Trojan/Centaur Reconnaissance Mission
(TCR)

Integrated Product Team
Spring 2010

Submitted By:

AERO

Astral Exploration and Reconnaissance Operations

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Submitted To:

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Proposal Summary Information

Section I

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Trojan/Centaur Reconnaissance Mission
Start Date: 1-1-2011
End Date: 6-15-2026

Section II

Submitted: 4-29-2010

Section III

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Section IV

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Section V

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Graphic Cover Sheet/Proposal Summary information in response to this Announcement of Opportunity, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified on the cover of this proposal:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the three Certifications contained in this AO (namely, (i) the Assurance of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, (ii) the Certification Regarding Debarment, Suspension, and Other Responsibility Matters Primary Covered Transactions, and (iii) Certification Regarding Lobbying).

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Section VI

Project Manager: Caleb Gooch, The University of Alabama in Huntsville
Principal Investigator: David Weiss, College of Charleston

Co- Investigator: Blake Hodges, College of Charleston
Project Systems Engineer: Ian Maddox, The University of Alabama in Huntsville
Propulsion Engineer: Shinji Kato, The University of Alabama in Huntsville
Power Engineer: Robert Gandy, The University of Alabama in Huntsville
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Cost & Risk Engineer: Garrett Williams, The University of Alabama in Huntsville
Technical Editor: Emily Hampton, The University of Alabama in Huntsville

Section VII
Proposal Summary

The New Frontiers Program Office's mission is to explore the solar system with frequent, medium-class spacecraft missions that will conduct high-quality, focused scientific investigations designed to enhance our understanding of the solar system.[1] The Trojan/ Centaur Reconnaissance (TCR) team proposes this mission which will gather data by performing a flyby of the Trojan asteroid Philoctetes and an orbit near the Centaur asteroid Okyrhoe. The information collected from this mission will complement the information gathered from other missions such as DAWN and New Horizons in giving more insight into solar system formation and evolution. A robust Science Extension Option is available to further investigate Okyrhoe and add to our knowledge about the origins of the universe.

Section VIII
- Is proprietary or privileged information included in this application? No
- Does this project involve activities outside the U.S. or partnership with non-U.S. collaborators? No
- Are NASA civil servant personnel participating as team members on this project (include funded and unfunded)? No
- Does this project have an actual or potential impact on the environment? No
- Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as a historic aircraft or spacecraft)? No

Section IX
- Trojan/Centaur Reconnaissance Mission: TCR
- Type of Institution: University
- New Frontiers Mission Concept: Trojan/Centaur Reconnaissance
- Launch vehicle: Atlas V 551 with a 5 m fairing
- Is use of NEXT proposed? No
- Is use of AMBR proposed? Yes
- Is student collaboration (SC) proposed? Yes
- Is a science enhancement option (SEO) proposed? Yes
- PI-Managed Mission Cost: Real year (RY) dollars: $1.23 billion
  Fiscal year (FY) 2009 dollars: $994.9 million

[1] New Frontiers Website: http://newfrontiers.nasa.gov/

- This proposal contains information and/or data that are subject to U.S. export control laws and regulations, including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR). No
- The export-controlled material (EAR and/or ITAR) has been identified in this proposal. N/A
- The proposer acknowledges that the inclusion of such material in this proposal may complicate the Government's ability to evaluate the proposal. Yes
- Is use of radioactive materials (e.g., radioisotope power sources, radioisotope heater units, or radioactive material sources for science instruments) proposed? Yes

A. Fact Sheet

Science Objectives

- Determine the physical properties of a Trojan asteroid and a Centaur asteroid
- Map the color, albedo and surface geology of a Trojan asteroid and a Centaur asteroid at a resolution sufficient to distinguish important features for deciphering the history of the object (e.g., craters, fractures, lithologic units)

Benefits of the TCR Mission

- First attempted survey of both a Trojan and a Centaur asteroid
- Low risk mission that exceeds all science requirements
- Includes an option for a robust and long-lived SEO
- Provides flight qualification for AMBR propulsion system

Mission Overview

- Launch on Atlas V 551 on June 15, 2016
- Flyby of Trojan asteroid Philoctetes on September 9, 2019
- Match trajectory of Centaur asteroid Okyrhoe on November 8, 2026
- Remain in proximity of Okyrhoe for SEO to conclude by 2031

TCR Mission Management

- Project Manager: Caleb Gooch, The University of Alabama in Huntsville
- Principal Investigator: David Weiss, College of Charleston
- Systems Engineer: Ian Maddox, The University of Alabama in Huntsville

Contributors

Engineering Disciplines

- Propulsion Engineer: Shinji Kato, The University of Alabama in Huntsville
- Power Engineer: Robert Gandy, The University of Alabama in Huntsville
- Structural Engineer: Matthew Watson, The University of Alabama in Huntsville
- Thermal Engineer: Chris Pittman, The University of Alabama in Huntsville
- GN&C Engineer: Steven Trotter, The University of Alabama in Huntsville
- Cost/Risk Engineer: Garrett Williams, The University of Alabama in Huntsville

Science Definition Team

- Co- Investigator: Blake Hodges, College of Charleston

Report Compilation

- Technical Editor: Emily Hampton, The University of Alabama in Huntsville

Science Payload

- OSIRIS: Narrow/Wide Angle Camera for survey of surface geology and albedo
- Alice: UV/IR Spectrometers for surface composition survey
- HAYABUSA: LIDAR for surface geology

Satellite Configuration

Figure 1 below is POIAS with callouts showing each element of the spacecraft.

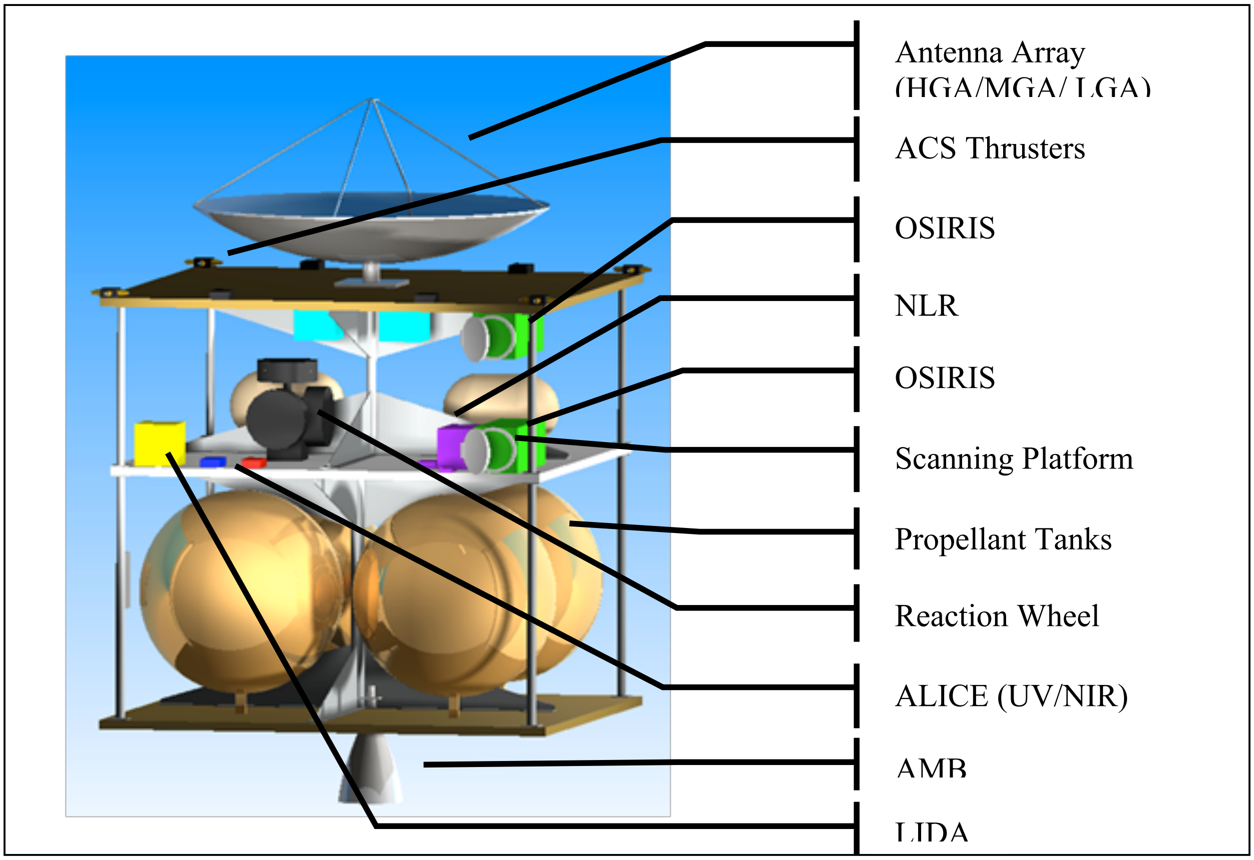

Figure 1: Satellite Configuration with callouts

Schedule

Below is a figure showing the TCR mission schedule.

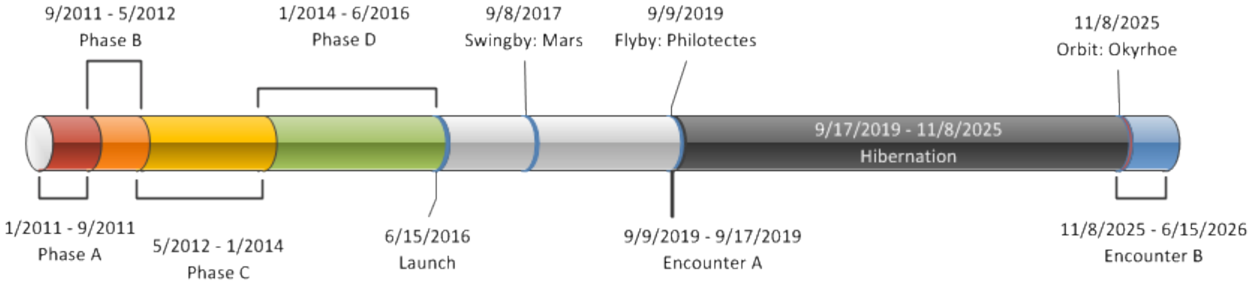

Figure 2: Schedule

Mission Cost

- PI Managed Mission Cost
  $994.9 million FY 09
  $1.23 billion Real Year Dollars

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B. Science Investigation

1. Scientific Background, Goals, and Objectives.

The goals of the Trojan/Centaur Reconnaissance Mission are to investigate the Trojan and Centaur asteroids to gain information about early solar system formation. The science objectives of the mission are to determine the physical properties of both a Trojan and a Centaur. Using spectroscopy, visible light photography, and LIDAR (Light Detection and Ranging), the mass, size, density, and geologic features such as composition will be determined. The color, albedo, and surface geology will be determined to better understand the history of the object. The Trojan asteroids share Jupiter's orbit and are located on equilibrium points on either side of it. The Centaurs orbit the Sun between the orbits of Jupiter and Saturn. The Trojans could have originated during the early period of our solar system. The centaurs are thought to have originated as Kuiper Belt Objects.

2. Science Requirements.

To attain the science objectives, the spectra of the asteroids will be measured in near infrared (near IR) wavelength ranges, a horizontal resolution requirement of 5 x 5 km, with a spectral precision requirement of 15-45 nm, targeting precision of 0.35-0.8 degrees, a spectral accuracy of +/- 4 nm, and a targeting accuracy of 0.5 degrees. The projected performance of the near IR spectrometer is a horizontal resolution of 3.9 km x 3.9 km/3.9 km x 1.95 km, a spectral precision of 21.6-43.1 nm, a targeting precision of 0.38 - 0.76 degrees, a spectral accuracy of +/- 3.5 nm, and a targeting accuracy of 0.4 degrees. The requirements for the UV spectrometer are a horizontal resolution requirement of 150 m, a targeting precision of 0.1 x 0.1 degrees, a spectral accuracy of +/- 8 nm, and a targeting accuracy of 0.0225 degrees. The projected performance of the UV spectrometer is a horizontal resolution of 73 m, targeting precision of 0.1 x 0.1 degrees, a spectral accuracy of 0.14-7.7 nm, and a targeting accuracy of 0.0225 degrees. LIDAR will determine the size and shape of the asteroids, with a required horizontal resolution of 900 x 400 meters, a range accuracy of 150 m, and a precision of +/- 10 m. The projected performance of the LIDAR is a horizontal resolution of 514.28 m x 210 m, a range accuracy of 100 m, and a precision of +/- 5 m.

A NAC/WAC (Narrow Angle Camera/Wide Angle Camera) will take pictures to show visible surface geology, with a required horizontal resolution of 15 x 15 m, a targeting precision of 20 x 20 degrees, and a targeting accuracy of 0.1 millidegree. The projected instrument performance is a horizontal resolution of 5.62 m x 5.62 m, a targeting precision of 12 x 12 / 2.35 x 2.35 degrees, and a targeting accuracy of 0.1 millidegree. In full operation, the science payload generates 45,470,894 bits of data per second. The high-gain antenna will be capable of transmitting a maximum of 38,000 bits per second at the Trojan and 6,000 bits per second at the Centaur. The Trojan encounter will generate 703 seconds of useful data collected with the NAC from a range of 900 km to 300 km from the body, generating 1400 pictures. Resolutions with the NAC will show the asteroid filling about 1/4 the screen to a zoomed in view of about 25% of the asteroid. The WAC will also be active for 703 seconds from the range of 900 km to 300 km from the Trojan generating 1400 pictures. Resolutions with the WAC will show Resolutions from 143 pixels (small) to 1075 pixels (about 1/4 of the screen). At 300 km from the Trojan, the UV spectrometer, LIDAR, and near IR spectrometer will be activated. The UV spectrometer will take 625 scans in 90 seconds. The near IR spectrometer will take 625 scans in 90 seconds. The LIDAR will take 180 scans in 90 seconds. Data from the Trojan will continuously be collected until it is 900 km away.

The Centaur encounter will generate 703 seconds of useful data collected with the NAC from a range of 900 km to 300 km from the body, generating 1400 pictures. Resolutions with the NAC will show the asteroid filling about 1/4 the screen to a zoomed in view of about 25% of the asteroid. The WAC will also be active for 703 seconds from the range of 900 km to 300 km from the Centaur generating 1400 pictures. Resolutions with the WAC will show resolutions from 143 pixels (small) to 1075 pixels (about 1/4 of the screen). At 300 km from the Centaur, the UV spectrometer, LIDAR, and near IR spectrometer will be activated. The UV spectrometer will take 625 scans in 90 seconds. The near IR spectrometer will take 625 scans in 90 seconds. The LIDAR will take 180 scans in 90 seconds. Data from the Centaur will continuously be collected until it is 900 km away.

The data products that will be returned will be in the form of spectra for the UV and IR spectrometers, which will be matched the known spectra of minerals to identify the mineral composition of the asteroids. By knowing the mineral composition of the asteroids, the mission is one step closer to fulfilling the science requirements of knowing the geologic history of the asteroids. Additionally, the joint analysis of how the minerals formed and the visible surface geology of the asteroid captured by the NAC/WAC will lead to a clearer picture of the history of the asteroid. The data the LIDAR returns will be used to calculate density shape and range measurements which are converted to profiles of asteroid radius and topographic height after correction for orbit and pointing errors, which will give a more clear history of how this object formed.

Table 1: Science Traceability Matrix

Science Goals	Science Objectives	Scientific Measurement Requirements		Instrument Functional Performance			Mission Functional Requirements
		Observables	Physical Parameter				
Determine the physical properties of a Trojan and Centaur	Determine mass, density, size, and shape	Deviation in satellite course	Mass				
		Light Detection and Ranging (LIDAR) instrument delay time relative to position	Volume	Alt. Range	300 km	500 km	
				Horiz. Resol.	900 x 400 m	514.28 x 210 m	
				Temp.Resol.	20 nsec	14 nsec	
				Accuracy	150 m	100 m	
				Precision	+/- 10 m	+/- 5 m	
Map the color, albedo, and surface geology of a Trojan and a Centaur at a resolution sufficient to distinguish important features for deciphering the history of the object	Determine what outside sources have changed these bodies Determine where these bodies originated	EM radiation: Near IR spectrometer	Surface comp.	Alt. Range	300 km	500 km	Spectral imagining and LIDAR to take place at 300 km distance Begin taking NAC/WAC pictures from 900 km
				Horiz. Resol.	5 x 5 km	3.9 x 3.9 km / 3.9 x 1.95 km	
				Temp. Resol.	5 seconds	2-5 sec	
				Spectral Precision	15-45 nm	21.6-43.1 nm	
				Spectral Accuracy	+/- 4 nm	+/- 3.5 nm	
				Targeting Precision	0.35-0.8 degrees	0.38-0.76 degrees	
				Targeting Accuracy	0.5 degrees	0.4 degrees	
		EM radiation: UV spectrometer	Surface comp.	Alt. Range	300 km	500 km	
				Horiz. Resol.	150 m	73 m	
				Temp. Resol.	10 ms-10 min	8 ms-15 min	
				Targeting Precision	0.1 x 0.1 degrees	0.1 x 0.1 / 0.1 x 0.4 degrees	
				Spectral Accuracy	+/- 8 nm	0.14-7.7 nm	
				Targeting Accuracy	0.0225 degrees	0.0225 degrees	
		Visible Light pictures with NAC/WAC	Size, shape, surface geology	Alt. Range	900 km	1000 km	
				Horiz. Resol.	15 x 15 km	5.62 x 5.62 m	
				Temp.Resol.	20 milliseconds	10 msec	
				Targeting Precision	20 x 20 degrees	12 x 12 / 2.35 x 2.35 degrees	
				Targeting Accuracy	0.1 millidegree	0.1 millidegree	

3. Threshold Science Mission.

A threshold Trojan/Centaur Reconnaissance Mission would travel to either of the L4 equilibrium point on the side of Jupiter's orbit. A flyby would be done of the Trojan Philoctetes, which shares Jupiter's orbit along with numerous other Trojan asteroids. Because of their orbital inclinations and locations, all the Trojans located around Jupiter's orbit could be studied similarly. Then the spacecraft would travel to the centaur asteroid Okyrhoe, which lies between the orbits of Jupiter and Saturn. A flyby would also be done of this body. To determine the physical characteristics of the asteroid a narrow angle camera and LIDAR light detection and ranging instrument will be used. Mass of the Trojan can be determined by changing the course of the vessel as it passes by. The LIDAR will be used in conjunction with the narrow angle camera to determine the volume of the body. Once the mass and volume have been determined, density of the body can be calculated. Using the narrow angle camera, high resolution pictures will be taken to show surface features such as craters and ejecta. The shape of the body will also be determined by LIDAR. Using the narrow angle camera, the near IR spectrometer, and the UV spectrometer, the mineralogical composition of the body can be determined. Based on the findings for the mineral composition and density, the general inner composition of the body can be determined. The mineralogical composition can be used to determine the history by use of phases to trace the alteration history of the bodies. This information can be used to learn about what outside sources have changed the bodies and where the bodies originated.

C. Science Implementation

The following expands requirements in the AO, particularly Requirements 4 through 17 and Requirements 43 through 45.

1. Instrumentation

NEAR (Near Earth Asteroid Rendezvous) Near IR Spectrometer:

The NEAR Near IR Spectrometer was selected because many of the minerals expected to be found on the asteroids will have a wavelength lying in the near IR range. This spectrometer offered excellent performance combined with low weight and power requirements. The light heritage of this spectrometer is the Near Earth Asteroid Rendezvous mission. The spectrometer will take a total of 625 scans in the near-IR of different parts of each asteroid, providing data in the form of spectra that will be matched with known mineral spectra to provide data in the form of mineral compositions of the selected areas. The spacecraft adequately accommodates the physical and power constraints needed by the spectrometer with a clear field of view. The NIS (Near Infrared Spectrometer) is a TRL (Technology Readiness Level) 8, having proven itself in space in the NEAR mission.[2] No development plan is needed since the NIS is projected to complete its mission requirements.

[2] "The Near Infrared Spectrometer (NIS) instrument on the Near Earth Asteroid Rendezvous (NEAR) spacecraft performed a comprehensive series of in-flight tests to validate its preflight radiometric characteristics and to characterize instrument stability, pointing, and co-alignment with other instruments under flight conditions. The results of these tests form the basis of the NIS data reduction and calibration procedure and will support the ability of NIS to achieve its science goal of spectrally mapping NEAR's target asteroid, 433 Eros. Key results include the following: (i) Radiometric calibration of NIS has been confirmed to be accurate to within 4–10%, based on NIS measurements of the Earth and Moon and comparisons to radiances derived from other (NEAR and non-NEAR)

System and Calibration Characteristics

Hardware:
The NIS design (Fig. 1) is copied from an earlier Applied Physics Laboratory (APL) spectrometer—the Defense Meteorological Satellite Special Sensor Ultraviolet Spectrographic Imager (SSUSI)—and modified for an infrared wavelength range. [WARRENETAL1997] detail the design characteristics, engineering, and construction of the instrument. A gold-coated scan mirror controls the direction of viewing over a range of 140 degrees. Light reflected from the scan mirror passes through a 20 x 25-mm aperture stop and is imaged by a telescope mirror at a slit. The field of view is selectable at the slit to 'narrow' (0.38 degrees x 0.76 degrees) or 'wide' (0.76 degrees x 0.76 degrees) settings. A shutter actuates the narrow slit, with the smaller slit opening coming down over the fixed wide slit. The two slits provide field-of-view sizes of 0.65 x 1.3 km or 1.3 x 1.3 km from 100 km distance. A second shutter can be actuated to completely block the slit for dark current measurements. After passing through the slit, light is dispersed and re-imaged off a gold toroidal diffraction grating (a Rowland circle configuration spectrometer) and hits a dichroic beam splitter mounted at 45 degrees to the beam which transmits or reflects the energy to fall on two 32-element linear detector arrays. Reflected 2nd order wavelengths (804-1506 nm) fall on a germanium (Ge) array. Each Ge channel has a bandwidth of 21.6 nm. The germanium detector has a selectable gain of 1x or 10x. Transmitted 1st order wavelengths (1348-2732 nm) go to an indium-gallium-arsenide (InGaAs) array with 43.1 nm channel bandwidth. [WARRENETAL1997] calibrated the central wavelengths of all NIS channels at three operational temperatures (-7 degrees C, -17 degrees C, and -23 degrees C) and found best-fit Ge spectral calibration given by:

lambda (nm) = 794.6 + 21.61**n* (Equation 1)

where *n* is Ge element number 1–32. The uncertainty of the wavelength calibration over the range of temperatures examined is +/-0.5 nm. InGaAs element center wavelengths are given by:

lambda (nm) = 43.11**n* - 50.8 (Equation 2)

where *n* is InGaAs element number 33–64. The temperature-dependent wavelength uncertainty is approximately +/-3.5 nm.

The lower two channels of the InGaAs detector (channels 33 and 34, at 1372 and 1315 nm respectively) are below the transition wavelength of the dichroic beam splitter, and therefore

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optical instruments; (ii) The radiometric response has been demonstrated to be stable on the scale of months; (iii) Gradual, expected detector sensitivity decay of 1–3% over 2 years of operations in space has been characterized; (iv) Temperature dependencies of detector response are identified and characterized; (v) The co-alignment of NIS with the Multi-Spectral Imager (MSI) and with respect to other NEAR instruments has been determined; (vi) A calibration program (NISCAL) that applies appropriate functions and algorithms to convert raw instrument data to analyzable spectra has been developed; (vii) Remaining unresolved instrument calibration and characterization issues have been identified, to be resolved with the help of approach and orbital observations from the main mission” (Izenberg et al. 2000).

always register very low signals. The upper 3 channels (channels 62–64 at 2622, 2665, and 2708 nm) are near or in detector cutoff, making the effective upper bound for good signal-to-noise ratio (SNR) around 2500 nm for the signal level expected at Eros. Additionally, two InGaAs channels (47 and 57 at 1975 nm and 2406 nm) have been extremely noisy since manufacture and do not produce easily usable data. Default operations for NIS utilize the narrow slit, providing a critically sampled spectral resolution of 22 nm in the Ge detector, and 44 nm in the InGaAs detector. The wide slit configuration provides half the spectral resolution (44 nm and 88 nm respectively), but passes twice the light and therefore has a higher SNR.

The NIS scan mirror can rotate the line of sight over 350 steps in 0.4-degree increments in the spacecraft Z-X' plane. The +Z axis is perpendicular to the plane of NEAR's solar panels, and +X' is the boresight of the instruments. Mirror position 0 (nominal caltarget observation geometry) is 30 degrees towards the Z-axis from the boresight. The boresight is aligned with mirror position 75. Position 300 points in the -Z (anti-Sun) direction.

For optimum performance the detectors are operated near -35 degrees C, maintained by passive cooling or active heaters, depending on the thermal environment. A solar-illuminated gold calibration plaque (caltarget) is mounted to the instrument for radiometric stability calibration.

Flight Software:

Inflight NIS data is acquired through the use of command sequences to the instrument that specify ten-instrument parameters as follows: 1. Spectrometer sequence ID (0–15). Sixteen sequences can be uploaded and stored while the instrument is powered. Sequences 0, 1, and 2 are hardcoded, but can be redefined. 2. Repeats: the number of times the commanded observations will repeat. 3. Seconds between repeats. 4. Number of observations. This is the number taken during a single repeat of the sequence. 5. Calibration interval (1-65535). Number of observations before acquisition of dark spectra. This is used to interleave shutter-closed dark observations with data observations. 6. Number of seconds to co-add spectral data in each observation (0-63). 7. Number of rest spectra (0-63). Used when interleaved darks are taken, between spectra acquisition and dark acquisition. 8. Number of co-added seconds of dark signal for interleaved dark spectrum. 9. Number of scan mirror steps between observations (sign indicates direction). 10. Seconds between observations.

For the purposes of the software discussion, a 'spectrum' is the result of a one-second integration of the instrument as it gathers data. An 'observation' is 0–63 consecutive one-second spectra summed together. The example sequence (15 3 5 10 5 16 2 4 2 2) is interpreted as follows: Sequence ID is 15. The sequence will repeat three times, each iteration to contain 10 observations consisting of 16 co-added spectra of accumulated data. The calibration interval of five means that every 5th observation (numbers 5 and 10 in each repeat) will instead co-add 10 spectra of the target, then rest 2 seconds while the shutter closes, then take four co-added spectra of dark signal. After each accumulated observation, the scan mirror will move +2 steps and the instrument will rest two seconds. During each repeat, the mirror will move 20 steps. Each repeat is separated by five seconds to allow the mirror to return to the start position. This example sequence would generate 30 NIS observations of the target, and 6 dark observations. Choice of the wide or narrow NIS slit, the high or low Ge detector gain, and the starting NIS scan mirror position are specified through separate commands to the instrument.[3]

QE65000 UV Spectrometer (Alice):
The QE65000 UV Spectrometer (UVS) was selected because many of the minerals expected to be found on the asteroids will have a wavelength lying in the UV range. This spectrometer offered excellent performance combined with low weight and power requirements. The flight heritage of this spectrometer is the Rosetta mission. The spectrometer will take a total of 625 scans in the near-IR of different parts of each asteroid, providing data in the form of spectra that will be matched with known mineral spectra to provide data in the form of mineral compositions of the selected areas. The spacecraft adequately accommodates the physical and power constraints needed by the spectrometer with a clear field of view. The UVS is a TRL 9, having proven itself in space in the Rosetta mission, the New Horizons mission to Pluto/Charon and the Kuiper Belt and the LCROSS mission. A mounting and slewing device must be developed for the QE65000. Reengineering is also available and has been proven successful by Aurora Design & Technology in withstanding the extreme temperature, radiation, shock, and vibration of space. The New Horizons Alice UV spectrometer was successfully launched on January 19, 2006, and is operating normally in space. All inflight performance tests have shown performance within specification; the pointing and automatic gain control (AGC) sensitivity tests completed in September 2006 are in analysis, and the initial results of these tests indicate nominal performance with no degradation yet observed.

Spectroscopic	
Wavelength range:	200–950 nm
Optical resolution:	~0.14–7.7 nm FWHM
Signal-to-noise ratio:	1000:1 (at full signal)
A/D resolution:	16 bit
Dark noise:	3 RMS counts
Dynamic range:	7.5×10^9 (system), 25000:1 for a single acquisition
Integration time:	8 ms to 15 minutes
Stray light:	<0.08% at 600 nm; 0.4% at 435 nm
Corrected linearity:	>99.8%
Electronics	
Power consumption:	500 mA at 5 VDC (no TE cooling); 3.5 A at 5 VDC (with TE cooling)
Data transfer speed:	Full scans to memory every 7 ms with USB 2.0 port, 18 ms with USB1.1 port, 300 ms with serial port
Inputs/Outputs:	10 onboard digital user-programmable GPIOs (general purpose inputs/outputs)
Analog channels:	No

[3] "Instrument Information" *Planetary Data System.*

Auto nulling:	Yes
Breakout box compatibility:	Yes
Trigger modes:	4 modes
Strobe functions:	No
Gated delay feature:	Yes
Connector:	30-pin connector
Power-up time:	< 5 seconds
Dark current:	4000 e-/pixel/sec at 25 ºC; 200 e-/pixel/sec at 0 ºC
Computer	
Operating systems:	Windows 98/Me/2000/XP, Mac OS X and Linux with USB port; Any 32-bit Windows OS with serial port
Computer interfaces:	USB 2.0 at 480 Mbps; RS-232 (2-wire) at 115.2 K baud
Network Access:	Remora's USB interface adapts for Ethernet Connectivity
Peripheral interfaces:	SPI (3-wire); I2C inter-integrated circuit
Temperature and Thermoelectric (TE) Cooling	
Temperature limits:	0 ºC to 50.0 ºC; no condensation
Set point:	Software controlled; lowest set point is 40 ºC below ambient
Stability	+/-0.1 ºC of set temperature in <2 minutes

Figure 3: System Characteristics[4]

LIDAR:
LIDAR was selected because it will provide a reliable shape model of each asteroid including topographic information. LIDAR offers reliability and high performance at adequate physical and power levels. The flight heritage of this instrument is the HAYABUSA mission. The LIDAR will take a total of 180 scans of each asteroid, providing data in the form of asteroid profile, topographic information, and range from spacecraft that will be corrected for orbit and pointing errors. The spacecraft adequately accommodates the physical and power constraints needed by the spectrometer with a clear field of view. The UVS is a TRL 7, having proven itself in space in the HAYABUSA mission. The current radial inaccuracies of the LIDAR data do not permit the generation of global grids of the surface of Itokawa. Additional refinements are still required. LIDAR functioned without flaws for the entire 3 month period of the encounter with Itokawa with no observed degradation.

System Characteristics:
Instrument Specifications

The following table summarizes LIDAR characteristics.

[4] "QE65000-FL Scientific-grade Spectrometer" 2010.

Table 2

Parameter	Value	Unit
Physical Characteristics		
Volume	0.0137	m^3
Mass	3.56	kg
Power (TOTAL)	22.00	W
Laser Transmitter (Laser type: Q-switched, diode-pumped Nd:YAG*)		
Wavelength	1.064	micrometer
Laser energy	10	mJ $pulse^{-1}$
Laser power consumption	17	W
Pulse width	14	ns (FWHM**)
Pulse repetition rate	1	sec^{-1}
Beam divergence	1.7x0.7	mrad
Altimeter Receiver (Telescope type: Cassegrain, Detector type: Silicon avalanche photodiode [Si APD])		
Mirror composition	SiC	
Telescope diameter	0.126	m
Receiver Electronics (Receiver type: Filtered peak trigger)		
Time resolution	3.0	nsec
Range resolution	0.5	m
Range accuracy (at 50km)	10.0	m
Measurements		
Footprint size (at 7 km)	12.0 x 4.9	m

Operational Considerations:

The LIDAR instrument measures the round-trip time of flight of infrared laser pulses transmitted from the HAYABUSA spacecraft to the surface of Itokawa. The instrument operates in a single autonomous mode, in which it produces ranging measurements. Surface topography estimates can be derived from these data, given appropriate corrections for the position and attitude of the spacecraft.

LIDAR's transmitter is a Q-switched, Nd:YAG laser oscillator. The Q-switch controls the emission of the laser, and Nd:YAG refers to the composition of the material that is optically excited to produce laser action: Neodymium-doped Yttrium Aluminum Garnet. The laser emits a 14-ns-wide (full width at half the maximum pulse amplitude, FWHM) pulses at 1.064

micrometers. The pulse repetition rate is 1 Hz, and the pulse energy was 10 mJ during the entire period of operation. The laser consumed 17 W when operating.[5]

OSIRIS NAC/WAC:
The OSIRIS NAC/WAC was selected because it consists of two independent camera systems sharing common electronics. This reduces the weight and size of the camera while providing the performance of both a NAC and WAC. This spectrometer offered excellent performance combined with low weight and power requirements. The flight heritage of this spectrometer is the Rosetta mission. The NAC and WAC each capture 1400 pictures in the visible spectrum of the asteroid from small sizes to up to 25% of the surface of the asteroid at a time, providing data in the form of visible light pictures that will be analyzed for each asteroid's surface geology. The spacecraft adequately accommodates the physical and power constraints needed by the OSIRIS with a clear field of view. The OSIRIS is a TRL 9, having proven itself in space in the Rosetta mission. Since March 2005 instrument health has been monitored in a checkout every 6 months. The instrument proved to be in good health in the checkouts performed so far. Operations have included mechanism tests, instrument calibration, alignment between the boresights of the different remote sensing instruments on Rosetta, and interference check between OSIRIS and other instruments.

System Characteristics:

The OSIRIS cameras are unobstructed mirror systems, equipped with two filter wheels containing 8 positions each, and with backside illuminated charge-coupled devie (CCD) detectors comprising 2048 x 2048 pixels with a pixel size of 13.5 µm. Both cameras use identical image acquisition systems, consisting of the Focal Plane Assembly and the CCD Readout Box.

OSIRIS comprises two cameras:

NAC (Narrow Angle Camera)
The Narrow Angle Camera is designed to obtain high-resolution images of the comet at distances from more than 500,000 km down to 1 km. The camera also should be able to detect small ejected particles close to the cometary nucleus (brightness ratio = 1/1000). The NAC is equipped with 12 filters to characterize the reflectivity spectrum of the nucleus surface over a wide spectral range from 250 to 1000 nm. The NAC has a square field of view (FOV) of width 2.2 degrees, has an instantaneous field of view (IFOV) of 18.6 µ rad (3.8 arcsec) per pixel, and is a moderately fast system (f/8). The system has a 717 mm focal length. A flat-field, three-anastigmatic-mirror system is adopted. It has a mass of 13.2 kg.

WAC (Wide Angle Camera)
The principal objective of this camera is to study the intensity of gas emissions and dust-scattered sunlight as functions of position and viewing angle in the vicinity of the nucleus. The WAC is accomplished by 14 filters from 240 to 720 nm. Seven of the narrow band filters isolate gas emissions from the cometary coma; the others filters measure the dust continuum at wavelengths close to that of the gas emissions. The WAC has a FOV of 12x12 degrees , has an angular resolution of 101 µ rad (20.5 arcsec) per pixel, and is a system with a fast focal ratio of

[5] "Instrument Information" 2010.

f/5.6. The system has a 140 (sag)/131 (tan) mm focal length. A two-aspherical-mirror system is adopted. It weighs 9.5 kg.[6]

[6] Keller 2006

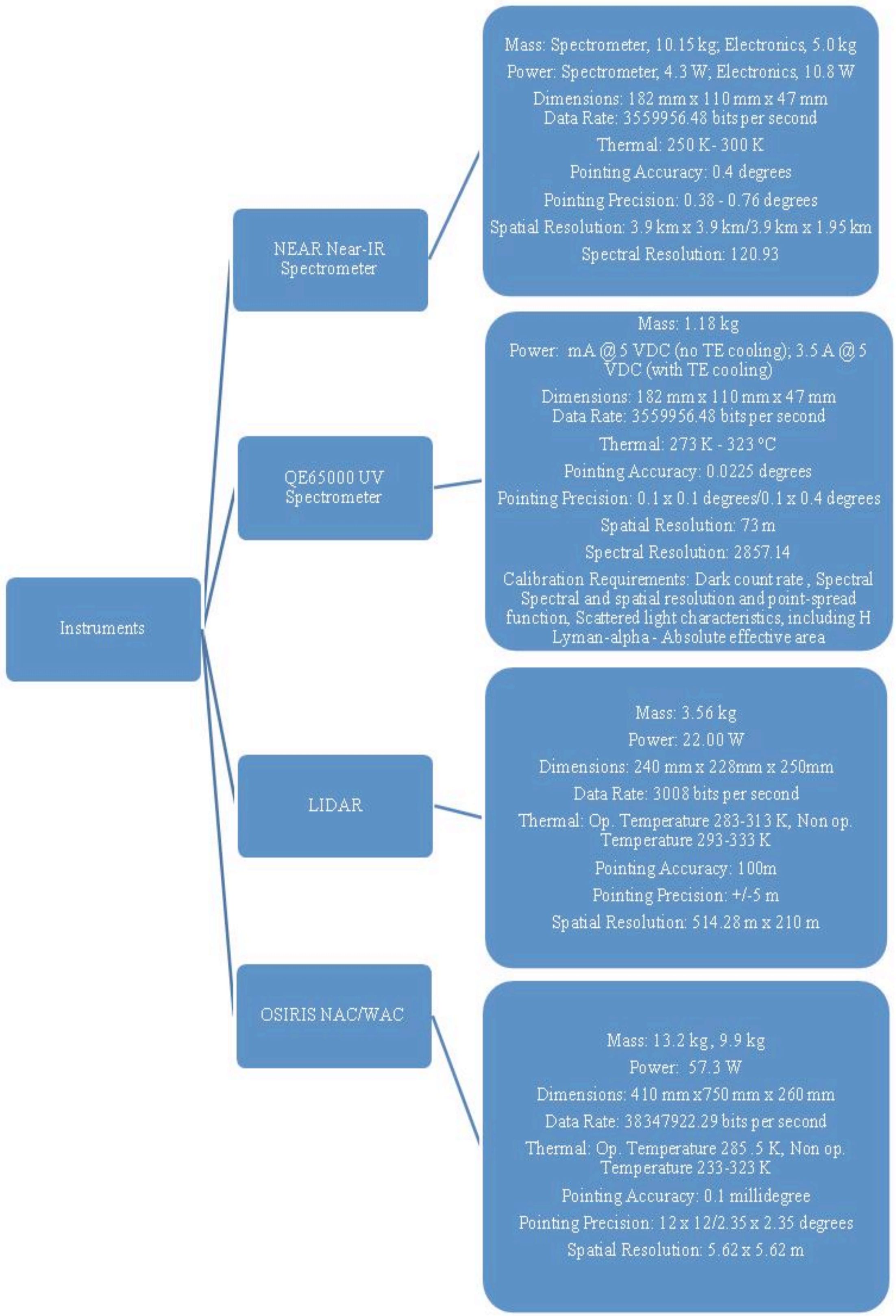

Instruments
NEAR Near-IR Spectrometer
Mass: Spectrometer, 10.15 kg; Electronics, 5.0 kg
Power: Spectrometer, 4.3 W; Electronics, 10.8 W
Dimensions: 182 mm x 110 mm x 47 mm
Data Rate: 3559956.48 bits per second
Thermal: 250 K - 300 K
Pointing Accuracy: 0.4 degrees
Pointing Precision: 0.38 - 0.76 degrees
Spatial Resolution: 3.9 km x 3.9 km/3.9 km x 1.95 km
Spectral Resolution: 120.93
QE65000 UV Spectrometer
Mass: 1.18 kg
Power: mA @ 5 VDC (no TE cooling); 3.5 A @ 5 VDC (with TE cooling)
Dimensions: 182 mm x 110 mm x 47 mm
Data Rate: 3559956.48 bits per second
Thermal: 273 K - 323 °C
Pointing Accuracy: 0.0225 degrees
Pointing Precision: 0.1 x 0.1 degrees/0.1 x 0.4 degrees
Spatial Resolution: 73 m
Spectral Resolution: 2857.14
Calibration Requirements: Dark count rate , Spectral Spectral and spatial resolution and point-spread function, Scattered light characteristics, including H Lyman-alpha - Absolute effective area
LIDAR
Mass: 3.56 kg
Power: 22.00 W
Dimensions: 240 mm x 228mm x 250mm
Data Rate: 3008 bits per second
Thermal: Op. Temperature 283-313 K, Non op. Temperature 293-333 K
Pointing Accuracy: 100m
Pointing Precision: +/-5 m
Spatial Resolution: 514.28 m x 210 m
OSIRIS NAC/WAC
Mass: 13.2 kg , 9.9 kg
Power: 57.3 W
Dimensions: 410 mm x750 mm x 260 mm
Data Rate: 38347922.29 bits per second
Thermal: Op. Temperature 285.5 K, Non op. Temperature 233-323 K
Pointing Accuracy: 0.1 millidegree
Pointing Precision: 12 x 12/2.35 x 2.35 degrees
Spatial Resolution: 5.62 x 5.62 m

Figure 4

NEAR Near-Infrared spectrometer
Mass: Spectrometer, 10.15 kg; Electronics, 5.0 kg
Power: Spectrometer, 4.3 W; Electronics, 10.8 W
Pointing Accuracy requirements: 0.35-0.8 degrees
Operational Modes: A narrow slit provides a critically sampled spectral resolution of 22 nm in the Ge detector, and 44 nm in the InGaAs detector. A wide slit provides half the spectral resolution (44 nm and 88 nm respectively), but passes twice the light and therefore has a higher SNR.
Operational mode timeline: 300 km from body NIS is activated taking 625 scans in 90 seconds, turning off 300 km away from body.
Data demand for each instrument operational mode: 3,559,956.48 bits per second
Onboard data processing and storage required from spacecraft: Storage will be handled on a group of 30 4Gbit memory modules. At the Trojan these modules will be used to create a dual-redundant 60 Gbit storage buffer, at the Centaur a quad-redundant 30 Gbit buffer to allow for better stability late in the mission.
Power demand for each instrument operation mode including peak, average, and stand-by power: 15.1 W
Instrument thermal control capability: A solar-illuminated gold calibration plaque (caltarget) is mounted to the instrument for radiometric stability calibration. For optimum performance the detectors are operated near -35 degrees C, maintained by passive cooling or active heaters.

QE65000 Ultraviolet spectrometer
Mass: 1.18 kg (without power supply)
Power: 500 mA @ 5 VDC (no TE cooling); 3.5 A @ 5 VDC (with TE cooling)
Pointing Accuracy requirements: 0.0225 degrees
Operational Modes: Optics Aperture Modes

Alice has two separate entrance apertures that feed light to the telescope section of the instrument: an 'airglow' aperture, which allows measurement of emissions from atmospheric constituents, and an 'occultation' aperture, when either the Sun or a bright star is viewed through the atmosphere producing absorption by the atmospheric constituents. The Alice occultation mode will be used just after New Horizons passes behind Pluto and looks back at the Sun through Pluto's atmosphere.

Data Acquisition Modes
P-Alice has two detector data collection modes: (i) Pixel List Mode; (ii) Histogram Imaging Mode. The P-Alice flight software controls both modes. Data are collected in a dual-port acquisition memory that comprises two separate 32kx16-bit memory channels. In both modes, the instrument is turned on and photons hitting a pixel on the detector result in analog pulses above a set threshold level, generating photon events that are then transferred to the flight software. Each photon event contains the pixel location of the event. The difference between the modes is how the flight software stores the photon events in the memory channels.

Pixel List Mode: continuous 1-D stream of photon events and time hacks

In Pixel List Mode (PLM), the 2-D pixel array location of each single photon event from the detector is transferred from Alice to the spacecraft memory as a stream of data; the data stream is also interspersed with timing information (time hacks) that can be used to constrain the time of each photon event.

In PLM, each Alice memory channel acts as a linear data stream buffer: while one memory channel is being written to with detector data, the other is written to spacecraft memory. Once the instrument fills the first memory channel, the roles switch and the detector data go to the second channel while the first channel is written to spacecraft memory. This double-buffering – called 'Ping-Pong' acquisition – allows continuous readout and storage of detector event data.

In this mode, a single event is represented by one 16-bit word in instrument memory and can be either a detector photon event or a time hack event. Photon events occur stochastically in time and are generated by photons hitting the detector. Time hack events, referred to simply as “time hacks,” occur at regular intervals in time and are generated by the Alice flight software. The time hack interval is programmable and can be as short as 4 ms. The PLM data stream comprises photon event locations interspersed with time hack values. Time hacks can be converted to timestamps in the series of events and may be used to provide temporal information about the PLM data stream and to constrain the time that any photon event occurs.

Histogram Imaging Mode: summing of photon events into a 2-D spectrogram

In Histogram Imaging Mode (HIM), the Alice flight software sums detector photon event counts for each pixel over a specified period (exposure) and then writes the result out as a 2-D array i.e. a spectral-spatial image or spectrogram. In this mode, the 1-D 32k memory channel is treated as a 2-D 1024x32 array; each memory channel location thus accumulates the photon event count acquired at its corresponding pixel location in the detector array. While some have found it confusing to call this a histogram, it is only an extension of the normally 1-D arrangement of histogram bins into pixels representing bins in two dimensions.

Note that the timing information present in the time hacks of the PLM data stream is neither generated nor saved in HIM. Therefore, while the PLM data stream can be analyzed to generate the equivalent of the HIM spectrogram, the HIM data cannot be used to generate the PLM data.

Besides the collection and binning of detector events, HIM collects pulse-height distribution (PHD) data from the detector electronics. These PHD data are collected and binned into a 64-bin histogram that is stored within the first two rows of the detector histogram, in a location where no physical pixel within the detector active area exists (therefore, the PHD data does not interfere with the collected detector data). During ground processing, the Science Operations Center pipeline software reads these PHD data and then zeroes the relevant area of the input array before creating the data products.

The same Alice instrument software that controls the PLM Ping-Pong.
Acquisitions also control the HIM.

Measured Parameters

Pixel List Mode
Each 16-bit word in the PLM data stream represents either the detector location of a photon event or the time of a time hack.

One bit in each word identifies that word as a photon event or as a time hack. The meaning of the remaining fifteen bits depends on which type of event the word represents. Photon events use ten bits for the spectral detector position (0 to 1023) and five bits for the spatial detector (0 to 31). Time hack events use all fifteen bits to represent the number of 4 ms time intervals since either the instrument was turned on or the most recent rollover of the time hack counter.

Histogram Imaging Mode

Accumulated count of photon events, which each generated an analog pulse above the set threshold, at each pixel location for the duration of each exposure.

MCP pulse-height distribution histogram.[7]

Operational mode timeline: 300 km from body UVS is activated taking 625 scans in 90 seconds, turning off 300 km away from body.
Data demand for each instrument operational mode: 3559956.48 bits per second Onboard data processing and storage required from spacecraft: Storage will be handled on a group of 30 4Gbit memory modules. At the Trojan these modules will be used to create a dual-redundant 60 Gbit storage buffer, at the Centaur a quad-redundant 30 Gbit buffer to allow for better stability late in the mission.
Power demand for each instrument operation mode including peak, average, and stand-by power: 500 mA @ 5 VDC (no TE cooling); 3.5 A @ 5 VDC (with TE cooling)
Instrument thermal control capability: The TE-cooled (down to -15 °C from 20 degrees C)

LIDAR (Light Detection and Ranging):
Mass: 3.56 kg
Power (TOTAL): 22.00 W
Pointing Accuracy requirements: +/- 10 m
Operational Modes: Single mode
Operational mode timeline: 300 km from body LIDAR is activated taking 180 scans in 90 seconds, turning off 300 km away from body.
Data demand for each instrument operational mode: 3008 bits per second
Onboard data processing and storage required from spacecraft: Storage will be handled on a group of 30 4Gbit memory modules. At the Trojan these modules will be used to create a dual-redundant 60 Gbit storage buffer, at the Centaur a quad-redundant 30 Gbit buffer to allow for better stability late in the mission.
Power demand for each instrument operation mode including peak, average, and stand-by power: 22.00 W
Instrument thermal control capability: None

[7] "Instrument Information" *Planetary Data System.*

OSIRIS NAC/WAC
Mass: 13.2 kg, 9.9 kg
Power: 57.3 W
Pointing Accuracy requirements: 0.1 millidegree
Power consumption: 20 W, including all electronics (nominal operational mode)
Operational Modes: NAC and WAC, can be operated simultaneously.
Operational mode timeline: At 900 km from body, both NAC and WAC will be activated, for a total operating time of 703 seconds from the range of 900 km to 300 km from the body generating 1400 pictures.
Data demand for each instrument operational mode: 19173961.14 bits per second for NAC, 19173961 bits per second for WAC, total: 38347922.29 bits per second.
Onboard data processing and storage required from spacecraft: Storage will be handled on a group of 30 4-Gbit memory modules. At the Trojan these modules will be used to create a dually-redundant 60-Gbit storage buffer, at the Centaur a quad-redundant 30-Gbit buffer to allow for better stability late in the mission.
Power demand for each instrument operation mode including peak, average, and stand-by power: 57.3 W in total
Instrument thermal control capability: None

2. Data Sufficiency

NEAR Near IR Spectrometer:
The NEAR Near IR Spectrometer will take 625 scans of different parts of the asteroids with a resolution of 3.9km x 3.9km/3.9km x 1.9km with a spectral accuracy of +/- 3.5 nm, a spectral precision of 21.6-43.1 nm, a targeting precision of 0.38 - 0.76 degrees, and a targeting accuracy of 0.4 degrees. The large number of scans with the accurate and precise targeting capabilities, as well as the large resolution area will enable us to scan a large area of the surface of the asteroids with little overlap. Additionally, selective scanning of different parts of the asteroids, i.e. general surface vs. crater surface, at a high resolution will give us a huge sum of accurate and precise spectral data on the mineralogical composition of the asteroids.

QE65000 UV Spectrometer:
The QE65000 UV Spectrometer will take 625 scans with a resolution of 73m with a spectral accuracy of 0.14 to 7.7 nm, a targeting accuracy of 0.0225 degrees, and a targeting precision 0.1 x 0.1 degrees/0.1 x 0.4 degrees. The large number of scans with the accurate and precise targeting capabilities in addition to the smaller resolution will enable us to scan selective parts of the asteroids, i.e. general surface vs. crater surface, and will give us a large amount of data on the mineralogical composition of the asteroids with confidence of accurate and precise spectral measurements.

LIDAR:
The LIDAR will take 180 scans with a horizontal resolution of 514.28 m x 210 m, allowing a high level of detail of the surface to be seen in each scan, which will enable the obtainment of a reliable shape model of the surface of the asteroid, required for establishing its volume and mass. In addition, the LIDAR is suitable for addressing the surface geology as well, providing additional information to determine the geology of the asteroids. The LIDAR has a range

accuracy of 100 m and a precision of +/- 5 m. This moderate accuracy and high level of precision should enable us to scan as much of the surface as possible in detail with the 180 available scans.

Osiris NAC/WAC:
The Osiris WAC will take 1400 pictures in which resolutions from the asteroid span from 143 pixels (small), to 1075 pixels, filling up ¼ of the screen. The Osiris NAC will take 1400 pictures in which resolutions from asteroid fill from about 1/4 the screen to a zoomed in view of about 25% of the asteroid. Measurements objectives are to map as much of the surface of each asteroid as possible, and to do this a high level of targeting accuracy and precision will be needed from the camera. The Osiris WAC has a targeting precision of 12 x 12 degrees and a targeting accuracy of 0.1 millidegree. The Osiris NAC has a targeting precision of 2.35 x 2.35 degrees and a targeting accuracy of 0.1 millidegree. The high level of accuracy and precision provided by the Osiris NAC/WAC will be critical in mapping out as much of the surface of the asteroids as possible without unnecessary overlap. These pictures will be enough to successfully observe the surface geology of the asteroid in enough detail to determine key surface features.

3. Science Mission Profile

Orbit and navigation accuracy: Use of AutoNav (qualified on DS1) will allow for a high degree of autonomy in course corrections, especially near the objects of interest. AutoNav has been proven capable of navigating to within 100km of a moving body, but our mission will require a 200 km point of closest approach. By employing an innovative mirror system, the main science instrument (OSIRIS) will be capable of taking usable science imagery from a distance of 1000 km from the body in question. The other science instrumentation has a lower effective range (approximately 300km) and will be employed only on the close approach period.

4. Data Plan

A schedule-based data management plan will be put into place to account for data retrieval, validation, preliminary analysis, and archiving of all data collected during the mission. The data will be transmitted from the spacecraft by data downlinks. A PI will be responsible for analysis of the data required to complete the science objectives of the mission. A PI will also be responsible for the publication of all newfound results of the mission to relevant scientific journals. There will be a short period of exclusive access to the data found by the mission in order to calibrate and validate the data. This period will not exceed six months and will be followed by the presentation of the data to the public, as is the policy of NASA. The mission data will be made presented to the public by means of the Planetary Data System. Raw data, or Level 0 data, will be analyzed by the PI before delivery to the archive. All data submitted to the archive will be processed data, or Level 1. All Level 2 or higher data products will be evaluated according to NASA data archive standards of format.

5. Science Team

Principal Investigator: David Weiss, College of Charleston

Role: Science and instrumentation team lead. Responsible for leading the analysis of the data required to complete the science objectives of the mission. Also responsible for the publication of all newfound results of the mission to relevant scientific journals.
Funding source: NASA/College of Charleston.

Co-investigator: Blake Hodges, College of Charleston
Role: Responsible for analysis of the data required to complete the science objectives of the mission. Also responsible for the publication of all newfound results of the mission to relevant scientific journals.
Funding source: NASA/College of Charleston.

D. Mission Implementation

1. Introduction

The TCR mission will consist of a flyby of the Trojan asteroid Philoctetes and an orbit near the Centaur asteroid, Okyrhoe. These asteroids were chosen based on their distances from earth. Philoctetes was also chosen because it is in a stable orbit and is one of the larger Trojan asteroids, which will aid in the viewing process. Okyrhoe was chosen based on its relative proximity to the sun and the fact that it outgases, which will provide interesting scientific data. A constraint of the trajectory was that it must launch prior to December 31, 2019. With this given constraint, a trajectory was found which will launch on June 30, 2016 with a 30 day contingency window built in. After launch, the spacecraft will swing by Mars on September 18, 2017, and reach Philoctetes on September 4, 2019. After this flyby at Philoctetes the spacecraft will reach Okyrhoe on November 18, 2025. This mission has a duration of 10 or more years. After the spacecraft reaches Okyrhoe, it will continue to take and transmit data until the end of its life. The TCR mission includes a robust Science Enhancement Option that allows for significant additional science operations after the baseline mission has been satisfied. The farthest point that the spacecraft will be is approximately 9.28 AU from the Earth. The concept of operations is shown in Figure 5 below. Based on TCR's mission duration and complexity, it is considered a Class B mission.

"QE65000-FL Scientific-grade Spectrometer."

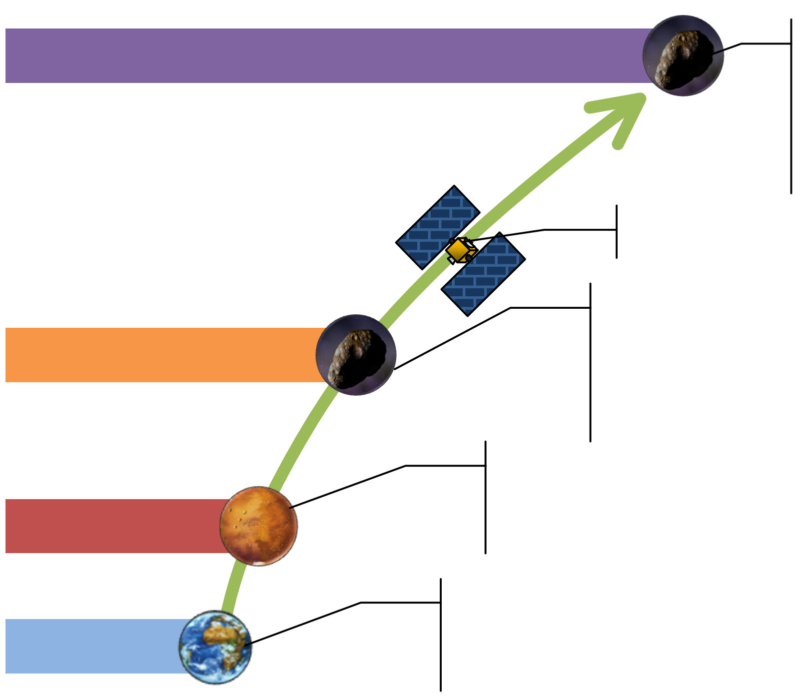


Figure 5: Concept of Operations

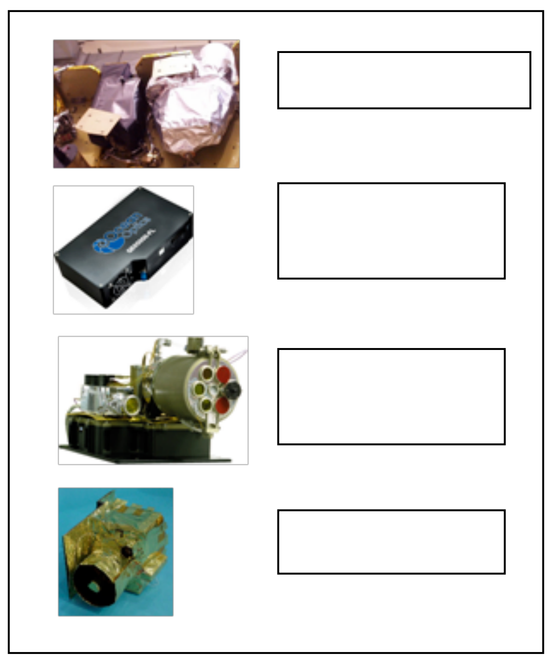
Figure 6: Science Instruments

The launch vehicle for TCR will be the Atlas V 551. The spacecraft bus will have a square design and will fit into the launch vehicle fairing. A more detailed look into the spacecraft bus can be found in the Structures section of this proposal.

Power for the spacecraft will be provided by two Stretched Lens Array Square Rigger (SLASR) solar arrays with a total surface area of 90 square meters. SLASR arrays will provide 27 kW at 1 AU and 270 W at 10 AU. The spacecraft will carry two 60 Ah Lithium Ion rechargeable batteries with a total energy storage of 3456 W/hr. Assuming 50% maximum depth of discharge (DOD) will supply less than 2000 cell level life cycles for the batteries. The batteries will be relied on heavily during launch until the solar arrays are deployed. The power system is described in more detail in the electrical power system below.

The thermal control system maintains all components within their specified temperature ranges and minimizes thermal cycling and gradients. The system is primarily passive, with the passive components consisting of surface finishes, multilayer insulation, conduction paths, radioisotope heater units, radiators, and louvers. The only active components are electric heaters and their attendant thermostats and temperature sensors. The system utilizes the passive components to maintain the spacecraft interior at a minimum temperature and then uses the electric heaters to keep critical components within their allowable temperature range. The risk from these elements is low due to heritage from previous spacecraft.

The spacecraft will house a dual mode bi-propellant engine.
The system will consist of two Aerojet AMBR engines with hydrazine as a fuel and nitrogen tetroxide as an oxidizer; only two of these engines will be active at any given time. AMBR is a new engine based on Aerojet's R-4D-15 dual mode apogee thruster. In addition, the dual mode AMBR system includes the monopropellant system. The monopropellant system will be used for spacecraft orientation and minor trajectory adjustments. The monopropellant system will use 12 Aerojet MR-103M engines with hydrazine propellant, up to six of which will be active at a time. The propulsion systems are described in more detail in the propulsion section of this proposal.



This mission will employ the use of many science instruments as shown in Figure 6. These instruments have been proven on recent missions. The OSIRIS was used on Rosetta and was explained further in the Science Investigation and Implementation section. The QE65000 Ultraviolet and Infrared Spectrometers flew on Rosetta under the name Alice. These science instruments will give TCR the ability to collect high-quality data, which will achieve the baseline science objectives of this mission. A traceability matrix of these science instruments and their functions can be found in the Science Investigation section.

The command and data storage system will be based in large part on the system used in the Juno mission;

dual redundant flight and data handling computers will be used in conjunction with 120 Gbits of storage on solid-state NVRAM in either a redundant 60 Gbit array or a dual-redundant 30 Gbit array depending on the expected data storage needs. Computing hardware will be based on the Mongoose-V chip and all internal components will be fully redundant.

Data collected with the science instruments and stored in the Command and Data Storage system will be transmitted to Earth. The onboard system will be based on the main antenna array of the New Horizons mission, and will transmit over the X band using a high-, medium-, and low-gain antenna. The medium and low gain antennas will be primarily used for housekeeping and position data and also to generate status tones for the DSN Beacon Tone System first qualified on DS1. The antenna array will be fully fixed; since data transmission and data collection will not occur simultaneously, the satellite is free to orient itself as necessary during transmission events. Major science data will be transmitted over the high gain antenna at a variable rate determined by the distance of the satellite from Earth; at the Trojan Philoctetes the downlink will occur at 38 kbits/s, and at the Centaur Okyrhoe the downlink will occur at 6 kbits/s.

TCR will be linked to Earth using the DSN 34 meter dish during normal operations and the DSN 70 meter dish during critical events. A more detailed look at the communication capabilities of TCR can be found in the Subsystem Breakdown section of this proposal.

2. Functional Design

Table 3 shows the mission traceability matrix with functional, design, spacecraft, ground system and operations requirements. This table is a summary of the overarching constraints put on the design team for this mission.

Table 3: Mission Traceability Matrix

Mission Functional Requirements	Mission Design Requirements	Spacecraft Requirements	Ground System Requirements	Operations Requirements
Must take pictures from 3600 km (80 km asteroid) and 1800 km (70 km asteroid) starting at 1 degree. Must begin collecting data at 500 km distance, 90º, beginning at ½ total observation time. .	Rocket Type: Atlas V -551 Launch Date: Aug. 2016 Mission Length: 8-15 years Type of orbit: Gravity assists followed by flyby or stable orbit near science objectives.	Stabilized with spinning components as required by science objectives. Mass: < 3000 kg Power to be primarily solar; expected insolation at Earth of approx. 2 kW. Temperature Range for spacecraft not to be more restrictive than 285+/- 5 K. Pointing control from combination of reaction wheels and attitude control thrusters for fine control. Radiation shielding using standard deep space protocols – using Juno and Cassini as models.	Deep Space Network will be utilized for housekeeping, status and position reporting, and for periodic scientific data transmission as required by science objectives.	Spacecraft will be required to take multiple photographs of quickly moving celestial objects at varying ranges. Spacecraft must be capable of primarily autonomous movement due to distance from Earth. Spacecraft must be capable of subsisting entirely on electrical power stored during initial travel. All operational requirements are in specific response to the science objectives of the mission.

Mission Concept Description

Mission Design

Tables 4 and 5 below show the Philoctetes and Okyrhoe encounters respectively in detail. The encounter strategies at both encounters are primarily governed by the velocity of the satellite with respect to the object and by the amount of storage available for scientific data.

At Philoctetes (Table 4), the OSIRIS camera begins taking photographs approximately two days prior to the encounter; those pictures are processed by AutoNav for course adjustments and targeting. Prior to the Philoctetes close encounter, the AutoNav will be instructed to send back targeting images in which the target body is centered or highlighted. This information will be used to perform debugging and verification of the AutoNav algorithms, mitigating the risk of using a relatively new technology. As the asteroid begins to fill the field of view, the data handling system will begin to record the images from first the NAC and then the WAC of OSIRIS; during the close encounter period where the spectrographs and LIDAR operate, the satellite will take in data at the maximum rate. After the satellite leaves the close approach envelope, all instrumentation with the exception of OSIRIS will be turned off - OSIRIS will be turned off when the available space for data storage is filled or when the object passes out of range. At this point, data transmission will begin and continue for a period of approximately 18 days.

At Okyrhoe (Table 5), the encounter strategy is affected by the propulsion burn; the velocity is significantly slower during the approach phase, allowing the OSIRIS NAC to view the asteroid for a significantly longer period; this will give the AutoNav system a long period of time to lock onto and match the velocity vector of the target body. Data collection from OSIRIS begins 8 minutes prior to the closest point of approach, and a period of approximately 5 minutes is available for data collection from the entire science payload before the available data storage is filled. The data transmission period will last for 60 days, but will require a small fraction of the DSN available bandwidth.

Table 4: Philoctetes Encounter

Encounter Point Subsystem	EP - 100000 km EP - 48 H	EP - 1000 km EP – 140 min	EP - 300 km EP - 46 s	EP + 300 km EP + 46 s	EP + 1000 km EP + 140 min	EP + 18 days
Science Instrumentation	NAC On	WAC On	Sci Payload On	Sci Payload Off	NAC / WAC Off	
Autopilot	AutoNav On					AutoNav Off
High-Gain Antenna	Xmit targeting images (HGA) (524 kbits every 15 minutes)	Halt targeting image Xmit			Commence Xmit science data (38000 bits/s)	Halt Xmit science data
Medium/Low-Gain Antennas	Xmit Position/HK data (LGA/MGA)				Position/HK data to hibernate.	
Mirrors	Verify WAC Mirror Status				Close NAC & WAC Mirror arrays	
Thermal	Increase Science Payload Temperature to OP status	Verify Payload Temp at Op Status		Payload Temperature to Hibernate		
Data recording	Data storage test and format (dual-redundant 60 Gbit)	Commence image recording (38.3 Mbit/s)	Commence full data recording (45.4 Mbit/s)	Data Recording (38.3 Mbits/s)	Halt Data Recording	
Satellite thrusters	SLEW: Point HGA to Earth, Mirrors normal to Philoctetes				SLEW: Adjust for HGA	SLEW: 180 degrees, prep for decel @ Okyrhoe
Hydrazine thrusters	Hyd. thrusters to correct position/ control jitter.		Kill thrusters	Thrusters active		Kill thrusters

Table 5: Okyrhoe Encounter

Encounter Point / Subsystem	EO – 350,000 EO – 6 days	EO - 500 km EO – 8 min	EO - 300 km EO – 183 s	EO +/- 300 km EO +153 s	EO +/- 300 km EO + 60 days
Science Instrumentation	NAC On	WAC On	Science Payload On	Science Payload Off, NAC/WAC Off	
Autopilot	AutoNav On				Enter Hibernation state, await wake command.
High Gain Antenna	Xmit Position/HK data			Halt Xmit Pos/HK Data, Commence Xmit science data (6000 bit/s)	Halt Xmit science data Commence intermittent Pos/HK
Medium/Low Gain Antennas					
Mirrors	Verify WAC Mirror Status			Close NAC/WAC mirror arrays	
Thermal	Increase Science Payload Temperature to OP status	Verify Payload Temp at Op Status		Payload Temperature to Hibernate	
Data recording	Data storage test and format (dual-redundant 60 Gbit)	Commence image recording (38.3 Mbit/s)	Commence full data recording (45.4 Mbit/s)	Halt Data Recording	
Satellite thrusters	SLEW: Point HGA to Earth, Mirrors normal to Philoctetes			SLEW: Adjust for HGA pointing	
Hydrazine thrusters	Hydrazine thrusters to correct position/ control jitter.		Kill thrusters	Thrusters active	

3. Trajectory

The trajectory utilized by the Trojan/Centaur Reconnaissance mission utilizes a rare orbital arrangement to enable a chemical propulsion trajectory with an acceptable overall payload. As seen in Figure 7 below, the Philoctetes/Okyrhoe Surveyor uses a Mars swing-by to effect a course correction that permits a ballistic flyby of the Trojan Philoctetes on the way to a rendezvous with Okyrhoe. The spacecraft requires only one burn to match velocity at Okyrhoe; it is otherwise on a ballistic trajectory. This trajectory design also acts as a point of redundancy should the main propulsion system fail – the spacecraft will be able to effect a flyby of both bodies with no main propulsion. Table 6 provides pertinent details about each encounter.

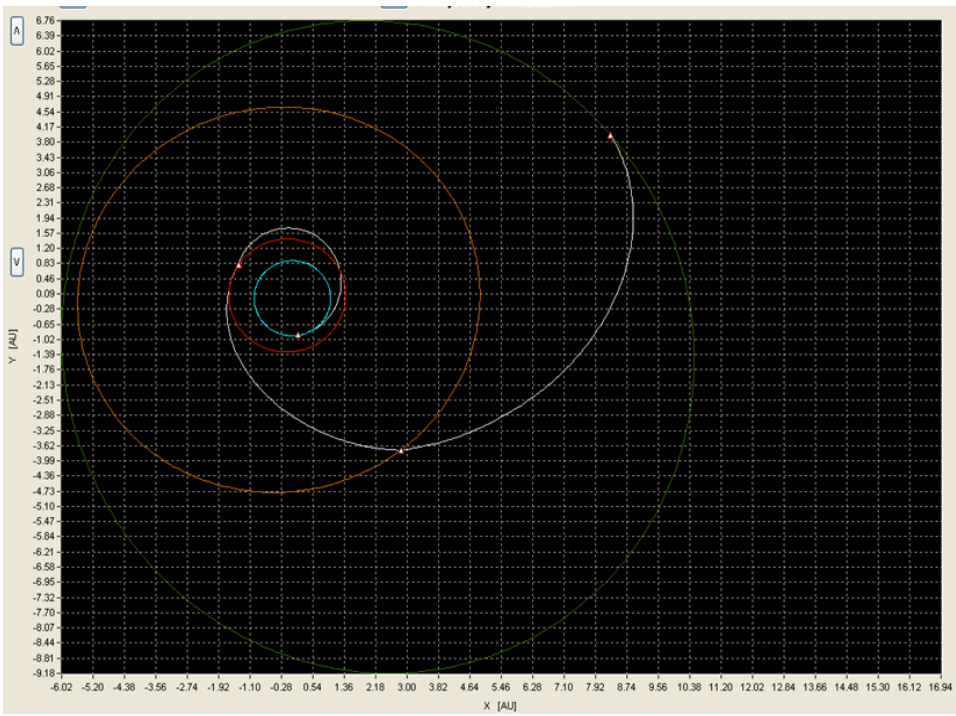


Figure 7: Trajectory

Table 6: Mission Analysis Event Timeline

Mission Sequence	Date (Julian and Days)	Mass	Arrival Vinf (km/s)	Departure Vinf (km/s)	Distance from Earth (AU)
Launch	06/30/2016	4375	0	4.53	0
Mars Swing-by	09/18/2017 (445)	4375	5.89	7.92	
Flyby of Philoctetes	09/04/2019 (716)	4375	8.30	8.26	4.69
Orbit near Okyrhoe	11/18/2025 (2267)	1188	3.66	N/A	9.28

4. Launch Vehicle Details

TCR will launch on an Atlas V 551 from Kennedy Space Center. The Atlas V 551 has a 5-m-class-diameter payload fairing. With given trajectory, the launch vehicle can support a spacecraft mass of 4,375 kg. For the given trajectory the C3 at departure is approximately $20.56\frac{km^2}{s^2}$ and the declination at departure is -10.1 degrees.

5. Flight System Capabilities

The chemical propulsion trajectory chosen for the Trojan/Centaur Reconnaissance mission places a constraint on the total available mass and on the amount of propellant required to achieve the velocity match at Okyrhoe; POIAS requires no delta-v burn to meet the Mars assist or the Philoctetes flyby. The remaining available mass was designated the maximum dry mass, and the JPL Design Criterion 1 was applied to that value to determine an allowable dry mass of 1155 kg. Table 7 shows the overall mass budget.

Table 7: Mass Budget

Total Available Mass		4375	kg
Required Propellant		2830	kg
Maximum Dry Mass (NLS)		1545	kg
Allowed Dry Mass (JPL Des. Crit. 1)		1155	kg
	Subsystem Group	Mass Contribution	
	Structural/Tanks	815	kg
	Science/ C&DH	70	kg
	Propulsion/ACS	90	kg
	Electrical/Thermal	178	kg

To successfully complete the mission at Okyrhoe, a redundant electrical generation and storage system was proposed. At either encounter, fully half of the solar array can be completely non-functional without impeding the overall performance of the mission; additionally, either of the on-board batteries can be non-functional without substantially affecting the mission. During the encounters, the maximum continuous power draw served as the design baseline; the approximately 45 square meter solar array was then doubled to achieve full redundancy. Intermittent power is required by thruster valves and the communications systems; this additional draw is intended to come from the batteries, which can then be recharged from excess power at a later point in the mission. For the purpose of the electrical power budget, any power draw of less than 5 minutes was considered to be a pulse draw. The maximum pulse draw and other parameters are shown in Table 8

Table 8: Power Budget

Critical Event	Philoctetes	Okyrhoe
Average Available Power	5,500 W	469 W
Maximum Continuous Draw	714 W	234 W
Maximum Pulse Draw	794 W	607 W
Margin	670%	200%

Figure 8 below shows the proposed spacecraft with the bus walls transparent to reveal science instruments and fuel tanks.

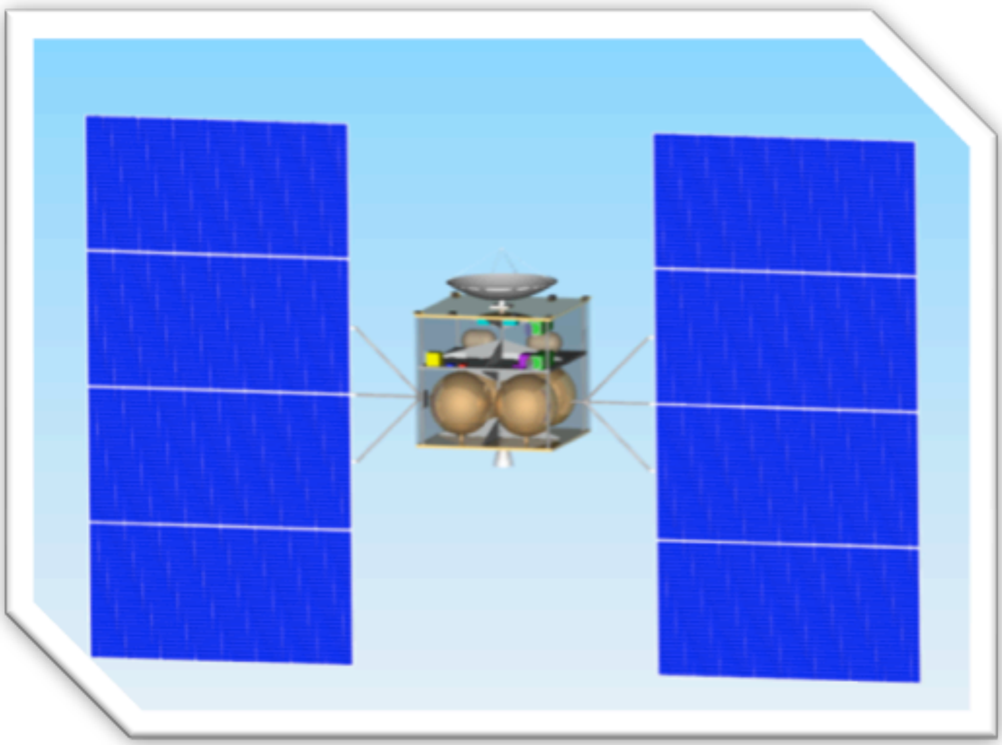


Figure 8: Satellite Configuration

Key Features

- Solar Arrays: Based on SLASR cell technology, this 90 square meter array is capable of providing 27 kW of power at Earth, and provides at least twice the maximum continuous power draw at all points during the mission.
- OSIRIS NAC/WAC: The primary science instrument onboard POIAS, OSIRIS consists of two separate and distinct cameras. The narrow angle camera has a 2.3 degree square field of view, and the wide angle camera has a 12 degree square field of view. Using these instruments, a variety of long-range and zoomed images of both Philoctetes and

Okyrhoe will be available. Additionally, the two-camera arrangement allows for the mission to be completed even if one of the cameras fail.

- Imaging Scan Platforms: The view of each camera is directed by these platforms; they rotate and articulate to provide a nearly full hemispherical available field of view without requiring that the spacecraft bus rotate or slew to maintain focus.
- AMBR: The Advanced Material Bi-propellant Rocket is a new technology offered as an option for chemical propulsion on the Trojan/Centaur Reconnaissance mission. The system installed on POIAS has a high specific impulse, therefore requiring a smaller total propellant load.

6. Concept of Operations

The Trojan/Centaur Reconnaissance mission requires a concept of operations that results in significant scientific observations at both a Trojan (in this case Philoctetes) and a Centaur (in this case Okyrhoe). The proposed mission launches from Cape Canaveral on or about June 30, 2016. Immediately after launch, the solar panels will be deployed and immediately used to replenish power used to maintain the propellant temperature during launch. System diagnostics and tests will be intermittently performed; the status of the overall satellite will be transmitted as a beacon tone to the Deep Space Network. The period of ballistic travel will continue past Mars, where a gravity-assist will be used to adjust the velocity vector of the craft.

The first encounter will occur on or about September 9, 2019, when the spacecraft approaches Philoctetes. The AutoNav system used on Deep Space I will be used to enable autonomous course corrections, although intermittent verification photographs will be transmitted to check the accuracy of the AutoNav solutions. The scanning platform on each OSIRIS camera will be automatically adjusted to keep Philoctetes in view over the entire encounter; these platforms enable photographs to be continually taken while the spacecraft is sufficiently close to the target body for other science instrumentation to effectively function. After the data has been collected, it will be transmitted over a period of 18 days to the DSN 70 m dish. The spacecraft, still on a ballistic trajectory, will enter a period of hibernation until the Okyrhoe approach.

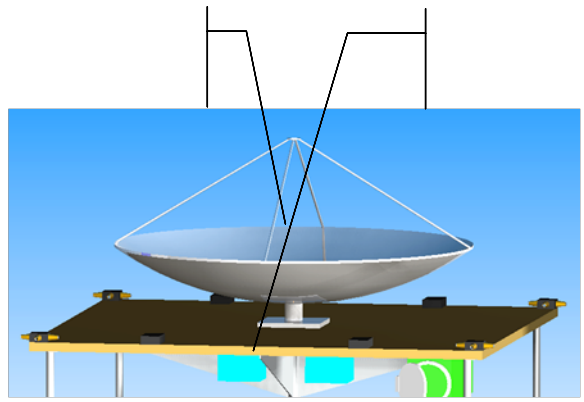
At Okyrhoe, the AutoNav will be used to navigate the spacecraft to a stable position approximately 200 km from the target body. Thirty Gbits of data will be taken at a time, and transmitted to the 70 m DSN dish over a period of 60 days. After the first 30-Gbit data set, the baseline mission will have been completed; any additional data runs constitute a Science Enhancement Option.

7. Data Handling and Storage

Components

- Command and data handling will take place on a flight computer similar in scope to the Mongoose-V based system used on the Juno mission. The computer system will be duplicated for redundancy purposes; the entire command and data handling system will be fully redundant.
- Data storage will occur on an array of 30 4Gbit SDRAM memory modules from 3D-Plus, similar to those used on the Juno mission. The memory modules will provide full redundancy for the Philoctetes encounter, during which approximately 60 Gbits of data will be collected. At Okyrhoe, the modules will be reconfigured into a quad-redundant 30-Gbit array – significantly longer transmission time at the Centaur places an effective limitation of 30 Gbit of data in a single period. The memory modules will be able to reconfigure on command from ground station for longer data runs or more redundancy as components fail.

Figure 9: Antenna configuration



- The antenna system used will be identical to the primary antenna array on the New Horizons mission; a high-gain, medium-gain, and low-gain antenna are combined onto a single dish. This antenna is designed to transmit on the X-band, and will provide an estimated 38000 bits per second downlink at the Philoctetes flyby, where excess power of approximately 4500 Watts will be available for transmission if the 180W transfer power is insufficient. Design specifications for the New Horizons dish suggest a minimum data rate of 1000 bits per second at 28 AU; a conservative estimate for data rate at the Okyrhoe encounter (approx. 9.5 AU) is 6000 bits per second. This will result in a total data transfer time of approximately 18 days at Philoctetes and approximately 60 days at Okyrhoe. While the data transmission period is lengthy, the high level of redundancy on the overall spacecraft and on the data storage system in particular reduces the chance of irretrievable data loss.
- Data will be received by the 70-m DSN dish and transferred to a science operations center at the National Space Science and Technology Center in Huntsville, AL, via the Downlink Server Database. After data validation and verification, all data sets will be delivered to the NASA Planetary Data Systems small-bodies node.

8. Data Collection and Transmission

- Housekeeping Data will be transmitted over either the low- or medium-gain antenna for the entire mission duration. During critical periods, position and health data will be transmitted continuously; during hibernation periods this information will be sent on a biannual schedule. At a minimum, housekeeping data will include:
    - Temperature readings at the batteries, the propellant tanks, the computer bus, and the science payload.
    - Battery charge level and health, power input from solar arrays, and power draw from the equipment.
    - Science payload health and diagnostics data
    - Data handling and storage health.
    - Current propellant load and verification of both valve movement and pipe pressure.
    - Current position data and position history.
- The satellite will use the DSN beacon tone system on weekly intervals to provide a general overview of system status.
- Science data will be transmitted over the high-gain antenna (HGA) after every period of collection to reduce the overall power requirements and avoid positioning conflicts. Table 9 below provides the current best estimate (CBE) data requirements for each instrument; each camera will collect images with a framing rate of 3.5 seconds; taken as a continuous data stream, the overall data rate will be approximately 19 Mbits/s. The spectrometers, LIDAR, and rangefinder together have an approximate data rate of 8 Mbits/s that will be added to the cameras during the close approach periods as described in the ConOps. The total data collection rate shown represents the absolute maximum speed at which the available storage will be filled.

Table 9: Data Rate Analysis

Instrument	File Type	File Size	File Frequency	Data Rate
OSIRIS NAC	Image: 2048 x 2048 pixels	67.1 Mbits	1 per 3.5 s	19 Mbits/s
OSIRIS WAC	Image: 2048 x 2048 pixels	67.1 Mbits	1 per 3.5 s	19 Mbits/s
NIR Spectrometer	Image: 1044x64 pixels	1.1 Mbits	1 per 300 ms	3.6 Mbits/s
UV Spectrometer	Image: 1044 x 64 pixels	1.1 Mbits	1 per 300 ms	3.6 Mbits/s
LIDAR	Plaintext	3 kbits	1 per s	3 kbits/s
NEAR	Plaintext			50 bits/s
	Total			45.5 Mbits/s
	Total w/ 25% Contingency			56.8 Mbits/s

9. Downlink Strategy

Given an estimated data transmission rate of 38,000 bits per second on the high-gain antenna (HGA) at Philoctetes and 6,000 bits per second at Okyrhoe, a downlink strategy for science data can be determined. The data profiles of POIAS at Philoctetes and Okyrhoe are shown in Figure 10 and Figure 11. The Okyrhoe data rate is estimated by scaling the Philoctetes data rate by the increase in distance to the second encounter.

1. Philoctetes:

- The OSIRIS NAC will be onlined at the beginning of the critical phase (approximately 24 hours prior to the encounter) and will take photographs continuously until the encounter is concluded. Onboard systems will use position data and these photographs to adjust course, using the AutoNav system first employed in Deep Space I.
- At a distance of 150,000 km, the OSIRIS NAC will come online. The photographs will be processed by the onboard computer and used to adjust course, but will not be stored.
- A single 256 x 256 image from the NAC camera centered on Philoctetes will be transmitted in 8-bit gray scale every 15 minutes. In conjunction with the positioning data transmitted continuously over the low-gain antenna (LGA), these photographs will be used to verify and if necessary manually adjust the targeting software of the onboard systems. Targeting images (256 x 256, gray scale) will require approximately 2 minutes to transfer. Near the encounter, latency will be approximately 30 minutes; if targeting adjustments are required, the ground support team will have adequate time to adjust before the close approach. Adjustments are not anticipated and serve primarily as a final debugging and verification opportunity before the Okyrhoe encounter, where a significantly higher latency will make manual adjustments nearly impossible.
- At a distance of 900 km from Philoctetes, full images from the NAC will be sent to data storage for later transmission. Targeting images will continue to transmit on schedule. At this time, the WAC will also activate and send data to storage. Figure 10 below describes the expected data rate in kbits/s as well as the total data stored.
- At a distance of 300 km, all other instrumentation will be onlined for a period of 156 seconds, constituting the close approach period.
- Once Philoctetes has passed out of the 900 km range, all science systems will be offlined and data transmission will begin.
- Data transmission will occur at 38,000 bits per second for a period of 18 days. After the data transmission has concluded, the satellite will move into hibernation mode.

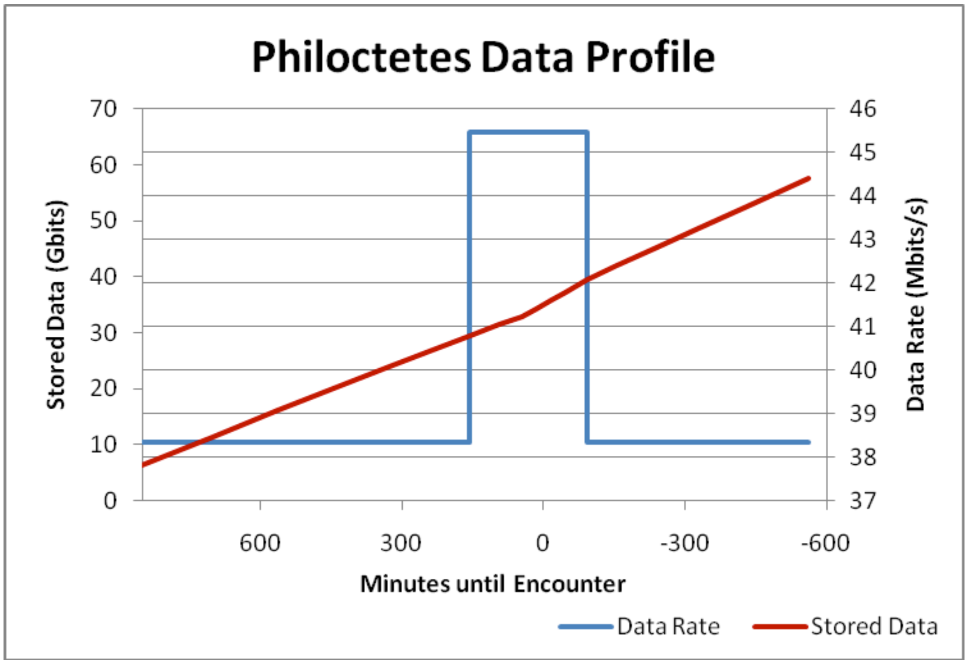


Figure 10: Philoctetes Data Transfer/ Storage

2. Okyrhoe:

- Due to high latency between the satellite and ground support and a low anticipated effective bandwidth, targeting photographs will not be transmitted. The opportunity to calibrate the AutoNav system during the Philoctetes encounter will minimize the likelihood of targeting malfunction during the Okyrhoe encounter.
- At the beginning of the critical phase (EO–6 days) the OSIRIS NAC will be onlined. The early start to the critical phase is designed to allow sufficient time for any errors or malfunctions to be corrected prior to the encounter.
- At a distance of 350,000 km, the OSIRIS NAC will online. Photographs will be processed by the onboard computer and AutoNav, but will not be stored.
- At a distance of 500 km, the NAC and WAC will begin recording data for later transmission.
- At 300 km, all other instrumentation will be onlined and run for a period of 336 seconds. After this period, the science payload will be deactivated and data transmission will begin.
- Data transmission will occur at 6000 bits per second for a period of 60 days. After this period, the satellite will enter a hibernation state and maintain a 300km distance from Okyrhoe until a wake command from ground support. At this time, the science team will have the opportunity to either further investigate Okyrhoe or to end the mission. Figure 11 below shows the expected rate of data collection over the Okyrhoe encounter.

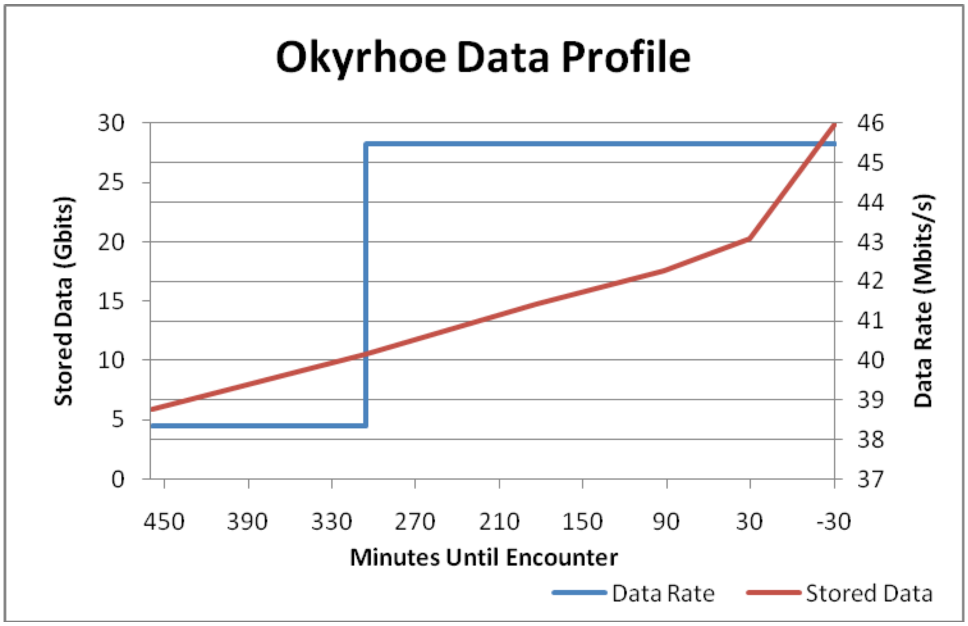


Figure 11: Philoctetes Data Transfer/ Storage

3. Science Enhancement Option

- Additional instrumentation passes will be limited primarily by the risk tolerance of the science team. A second of collected data requires approximately two hours to transmit to earth; if the satellite is damaged or destroyed, a long data run could be destroyed. The maximum recommended data collection period is 2 minutes for any additional instrumentation pass.

10. Electrical Power System

Power for the spacecraft will be generated by the Stretched Lens Array SquareRigger (SLASR) solar arrays. The spacecraft will carry a total of eight 2.5m X 5.0m SLASR solar cell bays that comprise the spacecraft's solar arrays. The total surface area of the solar arrays is 100sq.m with a mass of 88 kg. The eight bays are stationed on two arms having four bays on each arm. SLASR solar arrays have a specific power per unit area of 300 W/m^2. The total power output of the spacecraft is 30 kW at 1 astronomical unit (AU) and 469 W at 9.24 AU. In Table 10 below, there is a brief summary of the SLASR solar arrays use for the TCR mission. The electrical control buses of the power subsystem will ensure all science equipment and all electrical equipment will receive the nominal voltage and current required by each piece of equipment. The peak power usage for the TCR mission at Philoctetes is 832 W with science only and 725 W when transmitting data. At Okyrhoe the peak power usage required for the mission is 492 W with science only and 325 W when transmitting data. With the 100 m^2 SLASR solar arrays, TCR can perform all operations at the Trojan and Centaur asteroids by only using solar generated power. The size of the solar arrays gives TCR redundancy for the most of the duration of the mission. Power generated with the SLASR array is shown in Table 10. The power strategy of TCR will be explained in more detail below.

Table 10 - Solar Array Summary [5]

Solar Array Summary	
Mass- cell, lens, etc.	60 kg
Mass- structure	25.3 kg
Mass- Total	88 kg
Manufacture	ATK Space Systems
Area	100 m^2
Cell Technology	GaAs TJ SLASR cell
Power per unit Area	300 W/m^2
SLASR height per bay	5 m
SLASR width per bay	2.5 m
Solar Array dimensions	2 m x 5 m x 10 m

The electrical power system will be comprised of two 60 Ah Lithium-on rechargeable batteries with an energy storage capacity of 3456 W/hr. One 60 Ah Lithium-on battery weighs 20.32 kg and provides 145 Wh/m^2 of specific energy. The temperature range of the Lithium Ion battery ranges from -10° C to 40° C and for optimum efficiency the Lithium-ion batteries will be kept at around 21° C. Assuming 50% maximum Depth of Discharge (DOD) for the TCR mission, the Lithium-ion batteries will supply less than 2.000 cell level life cycles for the batteries. In Table 11 below, there is a brief summary of the data on the Lithium-ion batteries. **[1]** The 60 Ah Lithium-ion batteries have high energy density, a long storage life, and a wide temperature range, and are therefore adequate for the TCR mission. **[2]** The batteries will be relied on heavily during launch until the solar arrays begins deployment at 2,000 seconds into the TCR mission. The batteries will supply all power required for housekeeping during launch, separation from launch vehicle, and until the SLASR solar arrays are fully deployed. The batteries will be used very lightly during data collection at the Centaur. The primary role of the batteries is mainly for launch mode power, backup power, and redundancy. A battery summary is shown in Table 11.

Table 11: Battery Summary

Battery Type	Lithium-ion
Ampere	60 Ah
Energy Storage per battery	1728 Wh
Total Energy Storage	3456 Wh
Mass per battery	20.32kg
Temp. Range	-10° C to 40° C
Life Cycles	2000

Power Strategy

The large solar arrays called for in this design generate enough power to complete the mission. The electrical power system has complete redundancy over the entire mission by having stored battery power as backup; the two batteries are fully redundant in themselves. If only one of the two solar arrays and one of the two batteries are functional, all baseline mission objectives can still be met.

Figure 12 below shows the electrical power available to the mission at all points along the trajectory given three assumptions: the Beginning of Life (BOL) assumption does not allow for cell degradation over time, the End of Life (EOL) assumes that the cells are operating at 60% of their BOL specification for the entire life of the mission, and the "Degradation" assumption allows for a continuous and steady reduction in output from 100% to 60% over the 10 year life of the cells. The "Degradation" model is used in all future power calculations. Figure 13 is a graph of the available power at any time during the mission.

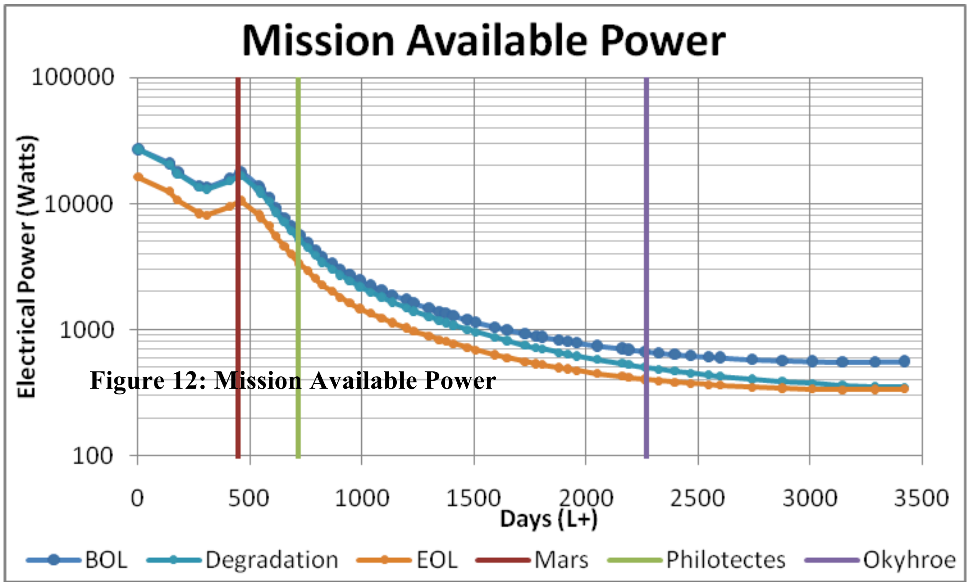


Figure 12: Mission Available Power

11. Philoctetes Encounter

The entire Philoctetes encounter operates with a power budget approximately ten times the required; excess power may be required for student science projects, and some power may be lost temporarily due to spacecraft maneuvers near the Trojan. Figure 13 below shows the power profile of the mission at Philoctetes; the power required to complete the mission is plotted on the left vertical axis, and the power available is plotted on the right vertical axis. Continuous power is expected to peak at just over 700 W, with possible pulses for thruster actuation and data transmission not to exceed 800W. Pulsed intermittent power is expected to be drawn from battery reserves and recharged as necessary.

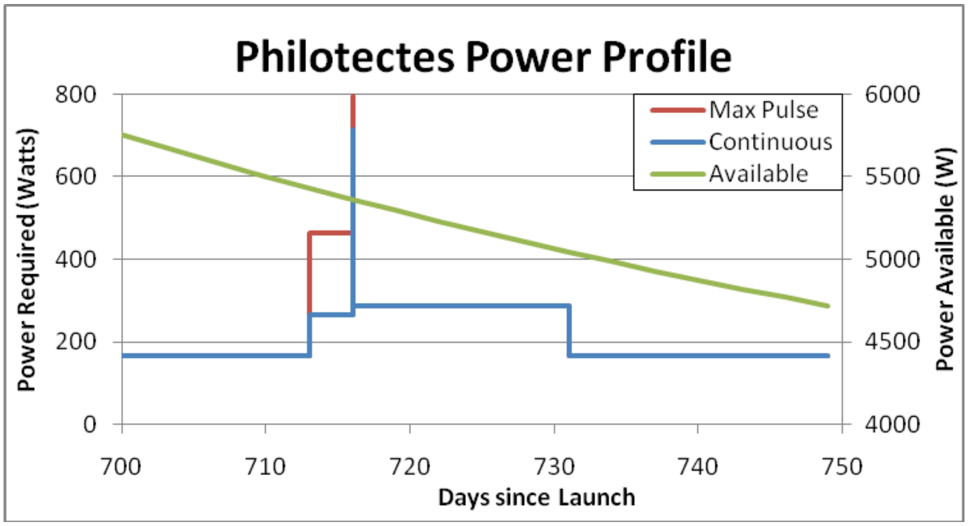


Figure 13: Power Profile at Philoctetes

12. Okyrhoe Encounter

The power budget for the Okyrhoe encounter is less forgiving; during the most intensive periods of data collection, approximately 0.84 Wh is drawn from the batteries. The transmission power at Okyrhoe is significantly lower than the power input from the arrays, so any required battery discharge can be recovered. Figure 14 shows the power profile at Okyrhoe, with required power and available power graphed over the same range. The maximum sustained power draw during data transmission is 234 W, which is equivalent to half the average expected power available from the solar arrays. During data collection, approximately 170 W will be required from battery storage; that draw continues for less than one hour and is not expected to significantly impact the 1.7 kWh total battery reserve.

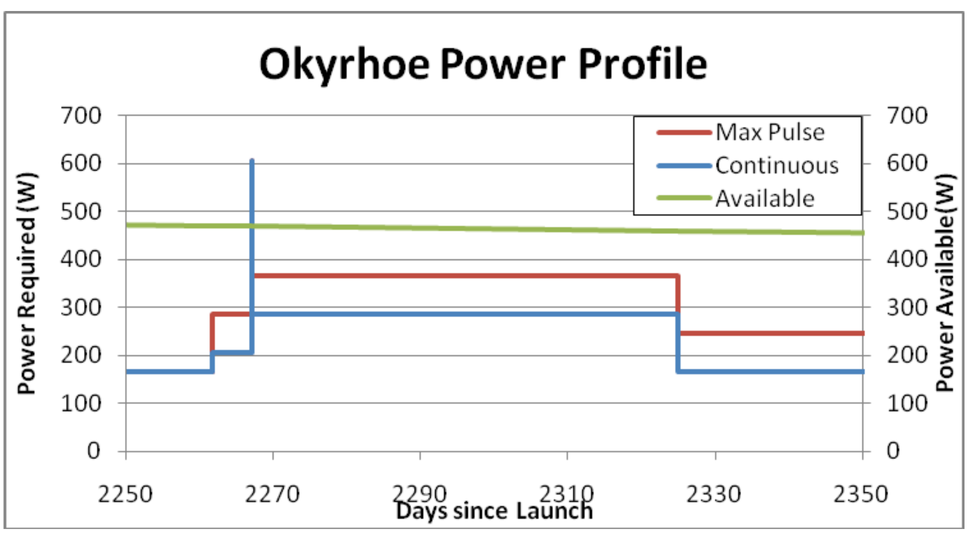


Figure 14: Power Profile at Okyrhoe

13. Power Trades

SLASR is a stretched lens array blanketed over a squarerigger solar array structure. This configuration allows for low mass, low stowed volume, high stiffness, low cost, and high efficiency of the solar arrays. SLASR arrays have an experimental specific power of 320 W/kg, a power per unit area of 310 W/m^2, and an efficiency of about 30%. [3] SLASR use advanced triple-junction solar cell technology to achieve these numbers. SLASR solar arrays have a wide operating temperature range. For the advanced triple-junction solar cells the maximum power increases when the temperature of the cell decreases. SLASR arrays can operate at temperatures from -300° C to 300° C as shown in Figure 16. [4]

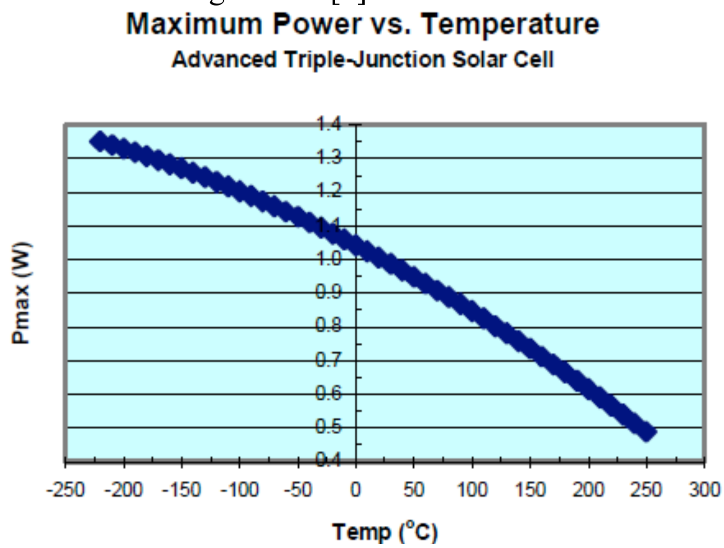


Figure 15: Power vs. Temp. Breakdown [4]

SLASR solar cells come in bays of 2.5 m x 5.0 m. Each bay provides 4 kW of power at 1 AU based on experimental tests. With multiple bays it is possible to reach 100 kW of power in Earth's orbit. SLASR arrays are light weight high efficiency solar arrays. The photovoltaic blanket and lens comprise 70% of the total mass of the arrays as shown in Figure 17. [5]

Element	Areal Mass Density
Lens & Cell/Radiator Blankets	0.600 kg/sq.m.
Harnessing	0.051 kg/sq.m.
Structure	0.076 kg/sq.m.
Mechanism	0.058 kg/sq.m.
Blanket Attachments	0.027 kg/sq.m.
Yoke Assembly	0.009 kg/sq.m.
Root Assembly	0.016 kg/sq.m.
Tiedowns	0.016 kg/sq.m.
Total	**0.853 kg/sq.m.**

Figure 16: Mass Breakdown [5]

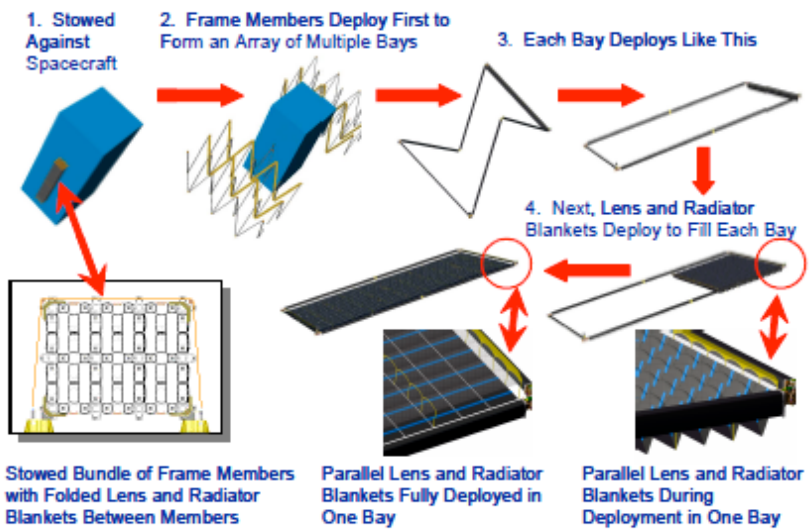


Figure 17: SLASR Deployment Breakdown [5]

The squarerigger configuration of the SLASR solar arrays allows for low mass and a small stowed area. This configuration also allows TCR to have solar arrays that are twice the size and half the weight of other solar arrays that are used in spaceflight applications shown in **Figure 19.** Batteries are electrochemical cells that convert stored chemical energy into electrical energy. Primary batteries can produce current upon assembly and are intended for one time use. Secondary batteries must be charged before they are used, and they can be recharged by applying current. Lithium-ion batteries have high energy density, long storage life, and wide temperature range. [2]

References

[1]- http://www.yardney.com/Lithion/Documents/Batteries/Spectrum%20 Astro%20Battery.pdf

[2]- http://explorersposts.grc.nasa.gov/post633/Explorer%20Post%20633%20-%202008-2009/Fuel%20Cell/Batteries_for_Dummies.pdf

[3]- http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050206379_2005207982.pdf

[4]- http://sri.auburn.edu/papers/2006/solar_concentrator_array_for_lunar_power.pdf

[5]- http://slasr.com/Papers/SLA-SEP-WCPEC4.pdf

14. Structures and Mechanisms

The dimensions of the nearly cubical spacecraft bus are 2.591 m x 2.591 m x 2.456 m. The bus is divided into an upper and lower section by an aluminum honeycomb shelf with a thickness of 5.08 cm. The lower tank area has a clearance height of 1.389 m to allow for the tank support structures as well as the necessary fuel lines for the propulsion system. The upper science compartment has a clearance height of 0.915 m to provide room for the science equipment and insulation.

The spacecraft body is primarily composed of aluminum honeycomb panels with aluminum face plates constructed of Alcoa's alloy 2090. This Al-Cu-Li alloy offers an 8% lower density (0.093 lbs/in^3) and 10% higher elastic modulus than other aerospace alloys. Alloy 2090 also offers excellent fatigue and cryogenic properties in addition to excellent weldability. The face plates will each be 1 mm thick, giving a total plate thickness of 2 mm. Assuming that the largest meteoroid to be encountered is 1.5 mm and that a double wall structure must be at least 1.2 times that diameter to prevent penetration, 1 mm plates in addition to 4.88 cm thick honeycomb panels should be sufficient to protect the internal components of the spacecraft.

Support structures for the spacecraft will be hollow circular columns in order to maximize the axial loading they can support while minimizing mass. The maximum axial load expected for our craft with a total launch mass of 4,375 kg experiencing 6 gs is approximately 257,425 N. Support structures for the spacecraft must not only be designed to support this simple axial load but also be designed with large factors of safety to handle eccentric loading conditions.

The primary, central supports will be composed of these circular columns with cross-shaped end supports which serve to reduce the bending of the plates as well as supporting torsional loads. The longer, lower support will have an outer diameter of 7.62 cm and an inner diameter of 6.985 cm. This should allow the column to support well over 1,000,000 N, which is over 4 times the maximum axial load. The shorter, upper support will have an outer diameter of 5.715 cm and an inner diameter of 5.08 cm and should support a similar axial load.

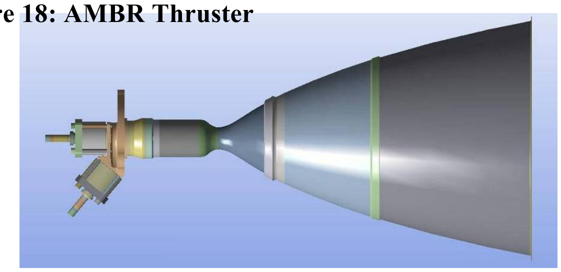
Secondary support structures will be similar hollow columns with an outer diameter of 5.08 cm and an inner diameter of 3.81 cm. These columns should each support an axial load of 369,000 N, or over 1.3 times the expected axial launch load.

SLASR (Stretched Lens Array SquareRigger) solar panel arrays were selected to provide power for the mission due to their small mass/area of only 0.853 kg/m^2. Two solar panel arrays will be mounted on opposite sides of the spacecraft. Each SLASR array will contain four 2.5 m x 5.0 m panels. The panels will extend laterally, rather than longitudinally in order to reduce the mass moments of inertia that will be encountered when the spacecraft is rotated to beam data back to earth. Although exact dimensions for the folded configuration are not known at this time, it is estimated that the panels will not exceed 0.4 m x 0.4 m x 2.5 m.

15. Propulsion

The spacecraft will include a dual mode bipropellant engine. The Advanced Material Bipropellant Rocket (AMBR) thruster, Figure 19, below will be used to change translational velocity in order to ensure approach to the two target bodies, the Trojan and Centaur asteroids. The system will consist of an Aerojet AMBR thruster with Hydrazine (N_2H_4) as a fuel and Nitrogen Tetroxide (NTO) as an oxidizer. AMBR is a new engine based on Aerojet's R-4D-15 dual mode apogee thruster. The dual mode AMBR system includes a monopropellant system. This system will be used for spacecraft orientation and minor trajectory adjustments. The monopropellant system will use 16 Aerojet's MR103M engines with N_2H_4 propellant.

Figure 18: AMBR Thruster



■ Delta-V budget & Propellant Mass

The launch date is June 30, 2016. The required delta-V is 3.201 km/s, and burning is operated only one time at Okyrhoe. The launch vehicle mass is 4375 kg. The dry mass of the spacecraft mass is 1188 kg, so 3169 kg of propellant mass can be loaded. The usable propellant is the portion of the propellant loaded which is actually burned. The total usable propellant is shown in Table 12. The table shows that 2923.18 kg is required for total propellants; however, the spacecraft mass will be reduced from 4375 kg because of the propellant for ACS and other things that are used. As a result, the vehicle mass will decrease in burning time compared to the initial mass, which means the mission requires less propellant than shown in the Table 12. Assuming that the total reduction of mass when the spacecraft reaches Okyrhoe is 150 kg, Table 13 shows the recalculation of the propellant mass. The spacecraft dry mass is 1188 kg, and the usable propellant mass is 2830 kg, which means only 357 kg of mass remains. However, since the TCR mission requires only one burn, this does not offer a significant problem. Table 16 shows the volume of each propellant, and it reveals that the propellant tank is feasible for those propellants.

Table 12

	Fuel (N2H4)	Oxidizer (NTO)	Total
Propellant for translational velocity change (kg)	1237.809091	1485.370909	2723.18
Propellant for ACS (kg)	200		200
Total usable propellant (kg)	1437.809091	1485.370909	2923.18

Table 13

	Fuel (N2H4)	Oxidizer (NTO)	Total
Propellant for translational velocity change (kg)	1195.454545	1434.545455	2630
Propellant for ACS (kg)	200		200
Total usable propellant (kg)	1395.454545	1434.545455	2830

■ Propulsion Type: Dual Mode AMBR system

An Aerojet's AMBR thruster will be used in the mission. The Aerojet's AMBR thrusters are chosen because AMBR thruster has higher performance than the prior-advanced engine, HiPAT, which is the trade name for the R-4D-15. Table 15 shows the comparison of performance

Table 14

between AMBR and HiPAT. As shown in the table, most characteristics of AMBR have larger values than those of HiPAT. In particular, the specific impulse of AMBR thruster is higher than that of HiPAT by 7 seconds. The specific impulse is an important factor in determining the propellant mass. If HiPAT is chosen instead of AMBR, the mission would fail because it would be over the mass budget. The mass calculation is shown in Table 14 below. As Table 14 shows, the total mass difference is about 30 kg, which may seem insignificant, but that difference in the amount of mass is sufficient for remaining under the mass budget. For this reason, AMBR is chosen for the TCR mission. AMBR uses NTO and N_2H_4 in its propulsion system, and N_2H_4 is also used in the Attitude Control System (ACS). The system is dual-mode because the same spacecraft fuel system supplies both the main engine and ACS (the specific impulse is 210 seconds). An advantage of the dual-mode system is the ability to use the N_2H_4 as a monopropellant in attitude control thrusters and as the fuel in bipropellant main engines, resulting in system simplification. Another advantage is a significant increase in the specific impulse for the orbit insertion burn.

Figure 19: Propellant Tank

	AMBR	HiPAT
Total DV (km/s)	3.201	3.201
Initial Mass (kg)	4375	4375
Propellant Mass (kg)	2723.18	2757.16
Propellant Mass (ACS) (kg)	200	200
Total Mass (kg)	2923.18	2957.16

Table 15

Desing Characteristics	AMBR	HiPAT
Thrust (lbf)	200	100
Specific Impulse (sec)	335	328
Inlet Pressure (psia)	400	250
Chamber Pressure (psia)	275	137
Oxidizer/Fuel Ratio	1.2	1
Expansion Ratio	400::1	375::1
Physical Envelope envelope	Within existing HiPAT	
Propellant Valves	Existing R-4D valves	

■ Propellant Tank for $N_2H_4$4 and NTO (ATK Part Number 80507-01)

ATK Commerce's tank part number, 80507-01 (Figure 21), is suitable because the tank satisfies the required volume in order to keep propellants at the required operating pressure needed to work the AMBR thrusters. Four tanks are used: two tanks for N_2H_4 (main engine), and the other two tanks for NTO. The pressure vessel is constructed of 6 AL-4V titanium and overwrapped at the center section. A Propellant Management Device (PMD) provides a gas-free expulsion of propellant. Table 16 shows the dimensions and some characteristics of the propellant tank.

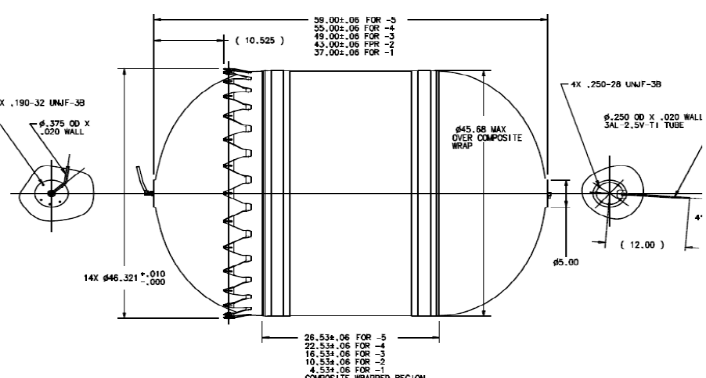
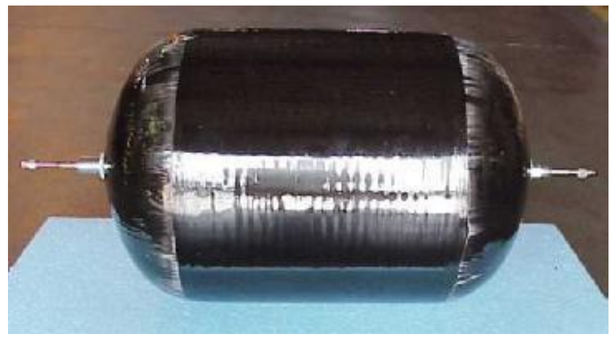


Table 16

Tank	Volume (in^3)	Weight (lbs)	Operating Pressure (psig)
ATK 80507-01	41,093	79.56	535

Figure 20: Pressurant Tank

■ Pressurant (Helium gas) & Pressurant Tank



Helium gas is chosen as a pressurant because the gas constant of helium is much higher than that of nitrogen gas, so the amount of pressurant mass with helium is less than that of nitrogen gas. The risk involved with using helium is treatment, because helium runs the risk of exploding.

The pressurant tank is ATK part number 80445-1 (Figure 21) since the tank satisfies the required operating pressure to pressurize the propellant in the tanks. Two tanks will be used: one is for pressurizing N_2H_4, and the other is for pressurizing NTO. The tank is a composite overwrapped pressure vessel (COPV) with a liner constructed of a center cylinder welded to end domes and overwrapped with T1000 carbon fiber. The commercially pure titanium liner has a nominal .020-inch membrane thickness. Table 17 shows the dimensions and characteristics of the pressurant tank.

Table 17

	psig	bar
Operating Pressure	4500	310.26
Proof Pressure	5625	387.82
Burst Pressure	6750	465.39

	inch	mm
Diameter	15.8	402
Long	26.25	667.3

■ The Propulsion System Schematic

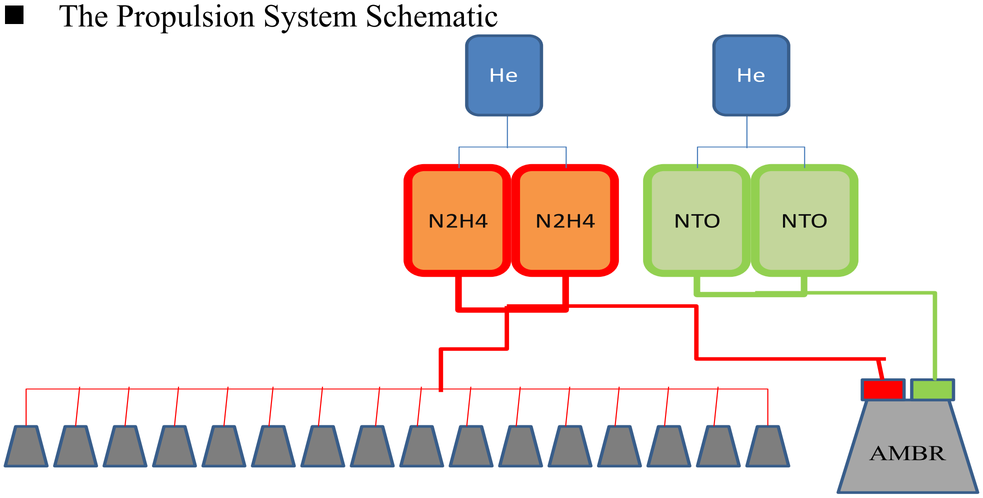


Figure 21

- Pressurant Mass (Helium, He)

The regulated system is used for pressurization. Blowdown pressurization has not been used with bipropellants because of the difficulty in keeping both tanks at the same pressure and the difficulties with varying inlet pressure to bipropellant engines. The initial weight of the stored pressurant can be calculated from the equation of state. The total weight of the pressurant on board is the initial weight of pressurant plus the initial weight of pressurant in each tank ullage. The total weight of helium in this system is 7.61 kg, as shown in Table 18.

Table 17: Component Temperature Ranges

omponents	Min Operational	High Operational	Min Survival	High Survival
atteries	0	30	-10	35
eaction Wheels	-10	40	-20	50
yros/IMUs	0	40	-10	50
tar Trackers	0	30	-10	40
ydrazine anks/Lines	15	40	5	50
ntennas	-100	100	-120	120
olar Panels	-150	110	-200	-130

Table 18: Helium tank summary

Helium pressurant R (J/kg*K)	2078.6
Regulated propellant tank pressure (Pa)	3688681
Initial pressurant pressure (Pa)	31026285
Volume of oxidizer consumed (m^3)	0.99
Volume of fuel consumed (m^3)	1.38
Initial oxidizer ullage (m^3)	0.030
Initial fuel ullage (m^3)	0.041
Temperature (K)	294
weight of initial gas load (kg)	7.18
weight of pressurant initially loaded (kg)	0.427
Total weight of the helium (kg)	7.61

16. Thermal Control Subsystem

1. Thermal Requirements:

The spacecraft has numerous components that must be maintained within certain temperature ranges. A list of the components and their temperature ranges can be found below in Table 17. The operational temperature band that is satisfactory to all of the components is from 15 to 30 degrees Celsius, which produces a 15 degree temperature range with no safety margin. If the hydrazine tanks and lines are assumed to be actively controlled, the acceptable temperature band goes from 0 to 30 degrees Celsius, giving a 20 degree safety band with a 5 degree safety margin in either direction.

2. Thermal Environment:

The spacecraft will be travelling from Earth orbit out to the Centaur asteroid Okyrhoe. Along the way, its trajectory takes it near Mars for a gravity-assisted course adjustment and a flyby of the Trojan asteroid Philoctetes. Given this trajectory, the spacecraft's minimum and maximum distance from the Sun is 1 AU to 9.43 AU, respectively. The thermal scenario with the largest amount of incoming heat energy will be at the beginning of the mission when the spacecraft is still close to Earth. Here it will experience direct solar radiation, indirect solar radiation from Earth's albedo, and infrared radiation from Earth itself. The thermal scenario with the smallest amount of incoming heat energy will be at the end of the mission near Okyrhoe. It will only receive about one percent of the direct solar radiation at Earth, and a miniscule amount of infrared radiation and reflected solar radiation from Okyrhoe. The thermal situations at other critical events in the mission are more moderate, but include an environment near Mars where there is direct and indirect solar radiation as well as planetary infrared radiation and an environment near Philoctetes where the only significant source of external heat is direct solar radiation. Figure 27 contains a chart of the different sources and values of incident radiation ranging from 1 to 10 AU. The maximum power input at Earth is approximately 2,200 W/m^2, and the maximum power input at Okyrhoe is approximately 14 W/m^2.

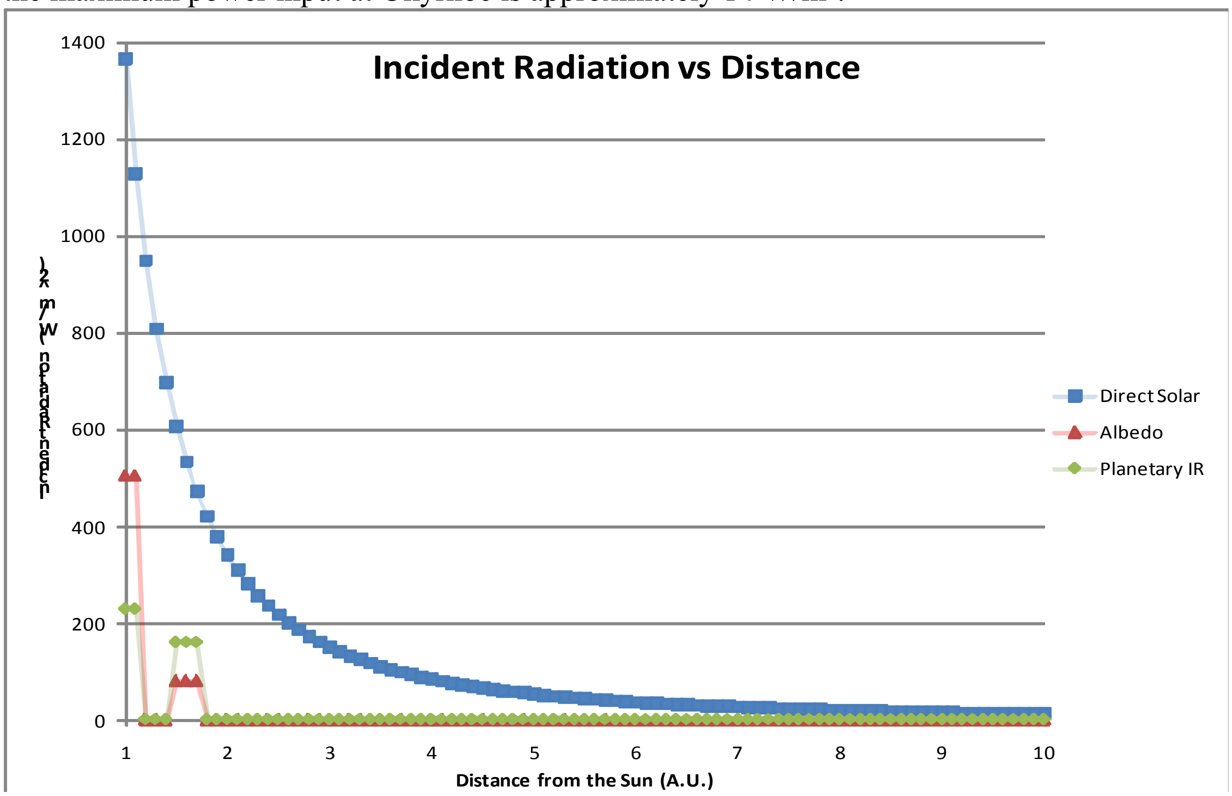


Figure 27: Incoming Radiation versus Distance from the Sun

3. Thermal Control Subsystem Design

The thermal control system is passively cold-biased with electric heaters to keep certain components, such as the hydrazine and nitrogen tetroxide fuel tanks and lines, within their required temperature bands. The first layer of passive thermal control consists of 20 layers of multilayer insulation and a vapor deposited aluminum surface finish. This insulates the spacecraft and helps to mitigate the effects of the large incident radiation variation throughout the mission. In order to reject excess heat while close to Earth but minimize the heat lost at Okyrhoe, the spacecraft contains a small louvered radiator. Thirty-five radioisotope heater units are also included to provide most of the heat as the spacecraft travels further away from the Sun, which is also where the available power is most limited. Finally, electric strip heaters are included to keep the fuel tanks and lines at their required temperatures. The hydrazine fuel in particular needs to be kept at a temperature that is higher than the spacecraft bus ambient environment. Table 19 contains a list of the quantity, mass, and power requirements of the components.

Table 19: Quantity, Mass, and Power Required for Thermal Control Subsystem Components

Component	Quantity	Total Mass	Total Power Required
Multilayer Insulation	55.67 m^2	50.066 kg	-
Surfaces and Finishes	55.67 m^2	Included in MLI	-
Radioisotope Heater Units	35 units	1.200 kg	-
Radiators and Louvers	0.14 m^2	0.728 kg	-
Electric Heaters	8	-	12 W
Thermostats	8	-	8 W
Total	**-**	**51.994 kg**	**20 W**

4. Thermal Control Subsystem Results

The worst case hot scenario exists while close to Earth. The spacecraft bus average temperature is approximately 297 K, which is within the temperature bounds of all the components that are not actively controlled. This was calculated as if the spacecraft were staying in Earth orbit long enough to reach a steady-state temperature. In reality, however, the spacecraft will be rapidly leaving Earth orbit, where planetary infrared radiation and the albedo will quickly become insignificant.

The worst case cold scenario exists while at the Centaur asteroid Okyrhoe. The spacecraft bus average temperature is approximately 282 K. It was calculated neglecting any infrared emissions or reflected sunlight from Okyrhoe, which are likely to be insignificant, but could only help to warm the spacecraft, however miniscule the effect may be.

These two extreme temperatures keep all of the passively controlled components within their acceptable temperature bands.

The spacecraft bus average temperature is expected to begin at the worst-case hot scenario and asymptotically approach the worst-case cold scenario. The only other scenario worth mentioning would be the gravity assist from Mars, but this event will not approach either extreme since the total incident radiation from all sources is less than a third of the total incident radiation at the worst case hot scenario, but almost fifty times greater than the worst case cold scenario.

17. Attitude Determination and Control System (ADCS)

1. Hardware Summary

The attitude determination and control system (ADCS) will consist of the hardware listed in Table 20, below.

Table 20: ADCS Mass and Power

Item	Model	Number	Mass Each (kg)	Total Mass	Peak Power (W)
Thrusters	MR-111C (Aerojet)	16	0.33	5.28	5.39
Reaction Wheels	RDR 68-3 and WDE 8-45 (Rockwell Collins)	4	8.85	35.4	90
Star Cameras	VF STC 1 (Valley Forge)	4	3.2	12.8	10.2
Sun Sensors	Medium Sun Sensor (Comtech AA)	4	0.036	0.144	0
IMU	LN-200 (Northrop Grumman)	2	1	2	12
			TOTAL:	**55.62**	**117.59**

2. Thrusters

The attitude thrusters will be mounted in a quad formation at each corner of the top face of the spacecraft. This location permits the greatest pointing control during main propulsion burns by maximizing the distance between the attitude thrusters and the main propulsion thrusters. The configuration also ensures that each direction will have 4 thrusters providing force. The thrusters were chosen to ensure that the slewing requirements discussed below would be met.

3. Reaction Wheels

A reaction wheel will be placed on each axis and one will be for reserve, bringing the total to 4. The reaction wheels were chosen for their high angular momentum of 68 Nms and torque of 0.75 Nm. The reaction wheels ensure accurate pointing angles that are crucial for the NAC/WAC payload cameras to take clear pictures.

4. Star Cameras and Sun Sensors

The star cameras and sun sensors will be placed on the sides of the spacecraft body not occupied by the solar arrays; two of each on each side. The star cameras will be used to update the inertial measurement unit (IMU) periodically to eliminate any pointing error that has built up since the last update. The sun sensors will determine the location of the sun and will ensure that the solar arrays are pointing at it.

5. Inertial Measurement Unit

The IMU will measure the change in spacecraft orientation and will feed the attitude control system the necessary information so that it can point the spacecraft in the proper direction. The IMU accumulates sensor error over time and will periodically be updated by the star camera.

6. Slewing Requirement

During the encounter with the Trojan asteroid, Philoctetes, the scanning platform described in Flight System Capabilities will provide the necessary slewing so that the entire spacecraft will not be required to change orientation. However, if this system fails, the spacecraft will have to slew during the encounter to allow the payloads to point at the target. For this reason, a contingency system was selected that will slew the spacecraft to ensure the mission objectives are still met.

This slewing maneuver was the primary driver behind attitude control hardware selection. Figure 23 and Figure 23 24 below show the required angular velocity and acceleration to keep the spacecraft pointed at Philoctetes during the encounter. Each curve represents a different point of closest approach. Some of the payload instruments require a minimum distance of 300 km away from the target, so it is desired to get as close to the target as possible to maximize the time that the payloads can gather data. For this reason, the 100 km point of closes approach was selected. This requires a slewing rate of 4.3 deg/sec and acceleration of 0.27 deg/sec^2. Further calculations need to be done to confirm that this maneuver is possible without damage to the spacecraft, particularly the solar panels. The maneuver is believed to be possible without causing any problems. However, if it cannot be done, the 150 km or 200 km point of closest approach can be used because the required angular rate and acceleration are significantly smaller. Furthermore, the mission objectives would still be completed.

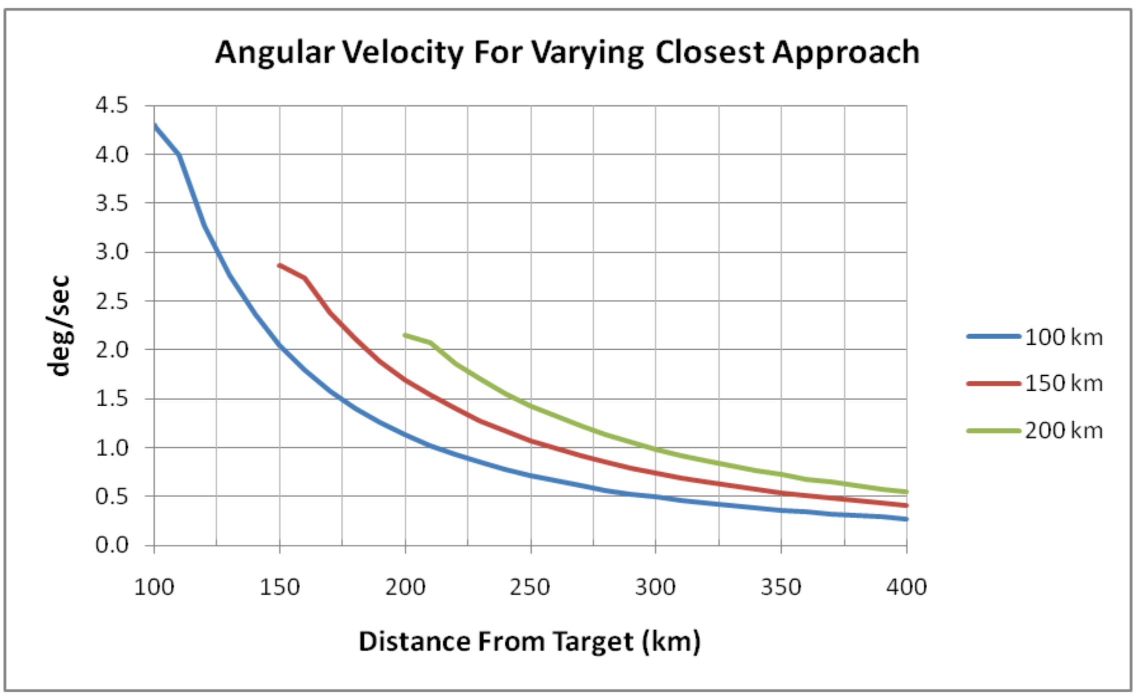


Figure 22

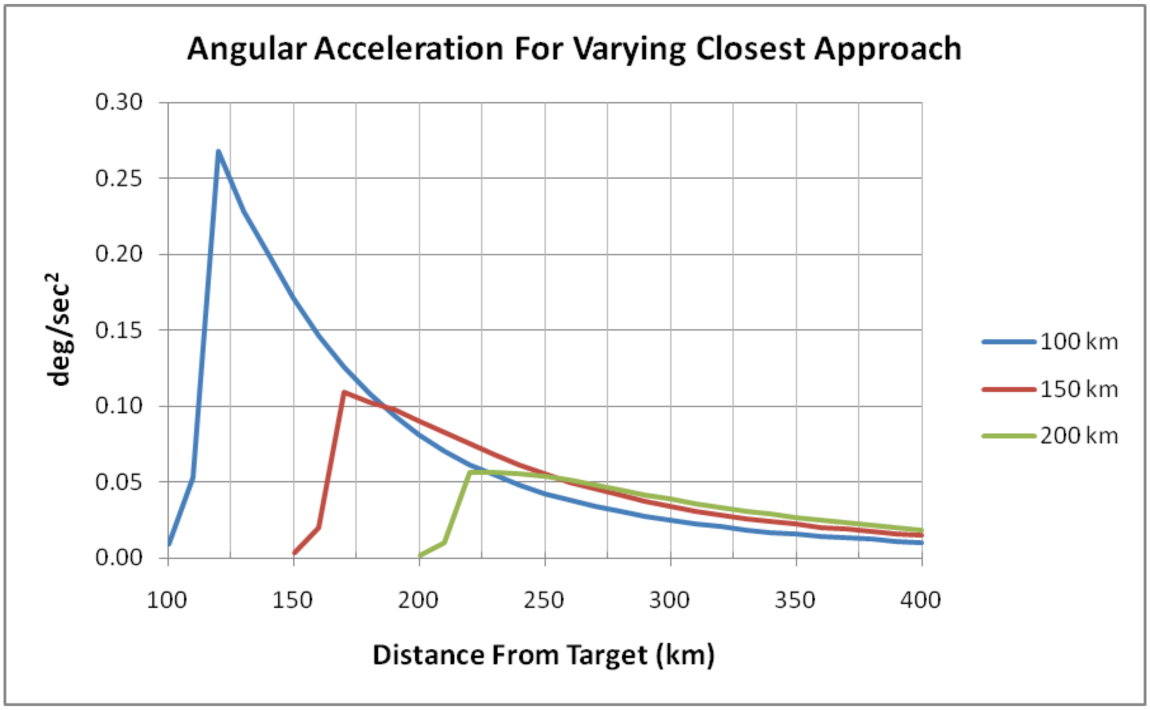


Figure 23

The attitude control system is capable of 5.75 deg/sec of angular velocity and 0.34 deg/sec^2 of angular acceleration during a 180° rotation about the y-axis (parallel to the solar panels supports). This permits the 100 km closest approach option with 34% contingency on angular velocity and 26% contingency on angular acceleration. The 180° degree maneuver can be achieved in 302 seconds using a single reaction wheel and 52 seconds using only the thrusters. These times include acceleration and braking periods; the spacecraft is assumed to be initially at rest and is returned to rest at the end of the maneuver. A shorter time can be achieved when both systems are used in tandem.

18. Growth, Contingency, and Margin Policy

A full 43% contingency has been applied on the dry mass of the spacecraft, satisfying the JPL Design Principle 1 recommendations. Electrical generation and storage systems are fully redundant; the baseline mission is achievable with the use of only one of the two solar panels and only one of the two installed batteries. The spacecraft is capable of satisfying the requirements of the baseline mission with a complete failure of the scanning platform or with a failure of either the attitude control thrusters or the reaction wheel assembly. Limited science at Philoctetes and the full science complement at Okyrhoe are still achievable with a failure of both the scanning platform and either of the ACS systems. The main thruster assembly is fully redundant. In the event of a complete failure of the main propulsion system, a flyby on both Philoctetes and Okyrhoe can be achieved. Under this contingency, the science requirements of the New Frontiers Announcement of Opportunity can still be satisfied with but not the full requirements of the baseline mission as determined by the Principal Investigator. In considering the science instrumentation, it should be noted that the OSIRIS NAC/WAC is composed of two separate and distinct imaging platforms; if either of the instruments are damaged or malfunctioning, the science requirements can be fulfilled. Data storage is set to be fully redundant at the Philoctetes encounter and triple redundant at the Okyrhoe encounter to compensate for a higher likelihood of failure. A 25% margin on the maximum data storage requirement is included for additional science and the inclusion of a possible student project. Resistance heaters have been included on all mission-critical systems to ensure thermal stability. The radiators used to vent excess heat energy are fully redundant systems, and each radiator uses multiple louvers that are individually and automatically actuated in response to the thermal conditions inside the spacecraft bus.

1. Mission Operations

Ground operations will be directed by the Principal Investigator with the support of a science team. After transmission to Earth, data from the Trojan/Centaur Reconnaissance mission will be sent to the JPL Downlink Server Database. From there, data will be collected and transferred to the TCR science data center to be established at the National Space Science and Technology Center in Huntsville, AL. After data validation and verification by the Principal Investigator, the validated data sets will be delivered to the JPL Planetary Data Systems database and presented for public consumption on an E/PO web site hosted on the NSSTC servers. Satellite operations will be handled at the Marshall Space Flight Center and at the TCR science center at the NSSTC; operations will be managed by the Principal Investigator with assistance from the mission design team in the event of system failure.

2. Development Approach

The mission development approach shall comprise a systems engineering management plan (SEMP) following NASA Systems Engineering Handbook (NASA/SP-2007-6105), and a mission assurance plan following the NASA Risk Classification for NASA Payloads Document (NPR 8705.4) for a Class 2, Category B mission. The SEMP covers all processes and procedures for the system engineering function of the mission, such as: design review success criteria, configuration management plan, test and evaluation management plan, engineering change process, and requirement verification closure. The mission assurance plan addresses mission reliability, fault tolerance and fault management, and product assurance.

For each spacecraft instrument, an Interface Control Document (ICD) will be defined in order to track requirements and resources across all interfaces. All mission elements, with the exception of the scanning platform, meet or exceed TRL level 6. With TRL levels at or above 6, the risk and schedule uncertainty is minimized due to flight heritage. The scanning platform required for this mission leverages Department of Defense technologies currently used to direct visible light at high radial accelerations; this technology is known to be currently in use and with a TRL greater than 6. While this technology may or may not be classified, access to the information is believed to be restricted and therefore unusable given the public-domain nature of this document. The scanning platform shown in renderings and described in the mission design should be taken as an estimation of the capabilities and general characteristics of the actual product. In the event this mission is selected, the use of existing DOD technology in place of the shown platform is highly recommended. Without this scanning, the point of closest approach to Philoctetes would be extended. The level of detail and amount of useful information recovered from the OSIRIS NAC/WAC will be somewhat degraded, and the amount of time the asteroid is in range of the remaining science instrumentation would be shortened.

3. Assembly, Integration, Test, and Verification

The TCR mission will be contracted to Lockheed Martin and Jet Propulsion Laboratory (JPL). Lockheed Martin will assemble all components for TCR. The PI and the College of Charleston will build and manage all science instruments. TCR will be integrated and tested at JPL. Test procedures and plans are developed by JPL onsite test engineers and technicians. Launch site integration and spacecraft launch occur at the NASA Kennedy Space Center in Florida.

In the process of verification, the science goals will lead to the science requirements. The science requirements will determine the mission requirements, which will in turn impact the spacecraft requirements. From the spacecraft requirements, the subsystem and instruments requirements will be derived. These requirements will go into demonstration, inspection, analysis, and tests which will be performed at JPL.

4. Schedule

In order to meet the launch date of June 30, 2016, TCR will require an accelerated project schedule which will be five years in duration. Our accelerated phase A is eight months in duration; Phase B is nine months in duration; Phase C/D is 49 months in duration. TCR has a launch window of 30 days to ensure mission completion. Below is a chart of the TCR schedule.

ID	Task Name	Start	Finish
1	**Pre-Phase A**	1/11/2010	4/29/2010
2	Mission Concept Review	4/29/2010	4/29/2010
3	**Phase A**	4/29/2010	3/1/2011
4	System Requirements Review	10/25/2010	10/25/2010
5	Mission Definition Review	1/13/2011	1/13/2011
6	**Phase B**	3/1/2011	12/1/2011
7	Preliminary Design Review	8/23/2011	8/23/2011
8	**Phase C**	12/1/2011	9/27/2013
9	Critical Design Review	1/8/2013	1/8/2013
10	System Integration Review	9/27/2013	9/27/2013
11	Fabrication and Test Overrun	9/27/2013	3/28/2014
12	**Phase D**	4/1/2014	9/29/2015
13	Test Readiness Review	9/18/2014	9/18/2014
14	Operational Readiness Review	6/1/2015	6/1/2015
15	Flight Readiness Review	10/1/2015	10/1/2015
16	Integration and Test Overrun	9/29/2015	6/15/2016
17	Launch	6/15/2016	6/15/2016
18	**Phase E**	6/15/2016	11/7/2025
19	Post Launch Assessment Review	10/13/2016	10/13/2016
20	Critical Events Readiness Review	11/28/2017	11/28/2017
21	**Phase F / SEO**	11/7/2025	12/30/2027

Figure 24: TCR Schedule

E. Management

1. Management Approach

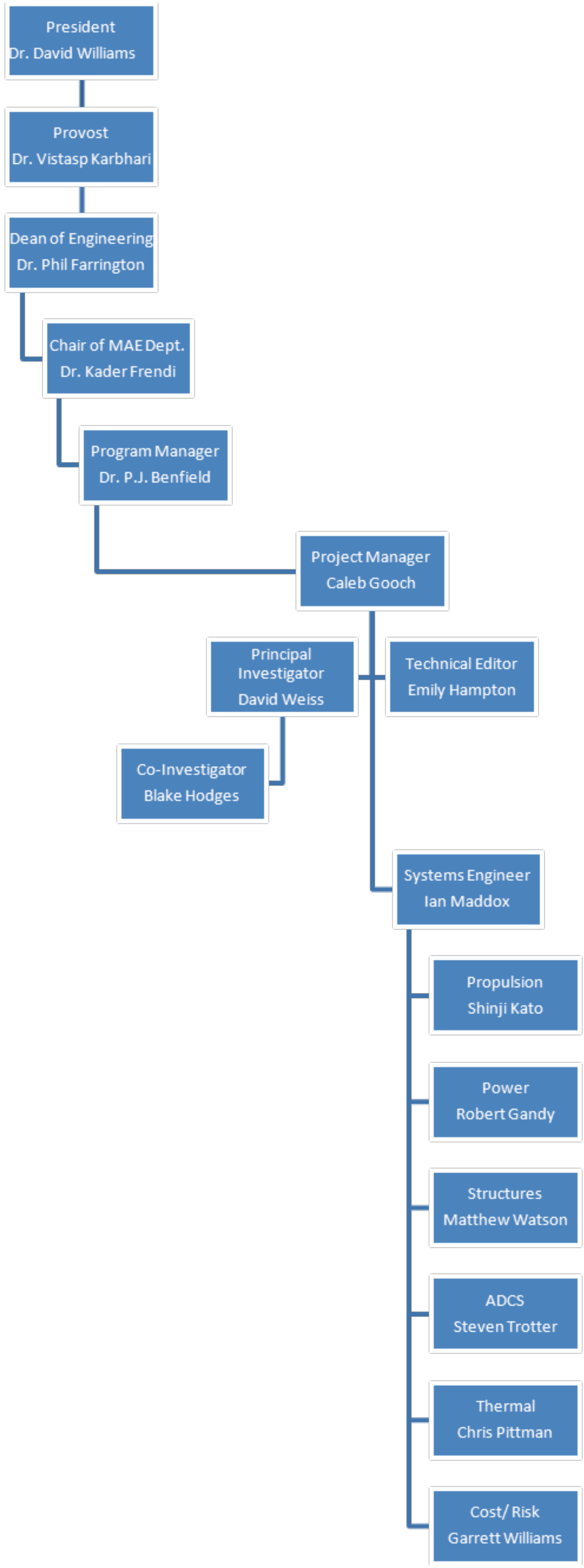


Figure 25: Management

2. Roles and Responsibilities

The Project Manager (PM) will oversee the technical and programmatic implementation of the project, working closely with the PI to ensure success of the project. Responsibilities will include leading project planning efforts and managing the program schedule and program cost.

The Principal Investigator (PI) will serve as a planetary scientist for the IPT. The PI will serve as the lead scientist on the project. He/she will take responsibility for completion of project, directing the research and reporting to the funding agency. Also, the PI will define science operations and spacecraft instrumentation for the project.

The Co-Investigator (Co-I) will serve as a planetary scientist for the IPT. The Co-I will also aid the PI in the science definition process.

The Systems Engineer (SE) will lead the project's Integrated Product Team (IPT) and any associated IPT Working Groups (WGs). The SE also will lead system design, CDD assessment, alternative design development, technology assessment, and configuration management activities as well as aid in risk assessment.

The Propulsion Engineer will provide engineering expertise in the area of propulsion system design and analysis to the IPT. The propulsion engineering will also design the propulsion system for the mission.

The Power Engineer will provide engineering expertise in the area of power storage and distribution system design and analysis to the IPT. The power engineer along with the SE will determine power budgets.

The Structural Engineer will provide engineering expertise in the area of structural design and analysis to the IPT. The structural engineer will also be responsible of providing engineering models of the spacecraft.

The Telemetry Engineer will provide engineering expertise in the area of telemetry and communication system design and analysis to the IPT.

The ADCS Engineer will provide engineering expertise in the area of attitude determination control system design and analysis to the IPT.

The Thermal Engineer will provide engineering expertise in the area of thermal radiation protection to the IPT.

3. Risk

Risks are potential events that can have negative impacts on the safety, project technical performance, cost or schedule of the mission. For the Trojan/Centaur Reconnaissance mission, there are no High-Level Risk concerns. However, there are a few Medium-Level Risks and many Low-Level Risks. These risks are shown in the Figure 27 below.

Probability of Occurrance						
	5		P-3			
	4	P-8; Pr-2				
	3	S-4	Pr-1; S-3			
	2	P-2; P-9	P-5; S-1; S-2; P-6	G-1		
	1	P-4; P-7	G-2; G-3		Pr-3	P-1; St-1
		1	2	3	4	5
		Impact of Occurrance				

Key:

Green	Low Risk
Yellow	Medium Risk
Red	High Risk

Figure 26: Risk Matrix

The probability of occurrence for the risk matrix is ranked from 1 to 5. A ranking of 1 assumes that the probability that the event will happen is extremely low. A ranking of 2 assumes that the probability of the event occurring is slightly higher than that of a 1 ranking, but the event is still considered unlikely to occur. With a ranking of 3, the event is considered likely to occur. An event with a 4 ranking is considered very likely to occur. The highest rank is 5, and it represents events with an almost inevitable probability of occurrence.

The impact of occurrence for the risk matrix is also ranked from 1 to 5. A ranking of 1 assumes that the occurrence has a minimal effect on the mission meaning that no science is lost. A ranking of 2 assumes that there is some science lost due to the occurrence. A ranking of 3 is given to those events in which nearly half of the science can still be obtained. With a ranking of 4 the impact of the event severely affects the mission and almost no science is obtained. The highest rank is 5, and it is given to those events whose results are catastrophic or mission ending.

Table 21: Risk Analysis

	Risks	Results	Impact	Probability
Guidance:				
G-1)	Reaction wheels fail	loss of accuracy in pointing angles	3	2
G-2)	Momentum dumping thrusters fail	inability to despin reaction wheels	2	1
G-3)	Sun sensors/ star cameras/ IMU fails	inability to determine orientation	2	1
Power:				
P-1)	Total power failure	mission cannot be completed	5	1
P-2)	Partial power loss	limited science collected	1	2
P-3)	Damage to solar arrays	partial power loss	2	5
P-4)	Solar arrays overheat	partial power loss	1	1
P-5)	Solar arrays cannot align with sun	partial to total power loss	2	2
P-6)	Solar arrays do not unfold	mission cannot be completed	3	2
P-7)	Batteries do not recharge	partial power loss	1	1
P-8)	Batteries lose charger over time	partial power loss	1	4
P-9)	Batteries become too hot or too cold	partial power loss	1	2
Propulsion:				
Pr-1)	Spills or leaks of propellants	Too much will result in inability to complete mission	3	3
Pr-2)	Propellants get stuck in tubes	Reduce mass flow/efficiency of engine	2	4
Pr-3)	Vehicle breaks up and fuel and oxidizer mix	Explosion within the spacecraft	4	1
Pr-4)	Propulsion system fails	inability to get into orbit for second asteroid	2	3
Science:				
S-1)	Lidar failure due to destabilization of spacecraft	Accurate information regarding asteroid will be lost	2	2
S-2)	Osiris failure due to excessive radiation	Science data will be lost	2	2
S-3)	Thermal seal breaks on NIS	Science data will be lost	2	3
S-4)	UVS fails	Science data will be lost	1	3
Structure:				
St-1)	Spacecraft impacts with a asteroid	Destruction of spacecraft	5	1

Figure 33

4. Mitigation Strategy

There are three events which fall in the medium risk category.

In the event that there is a failure in one of the reaction wheels, a backup reaction wheel is onboard to mitigate this risk; however, if more than one of the reaction wheels fails, loss of accuracy in pointing angles will occur. Science will still be able to be obtained, but the data will not be as accurate.

Total power failure is a catastrophic mission ending risk. The mitigation strategy for this event is the use of a fully redundant system.

There is no mitigation strategy for the possibility of an impact with an asteroid. In the event that this occurs, the mission would be over; this would be a catastrophic mission-ending event. However, the possibility that this will actually occur is very low.

Costs:

Table 22

Variable Description	Values		
Enter Spacecraft Bus + Instruments Total Dry Mass	1150		KG
Enter Spacecraft Total Power Generation Capacity (LEO Equivalent)	27000	27000	W LEO equivalent flux
Enter Design Life in Months	112.0		Months
Enter Number of Science Organizations	1.0	1	Count (Enter zero for projects with no science or science organization involvement)
Enter Apogee Class	4.0		LEO=1, HEO/GEO=2, beyond GEO=3, Planetary=4
Enter Maximum Data Rate Requirements Relative to SOTA Expressed as Percentile	50%		Kbps requirement relative to the state-of-the-art for the ATP date expressed as a percentile where 0%=very low, 50%=SOTA, 100% is maximum
Enter Test Requirements Class	2.0		Less than average testing=1, Average=2, More than average=3, Extensive=4, Very extensive=5
Enter Requirements Stability Class	3.0		Very low volatility=1, Low=2, Average=3, High=4, Very high volatility=5
Enter Funding Stability Class	1.0		Stable funding=1, Some instability=2, Significant instability=3
Enter Team Experience Class [Derived from Price Model; used with permission from Price Systems LLP]	4.0		Extensive experience=1, Better than average=2, Average (mixed esperience)=3, Unfamiliar=4 [Ref: Price Model]
Enter Formulation Study Class	2.0		Formulation study (1=Major, 2=Nominal, 3=Minor)
Enter New Design Percent	70%		Simple mod=30%, Extensive mod=70% (average), New=100%
Enter ATP Date Expressed as Years Since 1960	50		Years elapsed since 1960
Regression Model Result	$427.9		DDT&E + TFU (Phases C/D/E) in Millions of 2004 Dollars including fee, excluding full cost
--	-------------------	Factor	---
Enter Technology Readiness Level (TRL) Penalty Factor	7.0	0.90	Refer to NASA TRL scale (TRL 6 is nominal)
Enter Platform Factor [Derived from Price Model; used with permission from Price Systems LLP)	2.20	1.27	Platform factor (Airborne Military=1.8, Unmanned Earth Orbital=2.0, Unmanned Planetary=2.2, Manned Earth Orbital=2.5, Manned Planetary=2.7) [Ref: Price Mdoel]
Enter Functional Complexity Factor	To Be Added Later	1.00	To be added later
Subtotal (Non Full Cost Subtotal)	$488.5	-----	Subtotal (Millions of 2004 Dollars including fee)
Calculated Size of the Government Project Office (Project Office Only--Excludes Government Functional Line/Laboratory Labor)	76.2	-----	Civil service annual full time equivalents (FTE's)
Enter Override of Calculated Government FTEs (or leave zero to accept calculated size of project office)	0.00	-----	Civil service annual full time equivalents (FTE's)
Final Estimate of the Size of the Government Project Office and other Oversight (excludes government non-oversight labor which is included in subtotal above)	76.2	-----	Civil Service Full Time Equivalents (FTE's)
Enter Civil Service Loaded Annual Labor Rate Including Center and Corporate G&A	$280,000	-----	Thousands of 2004 Dollars
Calculated Project Phase C/D Schedule Duration (Excludes O&S Phase E)	52	-----	Months
Enter Override of Calculated Phase C/D Schedule Duration (or leave zero to accept calculated duration)	0	-----	Months
Final Estimate of the Project Phase C/D Schedule Duration	52	-----	Months
Calculated Cost of the Government Project Office	$93.3	-----	Millions of 2004 Dollars
Government Service Pool Use Intenstiy Factor	4	0.1200	1=Minimum use of service pools, 2=Less than average, 3=Average, 4=More than average, 5=Significantly more than average
Calculated Cost of Government Service Pool Use	$58.6	-----	
Enter Override of Calculated Cost of Government Service Pool Use (or leave zero to accept calculated service pool cost)	$0.0		
Final Estimate of the Cost of Government Service Pool Use	$58.6		
Subtotal (2004$)	$640.4		
Ground System	$57.6		
Enter Override of Calculated Ground System Cost	$0.0		
Final Estimate of the Cost of Ground System	$57.6		
Subtotal (2004$)	$698.0		
Enter Launch Services Cost	$0.0		
Enter Cost Reserves	$174.5		
Total (2009$)	$994.9		

The cells in blue are the inputs made into the cost model by the team.

The total dry mass for the spacecraft bus and the instruments is calculated at 1150 kg. The spacecraft total power generation (LEO equivalent measured in Watts) is calculated at being 27,000 W. The design life (measured in months) is the duration of the design process and is estimated to be 112 months. The apogee class classifies what type of mission is taking place. This mission is a planetary mission and will not be orbiting Earth therefore the value entered is a 4 for planetary mission. The maximum data rate requirements relative to SOTA is expressed as a percentile. In this cost model, there are three different values that can be input; 0% which is very low, 50% which is SOTA, and 100% which is the maximum. The value entered for this mission is 50%. The test requirements class is estimated as a level 2 in a range of 1 to 5, where 1 is less than average testing, 2 is average testing, 3 is more than average testing, 4 is extensive testing, and 5 is very extensive testing. The requirements stability refers to how volatile the mission is and again has a ranking of 1 to 5 where 1 is very low volatility, 2 is low volatility, 3 is average volatility, 4 is high volatility, and 5 is very high volatility. This mission is determined to have an average volatility therefore a ranking of 3 is assigned. The funding stability is set up into 3 classes; stable funding, some instability, and significant instability. This mission will have stable funding therefore it is given a ranking of 1. The team experience for this mission is given the lowest ranking of 4. For this input, 1 is extensive experience, 2 better than average experience, 3 is average experience, and 4 is unfamiliar experience. The formulation study is ranked on a scale of 1-3 where 1 is major, 2 is nominal, and 3 is minor. This mission was given a rank of 2. The new design percent is estimated at 70%. There are three different options in this category; 30% is simple mod, 70% is extensive mod, which is average, and 100% is new. The ATP date expressed in years since 1960 is 50. The technology readiness level (TRL) for this mission is 7. The platform factor defines the type of mission that will be taking place; 1.8 is airborne military, 2.0 is unmanned Earth orbital, 2.2 is unmanned planetary, 2.5 is manned Earth orbital, and 2.7 is manned planetary. This mission is defined as an unmanned planetary and is given a ranking of 2.2. The functional complexity factor will be added at a later time. The override of calculated government FTEs is left at 0 to accept the calculated size of the project office. The Civil Service loaded annual labor rate including center and corporate G&A is calculated as $280,000. The override of calculated phase C/D schedule duration is left at 0 to accept the calculated duration.

From this model, the total cost of this mission in 2009 dollars will be $994.9 million. The estimated costs for the design process are as follows: Phase A will be $18.1 million, Phase B will be $69.6 million, Phases C/D will be $600 million, and the remainder of the development will cost $541 million and will be distributed evenly over the next 10 years. The total cost of this mission in Real Year dollars, assuming a steady 2.7% inflation rate from the NASA inflation chart, would be $1.23 billion.

F. Education and Public Outreach

Note from the Principal Investigator.

"I understand the NASA SMD requirements for E/PO and I am committed to carrying out a core E/PO program that meets the goals described in the document *Education and Public Outreach Policies for AOs*. I will submit an E/PO plan with my Concept Study Report if this proposal is selected."

One percent of the total budget for the TCR mission will be designated for Education and Public Outreach.

With the 1% total budget for the E/PO, a full scale model of the Centaur asteroid, Okyrhoe, will be built and placed in the U.S. Space and Rocket Center in Huntsville, Alabama. This model will be built so people can walk through and get an up close view of the asteroid.

1. Student Collaboration

No student collaboration is proposed for TCR. However, for future collaborations, appropriate resources have been allocated on the TCR spacecraft per MOU-NFAAO-001.

G. Appendices

1. Letters of Commitment

UAHuntsville
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

April 27, 2010

Caleb Gooch
Project Manager
University of Alabama in Huntsville
Mechanical and Aerospace Engineering Dept.
N274 Technology Hall
Huntsville, AL 35899

Dear Mr. Gooch,

The University of Alabama in Huntsville is pleased to formally acknowledge your team's design for a Trojan/Centaur Reconnaissance mission as part of NASA's New Frontiers Program. We believe, should your design be selected, the science gained from this mission will not only provide a greater understanding of our solar system, but will help to distinguish our institution as a premier center for engineering education, research, and technological development. With this said, The University of Alabama in Huntsville is fully committed to support your team in its current and future endeavors. Best wishes on being selected!

Sincerely,

Michael P.J. Benfield, Ph.D.
Integrated Product Team Program Manager
The University of Alabama in Huntsville

INTEGRATED PRODUCT TEAM PROGRAM OFFICE »
Shelby Center 157 301 Sparkman Drive Huntsville, AL 35899
T 256.824.2976 F 256.824.4322 http://ipt.uah.edu

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: Caleb Gooch

Caleb Gooch
Project Manager
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: ______________________________

David Weiss
Principal Investigator
College of Charleston

"I acknowledge that I have been identified by name as a team member for the proposed project entitled “Trojan/ Centaur Reconnaissance Mission”, that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: ______________________________

Blake Hodges
Co-Investigator
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: ______________________________

Ian Maddox
Systems Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: Shinji Kato

Shinji Kato
Propulsion Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: Robert Gandy

Robert Gandy
Power Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: Matt Watson

Matthew Watson
Structural Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: ____________________

Steven Trotter
ADCS Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled “Trojan/ Centaur Reconnaissance Mission”, that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: ______________________

Christopher Pittman
Thermal Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: ____________________

Garrett Williams
Cost/Risk Engineer
The University of Alabama in Huntsville

"I acknowledge that I have been identified by name as a team member for the proposed project entitled "Trojan/ Centaur Reconnaissance Mission", that you are submitting in response to the Announcement of Opportunity, New Frontiers 2009, NNH09ZDA007O, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Signature: Emily Hampton

Emily Hampton
Technical Editor
The University of Alabama in Huntsville

2. Resumes

Caleb Landon Gooch

256-710-5521
Caleb.gooch@us.army.mil

Current Address	Permanent Address
55 Crestview Circle	6618 Highway 101
Florence, AL 35634	Rogersville, AL 35652

CITIZENSHIP	U.S.		
TECHNICAL SKILLS	Microsoft Office, Mathcad, MATLAB		
EDUCATION	**University of Alabama in Huntsville** Bachelor of Science in Engineering, Mechanical Engineering GPA: 2.94/4.0, Expected graduation July 2010		**Huntsville, AL**
WORK EXPERIENCE	**March 2009–Present** Research Assistant with the Apache Project Manager's Office, Redstone Arsenal	**University of Alabama in Huntsville**	**Huntsville, AL**
	October 2006–July 2008 Sales Associate	**Dick's Sporting Goods**	**Florence, AL**
CLEARANCE	Secret, Granted March 2009 by the University of Alabama in Huntsville		

Ian Maddox

256-772-7026; 256-724-1416
ian.maddox@uah.edu

Current Address
113 Belltower Lane
Huntsville, AL 35824

CITIZENSHIP U.S.

TECHNICAL SKILLS Competent in Linux, Windows, and Mac operating systems. Familiar with a variety of programming languages including PHP, Python, and Perl scripting. Familiar with SolidEdge, SolidWorks, MCS, Nastran/Patran, and Alibris 3D modeling packages. Familiar with MATLAB, Mathcad, Mathematica, and Octave mathematics software. Proficient with Microsoft Office 2003, 2007, and 2010; familiar with OpenOffice and iWork suites.

EDUCATION **The University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Science in Mechanical Engineering

Minor: Mathematics, GPA: 3.57/4.0 (3.75/4.0 in major), Expected graduation May 2010

- Integrated Product Team (MAE 491): Worked as a system engineer on a team tasked with designing a satellite mission to take scientific measurements and photographs of asteroids around Jupiter and Neptune using the requirements for NASA's New Frontiers 2009.
- Introduction to Engineering Design (MAE 490): Provided initial research and design in support of Objective Helicopter Deicing Spray (OHISS) proposal for Rotorcraft Systems Engineering & Simulation Center (RSESC) at UAH, including aerodynamic and structural analyses.
- Introduction to Math Modeling (MA 465): Topics include traffic flow modeling, population modeling, and advanced interpolation and extrapolation methods.
- Computer-aided Engineering (MAE 489): Performed finite-element analyses using MCD. Nastran and Patran.
- Applied Linear Algebra (MA 422): Topics included techniques for the solution of linear systems of differential equations in the MATLAB environment.
- Numerical Methods I/II (MAE 285/385): Selected topics in engineering mathematics using the MATLAB environment.
- Probability and Engineering Statistics (ISE 390): Probability and statistical sampling with engineering applications.

WORK EXPERIENCE

May 2008–May 2010 The University of Alabama in Huntsville, Huntsville, AL

Student Specialist: North Alabama Lightning Mapper Array

- Responsible for onsite repair and routine maintenance on North Alabama Lightning Mapper Array (NALMA) project at National Space Science and Technology Center (NSSTC) in Huntsville, a joint operation between University of Alabama in Huntsville (UAH) and the National Air and Space Administration (NASA).
- Performed initial software support for NALMA installations, operating exclusively in the Linux operating environment; wrote and modified programs using Matlab, PHP, Bash, and Python in support of NALMA operations.
- Designed Python and KML applications to provide real-time data visualization and network status in Google Earth.
- Discovered and researched deviations in Geographic Positioning System (GPS) hardware currently in use. Designed series of experiments to extensively test accuracy and time-to-lock on current system, and partnered with Huntsville Geographic Information Survey (GIS) station to analyze experimental results and improve location information.
- Updated and revised existing support documentation and standard operating procedures (SOP) for NALMA maintenance. Significantly reduced required learning curve for new employees by developing detailed step-by-step procedures that do not presume prior knowledge of Linux or hardware in use.
- Performed modeling, diagramming, and mathematical calculations for lightning and atmospheric conductivity research related to the NALMA project.

August 2006 - June 2007 St. Louis Community College Meremac, MO

Educational Assistant: Mathematics Tutoring Center

- Responsible for tutoring and small-group teaching for all mathematics classes taught at Saint Louis Community College – Meramac (STLCC-M), including remedial mathematics, algebra, trigonometry, calculus, differential equations, and linear algebra.
- Provided support to over 1,500 students over three semesters of employment in both supervised and unsupervised environments; consistently maintained order and effectiveness in classrooms with up to 50 students. Developed and implemented short lesson plans and study materials for algebra and calculus students.
- Provided grading and test-generation support for mathematics faculty.

AFFILIATIONS Member of ASME, AIAA

Shinji Kato

Phone: 256-824-3006
Cell: 256-604-7205
Email: sk0001@uah.edu

Current Address	Permanent Address
606 F/2 John Wright Drive	395-36 Yoro-Cho
Huntsville, AL 35805	Yoro-gun, Gifu,
	503-1321, Japan

CITIZENSHIP Japan

TECHNICAL SKILLS

Operating Systems: Microsoft Windows, Linux/Unix

Program Languages: C++ , Fortran90

Other Software: Mathcad, MATLAB, Solid Edge; Microsoft Word, Excel, and PowerPoint

EDUCATION

The University of Alabama in Huntsville **Huntsville, AL**

Bachelor of Science in Engineering, Aerospace Engineering

GPA: 3.927/4.0 (3.95/4.0 in major), Expected graduation Spring 2010

- Related Course Work

Computer Aided Design, Numerical Methods and Engineering Computations, Materials and Manufacturing Process, Control Systems, Design Project (Table Top Rocket Motor), Basic Engineering Knowledge (Statics, Dynamics, Fluids, Structures and Thermodynamics)

HONORS AND AWARDS

UAH Honor Scholar List, Fall 2006 - Present

Scholarship from Pratt & Whitney Rocketdyne

AFFILIATIONS Tau Beta Phi Honors Society

Robert H. Gandy

(334) 313-5311
gandyr@uah.edu

Current Address
364 Jack Coleman Dr.
Huntsville, AL 35805

CITIZENSHIP U.S.

TECHNICAL SKILLS C++, MATLAB, Multisim

EDUCATION

University of Alabama in Huntsville — **Huntsville, AL**

Bachelor of Science in Engineering, Electrical Engineering

GPA: 2.8/4.0 (3.0/4.0 in major), Expected Graduation May 2010

- **Relevant Coursework:** Digital Electronics, Optical Electronics, Electromagnetic Engineering, Power Systems Analysis, Intro to Control and Robotic Systems, IPT Senior Design

In School Projects: Optical Cloaking a group project in Optical Electronics, Power System Design Project in Power System Analysis, Control Design Project in Intro to Control and Robotic System, Product and Cost Analysis Project a group project in Engineering Economy, PE Report and Design Project in Electronics II, IPT Senior Design group project

WORK EXPERIENCE

August 2007 – Present — **Huntsville Utilities** — **Huntsville, AL**

Electrical Engineer Co-op

- Main responsibility was the maintenance and checking of capacitor bank controls and capacitor banks. Also performed field checks, gathered data, surveyed, staked new power lines, worked with a group and individually on projects, contacted and worked with contractors on projects, and worked closely with engineers to acquired knowledge of transmission, distribution, and substation systems.

AFFILIATIONS

December 2009 — **Santa's Village** — **Huntsville, AL**

Volunteered as a greeter and ticket collector

Matthew B. Watson

256-648-0493
mbw0003@uah.edu

Current Address
14828 Smith Drive
Harvest, AL 35749

CITIZENSHIP U.S.

TECHNICAL SKILLS AutoCAD, Solid Edge, NX, MATLAB, Mathcad, Patran, Nastran, C++

EDUCATION

The University of Alabama Huntsville **Huntsville, AL**

Bachelor of Science in Engineering, Mechanical Engineering

GPA: 3.35/4.0, Expected graduation December 2010

WORK EXPERIENCE

June 2009 **Harvest, AL**

Private Consultant

- Worked as a consultant for an electronic record company in Miami, FL, to create data analysis tools

August 2008 – December 2008 **CR Compressors Inc.** **Hartselle, AL**

Co-op Student

- Performed time studies, cost analyses, equipment recommendations, gage checks, created and used data analysis tools in Excel, received contractor quotes, completed drafting using AutoCAD, and presented my work for the term to company management

January 2006 – December 2006 **Moore's Heating & Air** **Tuscumbia, AL**

Laborer

- Performed installation of heating and air systems including wiring, copper tubing, and ductwork as well as cutting, threading, fitting, and installing gas piping

June 2005 – December 2005 **S&D Construction** **Rogersville, AL**

Laborer

- Performed installation of heating and air systems including wiring, copper tubing, and ductwork as well as cutting, threading, fitting, and installing gas piping

HONORS AND AWARDS

- Awarded 2^{nd} place in 2008-2009 Student Safety Engineering Design Contest by ASME International's Safety Engineering and Risk Analysis Division and the National Institute for Occupational Safety and Health for paper entitled "The XTL 490-Xtreme Trap Launcher"
- Undergraduate Engineering Dean's List at The University of Alabama Huntsville for the 2007/2008 school year
- Invited to join Pi Tau Sigma International Mechanical Engineering Honor Society in 2009
- Invited to join Delta Epsilon Iota National Honor Society in 2008
- Received the United States Army Reserve National Scholar/Athlete Award in 2003
- Received the Gold Medal of Achievement in the Royal Rangers program and recognized by the President George W. Bush in 2002
- Voted Most Reliable by Florence Christian Academy, Class of 2003

Steven R. Trotter

(256) 468-8508
steven.trotter@uah.edu

Permanent Address
1211 Grandeview Blvd. Apt 2628
Huntsville, AL 35824

CITIZENSHIP U.S.

TECHNICAL SKILLS Proficient with MATLAB, Microsoft Word, Excel, and PowerPoint; Familiar with Simulink, MathCAD, Solid Edge, NX, and C++.

EDUCATION

The University of Alabama in Huntsville **Huntsville, AL**

Bachelor of Science in Engineering, Aerospace Engineering

GPA: 4.0/4.0, Expected graduation: July 2010

WORK EXPERIENCE

May 2008 – Present **Dynetics, Inc.** **Huntsville, AL**

Engineer Trainee

- Extensive work with flight test data of the Sky Warrior ERMP UAS to support simulation studies of Hellfire missile shots. Created 3-D visualizations of simulation results using in-house software. Visualizations required extensive MATLAB code and knowledge of coordinate transformations. Wrote MATLAB code to read and parse binary simulation log files. Extracted wind data from available flight test data. Used flight test data to create a lift coefficient vs. angle of attack curve.
- Calculated the short period mode of the natural response of a UAV-delivered payload using flight test data. Calculated the location of the center of pressure for varying angles of attack and sideslip of a UAV-delivered payload using flight test data.
- Created a MATLAB GUI to predict the drift of a UAV while under parachute. GUI functionality included: user input, real-time retrieval of data from website, parachute drift calculation, and latitude/longitude gridlines and airspace boundaries drawn on satellite image. Modified existing algorithm to significantly reduce runtime.
- Assisted testing of an anti-ship cruise missile simulation. Aided in integrating the Simulink model with a MATLAB GUI. Documented test results in a report submitted to the Office of Naval Intelligence.
- Extensive experience with reading and writing text, Excel, XML, and MAT files using MATLAB, and with 2-D and 3-D plotting in MATLAB.
- Performed multiple presentations to large audiences including company executives.

CLEARANCE Secret, granted on 9/25/2008 by Dynetics, Inc.

HONORS AND AWARDS

- President’s List, The University of Alabama in Huntsville
- Member of Alpha Lambda Delta, National Academic Honor Society
- Invited to join Sigma Gamma Tau, National Honor Society of Aerospace Engineering
- Invited to join Tau Beta Pi, National Engineering Honor Society
- Invited to join Delta Epsilon Iota, Academic Honor Society
- Recipient of the UAH Presidential Scholarship

Christopher Pittman

256-783-4564
pittman.christopher@gmail.com

Current Address
199 Federal Lane
Huntsville, AL 35811

CITIZENSHIP U.S.

TECHNICAL SKILLS Experience with C, C++, VB, Patran/Nastran, LabVIEW, Mathcad, and MATLAB

EDUCATION

The University of Alabama in Huntsville **Huntsville, AL**

Bachelor of Science in Engineering, Mechanical Engineering

GPA: 3.17/4.0, Expected graduation May 2010

WORK EXPERIENCE

May 2008 – Present **Continental Corporation** **Huntsville, AL**

Co-op Student

- Perform testing and data processing for electronic clusters. Tests performed include acoustic, control system, lighting, materials, mechanical, signal integrity, thermal, and vibrational.
- Design and create new tests in compliance with customer-approved testing methods.

Garrett Williams

(256) 828-6214; (256) 679-5089
williag@email.uah.edu

Current Address
381 Monroe Rd
Meridianville, AL 35759

CITIZENSHIP U. S.

TECHNICAL SKILLS

Microsoft Office: Word, Excel, PowerPoint;

MATLAB, Mathcad, Solid Edge, NX 3

EDUCATION

The University of Alabama in Huntsville **Huntsville, AL**

Bachelor of Science in Engineering, Aerospace Engineering

GPA: 2.90/4.0 (2.95/4.0 in major), Expected graduation May 2010

WORK EXPERIENCE

June 2007 – July 2008 **Wilson Lumber Co.** **Huntsville, AL**

Door Shop Interior Specials Unit Lead

- Responsible for fabrication and assembly of custom doors to customer specifications, performing tasks such as precision milling and trim work, using various tools such as pneumatic nail guns, table and radial arm saws, etc.

September 2006 – June 2007 **Gander Mountain** **Huntsville, AL**

Sales Representative

- Worked in merchandising department as sales representative, displaying new products and keeping current products in stock.

August 2005 – December 2005 **UAH** **Huntsville, AL**

Computer Technology Assistant

- Involved software and hardware installation, as well as troubleshooting of computer systems.

HONORS AND AWARDS

Hazel Green High School Advanced Academic diploma
UAH Academic Excellence Scholarship
UAH Scholar Athlete Award for the 2005/2006 school year

Emily Hampton

256-829-0706; 256-503-1182
ejh0002@uah.edu

Current Address
430 Mason Road
Hazel Green, AL 35750

CITIZENSHIP U.S.

TECHNICAL SKILLS Microsoft Office Suite (2003, 2007, 2010 Beta), FrameMaker

EDUCATION **University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Arts in English

Minor: History, GPA: 3.7/4.0 (3.8/4.0 in major), Expected graduation May 2010

PROFILE

- Organizing tasks, checking for accuracy, handling complaints, collecting money, fundraising, writing and editing papers, reading volumes of materials and extracting key information, managing people and delegating tasks, sales, training individuals, interacting with people at different levels, providing customers with service.

PUBLICATIONS "Rosalind: Playing Both Sides of Love and Gender in *As You Like It,"* in *Undergraduate Annals of Honors Research*, an electronic journal to be published by the UAH Honors Program.

HONORS AND AWARDS Girl Scout Gold Award recipient, UAH Foundation Presidential Scholarship recipient, UAH Liberal Arts Deans List.

AFFILIATIONS UAH Honors Program, Alpha Lambda Delta, Delta Epsilon Iota, Sigma Tau Delta, Phi Kappa Phi.

3. Master Equipment List

Budget Quicksheet				
	Allowable	Used	Contingency	Available
Mass	1697	#NAME?	0	#NAME?
Power (PH)	5497	#NAME?	1649.1	#NAME?
Power (OK)	392	#NAME?	58.8	#NAME?
Cost	650,000,000	0	5,000,000	645,000,000

4. List of Abbreviations and Acronyms

ACS: Attitude Control System
ADCS: Attitude, Determination, and Control System
AGC: Automatic Gain Control
AMBR: Advanced Material Bi-propellant Rocket
AO: Announcement of Opportunity
APL: Applied Physics Laboratory
AU: Astronomical Unit
BOL: Beginning of Life
CBE: Current Best Estimate
CCD: Charge-Coupled Device
ConOps: Concept of Operations
CPOV: Composite Overwrapped Pressure Vessel
DOD: Depth of Discharge
DSN: Deep Space Network
EDL: Entry, Descent, and Landing
EOL: End of Life
EPO: Education Public Outreach
FOV: Field of View
FTE: Full Time Equivalent
FY: Fiscal Year
HGA: High Gain Antenna
HIM: Histogram Imaging Mode
ICD: Interface Control Document
IFOV: Instantaneous Field of View
IR: Infrared
Isp: Specific Impulse
ISPT: In Space Propulsion Technology
JPL: Jefferson Propulsion Laboratory
LGA: Low-Gain Antenna
LIDAR: Light Detection and Ranging
MCP: Micro-Channel Plate
MLI: Multi-Layer Insulation
MR: Mixture Ratio
MRC: Mixture Ratio Control
MSI: Multi Spectral Imager
NAC: Narrow Angle Camera
NEAR: Near Earth Asteroid Rendezvous
NIR: Near Infrared
NIS: Near Infrared Spectrometer
NTO: Nitrogen Tetroxide
NVRAM: Non-Volatile Random Access Memory
OSIRIS: Optical, Spectroscopic, and Infrared Remote Imaging System
PDR: Preliminary Design Review
PHD: Pulse Height Distribution

PI: Principal Investigator
PLM: Pixel List Mode
PMD: Propellant Management Device
RHU: Radioactive Heater Unit
SDRAM: Synchronous Dynamic Random Access Memory
SEMP: Systems Engineering Management Plan
SLASR: Stretched Lens Array SquareRigger
SNR: Signal to Nose Ratio
SOTA: Science Operations and Test Area
SSUSI: Special Sensor Ultraviolet Spectrographic Imager
TBD: To Be Determined
TCR: Trojan/Centaur Reconnaissance
TE: Thermoelectric
TRL: Technology Readiness Level
UV: Ultraviolet
UVS: Ultraviolet Spectrometer
WAC: Wide Angle Camera
Xmit: Transmit

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6. AMBR Propulsion Technology Infusion Plan

1. Understanding AMBR technology and the inherent risks associated with this technology
The Advanced Material Bipropellant Rocket (AMBR), shown in Figure TBD, is a new engine based on the existing Aerojet's R-4D-15. The AMBR thruster is a high temperature thruster addressing the cost and manufacturability challenges with iridium-coated rhenium chambers. AMBR works by consuming Hydrazine (N_2H_4) as a fuel and Nitrogen Tetroxide (NTO) as an oxidizer as well as Aerojet's R-4D-15. The inherent risk is that AMBR has no heritage. Though AMBR has been tested several times, it has not yet been operated in space. In space, there is a possibility that AMBR's performance will be decreased, which would lead to a failure of the mission, but repeating tests and improvements helps mitigate that inherent risk.

Figure 27

2. Assessment of and rationale for determining the TRL of AMBR
Since 2001 the objective of the ISPT project has been to develop inspace propulsion technologies that can enable NASA science missions by significantly reducing cost, mass, and travel times. The ISPT project is charged with the development of new enabling propulsion technologies that cannot be reasonably achieved within the cost or schedule constraints of the mission development timelines, specifically the requirement of achieving technology readiness level (TRL) 6 prior to preliminary design review (PDR). ISPT is NASA's one technology program that develops primary inspace propulsion technologies. Earth departure, entry, descent and landing (EDL), and attitude/reaction control systems are not currently in the project's scope. Since the ISPT objective is to develop products that realize near-term and mid-term benefits, ISPT primarily focuses on technologies in the mid TRL range (TRL 3 to 6 ranges) that have a reasonable chance of reaching maturity in 4 to 6 years provided adequate development resources.

3. Description of technology infusion implementation plan
AMBR has already undergone several tests, and some components have been improved during tests. These advancements are shown in Table TBD and Table TBD.

Table 23

AMBR Thruster within a Technology Plan	
Year	Advancement
2001	Pump-driven, high pressure engines
	Low pressure drop components
	High-temperature, oxidation-resistant materials
	Combustion stability
2002	Fluorinated oxidizers
	Material compatibility
	High-temperature, oxidation-resistant materials
	Combustion stability
2005	High-temperature, oxidation-resistant materials (eg..iridium liners)
	High temperature thermal management
	Rapid, lw-cost chamber fabrication
	Optimized injectors, nozzles
2009	High-energy Propellants
	Pump-fed Engines
	Higher Pressure

Table 24

Key Milestones	
Kickoff	Sep-06
Mission and System Analysis TIM	Sep-06
Baseline Testing	Feb-07
Risk Mitigation Chamber Testing	Nov-07
Prototype Engine Testing	Sep-08
Environmental Testing	Nov-08

According to NASA, AMBR is scheduled to undergo environmental tests including vibration, shock, and life-firing tests. Those tests will have been completed as early as 2009. ISPT continues to evaluate plans to further improve the combustion chamber film cooling that allows the AMBR engine to operate closer to its original target.

4. Description of the application use, and benefits of AMBR in the proposed investigation
Aerojet's AMBR thruster has a higher performance than the prior advanced thruster, HiPAT, which is the trade name for Aerojet's R-4D-15. According to the Tsiolkowski equation, the usable propellant mass is determined by basically three factors: initial launch vehicle mass, specific impulse, and delta-V. The initial launch vehicle mass and delta-V are determined by the relationship between the launch date and the trajectory, which means the specific impulse is the only factor that can change the overall propellant mass. Thus, the propellant mass is determined by the specific impulse, and the higher the specific impulse is, the smaller the usable propellant mass is, which reduces the mission cost and the spacecraft mass.

AMBR's specific impulse is 335 seconds, which is higher than the existing HiPAT thruster by 7 seconds; thus using the AMBR thruster instead of the HiPAT reduces the mission cost and mass. Table TBD shows a comparison between the AMBR thruster and the HiPAT thruster.
In the Trojan/Centaur Reconnaissance mission, Aerojet's AMBR thruster is feasible. The use of AMBR in the Cassini mission, which has an R-4D thruster which is similar to that of the TCR mission, suggests that the AMBR thruster is feasible for the TCR Mission. The Cassini mission is flyby of Jupiter, Earth, Venus, and Saturn's moons, and Trojan/Centaur mission is flyby of Trojan and orbit Centaur. Even Aerojet's R-4D thruster, which has the lower performance than AMBR, enables thr Cassini mission, so it is surely possible to say that the high-performance AMBR thruster also enables the Trojan/Centaur mission. For this reason, Aerojet's AMBR thruster is selected for the Trojan/Centaur Reconnaissance mission.

Table 25

Desing Characteristics	AMBR	HiPAT
Thrust (lbf)	200	100
Specific Impulse (sec)	335	328
Inlet Pressure (psia)	400	250
Chamber Pressure (psia)	275	137
Oxidizer/Fuel Ratio	1.2	1
Expansion Ratio	400::1	375::1
Physical Envelope envelope	Within existing HiPAT	
Propellant Valves	Existing R-4D valves	

5. Description of how the offer would engage with the ISPT program's intention to have insight into the flight hardware development

Mixture Ratio (MR) control is a concept either to reduce the residuals propellants carried or to allow additional extended mission operation otherwise lost due to an imbalance in the oxidizer-to-fuel ratio experienced during operation. Small investments were made to characterize balance flow meters, validate MR control to maximize precision, and determine the potential benefits of MR control. A hot-fire test of the required system hardware is expected near the end of 2008.
Small investments were also made to evaluate manufacturing techniques for thin liner composite overwrap pressure vessels (COPV). The task involves evaluating liner bonding and welding techniques. The product is intended to meet manufacturing recommendations and standards to minimize risk and increase yields for COPVs. The program works directly with members of NASA's COPV working group, who will implement the standard processes in future COPV efforts.
Light weight tanks can be used in all liquid propulsion systems using either storable or cryogenic propellants. They can be applied to reduce propulsion system dry mass for all classes of science missions. Improvements in the light weight tanks could result in substantial reduction of the overall propulsion systems weight and allow for more payload and scientific instrumentation, resulting in greater scientific return.

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7. Calculations and Assumptions

1. ADCS

MASS				
Item	**Model**	**Number**	**Mass Each (kg)**	**Total Mass**
Thrusters	MR-111C (Aerojet)	16	0.33	5.28
Reaction Wheels	RDR 68-3 and WDE 8-45 (Rockwell Collins)	4	8.85	35.4
Star Cameras	VF STC 1 (Valley Forge)	4	3.2	12.8
Sun Sensors	Medium Sun Sensor (Comtech AA)	4	0.036	0.144
IMU	LN-200 (Northrop Grumman)	2	1	2
			TOTAL:	**55.624**

Figure 28

POWER						
Item	**Model**	**Used (NOT total**	**Standby**	**Nominal**	**Max**	**Total**
Thrusters	MR-111C (Aerojet)	16	--	5.39	--	86.24
Reaction Wheels	RDR 68-3 and WDE 8-45 (Rockwell Collins)	4	5	20	90	
Star Cameras	VF STC 1 (Valley Forge)	1	--	10.2	--	10.2
Sun Sensors	Medium Sun Sensor (Comtech AA)	1	0	0	0	0
Inertial Measurement Unit	LN-200 (Northrop Grumman)	1	--	12	--	12

Figure 29

2. Thermal Systems

Assumptions

-Spacecraft bus is isothermal – This assumption is made to simplify the calculations. For this proposal, there was no access to thermal finite element (difference) analysis software, and breaking the spacecraft into small nodes would be very time intensive and tedious, which would also introduce more human error.

-There are no surface or cross-sectional area changes due to the depressurization of the MLI – This assumption is made because data on the expansion factor cannot be found, even given that it is uniform and predictable. Also, it might be somewhat difficult to calculate the effects of expansion given a relatively complicated geometric surface.

-The MLI functions ideally – Sometimes layers of MLI do not separate from one another perfectly during depressurization, leading to inconsistent results. This is ignored for this analysis due to the lack of data on how to handle the inconsistent results. Also, there are assumed to be no heat leaks in the MLI due to seams or edges or any other effects.

-Solar panels are thermally isolated from the spacecraft bus – This assumption simplifies calculations as well, but it is made primarily because of a lack of data on the subject. The cross-sectional area of the solar panels is known, but the infrared emissivity/absorptivity values are not.

With those values, the steady-state temperatures of the solar panels could easily be calculated, but even then the cross-sectional area and length of the support structures linking the solar panels to the spacecraft bus would need to be known. The best that could be done would be to make up a cross-sectional area, length, and thermal conductivity value for the support structure and run the calculations that way, but it would be meaningless if not misleading.

-<u>Any other protrusions are considered thermal isolated from the spacecraft bus and do not affect the cross-sectional or surface area</u>– This includes the communications equipment, thrusters, etc. This assumption will hold until the team member in charge of structural design on the given pieces of equipment can provide the data. With all the necessary data, such as the dimensions, geometry, location, and support structure characteristic, it can be assumed that each protrusion is an isothermal node and include them in my calculations, but it is unlikely that all of the needed data will be provided.

*This assumption is probably what introduces the largest amount of error into the calculations. As various protrusions are added to the spacecraft bus, the surface area can start to increase rather dramatically compared to the cross-sectional area. This could cause a significant cooling effect on the spacecraft bus as the solar power absorbed increase with the cross-sectional area and the heat lost increases with the surface area.

-<u>The radiator(s) and louver(s) perform exactly as mentioned on page 440 of SMAD 3rd edition</u> – With the louver fully open and the radiator at a temperature of 304 K, the heat rejection rate is 430 $W*m^{-2}$. With the louver fully closed and the radiator at a temperature of 283 K, the heat rejection rate is 54 $W*m^{-2}$. The heat rejection rates can be calculated for any given temperature since the emissivity value can be assumed to stay constant.

-<u>The scientific instruments can maintain their own temperature. They neither produce nor absorb any excess heat</u>– According to Dr. Benfield, as long as the instruments have flown before, they can take care of themselves thermally if they are given their required power. Therefore, by trusting Dr. Benfield's expertise, they are effectively being treated as thermally absent in my calculations.

*This assumption does make the calculations much easier, but it is an uncomfortable assumption to make. It was initially thought that the purpose of all of the subsystems was to make sure the scientific payload was taken care of and taken to the right place. It seems based on this assumption that the thermal control system exists solely to keep the other subsystems safe.

8. Cost

The Science Costs are provided by the Science Lead and include Science Team support for development, integration, and testing, as well as pre-launch science algorithm development. The costs are shown in Table 26 below.

Table 26

COLLEGE OF CHARLESTON								
Science Team XYZ		12 Months	12 months	12 months	12 months	12 months	12 months	
Jan 2011 - Dec 2016		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	
		FY11	FY12	FY13	FY14	FY15	FY16	TOTAL
	Effort	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	
Salaries								
Name [PI]	Acad Year	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	**$600,000**
Name [Co-I]	Acad Year	$70,000	$90,000	$90,000	$90,000	$90,000	$90,000	**$7,280,000**
	PI Summer	$30,000	$30,000	$30,000	$30,000	$30,000	$30,000	**$180,000**
	Co-I Summer	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	**$1,680,000**
Students (TBD)	Grad AY	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	**$600,000**
	Grad Summer	$6,000	$6,000	$6,000	$6,000	$6,000	$6,000	**$180,000**
	Undergrad-AY	$3,000	$3,000	$3,000	$3,000	$3,000	$3,000	**$54,000**
	UndergradSum	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	**$72,000**
Technician	AY	$70,000	$70,000	$70,000	$70,000	$70,000	$70,000	**$2,100,000**
	Summer	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	**$600,000**
Total Salaries:		***$343,000***	***$273,000***	***$273,000***	***$273,000***	***$273,000***	***$273,000***	**$13,166,000**
Fringe benefits (list rates)								
PI Acad Year (30%)	30.00%	$30,000	$30,000	$30,000	$30,000	$30,000	$30,000	**$180,000**
PI Summer (24%)	24.00%	$7,200	$7,200	$7,200	$7,200	$7,200	$7,200	**$43,200**
Co-I - Acad Year (30%)	30.00%	$21,000	$27,000	$27,000	$27,000	$27,000	$27,000	**$2,184,000**
Co-I - Summer (24%)	24.00%	$4,800	$4,800	$4,800	$4,800	$4,800	$4,800	**$403,200**
Student - Grad Summer and Acad Y	1.60%	$416	$416	$416	$416	$416	$416	**$12,480**
Student Undergrad Summer	9.00%	$360	$360	$360	$360	$360	$360	**$6,480**
Total Fringe Benefits:		***$26,576***	***$32,576***	***$32,576***	***$32,576***	***$32,576***	***$32,576***	**$2,829,360**
Total Salaries and Fringe:		**$369,576**	**$305,576**	**$305,576**	**$305,576**	**$305,576**	**$305,576**	**$15,995,360**
Equipment								
LIDAR		$100,000						**$100,000**
Near IR Spectrometer		$100,000						**$100,000**
UV Spectrometer		$20,000						**$20,000**
NAC/WAC		$100,000						**$100,000**
Total Equipment		**$320,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$320,000**
Materials, supplies								
Printing / Office Supplies		$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	**$120,000**
Portable Lunar Exhibit		$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	**$60,000**
Workshops		$30,000	$30,000	$30,000	$30,000	$30,000	$30,000	**$180,000**
Total Supplies		**$60,000**	**$60,000**	**$60,000**	**$60,000**	**$60,000**	**$60,000**	**$360,000**
Subcontracts	Workspace	$900,000	$900,000	$900,000	$900,000	$900,000	$900,000	**$5,400,000**
Total Subcontracts		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$5,400,000**
Travel								
LPSC and AGU Mtgs (2/ yr)		$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	**$120,000**
Team Mtgs /Wkshp		$40,000	$40,000	$40,000	$40,000	$40,000	$40,000	**$240,000**
Total Travel		**$60,000**	**$60,000**	**$60,000**	**$60,000**	**$60,000**	**$60,000**	**$360,000**
Total Direct Costs		**$809,576**	**$425,576**	**$425,576**	**$425,576**	**$425,576**	**$425,576**	**$22,435,360**
Indirect Costs								
(40% TDC)		$323,830	$170,230	$170,230	$170,230	$170,230	$170,230	**$8,974,144**
TOTAL COFC COST:		**$1,133,406**	**$595,806**	**$595,806**	**$595,806**	**$595,806**	**$595,806**	**$31,409,504**