National Aeronautics and Space Administration

RADIOISOTOPE
POWER SYSTEMS

Small RPS (<40 W_e) Mission Architectures

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POWER TO EXPLORE

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Agenda

- Mission Pulls for Small RPS
  - Study Rationale, Objectives, Assumptions and Approach
  - Potential Mission Concepts
  - Mission Concepts Power, Volume and Mass Spectrum
  - Conclusions and Considerations
  - Study Participants

Mission Pull for Small RPS

- Rationale
  - The RPS Program is interested in understanding the mission pull for small radioisotope power systems (1 mW_e - 40 W_e) in order to identify what future power system developments should be focused on.
    - » What types of missions are enabled or enhanced if there was a small RPS?
    - » What science questions could we answer?

- Objectives of Study
  - 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 average power draw
  - Determine the minimum amount of power required for a deep space small mission with RPS
  - Create a spectrum of potential mission ideas based on available power

Study Assumptions

- RPS assumptions:
  - Expect a power range of milliwatts to 10's of watts
  - For this study, the type of conversion technology won't be factored in
  - Small RPS that could generate 40+ W_e are already under consideration for further development
    - » Mission concepts that require 40+ W_e won't be considered for this study
  - Waste heat can be used for thermal control on the spacecraft

- Spacecraft systems assumptions:
  - A "CubeSat" is defined as a spacecraft that can be modeled as a series of 10x10x10 cm cubes (called "U"s), each having a mass of ≤ 2 kg
    - » The largest CubeSat is a 12U, measuring 20x20x30 cm with a mass of ~24 kg
  - A "SmallSat" is a spacecraft with a mass ≤ 100 kg that does not fit the CubeSat form factor
    - » Spacecraft with a mass greater than 100 kg will not be considered for this study
  - Other types of small missions that require < 40 W_e can be considered
    - » Example: small landers, micro-landers

Approach

- One day A-Team session at JPL
- Participants included:
  - Scientists
  - Instrument experts
  - Mission architects
  - CubeSat, SmallSat, small mission (i.e, small lander, micro lander) systems engineers
  - RPS experts
- Study structure:
  - Initial background presentation on small RPS and study goals
  - A group discussion on the current status and future plans for small instruments development
  - A group brainstorming session to identify types of mission classes that could be enabled by small RPS
  - Breakout groups to brainstorm and create mission architectures to populate the power spectrum using identified mission classes
  - Groups reconvene to brief each other and generate a final mission classes power spectrum

Mission Concept Trade Space Identification

- Identified a list of instruments that are available now or are expected to be available in the future for small spacecraft systems, including estimates for masses and powers
- Brainstormed a list of science objectives that could be accomplished with a small RPS mission
  - Questions were organized based on targeted destinations
- Brainstormed mission classes that could be enabled by small RPS
  - Small Landers
  - Small Rovers/Mobility Systems
  - SmallSat Swarms
  - Mother-Daughter craft

Mission Concept Generation

- Study participants were then split into three groups with representatives from the following areas:
  - RPS
  - Scientists
  - Mission Architects
  - Small Mission Systems Engineering
  - Instruments Engineers

- Groups worked from the identified instruments, science objectives, and mission classes to create potential mission concept architectures in more detail

- Individual groups then presented their mission concepts using a concept template to all participants

Concept Template

Short description of mission concept

Science objectives: a list of science questions about the target body or observation

Mission concept sketches

Concept Summary

- A summary of the mission and flight system
- Include details on the destination

Science Instruments

- List required instruments, including the accommodation requirements for spacecraft and RPS
- List science modes, CONOPs, and measurements taken
- Include other spacecraft requirements needed, when possible (ex. pointing)

RPS Requirements

- RPS power requirements
- Other requirements on the RPS
  - Volume
  - Mass
  - Thermal output
  - Packaging
  - Lifetime

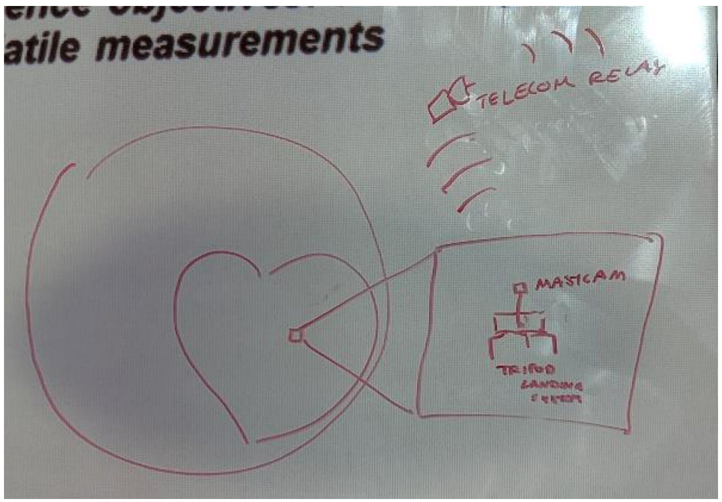
Mission Power Requirements

- Required power for mission modes
- Subsystem power requirements
- Other details on power system (i.e. battery sizing)

Pluto Lander

Description: A small, long-lived lander on Pluto.

Science objectives: Ice composition, trace elements, temporal information, volatile measurements



Concept Summary

- Cruise to Pluto with a carrier that orbits for telecom relay (10 year cruise)
- Propulsive landing – 1 km/s (20 - 30 kg propellant)
- Remain on surface for ~10 years
- Waste heat for thermal management
- Lander dry mass: 40 kg

Science Instruments

- Mast camera, GCMS, IR Spectrometer/Raman
    - Per instrument: 2-3 kg, 10 W_e active
    - Minimal survival heating requirements
- Thermal: passive cooling system for instruments off of cold side of RPS
- CONOPS: Camera takes a picture every hour, GCMS daily measurements, IR Spectrometer every hour

RPS Requirements

- Power requirement: 10 W_e EOL
    - Estimated thermal output: 110 W_t
- Lifetime: 20 years
- Mass: 3-4 kg
- Volume: 6 inch diameter, 6 inch tall

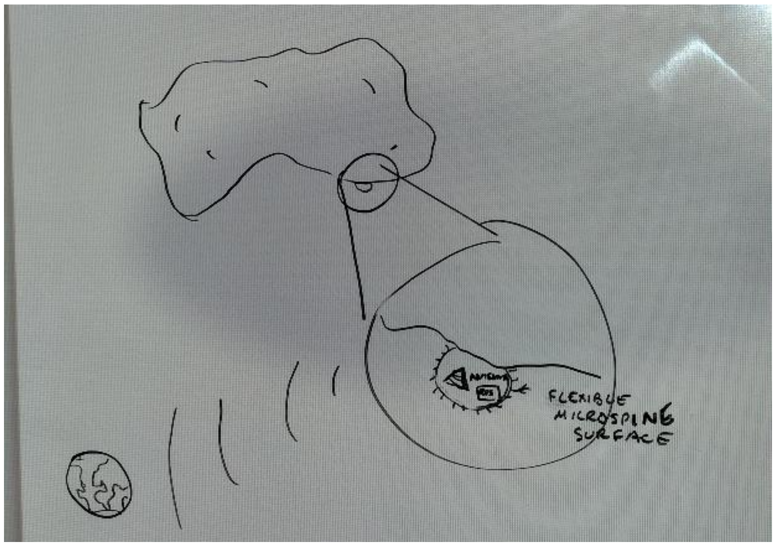
Mission Power Requirements

- Power modes: Science -> recharge -> telecom -> recharge
    - Telecom – 4 W_e transmitter
    - Science - 10 W_e per measurement, 1 measurement at a time

Asteroid Beacon

A small system that attaches to asteroids and provides pings for increased tracking accuracy

Science objectives: Origin science of the solar system, planetary defense



Concept Summary

- A small flight system that attaches to near Earth asteroids
- Provides pings for tracking
- A carrier spacecraft (SEP) travels to NEA and drops off small spacecraft
- Attaches with microspine gripper
  - No power required for attachment

Science Instruments

- Transmitter: 10 mW_e
  - Note: DSN can receive signals of 10^{-19} W
- Always transmitting
- Note that thermal analysis needs to be done to determine if 1 W_t can provide enough survival heat

RPS Requirements

- Power: 40 mW_e
- Thermal output: 1 W_t
- Could use the RHU as a heat source (rated for 10,000 g)
- Volume: 2-3 inch diameter, 4-5 inch tall
- Mass: 0.8 kg

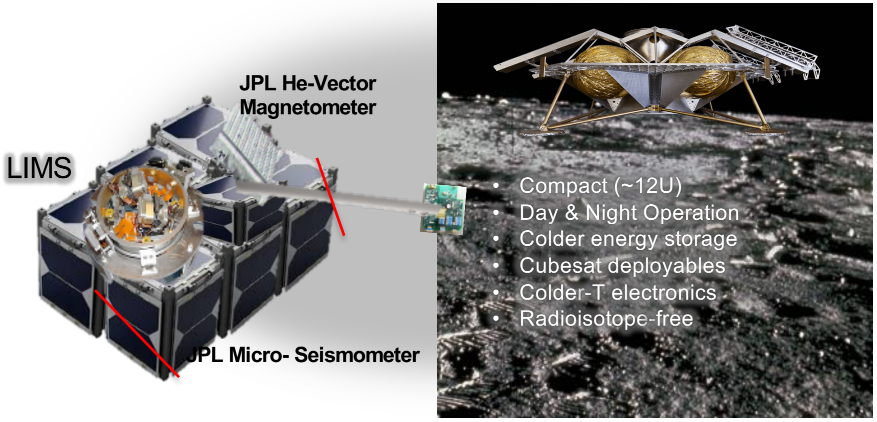
Mission Power Requirements

- Carrier spacecraft has it's own power system during cruise
- Constantly transmitting pings

Lunar Geophysical Network

Network of very small packages for seismometry and magnetometry.

Science objectives: Study structure and composition of Lunar interior



Concept Summary

- ~250 kg lander package, 30 kg, 12U payload
- Deployable radiators
- Quantity: 4
- 6 year mission
- Study structure and composition of Lunar interior
- Possible need for network communication relay

Science Instruments

- Seismometer: 0.1 W_e to 1 W_e
  - **Need robotic arm to deploy on lander**
- Magnetometer: <1 W_e
  - Deployable boom

RPS Requirements

- 10 W_e end of mission required
- Other requirements on the RPS
  - Volume: < 10x20x30 centimeter (6U)
  - Mass: 4 kg
  - Thermal output: 100 W_t
  - Packaging: integrated into payload
  - Lifetime: 6 years

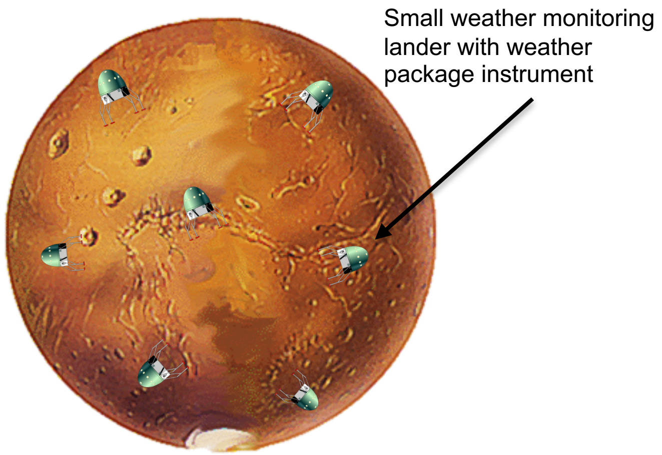
Mission Power Requirements

- Continuous Science Recording, no computer: 3 W_e
- Need power periodically for telecom, once daily
  - X-Band IRIS, ~35 W_e
- Need approx. 150 Wh backup Li-Ion battery capacity for telecom and other systems in standby
  - Trade: RPS power vs. solar array for batteries

Long-Term Weather Monitoring; Mars

A weather monitoring package that can be deployed on Mars (Venus, Titan).

Science objectives: monitor weather and atmospheric patterns from the surface.



Concept Summary

- Low-power weather monitoring on the surface.
- Weather package operates every 10 seconds for TBD seconds, requires 10 mW_e
- Other instruments require ~1 mW_e continuous
- Sends data back to an orbiter, twice a day 1 min each
- Life driven by RPS and instrumentation lifetime
- > 10 year mission

Science Instruments

- Temperature
- Pressure
- Wind speed
- Weather package for 10 mW_e
- Geophone
- Transmitter

RPS Requirements

- 2 to 20 mW_e
- > 10 year mission
- Mass: TBD
- Volume: TBD

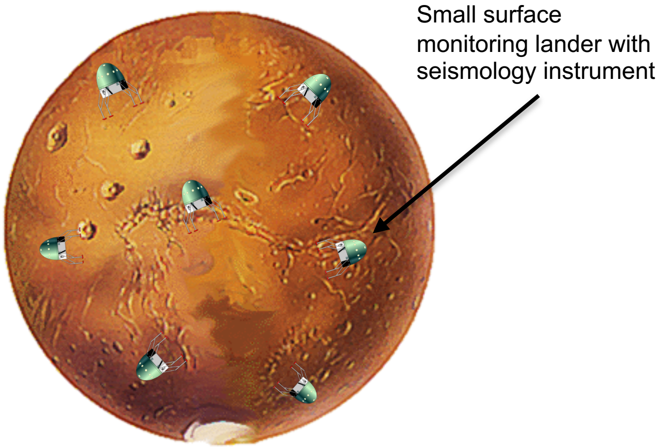
Mission Power Requirements

- 1 to 10 mW_e for instrumentation depending on duration of readings from weather package
- 1 W_e transmitter

Surface Monitoring; Mars

A surface monitoring package that can be deployed on Mars (Venus, Titan).

Science objectives: monitor seismic events and model interior structures from the surface.



Concept Summary

- Low-power continuous seismic monitoring on the surface.
- Sends data back to an orbiter, twice a day 1 min each
- Life driven by RPS and instrumentation lifetime
- > 10 year mission

Science Instruments

- Seismic package (50 mW_e)
  - Instrument needs to be isothermal
- Transmitter

RPS Requirements

- 100 mW_e
- > 10 year mission
- Mass: TBD
- Volume: TBD

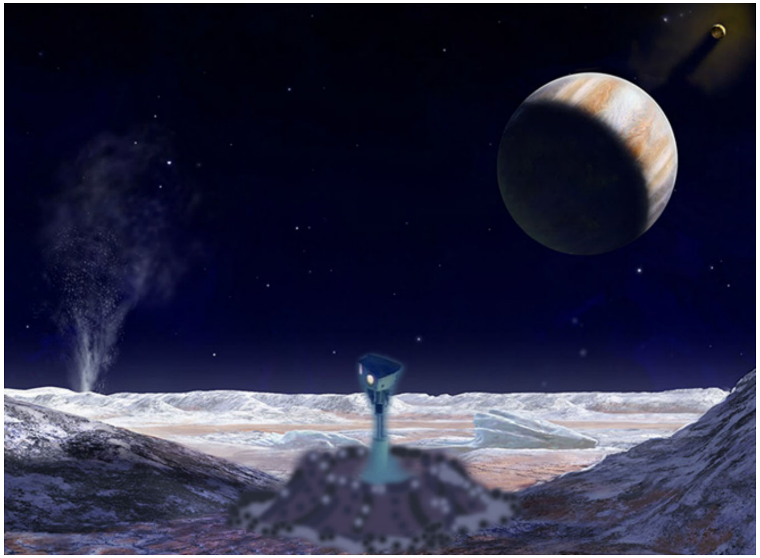
Mission Power Requirements

- 50 mW_e for instrumentation for continuous readings from seismic package
- 1 W_e transmitter

Long-Lived Penetrator

Long-lived penetrator targeting outer planet moons, comets, asteroids, etc.

Science objectives: Geophysical assessment and temporal monitoring of distant bodies and near-surface crust characterization.



Concept Summary
- Subsurface penetrator delivered by orbiter spacecraft to distant bodies (e.g. Jovian and Saturnian moons or small bodies)
- Launch 4 or more per body
- Uses RPS to perform low-power operations and charge capacitor for periodic data return
- Requires an orbital asset to relay data

Science Instruments
- Seismometer (0.05 W_e, 100% duty cycle)
- Dialectric Spectrometer (0.01 W_e, low duty cycle)
- Thermal Conductivity Probe (1 W_e, low duty cycle)

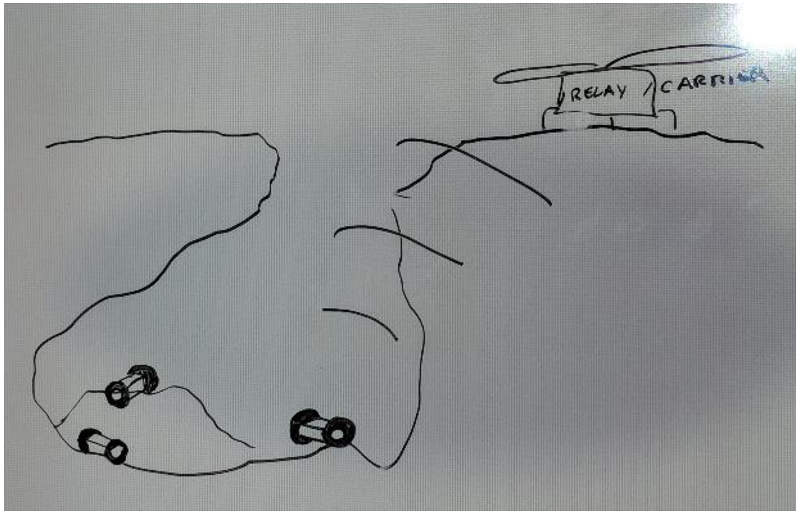
- ~80 mW_e EOM
- Other requirements on the RPS
  - Diameter < 10 cm, Length < 15 cm
  - Mass < 2 kg
  - ~3 W_t thermal
  - Needs to withstand 10,000 g landing loads
  - 15 year Lifetime

Mission Power Requirements
- Seismometer requires 50 mW_e constant.
- Supercapacitor for higher power modes
  - Telecom, spectrometer, and thermal probe operation

Mini Spelunker Rover

A small rover that is dropped into a cave/lava tube

Science objectives: Map cave interior, cave composition (reflectivity), ice mapping, temperature, pressure, relative humidity



Concept Summary

- Could be dropped by a helicopter or larger rover
- Wheeled mobility system
- About the size of a shoebox
- Explores the cave to map the interior with radar/lidar
- 4 x 6 x 12 in for rover
- Communication back to rover/helicopter with UHF transceiver
- Could have multiple rovers that communicate with each other

Science Instruments

- Radar/Lidar: interior mapping
  - ~100 mW_e radar
  - ~100-500 grams
- Dosimeter: radiation levels, 400 mW_e, 20 g
- Temperature, Pressure, Relative Humidity: ~ 50 mW_e, 75 g

RPS Requirements

- Power: 1 – 2 W_e
- Thermal output: 25 W_t
- Could use multiple RHU (10-25) as a heat source
- Volume: 6 inch diameter, 4 – 5 inch tall
- Mass: 1 kg
  - Puffer can accommodate this mass

Mission Power Requirements

- Power modes:
  - Science – 550 mW_e
  - Driving – 1 W_e
  - Transmitting – 1 W_e

Martian Deep Cave Explorer

Science objectives: Explore Martian caves and seek potential habitability

Concept Summary

- One larger rover deploys a network of 16 small rovers into the cave
    - Small rovers are powered by small RPS
- Small rovers communicate through each other to the large rover, which relays data to an orbiter
- Small rovers study and map the interior of the cave

Science Instruments

- Temperature and Pressure (1 mW_e)
- Visible near-IR camera with light source and dosimeter (1 mW_e, capacitor charge)
- Mapping Lidar (1 W_e), Penetrometer (1 mW_e)
- IR and passive NMS spectrometer (50 mW_e)
- Magnetometer (50 mW_e)

RPS Requirements

- 1.5 W_e
- Must be magnetically clean
- As low mass as possible for mobility
- Volume: TBD

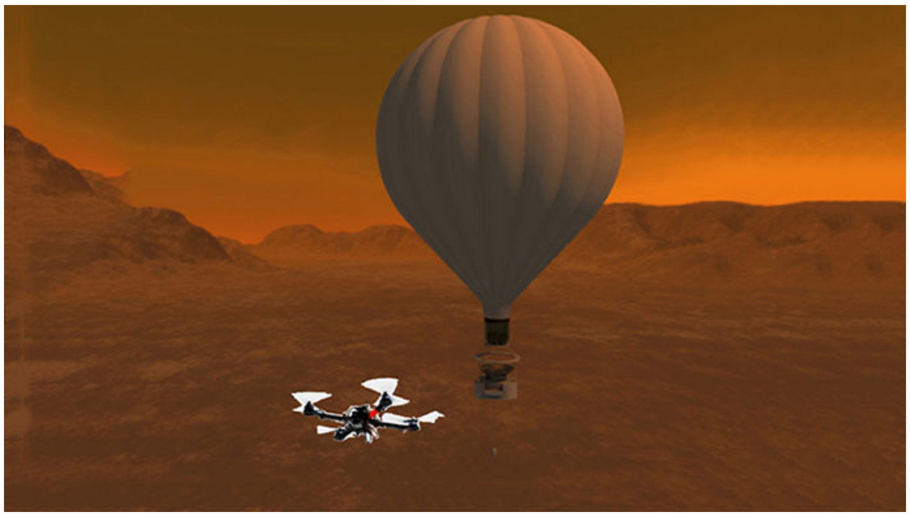
Mission Power Requirements

- 1.5 W_e

Titan Quadcopters

Titan balloon with RPS-powered quadcopters to fetch samples

Science objectives: Compositional characterization of Titan's surface, both solid and liquid, across wide geographic ranges



Concept Summary

- Deploy quadcopter "gofer" drones from constant-altitude balloon to investigate surface and return samples for analysis by instruments on balloon
- Multiple drones capable of near-continuous flight
- ~10 kg drone mass

Science Instruments

- Camera for context and surface imaging
- Sample collection device for solid and liquid surface samples

RPS Requirements

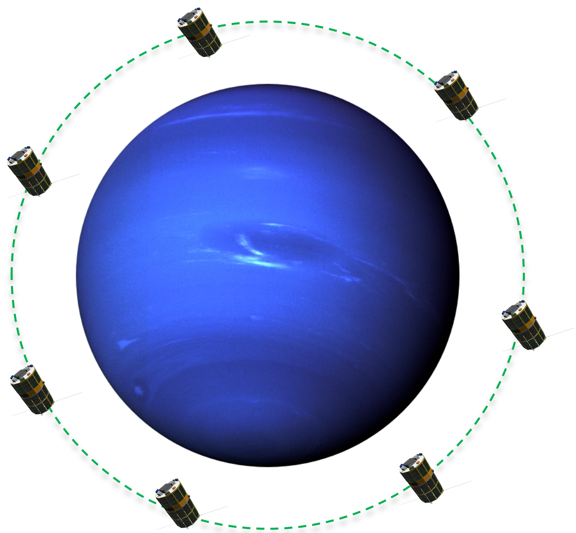
- Need ~20 W_e for unlimited mobility and science
- Other requirements on the RPS
  - Volume: disk 30 cm diameter x 10 cm height
  - 3-5 kg
  - Needs to have thermal design compatible with operation in Titan environment
  - Lifetime 15 years (mission)

Mission Power Requirements

- ~15 W_e for flight
- RPS should provide all power – no battery required

Magnetosphere Study Fleet

Science objectives: characterize the variation of the magnetosphere over a year. Potentially understand magnetosphere rotation for Uranus / Neptune.



Concept Summary

- 16 SmallSats deploy from a larger spacecraft to orbit the target destinations
- SmallSats are spin stabilized; no active attitude control

Science Instruments

- Magnetometer (10 mW_e)
- Electric field (10 mW_e)
- Particle analyzer (1 W_e; 10% duty cycle)
- Plasma wave spectrometer (10 mW_e)
- Telemetry to mother spacecraft (5 W_e; 20% duty cycle)
- *Instruments need to be developed to meet power levels*

RPS Requirements

- 1.5 W_e
- 10 - 13 year cruise, 1 - 5 year orbit
- Mass: TBD
- Volume: TBD

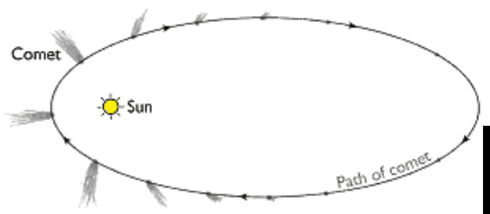
Mission Power Requirements

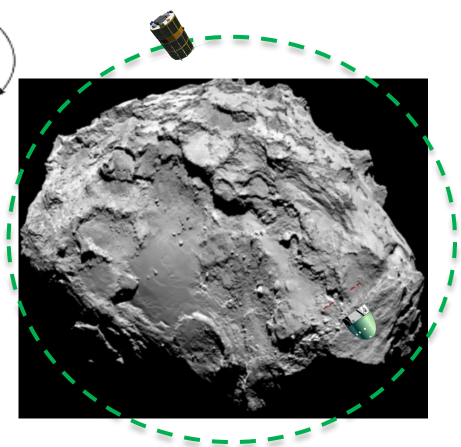
- Excluding main mothership orbiter
- ~1.4 W_e for instruments average power
- ~0.1 W_e for command data systems
  - This is *challenging*

Long-Period Comet Observer

Most of the time it is on the surface (far from sun); otherwise orbits.

Science objectives: long-term science study of a comet.





Concept Summary

- Long-lived (~75 year) comet observer, orbiting then package drop (or orbiter lands)
- Time-capsule concept: uses solar power when close to Sun and RPS when far from Sun
- Land a seismic package
- Monitor outgassing, comet dust, radiation environment, charging and magnetic fields, comet jets, chemical evolution
- Could have battery lifetime issues

Science Instruments

- Seismic package (1 W_e), Langmuir probe (0.5 W_e)
- GC-MS mass spec (16 W_e; 0.01 W_e average power)
- Quartz crystal microbalances (0.05 W_e)
- Visible camera (1 W_e)
- Ground penetrating radar (10 W_e; 5 min / week)
- Millimeter spec (7 W_e; 10 min / 24 hr), Dosimeter (0.05 W_e)

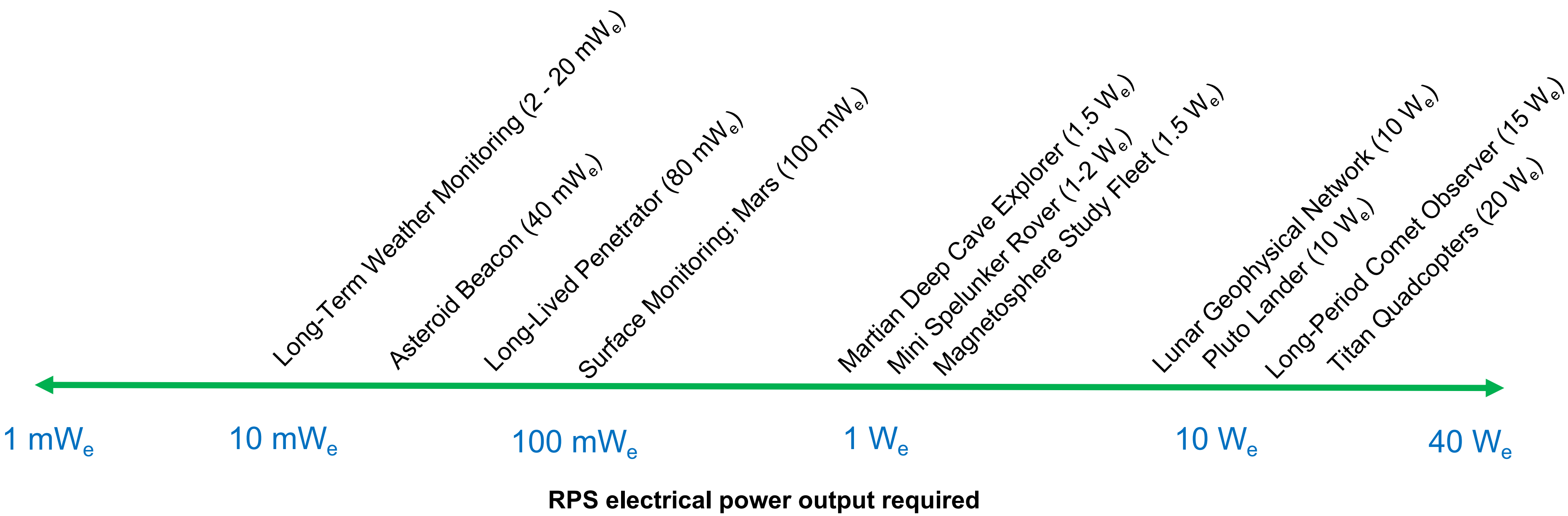
RPS Requirements

- 15 to 20 W_e (based on a quick ciphering of the other power requirements, should be verified)
- Use the RPS thermal output to keep flight instruments at required temperatures
- Mass: TBD
- Volume: TBD

Mission Power Requirements

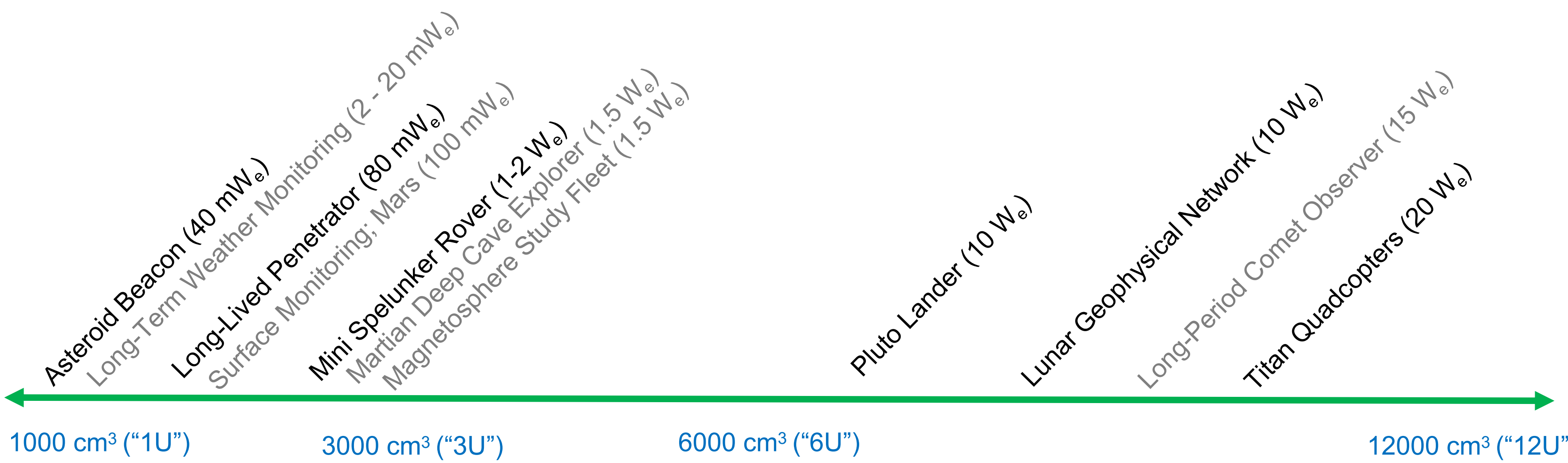
- Keep warm for instrumentation (5 W_t)
- Orbiter (4 W_e)
- Telemetry (60 Wh per week)
- Needs large batteries for trickle charging
- REP required for orbit maintenance (few watts)
- Attitude control (15 W_e) (problem, orbiter only)

Mission Concepts Power Spectrum



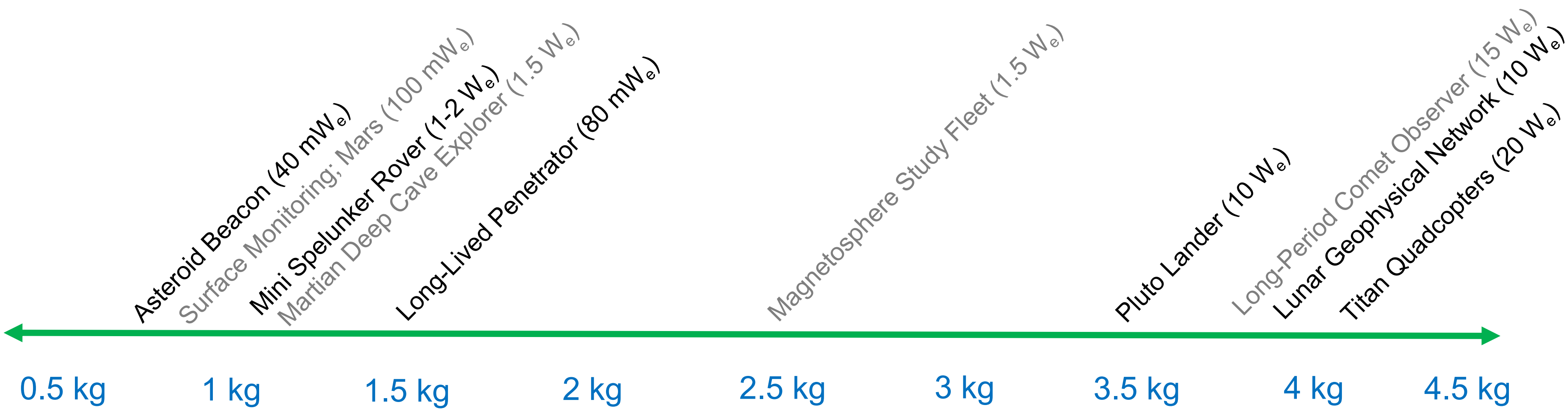
- The mission concepts are presented here in terms of required electrical power output from the RPS
- Potential mission concepts were identified across the power spectrum

Mission Concepts Size Spectrum



- The mission concepts are presented here in terms of estimated volume available for RPS
  - The RPS size estimates were based on GPHS experiences. Future RPS based on other heat sources may differ.
- Concepts in grey did not estimate a size during the study, but were estimated by the Mission Analysis team post-study

Mission Concepts Mass Spectrum



- The mission concepts are presented here in terms of estimated mass available for RPS
  - The RPS mass estimates were based on GPHS experiences. Future RPS based on other heat sources may differ.
- Concepts in grey did not estimate a mass during the study, but were estimated by the Mission Analysis team post-study

Conclusions

- There are a range of mission concepts that could be enabled by small RPS with a power from 1 mW_e – 40 W_e
  - Concepts from this study were concentrated in range 2 mW_e – 20 W_e
  - Prior 2004 "Enabling Exploration with Small Radioisotope Power Systems*" study mission pull findings covered 51 mission concepts (landers, rovers, sub-satellites, and deployable mini-payloads) in a similar power range from 5 mW_e – 50 W_e
- These missions could enable otherwise impossible mission classes with current/near-term technology
- A widely available small RPS could enable a great number of small science missions with lower cost
  - Leveraging the current rise in technology development for CubeSat/SmallSat components and instruments
- There is a strong trend amongst NASA and industry for small space missions
  - RPS can support and enhance this

** Enabling Exploration with Small Radioisotope Power Systems, NASA Jet Propulsion Laboratory, JPL Pub 04-10, September 2004*

Considerations for the RPS Program

- The RPS Program may want to consider development of a new system for small missions
  - A 1 – 5 W_e RPS building block may have a number of uses
  - Modularity of the system could allow for adaptability to a number of mission concepts in the 1 – 20 W_e power requirement range
- Future small RPS systems should accommodate in-situ missions and instruments
  - Many identified mission concepts were on the surface of planetary bodies
  - Some of these destinations have atmospheres that the RPS would need to operate in
- 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
  - Small satellite missions do not imply that they must be CubeSats

Study Participants

- **RPS Program Office**
  - Young Lee (Client Lead)
  - Brian Bairstow (RPS Systems)

- **A-Team**
  - Alex Austin (Study Lead)
  - Jonathan Murphy (Assistant Study Lead)
  - Steve Matousek (Facilitator)
  - Melissa Brown (Logistics)

- **Subject Matter Experts**
  - Jean-Pierre Fleurial (RPS Power)
  - Terry Hendricks (RPS Power)
  - Aaron Noell (Instruments)
  - Pamela Clark (Instruments)
  - Morgan Cable (Science/Instruments)
  - John Elliott (Mission Architecture)
  - John Brophy (Mission Architecture)
  - Valentinos Constantinou (Data Science)
  - Bill Smythe (Planetary Science)
  - Alan Didion (SmallSat Systems Engineering)
  - Macon Vining (SmallSat Systems Engineering)
  - Kristina Hogstrom (SmallSat Systems Engineering)
  - Colin Sheldon (SmallSat Systems Engineering - APL)
  - Kalind Carpenter (Small Missions, Robots and Instruments)

Note: SMEs are from JPL unless specified

Questions?