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

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Distribution Statement A: Distribution Unlimited.
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 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

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

Example Ion Spectrometer Payload “TerDLE” by NASA GSFC

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\textsubscript{2}; verified that I\textsubscript{2} can be a drop-in replacement for Xe based on thrust-to-power ratio (22.5mN/kW for I\textsubscript{2} vs. 24mN/kW for Xe).
- I\textsubscript{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.
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 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 3.2km/s delta-V to the 6U/12kg LunarCube.
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.
**LunarCube Propulsion: Preliminary Packaging**

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

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

I₂-Compatible Subminiature Hollow Cathode as Ion Beam Neutralizer; Heaterless, 5W Nominal

320cc Iodine Propellant Stored as Solid Crystals

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LunarCube Bus: ADCS and Navigation

• ADCS & GNC is based on a 4-wheel Reaction Wheels Assembly (RWA), star tracker, sun sensor 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).
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.
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

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

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.

<table>
<thead>
<tr>
<th>Generation</th>
<th>PMAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x deployable solar panels array wings</td>
<td>Direct Energy Transfer system</td>
</tr>
<tr>
<td>Deployable arrays point to illumination with one-axis gimbals</td>
<td>Shunt regulation for charging</td>
</tr>
<tr>
<td>~72 W continuous after sun acquisition at BOL</td>
<td>3.3V, 5V, and 12V available</td>
</tr>
<tr>
<td>Optional fixed solar panel for added ~12W at BOL (for 84W total)</td>
<td>Raw battery voltage available</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>8x Molicel Lithium Ion 18650 batteries</td>
</tr>
<tr>
<td>2S4P configuration: 16.8V @ 4400 mAh</td>
</tr>
<tr>
<td>18 mm dia. X 65 mm long</td>
</tr>
<tr>
<td>Battery protection circuitry</td>
</tr>
</tbody>
</table>

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 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.
• 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.