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AN EXPLORATION OF MISSION CONCEPTS THAT COULD UTILIZE SMALL RPS

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The NASA Radioisotope Power Systems (RPS) Program Mission Analysis Team at the Jet Propulsion Laboratory (JPL) requested a JPL Innovation Foundry Architecture Team (A-Team) study to assess mission pull for small RPS (1 mW$_e$ - 40 W$_e$) in order to inform the RPS Program Office on what future power system developments should be focused on. The A-Team is JPL's concurrent engineering design team for science definition and early mission concept development, targeting concept maturation levels of 1 through 3. The requested small RPS study was tasked to identify the architecture space of potential small RPS missions, and suggest power levels that could enable or enhance potential future small spacecraft missions.

This paper describes the collaborative engineering processes that the A-Team and Mission Analysis Team used to reach results quickly and the findings to inform the RPS Program about mission concept power requirements on RPS for small missions.

I. INTRODUCTION

There is an increasing drive toward smaller spacecraft mission concepts in order to generate science returns given limited resources and limited access to space. At a unit size of > 40 kg, existing Radioisotope Power Systems (RPS) can be mass prohibitive for small spacecraft missions. In order to enable outer planets and in-situ small spacecraft missions, smaller RPS may be necessary. Thus, the RPS Program is interested in understanding the mission pull for small RPS, in the range of milliwatts to tens of watts, in order to identify what future power system developments should be focused on. The program would like to know what types of mission could be enabled or enhanced if there was a small RPS and what science questions could be answered.

To address the need for small RPS mission pull, the Mission Analysis Team at JPL conducted a JPL Architecture Team (A-Team) study to better understand the science goals and architecture space surrounding the use of small RPS. Specifically, mission concepts were sought that could utilize ≤ 40 W$_e$, as the Next-Generation Radioisotope Thermoelectric Generator (RTG) is expected to include a variant with two General Purpose Heat Source (GPHS) modules that could generate 40 W$_e$ at the beginning of life[1].

The architecture study included the following objectives:

- Explore the needs and applications for small spacecraft systems in planetary science;
- Brainstorm what types of mission classes would be possible with small systems that require low constant power draw;
- Determine the minimum amount of power required for a deep space small mission with RPS; and
- Create a spectrum of potential mission concepts based on available power.

The study did not factor in the type of power conversion technology, but rather organized mission concepts based on the expected required power that they would need. For all of the mission concepts considered, it was important that RPS be enabling or enhancing, when compared to other power sources, such as photovoltaics or primary batteries. The standard definitions of CubeSat and SmallSats were used, with the maximum spacecraft mass considered for this study being 100 kg, which included both CubeSats/SmallSats and in-situ mission concepts, such as small or micro landers.

II. STUDY PLAN

The small RPS study was conducted over a single day at JPL with the Innovation Foundry A-Team. The A-Team is JPL's concurrent engineering design team specializing in science definition, early mission concept development, and technology roadmapping[2]. Study participants included RPS experts, scientists, instruments developers and engineers, mission architects, and specialists in small satellites and robotics.

To ensure that all participants were on the same page, an initial background presentation on small RPS and study goals was provided. The study was structured to quickly define potential *science driven* mission concepts that could be enhanced or enabled by small RPS. First, scientists described desired or highly interested science measurements that could be possible with the use of RPS, organized by destinations. Then, instrument experts briefed the group on what instruments are currently available, or are expected to be available in the future, to perform the desired measurements with small spacecraft systems. This list of instruments, including estimates for masses and required power, was used to brainstorm what science objectives may be able to be answered with a small spacecraft.

With the science objectives and instruments that could be utilized, the study team brainstormed a number of generalized mission classes that small RPS could be used for. Next, the study team generated dozens of potential mission concepts that fit within these classes. Eleven notional concepts were elaborated on further to define preliminary power requirements, as well as mass and volume allocations for a small RPS. Finally, the mission concepts were sorted and summarized on "power, mass and size spectrums" to draw initial conclusions and suggestions on the type of small RPS that may be useful for small science missions.

III. STUDY FINDINGS

III.A Potential Instruments, Science Objectives, and Mission Types

III.A.1. Potential Instruments

Before generating any potential mission concepts, it was important for the study team to understand what types of instruments could be available for a small science mission and what the notional accommodation requirements could be. The list of instruments summarized in Table 1 was generated by instrument experts that participated in the study, based on systems that are either currently available or expected to be available in the future. The mass and power ranges given are estimates based on experience and analogous devices. Some of the lower values of the mass and power ranges are representative of the current push in research and technology development to make instruments smaller and more efficient.

III.A.2. Potential Science Objectives

Important to the process of brainstorming mission concepts was that they must be *science driven*. If any of the concepts are to be selected someday to become a flight mission, they must demonstrate that they have achievable and meaningful science goals. Therefore, the study team spent time to brainstorm potential science objectives that could be answered with a small RPS mission.

Potential destinations spanned the solar system and included the Moon, comets, asteroids, Venus, Mars, the gas giants, the ice giants, and Pluto. Also included were areas outside of the immediate solar system, including the Kuiper belt, Oort cloud, and interstellar space.

TABLE I. Potential instruments that could be utilized in a small RPS mission, with estimates for mass and power.

Instrument	Mass (kg)	Power Required (W_e)
Microfluidics (life detection)	1-10	0.5-20
Seismic Package	0.1-1.2	0.005-10
GC-MS (mass spectrometer)	0.5-2-25	0.5-16
Environmental sensing	1.2-5	17
Mastcam (camera)	0.1-1.3-8	13
MicrOmega (IR, microscope)	0.1-1-3	1-7
Digital Microscope	0.5-10	4-15
IR Spectrometer (BIRCHES)	0.1-3-25	10-15
Alpha-Particle-X-Ray-Spectrometer (APX)	0.1-5	0.1-<5
Gamma Ray Spectrometer (GRS)	0.1-5-20	0.1-5-10
Neutral Mass Spectrometer (NMS)	0.1-5-20	0.1-5-10
Ground Penetrating Radar	0.5	10
Altimeter	2-5	3-10
Magnetometer	0.1	<1
TLS (Tunable Laser Spec)	0.5-5	1-10
Dialectric Spectrometer	0.1-4	<1
Sensor on Chip (diff types)	1	<1
UV Spectrometer	3	4
Dosimeter	<1-2	0.5-20
Atomic Force Microscope	5-10	5-10
Anemometer	<0.1-1	<1
Electric Field Detector	0.1-2	<1
Radio Science	1	20-30
Langmuir Probe	0.1-5	0.1-2
Dust Detectors	3-4	5
X-ray Spectrometer	3-5	5
Biological Instrument	5-10	10-20
X-ray Micro Imager	1.5	10
Laser-Induced Breakdown Spectroscopy (LIBS)	3	1-2
Thermal Conductivity Probe	<1-1	1
Microphone	0.01-0.1	<1

The identified potential science objectives are summarized below according to the body/area of interest.

Earth's Moon:

- Measurement of radiation and water ice in caves and shadowed regions
- Seismology measurements
- Measurement of polar volatile content

Comets:

- Long-term measurements of mass loss throughout the orbit
- Seismology measurements
- Composition of gases

Venus:

- Geological measurements
- Heat flux measurements
- Seismology measurements

Mars:

- Exploration of caves and lava tubes
- Determination of geographic and temporal distribution of methane
- Weather monitoring
- Seismology measurements
- Measurement of atmospheric composition with latitude/longitude variation

Gas Giants and their Moons:

- Storm system monitoring
- Seismology measurements on moons
- Composition of icy moon surfaces
- Subsurface ocean exploration
- Measurements of moon plume compositions
- Study of ring dynamics
- Long-term weather monitoring
- Determination of magnetic fields
- Gravity field measurements

Ice Giants and their Moons:

- Surface composition measurements of moons
- Measurements of magnetic fields
- Gravity field measurements
- Determination of spatial and temporal distribution of fields and particles

Pluto:

- Measurements of surface composition
- Weather monitoring

Kuiper Belt Objects/Oort Cloud:

- Measurement of object size, composition, and geology

Interstellar:

- Measurements of exoplanets & interstellar space

III.A.3. Potential Mission Classes

With potential instruments and science objectives identified, the study team brainstormed a grouping of mission classes that could be enabled or enhanced by small RPS. Mission classes are a broad description of a potential mission type, with multiple potential mission concepts that could fit within each class. The four identified mission classes were:

Small Landers

- Small, stationary in-situ elements for many bodies throughout the solar system.

Small Rovers/Mobility Systems

- Small, mobile in-situ elements for many bodies throughout the solar system.

SmallSat Swarms

- A swarm or constellation of many SmallSats in different orbits around a body, or performing a flyby.

Mother-Daughter craft

- A small spacecraft that deploys from a larger spacecraft. The larger spacecraft could perform complimentary science and/or act as a telecommunications relay.

These mission classes do not necessarily represent all of the types of missions that could be a good candidate for small RPS, but they were deemed by the study team to be the most probable and, for the purposes of defining notional small RPS requirements, were the focus of the conceptual mission architectures discussed in Section II.B.

III.B Conceptual Mission Architectures

Using the identified mission classes, potential science objectives, and potential instruments, the study team brainstormed dozens of mission architecture concepts that could be enabled or enhanced by small RPS. To define notional small RPS requirements, eleven concepts were selected to be explored in more detail. These concepts included small satellites, landers, rovers, and flying vehicles. For each concept, the study team defined notional science objectives, instruments, and technical parameters, including mass and power of the spacecraft. Finally, the required power for the small RPS was estimated, along with the lifetime and mass and volume allocations.

Figure 1 gives one example mission architecture concept for a Pluto lander of approximately 70 kg wet mass. The study team used engineering judgment and analogies to prior missions and concept studies to estimate notional technical parameters, given the science goals and instruments identified. This information was then used to estimate the required end-of life (EOL) power output required from the RPS, in this case 10 W_e. Also, estimated was an allocation for the RPS mass and volume that would be available on the lander.

This process of defining the mission concept and then working to notional requirements was repeated for the other ten concepts selected to be explored in more detail. The result was a data set to populate the “power, mass and size spectrums” described in Section II.C.

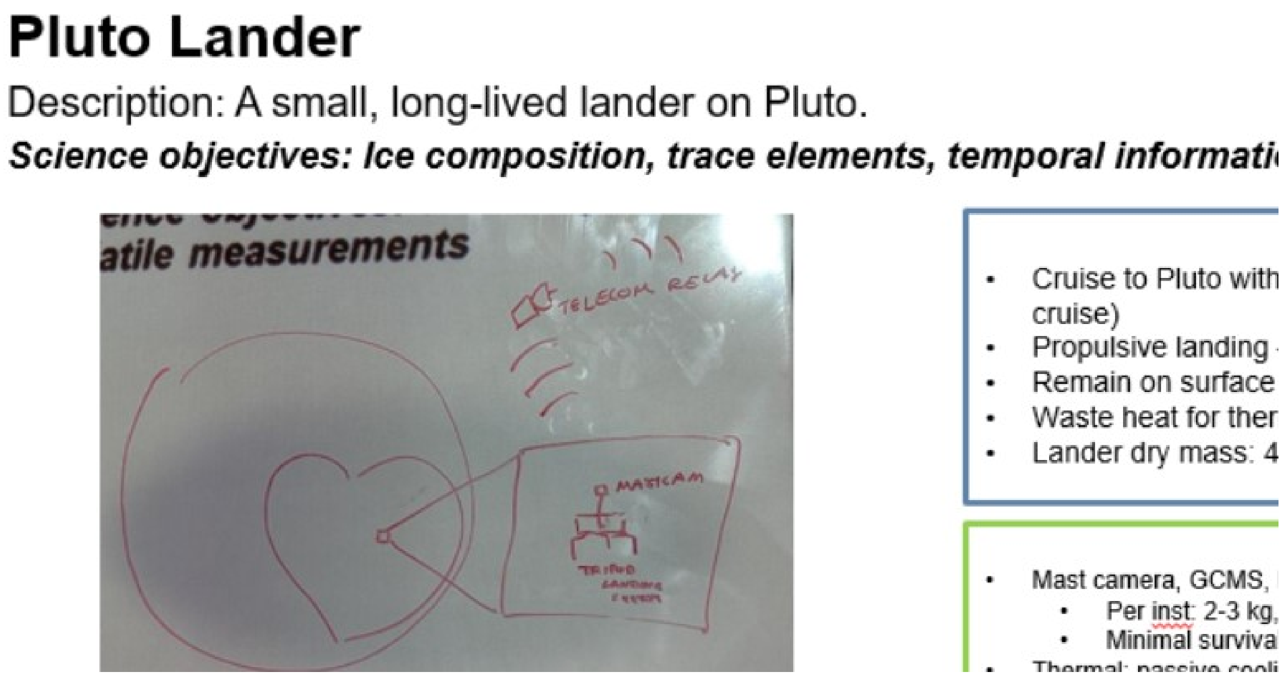

Fig. 1. Example mission architecture concept generated during the study for a small Pluto lander.

III.C Mission Power, Size and Mass Spectrums

Figure 2 shows all eleven of the studied mission concepts sorted onto a power spectrum by the estimated EOL power required by the small RPS. It can be seen that the mission concepts identified cover a range of power requirements from a few milliwatts to approximately 20 watts. Moreover, there are a few select groupings of missions, with one group in the ≤ 100 mW_e range, a group in the 1 – 2 W_e range, and a group in the 10 – 20 W_e range.

Figure 3 shows the 11 mission concepts sorted onto a spectrum based on the estimated available volume that would be available for the RPS. Similarly, Figure 4 shows the concepts sorted onto a spectrum based on the estimated available mass that would be available for the RPS. It can be seen that there is a similar grouping of concepts to the power spectrum in Figure 1.

These 11 mission concepts are not meant to convey the only potential missions that could be enabled or enhanced by small RPS, but they give an idea of what types of RPS may be most useful for future small missions.

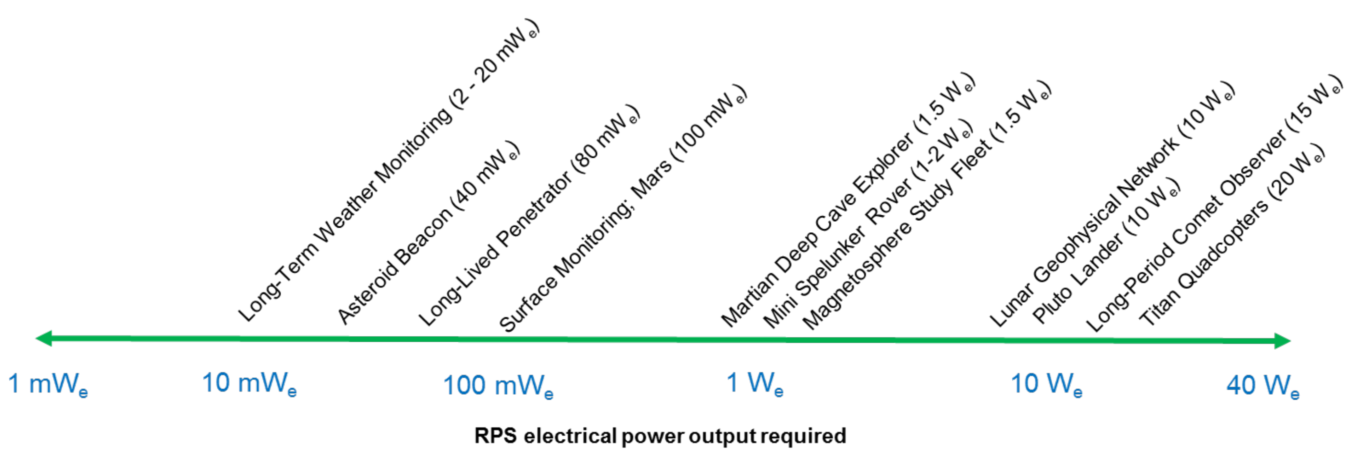

Fig. 2. The 11 studied mission concepts are populated on a power spectrum according to the estimated required EOL power output from the RPS. The mission concepts cover a range of power requirements.

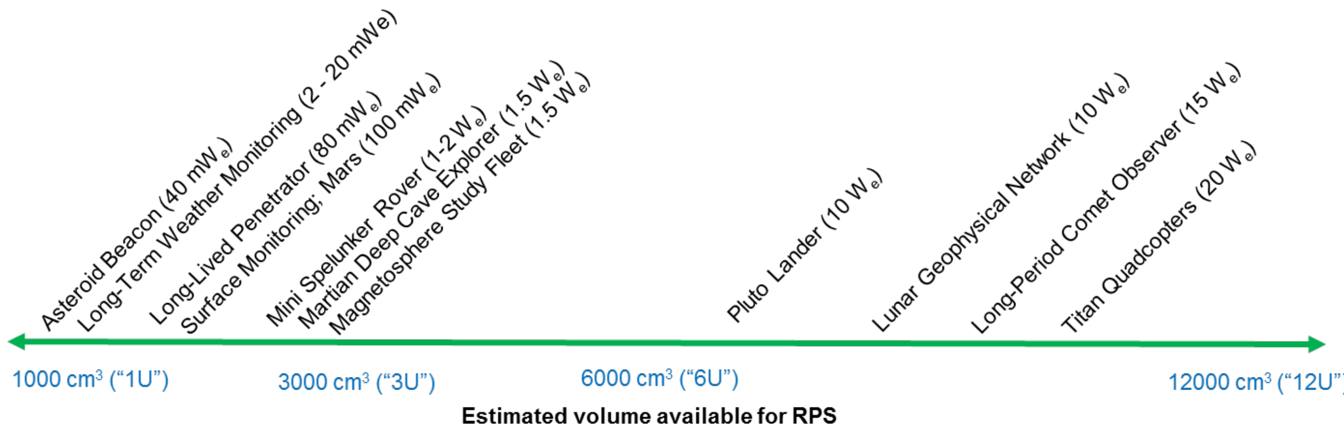

Fig. 3. The 11 studied mission concepts are populated on a size spectrum according to the estimated volume available for the RPS.

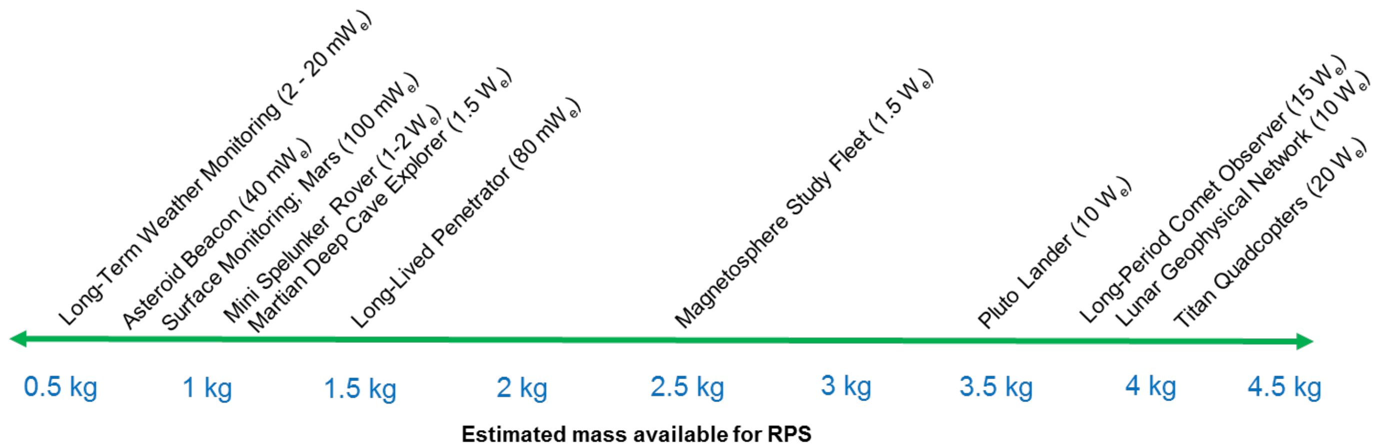

Fig. 4. The 11 studied mission concepts are populated on a mass spectrum according to the estimated mass available for the RPS.

IV. CONCLUSIONS

This study has concluded that there are a range of mission concepts that could be enabled or enhanced by small RPS with a power output of ≤ 40 W_e. These missions could enable otherwise impossible mission classes with unique and important science objectives. Given the strong trend amongst NASA and industry for small space missions and the current rise in technology development for small space systems and instruments, a small RPS could support a number of small science missions with lower cost, leveraging the current rise in technology development for CubeSat/SmallSat components and instruments.

Given the range of mission concepts identified, it may be advantageous to support the development of a 1 – 5 W_e RPS building block. A modular system of this scale could support mission concepts in the 1 – 20 W_e power requirement range. A system that fits within the CubeSat form factor could be useful, but for planetary science missions conforming to this form factor is not a top priority since small satellite missions do not imply that they must be CubeSats. In addition, it is suggested that a future small RPS support in-situ missions, which could require functioning in an atmosphere, as many of the identified mission concepts included measurements on the surface of planetary bodies.

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