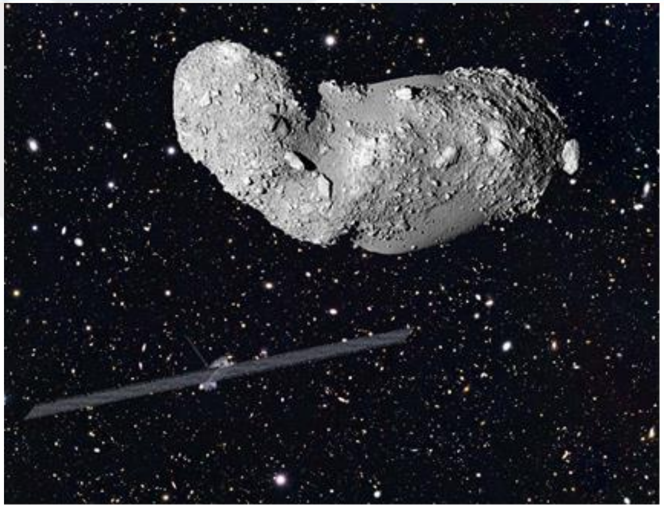
The World's Forum for Aerospace Leadership

The Near Earth Object Scout Spacecraft: A low-cost approach to in-situ characterization of the NEO population



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A new approach to NEO exploration exploiting CubeSat technology

- **Numerous NEOs pass close (< 0.3 AU) to the Earth-Moon system every year**
- **NEO-Scouts to rendezvous with target NEOs during close approach to the Earth-Moon system**
  - Small largely "COTS" spacecraft launched as secondary payloads
  - Short mission duration (100 to 400 days) to reduce:
    - Spacecraft hardware reliability requirements/cost
    - Telemetry system power/size/cost
    - Spacecraft operations cost
    - Mission success risk
  - Short mission duration (100 to 400 days) to increase:
    - Rate of data return from NEO population
- **Benefits**
  - **High rate of return of in-situ measurements of NEO physical properties supporting Global Exploration Roadmap objectives at relatively low dollar cost**

NEO-Scout Mission Objectives

- Our present knowledge of NEO surface and bulk properties is not sufficient to support high-confidence design and verification of NEO missions and mission hardware
    - Physical size, density, spin rate, surface mechanical properties, composition and volatiles content are unknown for most NEOs.
    - Recent NASA efforts to define an asteroid retrieval/redirection mission architecture struggled with the largely unknown and wide possible range of possible physical properties of the target NEOs.
- NEO-Scout will perform a limited set of target physical characterization measurements designed to provide:
    - Ground truth data supporting interpretation of remote sensing observations of NEOs in the visible, near infrared, thermal infrared, and radar wavelength ranges
    - Data supporting high-confidence engineering hardware and mission design for more ambitious manned and robotic missions
        - **NEO physical dimensions and density**
        - **NEO appearance and albedo**
        - **NEO surface mechanical properties**
        - **NEO surface mineralogy**
        - **NEO water/volatiles content**
- NEO-Scout can close some of these important strategic knowledge gaps

NEO-Scout Concept of Operations

- NEO-Scout Spacecraft can be launched as either secondary or primary payloads on launch vehicles placing primary payloads in GEO, cis-Lunar space or Earth escape trajectories
  - After placement by the launch vehicle, the NEO-Scout(s) can begin transit to the target NEOs immediately or loiter as needed prior to departure for rendezvous with the target
  - Multiple NEO-Scouts can be launched on a carrier vehicle (e.g. a Boeing 702 SP) and then begin transit to target NEOs as required
- NEO-Scout is designed to operate at GEO and beyond
  - Solar electric propulsion (as described in the following)
  - Spiral out from LEO is not considered a desirable option at this time
    - Radiation belt hardware degradation
    - Increases mission time
  - Largely autonomous spacecraft operations
    - Continuous Beacon Monitor mode operations (e.g. Deep Space 1 and New Horizons)
    - High rate telemetry on command only
    - Deep Space Network 34 meter dish receivers nominal - 74 meter dishes as needed.

The NEO-Scout Spacecraft - Overview

NEO-Scout Spacecraft General Requirements and Characteristics

Dry Mass range	< 20 kg
Wet Mass range	< 35 kg
Delta V range	< 10 km/s
Mission Duration Range	100 to 400 days
Solar Electric Propulsion Thrust to Weight Ratio	> 3 x 10^{-4}
Maximum Distance to Earth at NEO Rendezvous	0.3 AU
Maximum Telemetry Range	0.3 AU
Minimum Telemetry Data Rate at Maximum Range	1000 Bps
Telemetry Bit Error Rate at Maximum Range	10^{-6} to 10^{-4}
Solar Particle Event (SPE) Survivability	must survive 1 SPE
Payload Mass/Mass Fraction	3.5 kg/0.10
Single Spacecraft Cost Cap	< $ 15 M

NEO-Scout Design Approach

- Define high level NEO-Scout performance requirements and general characteristics (summarized in previous chart)
- Next, we select a relatively challenging NEO target
  - determine the characteristics of a low-trust trajectory for rendezvous with that target within the 400 day maximum mission duration limit and,
  - determine if we can design and assemble a spacecraft to fly the mission while staying within the desired weight and cost limits.
- The spacecraft dry weight limit is first combined with the maximum delta V requirement of 10 km/sec in the Tsiokolvsky rocket equation to calculate required propellant mass as a function of thruster specific impulse
  - Select the type of thruster type that would be able to meet the wet mass requirement
  - Only high specific impulse (hence exhaust velocity) electrostatic ion engines and Hall Effect thrusters can meet the propellant mass requirements for a 10 km/sec delta V and a 35 kg maximum wet mass

NEO-Scout Design Approach (continued)

- Next survey commercially available high specific impulse satellite thrusters
    - Identify possible candidates for the NEO-Scout spacecraft design
    - An additional constraint appears at this point driven by the maximum mission duration limits
        - **The NEO-Scout thrust-to-weight ratio needs to be high enough to enable acceleration to the desired final velocity in the allotted mission time**
- The balance of the design effort involved determining whether or not the remaining spacecraft systems could be assembled into an integrated functional spacecraft that conformed to the general requirements and constraints
    - Use mature (TRL 6/7 or above) commercially available components with LEO flight heritage whenever possible
    - The design was further refined and optimized the meet the more detailed delta V and trajectory requirements for the specific target NEO selected

NEO Target Selection for this Design Study

- To find NEOs whose orbit allows a rendezvous trajectory within the constraints of the NEO-Scout requirements, NASA’s JPL/NEO/NHAT database was used
- This database includes all known NEO orbital elements and lists possible rendezvous and return trajectories using an impulsive Lamberts Problem solver
- Due to the large number of NEOs, a table was created from those which fall under the constraints shown in the table below . From these constraints, **2007 SQ6** was chosen, the constrained values for this NEO are included in the table

Parameter	Value Range	2007-SQ6
Launch Epoch/Date	Jan. 1, 2020 – Jan. 1, 2025	Oct. 10, 2023
Flight Time, Days	<365	105
Closest Approach at Rendezvous, AU	$\leq$ 0.15	0.05
Orbital Inclination, Degrees	$\leq$ 10	9.101
Eccentricity	$\leq$ 0.15	0.1456
Semi-major Axis, AU	0.7 to 1.3	1.0430

Trajectory and rendevous analysis – NEO 2007 SQ6

- The 2007 SQ6 rendezvous trajectory reported here constitutes proof of concept that low thrust microsatellites will be able to rendezvous with asteroids that are not optimal targets, and therefore proves that low thrust microsatellite exploration of the NEO population is possible in general
- 2007 SQ6 was selected, not because it is an easy target, but instead because it is difficult to reach

Engine Burn	Epoch Engine Burn Start	Epoch Engine Burn Stop	Delta V (m/sec)	Propellant Consumption (kg)	Reason for Burn
1	23 Sept. 2022 06:58 UTC	26, Oct, 2022 22:09 UTC	5628.35	7.291	Inclination Change; Lower Periapsis; Raise Apoapsis
2	23 Jan. 2023 21:34 UTC	31 Jan, 2023 16:26 UTC	1639.5	1.673	Inclination and apse line change
3	11 Aug. 2023 21:34 UTC	15 Aug. 2023 0:00 UTC	0.672	0.672	Orbit matching
Total	23 Sept. 2022, 06:58 UTC	15 Aug. 2023, 0:00 UTC	7978.69	9.636	2007 SQ6 Rendezvous

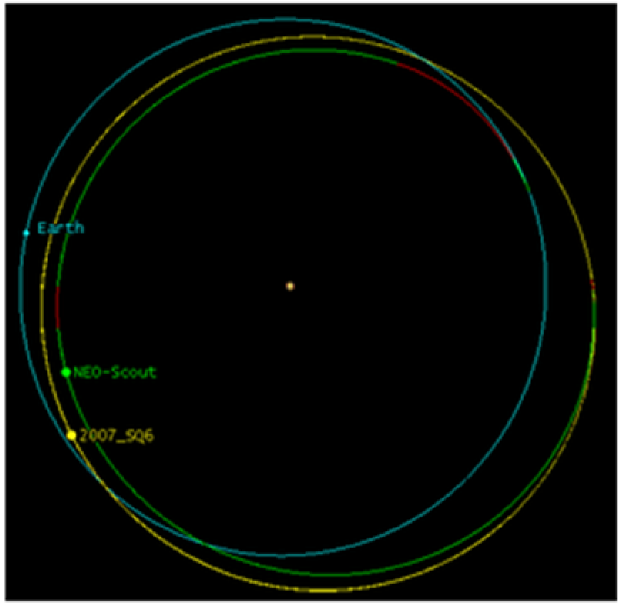
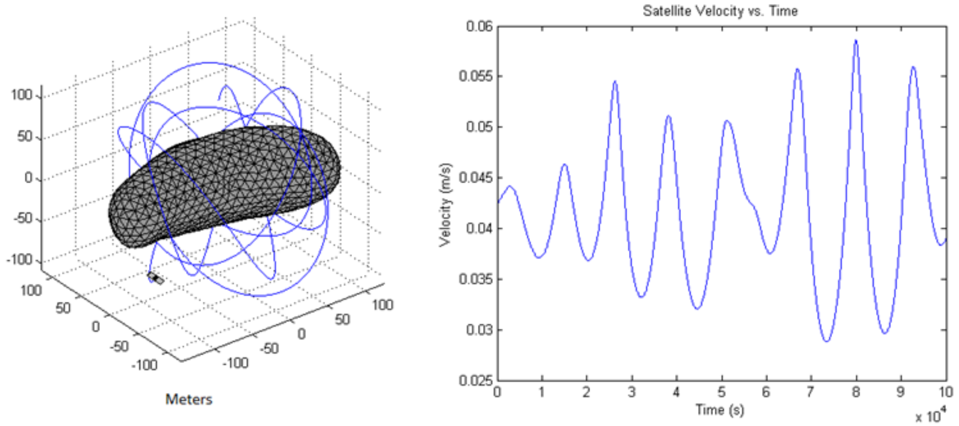
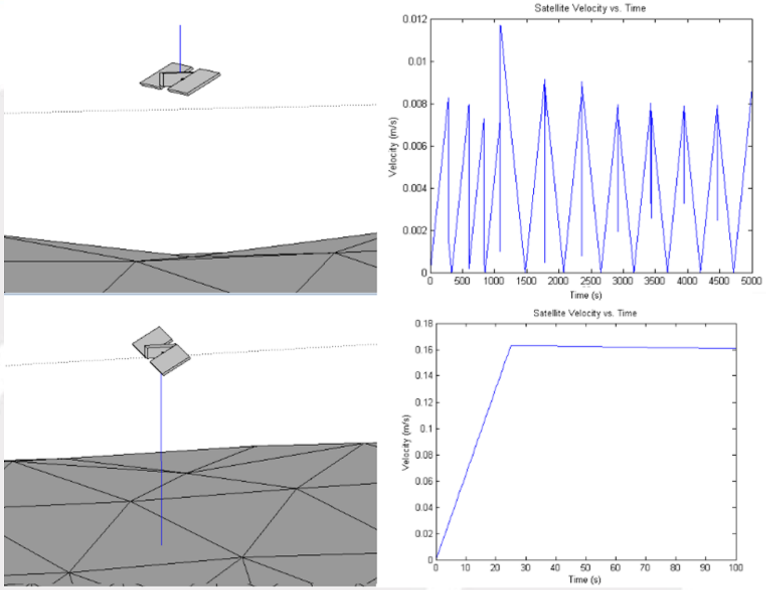


Figure 1. Locations on 8 February, 2023 and planned trajectory for rendezvous trajectory with 2007 SQ6

Proximity Operations at 2007 SQ6



A - Shows the NEO-Scout in a Passive Orbit over 1.157 days with initial velocity. Figure B - Shows the velocity as a function of flight time (a non-spherical shape is assumed for 2007SQ6 for purposes of demonstration)



A - Station keeping trajectory. B - Station keeping velocity profile. C - Asteroid launch trajectory. D - Asteroid launch velocity profile.

- Estimated diameter of 2007 SQ6 = 248 meters and assumed density of 2500 kg/m^3 => g = 8.7 x 10^{-5} (m/s^2); assuming a spherical shape -
  - near surface orbital velocity = 10.4 cm/s;
  - escape velocity = 14.7 cm/s
- Since there is currently no shape model of 2007 SQ6, a scale model of 433 Eros with maximum dimension of 248 meters is used for the asteroid proximity operations simulations
- NEO-Scout will use 12, 0.050 N cold gas attitude control thrusters for proximity operations.
  - NEO-Scout can accelerate to escape velocity from the asteroid surface in 15 seconds using two cold gas thrusters only.
- Actual NEO mass, density, and shape determined upon arrival at the asteroid

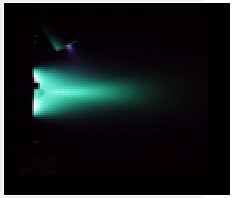
The NEO-Scout Spacecraft - Propulsion

The specific commercial products mentioned are examples only. Such mention does not constitute endorsement by the USG

- Main Propulsion - Busek BHT 600 Hall Effect Thruster

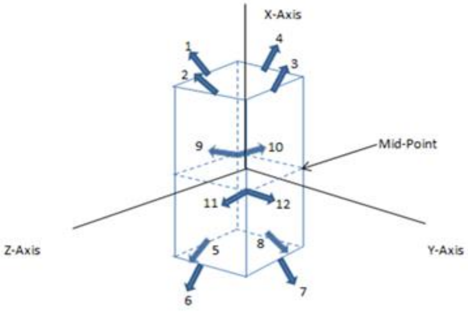
Engine	Tested Fuels	Thrust, mN	I_{sp} , s	Power Input, W	Mass, kg
Busek BHT-600	Xe, Ar, Kr, **I**, Bi, Zn, Mg	39 (at 600W)	1585 (at 600W)	300-800	3

  - Spacecraft dry mass 20 kg
  - 9.5 kg I_2 propellant
  - Total thruster operating time = 47 days
  - Total Delta V = 7.979 km/sec



Busek Hall Engine operating on I_2

- Proximity operations - The Marotta Cold Gas Microthrusters (CGMs)
  - 12 thrusters/spacecraft and for each thruster
    - Thrust of 0.05 N, an Isp of 65 s, a mass of less than 60 g, N_2 propellant.
    - Open response time of 5 ms; close response time of 5 ms
    - Ideal operating pressure of 100 psia.
  - The Marotta thruster is flight qualified and was previously developed for the GSFC Nanosats and the ST-5
  - 4 CGMs operating for 15 seconds can accelerate the spacecraft from rest on the surface of 2007 SQ6 to escape velocity



Placement of Marotta CGM thrusters

Marotta CGM

The NEO-Scout Spacecraft - Telemetry

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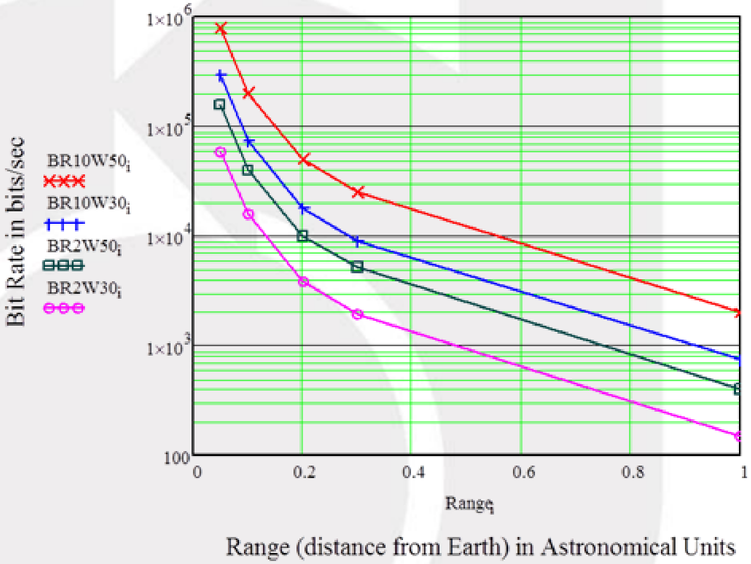
- Beacon Monitor
  - Deep Space 1 technology validation
  - S-Band
  - Commercially available 1 to 2 Watt CubeSat S-Band transmitter with matching wide beam antennas
  - Beacon Monitor on-board software package
- High Rate Telemetry
  - X-band
  - Link budget for different combinations of satellite high gain antenna diameter shown to the right
    - 34 meter Deep Space Network ground stations assumed
  - Commercial 2 watt X-band CubeSat transmitter with 30 cm diameter high gain directional satellite antenna
    - Transmitter power increase to 10W using X-band linear amplifier (IC) for short periods of time to increase bit rate
  - 1 megabit image downlink times @ 0.1 AU
    - 2 Watts/30 cm antenna - 63 seconds
    - 10 Watts/30 cm antenna - 13 seconds



Expected NEO-Scout down link bit rates as a function of distance from Earth (AU) for 4 different combinations of satellite high gain antenna diameter and satellite X-band transmitter output power; e.g. BR10W50 = 10 W transmitter and 50 cm dish. Use of the 34 meter diameter DSN ground stations is assumed and the link margin is greater than 1 dB is all cases.

The NEO-Scout Spacecraft

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- Command and Data Handling
  - Deep Space 1 metric validation of the Data Processing System are shown to the right
  - Tyvek Intrepid Pico-Class
    - Compatible with autonomous software
    - Capable of MicroSD data storage
    - Variety of interfaces that are compatible with onboard avionics
    - 2 additional lower level processors for redundancy
- Attitude Determination and Control
  - Ability to interface with GNC
  - Micro Reaction Wheel Module (BCT XACT) provides an axial Torque of 0.6 mN m
  - 0.05 N Cold Gas thrusters capable of reaction wheel desaturation and proximity maneuvers
- Guidance, Navigation, and Control
  - NanoTracker (included in the BCT XACT) gets orientation with respect to celestial reference frame (with 2 s processing delay)
  - Position and velocity can also be determined with the S-Band antenna via communication with DSN and ground stations

Processor (CPU)	Tyvak Intrepid Pico-Class	Deep Space 1 (RAD6000)
RAM	128 MB	128 MB
Flash	512 MB	6 MB
Processor Speed	400 MHz	20 MHz
Radiation Protection	not specified Latch-up protected	> 100 krad Latch-up Immune
Mass	.055 kg	~0.9 kg

The NEO-Scout Spacecraft

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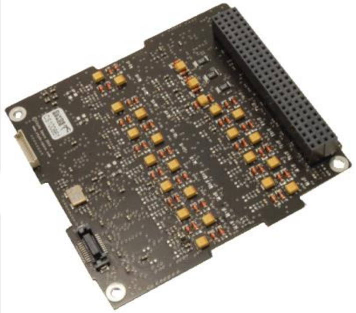
- Electrical Power and Power Management
  - Peak Power Requirements
    - 650 W (engine on)
    - 100 W (engine off)
  - PV arrays
    - 4.05 kg (2.3 m^2) generates excess of 650 W at 27.7% efficiency
  - Power Processing Systems
    - Busek PPU-600 selected to convert solar energy to the required voltage input for the BHT-600's operation
    - An additional PDM was selected for the low voltage avionics
- Thermal Design and Control
  - Operation: 0 to 50 ºC, Survival: -20 to 70 ºC
  - Passive MLI – Aluminized Teflon
    - 0.7AU-1.3AU
  - The PMS and thruster must be thermally isolated from neighboring modules and connected to a heat sink
  - Foil heaters are used for the thermal throttle in the PMS system

UTJ Solar cell



PDM for low voltage avionics

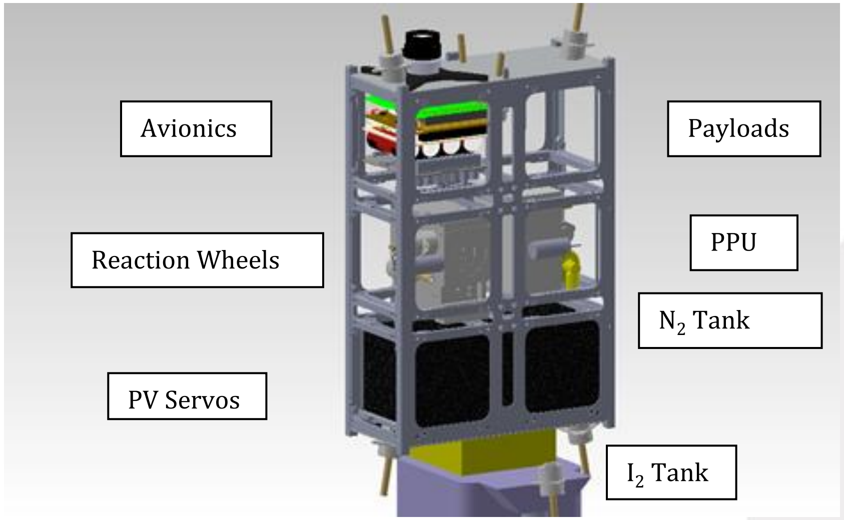
NEO-Scout Payload Options

The specific commercial products mentioned are examples only. Such mention does not constitute endorsement by the USG

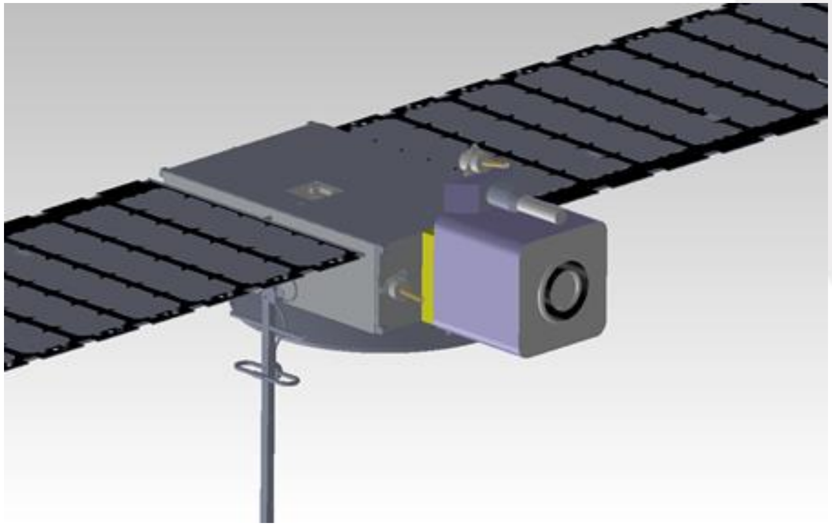
Instrument	**Measurements**	**Mass (kg)**
FLIR MLR-2k LIDAR	Distance to Object	0.115
NanoCam C1U	**Visible Imaging: Size, Appearance, Albedo**	**0.166**
FLIR Tau SWIR	Near IR Imaging: Size, Appearance, Albedo	0.131
FLIR Quark 640	Thermal IR Imaging: Surface Temperature Distribution	0.028
Surface Contact/Penetrator (TBD)	Mechanical Impact Properties	0.5
Miniature Radar Altimeter T2	Distance to Object and Surface Profile	0.375
Argus 1000 IR Spectrometer	**Near IR spectrometer for surface mineralogy**	**0.23**
Compact Neutron Albedo Instrument (TBD)	**Water, Hydrogen, Trapped Volatiles (Lunar Prospector)**	**0.5**
Alpha Proton Spec. (TBD)	**Composition: Light elements, Na, Al, Mg, Si, S (Mars Sojourner)**	**0.5**

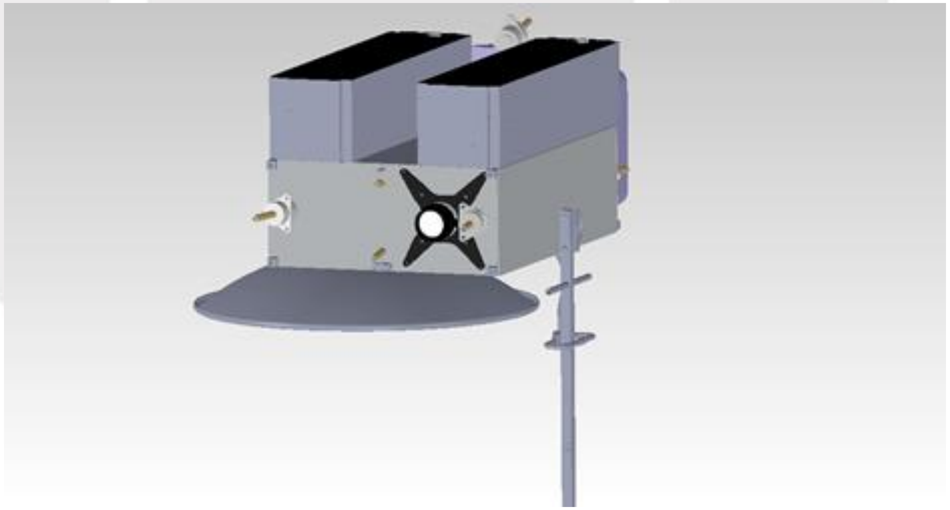
- To Be Developed (TBD)
- **Bold red => CubeSat LEO flight heritage**
  - Risk assessment/possible modification for interplanetary environment
- **Bold black => Interplanetary flight heritage on larger spacecraft**
  - Development work required for NEO-Scout integration
- Plain text => commercial products only – no flight heritage
  - Development work required for NEO-Scout integration with assessment/upgrade for interplanetary flight environment

The NEO-Scout Spacecraft



Parameter	Design Criteria	Achieved Metrics
Dry Mass range	< 20 kg	15 kg
Wet Mass range	< 35 kg	24.5 kg
Delta V range	< 10 km/s	7.629 km/s
Maximum Mission Duration	100 to 400 days	345 days
Maximum Distance to Earth at Rendezvous	0.3 AU	0.18 AU
Maximum Telemetry Range	0.3 AU	0.3 AU
Minimum Telemetry Data Rate	2000 to 10000 Bps	2000 Bps
Spacecraft Cost	$ 15M	$15M to $25M



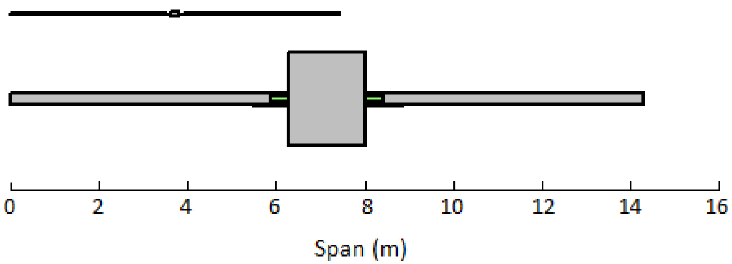


NEO-Scout Cost Model

- Aerospace Corporation Small Satellite Cost Model
  - Based on historical cost data from satellite projects substantially larger than contemporary CubeSat projects including the one proposed here
  - The model has been used successfully for NEO-Scout sized spacecraft projects
    - Satellite complexity index of 0.3 to 0.4
    - Wet mass 35 kg
    - Conservative cost estimate range $15M to $25M for the first flight unit including software and limited spacecraft qualification and acceptance testing
- Recent 3U CubeSat project cost examples
  - Boeing PhantomPhoenix Nano commercially available for an estimated $2M -$3M including qualification and acceptance testing
    - Two string avionics system redundancy and 1.8 kg of payload capacity
    - LEO service
  - Several commercial CubeSat suppliers offer single string 3U spacecraft for LEO service for < $1M
  - NASA Ames Research center has completed a number of successful 3U CubeSat flight projects in less than 2 years and at a total cost of less than $10M

Summary and Conclusions

- Technology tends to go from large to small, so why not satellites?
- The NEO scout concept is aligned support NASA's Space Technology Roadmap
  - TA-07 In Situ Resource Utilization - Destination Reconnaissance
- Limited specific technology development and refinement is indicated
- The preliminary NEO-SCOUT cost model is compatible with the NASA budgetary environment
  - Cost and scope growth will need to be controlled
- The NEO-Scout is a viable, low cost alternative to expensive Discovery class missions
  - The technical feasibility of the NEO-Scout concept has been demonstrated
  - Lightweight subsystems allow for lower thrust, decreased flight time, and less fuel used.
  - Utilizing COTs products allows for decreased research turnaround time.



Spacecraft	NEO-Scout	Deep Space 1
Cost, million USD	15 to 25	152.3
Mass, kg	24.5	486.3
Span, m	7.5	14.2

BACK-UP

NEO-Scout Programmatics

An affordable approach to in-situ characterization of the Near Earth Object (NEO) Population: The NEO-Scout Spacecraft

STATUS QUO

- Discovery Class Spacecraft
  - Examples : Osiris-REx, Dawn, Hayabusa, Rosetta, Deep Space-1
  - Weight (wet): 200 to 1500 kg
  - Multi year mission timelines
  - Limited number of targets per spacecraft
  - Program Cost range $100 to $800 million dollars per spacecraft/mission

NEW INSIGHTS

- The NEO population is known to be highly diverse
  - Characterizing one or two targets doesn't characterize the population as such
  - CubeSat based technology and miniaturized/low power avionics and instruments can enable characterization of many NEOs at relatively low cost
  - Supports high confidence target selection, mission planning, and hardware design for more ambitious and costly missions

PROBLEM / NEED BEING ADDRESSED

An affordable approach to providing in-situ characterization of NEOs is needed to support high-confidence hardware design and mission planning for more ambitious manned and robotic programs

PROGRAM DESCRIPTION:

- Produce in-situ characterization data on 20 NEOs between 2017 and 2027
  - Rendezvous/landing during close approach of NEO to Earth-Moon system (<0.3 AU)
  - Neo-Scouts depart from GTO, GEO, or cis-lunar space
  - escape trajectories can be provided by the launch vehicle
- NEO-Scout Spacecraft
  - CubeSat technology with limited upgrades for short term (<400 days)interplanetary operations
  - 15 to 30 kg wet mass
  - High impulse solar electric propulsion with high thrust to weight ratio (~10^{-4} to 10^{-3}) and a total delta V capability of 6 to 12 km/sec
  - 100 to 400 day mission timeline
  - Telemetry range 0.3 AU or less.
  - Spacecraft cost cap objective set at $15M

QUANTITATIVE IMPACT

- Cost for in-situ characterization of 20 NEOs with Discovery class spacecraft
  - ~ $8 billion (@ $400M ea)
- Cost for in-situ characterization of 20 NEOs with NEO-Scouts
  - ~ $ 0.3 billion (@$15M ea)

PROGRAM GOAL

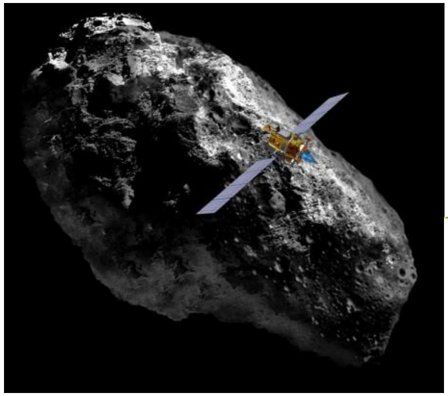
- Short Term Goal
  - Authorization and funding to proceed with design and build of technology demonstration spacecraft for flight demonstration on EM-1 or ISS
- Long Term Goal
  - Authorization and funding to proceed with full implementation of NEO-Scout program in support of eventual manned NEO operations

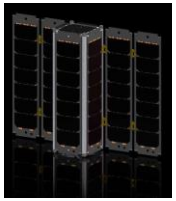
NEO-Scout Programmatics (Cont.)

An affordable approach to in-situ characterization of the Near Earth Object (NEO) Population: The NEO-Scout Spacecraft

Description and Objectives

- **Short Term Objectives** – Design, develop, build, test, and fly one 15 to 30 kg (wet) NEO-Scout flight prototype to demonstrate basic spacecraft functionality and qualify new technologies
    - Flight on EM-1 preferred with ISS as back-up plan
    - Interplanetary GN&C (including prox-ops)
    - Novel Solar Electric Propulsion System
    - Long range (< 0.3 AU) communications and tracking
    - Miniaturized sensors function and reliability
- **Long Term Objectives** – Design develop build test and fly fully capable, 15 to 30 kg (wet), NEO-Scouts and implement the NEO population characterization campaign
    - NEO size, albedo, and and spin rate determination
    - NEO soft landings and surface property characterization





Approach

- Program Management Approach
    - NASA to partner with universities and small innovation driven CubeSat companies to produce the technology demonstration unit and the fully capable NEO-Scout fleet
        - Multiple NASA center participation
        - Rensselaer Polytechnic Institute and Utah State University
    - Spacecraft integration and acceptance testing by NASA CS and site support contractors
    - Rigorous cost control with extensive use of verifiable COTS components to manage program cost
        - Flight proven NASA/Ames low-cost CubeSat project and hardware management approach

Cost, Schedule, and Status

- Status - the NEO-Scout project is in the concept formulation stage with no available funding at this time
    - JSC CS FTE with limited Ames/JPL and private sector collaboration
    - NEO-Scout abstract accepted at Space-Ops 2014
    - Major ESMD Senior Design Project (Rensselaer) reporting out 12/12/13 – Second semester effort planned
- Schedule
    - None defined at this time: Still building advocacy and seeking management position on priority and funding
    - Estimate two to three years from funding and project kick-off to flight ready hardware for the Short Term (EM – 1 flight) Objective
- Cost
    - Short Term Objective: estimate $10M to $15M for flight prototype
    - Long Term Objective: estimate $450M for Program

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