RADIOISOTOPE POWER SYSTEMS

A Low-Cost Small Radioisotope Power System Centaur Flyby SmallSat Mission Concept

Brian Bairstow, NASA JPL/Caltech
and
Robert L. Cataldo, NASA GRC

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POWER TO EXPLORE
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Young H. Lee¹, Steven R. Oleson², Dr. Andrew Rivkin³, Rashied Amini¹, Dr. Julie Castillo¹, and COMPASS Team²

Jet Propulsion Laboratory, California Institute of Technology¹, NASA Glenn Research Center², The Johns Hopkins University Applied Physics Laboratory³

COMPASS Team Members:
• System Integration, MEL - Melissa Mcguire
• PEL, CONOPs, Launch Vehicle – Jeff Woytach
• Mission – Waldy Sjauw
• GN&C - Mike Martini
• Propulsion - James Fittje
• Structures - John Gyekenyesi
• Environmental - Tony Colozza
• Power - Paul Schmitz
• C&DH/Software - Glenn Williams
• Communications - Joe Warner
• Configuration - Tom Packard
• Cost - Jon Drexler
Introduction

• Radioisotope Power Systems (RPS) enable many deep space missions, particularly outer planet missions

• Current RPS Program Product Line: >100 We with RPS masses > 30 kg
  • Multi-Mission Radioisotope Thermal Generator (MMRTG)
  • Advanced Stirling Radioisotope Generator (ASRG)

• Currently exploring mission applications for Small RPS (sRPS) for low-cost missions with:
  • Stricter mass and volume-constraints
  • Lower power requirements

• Recently, Centaur Flyby SmallSat mission concept was studied to determine optimal qualities of sRPS
RPS Product Line

Power levels supplied by historical, current, and potential RPS

- **Pu-238 (kg)**
  - **Large RPS**
    - RHU
    - GPHS RTG
    - MHW RTG
    - SNAP-27
    - SNAP-3B
    - SNAP-19
    - SNAP-9A
  - **Small RPS**
    - Transit RTG
    - SNAP-19
    - SNAP-19B
    - SNAP-9A
    - SNAP-3B
  - **Milli-Watt Gap**
  - **Multi-Watt Gap**
  - **Dekawatt Gap**
  - **Kilowatt Gap**

**Focused RPS products for the study**
Study Motivations

- Can Discovery class missions be enabled by small RPS?
- Can mission concepts be closed with 1 General Purpose Heat Source (GPHS) module?
- What are the science and mission drivers for small RPS enabled mission power needs?
- What are the mission concept parameters that are key trade attributes when using small RPS in a Discovery class mission?
  - Number of spacecraft?
  - Number of instruments?
  - Number of objects to fly by?
Study Constraints and Assumptions

• Constraints
  – Standalone spacecraft enabled by small RPS
  – Low cost mission
    - Discovery class cost profile with multiple SmallSats
  – Use of 1 GPHS Module
  – Mission duration to be up to 14 years
  – Data return phase up to 1 year
  – Launch date to be after 2020

• Assumptions
  – Availability of RPS to be within 7 years from today
  – 4 spacecraft each in 100-200 kg range
  – Same spacecraft configurations with same science instruments
  – All spacecraft could be launched on the same launch vehicle
  – Use of small (20-60 We) radioisotope power
    - Reasonable power level available for timely data return
    - Battery supplies additional power during science operations and data return communication periods
  – Secondary science instrument contributed
Centaur Flyby Mission Concept

- Send four similar or identical SmallSats (of about 100-200 kg) to at least two different Centaur objects, focusing primarily on 2060 Chiron.
  - A representative science mission which should remain relevant at a point when sRPS would become available
  - A breadth of architectures with varying mission parameters.

- Why Centaur objects?
  - Difficult to observe remotely due to distance and albedo.
  - Previously unexplored
  - Appropriate fly-by target
  - Exhibit diverse spectra
  - May be related to the Kuiper-Belt Objects (KBO) but are significantly more accessible
  - New Frontiers 2009 AO recommended Centaur reconnaissance mission

- Why 2060 Chiron?
  - One of several unique Centaurs with detected coma activity
    - Indicating it was perturbed from an orbit at a larger heliocentric distance.
    - Possibly KBO
  - Large Centaur object with ephemeris reasonably well known
Specific Science Goals

• Characterize Chiron: surface morphology, structure, and composition
  
  • Surface Morphology determined via camera
    • Maps of target and flyby closest approach images
      • Based on MESSENGER MDIS NAC heritage
      • 2048 x 2048 pixel, 1.5º FOV
      • 2.4 kg, 5 W

  • Structure determined via gravity science with two-way Doppler radio
    • 2-way ranging through medium gain antenna to/from DSN

  • Composition determined by via hyperspectral IR spectrometer (Contributed instrument)
    • Maps of target and flyby closest approach images
      • Based on Marco Polo VIS-IR heritage
      • 128 pixel pushbroom with 10 spectral bands, 0.014º FOV
      • 4 kg, 12.5 W
Science Operations Concept

- Science measurements could begin when target could be resolved to 5 pixels
- Initial Science Observation would begin 1 week before closest flyby
  - OPNAV Observation by S/C (with camera) to better determine target ephemeris and rotation properties
  - @ 5km/s camera could resolve target ~ 1 week before flyby, spectrometer ~1 day before
  - Mapping: Image every ½ hr (30° rotation of object), 50 Mb per image uncompressed
- Flyby Observation (starting at 4 hrs before closest approach ~800 km)
  - Simultaneously run NAC/Spectrometer and 2-way Doppler
  - Spectrometer and NAC closest approach imaging from T-30m to T+30m
  - DSN Track from T-4 h to T+4h (2-way ranging thru MGA to/from DSN. 12 dBHz S/N)
- Post-flyby observation (similar to initial science observation mode from other side)
- Data Return 91 days of one 8 hr pass/day
  - 10,200 Mb uncompressed, 3.4 Gb compressed (3x lossless)
Mission Scenarios

- **Selected Mission Scenario for Study**
  - Four identical SmallSats targeting two Centaur objects (two SmallSats to each object)
    - Redundant spacecraft
    - More angles for observations
    - More time on target
    - Better gravity science

- **Other Considered Mission Scenarios**
  - Four identical SmallSats targeting four Centaur objects (one SmallSat to each object)
  - Four SmallSats with two different payloads targeting two Centaur objects (one SmallSat of each payload to each object)
  - Four SmallSats with four different payloads targeting one Centaur object
Mission Design Concept

- Trajectory constraints:
  - $C_3 \sim 100 \text{ km}^2/\text{s}^2$
  - Cruise time must be $< 13$ years
    - Based on spacecraft and RPS lifetime
  - Flyby speed at target body must be $\sim 5 \text{ km/s}$ or lower
    - Based on surface mapping science requirements

- Jupiter flyby for gravity assist trajectories were developed
  - **Phase 1 Cruise**: 1.5-2 years depending on Centaur target
  - Jupiter Flyby/Gravity Assist
  - **Phase 2 Cruise**: 8-10 years depending on Centaur target
    - During this phase the spacecraft split to different targets via propulsive burns

![Diagram of Chiron](image1)

![Diagram of Okyrhoe](image2)
SmallSat and Launch Stack Configuration

Atlas 431 with STAR 48B kick stage
Four identical SmallSats each with radioisotope power system

Conceptual Design

- RPS SmallSat (4)
- Rideshare Adaptor
- Payload Adaptor
- Star 48 BV
- Adaptor to Solid Rocket Motor
- C22 PLA

* 3-Axis Stabilization Stage for the Star 48 BV not shown
SmallSat Launch Vehicle Configuration

Conceptual Design

Atlas V 4-meter Launch
Payload Fairing

3.75-m Diameter
Payload Envelope
SmallSat Components

Conceptual Design

- Secondary Battery
- Power Management and Control Electronics
- IMU
- Star Tracker Electronics
- cPCI Enclosure with Power Supply
- Small SRG (Small RTG option)
- RCS Propellant Tank
- sSRG Controller Unit
- Main Engine Propellant Tank
- Comm Switch
- EPC
- TWT
- Small Deep Space Transponder
- RCS Propellant Tank
SmallSat Dimensions

Conceptual Design

110.0 cm  
107.9 cm  
47.5 cm  
114.8 cm  
176.3 cm  
68.1 cm  
36.0 cm
## Representative Small RPS Attributes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1-GPHS Small SRG</th>
<th>1-GPHS Small RTG</th>
<th>3-GPHS Small RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BOM Power</strong></td>
<td>65 W</td>
<td>21 W</td>
<td>64 W</td>
</tr>
<tr>
<td><strong>EOM Power (12 year mission)</strong></td>
<td>57 W</td>
<td>16 W</td>
<td>48 W</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>18 kg</td>
<td>10 kg</td>
<td>20 kg</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>49 x 39 x 38 cm</td>
<td>64 cm dia (inc fins) 17 cm hgt</td>
<td>64 cm dia (inc fins) 31 cm hgt</td>
</tr>
<tr>
<td><strong>Cold-side Temp (BOM, 4K sink)</strong></td>
<td>38 C</td>
<td>50 C</td>
<td>50 C</td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
<td>28 +/- 6 V</td>
<td>5 +/- 1 V</td>
<td>28 +/- 8 V</td>
</tr>
<tr>
<td><strong>Degradation</strong></td>
<td>1.16 %/year</td>
<td>2.5 %/year</td>
<td>2.5 %/year</td>
</tr>
<tr>
<td><strong>Efficiency (BOM)</strong></td>
<td>26%</td>
<td>8.5%</td>
<td>8.5%</td>
</tr>
</tbody>
</table>

- BOM values are at Beginning of Mission: at launch after 3 years in storage. EOM values are at End of Mission after an additional 12 years of operations.
- **sSRG**: One ASRG engine with a passive balancer and a two-card controller. The controller is included in the mass above, but not in the volume or diagram. Attributes are based on ASRG current best estimate.
- **sRTG**: Follows MMRTG design but with 3 GPHS bricks and advanced PbTe/TAGS/BiTe thermocouples. Estimated 6 parallel strings for average 28 V power. Attributes are estimated requirements.
- Systems assumed qualified for 17 year lifetime, including 3 years of storage.
## (Notional) Spacecraft Mass Equipment List

<table>
<thead>
<tr>
<th>Main Subsystems</th>
<th>Basic Mass (kg)</th>
<th>Growth (kg)</th>
<th>Predicted Mass (kg)</th>
<th>Aggregate Growth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RPS SmallSat</strong></td>
<td>261.36</td>
<td>40.25</td>
<td>301.61</td>
<td></td>
</tr>
<tr>
<td><strong>Microsat Bus</strong></td>
<td><strong>139.31</strong></td>
<td><strong>18.28</strong></td>
<td><strong>157.58</strong></td>
<td>13%</td>
</tr>
<tr>
<td>Science Payload</td>
<td>7.40</td>
<td>2.10</td>
<td>9.50</td>
<td>28%</td>
</tr>
<tr>
<td>Attitude Determination and Control</td>
<td>3.61</td>
<td>0.11</td>
<td>3.71</td>
<td>3%</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>13.80</td>
<td>3.73</td>
<td>17.53</td>
<td>27%</td>
</tr>
<tr>
<td>Communications and Tracking</td>
<td>10.05</td>
<td>2.48</td>
<td>12.53</td>
<td>25%</td>
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<tr>
<td>Electrical Power Subsystem</td>
<td>40.18</td>
<td>6.03</td>
<td>46.20</td>
<td>15%</td>
</tr>
<tr>
<td>Thermal Control (Non-Propellant)</td>
<td>12.94</td>
<td>1.94</td>
<td>14.89</td>
<td>15%</td>
</tr>
<tr>
<td>Propulsion (Chemical Hardware)</td>
<td>12.75</td>
<td>0.53</td>
<td>13.29</td>
<td>4%</td>
</tr>
<tr>
<td>Propellant (Chemical)</td>
<td><strong>12.73</strong></td>
<td></td>
<td><strong>12.73</strong></td>
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<tr>
<td>Structures and Mechanisms</td>
<td>25.85</td>
<td>1.36</td>
<td>27.21</td>
<td>5%</td>
</tr>
<tr>
<td>Estimated Spacecraft Dry Mass (no prop,consum)</td>
<td><strong>126.58</strong></td>
<td>18.28</td>
<td><strong>144.85</strong></td>
<td>14%</td>
</tr>
<tr>
<td>Estimated Spacecraft Wet Mass</td>
<td>139.31</td>
<td>18.28</td>
<td>157.58</td>
<td></td>
</tr>
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</table>

### System Level Growth Calculations

<table>
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<tr>
<th></th>
<th>Total Growth</th>
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<tr>
<td>Dry Mass Desired System Level Growth</td>
<td><strong>164.55</strong> 30%</td>
</tr>
<tr>
<td>Additional Growth (carried at system level)</td>
<td>19.69 16%</td>
</tr>
<tr>
<td>Total Wet Mass with Growth</td>
<td><strong>177.28</strong></td>
</tr>
</tbody>
</table>

*Estimated Spacecraft Dry Mass (no prop, consum) 126.58 18.28 144.85 14%*
Mission
• Four 170 kg RPS powered SmallSats would flyby Jupiter then flyby two Centaur objects (two SmallSats flyby each object). Flybys would occur 10-12 yrs after launch at 4-6 km/s velocity.

Launcher
• Atlas 431 with Star 48BV to C3 97 km^2/s^2

Science: Narrow Angle Camera, Gravity Science, Spectrometer
• >3 Gb of data (~200 10m/pixel resolution images from NAC per spacecraft, ~148 200m/pixel resolution images from the spectrometer per spacecraft, gravity science estimates mass of Centaur to 1% accuracy)

Spacecraft
• Power (~60W provided by RPS)
  • Case 1: Single Stirling power system using parts from current ASRG
  • Case 2: 3-GPHS Small Radioisotope Thermal Generator using advanced thermoelectric couples
  • Spun hibernation mode for most of mission
• Comm: ~ 1350 bps data rate assuming X-band, 1 m dish to DSN (70 m or groups of 34 m)
• AD&CS (IMU, Sun sensors, Star trackers, Cold Gas RCS)
  • Science Collection mode: ~ 1 month at Centaur, active for 1 hr at a time, 3 axis RCS pointing to 0.5 deg accuracy
  • Hibernation and Data Return Mode: Spin-stabilized pointed to earth
• Propulsion (N2 cold gas for RCS and Hydrazine for mid-course corrections)
• C&DH: Microsat class (LEON)
  • Additional watchdog processor for hibernation mode
• Mechanical: Star 48 final burn, pointing mirror for science
Mission Phased Power Requirements

Mission Phase:
- Launch
- Check Out
- Cruise
- MCC
- Initial Sci. Ops
- Flyby Imaging
- Flyby Grav Sci
- Post Flyby Sci
- Data Return

S/C Power Load We (Watts)
- 10 (Launch)
- 146 (Check Out)
- 47 (Cruise)
- 92 (MCC)
- 74 (Initial Sci. Ops)
- 156 (Flyby Imaging)
- 126 (Flyby Grav Sci)
- 120 (Post Flyby Sci)
- 102 (Data Return)

Battery Sizing Phase (One Discharge Cycle)
- sSRG (65 W BOM, 57 W EOM)
- 3-GPHS sRTG (64 W BOM, 48 W EOM)
- 1-GPHS sRTG (21 W BOM, 16 W EOM)

# Battery Cycles for each mode in parentheses

Radioisotope Power Systems Program
Pre-decisional For Planning and Discussion Purposes Only
Study Power System Findings

- **Power Systems Requirements**
  - Batteries cannot supplement RPS for 10-12 years of cruise
  - There must be a power mode for recharging secondary batteries

- During the study, it became apparent that the driving power case is the cruise/hibernation mission phase.
  - Requires ~40 W with science instruments off and C&DH in a low-power mode

- High power mission phases do not drive RPS power level
  - Use supplemental power from the 9kg Li-ion battery during shorter telecom and science operations modes

- The mission was initially studied with a single 1-GPHS sRTG producing 16 W EOM
  - This case could not get power usage low enough to recharge even after turning off the IMU and further reducing the C&DH power.
  - To be feasible with a 1-GPHS sRTG, the mission would need to take on more risk by turning off the star tracker, computer, and/or receiver, or by using lower-power components.
  - The 3-GPHS sRTG configuration met the mission’s power requirements.
Mission Cost Summary (ROM)

• Key Cost Assumptions
  • All costs are in FY13 $M
  • Use Discovery 12 Cost Guidelines
    • Mission managed cost cap is 447 FY13 $M (425 FY10 $M)
    • Cost of standard Launch Vehicles not included in cap
    • RPS flight H/W is Government Furnished Equipment (GFE)
    • RPS Launch Approval cost is $20M
    • Phase A-E Reserves at 25% (We used reserves of 30%)
  • Development (DDT&E) and Flight Hardware (FH) estimates represent prime contractor cost with fee
  • Four spacecraft are of identical design with same science package:
    • Camera and Mirror Linear Actuator costs included
    • Spectrometers are assumed to be contributed
  • Estimates do not include any cost for technology development lower than TRL 6
  • System Integration costs calculated using wraps as a planetary mission
  • Flight software costs are included in development cost
  • Secondary science instrument contributed

• COMPASS point design put mission costs within reach of the Discovery cost cap
  • Identified several cost reduction options with potential to meet cost cap that can be explored in further detail

<table>
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<th>WBS</th>
<th>Description</th>
<th>DDT&amp;E Total (FY13$M)</th>
<th>Flight HW Total (FY13$M)</th>
<th>Total (FY13$M)</th>
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<td>Science Payload</td>
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<td>4</td>
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<td></td>
<td><strong>Subtotal</strong></td>
<td><strong>45</strong></td>
<td><strong>19</strong></td>
<td><strong>64</strong></td>
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<td></td>
<td>Systems Integration</td>
<td>35</td>
<td>6</td>
<td>41</td>
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<td></td>
<td><strong>Spacecraft Total</strong></td>
<td><strong>80</strong></td>
<td><strong>24</strong></td>
<td><strong>105</strong></td>
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<tr>
<td></td>
<td>Prime Contractor Fee (10% less science)</td>
<td>8</td>
<td>2</td>
<td>9</td>
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<td></td>
<td><strong>Total Project with Fee included</strong></td>
<td><strong>88</strong></td>
<td><strong>26</strong></td>
<td><strong>114</strong></td>
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Development & FH Estimates (above); Lifecycle Cost (Below)

<table>
<thead>
<tr>
<th>FY13$M</th>
<th>Description</th>
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<tr>
<td>NASA insight/oversight</td>
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<tr>
<td>Phase A</td>
<td>3</td>
</tr>
<tr>
<td>Development Effort &amp; Adapter</td>
<td>98</td>
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<tr>
<td>Flight Units (4)</td>
<td>106</td>
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<tr>
<td>Launch Vehicle</td>
<td>32</td>
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<tr>
<td>Launch Services Adder</td>
<td>20</td>
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<tr>
<td>Mission Ops/GDS</td>
<td>131</td>
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<tr>
<td>Reserves</td>
<td>102</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>511</strong></td>
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</table>
Study Conclusions

• Preliminary study results show that a SmallSat using a small Radioisotope Power System for deep space destinations could potentially fit into a Discovery class mission cost cap and perform significant science with a timely return of data.
  • Only applicable when the Discovery 12 guidelines were applied
  • Commonality of hardware and science instruments among identical spacecraft enabled to meet the Discovery Class mission cost cap
  • Multiple spacecraft shared the costs of the Launch Approval Engineering Process
  • Assumed a secondary science instrument was contributed

• sRPS could provide small spacecraft with a relatively high power (~60 We) option for missions to deep space destinations (> 10 AU) with multiple science instruments.
  – Study of Centaur mission demonstrated the ability to achieve New Frontiers level science
Questions?