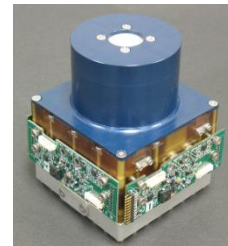
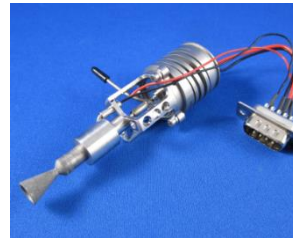
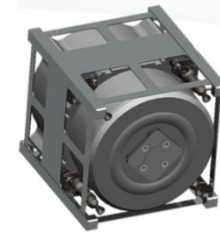
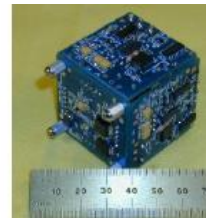
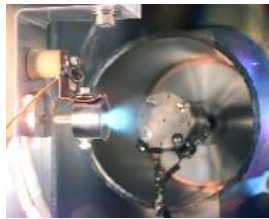
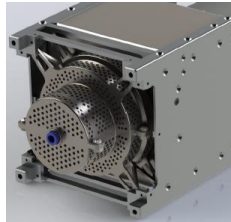


Small Satellite Propulsion



AstroRecon 2015

January 8-10, 2015

Arizona State University, Tempe, Arizona

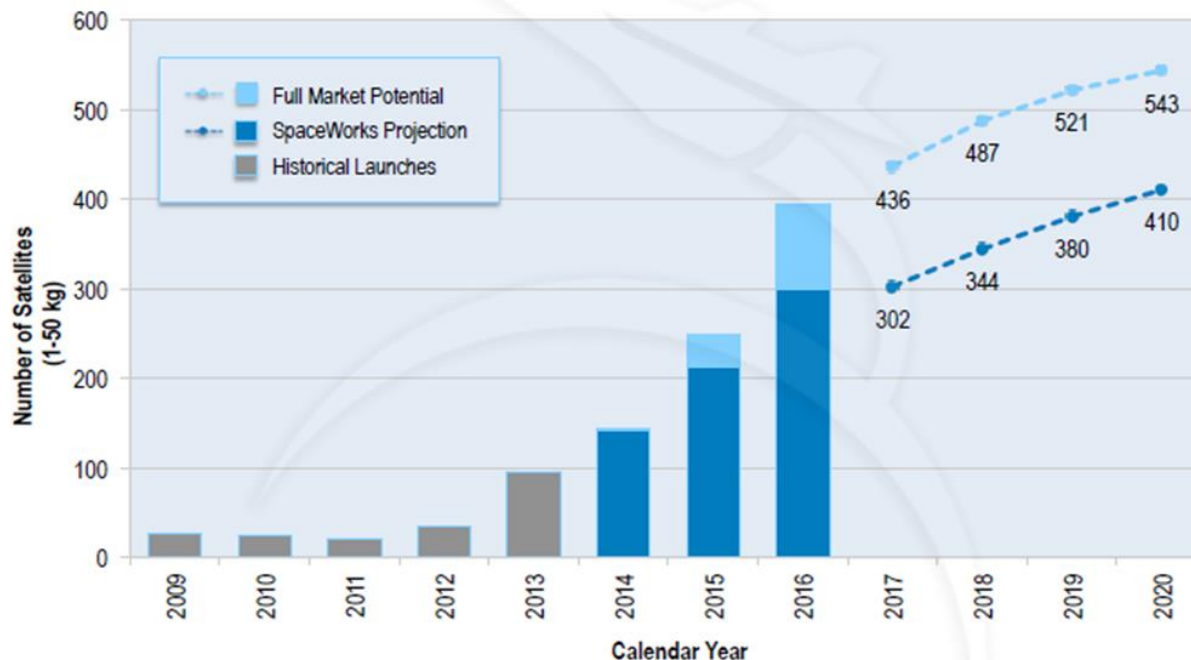
Information presented for discussion purposes only.



The SmallSat Market

Nano/Microsatellite Launch History and Projection (1 - 50 kg)

Projections based on announced and future plans of developers and programs indicate between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020



The Full Market Potential dataset is a combination of publically announced launch intentions, market research, and qualitative/quantitative assessments to account for future activities and programs. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

* Please see End Notes 1, 2, 4, 5, and 6.



Low Cost Mission Benefits to NASA

Strategic (i.e. High Cost) Missions: The cost of access to space limits the mission portfolio significantly

- Cadence between missions is very long
- NASA learns from one mission, increases desire for another
- NASA considering constellations in geocentric space
- **NASA considering diverse asteroid reconnaissance missions**

Low Cost Missions:

- Wide breadth of investments in new technology
- Investments in SmallSat subsystems
 - \$1M investment may lead to 10 subsystems ready for flight validation
 - Subsystems are ~1kg each

What if the program can only get one launch per year? Or only afford 1 launch entirely?

- Frequent low cost launches allow for iteration
 - Doesn't need to be perfect the first time, reduced cost development
- Opportunities to iterate and improve technologies

Access to space severely limits strategic missions and technology innovation in flight systems.



The Value Proposition

For Discovery Class Mission: \$25M for science, \$250M for launch → \$475M for S/C and operations

Science value: Only 1 / 25 dollars spent on science.

Can only afford one launch per 3-4 years, it has to work.

High leverage of in-space propulsion

How do you scout 20 asteroids? \$15B?

Need lower cost spacecraft and launch

NASA is making significant investments for in-space propulsion for SmallSats

- Launch with loose requirements and transfer to desired orbit

Case Study: Science instrument/payload	Class A	Class D	
Success Probability	99.5%	80%	x4 = 99.8%
Cost	\$8M	\$800k	\$3.2M
What if launch = \$10M?	\$18M, it will work	\$10.8M, 1/5 fail	
		x2 = \$21.6M, 1/25 fail	

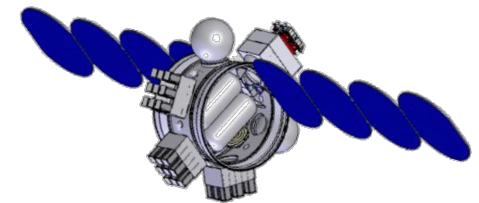
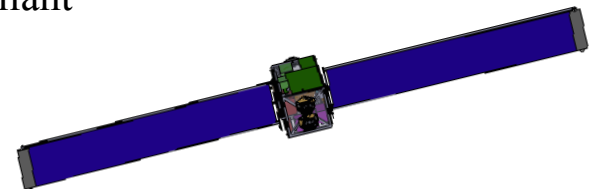
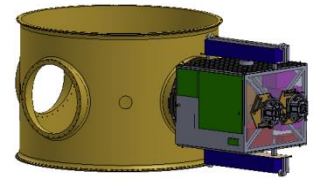
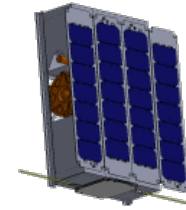
**The value of a launch causes large increase in payload costs.
Diverse targets exacerbates the issue.**

All estimates are hypothetical only for discussion purposes.



Propulsive SmallSat Solutions

- 20-200W Propulsion Options Available in the near-term (e.g. Iodine Hall, MEP, solar sails)
 - 3U, 6U and 12U Spacecraft starting with escape orbits
 - Limited payload capability
- 200-600W ESPA Class Options (e.g. Iodine Hall, Long Life Hall)
 - Can provide $\sim 10\text{km/s } \Delta V$
 - Enables GTO to Asteroids, Comets, Moon and Mars
- 600W ESPA Grande “Discovery Class” ($\sim 300\text{kg}$) Options (e.g. Iodine Hall, Long Life Hall)
 - Volume limitations require high density propellant
 - New class of HEOMD and SMD missions
 - 3x – 5x reduction in total mission cost
- 600W – 1500W Class Orbit Maneuvering Systems
 - Enables high ΔV using volume within the ESPA Ring
 - Delivery diverse payloads to various orbits



Small spacecraft with advanced in-space propulsion may offer a potential solution for high value missions to a diverse target set.

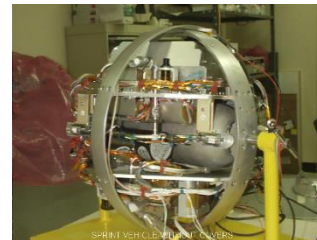


State of the Art: Cold Gas – GN₂

Technical Attributes

- Thrust range: 10mN – 100N
- 1U Prop Module deltaV ~ 50fps (15 m/s)
- 2U Prop Module deltaV ~ 78fps (24 m/s)

Propellant	Isp	Relative Impulse Density	Storage Pressure
Nitrogen	~70 s	1.0	~300 psia



State of Technology

- TRL 9
- Missions flown: many, e.g. SAFER, XSS10,
- Potential Providers: Large number; e.g. Moog, Valvetech, Surrey
- Current or past known investments: Previous NASA investments, no ongoing NASA CubeSat investments

Pros / Cons

- Pros: Inert, non-toxic, relatively cheap, simple, reliable
- Cons: low impulse density

* Relative Impulse density $(\text{Rho} \cdot \text{Isp}) / (\text{Rho} \cdot \text{Isp})_{\text{GN}_2}$



State of the Art: Cold Gas

Technical Attributes

- Thrust range: 10mN – 1N
- 1U Prop Module deltaV ~ 88fps (27 m/s)
- 2U Prop Module deltaV ~ 136fps (42 m/s)

Propellant	Isp	Relative Impulse Density	Storage Pressure
Multiple	~70 s	1.77	Up to 900 psia



State of Technology

- TRL 7
- Missions flown: None yet
- Manufacturers: Vacco, Surrey
- Current or past known investments:
Previous NASA investments, no ongoing NASA CubeSat investments

Pros / Cons

- Pros: generally Inert, non-toxic, relatively cheap, simple, reliable
- Cons: low impulse density; requires heat, “long” burns may be limited, some propellant options are flammable



State of the Art: Pulsed Plasma Thrusters

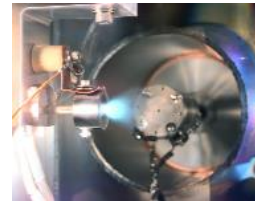
Technical Attributes

- Thrust class: <1.3 mN
- Power requirements: 1.5-100W

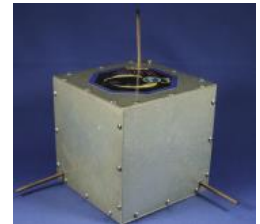
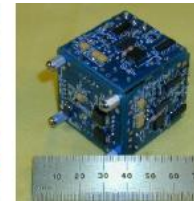
Propellant	Isp	Specific Power (W/mN)	Storage Pressure
Teflon® and Metals	~500-3000-sec	~70-400	N/A - Solid

State of Technology

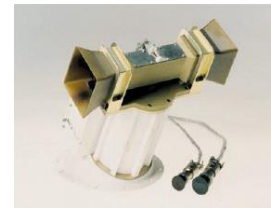
- Technology Readiness: Number of well proven flight systems exist. Advanced technology metal based have been explored are low TRL
- Compact solid state system that uses solid Teflon® as the propellant.
- Potential Providers: Aerojet-Rocketdyne, Busek, George Washington University
- Current or past known investments: NASA, Commercial development



JPL/Alameda Vacuum Arc Thruster



Busek micro PPT



Aerojet PRS-101



GWU μCAT with PPU

Pros/Cons

- Pro: Technology has flown
- Pro: Robust, simple modular design
- Pro: Low power requirement
- Pro: Volumetrically efficient
- Pro: Enables precision control
- Con: Limited total life operation
- Con: Very low thrust
- Con: Pulsed operation may impact spacecraft /science



Near-term: Green Liquid Propulsion

Thrust range:

- Typical CubeSat concepts show thrusters/multiple thruster systems ranging from 0.1 N to 5 N, other theory/demonstration ranging from <1 mN to levels >45 N

Propellant	Isp	Relative Impulse Density	Storage Pressure
Low temperature decomposition (e.g.: hydrogen peroxide, tridyne, nitrous oxide)	130 to 200 s	Gasses: ~1.8 Liquids: ~5 to 9	Gasses: up to 5000 psi Liquids: 100 to 400 psia
Hydrazine	150 to < 250 s	~8	100 to 400 psia
Nitrous Oxide Fuel Blends	< 300 s	~8.8	100 to 400 psia
Water (electrolyzed to bipropellant)	300 to 350 s	~14	Inert as launched
Ionic Liquids (e.g.: AF-M315E, LMP-103S)	220 s to 250 s	~12 to 15	100 to 400 psia



State of Technology

- TRL:
 - Many propellants flown or soon to fly in non-CubeSat applications
 - Multiple thrusters of this scale demonstrated to TRL 6 or flown
 - Only one known CubeSat system at TRL 6, likely 3 or more within a year
- Systems are at laboratory testing stages
- Potential Manufacturers: Busek, Tethers Unlimited, Aerojet Rocketdyne, Vacco, Micro Aerospace Systems, Firestar, ECAPS, some NASA in-house, academia
- Current or past known investments: Currently two ongoing CubeSat propulsion awards (Aerojet – Hydrazine, Busek – AF-M315E Ionic Liquid), some past SBIR contracts for components (valves, thrusters), NASA

* Relative Impulse density ($\text{Rho} \cdot \text{Isp}$) / ($\text{Rho} \cdot \text{Isp}$)_{GN2}

Pros/Cons

- Pro: Certain propellants (ionic liquids) may not cold start; have been shown to require less safety inhibits minimizing system mass
- Pro: High thrust levels enable rapid response maneuvers
- Pro: Monopropellant systems have minimal complexity, may require minimal control logic/hardware
- Con: Most systems require increased power (compared to cold gas) for ignition/catalyst preheat
- Con: Stored chemical energy may be an issue with most designs (save electrolysis); require exemption
- Con: High temperature chemical systems may require additional hardware and mass for thermal regulation of the subsystem and/or whole CubeSat
- Con: Pressurized vessels traditionally required for chemical systems
 - Alternate pressurization mechanisms (like electrolysis of water or chemical for pressurization, solid gas generator, mechanical means, etc.) have been studied

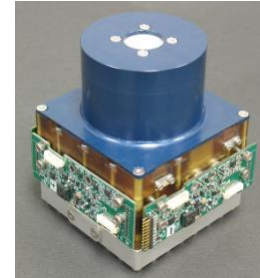


Near-term: Water Electrolyzed

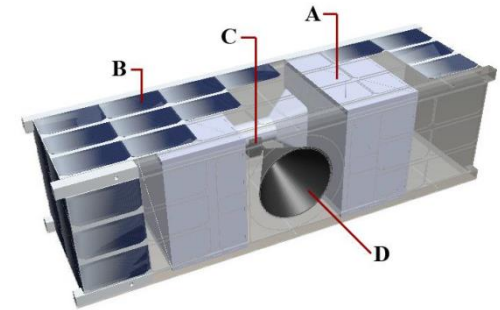
Thrust range:

- Typical CubeSat concepts show thrusters/multiple thruster systems ranging from 0.1 N to 5 N, other theory/demonstration ranging from <1 mN to levels >45 N
- Architecture: Propellants are stored as water, then electrolyzed and stored as gaseous O₂ and H₂ for combustion.

Propellant	Isp	Impulse Density	Storage Pressure
Water (electrolyzed to bipropellant)	300 to 350 s	~14	Inert as launched



Tether Unlimited - Hydros



Cornell University Concept

State of Technology

- TRL:
 - CubeSat system at/approaching TRL 6
 - Loaded propellant is water; qualification not required
- Systems are at laboratory testing stages
- Potential Manufacturers: Tethers Unlimited, Cornell University
- Current or past known investments: Previous NASA SBIR

Pros/Cons

- Pro: Propellant stored as water during launch; safe
- Pro: Inexpensive propellants
- Pro: High thrust levels enable rapid response maneuvers
- Pro: Gaseous O₂/H₂ make for easily combusted propellants
- Con: Time to produce propellant may limit capability / responsiveness
- Con: Complexity of the system may mean increased dry mass
- Con: Command control needed to regulate system adds some complexity to system integration & operation
- Con: Requires increased power (compared to cold gas) for electrolysis and ignition
- Con: High temperature chemical systems may require additional hardware and mass for thermal regulation of the subsystem and/or whole CubeSat



Near-term: Hydrazine

Thrust range:

- Typical CubeSat concepts show thrusters/multiple thruster systems ranging from 0.5 N to 4 N
- Other theory/demonstration ranging from 0.02 to 10000 N

Propellant	Isp	Impulse Density	Storage Pressure
Hydrazine	150 to < 250 s	~8	100 to 400 psia



Aerojet-Rocketdyne modular propulsion system (MPS)

State of Technology

- TRL:
 - Hydrazine has significant flight heritage, including thrusters of this class
 - One development effort currently underway to bring system to TRL 6
- Currently at system level laboratory testing stages
- Potential Manufacturers: Aerojet-Rocketdyne
- Current or past known investments: Currently one ongoing CubeSat propulsion awards with Aerojet-Rocketdyne of Redmond, WA

Pros/Cons

- Pro: High thrust levels enable rapid response maneuvers
- Pro: Monopropellant systems have minimal complexity, may require minimal control logic/hardware
- Pro: Hydrazine can cold start at the cost of catalyst life if power is lacking
- Con: If hydrazine leaks through its valve, will cold start, requiring additional hardware for safety measures
- Con: May require thermal regulation for safety
- Con: Requires increased power (compared to cold gas) for catalyst preheat
- Con: Stored chemical energy may be an issue; require exemption
- Con: Pressurized vessels traditionally required for chemical systems
- Con: High temperature chemical systems may require additional hardware and mass for thermal regulation of the subsystem and/or whole CubeSat

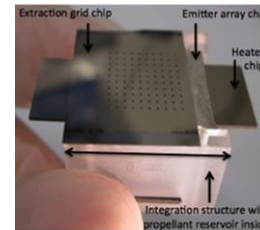


Near-term: Micro Electro Spray Propulsion

Thrust range:

- 10-100 μ N, scalable by adding thrusters

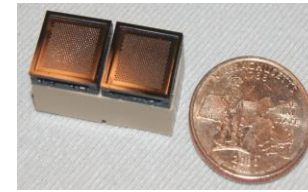
Propellant	Isp	Impulse Density	Storage Pressure
Ionic liquids, Indium	500 to < 5000 s	1000 - 6500	Unpressurized – Passive Feed System



JPL Indium MEP Thruster



Busek HARPS Thruster



MIT S-iEPS Thruster Pair

State of Technology

- TRL:
 - Several concepts at low TRL
 - Three concepts maturing to TRL 5 under NASA STMD
- Currently at integrated propulsion system level testing
- Ongoing NASA STMD Awards with JPL, Busek and MIT

Pros/Cons

- Pro: Relatively high system level efficiency
- Pro: High efficiency at CubeSat power levels
- Pro: Efficient system packaging
- Pro: High specific impulse density (ΔV / volume)
- Con: Lifetime challenges for interplanetary mission applications
- Con: System scalability challenges

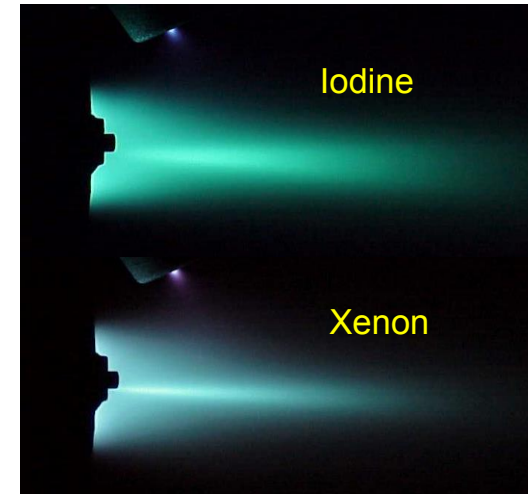
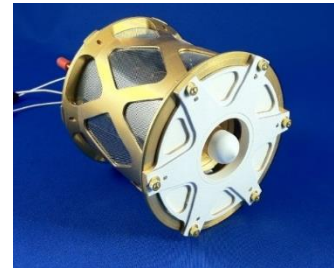


Near-term: Iodine Hall Propulsion

Thrust range:

- Near-term: 10 – 50mN
- Mid-term: <150mN (<1N achievable with thruster if funded)

Propellant	Isp	Impulse Density	Storage Pressure
Iodine	1000 to < 1750 s	5000	Unpressurized



State of Technology

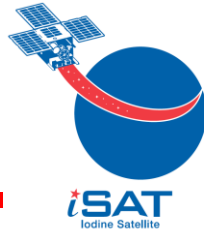
- TRL:
 - Several thrusters at TRL 5
 - 200W and 600W systems funded to TRL 6 by 2016
 - 200W System approved for flight demonstration in 2017

Pros/Cons

- Pro: High specific impulse density (ΔV / volume)
- Pro: Stored unpressurized
- Pro: Maximum operating pressures ~2psi
- Pro: Small modifications to flight heritage systems
- Con: Lifetime challenges for ESPA class spacecraft with 200W thruster
- Con: Low propellant tank maturity for ESPA class spacecraft



Iodine Propulsion - iSAT



The iSAT Project is the maturation of iodine Hall technology to enable high ΔV primary propulsion for NanoSats (1-10kg), MicroSats (10-100kg) and MiniSats (100-500kg) with the culmination of a technology flight demonstration.

- NASA Glenn is the propulsion system lead
- NASA MSFC is leading the flight system development and operations



The iSAT Project launches a small spacecraft into low-Earth orbit to:

- Validate system performance in space
- Demonstrate high ΔV primary propulsion for SmallSats
- Reduce risk for future higher class iodine missions
- Demonstrate new power system technology for SmallSats
- Demonstrate new class of thermal control for SmallSats
- Gain knowledge on iodine environment impact to payloads
 - Increase expectation of follow-on SMD and AF missions
- Demonstrate SmallSat Deorbit
- **Validate iodine spacecraft interactions / efficacy**
- **Planned for launch in early 2017**

High Value mission for SmallSats and for future higher-class missions leveraging iodine propulsion.

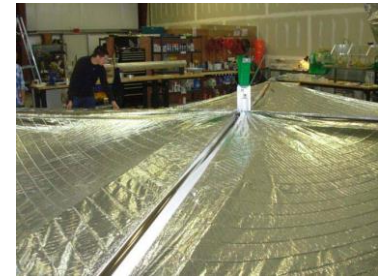
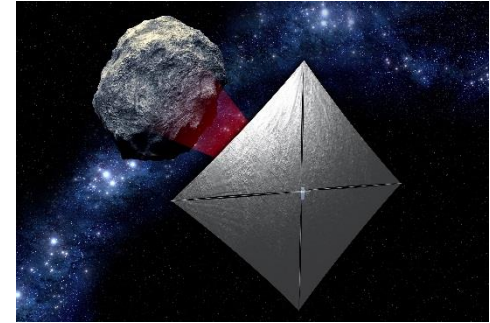


Near-term: Solar Sail Propulsion

Technical Attributes

- 1U Prop Module (35 m² sail)
 - $\Delta V \sim 1.3$ km/s/yr
 - Thrust ~ 0.25 milli-Newtons
- 2U Prop Module (85 m² sail)
 - $\Delta V \sim 1.6$ km/s/yr
 - Thrust ~ 0.60 milli-Newtons

Sail Type	Size	Characteristic Acceleration	Materials
3-axis stabilized	85 m ²	0.0565 mm/sec ²	Stainless Steel Boom Aluminized CP1 fabric



State of Technology

- TRL-6 (85 m²) / TRL-7 (10 – 35 m²)
- Missions flown: NanoSail-D (2010)
- Manufacturers: 1) NASA MSFC 2) Stellar Exploration
- Current or past known investments: NASA AES (NEA Scout & Lunar Flashlight) / Commercial (LightSail-A and -B)

Pros / Cons

- Pros: very high total ΔV , lightweight, small stowed volume
- Cons: currently restricted to inner solar system, complex ADCS



Solar Sail Propulsion – NEA Scout

The Near Earth Asteroid Scout Will

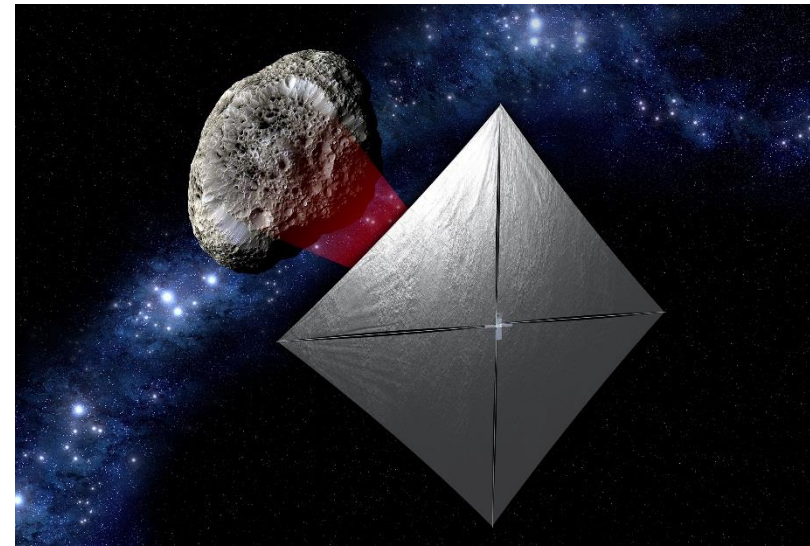
- Image/characterize a NEA during a slow flyby in order to address key Strategic Knowledge Gaps (SKGs) for HEO
- Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~85 m² solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

Solar Sail Propulsion System Characteristics

- ~ 7.3 m Trac booms
- 2.5μ aluminized CP-1 substrate
- > 90% reflectivity





Mid-Term: Ambipolar Thruster

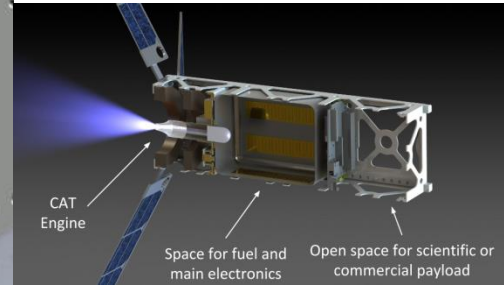
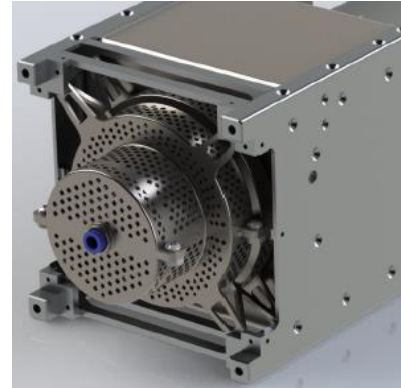
Technical Attributes

- Thrust class: 2-25 mN
- Power requirements: 3-300W
- No direct performance measurements yet

Propellant	Isp	Specific Power (W/mN)	Storage Pressure
Multiple	~1200-sec	Unknown	Unknown

State of Technology

- Technology Readiness: TRL 2 – university laboratory testing to date
- Multiple propellant options: Xenon, Krypton, Iodine
- Potential Provider: Aether Industries
- Current or past known investments: NASA contracts, DARPA



CubeSat Ambipolar Thruster (CAT) – Aether Industries / University of Michigan

Pro/Con

- Pro: Potential for high ΔV in small package
- Pro: Simple / scalable manufacturing
- Pro: Volumetrically efficient
- Con: Limited total life operation
- Con: Performance levels have not been verified
- Con: Low efficiency



Mid-Term: Long Life Hall and Mini-Ion

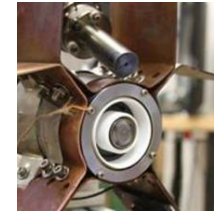
Technical Attributes

- Thrust range: 0.1-10 mN
- System power 25-200W
- System efficiency 5%-35%

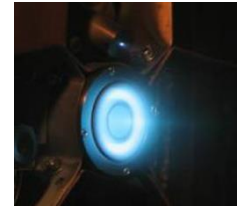
Propellant	Isp	Specific Power (W/mN)	Storage Pressure
Xenon and Iodine	~500-5000-sec	50-300	Xe: 1000 psia I: Solid



Busek BRFIT-3
3 cm RF Ion Thruster



UCLA MaSMi
Hall thruster



State of Technology

- TRL~4: Breadboard demonstrations - Available in 2-5 years
- Miniature in laboratory only, flight thrusters >200W
- Research by Busek, UCLA, JPL, GRC, AFRL
- Current or past known investments: SmallSat technology award: Busek Iodine Ion Thruster, SBIR

Pro/Con

- Pro: Potential $\Delta V > 1000$ m/s
- Pro: Iodine a high density propellant
- Pro: Demonstrated efficiency
- Best propulsion systems for 50kg-200kg S/C
- Con: Power & size very high for CubeSats
- Con: Small (e.g. 1cm) thruster efficiency very poor (~5%)
- Con: Iodine system low TRL & S/C interactions
- Con: Scaling to cubesat size hurts efficiency
- Con: Life requirements very demanding



Summary

- Small Low-cost / High Value missions are the only viable path to a high cadence or diverse reconnaissance campaign for asteroids and comets
 - One of the critical gaps for low cost reconnaissance is SmallSat propulsion system limitations
 - Maturity
 - Specific Impulse Density
 - Moderate Lifetimes
- There are a large number of Small Satellite propulsion concepts receiving investment
- NASA's Small Spacecraft Technology Program is completing a Propulsion State of the Art Assessment
 - Should be publicly available early 2015
- Existing systems are very limited in capability
- Existing propulsive RCS options are far more limited with insufficient total impulse capability
- Near-term options are available for primary propulsion
 - Solar Sails
 - Iodine Hall
 - MEP
- Mid-term options with additional potential
 - Monopropellant Liquids
 - Small Ion
 - Long Life Low Power Hall



Acknowledgement

Much of the information presented is based on the work and data gathered by several members of the propulsion community including: Matt Deans, Dave Jacobson, and Tim Smith from NASA GRC, Ira Katz from JPL, Chuck Pierce from NASA MSFC, Bill Studak from NASA JSC and Jeff Logan from NASA ARC. Several studies for SmallSat propulsion have been sponsored by Chuck Taylor and Andy Petro of STMD. Also, several studies have been completed by the NASA GRC COMPASS team led by Steve Oleson.