CubeSat technology adaptation for in-situ characterization of NEOs

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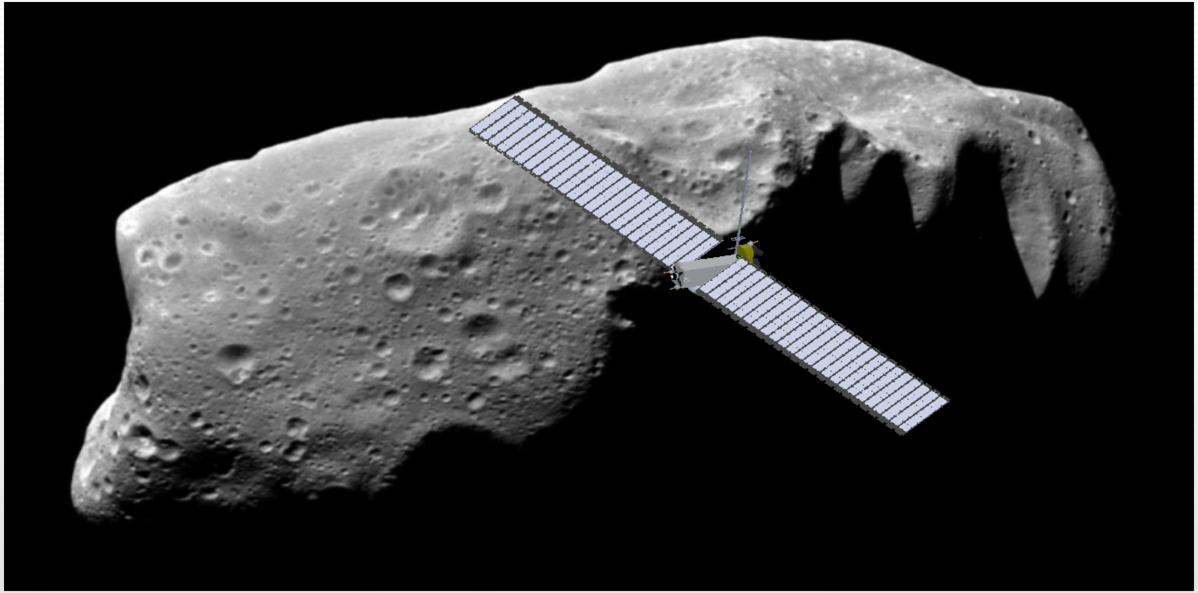
Overview

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



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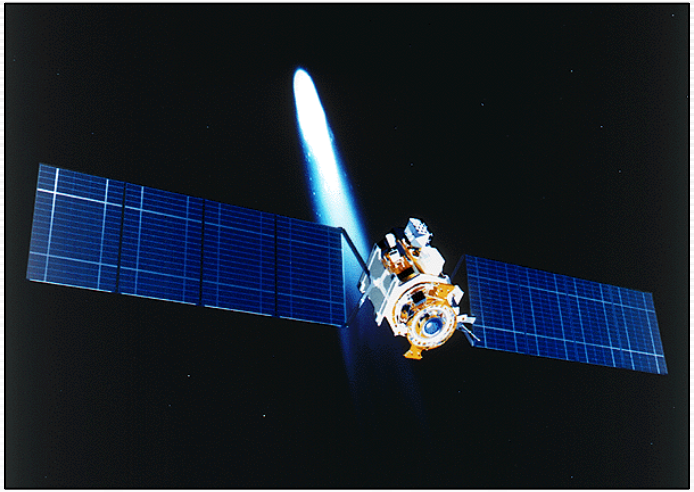
Progenitors



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

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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

Dry Mass range	< 10 kg
Wet Mass range	< 15 kg
Delta V range	< 10 km/s
Mission Duration Range	100 to 365 days
Solar Electric Propulsion Thrust to Weight Ratio	> 3×10^{-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	$ 25 M

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NEO Target Selection

- 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 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, 1998 KG3 was chosen, the constrained values for this NEO are included in the table

Parameter	Value Range	1998 KG3
Launch Epoch/Date	Jan. 1, 2015 – Jan. 1, 2020	May 2, 2017
Flight Time, Days	<365	249
Closest Approach at Rendezvous, AU	$\leq$ 0.15	0.13
Orbital Inclination, Degrees	$\leq$ 10	5.5046
Eccentricity	$\leq$ 0.15	0.1181
Semi-major Axis, AU	0.7 to 1.3	1.1603

Trajectory Determination

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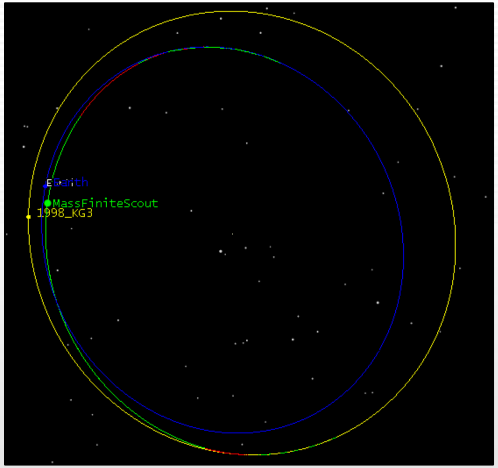
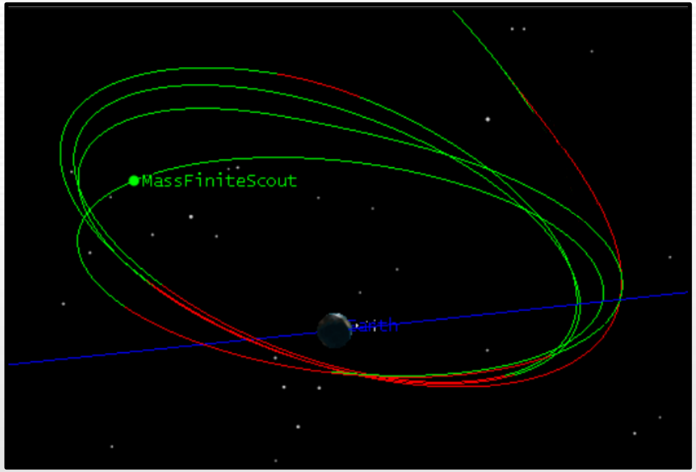
- The 1998 KG3 rendezvous trajectory reported here constitutes proof of concept that low thrust microsatellites will be able to rendezvous with asteroids that are not optimal targets, and therefore proves that low thrust microsatellite exploration of the NEO population is possible in general
- 1998 KG3 was selected, not because it is an easy target, but instead because it is difficult to reach





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Mission Plan

Engine Burn	Epoch Engine Burn Start (times in UTC)	Epoch Engine Burn Stop (times in UTC)	Delta V, m/s	Propellant Consumption, kg	Reason for Burn
1	16 Sep 2017 20:03	17 Sep 2017 10:17	46	0.05	Raise apoapsis
2	26 Sep 2017 8:43	26 Sep 2017 19:54	36	0.04	Raise apoapsis
3	6 Oct 2017 12:27	7 Oct 2017 2:37	33	0.04	Raise apoapsis
4	12 Oct 2017 4:16	13 Oct 2017 16:48	119	.13	Inclination & apse line change
5	18 Oct 2017 18:54	25 Oct 2017 10:29	534	.57	Earth Escape
6	28 Oct 2017 20:51	28 Nov 2017 24:44	2767	2.58	Inclination & apse line change
7	10 Mar 2018 13:05	28 Mar 2018 00:00	1999	1.56	Orbit Matching
Total	16 Sep 2017, 06:58 UTC	28 Mar 2018 00:00	5537	4.97	Asteroid Rendezvous

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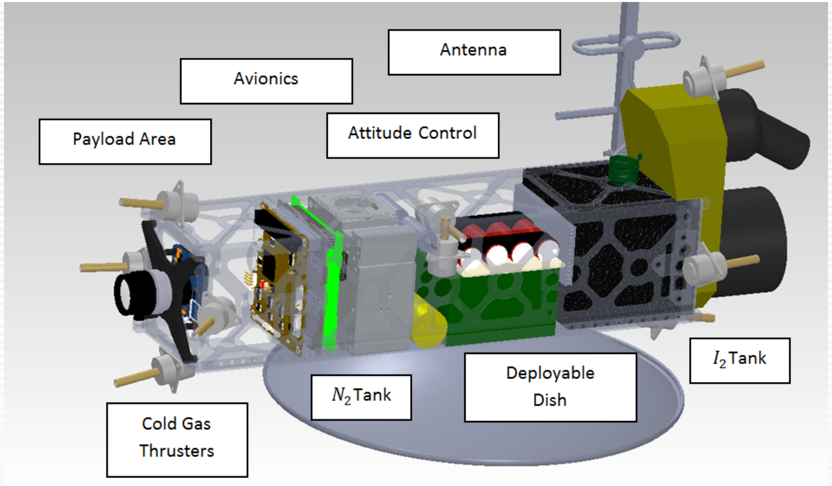
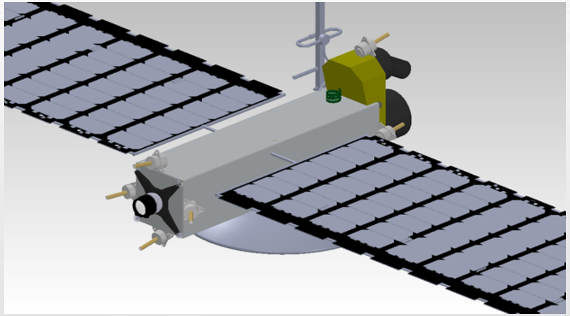
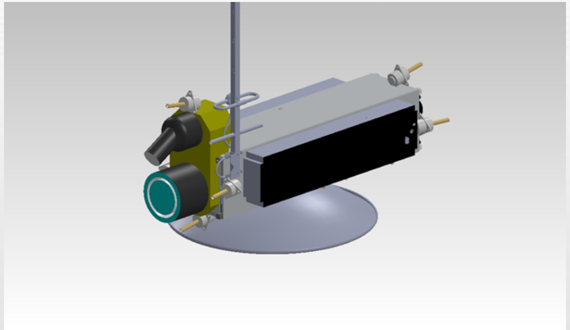
The NEO-SPOC Spacecraft

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







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

Tyvek Intrepid Pico-Class Module
Image Courtesy of Nano-Satellite Systems LLC

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

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

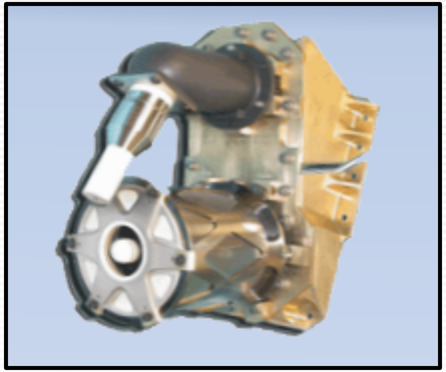
Propulsion

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



BHT-200
Image courtesy of BUSEK

Tested Fuels	Thrust [mN]	I_{sp} [s]	Power Input [W]	Mass [kg]
Xe, Ar, Kr, I, Bi, Zn, Mg	13 (@ 200W)	1390 (@ 200W)	100-300	~2.5

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Power

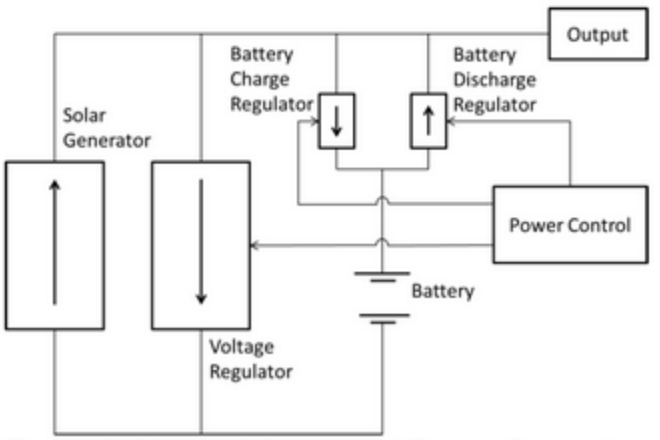
Electrical Power and Power Management

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

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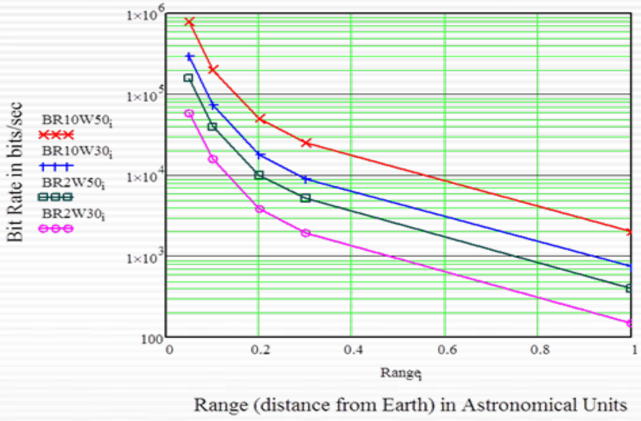
Telemetry

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.

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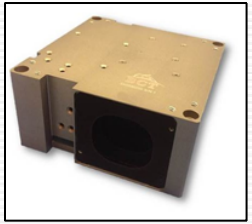
Attitude Control

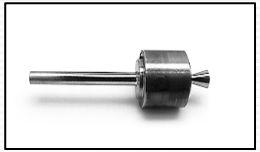
Attitude Determination, Control, and Navigation

- Ability to interface with GNC
- Micro Reaction Wheel Module (BCT XACT) provides an axial Torque of 0.6 mN mr
- 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



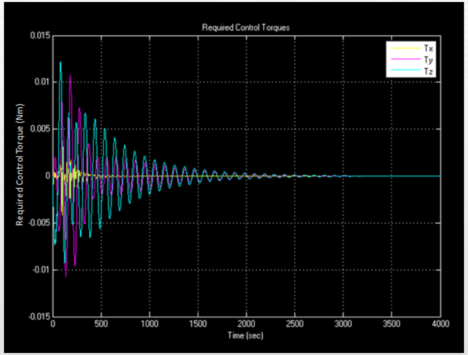
BCT XACT
Precise 3-axis stellar attitude determination

Image courtesy of
Blue Canyon Technologies

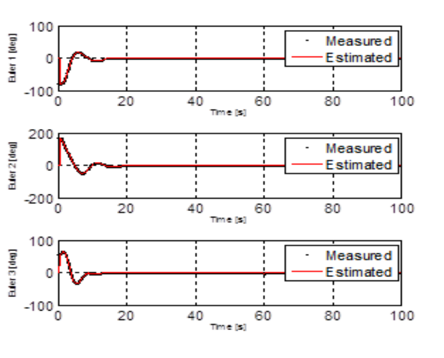


Cold Gas Thruster

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

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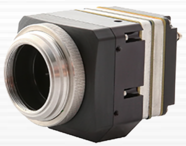
NEO-SPOC Payload Options

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

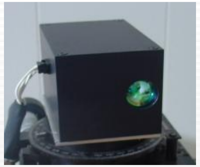
Instrument	Measurements	Mass (kg)
FLIR MLR-2k LIDAR	Distance to Object	0.115
NanoCam C1U	**Visible Imaging: Size, Appearance, Albedo**	**0.166**
FLIR Tau SWIR	Near IR Imaging: Size, Appearance, Albedo	0.131
FLIR Quark 640	Thermal IR Imaging: Surface Temperature Distribution	0.028
Miniature Radar Altimeter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



FLIR Tau SWIR

FLIR Quark 640

Images Courtesy of FLIR



Argus IR Spectrometer

Image Courtesy of Thoth Technology, Inc.

NanoCam

Image Courtesy of GOMSPACE

- **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

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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

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Summary and Conclusions

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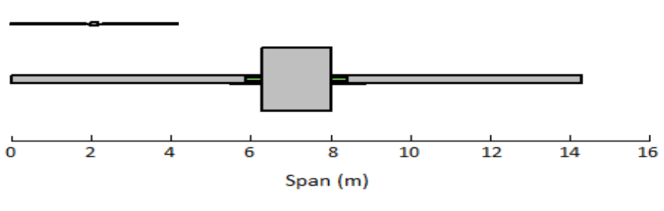
- Limited specific technology development and refinement is indicated
- The preliminary NEO-SPOC cost model is compatible with the NASA budgetary environment
    - Cost and scope growth will need to be controlled
- The NEO-SPOC can be used in conjunction with Discovery class and manned missions as a 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.



Basic size comparison between NEOSPOC (top) and DS-1 (bottom)

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

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Acknowledgements/ Contact Info

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

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References

•[1]3rd Interplanetary CubeSat Workshop, URL: http://icubesat.org/ [cited 6 April 2014].

•[2]AIAA/USU Conference on Small Satellites, URL: http://digitalcommons.usu.edu/smallsat/ [cited 6 April 2014].

•[3]Staehle, R. L., et al., "Interplanetary CubeSats: Opening the Solar System to a Broad Band Community at Lower Cost," *Journal of Small Satellites* [online journal], Vol. 2, No. 1, URL: http://www.jossonline.com/Papers.aspx?id=ftu84kjc [cited 6 April 2014].

•[4]Conversano, R. W., and Wirz, R. E., "Mission Capability Assessment of CubeSats Using a Miniature Ion Thruster," *Journal of Spacecraft and Rockets*, AIAA Journal, Vol. 50, No. 5, 2013, pp. 1035-1046.

•[5]"Target NEO: Open Global Community NEO Workshop Report," *Proceedings of the Open Global Community NEO Workshop*, edited by B. Barbee, George Washington University, Washington D. C., 2011.

•[6]McFadden, L. A., Binzel, R. P.; Near Earth Objects, Chapter 14, Encyclopedia of the Solar System, Academic Press, New York, 2007, pp 283-300.

•[7]Rivkin, A. S.; "An Introduction to Near-Earth Objects," *Johns Hopkins APL Technical Digest*, 27(2), 2006, pp 111-120.

•[8]"Near Earth Object Program," *National Aeronautics and Space Administration* [online database], URL: http://neo.jpl.nasa.gov/ [cited 6 April 2014].

•[9]"NEO Earth Close Approaches," *National Aeronautics and Space Administration* [online database], URL: http://neo.jpl.nasa.gov/ca/ [cited 6 April 2014].

•[10]"Near-Earth Object Human Space Flight Accessible Targets Study," *National Aeronautics and Space Administration* [online database], URL: http://neo.jpl.nasa.gov/nhats/ [cited 6 April 2014]

•[11]Landau, D., Strange, N., "Near Earth Asteroids Accessible to Human Exploration with High Power Electric Propulsion", *Proceedings of the AAS/AIAA Astrodynamics Specialist Conference*, paper AAS 11-146, July 31-August 4, 2011, Girdwood, Alaska.

•[12]Lee S., Hutputanasin A., Toorian A., and Wenschel Lan W., "CubeSat Design Specification." California Polytechnic State University, San Luis Obispo, CA

•[13]Karmer, H. J., "CubeSat Concept," *eoPortal Directory* [online encyclopedia], URL: https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cubesat-concept [cited 8 April 2014].

•[14]"Hayabusa," *Encyclopedia Astronautica* [online encyclopedia], URL: http://www.astronautix.com/craft/hayabusa.htm [cited 6 April 2014].

•[15]Olds, J. R., Charania, A.C., and Koenig, J., "Foresight: Designing a Radio Transponder Mission to Near Earth Asteroid Apophis," *IAA Planetary Defense Conference*, 28 April 2009, URL: http://www.sei.aero/eng/papers/uploads/archive/IAA PD2009 1544473.pdf [cited 4 April 2014]

•[16]Systems Tool Kit. Software Package, Vers. 10.1. Analytical Graphics, Inc., Exton, PA, 2013.

•[17]"NEAR Mission Profile," *National Space Science Data Center* [online database], URL: http://nssdc.gsfc.nasa.gov/planetary/mission/near/near_traj.html [cited 6 April 2014].

•[18]Kahn, E.G., Barnouin, O.S., et al, "Improved Estimation of the Hayabusa SpaceCraft Trajectory and Lidar Tracks," 2012, 1648-1649, URL: http://www.lpi.usra.edu/meetings/lpsc2012/pdf/1648.pdf [cited 18 March 2014].

•[19]Kuninaka, H., Nishiyama, K., et. al., "Hayabusa Asteroid Explorer Powered by Ion Engines on the way to Earth," *Proceedings of the 31st International Electric Propulsion Conference*, Michigan, USA. 2009.

•[20]Sutton, G., and Biblarz, O., *Rocket Propulsion Elements*, 8th ed., John Wiley & Sons, Inc., Hoboken, NJ, 2010.

•[21]Szabo, J., et al. "Performance Evaluation of an Iodine-Vapor Hall Thruster," *Journal of Propulsion and Power* Vol 28.4, 2012, pp. 848-857.

•[22]Kieckhafer, A., and King, L.B., "Energetics of Propellant Options for High-Power Hall Thrusters," *Proceedings of the Space Nuclear Conference*, San Diego, CA, 2005.

•[23]"Hall Effect Thrusters," *Busek Space Propulsion and Systems*, [manufacturer website], URL: http://www.busek.com/technologies__hall.htm [cited 8 April 2014].

•[24]"Hall Effect Thrusters," *Alta* [manufacturer website], URL: http://www.alta-space.com/index.php?page=electric-propulsion [cited 8 April 2014].

•[25]"Low Mass Low Power Hall Thruster System," *Small Business Innovation Research* [online database], URL: https://www.sbir.gov/sbirsearch/detail/369381 [cited 8 April 2014].

•[26]Lobbia, R.B., and Gallimore, A.D., "Performance Measurements from a Cluster of Four Hall Thrusters," *Proceedings of the 30th International Electric Propulsion Conference*, Florence, Italy, 2007.

•[27]Bui, D.M., "Plume Characterization of Busek 600W Hall Thruster," Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 2012.

•[28]Oslyak, S., et al. "Characterization of an Adjustable Magnetic Field, Low-Power Hall Effect Thruster", *Proceedings of the 32nd International Electric Propulsion Conference*, Wiesbaden, Germany, 2011

•

References (cont.)

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- [29]"COBRA Gimbal," *Tethers Unlimited* [online datasheet], URL: http://www.tethers.com/SpecSheets/Brochure_Gimbal.pdf [cited 8 April 2014].
- [30]Dankanich, John W., Hani Kamhawi, James Szabo and Bruce Pote, "Iodine Electric Propulsion for Interplanetary Small Satellite Applications," *2013 Interplanetary Small Satellite Conference* [online database], URL: http://www.intersmallsatconference.org/2013/docs2013/C.2.2_Dankanich_Presentation.pdf [cited April 6 2014].
- [31]"Kapton Heaters," *TEMPCO Electric Heater Corporation* [online datasheet], URL: http://www.tempco.com/Catalog/Section%209-pdf/Foil%20Heaters.pdfEMPCO Flexible Heaters [cited 8 April 2014].
- [32]Hillier, A. C., "Revolutionizing Space Propulsion through the Characterization of Iodine as fuel for Hall Effect Thrusters," Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 2011.
- [33]Szabo, J., Mike R., Surjeet P., Bruce P., Vlad H., Chas F.. "Iodine Propellant Space Propulsion," *Proceedings of International Electric Propulsion Conference*, Washington D.C., October 2013.
- [34]Nakles, M. R., Brieda L., Hargus Jr., W. A., Spicer R. L., "Experimental and Numerical Examination of the BHT-200 Hall Thruster Plume," *43rd AIAA/ASME/SAE/ Joint Propulsion Conference & Exhibit* [online database], URL: http://arc.aiaa.org/doi/abs/10.2514/6.2007-5305 [cited April 6 2014].
- [35]"BCT XACT," *Blue Canyon Technologies* [online datasheet], URL: http://bluecanyontech.com/wp-content/uploads/2012/07/BCT-XACT-datasheet-1.5.pdf [cited April 6 2014].
- [36]"Cold Gas Microthruster," *Marotta* [manufacturer website], URL: http://www.marotta.com/fluid-control-building-blocks/cold-gas-microthruster.html [cited 8 April 2014].
- [37]Mueller, J., Hofer, R., and Ziemer, J., "Survey of Propulsion Technologies Applicable to Cubesats," *NASA JPL* [online database], URL: http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/41627/1/10-1646.pdf [cited 9 April 2014].
- [38]Maini, Anil Kumar., and Varsha Agrawal. *Satellite Technology: Principles and Applications*. Chichester: John Wiley, 2007. Print.
- [39]"Space Solar Panels," Spectrolab [online datasheet], URL: http://www.spectrolab.com/DataSheets/Panel/panels.pdf [cited 8 April 2014].
- [40]"Nano Power BP4 Series," *GomSpace* [online datasheet], URL: http://gomspace.com/documents/GS-DS-BP4-series-1.6.pdf [cited April 6 2006].
- [41]"CubeSat Power Distribution Module," *Clyde Space* [online datasheet], URL: http://www.clyde-space.com/cubesat_shop/power_distribution_and_protection/95_cubesat-power-distribution-module
- [42]Kaminski, D. and Jensen M. K., *Introduction to Thermal and Fluids Engineering*. Hoboken, NJ: Wiley, 2005. Print.
- [43]Taylor, J., Fernandez, M. M., Alamanac, A., B., Cheung, K., M.,; "Deep Space 1 Telecommunications," NASA, JPL, California Institute of Technology, Pasadena, California, 2001
- [44]DeCoste, D., Finley, S. G., Hotz, H. B., Lanyi, G. E., Schlutsmeyer, A. P., Sherwood, R. L., Sue, M. K., Szijjarto, J., Wyatt, E. J.; "Beacon Monitor Operations Experiment DS-1 Technology Validation Report," Jet Propulsino Laboratory, California Institute of Technology, Pasadena California, 91109,
- [45]http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=9&category_id=5&option=com_virtuemart&Itemid=67
- [46]http://www.isispace.nl/cms/index.php/products-and-services/products
- [47]Doody, D.; Deep Space Craft Chapter 1, Telepresence, Springer, Berlin, Heidelberg, New York, 2009, ISBN 978-3-540-89509-1
- [48] http://deepspace.jpl.nasa.gov/
- [49] http://www.syrlinks.com/en/products/cubesats/hdr-x-band-transmitter.html
- [50] http://www.rfmd.com/CS/Documents/RFHA5966ADS.pdf
- [51]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.
- [52] http://www2.jpl.nasa.gov/basics/bsf10-1.php
- [53]"NanoMind A712C Datasheet," *GomSpace* [online datasheet], URL: http://gomspace.com/documents/GS-DS-NM712C-1.1.pdf [cited April 6 2014].
- [54] http://www2.jpl.nasa.gov/basics/bsf13-1.php
- [55]"MLR-2K Laser Rangefinder," FLIR Electro-Optical Components, [online datasheet], 2013, Issue 1, Rev. 1, URL: http://www.flir.com/uploadedFiles/CVS_Americas/Cores_and_Components_NEW/Products/Components/Laser_Products/FLIR-MLR2K-Datasheet.pdf [cited 9 April 2014].
- [56]"NanoCam C1U Datasheet," GomSpace, [online datasheet], 2011, Issue 6, Rev. 1, URL: http://gomspace.com/documents/GS-DS-NANOCAM-6.1.pdfs. [cited 9 April 2014].

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References (Cont.)

•[57]"Tau SWIR 25 Miniature High-Performance Shortwave Infrared Camera," FLIR Electro-Optical Components, [online datasheet], 2013, URL: http://cvs.flir.com/tau-swir-25-datasheet. [cited 9 April 2014].

•[58]"Longwave Infrared Thermal Core Camera," FLIR Electro-Optical Components, [online datasheet], 2013, URL: http://cvs.flir.com/quark-brochure [cited 9 April 2014]

•[59]Galeev, A. A., and Zakharov, A. V., "Mars 96 Penetrator," *NASA-NSSDC* [online database], URL: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=MARS96E [cited 8 April 2014].

•[60]Webb, P., "Miniature Radar Altimeter," Roke Manor Research Limited, Hampshire, UK, [online datasheet], 2013, URL: http://www.roke.co.uk/resources/datasheets/mra-type-2.pdf [cited 9 April 2014].

•[61]"Argus 1000 Infrared Spectrometer," *CubeSatShop.com* [distributor website], URL: http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=91&category_id=16&option=com_virtuemart&Itemid=80 [cited 8 April 2014].

•[62]Mitrofanov, I., "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].

•[63]"Mars Pathfinder Science Results," *NASA-JPL Mineralogy and Geochemistry* [online database], URL: http://mars.jpl.nasa.gov/MPF/science/mineralogy.html [cited 8 April 2014].

•[64]Soderblom, L., et al., "Miniature Integrated Camera Spectrometer (MICAS)," *Technology Validation Symposium*, Pasadena, CA, February 2000.

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

•[66]Bearden, D. A., "Small-Satellite Costs," Crosslink, pp 33-44, Winter 200/2001, Aerospace Corporation, El Segundo California.

•[67]Tafazoli, M.; "A study of on-orbit spacecraft failures," Acta Astronautica, 64, (2009) 195-205

•[68]Maurer, R. H., Fraeman, M. E., Martin, M. N., Roth, D. R.; "Harsh Environments: Space Radiation Environments, Effects, and Mitigation," Johns Hopkins, APL Technical Digest, Vol. 28, No. 1 (2008)

•[70]Koontz, S. L., Reddell, B., Boeder, P.; "Calculating Spacecraft Single Event Environments with FLUKA," Proceedings of the 2011 IEEE Radiation Effects Data Workshop, pp 188-195, July 25-29, 2011, Las Vegas, Nevada

•[71]Koontz, S., Atwell, W., Reddell, B., Rojdev, K.; "Spacecraft Solar particle Event shielding," NASA/TP-2010-216-33, Sept, 2010.

•[72]Jackman, Charles. "The Influence of Large Solar Proton Events on the Atmosphere," 2012 SORCE Science Meeting [online database], URL: http://lasp.colorado.edu/sorce/news/2012ScienceMeeting/docs/presentations/S2-04_Jackman_SORCE_SPEs_shown_NEW.pdf [cited on 6 April 2014].

•[73]Masti, D., Gandomkar, S., and Zeynali O., "Shielding protection of electronic circuits against against radiation effects of space high energy particles," *Advances in Applied Science Research*, Vol. 3 ,Issue 1, 2012, p446.

•[74]Sigmund, P., *Particle Penetration and Radiation Effects.* Berlin: Springer, 200

[71]Woeppel, E. A., Balsamo J. M., Fischer, K. J..; "The Near Earth Object (NEO) Scout Spacecraft: A Low-Cost Approach to In-situ Characterization of the NEO Population," 2014 AIAA SpaceOps, May 5-9, 2014, Pasadena, California

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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 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

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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

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Thermal

Thermal Control

- Multi-layer insulation utilized for passive thermal protection throughout flight envelope
    - Operational environment: 0 to 50 ºC, 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

Location	T, K	$q''_{Sun}, \frac{W}{m^2K^4}$	$q''_{Earth}, \frac{W}{m^2K^4}$	$q''_{Albedo}, \frac{W}{m^2K^4}$	$\sigma, \frac{W}{m^2K^4}$	α/ϵ
GEO	273 - 333	1376.5	230	408	5.67E-8	0.156-0.346
0.7 AU	273 - 333	2809.2	0	0	5.67E-8	0.112 - 0.246
1 AU	273 - 333	1376.5	0	0	5.67E-8	0.229 - 0.507
1.3 AU	273 - 333	814.5	0	0	5.67E-8	0.387 - 0.856

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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