LunarCube: A Deep Space 6U CubeSat with Mission Enabling Ion Propulsion Technology

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Michael Tsay, Ph.D
Chief Scientist, Electrothermal Propulsion Group

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Space Propulsion and Systems

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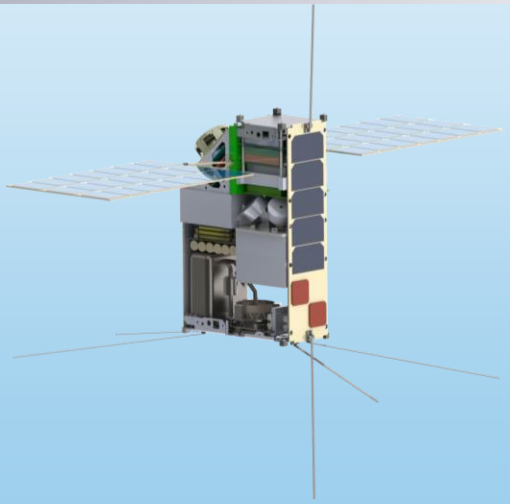
Introduction

- LunarCube is a 6U deep-space CubeSat platform with ion propulsion currently under development.
  - Innovative iodine-fueled micro ion propulsion by Busek (3cm RF ion thruster “BIT-3”); 3.2km/s delta-V for 12kg s/c.
  - Spacecraft bus supplied by partner Morehead State University, with customized EPS, C&DH, ADCS and comms.
  - MSU supports tracking and comm via 21m-dish ground station, won’t tie up DSN resource.
  - A “COTS” vehicle for payload developers (~1.5U space); no need to worry about getting there or transmitting telemetry.
- Enables a multitude of mission profiles.
  - Lunar, NEO, inner planet, low-flying Earth Observation.
- Has been selected as part of the 2018 SLS EM-1 CubeSat mission under the “Lunar IceCube” name (NASA NextSTEP).
  - IR spectrometer science payload and trajectory support will be provided by NASA Goddard Space Flight Center.
  - EM-1 already has 6 out of 11 CubeSat slots filled: Lunar Flashlight (JPL), NEA Scout (Marshall), BioSentinel (Ames), Lunar IceCube (Morehead/Busek/Goddard), SkyFire (Lockheed), and CuSPP+ (SwRI).



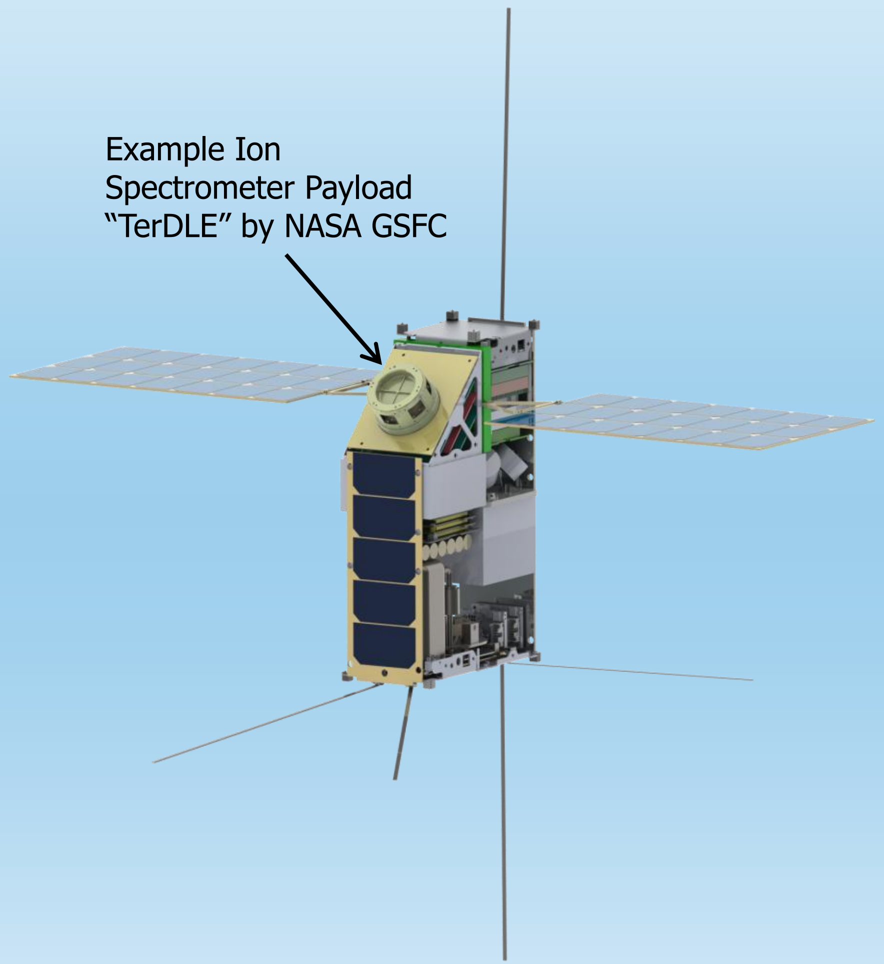
Preliminary Design of LunarCube with Example Science Payload

The Upcoming “Lunar IceCube” Mission is Based on the 6U LunarCube Platform

Preliminary Design of 6U LunarCube

- Initial design completed with standard 6U volume envelope (10×20×30cm); 1.3U/1.2kg payload.
- Propulsion system will receive 65W max at PPU input (sans iodine heater power), producing 1.1mN thrust, 2500sec total Isp and max 3.2km/s delta-V.

LunarCube 6U S/C Baseline Design Spec	
Parameter	**Value**
Launch mass:	12.0 kg
Bus Mass (w/o Payload or Propulsion)	7.6 kg
Propulsion Dry Mass	1.7 kg
Propellant Mass (Iodine)	1.5 kg
Payload Mass Capability	1.2 kg
Payload Volume	1.3 U
Pointing Accuracy	±.002°
Orbit Knowledge	10m, 0.15m/s
Maneuver Rate	10°/s
Payload Power Capability	5W (peak), 3.8 W
Prime Power Generated	84W nominal
Voltages Available	12V, 5V, 3.3V
Propulsion Max Delta-V Capability	3.2 km/s
Propulsion Total Impulse	37,000 N-sec
Downlink Data Rate	12 kbps
Spacecraft Op Lifetime	>2 years

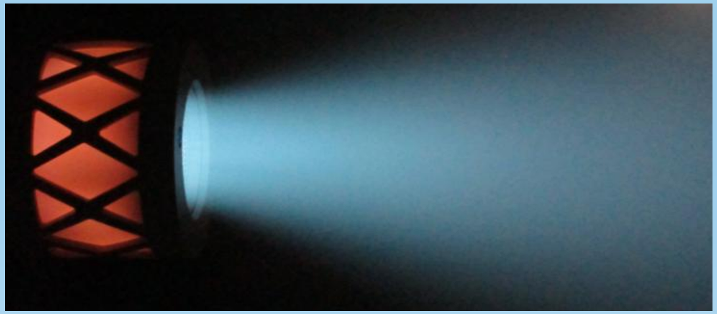


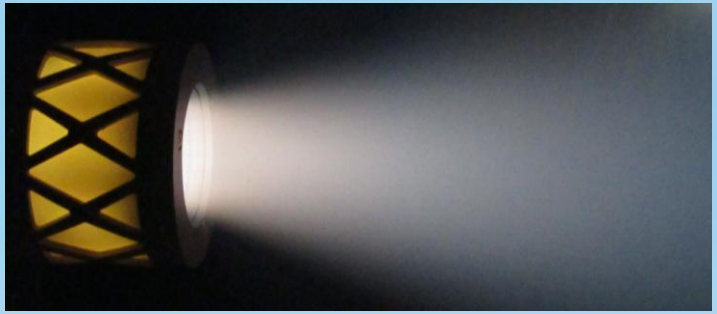
Note: design and spec are being matured under the Lunar IceCube flight program and therefore subject to change

LunarCube Propulsion: Iodine BIT-3 RF Ion Thruster

- BIT-3 thruster was designed for nominal 60W operation & targets 6U CubeSat as initial platform. Nominal 1.4mN thrust at 3500sec Isp. With lab cathode total Isp ~3050sec.
- At 60W the thrust efficiency is 42% on Xe (thruster only); ~30% if counting PPU & neutralizer.
- Successfully demonstrated BIT-3 on both Xe and I_2; verified that I_2 can be a drop-in replacement for Xe based on thrust-to-power ratio (22.5mN/kW for I_2 vs. 24mN/kW for Xe).
- I_2 flow is controlled by varying reservoir temperature and measured in real-time by injector pressure reading, based on choked flow condition. Feed line kept higher temp than reservoir.

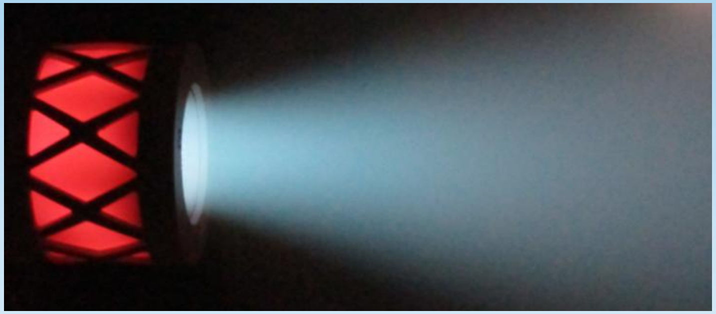
Xe 60W

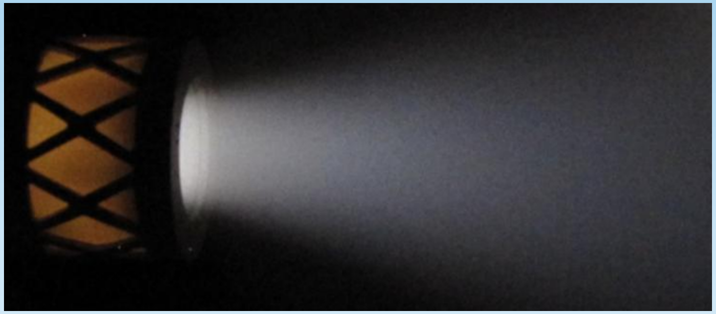




I_2 60W

Xe 30W

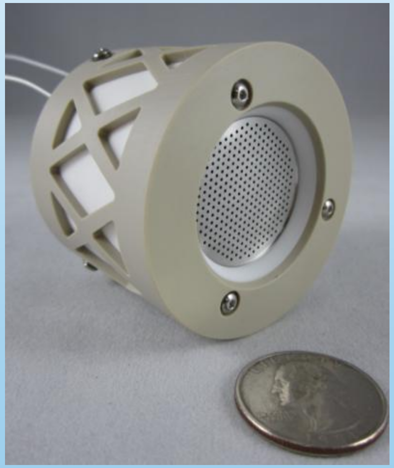


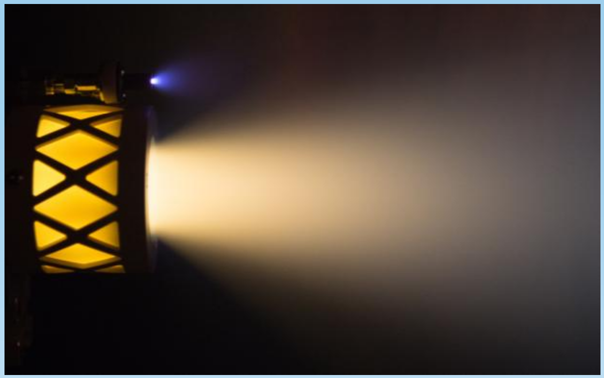


I_2 30W

LunarCube Propulsion: Why Use Iodine

- Iodine is stored as a solid at room temperature.
  - This allows for lightweight and highly configurable tanks (not constrained to high pressure tanks shapes).
  - No need for launch waivers as there is min. stored energy & no pressure vessel (important for secondary payloads).
  - Simple to operate: sublimes with minimal heat input to form iodine vapor which is then fed to the EP device.
- Busek has shown with HETs that iodine provides almost identical performance as with xenon (legacy EP fuel) – very much a drop-in replacement.
- Iodine costs only 1/5 compared to xenon at today's rate – could be even less in quantity or at lower purity.
- Iodine's low vapor pressure suggests that plume condensation should not be a concern on s/c.
- Traditional high-Isp, gridded ion thrusters difficult to run on iodine due to chamber material incompatibility. Busek's induction-type RF ion thrusters don't have such issue so it can take advantage of iodine's benefits while providing very high Isp (important for DS missions).

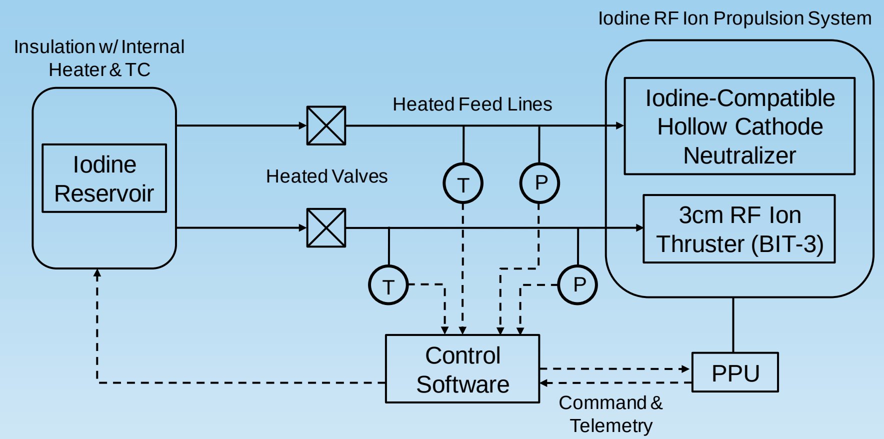




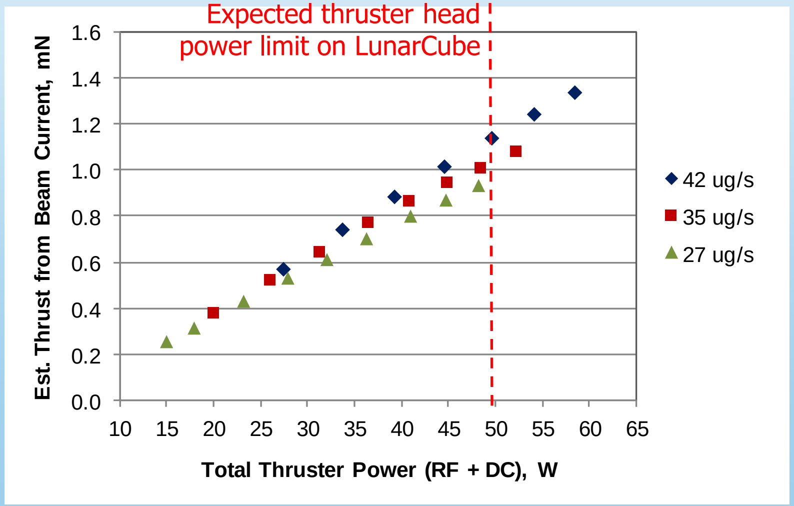
BIT-3, World's First Iodine-Fueled Gridded Ion Thruster, Baselined for LunarCube Propulsion

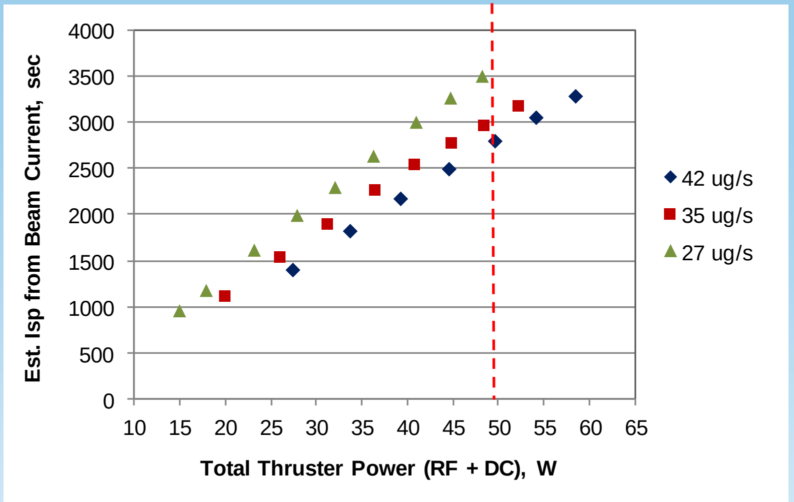
LunarCube Propulsion: BIT-3 Thruster Performance with I_2

- BIT-3 has demo'd wide throttleability with I_2.
- For LunarCube, max 65W propulsion system power at PPU input = max 50W thruster head power (converter efficiency & neutralizer).
- BIT-3 will likely be limited to ~1.1mN thrust and 2800sec Isp (2500sec total system Isp when counting neutralizer consumption).
- With a ~2.5U package, including 1.5kg solid iodine propellant, the BIT-3 system can provide <u>3.2km/s delta-V to the 6U/12kg LunarCube</u>.



BIT-3 System Block Diagram

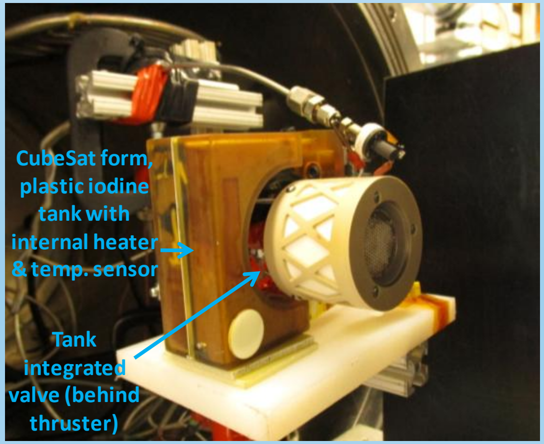


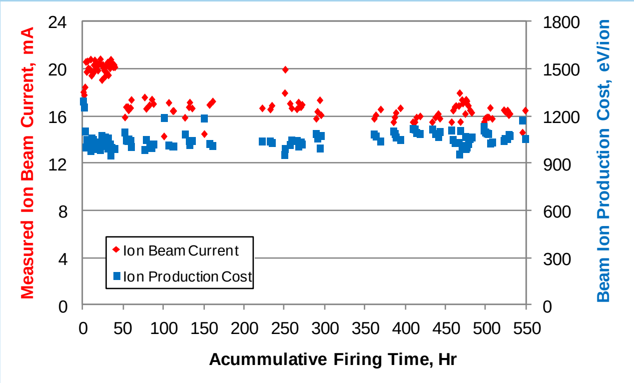


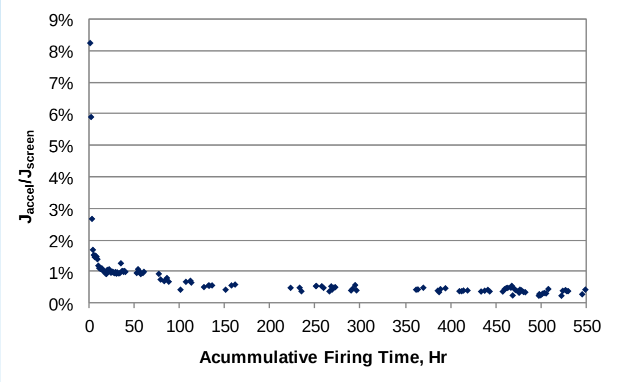
BIT-3 Performance with Iodine, 42µg/s Flow is Nominal

LunarCube Propulsion: BIT-3 Thruster Demo w/ CubeSat Tank

- Demonstrated firing with a CubeSat-style, lightweight plastic iodine tank and micro feed.
- The storage feed system requires ~10W to reach operating temp (3W tank & 7W line), but after steady state that requirement drops to ~5W (2W tank & 3W line).
- Completed 550hrs initial endurance test; grid burn-in mostly completed in 10hrs.

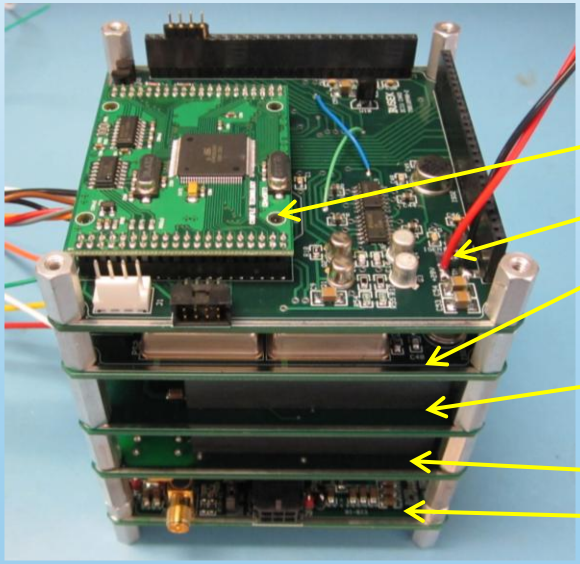




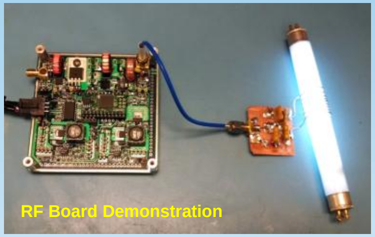


LunarCube Propulsion: BIT-3 PPU Development

- Electronics is a critical component of any EP system; miniaturizing PPU can be challenging.
- A CubeSat-style breadboard PPU has been developed for the smaller BIT-1 system.
  - Approximately 1.25U size and rated for 30W (10W RF + 20W DC).
  - Microcontroller-based DCIU that requires only comm and bus voltage.
  - Grid's HV circuit topology has heritage from Busek's CubeSat electrospray thruster systems.
  - Features an innovative RF generator board capable of auto matching. DC-to-RF conversion efficiency 75-80%. Integrated RF load power sensor.
- Feasibility study completed for scaling up to a BIT-3 compatible PPU; development pending.
  - Size can be reduced to 3/4U volume while power can be increased to max 124W (40W RF + 84W DC). Integrated heat sink.
  - Efficiency of both DC and RF boards will increase to ~83% due to higher power outputs.

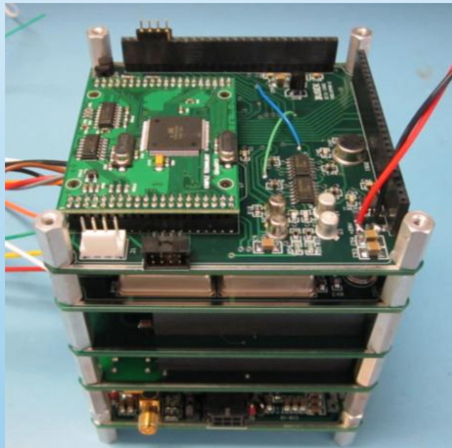


BIT-1 System PPU Prototype with DC Components Shown on Top and RF Generator/Amplifier Board at Bottom

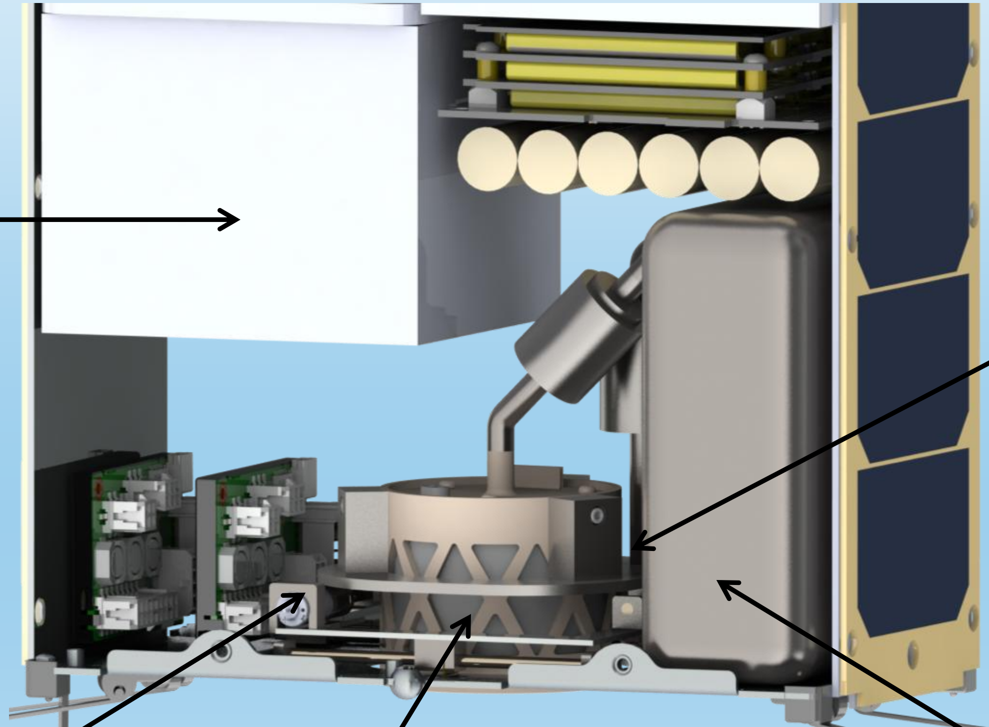


CubeSat Form Factor, Innovative RF Power Board for the BIT Series RF Ion Thrusters

LunarCube Propulsion: Preliminary Packaging



CubeSat Compatible Ion Propulsion PPU; (from top) DCIU, Housekeeping, Cathode/Valve, Grid HV, RF Generator & Power Amplifier



I_2-Compatible Subminiature Hollow Cathode as Ion Beam Neutralizer; Heaterless, 5W Nominal

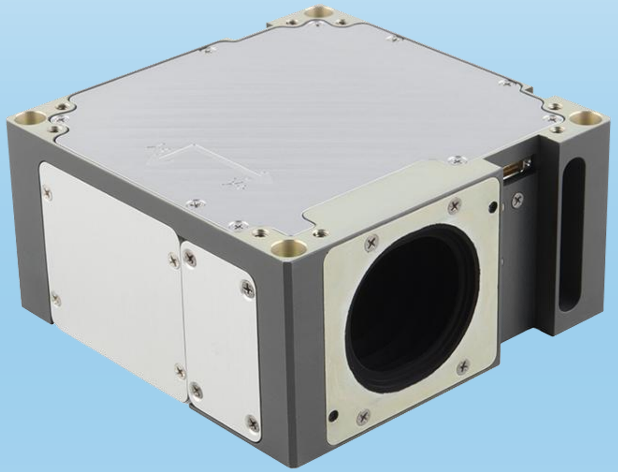
2-Axis Stage for Thrust Vectoring (Mainly for RWA De-Sat). Ongoing Work for Ball-Bearing Type Gimbal with Piezoelectric Actuator.

Busek 3cm RF Ion Thruster BIT-3; 50-60W Nominal at Thruster Head

320cc Iodine Propellant Stored as Solid Crystals

LunarCube Bus: ADCS and Navigation

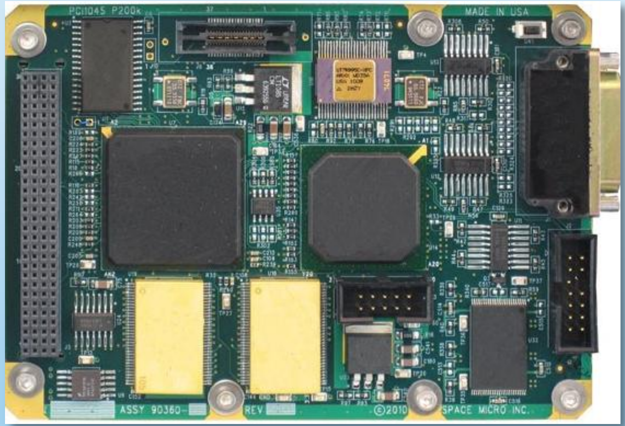
- ADCS & GNC is based on a 4-wheel Reaction Wheels Assembly (RWA), star tracker, sun senor and IMU. There are 4 modes of operation:
  - *Sun Acquisition Mode* : initially at deployment for power positive control; will use RWA and sun sensors.
  - *Observing Mode* : during science data taking and cruise operations; will use RWA, star trackers, and IMU to provide inertial, sun, and nadir attitude control as well as slew maneuvers.
  - *Delta-V Mode* : utilizes a gimbaled primary thruster to provide trajectory and orbit maneuvers.
  - *Delta-H Mode* : utilizes the gimbaled thruster on an infrequent basis for RWA momentum dumping.
- Gimbaled thruster can de-sat pitch & yaw axis wheels easily, simplifying ACS hardware req.
  - Roll momentum de-sat is doable with 3-burn maneuver, not very efficient but is infrequent.
  - Could carry redundant wheel for the roll axis to mitigate RPM limit (delay to saturation).



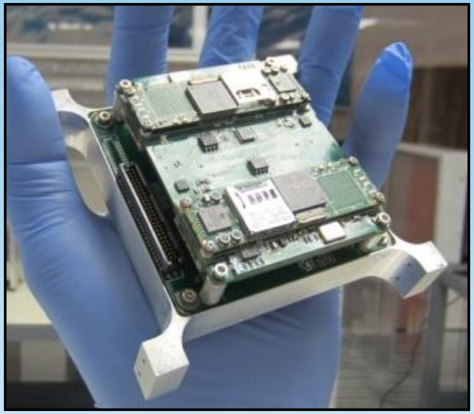
Blue Canyon Technologies (BCT) XACT Highly Integrated ADCS Module (0.5U); Customizable by Replacing Torque Rods with Redundant Roll Axis Wheel.

LunarCube Bus: Command & Data Handling

- C&DH architecture is distributed among 3 subsystems for redundancy and risk mitigation.
- Flight Computer: Space Micro Proton Lite 200k.
  - Rad tolerant processor.
  - Can send unprocessed data to ground if payload processor fails.
- Avionics Controller: Blue Canyon XB1 C&DH module.
  - Compact and integrated into ADCS unit (BCT XACT).
  - Reconfigurable on-orbit and responsible for ADCS and GNC, but can also control basic spacecraft functions (i.e. real-time command processing).
- Payload Processor: Honeywell-MSU Dependable Multiprocessor (DM).
  - Low cost, rad tolerant & high speed.
  - Can preprocess raw science data (minimizing downlink rate) and host spacecraft functions if necessary.
  - Fault tolerant Middleware + 8 processors mitigate high-current SEFIs and will be resilient to total radiation doses expected in the lunar environment.



Proton200k Lite DSP Processor Board



Honeywell-MSU DM

LunarCube Bus: Communication

- Requirement for lunar mission:
  - Close link at Lunar distances with 3dB of margin.
  - Command rate of 9.6k bps and telemetry downlink at 115k bps.
  - Security protocol and data encryption on the uplink side is required.

- Baselined with JPL Iris X-band radio
  - CubeSat compatible: 0.4U + antennas, 400g, ~10W DC.
  - DSN compatible: full duplex Doppler, ranging.
  - Telecom rates 62.5 – 256k bps telemetry; 1000 bps command.
  - Software defined radio; reconfigurable in flight.
  - SPI interface to C&DH handles standard coding.
  - First flight on INSPIRE "First CubeSat to Deep Space"; launch expected in 2015.

JPL Iris Prototype X-Band Stack

Frequency X-band	**7.1-7.6 GHz**
RF Transmit Power	1 Watt (minimum)
Transmit Antenna Gain	6 dBi nominal (X-band patch antenna)
Transmit Distance	Lunar to Earth (410,000 km, nominal)
Receive Antenna	21 meter dish
Receive Antenna G/T	38.7 dB/k
Receive Antenna Gain	62 dBi
Link Margin	3 dB
Data Rate	12 kbps nominal

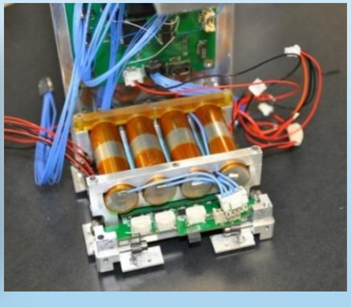
Comm Link Model between JPL Iris Radio and MSU 21m Dish

LunarCube Bus: Power Generation and Management

LunarCube Electrical Power System (EPS):

- Flight proven MMA eHaWK deployable solar panel array, 72W nominal at BOL.
  - Two Honeybee Robotics solar array actuators (one-axis gimbals).
  - Optional fixed solar panels for additional 12W.
- Currently working with MMA to develop a modified deployable array capable of 90-100W prime power generation.
- 8x Molicel 18650 Li ion batteries for storage; LEO flight heritage.
- MSU Power Management and Distribution (PMAD) System with LEO flight heritage.
  - High energy rad-tolerant TI MCU (100 kRad TID).
  - Under-voltage & over-voltage protection.
  - 100W capacity, 17 output channels with 93% measured output efficiency.
  - Reprogrammable in flight.

MMA eHaWK Solar Array in Flight Configuration



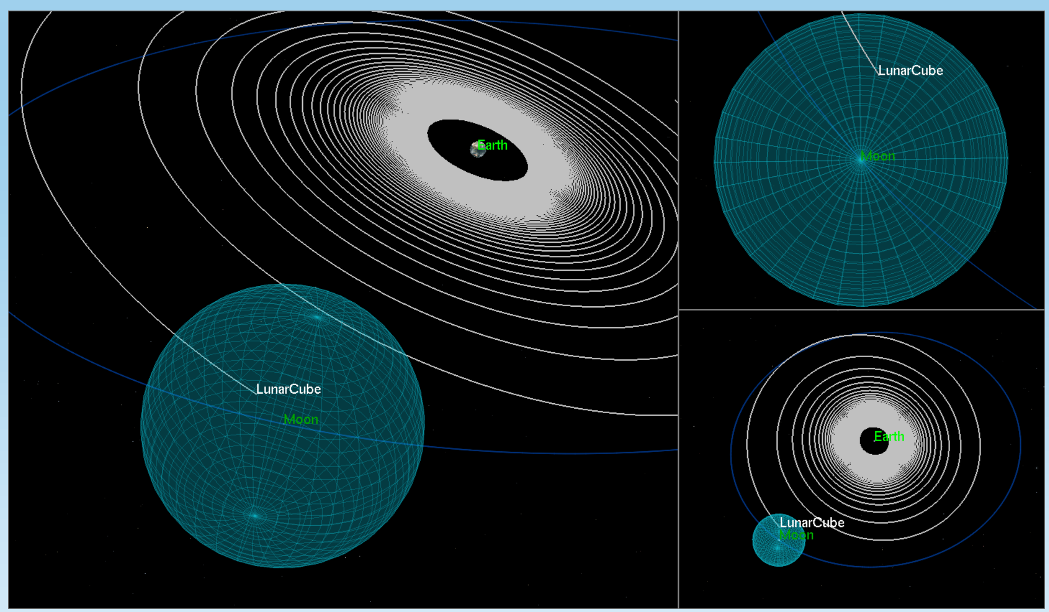
MSU LEO CubeSat EPS

Generation	PMAD
▪ 2x deployable solar panels array wings	▪ Direct Energy Transfer system
▪ Deployable arrays point to illumination with one-axis gimbals	▪ Shunt regulation for charging
▪ ~72 W continuous after sun acquisition at BOL	▪ 3.3V, 5V, and 12V available
▪ Optional fixed solar panel for added ~12W at BOL (for 84W total)	▪ Raw battery voltage available
Power Storage	▪ Up to 9 power ports available
▪ 8x Molicel Lithium Ion 18650 batteries	▪ RBF and Deployment Switch circuitry
▪ 2S4P configuration: 16.8V @ 4400 mAh	▪ Dedicated microcontroller (MSP-430)
▪ 18 mm dia. X 65 mm long	
▪ Battery protection circuitry	

LunarCube EPS including Generation, Storage and PMAD

Example Mission 1: 6U CubeSat to the Moon

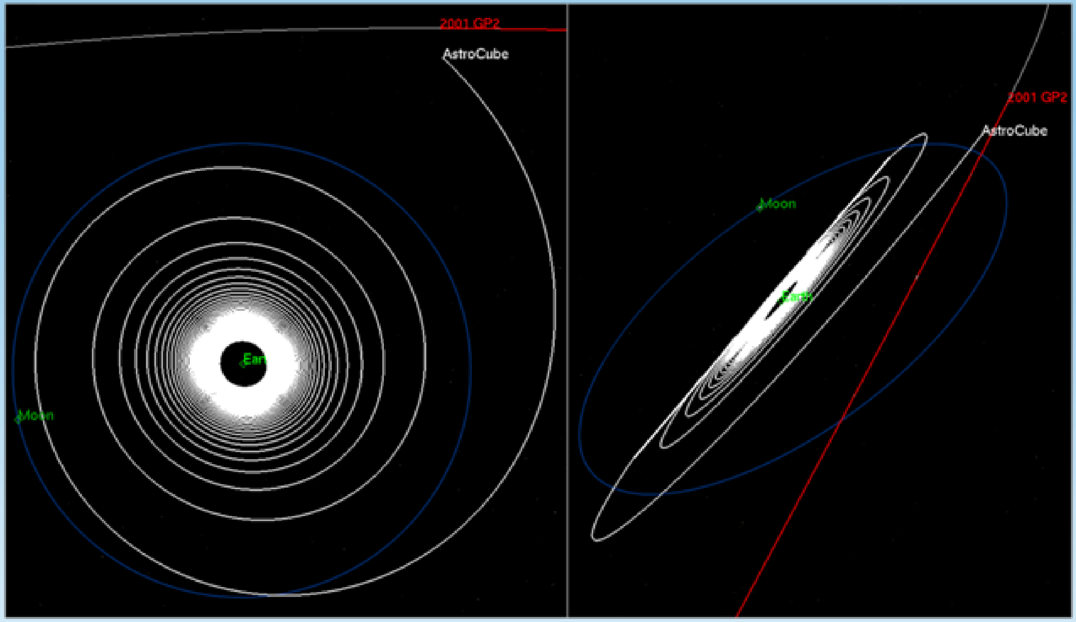
- With 3km/s delta-V capability, a 6U/12kg CubeSat can reach lunar orbit from GEO using the iodine BIT-3 propulsion system alone.
  - Transfer takes 258 days to complete.
  - GTO departure is possible with additional propellant or a more lightweight bus.
  - Starting from L1 transfer trajectory (e.g. recent Falcon9 mission) is possible.
  - Starting from SLS/EM-1 drop-off will result in excess delta-V margins (not a bad thing).
- The ability to get to the moon without a free ride is attractive to NASA and industry users eyeing future lunar missions with small robotic scout vehicles.



Example Mission Scenario Showing GEO-to-Lunar Capture Transfer Orbit of a 6U "LunarCube". Credit: NXTRAC

Example Mission 2: 6U CubeSat to Asteroid Rendezvous

- With 3km/s delta-V capability, a 6U/12kg CubeSat can rendezvous (not just flyby) with Asteroid 2001 GP2 during its next closest approach in October 2020.
  - Example mission scenario using departure from GEO; transfer takes 242 days to complete.
  - 2km/s of delta-V is spent climbing out of Earth's gravity well and re-aligning.
  - The additional 1km/s of delta-V is spent catching up to the asteroid. At rendezvous, both objects would be moving at a rate of ~2.5km/s with velocity vectors aligned. Landing will be possible.
- The 2001 GP2 asteroid rendezvous mission will also be possible by departing from L1 transfer orbit, SLS/EM-1 drop-off or direct injection.



Example Mission Scenario Showing GEO-to-Asteroid Transfer Orbit of a 6U "AstroCube". Credit: NXTRAC

Summary and Acknowledgement

- Significant progress has been made toward the 6U LunarCube platform design with ion propulsion. System will fly in the name of "Lunar IceCube" as part of the SLS EM-1 CubeSat mission. NRE of flight system will be paid for.
- Busek's BIT-3 RF ion thruster enables high delta-V (>3 km/s) missions for low cost, tiny spacecraft like 6U CubeSats. Lunar, NEO and interplanetary flights possible.
- Iodine propellant for EP is game changing – high density, stored as solid, low cost, near zero pressure with conformal plastic tanks, no typical "secondary payload" and "launch safety" concerns.
- This work was funded by NASA Small Spacecraft Technology Program under Space Technology Mission Directorate (STMD), contract #NND14AA67C.
- The upcoming Lunar IceCube flight program will be funded by NASA Advanced Exploration Systems (AES) under Human Exploration and Operations Mission Directorate (HEOMD).
- Co-authors: John Frongillo and Kurt Hohman of Busek, Dr. Ben Malphrus of Morehead State University.