SHOTPUT: A JPL Planetary Summer Science School study

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Abstract—During 2015, a unique launch opportunity exists that allows for a New-Frontiers-class mission to discover a compositional gradient of small bodies in our solar system. [1,2]The proposed seven year mission includes a flyby of main belt asteroid (108144) 2001 HM1, a flyby and impactor release (a la Deep Impact) at the Trojan asteroid (624) Hektor (a suspected contact binary) with companion P/2006, and a flyby with impactor release at the Centaur asteroid 39P/Oterma. The variety of types and positions of these small bodies will help answer some of the fundamental questions we have for the evolution and composition of our solar system.

The Jet Propulsion Laboratory (JPL) Planetary Science Summer School team has designed a mission designed to address all of these scientific questions and design objectives. We will describe instrument selection, launch dates and mission timetables, measurement and encounter strategies, impactor design and benefits, data acquisition and communication tradeoffs and provide background into the mission science goals. Furthermore, cost estimates and a work breakdown will be provided to prove the practicality
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of meeting all the science objectives within a short period of time. A strategy for the development of our system based upon previously used instruments and hardware will also be presented.

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[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE
[2] IEEEAC paper#1634, Version 2, Updated 2009:01:09

1. Introduction

Interest in small-bodies throughout our solar system has steadily increased over the last several decades. Several missions [4], [9] have been launched to visit these objects, but a comprehensive view of their composition [7] and morphology has yet to be undertaken. We propose a unique mission designed to visit a broad spectrum of objects forming a compositional gradient.

Motivation

Based on science objectives derived from the Decadal survey (2), National Research Council reports (1) and a NASA Announcement of Opportunity (AO), we intend to answer questions about the origins, physical properties, and compositions of Trojans and Centaurs and how the color, structure and evolution of these objects compare to those of comets. A unique aspect of our mission is the double-impactor: two tungsten spheres to be used at Hektor and Oterma to give a glimpse of the subsurface composition, which may provide suggestions about the origins of these objects.

Rather than rely on ground-based or near-Earth telescopes, this mission will provide *in situ* measurements across a broad spectrum of the solar-system. These objects also provide an accessible source of Kuiper Belt and cometary material without traveling beyond 6 AU. Fundamental properties, the possibility of organic molecules, and the evolution of orbits can only be addressed by sampling the small bodies up close. Results from the mission can be compared with formation scenarios, such as the Nice Model for consistency and accuracy.

This mission will significantly advance our understanding of the outer solar system and provides never-before-seen data for several different types of objects. The instrument suite is robust with proven and reliable science capability and relies upon a well-designed trajectory to visit all of the various bodies. Overall the mission is priced below the budget cap and sized for a medium launch vehicle.

Mission Heritage

Much of the spacecraft heritage stems from other asteroid encounter missions. The impactors in particular are similar in design to the Deep Impact mission [9], and the computer system and software were originally designed for the Mars Science Laboratory. By using parts and designs from previous missions, we have significantly reduced the cost of this mission.

2. Target Selection

This mission targets three small bodies: one main belt asteroid, one Jupiter Trojan asteroid and one Centaur asteroid. The focus of the mission is the science relating to the Trojan asteroid and the Centaur, the main belt asteroid observation is the result of a fortuitous trajectory selection.

Little is known about the Trojan asteroids due to the inherent difficulty in observing low albedo objects both small and distant (~ 4 AU in opposition) [10]. It is known that these objects lie in the stable L4 and L5 Lagrange points ahead of and behind Jupiter in its orbit.

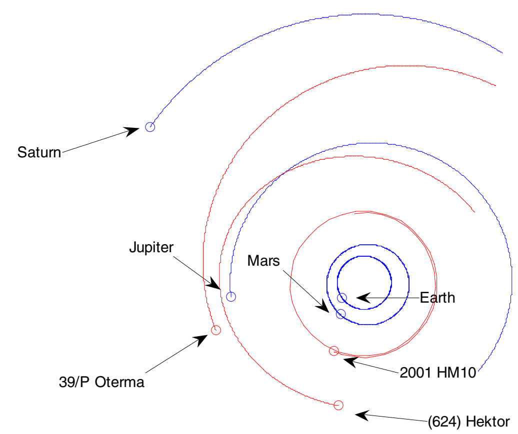


Figure 1: *A view of the solar system including the location of the small-bodies of interest at the time of the Oterma encounter.*

The two competing theories as to the origin of these bodies are (1) the bodies formed in the region near Jupiter and were captured into the Lagrange points during Jupiter's growth and [11] (2) the Trojan asteroids were captured from chaotic orbits into their current orbits [3]. Little is known about the composition of these bodies other than Trojans are composed of generally dark material, thus implying that they could consist of organics. The chosen Trojan asteroid (624) Hektor is the largest of the Trojan asteroids and is known to have a companion object (S/2006) [12]. The mission will provide compositional data and will verify verifying gravitational and dynamical models of this binary systems. With the expected large population of binary asteroids as well as Kuiper Belt objects in our solar system, a greater understanding is needed of their origin and behavior, especially if Jupiter Trojan asteroids originated from further out in the solar system. By traveling along a trajectory that has an inclination of six degrees to meet Hektor, this mission will additionally collect and analyze dust samples above the ecliptic plane.

The mission will culminate with a trip to a 39/P Oterma (1000177), a suspected active Centaur, a member of a class of bodies on chaotic orbits stable on the order of 10,000 years [13]. Oterma was first discovered in 1943 as an active body although active outgassing was last seen in 2004. Aside from one object, active Centaurs have been poorly studied and never visited. Because the Centaur asteroids have dynamically migrated from one of the outer cometary reservoirs (either the Kuiper Belt or the Oort Cloud) these objects present a relatively close to Earth opportunity to observe bodies. Both comets and asteroids are believed to have delivered most of the volatiles to the Earth [14]; thus studying the materials contained within the cores of these objects as well as Centaurs may be key to understanding the organic and volatile material delivered to Earth. Therefore this impactor mission along with the remote sensing instruments will provide unprecedented views of a recently active body beyond Jupiter's orbit.

3. Scientific Instruments

The science instrumentation onboard the SHOTPUT mission contains several observational instruments as well as an *in-situ* ion mass spectrometer. The choice of the imaging instruments is leveraged from the success of the Deep Impact mission which obtained significant increases in our understanding of cometary bodies. The addition of a dust analyzer allows for *in-situ* measurements of the composition of these bodies.

The primary observational science will be obtained by the high resolution multi spectral imager which will give general topology and mineralogy as well as detection of some volatiles if present. This instrument covers the 430 to 3000 nanometers (0.43 to 3 microns), which covers visible light and the near-infrared. This imager is able to detect OH and H_2O if present. The presence of any volatiles on the surface of the Trojan asteroid would raise questions as to the origins of these bodies. Though the orbit of Jupiter is outside of the frost line where volatiles are found in ice forms, the Trojan asteroids are expected to be devoid of volatiles. These bodies are observed to have very low albedos suggesting that they are covered by carbon compounds[7]. The subsurface of these bodies may contain volatiles trapped during their formation. This would be observable by this imager. The centaur is expected to contain some volatiles. Obtaining an inventory of the volatiles on this body will provide information regarding the origins and evolution of the solar system.

The thermal infrared imager will provide enhanced mineralogy measurements as well as the possibility of imaging the resultant crater floor and determining the pristine materials' composition. This imager is optimized for determining the mineral composition of these bodies. The mineralogy gives information as to the conditions in which these bodies are formed. For example this instrument would be able to differentiate between compounds produced in extremely high temperature environments versus those that have been produced in more mild environments. Since little is known about how both the Trojans and the Centaurs formed, any information may be paradigm changing.

Navigation cameras onboard will provide stereo images of the body to determine the topology of the body. It is not clear how solidly these bodies are held together. Some asteroids are supposed "rubble piles," which are basically pieces of rock loosely bound and orbiting their respective center of gravity. If these bodies are in touching each other than they are considered contact binaries; the Trojan asteroid target, Hektor, supposedly has a binary that may be a contact binary. Investigating the topology of the body will give information as to the cratering of the surface as well as any weathering processes that are visible.

SHOTPUT GOALS AND OBJECTIVES		**Measurement**	**MSI**	**RSE**	**TIS**	**DSIMS**	**UVIS**
Chemical and physical composition	Measure fundamental properties	Mass of bodies (and binaries, if possible)	x	x			
		Topography	x				
		Surface and subsurface thermophysics			x		
	Characterize organic components	Organic composition of volatiles and dust from ejecta				x	x
		Organic composition of surface/subsurface (as ejecta)	x		x		x
		Organic composition of dust				x	x
Origin and evolution	Where in the solar system did these bodies originate?	Measure stable isotope ratios of hydrogen					x
		Measure stable isotope ratios of C, N, O				x	
		Selected mineralogical composition of surface/subsurface	x		x		x
		Bulk chemistry of surface	x		x	x	x
		Density		x			
		Ice presence and abundance	x		x		
	Has dynamical migration occurred?	Morphology – e.g., has the object experienced jetting?	x				
		Determine degree of activity, outgassing rate	x		x		x
		Presence of volatiles surrounding object				x	x
		Relationship between body, binary, and satellites	x	x	x		
	What evolutionary processes have	Degree of weathering that has occurred	x				x
		Morphology of surface	x				
		Selected mineralogical composition of surface/subsurface	x		x		x
		Bulk chemistry of surface and subsurface	x		x	x	x

	occurred?	Density		x			

Table 1: *Science Traceability Matrix*

Abbreviation	Name	Mass (kg)	Power (W)	Description
MSI	Multi-Spectral Imager	52	58	Narrow angle camera and IR spectrometer. Determine topography, mineralogy (Fe- and Mg-bearing silicates, and organics), presence and abundance of water ice, and potentially the degree of space weathering. Wavelength range 1.05 - 4.8 µm.
TIS	Thermal Infrared Spectrometer	14.1	13.2	Additional IR spectrometer for further identification of surface and subsurface mineralogy, volatiles, and thermophysical properties. Spectral range 8 to 25 µm.
DSIMS	Dust Secondary Ion Mass Spectrometer	19.8	20.4	Time of flight mass spectrometer. Characterizes the chemical composition of dust grains in each region. Measures elements, isotopes, and functional groups.
UVIS	Ultraviolet Imaging Spectrograph	15.6	12	Determine D/H ratio, hydrocarbon content, ion emission spectra (e.g., N^+, N^{2+}, O^+, O^{2+}), and volatiles (e.g., H, H_2, N, N_2, Ar, CO, C_2N_2). Can also assess UV spatial variation due to surface/exposure ages.
RSE	Radio Science Experiment	n/a*	n/a*	Uses spacecraft radio system to measure the mass of the target bodies. During the flyby the spacecraft will be gravitationally attracted to the target body and create a velocity perturbation.
WAC	Wide Angle Camera	4	3	Required for optical navigation. Includes 2 cameras for stereo images and a 5 color filter wheel (SDSS – ugriz). Can also serve scientifically for mapping and topography.

*using the radio system for measuring mass does not add any extra weight or power requirement to the spacecraft

Table 2: *Science Instrumentation Description*

Lastly the UV spectrometer will be able to measure the composition and isotopic composition of plume material through stellar occultations. This measurement will be obtained by viewing a known star before looking through the plume and after and comparing the spectra produced. Any absorption within this spectrum will give information about the composition of the plume material. In many cases volatiles can be observed by UV stellar occultations and with this instrumentation isotope ratios of these volatiles can be obtained. The measurement of the isotopic ratio of volatiles in these bodies has implications for the origin of the solar system. The D/H ratio in water ices can specifically place a range on the location of the formation of the ices in the context of several models[8].Table 1 below provides the science traceability matrix based on the goals and investigations for this mission

4. MISSION AND TRAJECTORY

One of the scientific goals of the SHOTPUT mission is to acquire a compositional gradient of small body objects in our solar system. By utilizing a unique and innovative trajectory, the mission will capture information about a main-belt asteroid, a Jupiter Trojan and a Trans-Neptunian Centaur. In addition, the Trojan is a suspected contact binary with companion while the Centaur is possibly active. No previous mission has visited such a diverse selection of targets let alone return so much data.

Launch and Early Mission

On March 27, 2015, a unique launch opportunity exists that allows completion of this complex and exciting mission. Onboard an Atlas V 531, SHOTPUT will launch from the Kennedy Space Center with an initial C3 of 51.4 km^2/s^2. This initial trajectory will send the spacecraft away from Earth and towards deep space. Along the way we will encounter 2001 HM10, a main belt asteroid on January 13, 2016.

Later that year, on June 14, 2016, the spacecraft will perform a deep space maneuver to return to Earth for a powered flyby. The spacecraft will pass within 300 km of Earth on May 17, 2018 and gain the inclination change needed. Upon leaving Earth orbit, the spacecraft will briefly flyby the Moon. These two bodies will serve as calibration points for the instruments and cameras onboard SHOTPUT.

Trajectory and Cruise

The majority of the seven year mission will take place in a cruise phase. On March 25, 2020, SHOTPUT will encounter the Jupiter Trojan Hektor (a suspected contact binary) and its companion S/2006. Directly after this encounter a deep space maneuver will be performed to align the spacecraft trajectory for the Oterma Encounter.

On October 30, 2022, the possibly active trans-Neptunian object Oterma will be encountered.

Encounter Strategy

There are three primary encounters taking place during this mission, one each for 2001 HM10, Hektor and Oterma.

The 2001 HM10 encounter will be a calibration test for the instruments before passing near the primary targets, Hektor and Oterma. The vehicle will enter an approach mode approximately 4 days or 3 million kilometers away. The imager will turn on for 4 hours per day and instrument checkout will continue (checkout begins two weeks out). During Far Encounter Mode, 3 days out, the IR imager turns on and the dust analyzer will be continuously. Radio science will begin and continuously collect data.

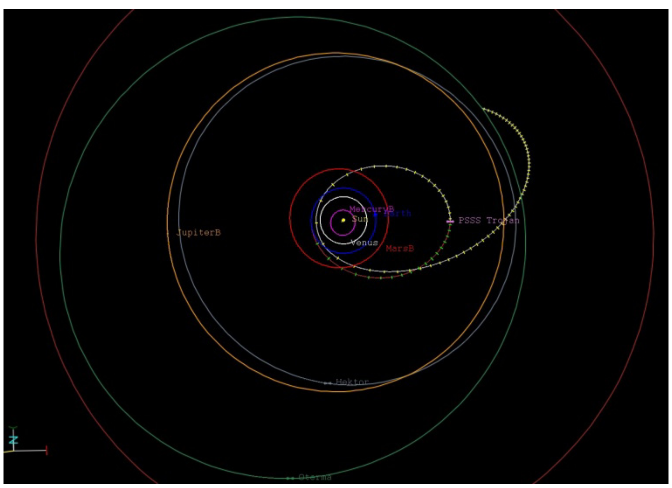


Figure 2: *Mission Trajectory*

Close Encounter begins 30 minutes away and 15 thousand kilometers. The TIS and UVIS will be turned on as the spacecraft speeds towards 2001 HM10 at 8.24 km/sec. The closest approach will take place at approximately 900 kilometers with the slewing maneuver described earlier. Instruments will then be shut off in the opposite order and time they had been turned on in returning the spacecraft to a cruise mode before its next encounter.

Science data will be transmitted to Earth for two weeks immediately following each encounter.

The encounters for Hektor and Oterma are more complicated due to the distance from Earth as well as the impactor science.

The approach mode will begin approximately 110 million kilometers away or approximately 150 days. Instrument checkout will begin and the imager will be on for 4 hours a day for trajectory correction. Far Encounter mode will begin 7 days out with the dust analyzer, continuous radio science and the IR imager. At 6 days out the impactor will release. The early release of the impactor will provide an impact approximately 1 hour before the closest approach for imaging and cloud dissipation.

Hektor will be encountered at 8.2 km/sec and with a closest approach of approximately 700 kilometers. The instruments will again turn off in the opposite order that the turn on sequence is initiated.

The encounter at Oterma is essentially the same as the Hektor encounter with an approach speed of 9.11 km/sec and closest approach of 800 kilometers. The approach mode will be entered approximately 34 million kilometers out or about 44 days.

Post-Mission

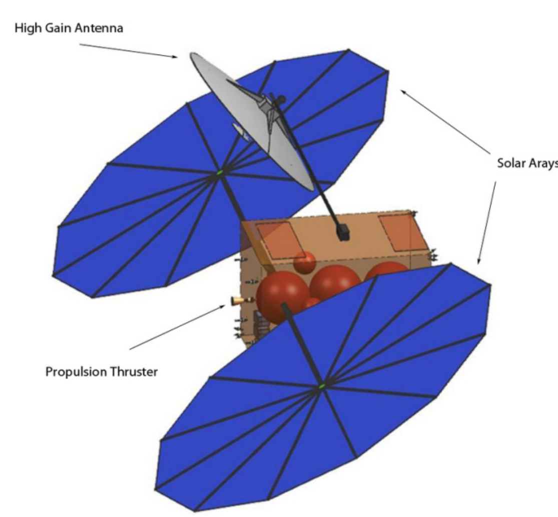
After October 30th, 2022, the spacecraft will continue to broadcast science data back to Earth for approximately two weeks. Following this time period the spacecraft can be used for deep space science or shut down. Its trajectory will not intersect with Earth until 2037 at which point it is approximately 0.6 AU away posing no hazard.

5. Spacecraft Design

The following sections describes the structural, power, thermal, propulsion, Altitude Control System (ACS), Computer Data System (CDS), software, and telecommunication subsystems design.

Structures

The main structure of the spacecraft bus assumes bearing carbon fiber panels encasing an aluminum honeycomb core,



with additional mounts for the instruments and tanks. The probe, shown in Fig. 3, consists of the probe body, a single propulsion thruster, two solar arrays and a deployable high-gain antenna. A close up view of the probe,

Figure 3: *External Structure of SHOTPUT*

shown in Fig. 4, include a single oxidizer tank, two fuel tanks, four radiator panels, twelve RCS thrusters, four reaction wheels, three pressurant tanks, the instrument package and impactor, as well as CDS and the backup battery system.

The high gain antenna has a requirement of maintaining Earth facing during the entire close encounter for both Hektor and Oterma. During this time, the spacecraft rotates 180 degrees so that the instruments panel faces the asteroid during the close encounter mode. The antenna is attached to a single axis gimbal on the end of the deployable boom. The boom length and location is dictated by several requirements: thruster plume impingement,, and maintaining Earth contact during the close encounters. The antenna is located such that a portion of the antenna hangs

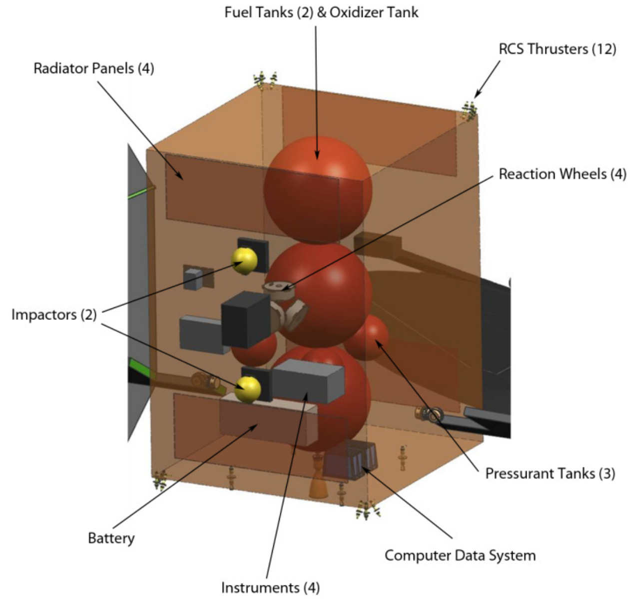


Figure 4: *Internal Structure of SHOTPUT*

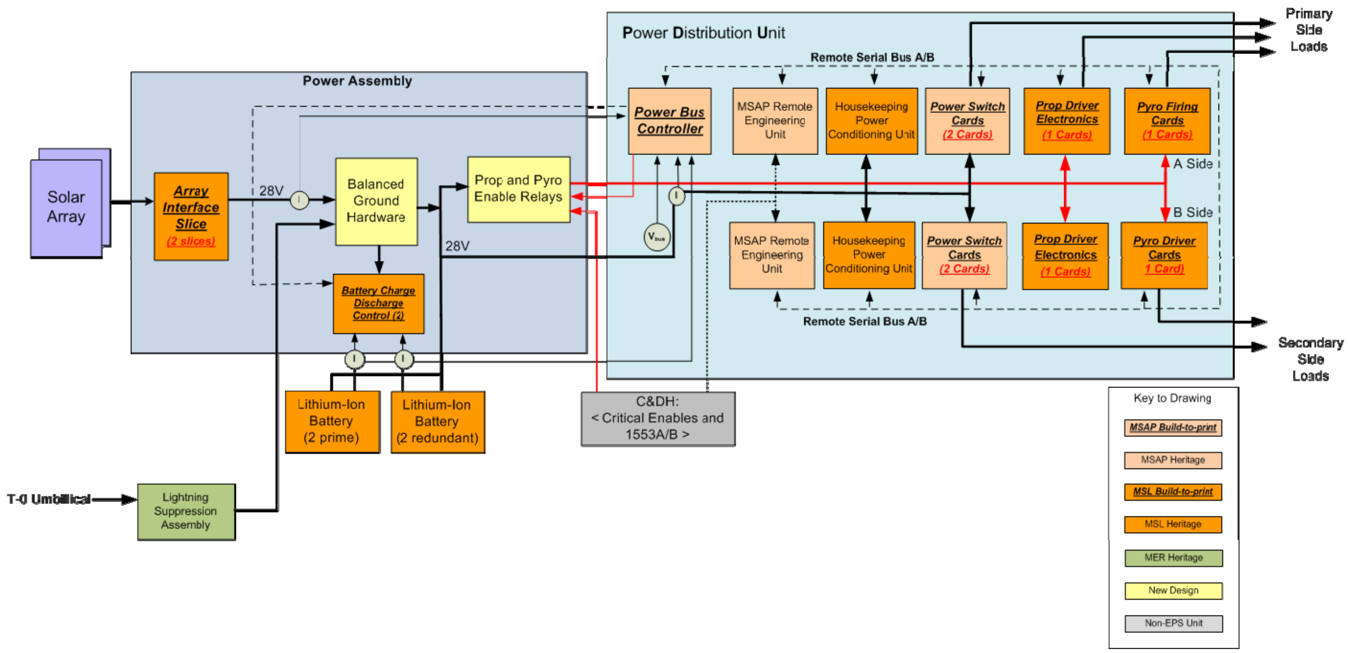


Figure 5: *Power Distribution and Assembly*

over the side with the propulsion thrusters. However, the antenna is placed such that the antenna pattern coming directly from the dish avoids going through the spacecraft (ignoring coning). During any planned thruster firings, the antenna would be turned away from the spacecraft to have the back of the dish facing any possible plume impingement.

The two solar arrays are on the opposing faces of the spacecraft and are each connected to the spacecraft by a single-axis gimbal. The arrays will rotate in the same plane as the high gain antenna, since the Sun and the Earth will be in generally the same direction during the science observing portions of the mission. The solar arrays are particularly

vulnerable to space debris and will be feathered during the close approach encounter, to reduce footprint exposed.

Power

The power subsystem inherits its design from previous systems used for the MSAP, MSL, and MER missions.

Designed for the farthest encounter distance at 5.5 AU, the power subsystem is rated Class A/B with a dual string redundancy. The power distribution and assembly is shown in Fig. 5.

Two GaAs TJ UltraFlex solar arrays with 29% efficiency and 80% cell packing factor provide power for the majority of the mission. Sized for the approach mode, the solar arrays have a combined mass of 115.20 kg and measure 42.59 m^2, providing a total of 546 W EOL; the solar array power draw at the far and close encounter is 2.5kw-hr and 0.5 kw-hr, respectively. Two 8-cell Li-Ion batteries measuring 864 W-hr each and a 25% maximum discharge provide additional power for the spacecraft, up to 0.32 kW-hr at the far encounter and 0.52 kW-hr during the close encounter. Two backup batteries are available in case of power failure, and overall, the power is compliant with the launch and eclipse requirements. The power requirement for the various subsystems and phases is shown in Table 3.

Table 3: *Power Budget*

Subsystem / Instruments	Power (W)									
	Launch	**Maneuver**	**Cruise**	**Deploy Impactors**	**Close Encounter**	**Far Encounter**	**Approach**	**Telecom m**	**Safe**	**Eclipse Cruise**
ACS	43.4	85.9	85.4	93.3	95.9	93.3	93.3	85.9	45.9	85.4
CDS	51.4	55.8	55.8	55.8	111.5	55.8	55.8	55.8	55.8	55.8
Instruments	0.0	0.0	0.0	58.0	97.7	97.7	58.0	0.0	8.8	0.0
Propulsion	33.3	117.3	15.3	15.3	15.3	15.3	15.3	15.3	33.3	15.3
Telecomm	12.0	63.8	12.0	63.8	63.8	63.8	12.0	63.8	63.8	12.0
Thermal	23.3	39.6	39.6	34.6	29.6	39.6	39.6	39.6	39.6	39.6
Power	37.7	62.3	45.8	58.3	73.5	63.3	53.3	51.3	46.7	45.8
Total	201.2	424.7	253.9	379.1	487.3	428.7	327.3	311.6	293. 9	253.9

Thermal

The spacecraft is designed to handle extreme external temperature while maintaining stable internal temperature in an acceptable range. The high-end external temperature occurs around Earth's orbit where the spacecraft has the maximum exposure to the sun's radiation. On the other hand, the low-end external temperature occurs during the Centaur fly by and is less than 1/100 than that of the Earth flyby. The spacecraft can take the advantage of the minimum heat of 287 Watt generated during its operation as the main energy to keep components warm within the acceptable operating temperature. Using this approach, the thermal control hardware can be realized entirely with thermal blankets, heaters, and radiators with no moving parts. This increases the system reliability while minimizing the mass and construction cost.

Twenty layers of thermal blankets are used on the outer layer of spacecraft enclosure to provide insulation that is sufficiently thick to withstand the Sun's radiation near the earth flyby. A radiator with the surface area of 0.45 m^2 is placed outside the spacecraft container for radiating excessive heat throughout the mission to the Trojans and Centaurs. When combined with silver Teflon coating on the radiating surface, the radiator can effectively reflect the Sun's radiation with minimal effect on the spacecraft internal temperature. In addition, heaters are used to provide stable temperature control for onboard equipment within their operating range and the total maximum heating requirement is approximately 40 W.

As the spacecraft travels away from the Sun, most components in the spacecraft must be kept warm above their lowest operating temperature limits. Inside the spacecraft, all component modules are coated with black paint to increase emissivity. Heaters are used sparingly to bring equipment up to operating temperature. Thirty-five heaters are used to keep fuel lines and propulsion tanks above 10˚C. Thirty thermistors are mounted on various places in the spacecraft and are monitored by the onboard computer to maintain the operating temperature between 10 ˚C and 40 ˚C. In addition, precision thermal sensors and heaters are used on all instruments containing precision references to assure ultra-stable operating temperature which results in accurate data acquisitions and downlink communications. During the entire operation, the spacecraft does not travel exceed 6.8 AU. The solar panels will be operating at the temperature above -147 ˚C and requires no extra heating.

Propulsion

The propulsion subsystem is a dual-mode system, driven by the specified mission Delta-V, ACS momentum dumping, and the payload limit of 1890 kg for the Atlas 531 rocket.

The dual-mode system entails a bipropellant main engine and monopropellant reaction control systems (RCS) and thrust vectoring control (TVC) thrusters, shown in Fig. 5. N_2O_4 is used as the bipropellant oxidizer, with N_2H_4 as the fuel for the monopropellant RCS and TVC thrusters, and helium as the pressurant. Identical tanks are used for oxidizer and pressurant as well as the oxidizer and fuel, and are sized for the launch vehicle capability. The propellant tanks use surface tension propellant management devices.

As the use of a gimbal system is expensive and risky, the main engine is fixed and utilizes four TVC thrusters; the

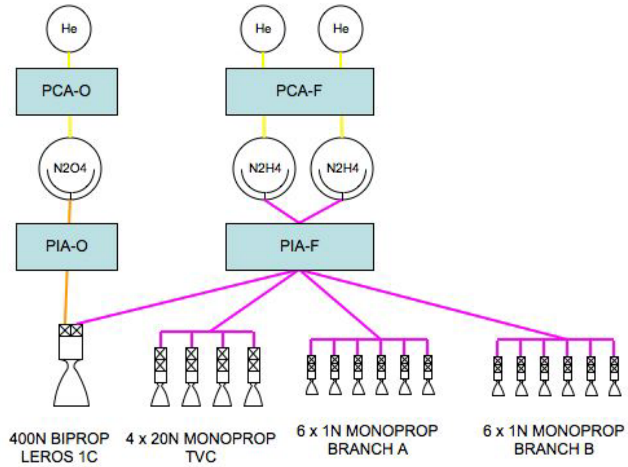


Figure 6: *RCS and TVC Thruster Architecture*

RCS thrusters are divided into two branches of six thrusters, each branch further divided into two sets of three thrusters, as seen in the spacecraft configuration (Fig. 6). All 12 of the thrusters are used nominally with pure couples; six can be used for degraded redundancy.

The ACS momentum dump requires 20 kg of propellant, and accounting for the mission's total Delta-V, storable bipropellant is used, creating an approximate propellant fraction of 30%. Off-the-shelf components are preferred for the dual mode design, and the selective redundancy is appropriate for class A/B missions such as this. The main engine and TVC thrusters are single string, comparable to previous missions such as Galileo. The design of this dual mode propulsion system supports mass growth up to the maximum of the launch vehicle capability as well as the next rocket size up, Atlas V41. All components are taken from existing designs, requiring no additional cost or risk for development.

Attitude Control System (ACS)

The attitude control system requirements are driven by the optical cameras during the various encounter phases. The objective is to minimize the pixel smear during the close encounter while still having pointing accuracy during far encounters. Four reaction wheels will be set up in a pyramid formation to provide for a single reaction wheel failure.

The most complicated maneuver for the ACS system is the slew maneuver upon close approach. At the minimum approach distance, SHOTPUT will have to turn very quickly to minimize pixel smear. The reaction wheels are rated for 2000 rpm providing 6.5 deg/min rotation. During slew, the spacecraft will first reverse the wheels to -2000 rpm and then speed them up 4000 rpm providing 13 deg/min with only three wheels (in case of a single failure) or 19 deg/min with all four wheels.

Computer Data System (CDS)

To meet the New Frontiers cost limit, the Computer Data System (CDS) utilizes the Multi-Mission System Architectural Platform (MSAP) with a heritage from the Mars Science Laboratory (MSL). Compared to Solid State Recorders (SSR), MSAP is lower in mass, volume, and power consumption, and is chosen to reduce the cost and risk of the mission. The CDS has an estimated data volume of 11.5 Gbits during the mission, and requires four 3-Gbits Non-Volatile Memory (NVM) cards, providing a total of 12 Gbits of storage capacity. The science data are compressed by the individual instruments, and the actual implementation of the data compression is decided by the instrument developers. The data storage requirements for the mass memory are 8.5 Gbits total for science and engineering data storage during close encounter, 1 Gbits for flight software, and 2 Gbits for engineering telemetry and margin during post encounter phase.

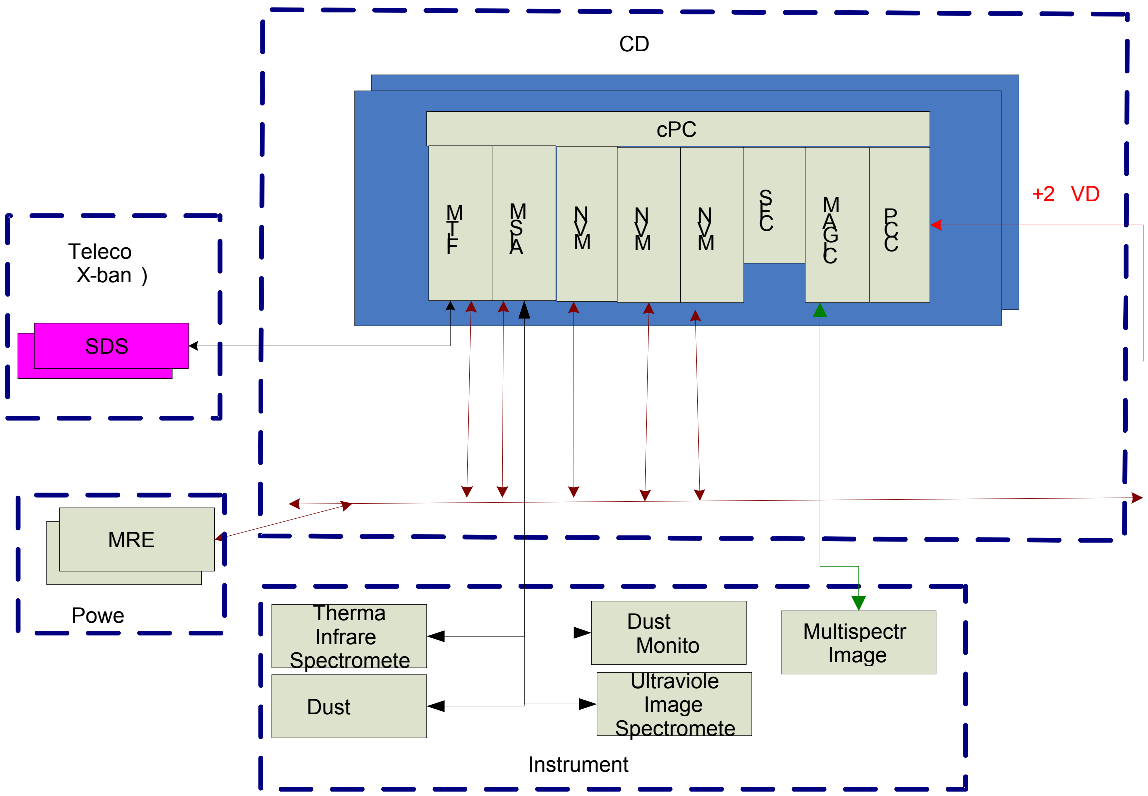


Figure 7: Diagram of the Command and Data Handling System

The CDS uses a redundant flight controller to perform science data processing and flight system processing and control. The dual-string CDS configuration for the mission includes

- RAD750 Processors with 128 MB of rad-hard SRAM
- Three Non-Volatile Memory (NVM) card with 4 Gbits of chalcogenide RAM (CRAM)
- MSAP Telecommunication Interface (MTIF) board
- MSAP System Interface Assembly board (MSIA)
- MSAP Analog GNC Interface Card (MAGIC)
- MSAP Remote Engineering Unit (MREU)

A block diagram of CDS system is provided in Fig. 8.

Once the science data is retrieved and stored, the spacecraft transitions into telemetry mode where the collected data is transmitted back to mission operation center at JPL through NASA's Deep Space Network. The spacecraft uses a 3.6 meter dish high gain antenna with X-Band to maintain high data rate. Once the data is retrieved, science data is processed at JPL and then data are categorized into five levels for processing:

- Level 0: Raw telemetry from instruments (time-tagged, quality checked, chronological sequence)
- Level 1: Calibrated instrument data giving the physical parameter actually measured by the sensors
- Level 2: Calculated from Level 1 data; are related directly to the instrument measurement "footprint"
- Level 3: Smoothed and gridded data; level 2 data transformed into a common format
- Level 4: Derived Quantities

At the same time, data is also sent to the National Space Science Data Center to be stored and made accessible. The NSSDC is also responsible for the distributing portions of the data over the internet.

Software

Highly reliable software is a critical component of any long-life, highly visible missions. It is responsible for integrating all flight hardware functionalities into a cohesive system. At JPL, the established set of institutional software development and acquisition practices calls for conformity to the NASA Procedural Requirements for Software (NPR 7150.2) and requires the software management organization to be certified at CMMI Level 2 (or greater), which has been shown to correlate strongly with reduced defects and improved cost and schedule performance. Onboard the spacecraft, the flight software:

- Allocates and manages onboard computational resources for all engineering and science processing needs
- Performs memory management of command sequences and science data
- Executes command receipt verification and validation
- Performs self-test
- Gathers and reports health/safety status at the subsystem and flight system level
- Hosts onboard autonomy necessary to recover the flight system from anomalies encountered during all phases of the mission.

The flight software inherits from the Multi-Mission System Architecture Platform (MSAP), which provides portions of the Computer Data System (CDS), Systems Services & Fault, as well as Payload Accommodation. Minimal effort is assumed for the adaptation of these specific MSAP components for this mission, and efforts will be concentrated on re-testing these mechanisms. It is assumed that the flight software is only responsible for the high-level control of the flight components, with no role in the software components for the individual instruments. There are no data analysis components onboard, and the data is only stored and sent back. All implementations of the flight software are done in-house and fully co-located. The estimated development time is 71.1 work-years, an equivalent of 210.3k lines of code.

Telecommunication

The telecommunication subsystem requires two-way X-Band communications throughout the mission. The requirements for downlink data rates using the 34-meter Deep Space Network depend on the separation between the spacecraft and Earth and are listed in Table 4.

Distance between the spacecraft and Earth	Downlink data rate
3.66 AU	75 kbps
4.5 AU	50 kbps
6.4 AU	25 kbps

Table 4: *Requirements for downlink data rates*

The command bit error rate (BER) is required to be 1e-5 and the telemetry frame error rate (FER) is required to be 1e-4. A minimum link margin of 3 db is required in the communication links.

The pointing error depends on the beamwidth of the antenna and assumes the pointing loss to be less than 1 dB. The high gain antenna (HGA) is pointed within 0.2 degrees, the medium gain antenna (MGA) is pointed within 10 degrees, and the low gain antenna (LGA) is pointed within 45 degrees. The design assumes an error correcting 1/6 turbo code with 8920 bit frames for high rate links, and an error correcting 1/6 turbo code with 1784 bit frames for low data rate links.

The subsystem is a fully redundant X-Band deep space system. It contains two small deep space transponders (SDST) for X-Band uplink and downlink (with single redundancy). There are two traveling wave tube amplifiers (TWTA), each outputting 30 W. The X-Band high gain antenna is 3-meter parabolic dish with a single axis gimbal and has a gain of 45 db. A medium gain horn with a half power beamwidth (HPBW) of 20 degrees, and two low gain antennas with a combined HPBW of 90 degrees are operated during safe mode. The horn and the omni antennas operate at 10 kbps with the 70 meter DSN dish in safe mode. The system has two diplexers which allow the use of a single antenna for both uplink and downlink. The hybrid splits/ combines the signals while the Waveguide Transfer Switch (WGTS) and the Coax Switch (CXS) are required for switching the antennas. The total estimated mass of the telecommunication subsystem is 51.3 kg, with a peak transmit power of 64 W and a minimum (receiver on) power of 12 W.

6. Work Breakdown and Costs

Costs

The total cost of the mission is estimated to be $622.8 M, under the $650 M limit specified by the New Frontiers AO. A breakdown of the costs, detailing developmental, payload, flight, and operations is given in the subsequent sections.

Summary

The launch vehicle, an Atlas V 531, is provided through the AO and does not contribute cost to this mission proposal. The overall cost summary is presented in Table 5.

Launch Vehicle	$0.0 M
Development Cost (30%)	$520.0 M
Phase A	$2.0 M
Phase B	$46.8 M
Phase C/D	$471.2 M
Operations Cost (15%)	$102.7 M
Project Cost	$622.8 M

Table 5: *Overall Cost Summary*

Development Cost (Phase A-D)

Developmental cost of our spacecraft takes the majority of our budget with the flight system being most expensive. The costs are summarized in Table 6.

Project Management	$17.2 M
Project Systems Engineering	$16.9 M
Mission Assurance	$15.0 M
Science	$11.3 M
Payload System	$65.9 M
Flight System	$211.3 M
Mission Operations Preparation	$16.8 M
Ground Data Systems	$14.9 M
ATLO	$19.4 M
Education and Public Outreach	$1.2 M
Mission and Navigation Design	$10.0 M
Development Reserves (30%)	$119.9 M
Total	$520.0 M

Table 6: *Development Cost for Phases A-D*

Payload Systems Cost

The cost of the payload system is primarily the instrumentation needed to achieve the science objectives and ends up being a relatively small fraction of the total cost, as presented in Table 7.

High Resolution Multispectral Imager	$20.4 M
Thermal IR Spectrometer	$12.0 M
Dust Secondary Ion Mass Spectrometer	$26.8 M
UV Imaging Spectrograph	$6.0 M
Impactor capsules (2)	$0.7 M
Total	$69.5 M

Table 7: *Payload and Instrumentation Cost*

Additional science instruments include Radio Science and Wide Angle Camera - not included in instrument cost calculation

Flight Systems Cost

The flight system, including the entire spacecraft bus, is a significant fraction of our total budget as summarized in Table 8.

Power	$40.0 M
C&DH	$13.8 M
Telecom	$19.0 M
Structures (includes Mech. I&T)	$24.3 M
Thermal	$9.9 M
Propulsion	$20.1 M
ACS	$32.5 M
Harness	$2.1 M
S/C Software	$21.5 M
Total	$183.2 M

Table 8: *Flight System Cost Summary*

Operations Cost (Phase E-F)

Operation costs, including data analysis, is provided in Table 9.

Project Management	$9.1 M
Project Systems Engineering	$0.0 M
Mission Assurance	$0.5 M
Science	$19.8 M
Mission Operations	$51.1 M
Ground Data Systems	$7.6 M
Education and Public Outreach	$3.7 M
Total (15%)	$91.8 M

Table 9: Operation Costs

7. Conclusions

The SHOTPUT mission , its unique trajectory and potential encounter with six different small bodies will provide a novel view of the composition of the solar system. The science return from the mission will help answer questions on formation, composition and evolution of small bodies in our local neighborhood.

In addition, the team has proposed a mission that is within budget based on heritage instruments satisfying the decadal survey requirements. The opportunity for spectacular science return on this rare trajectory should not be missed. The innovative SHOTPUT mission is truly one of a kind.

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BIOGRAPHY

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Figure 9: SHOTPUT Mission Design Team