CubeSat technology adaptation for in-situ characterization of NEOs

• James M. Balsamo, Christopher D. Doherty, Matthew J. East, Karl J. Fischer, Mackenzie D. Ott, Christopher A. Roche, Matthew J. Scorza, Jeremy A. Styborski, Andrew J. Trovato, Christopher P. Volk, and Eric Woeppel

Rensselaer Polytechnic Institute, Troy, NY, 12180, USA

• Dr. Steven L. Koontz

NASA JSC, Houston, TX, 77058, USA

• Dr. Riccardo Bevilacqua

Rensselaer Polytechnic Institute, Troy, NY, 12180, USA

• Dr. Charles Swenson

Utah State University, Logan, Utah 84322-1400, USA

Specific commercial productions mentioned in the following presentation are examples only and are used as an academic exercise. Such mentions do not constitute endorsement by either the presenters nor by Rensselaer Polytechnic Institute.
Overview

The NEO-SPOC offers a low-cost alternative to enable in-situ measurements of Near-Earth Objects (NEOs). Multiple spacecraft could be launched for the cost of one Discovery class mission, enabling higher acceptable risk. Designed to be largely autonomous, further reducing mission and infrastructure costs.
Progenitors

Deep Space One
Advanced technology testbed demonstrated new spacecraft systems including Ion propulsion, AI spacecraft control, and methods to reduce the use of Deep Space Network through Autonav and beacon monitoring.

Hayabusa
Extensive use of autonomous systems for navigation and proximity operations, including a sample collection touchdown. Provided wealth of in-situ measurements.

Images courtesy of NASA
NEO-SPOC Operations

- At an estimated cost of 25 million dollars (including testing and parts), several vehicles could be acquired for the cost of a Discovery-class mission (Deep Space 1: 152 million dollars)
- The NEO-SPOC can be launched as a secondary payload during missions to GEO, cis-Lunar space or beyond
- Solar-electric propulsion and iodine propellant greatly reduce required mass and volume
- Highly 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.
### NEO Spacecraft Proof Of Concept

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Mass range</td>
<td>&lt; 10 kg</td>
</tr>
<tr>
<td>Wet Mass range</td>
<td>&lt; 15 kg</td>
</tr>
<tr>
<td>Delta V range</td>
<td>&lt; 10 km/s</td>
</tr>
<tr>
<td>Mission Duration Range</td>
<td>100 to 365 days</td>
</tr>
<tr>
<td>Solar Electric Propulsion Thrust to Weight Ratio</td>
<td>&gt; 3 x 10^{-4}</td>
</tr>
<tr>
<td>Maximum Distance to Earth at NEO Rendezvous</td>
<td>0.3 AU</td>
</tr>
<tr>
<td>Maximum Telemetry Range</td>
<td>0.3 AU</td>
</tr>
<tr>
<td>Minimum Telemetry Data Rate at Maximum Range</td>
<td>1000 Bps</td>
</tr>
<tr>
<td>Telemetry Bit Error Rate at Maximum Range</td>
<td>10^{-6} to 10^{-4}</td>
</tr>
<tr>
<td>Solar Particle Event (SPE) Survivability</td>
<td>must survive 1 SPE</td>
</tr>
<tr>
<td>Payload Mass/Mass Fraction</td>
<td>3.5 kg/0.10</td>
</tr>
<tr>
<td>Single Spacecraft Cost Cap</td>
<td>$ 25 M</td>
</tr>
</tbody>
</table>
To find NEOs whose orbit allows a rendezvous trajectory within the constraints of the NEO-SPOC 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 Lambert's 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, 1998 KG3 was chosen, the constrained values for this NEO are included in the table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value Range</th>
<th>1998 KG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Time, Days</td>
<td>&lt;365</td>
<td>249</td>
</tr>
<tr>
<td>Closest Approach at Rendezvous, AU</td>
<td>≤ 0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>Orbital Inclination, Degrees</td>
<td>≤ 10</td>
<td>5.5046</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>≤ 0.15</td>
<td>0.1181</td>
</tr>
<tr>
<td>Semi-major Axis, AU</td>
<td>0.7 to 1.3</td>
<td>1.1603</td>
</tr>
</tbody>
</table>
Trajectory Determination

- The 1998 KG3 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.
- 1998 KG3 was selected, not because it is an easy target, but instead because it is difficult to reach.
## Mission Plan

<table>
<thead>
<tr>
<th>Engine Burn</th>
<th>Epoch Engine Burn Start (times in UTC)</th>
<th>Epoch Engine Burn Stop (times in UTC)</th>
<th>Delta V, m/s</th>
<th>Propellant Consumption, kg</th>
<th>Reason for Burn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16 Sep 2017 20:03</td>
<td>17 Sep 2017 10:17</td>
<td>46</td>
<td>0.05</td>
<td>Raise apoapsis</td>
</tr>
<tr>
<td>2</td>
<td>26 Sep 2017 8:43</td>
<td>26 Sep 2017 19:54</td>
<td>36</td>
<td>0.04</td>
<td>Raise apoapsis</td>
</tr>
<tr>
<td>3</td>
<td>6 Oct 2017 12:27</td>
<td>7 Oct 2017 2:37</td>
<td>33</td>
<td>0.04</td>
<td>Raise apoapsis</td>
</tr>
<tr>
<td>7</td>
<td>10 Mar 2018 13:05</td>
<td>28 Mar 2018 00:00</td>
<td>1999</td>
<td>1.56</td>
<td>Orbit Matching</td>
</tr>
<tr>
<td>Total</td>
<td>16 Sep 2017, 06:58 UTC</td>
<td>28 Mar 2018 00:00</td>
<td>5537</td>
<td>4.97</td>
<td>Asteroid Rendezvous</td>
</tr>
</tbody>
</table>
The NEO-SPOC Spacecraft

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Criteria</th>
<th>Achieved Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Mass range</td>
<td>&lt; 10 kg</td>
<td>9.5 kg</td>
</tr>
<tr>
<td>Wet Mass range</td>
<td>&lt; 15 kg</td>
<td>14.5 kg</td>
</tr>
<tr>
<td>Delta V range</td>
<td>&lt; 10 km/s</td>
<td>5.5 km/s</td>
</tr>
<tr>
<td>Maximum Mission Duration</td>
<td>&lt;= 365.25 days</td>
<td>249 days</td>
</tr>
<tr>
<td>Maximum Distance to Earth</td>
<td>0.15 AU</td>
<td>0.13 AU</td>
</tr>
<tr>
<td>Earth at Rendezvous</td>
<td>0.3 AU</td>
<td>0.3 AU</td>
</tr>
<tr>
<td>Maximum Telemetry Range</td>
<td>1000 Bps</td>
<td>2000 Bps</td>
</tr>
<tr>
<td>Minimum Telemetry Data Rate</td>
<td>$ 25M</td>
<td>$15M to $25M</td>
</tr>
<tr>
<td>Spacecraft Cost</td>
<td>$ 25M</td>
<td>$15M to $25M</td>
</tr>
</tbody>
</table>
Command

Command and Data Handling

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

Deep Space 1 metric validation of the Data Processing System is shown to the below

<table>
<thead>
<tr>
<th>Processor (CPU)</th>
<th>RAM</th>
<th>Flash</th>
<th>Processor Speed</th>
<th>Radiation Protection</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyvek Intrepid Pico-Class</td>
<td>128 MB</td>
<td>512 MB</td>
<td>400 MHz</td>
<td>not specified</td>
<td>0.055 kg</td>
</tr>
<tr>
<td>Deep Space 1 (RAD6000)</td>
<td>128 MB</td>
<td>6 MB</td>
<td>20 MHz</td>
<td>&gt; 100 krad Latch-up Immune</td>
<td>~0.9 kg</td>
</tr>
</tbody>
</table>
Propulsion

BHT-200 Hall effect thruster
- Flight proven design (TacSat-2, FalconSat-5)
- Compatible with iodine propellant

Iodine Propellant: Mass and volume savings
- 30% the volume of a comparable Xenon system
- Low pressure tank reduces tank mass
- Flow control through heating to increase tank pressure

<table>
<thead>
<tr>
<th>Tested Fuels</th>
<th>Thrust [mN]</th>
<th>$I_{sp}$ [s]</th>
<th>Power Input [W]</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe, Ar, Kr, I, Bi, Zn, Mg</td>
<td>13 (@ 200W)</td>
<td>1390 (@ 200W)</td>
<td>100-300</td>
<td>~2.5</td>
</tr>
</tbody>
</table>
Power

Electrical Power and Power Management

Peak Power Requirements

- 250 W (engine on)
- 50 W (engine off)
- 2.3 m^2 of PV arrays (1.6 kg) generates excess of 250 W at 27.7% efficiency

Power Processing Systems

- Busek PPU-200 selected to convert solar energy to the required voltage input for the BHT-200’s operation
- Additional PDM used for the low voltage avionics

Simple Schematic of Power generation, Storage, and Distribution System
Telemetry

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

From 2014 NEO-Scout paper: Expected 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.
Attitude Control

Attitude Determination, Control, and Navigation

- 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
- NanoTracker (included in the BCT XACT) gets orientation with respect to celestial reference frame
- Position and velocity can also be determined with the S-Band antenna via communication with DSN and ground stations

---

BCT XACT
Precise 3-axis stellar attitude determination
Image courtesy of Blue Canyon Technologies

Cold Gas Thruster
Image courtesy of MOOG

Theoretical result of Reaction Wheel orientation code, as predicted by MATLAB and Simulink

Theoretical result of Cold Gas Thruster orientation code, as predicted by MATLAB and Simulink
## NEO-SPOC Payload Options

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

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurements</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLIR MLR-2k LIDAR</td>
<td>Distance to Object</td>
<td>0.115</td>
</tr>
<tr>
<td><strong>NanoCam C1U</strong></td>
<td><strong>Visible Imaging: Size, Appearance, Albedo</strong></td>
<td>0.166</td>
</tr>
<tr>
<td>FLIR Tau SWIR</td>
<td>Near IR Imaging: Size, Appearance, Albedo</td>
<td>0.131</td>
</tr>
<tr>
<td>FLIR Quark 640</td>
<td>Thermal IR Imaging: Surface Temperature Distribution</td>
<td>0.028</td>
</tr>
<tr>
<td>Miniature Radar Altimeter T2</td>
<td>Distance to Object and Surface Profile</td>
<td>0.375</td>
</tr>
<tr>
<td><strong>Argus 1000 IR Spectrometer</strong></td>
<td><strong>Near IR spectrometer for surface mineralogy</strong></td>
<td>0.23</td>
</tr>
</tbody>
</table>

- **Bold red** => CubeSat LEO flight heritage
  - Risk assessment/possible modification for interplanetary environment
- **Plain text** => commercial products only – no flight heritage
  - Development work required for NEO-SPOC integration with assessment/upgrade for interplanetary flight environment

Images Courtesy of FLIR

Image Courtesy of Thoth Technology, Inc.

Image Courtesy of GOMSPACE
Future Work

Mission Plan
- Utilize JPL finite burn trajectory solver to produce higher fidelity mission plan
- Prove possible implementation as secondary mission payload. (e.g. Orion EM-2)

Structural
- Structural analysis on fully-deployed panel configuration
- Mounting of engine to cubesat structure

Payload
- Exploration of other payloads including: surface contact penetrator, compact neutron albedo instrument
- Miniaturization of current payload system

Propulsion
- Identification of corrosion resistant, cost-effective material for iodine storage
- Development and testing of a compact PPU capable of supplying hundreds of watts
Summary and Conclusions

- Limited specific technology development and refinement is indicated
- The preliminary NEO-SPOC cost model is compatible with the NASA budgetary environment
  - Cost and scope growth will need to be controlled
- The NEO-SPOC can be used in conjunction with Discovery class and manned missions as a way of mitigating risk associated with the unknown NEO characteristics
  - Lightweight subsystems allow for lower thrust, decreased flight time, and less fuel used.
  - Utilizing COTS products allows for decreased research turnaround time.

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>NEO-SPOC</th>
<th>Deep Space 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost, million USD</td>
<td>15 to 25</td>
<td>152.3</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>24.5</td>
<td>486.3</td>
</tr>
<tr>
<td>Span, m</td>
<td>7.5</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Basic size comparison between NEO-SPOC (top) and DS-1 (bottom)
Acknowledgements/ Contact Info

Special Thanks to Dr. Steven Koontz and Dr. Riccardo Bevilacqua,

Contact Info:
NEO-SPOC design group
space.systems.design.team@gmail.com
BACK-UP
References

*3rd Interplanetary CubeSat Workshop, URL: http://icubesat.org/ [cited 6 April 2014].

References (cont.)


**http://deepspace.jpl.nasa.gov/**


**http://www.rfmd.com/CS/Documents/RFHA5966ADS.pdf**

**No COTS CubeSat X-Band receivers have been identified to date – this will be a custom build or commands will be uplinked via the S band beacon system.**

**http://www2.jpl.nasa.gov/basics/bf10-1.php**


**http://www2.jpl.nasa.gov/basics/bf13-1.php**  


**http://www.flir.com/CS/Documents/RFHA5966ADS.pdf**


**http://www.clyde-space.com/cubesat_shop/power_distribution_and_protection/95_cubesat-power-distribution-module**


**http://www2.jpl.nasa.gov/basics/bf10-1.php**


**No COTS CubeSat X-Band receivers have been identified to date – this will be a custom build or commands will be uplinked via the S band beacon system.**


**http://www2.jpl.nasa.gov/basics/bf13-1.php**  


• "Dynamic Albedo of Neutrons (DAN)," NASA-JPL MSL Science Corner [online database], URL: http://msl-scicorner.jpl.nasa.gov/instruments/DAN/ [cited 8 April 2014].


• https://www.aerospace.org/expertise/technical-resources/small-satellite-cost-model/


• "Particle Penetration and Radiation Effects. Berlin: Springer, 2002


NEO-SPOC Design Approach

- Define high level NEO-SPOC performance requirements and general characteristics (summarized in previous chart)
- Next, we select a relatively challenging NEO target
  - determine the characteristics of a low-thrust 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 Tsiokovskiy 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-SPOC Design Approach (continued)

- Next survey commercially available high specific impulse satellite thrusters
  - Identify possible candidates for the NEO-SPOC spacecraft design
  - An additional constraint appears at this point driven by the maximum mission duration limits
    - The NEO-SPOC 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
Thermal Control

- Multi-layer insulation utilized for passive thermal protection throughout flight envelope
  - Operational environment: 0 to 50 °C, 0.7AU-1.3AU
- The PMS and thruster must be thermally isolated from neighboring modules and connected to a heat sink
- Kapton foil heaters utilized to pressurize Iodine in the PMS system

<table>
<thead>
<tr>
<th>Location</th>
<th>T, K</th>
<th>$q_{\text{Sun}} \frac{W}{m^2K^4}$</th>
<th>$q_{\text{Earth}} \frac{W}{m^2K^4}$</th>
<th>$q_{\text{Albedo}} \frac{W}{m^2K^4}$</th>
<th>$\frac{W}{m^2K^4}$</th>
<th>$\sigma \frac{W}{m^2K^4}$</th>
<th>$\frac{\alpha}{\varepsilon}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>273 - 333</td>
<td>1376.5</td>
<td>230</td>
<td>408</td>
<td>5.67E-8</td>
<td>0.156 - 0.346</td>
<td></td>
</tr>
<tr>
<td>0.7 AU</td>
<td>273 - 333</td>
<td>2809.2</td>
<td>0</td>
<td>0</td>
<td>5.67E-8</td>
<td>0.112 - 0.246</td>
<td></td>
</tr>
<tr>
<td>1 AU</td>
<td>273 - 333</td>
<td>1376.5</td>
<td>0</td>
<td>0</td>
<td>5.67E-8</td>
<td>0.229 - 0.507</td>
<td></td>
</tr>
<tr>
<td>1.3 AU</td>
<td>273 - 333</td>
<td>814.5</td>
<td>0</td>
<td>0</td>
<td>5.67E-8</td>
<td>0.387 - 0.856</td>
<td></td>
</tr>
</tbody>
</table>
NEO-SPOC 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 implemented for the NEO-SPOC; however, it is generally acknowledged that micro-sized spacecraft lacks historical data backing and the estimates tend to be conservative
    - 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