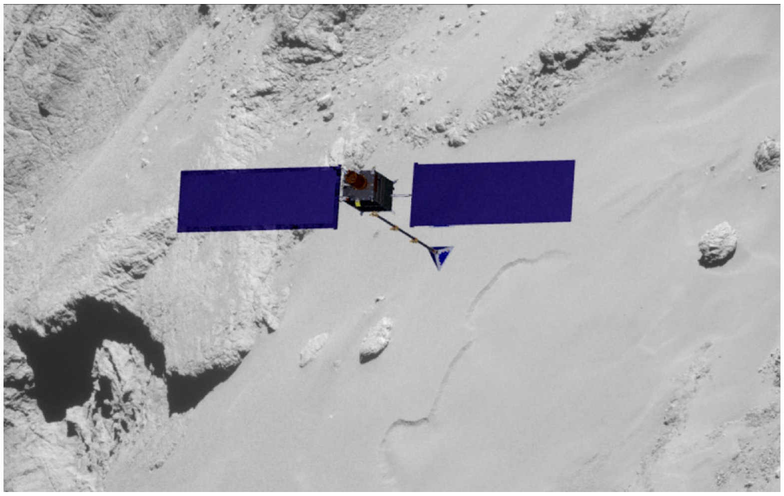


Figure 2. Illustration of the Phase I spacecraft deploying a seismometer. The spacecraft is hovering over the surface, its solar panels extended. A seismic package is at the end of a boom to be deployed on the surface.

Under the auspices of other NASA programs, Hongyu Yu (Arizona State University) and colleagues have developed a micro-seismometer than is small, low power, and can be deployed in any orientation thus avoiding the issue of leveling.

With such an instrument in mind, we wished to explore where a mission to a small body could be conducted with a simple, low cost approach. That was the motivation for the Phase I study. In short, our Phase I work demonstrates that such a concept is viable (Figure 2). Clearly such a mission could be conducted within the context of a NASA Discovery or New Frontiers mission, but such missions are large, complicated and expensive, and therefore relatively rare. By determining if this could be done on a small sat scale, we have attempted to demonstrate that such experiments could be achieved cheaply, yet also produce important scientific data.

2.0 Objectives and Products of Phase I Study

For Phase I, we outlined a series of tasks that we believed needed to be resolved to demonstrate the viability of the small mission architecture. The specific problem is to understand how a micro-seismometer can be flown to and deployed on a small body, how energy can be input into the surface to conduct an active seismic experiment, and what the mission would require to support these activities and return the science and engineering findings.

The specific tasks of Phase I specific tasks include:

1. Design a deployable sensor package for the seismometer that can be placed on or into the surface of an asteroid or comet.
2. Determine the amount of seismic energy required for an active experiment.
3. Examine different experiment approaches (multiple sources and/or multiple receivers) for a tomographic analysis.
4. Design spacecraft carrier system that will deliver the sensor package and relay the data to the Earth.
5. Analyze a complete reference mission.

2.1 Objective 1: Design a deployable sensor package for the seismometer that can be placed on or into the surface of an asteroid or comet.

The objective here was to understand the design of a surface package to be placed on the surface that housed the sensor, electronics, power and communications. Figure 3 illustrates the sensing cell. The sensing cell is filled with an electrolyte fluid that passes through the sensing element (Huang et al., 2013; Yu et al., 2009). Motion of the fluid through the element generates a current that is proportional to the actual motion of the sensor. Several of these sensing cells are packaged together to provide the motion in all three axes as well as redundancy. Figure 4 illustrates a concept design housing several of the sensors.

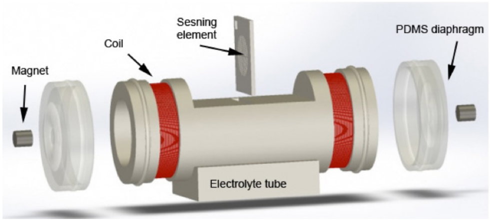


Figure 3. Sensing cell. A permeable membrane senor is located in the center of a fluid filled tube, capped at both ends with flexible caps to allow motion of the fluid induced by seismic ground motion..

We initially considered the source and the senor as independent packages. However, in the interest of keeping things simple, we decided to package them together into single deployable package for each station. This had the advantage of reducing the number of deployments (and in the context of the current spacecraft design, the number of arms - see below). However, this may not actually be a viable concept in the context of a detailed design of the sensor, the source and the anchor. Thus, we have made the focus on the Phase II proposal.

A nominal design was achieved in which the sensor is housed in a polyhedron package. The polyhedron contains a set of sensors, also mounted on a smaller polyhedron ~10 cm on a side and having a mass of about 2 km (Figure 4). The exterior the outer casing is coated with solar cells to provide power to the package once it is placed on the surface. The package holds the sensor, control electronics, communications, and battery.

The top of the polyhedron has a connector for deployment. We have not considered in detail how to anchor the sensor to the ground. Nominally, we considered a series of small spikes placed on the bottom of the package to ensure coupling to the ground.

This task did not advance as far as we had intended. However, as part of the requested No Cost Extension (NCE) we will complete the design of the surface package.

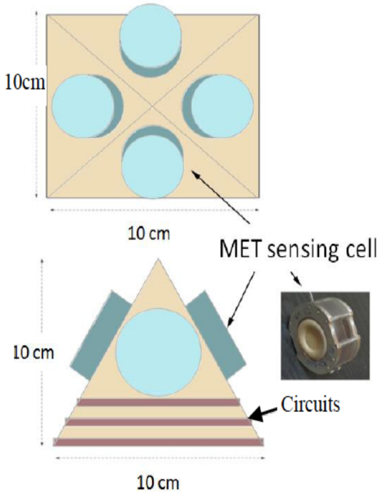


Figure 4. Sensor arrangement. Four sensors are mounted on the polyhedron to collect information of the three axes of motion and for redundancy.

2.2 Objective 2: Determine the amount of seismic energy required for an active experiment.

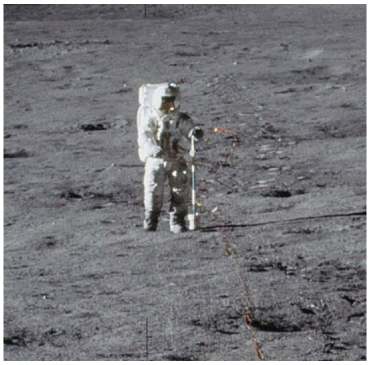


Figure 5. Ed Mitchell using the thumper at the Apollo 14 site. AS14-67-9374.

Small bodies are subject to several types of seismic activity, including impact events, thermal and tidal deformation, and possibly internal brittle failure along fractures. To determine the interior structure requires a seismic energy source that possesses a known location, energy, and coupling. Since it is the time delay between the energy event and reception at the receiver that defines the integrated velocity along the path, the location of both the source and receiver must be well defined to invert the data for internal structure. A key approach to removing this source location uncertainty is to use an active source. This approach was used as part of the active seismic experiment that was conducted on Apollo 14 (Figure 5). In that experiment, the "thumper," 21 Apollo initiators were mounded in a housing mounted on a staff. The housing was pressed against the surface and the initiators were fired independently along a profile. That experiment provided data down to about 100 m (Watkins and Kovach, 1972).

In order to estimate the energy required for an active source we must consider a variety of internal structure models and study wave propagation in small bodies. For relatively small bodies, a highly pulverized rubble pile versus a stone monolith serve as two reasonable end member cases. Rubble piles have seismic velocities (300-1000 m s^{-1} and densities resembling the lunar regolith and megaregolith (1000-2000 kg m^3). A more monolithic body would have higher velocity (1500-5000 m s^{-1}) and density (2500-3500 kg m^3).

It has been suggested (Figure 1) that both rubble pile asteroids and more coherent asteroids occur (Britt et al., 2002; Richardson et al., 2002). The asteroid Itokawa (Figure 6) is the poster child for rubble pile asteroids. However, even in this context it is not clear if the entire body consists of unsorted debris as occurs on the surface or if the interior might contact an intact core. A body such as Itokawa is most challenging, not only because of the low density but because of the range of particles sizes that would be very efficient energy scatters.

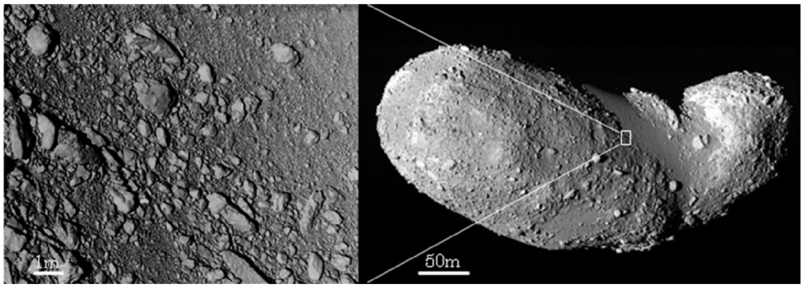


Figure 6. Itokawa - rubble pile. Left panel shows a high-resolution view of the center area characterized by fine-grained material. Right panel shows the entire asteroid and large blocks on the surface and an irregular shape.

Past work on the seismology of asteroids focused on determining the seismic shaking induced by impacts and its affect on surface features and craters (Richardson et al., 2005). Such approaches assume energy diffusion throughout the asteroid and convolve the expected seismic response to a source spectrum generated by a hydrocode mesh (Richardson et al., 2004). Such models approximate the seismic response, but do not fully replicate the partitioning of seismic energy at internal interfaces and nor the transfer between compressional and shear modes.

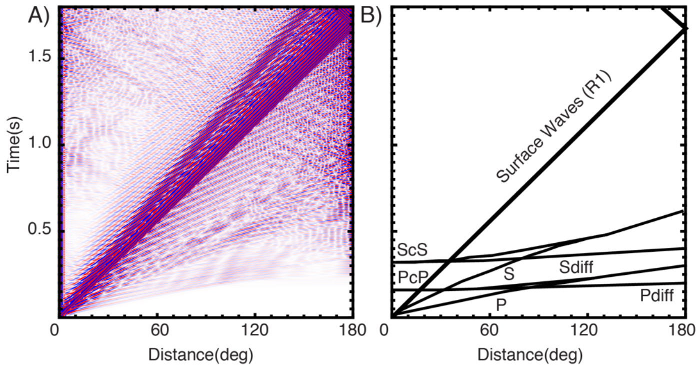


Figure 7. Synthetic seismograms generated for a 250 m stone monolith with a 100 m veneer of megaregolith using the GEMINI code. A) Seismic amplitudes as a function of epicentral distance on the surface of the asteroid, positive amplitudes are red and negative amplitudes are blue. B) Expected arrival times of major body waves traversing the asteroid body, corresponding to the major arrivals seen in A.

To investigate the full wavefield, including transfer and partitioning of seismic energy through the interior of such asteroids, we have taken a 1-D spherical wave propagation code GEMINI (Green's Functions by Minor Integration) developed by Friederich and Dalkolmo, 1995) and modified it for wave propagation within small bodies. This includes scaling of the vertical component of motion for asteroid gravitation, increased array size for accurate computation of higher frequencies, additional modes for the spherical harmonic expansions in the code, and adoption of a generic radius for scaling source/station distances. GEMINI computes the Green's function in the frequency domain of a spherically symmetric body, allowing us to specify different models of attenuation, velocity, density, and source types, including impulse functions appropriate for impacts, and explosion-like moment tensors. Given the small size of the model and our modifications, the code creates synthetic seismograms for frequencies as high as 300 Hz (Figure 7).

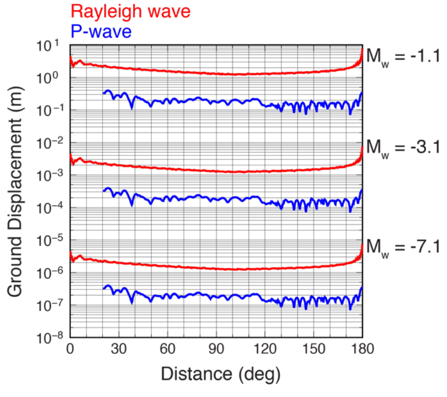


Figure 8. Amplitude of propagated seismic energy as a function of angular distance across body at different energies. M -1.1 is an energy of $1.4x10^8$ *J, -3.1 =* $1.4x10^5$ *J and -7.1 =* $1.4x10^{-1}$ *J. Red line: surface (Rayleigh) wave; blue lines: propagated (P waves). 0° is source, 180° at antipode.*

To study the amplitudes of seismic waves resulting from different source energies, we use GEMINI to simulate explosive-type source mechanisms and impact point forces, although we find the resulting ground motion is similar from both (Figure 8). The transfer of energy is an inefficient process, and the energy radiated from the source as seismic energy is typically much smaller than the energy released from the explosion or impact, thus we scale our input source energy using a seismic efficiency, k. Values of k range from 10^{-2} to 10^{-6} and are dependent upon the properties of the target medium, for an asteroid, surface materials are usually a loosely aggregated rubble or regolith, resulting in a lower seismic efficiency than bedrock or consolidated materials (Figure 9). Past seismic simulations have adopted a value of k=10^{-5}, according to the seismic efficiency observed for the Apollo SIV-B and LM impacts (Schultz and Gault, 1975; Melosh, 1989).

From our modeling and an assumption about the sensitivity of the new micro-seismometer (e.g., a detection limit of 1 nm of displacement at 10 Hz), we can use GEMINI to determine the minimum size of an impact or explosive source needed to excite a seismic response detectable by an instrument deployed anywhere on an asteroid. The results of modeling effective source energies are shown in Figure 4, where the expected amplitude seismic energy from both body waves and surface waves is shown as a function of source magnitude. Given the small size of the asteroid (250 m diameter), ground motion saturates near an effective source magnitude of -1.0; any larger seismic events would result in ground motion that would exceed to local gravity field and the destruction of the asteroid.

An analysis of the ground displacement across a range of source energies is shown in Figure 8. A similar seismic efficiency is applied, although in this figure, the energy shown is for the un-scaled initial energy of the explosion source. The size of the explosion needed to generate surface or P-waves of a particular amplitude can thus be read directly off of the graph. Any body-waves with amplitudes of some fraction less than the P-wave can also be inferred from this diagram.

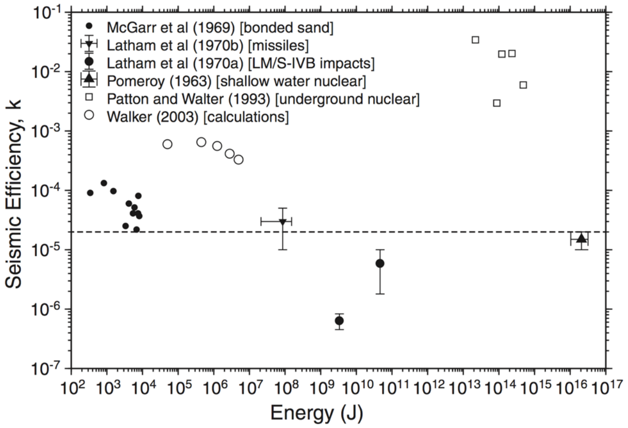


Figure 9. Compilation of observed seismic efficiencies for impacts and explosive sources energy in varying media [Brune and Pomeroy, 1963; McGarr et al., 1969; Latham et al., 1970a; Latham et al., 1970b; Patton and Walter, 1993; Walker, 2003; Teanby and Wookey, 2011]. Except for very large sources buried in bedrock (nuclear testing), most materials exhibit a seismic efficiency of 10^{-4} to 10^{-5}, independent of the source energy.

Modeling studies were conducted to determine how much energy would be required to allow for propagation of seismic waves across a small asteroid sufficient to be detected by the microseismometer. As noted above the seismic efficiency needs to be understood. However, in addition to the efficiency of converting the energy into seismic energy, the issue of coupling between the source and the target is important. Even if the seismic efficiency is high, if little of the energy is actually transmitted into the interior, the resultant signal will not be sufficient.

We conducted an analysis of the propagation of seismic wave from a single NASA Standard Initiator (NSI). An NSI contains 114±4 mg of zirconium-potassium perchlorate that produces 668 J of energy (Hohmann et al., 2000). Assuming $k = 10^{-5}$, about 6.7 mJ of energy is converted into seismic energy and would produce seismic P waves. The analysis indicates that this amount of energy is at or below the noise floor for typical seismic instruments, thus a larger energy source is required to provide high signal-to-noise performance and to generate detectable Rayleigh waves across the bodies. This analysis, however, did not consider transfer of energy from the source to the surface.

2.3. Objective 3. Examine different experiment approaches (multiple sources and/or multiple receivers) for a tomographic analysis.

The experiment requires both an energy source and a sensor. Two different implementations can be considered. The first is that the energy source and sensor are separate packages that are independently deployed on the surface; the second is has the source and sensor in a single deployed package. Additionally the trade space can include a surface package or a subsurface package. Each of these approaches has advantages and disadvantages.

Separate sources and receivers require more deployments. In the spacecraft concept that we developed (see below) that would require twice the number of arms. However, separate source and receivers provides more flexibility as to how the array is deployed as they can be placed such that the transmission geometry is optimized. Surface packages are easier to deploy and can simply be placed on the surface. Subsurface packages (penetrators), the typical approach considered in other studies, are more complicated to deploy because they must be fired at the surface with sufficient energy to penetrate. Such a deployment is also riskier because there are more failure modes.

With the motivation to keep things as simple as possible at this stage, we decided to keep the source and receiver together in a single deployable package. However, there was no technical analysis to determine if this was the correct approach in terms of energy coupling.

Explosions as a source of seismic energy (intentional or not) is a function of the so-called "depth of burst," particularly as it relates to the excavation of material during the formation of impact craters. For an given target and energy (and shape charge) there is a depth at which a maximum excavation efficiency is achieved. We are not interested in excavating craters, but those studies do show that when the charge is positioned at or above the surface, the excavation and energy transfer to the ground is minimized.

While a surface deployed package can work, it requires appropriate coupling with the ground. As noted above, in the Apollo 14 experiment, coupling was ensured by the astronaut pressing the thumper against the surface. We will need a passive mechanism to couple the device to the surface.

When considering how the source would be packaged and how it would transmit the energy to the surface (a gas driven impulse) combining the source and sensor is probably not an appropriate configuration. We would explore this in more detail in Phase II.

The method of deployment, however, does appear to be viable. Each package (source or receiver) is mounted at the end of arm (Figure 10). One end of arm is attached to the spacecraft, the other holds the surface package. The arm is folded for launch and cruise. Upon arrival at the target, the arm is unfolded with a length of about 3 m. The spacecraft maneuvers toward the surface making contact with the surface and pressing the package against the surface to achieve coupling. We did not consider the forces required for this in Phase I.

The arm releases the surface package and back away, moving on to the next location for deployment. The arms can be jettisoned after deployment to reduce spacecraft mass.

Once all of the packages are deployed, the sources can be detonated. The sources would detonated one at a time. The resulting data would be transmitted to the spacecraft. This proceeds in sequence until all of the sources have been detonated.

We considered the use of a NASA Standard Initiator (NSI) - PC23. Pyrotechnic devices are typically used for separation systems and explosive disconnects. The energy source consists of fine particle zirconium fuel mixed with fine potassium perchlorate as an oxidizer all bounded together with a Viton rubber binder. The unit is detonated by an electric current.

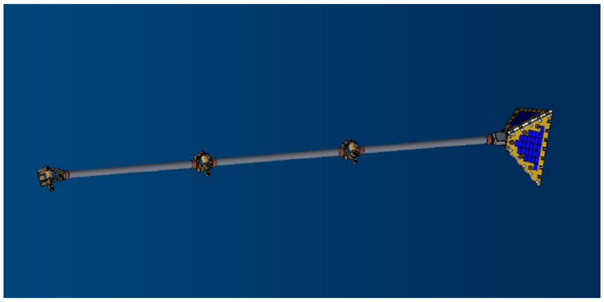


Figure 10. Arm holding the surface package. When extended the arm is 3 m long.

As noted above, these devices have an explosive yield of about 668 J. While we considered the seismic efficiency (*k*) in the modeling calculations, we did not consider the efficiency of the transmission of energy into the surface.

2.4 Objective 4: Design spacecraft carrier system that will deliver the sensor package and relay the data to the Earth.

An underlying theme of the Phase 1 was to minimize the resources required to conduct this type of mission, including not only costs, but also spacecraft mass and complexity. With that in mind, a spacecraft concept was developed that provided the necessary resources to conduct this type of mission (Figure 11). Figure 12 shows the spacecraft (with only two arms and surface packages) with the arms and the solar panels stowed.

This design assumed the targets listed below (Table 2) in terms of sizing the propulsion system and other factors (e.g., array size). Other targets in the solar system would require greater spacecraft capability. However, this design serves as a reference point.

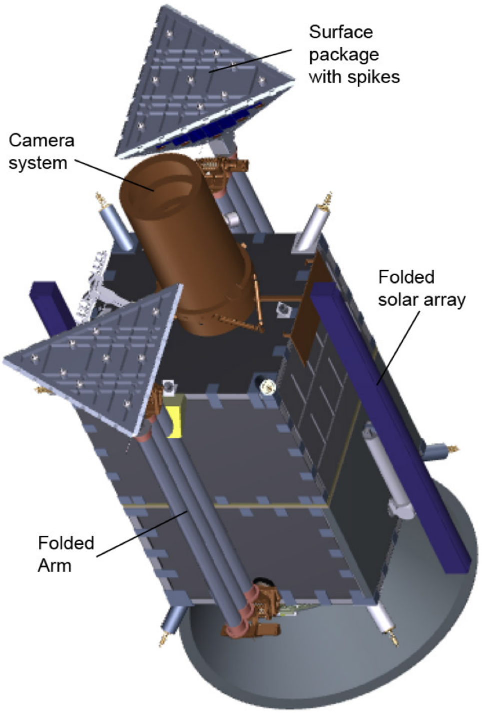


Figure 11. Oblique view of the spacecraft showing the arms and solar panel in a stowed configuration.

The spacecraft has a total dry mass of 195 kg (with margin) including the sensors. The average mass margin of about 11%. The main bus is square, 0.65 x 0.65, and about 1.1 m tall. Power is supplied by two solar arrays that are deployed after launch.

Arms are mounted to the side of the spacecraft the hold the surface package. During flight, the arm is folded and stowed against the spacecraft. Upon arrival at the target body, once a survey has been made to identify appropriate locations, an arm is unfolded. The spacecraft then navigates up to the body and presses the instrument package against the surface.

A camera system is mounted on one end of the spacecraft to observe the surface and determine the geology and topography and to define locations for placement of surface packages.

The intent here was not to develop a complete spacecraft design but rather to understand the principal components that would be necessary to conduct such a mission.

The assumption made here is that the target bodies are small enough that they are effectively zero-g environments and the spacecraft can simply maneuver up to and away from the body with minor propulsion.

Table 1. Flight System Mass Summary

Subsystem	**CBE (kg)**	**Cont. (%)**	**MERV (kg)**
Structures	52	10	57
Integrated Propulsion	16	3	17
Avionics	11	4	11
Electrical Power	27	7	29
Attitude Determination Control	12	7	12
Thermal Control	4	15	4
RF Communications	4	6	4
Harness	11	10	12
Spacecraft Bus	136	8	146
Instrument packages	42	15	49
Total Dry Mass	**174**	**10**	**195**
Usable Hydrazine Propellant*			109
Propellant Residual & Pressurant			5
Total Mass*			**309**
Launch Capability*			**358**

* These values are for target 1991VG.
Maximum expected resource value: MERV
Contingency = Maximum expected resource value - current estimate of resource value
% Contingency = [Contingency / (MERV-Contingency)] *100

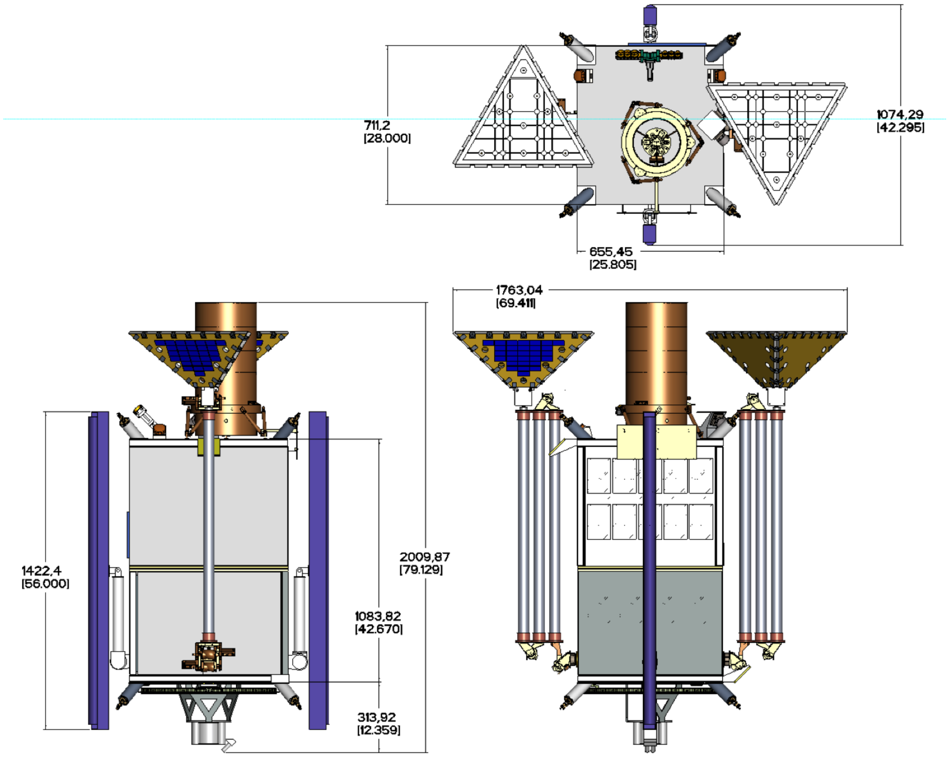


Figure 12. Two side and one vertical view of the spacecraft design. Dimensions are in mm (inches). The vertical view shows the top of the spacecraft with the imaging system.

2.5 Objective 5: Analyze a complete reference mission.

We identified a number of target near-Earth asteroids that would be candidates for such a mission (Table 2). The targets were selected as they had relatively low ΔV and C_3 requirements. Again the objective was to examine the minimum mission requirements. Main belt asteroids or comets would have high energy requirements because of the distance or the orbit inclination.

Table 2. NEO Targets

					Athena II Launch Vehicle	
Target	**ID Number**	**Absolute Magnitude**	**Launch Year**	**Spacecraft ΔV (km s^{-1})**	**Dry Mass (kg)**	**Wet Mass (kg)**
1991VG	3005816	28.5	2020	0.8	249	358
2007UN12	3390109	28.7	2020	1.0	235	369
2006RH120	3403148	29.5	2024	1.1	216	350
2008HU4	3409707	28.2	2024	1.3	206	268

The targets listed in the table are all relatively small in the 3-15 m size class. The objects are unresolved from the Earth, the dimensions are based on standard albedos (0.025 to 0.05) used to estimate the size (Pravec et al., 2012).

In an effort to design a representative NEO mission, we explored transfer trajectories in the early 2020's to a set of identified highly accessible NEOs. The search evaluated a grid of two-impulse Lambert trajectories from Earth to each of the targets over a 3-year span. Here, it is presumed that the launch vehicle will provide the initial ΔV to escape Earth, and the spacecraft will use monopropellant hydrazine (specific impulse of 233 sec) to provide the rendezvous burns. The smallest compatible launch vehicle is Athena II, for which two values are estimated: the wet mass and the dry mass (Table 2). The wet mass is the total mass that the launch vehicle needs to accelerate to the requisite escape velocity. This value includes the propellant required by the spacecraft to rendezvous. The dry mass is the spacecraft mass excluding this propellant, and thus represents the available bus and payload mass for the spacecraft design.

Among these coarse-search trajectory solutions, we selected 1991VG as a candidate target. The trajectory to this target was locally optimized to balance the launch vehicle and spacecraft propellant requirements. The nominal trajectory is shown in an inertial frame in (Figure 13). From this plot, it is clear that the target (1991VG) is in a very Earth-like orbit. The transfer consists of a 790 day time-of-flight, in which the spacecraft completes just under 2 heliocentric revolutions.

1991VG has an orbit that is very close to the Earth's making it an easy target to reach. Because its orbit is close to that of the Earth, it must be a relatively new near-Earth asteroid as such objectives rapidly either impact the Earth or are ejected from the inner solar system. The object is an interesting target because objects in this near-Earth orbit are difficult to explain.

The nominal trajectory was extended into a 21-day launch window, which is depicted in Figure and summarized in Table. The launch vehicle needs to provide an escape energy (C3) of 1.5 $km^2 s^{-2}$ and the spacecraft needs to provide at least 600 $m s^{-1}$. For an Athena II, the corresponding lift mass and available dry mass are 355 kg and 276 kg respectively. In addition to the rendezvous burn, the spacecraft will need ΔV for trajectory correction maneuvers, launch vehicle dispersion corrections, and proximity operations. Estimates for these values are given in Table 3.

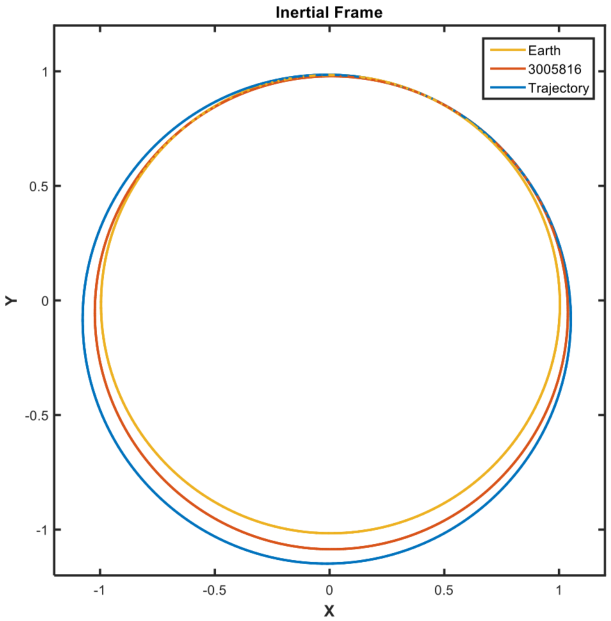


Figure 13. Plot of target NEO, Earth, and transfer trajectory in an inertial frame. Units in AU.

The mission would launch on November 28, 2019 and take 790 days to reach the asteroid (Table 4). The mass of the spacecraft and instruments is such that we can reach these targets using the capabilities of an Athena IIc launch vehicle, with adequate margins (Table 1). Once at the asteroid, the spacecraft establishes a station-keeping position and we begin to image the surface to determine the shape and geology. Using those data, we select locations for the deployment of the surface packages using the spacecraft arms.

Figure 14. Artist's conception of the Hayabusa spacecraft at Itokawa. The image does illustrate how the scene as the surface packages are deployed.

Figure 14 (also Figure 1) illustrates how the deployment might appear. While this image depicts the Hayabusa spacecraft, the general features are applicable here. The spacecraft maneuvers toward the body until the arm and surface package touch the surface. The package is deployed and the spacecraft backs away.

After all of the packages are deployed, the spacecraft will navigate away to a safe distance. We will spend at least several days in a passive listening mode with the sensors on to collect background noise data. It is unlikely that bodies of these sizes will have significant internal seismic activity. Assuming the solar panels on the surface package can provide sufficient power to keep the stations alive, there is no limit to the length of time that could be spent in a passive listening mode. It is possible that over a heliocentric orbit that tidal-effects could create enough stress within the body to generate internal seismic activity. That same long term listening mode could be conducted after the active seismic experiment. While we originally considered combining the source and receivers together into single packages, with the result that all but the last receiver was destroyed, further analysis suggest that might not be the optimum solution. If the sources and sensors are packaged separately, then the array could listen for internal activity after the active experiment ends.

Table 3. Preliminary ΔV Budget	
Parameter	**m s^{-1}**
Rendezvous Burn (maximum over launch window)	600
Launch Vehicle Dispersion	50
Trajectory Correction Maneuvers	25
Proximity Operations	100

Once the noise environment is defined, we will detonate the charges in a series of separate events. The data from each event will be downloaded for quick analysis before the next source is detonated. Depending upon the rotation rate, data collection from each package could be accommodated either by waiting until the station rotates into view of the spacecraft or the spacecraft can move to see the station. The total data volume is extremely low as it consists only of a few minutes of data following the detonation of a source.

Table 4. 21 Day Launch Window for Mission to 1991 VG	
Parameter	**Value**
Launch Window Duration (days)	21
Launch Window Opens	November 28, 2019
Launch Window Closes	December 19, 2019
Maximum ΔV (km s^{-1})	0.6
Maximum C_3 (km^2 s^{-2})	1.5
Athena II Lift Mass Capability (kg)	355
Maximum Available Dry Mass (kg)	276

3.0 Participants and Contributions

The group consisted of individuals directly funded to work on the project and collaborators to whom we turned for specific expertise. Below the major contributions of each of the participants are outlined.

Jeff Plescia (JHU/APL): Plescia was the PI and was responsible to ensure that the work is completed on schedule and on budget. He defined the overall objectives of the study and sets requirements for engineering analysis. He is responsible for reporting the results at the PI meeting and in the final report.

Clint Apland (JHU/APL): Apland led the spacecraft design effort and identified possible explosive components that could be used as energy sources on target bodies.

Justin Atchison (JHU/APL): Atchison did the detailed analysis of the candidate asteroid targets and the propulsion requirements and launch capabilities.

James Leary (JHU/APL): Leary lead the APL engineering activity to define the mechanical systems required for the mission. He was responsible for the overall spacecraft system design.

Nick Schmerr (Univ. Maryland): Schmerr was responsible for modeling studies that defined the seismic transmission and scattering characteristics of the target bodies. Those studies also defined the required energies necessary to conduct the experiment.

Kim Strohbehn (JHU/APL): Strohbehn was responsible for the overall design of the sensor and for the components that are required for the surface package.

4.0 Outstanding Questions

The work done under Phase I has demonstrated the viability of a low-cost, relatively simple mission concept to address significant scientific questions - a small spacecraft sent to a near-Earth object, rendezvous with that object, deploy surface packages and conduct an active seismic experiment. We approached the Phase I with the objective of defining a minimum mission and to define those areas that would require additional work.

The areas that require additional analysis include:

Energy sources: The analysis determined that a single NSI was insufficient to produce the required seismic energy. A larger source is required. That could consist of groups of NSI fired simultaneously or a larger single charge. There are several trades in this area that should be examined. An NSI is known, space-qualified component, but it is unclear if they can be detonated with sufficiently precise start time and yield duration that they would appear as a single impulse. Multiple NSI reduces risk because if a single charge fails to ignite the remaining charges will produce some energy. A larger single charge would allow for a single impulse. However, if that charge fails, there is no recovery. That assumes that extra charges are not carried to mitigate such a risk.

Surface coupling: A critical issue is the coupling between the sensor and source and the surface in order to provide for energy to be injected into the surface and the subsequent ground motion recorded. We understand the relation between total energy released by a charge and the amount that would be converted to seismic energy. However, we do not understand how the source would be coupled to the surface to optimize energy transfer into the ground. That energy transmission will be a function of how the source is coupled to the ground.

Anchoring: During Phase I we assumed a simple anchoring scheme in which a number of small spikes were attached to the bottom of the surface package. While that may be sufficient for the sensor, it is unlikely to be appropriate for the source. If the coupling between the source and the surface is weak, under the low-g environments to be explored, the source could simply propel itself away from the surface imparting little energy into the surface.

Analysis of complex bodies: The seismic analysis we conducted was for a simple object with a surface regolith and a solid interior. Most asteroids and comets are irregular and many have complex surface geology and presumably subsurface geology (Figure 6). The irregular shaped and complex heterogeneous target properties will significantly influence the propagation of seismic energy. Additional analysis of complex shapes and physical properties needs to be done to understand what types of targets could be successfully studied with this technique.

Target body mass limits: We assumed during Phase I that the surface gravities of the target bodies were small enough that it did not significantly influence spacecraft motion. Such a requirement limits the size of the target body that can be investigated. Larger bodies are important targets for exploration, but the larger gravity fields will place higher propulsion requirements on the spacecraft. Understanding the transition between what might be considered passive station keeping and landing should be understood. Such an analysis would need to be done in the context of a particular spacecraft design.

Target Population: The Phase I study examined a number of near-Earth asteroids whose orbit parameters were similar to the Earth's. While such targets may be useful for a general proof-of-concept study, the population of objects that are of interest to science is incredibly larger with greater distances from the sun, more elliptical orbits and greater orbital inclinations. Certainly a spacecraft could be designed (and have been designed) to reach these various targets. The issue would be the trade between target location and spacecraft requirement and where the boundary between a small mission and a large mission lies.

5.0 Conclusions

As a result of the Phase I study, we have demonstrated that a mission to a small body (asteroid, comet) whose objective is to conduct a seismic experiment to understand the interior structure, can be accomplished with small (<200 kg) spacecraft launched on a small launch vehicle (Athena IIc).

We modeled the seismic response of a small body and calculated that the energy necessary to propagate through the body and be detected by a seismometer. These calculations provide guidance as to the type of energy source that is required. A simple energy source similar to a NASA standard initiator (NSI) can be used, although a single NSI is insufficient. An NSI is an explosive pyrotechnic that is used to sever connections on spacecraft. Use of such an energy source has illustrated two additional areas of study - anchoring of the source and sensor to the surface and understanding the efficiency of energy propagation from the source into the surface.

The spacecraft has the ability to carry and deploy a series of source/sensors to conduct the experiment by placing them on the surface. We identified a suite of candidate near-Earth asteroids as targets and used one 1991VG as the target to calculate the mission trajectory and ΔV requirements. Spacecraft and launch vehicle performance are launch that any of the candidates could be reached with appropriate mass and launch margins.

Sources and sensors are deployed from arm attached to the spacecraft. The spacecraft maneuvers next to the target body and presses the sensor against the surface and releases it. After emplacing all of the surface packages, the sensors are monitored for a period of time to measure the seismic noise. Finally, the active seismic experiment is conducted.

The work conducted during Phase I demonstrates that a small mission can be designed to conduct an active seismic experiment on a small near-Earth body. While other targets may require more performance, the basic architecture is viable for any target.

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