Deployable Mini-Payload Missions Enabled by Small Radioisotope Power Systems (RPSs)

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Abstract

Deployable mini-payloads are envisioned as small, simple, standalone instruments that could be deployed from a mother vehicle such as a rover or the proposed Jupiter Icy Moons Orbiter to key points of interest within the solar system. Used in conjunction with a small radioisotope power system (RPS), these payloads could potentially be used for long-duration science missions or as positional beacons for rovers or other spacecraft. The RPS power source would be suitable for deployable mini-payload missions that would take place anywhere there is limited, intermittent, or no solar insolation. This paper introduces two such concepts: (1) a seismic monitoring station deployed by a rover or aerobot, and (2) a passive fields and particles station delivered by a mother spacecraft to Jupiter.

Introduction

Deployable mini-payloads would be small, standalone instruments with low power requirements (tens of milliwatts to a few watts) that could take scientific measurements of a localized area or an entire region depending on how many units were deployed. Alternately, mini-deployable payloads could include non-scientific applications such as positional beacons that would be dropped off by rovers or aerobots for precise positional marking or transponders to extend the communications range of rovers, cryobots, aerobots or spacecraft. Combined with a conceptual small radioisotope power system (RPS), the range of operation of these instruments could be extended throughout the solar system and the mission duration could be measured in years or decades. This paper describes two conceptual mini-deployable scientific payloads, a seismic monitoring station (SMS) and a passive fields and particles (PFP) monitoring station, that could be deployed from a mother vehicle to various points of interest.

Seismic Monitoring Stations (SMS)

Seismic monitoring stations could be used to detect and measure a target body's seismic activity to determine its interior structure, composition, and physical state. These stations could potentially be deployed from a rover or an aerobot, and would be designed to be simple, low-power, and lightweight. Each station would contain five key subsystems: a science instrument, avionics, communications, thermal control, and power. The station would be powered via a body-integrated small-RPS unit. Figure 1 shows a potential concept for a seismic monitoring station. With the exception of thermal and power, all of the subsystems would be housed within the upper portion of the seismic monitoring station. The small-RPS would make up the bottom structure along with thermal radiators used to reject excess RPS heat and to provide a stable base.

SMS Science and Mission Objectives

Seismic monitoring stations powered by RPSs would allow seismic activity to be monitored on bodies in both the inner and outer solar system, in areas of limited sunlight, over long periods of time. The outer solar system contains bodies such as the icy Jovian moons, Europa, Callisto, and Ganymede. Scientists believe an ocean may lie beneath Europa's icy surface, making it one of the best candidates for potential life in our solar system [1]. A network of seismic monitoring stations could monitor Europa's seismic activity to determine crustal thickness. The stations could also be used to determine if Europan seismic and, perhaps, cryovolcanic activity is driven by tidal forces as seen on Earth [2]. Similarly, Ganymede has a distinct grooved terrain that appears to be tectonically produced. Seismic monitoring stations could determine crustal thickness and structure and provide insight on how these grooves were formed.

The inner solar system includes areas such as the polar regions of both the Moon and Mars. A seismic monitoring station could be deployed in the shadowed craters of the Moon to observe lunar quakes, learn about subsurface conditions, seismically image the subsurface, and aid in understanding how the Moon was formed. Seismic activity is also believed to have occurred on Mars, making it another viable candidate for seismic monitoring [3].

Seismic monitoring stations could be piggybacked onto larger missions involving a rover or aerobot, the "mother vehicle." The mother vehicle could deploy a single monitoring station or an entire array of stations depending on the coverage area and available payload capacity of the mothership. The stations would then communicate with the mother vehicle, which would relay data back to Earth.

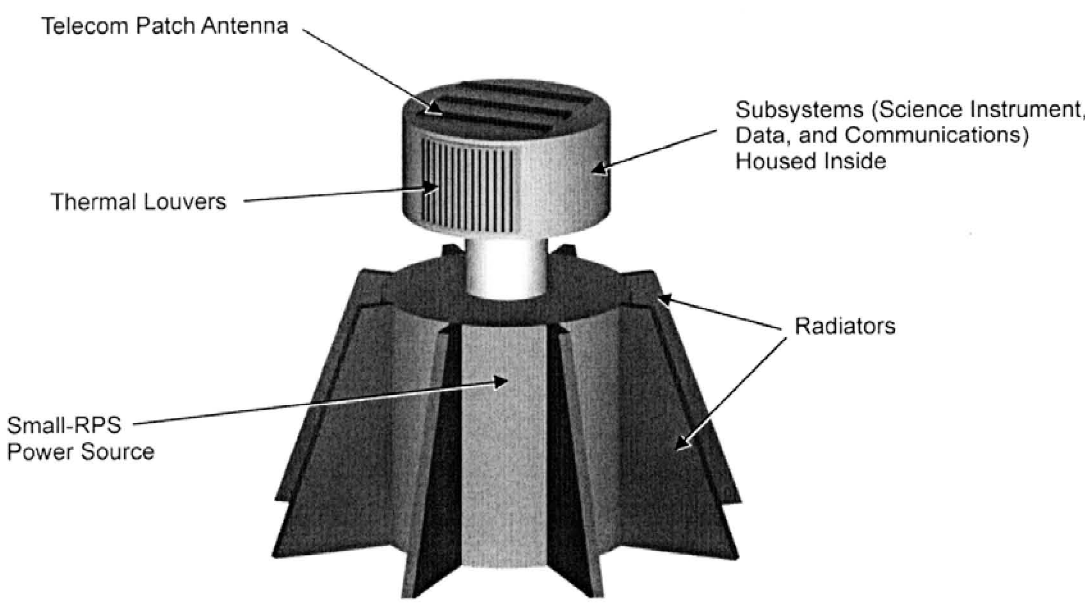

Figure 1. Configuration concept for a seismic monitoring station

SMS Mission Architecture

Because they would be small and lightweight, many seismic monitoring stations could be loaded onto a rover or aerobot for eventual deployment. The science community would determine where to place the monitoring stations before launch, based on prior knowledge of the planet; or the mother vehicle could determine the location based on information it obtains on or near the surface.

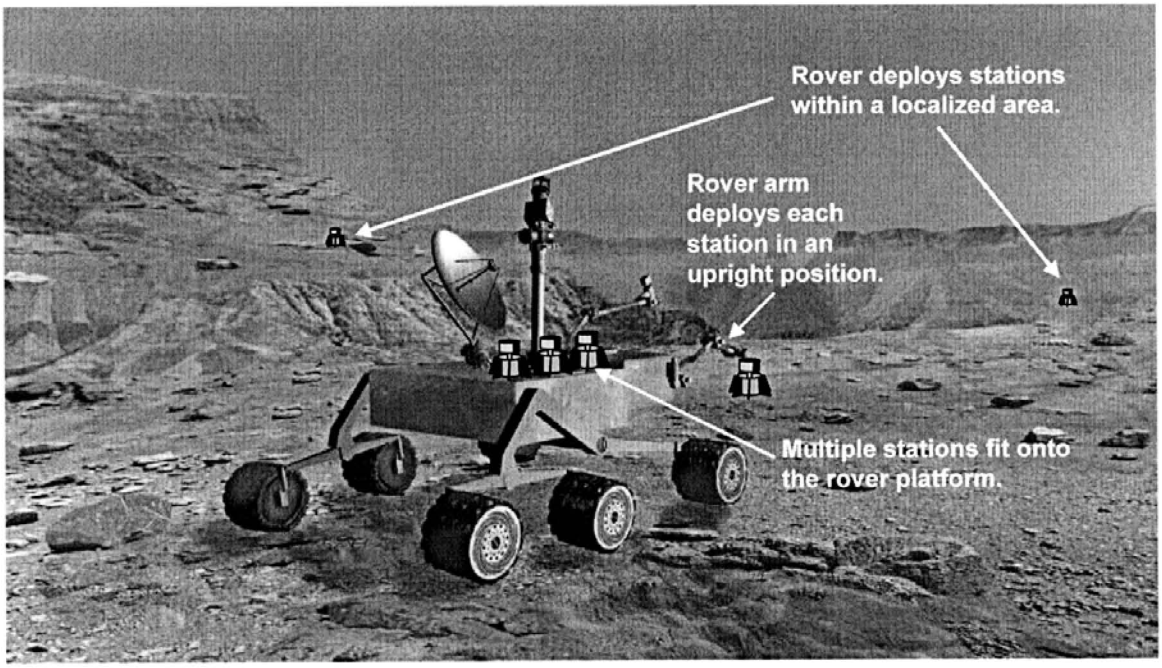

Figure 2. Seismic monitoring stations deployed via a rover to monitor a localized area.

If necessary, the rover could prepare the surface for deployment (e.g., remove debris or obstacles) before the rover arm deploys the station onto a suitable location, ensuring adequate contact with the ground. One rover could deploy the stations to a localized area of the planet for surface mapping, as illustrated in Figure 2. Two rovers could be used to deploy seismic monitoring stations to different regions of a planet, similar to the Mars Exploration Rovers. Deployment via rover could be used to study localized areas and is limited only by the range of the rover itself.

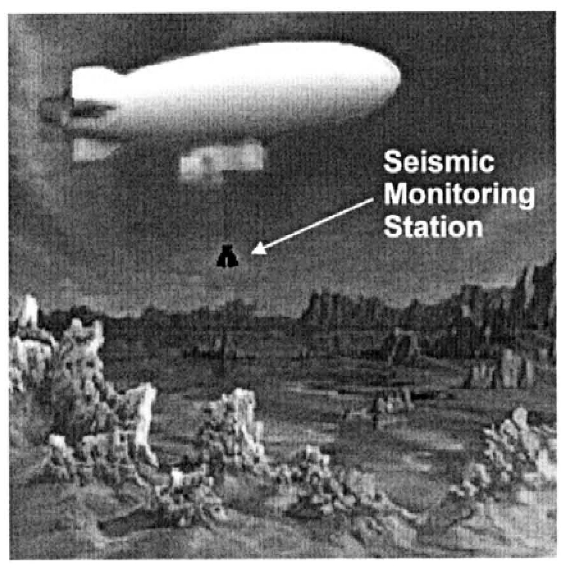

Figure 3. Conceptual Deployment of a Seismic Monitoring Station by an Aerobot

Alternatively, aerobots (balloons and blimps) could deploy the seismic monitoring stations to achieve a more global reach. This concept is similar to the aerial drop-off probes proposed for Titan. The aerobot could descend near the planet's surface, release the seismic monitoring station, ascend, move to the next monitoring location and repeat until all of the stations were deployed (Fig. 3).

Seismic monitoring stations would communicate with a mother vehicle (e.g., an orbiter or rover) that then communicates with Earth. The mother vehicle would provide position and attitude information for these stations at the time of drop-off, allowing the stations to be as simple as possible. The stations could potentially take measurements for more than 10 years, conceivably limited only by the lifetime of the relay element.

SMS Small-RPS Characteristics

The power source proposed for this type of mission is a conceptual RPS based on a single General Purpose Heat Source (GPHS) fuel capsule using thermoelectric (TE) power conversion technology [4,5] as shown in Figure 4. It has a mass of ~2 kg, and produces approximately 62 Wt of thermal output and 3 We of electrical output at beginning of life (BOL). Due to radioactive decay of the plutonium fuel ($T_{1/2}$=87.8 years) and degradation of the thermoelectric material, the power output at the end of a 10-year mission would be decreased to ~57 Wt and 2.6 We.

The TE operating temperatures of the conceptual RPS are estimated at approximately 550 °C (hot side) and 155 °C (cold side).

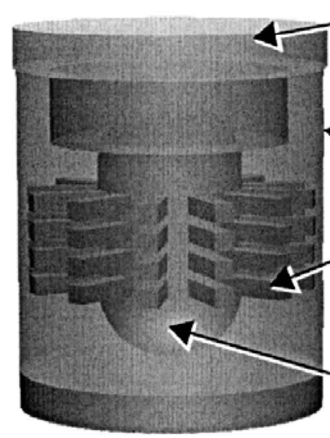

Figure 4. RPS Power Source Concept for the Seismic Monitoring Station

SMS Science Instruments

The science instrument proposed for this application would be a JPL micro-seismometer [6], illustrated in Figure 5. This instrument has a micro-machined silicon suspension. The suspension has a 10 Hz resonance, a 6×10^{-9} m/s^2/Hz noise floor, and a UHF capacitive displacement with a sensitivity of 5×10^{-13} m/Hz. The transducers are arranged in a tetrahedral configuration to provide 3 components of acceleration, in addition to a redundant transducer. It is 5 cm along the edge, and has an acceleration sensitivity better than 10^{-8} m/s^2 over a frequency range of 0.01–100 Hz.

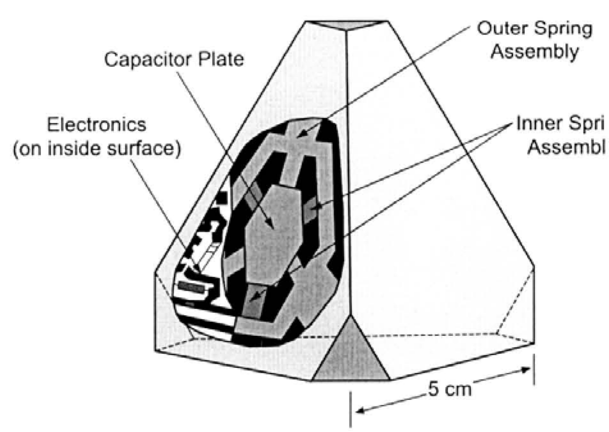

Figure 5. JPL Micro-seismometer

SMS Data

The JPL micro-seismometer would continuously record seismic data during the science mission, and it is the station's avionics subsystem that would process it. The proposed avionics subsystem is based on that designed for the MUSES-CN Nanorover [6], and would consist of a Mongoose CPU, SRAM, EEPROM, digital/analog input/output, and power supplies and switches. The flight electronics are based on the Synova R3000 32-bit flight processor, fabricated on the Honeywell rad-hard Foundry production line, and a radiation hard custom gate-array. In addition, 2 MB of rad-hard RAM and 1 MB of rad-hard EEPROM would be used.

The output data rate from the JPL microseismometer would depend on the sampling rate, which in turn depends on the seismic frequency range of interest. Sampling at 5 Hz with 16-bit samples (each of three axes) yields a total data rate of ~ 240 b/s. Achievable data compression for this instrument was not assessed but could potentially reduce the data rate significantly.

SMS Communications

The communications subsystem of the seismic station would be based on that developed for the MUSES-CN mission [6]. It would consist of an L-band (1900 MHz PCS) transceiver with a matching transceiver on the mother vehicle. This system was designed to provide a 9.6 kbps data rate at a range of 20 km at up to 1 radian off-axis of the station top surface normal. The receive antenna must be pointed at the station within 0.1 radian. This system could conceptually provide a data rate on the order of 96 bps to an orbiter 200 km away (assuming the data rate scales as $1/R^2$).

The telecom subsystem would be fabricated from commercial radiation hardened gallium arsenide (GaAs) packaged parts. Clock recovery and Manchester decoding would be implemented in a radiation hardened field-programmable gate array. The MUSES-CN antenna is a right-hand circularly polarized square patch with an offset-pin feed, but other antenna configurations could also be considered for this application. The seismic station's communication system would occupy a single board with dimensions of approximately 12 cm x 6 cm x 2 cm.

SMS Thermal

The baseline thermal control system of the seismic monitoring station would rely on using passive means to maintain and regulate system temperatures, and would include multilayer insulation (MLI), low thermal conductance materials, louvers, and/or thermal coatings. Additionally, RPS waste heat could be used to keep the station electronics warm in cold environments, and the body-integrated radiator fins would be used to radiate and conduct excess heat to the local environment. Preliminary conductive heat transfer calculations indicate that on the surface of Titan (T~94 K), one of these stations could passively maintain an interior temperature of 155 °C using ~25 Wt. The remaining waste heat would be rejected via conductive coupling to the Titan atmosphere and regulated using thermal louvers.

SMS Power

The seismic monitoring station would have two basic power modes: *Science Data Acquisition* (Mode A) and *Science Data Acquisition with Downlink* (Mode B). In Mode A, the station would continuously collect seismic data and store it in internal memory. This mode uses ~1.4 We of power (including a 50% contingency). In Mode B, the station would continuously collect data while simultaneously downlinking it to a rover or orbiter for eventual relay to Earth. This mode uses ~2.5 We of power (including a 50% contingency). Using the small RPS power source described in section 2.4 would permit over 10 years of continuous operation based on the end of mission (EOM) RPS power output of 2.6 We. The modes and the subsystem power levels are summarized in Table 1.

Table 1. Seismic Monitoring Station Power Modes

Subsystem	Mode A (We)	Mode B (We)
Instrument	0.10	0.10
C&DH	0.81	0.81
Telecom	(off)	0.75
Subtotal	**0.91**	**1.67**
50% contingency	0.46	0.83
Total	**1.37**	**2.49**

The power subsystem hardware would be based on a concept developed by JPL's Team A for a micro-rover powered by a small (milliwatt-class) radioisotope power source [7]. The power subsystem would take the electrical power output from the small-RPS and convert it to the different voltages required for the various SMS subsystems. It would also provide power regulation and switching functions. This particular design includes a small Li-Ion battery to accommodate applications with short periods of higher power use. Figure 6 shows a block diagram of the seismic monitoring station's power electronics and subsystems.

SMS Mass

The seismic monitoring stations would be designed to be lightweight, with an estimated total mass of approximately 6.6 kg, including 50% contingency (Table 2). The heaviest subsystem of the seismic station is the RPS power source estimated at 3 kg, followed by the structure (with integrated thermal control fins) weighing ~2 kg. The remaining subsystems (instruments, avionics, communications and thermal) jointly weigh less than 1 kg.

Table 2. Seismic Monitoring Station Mass Summary

Subsystem	CBE Mass (kg)	Margin (50%) (kg)	Mass Allocation (kg)
Instrument	0.10	0.05	0.15
Avionics	0.15	0.08	0.23
Communications	0.53	0.03	0.08
Thermal	0.30	0.15	0.45
Small RPS	2.00	1.00	3.00
Structure	1.32	0.66	1.98
Total	**4.4**	**2.2**	**6.6**

SMS Radiation Environment

The seismic monitoring station would be exposed to externally produced (natural) and internally produced radiation during the course of its mission. Key sources of natural radiation include the Van Allen radiation belts traversed during the Earth egress, cosmic radiation received during the cruise phase, and the inherent radiation environment of the final mission destination. As a result, the seismic station would potentially be exposed to gammas, neutrons, and other high-energy particles. Internal radiation would be generated from the decay of the plutonium fuel within the GPHS fuel capsules and from resulting secondary fission reactions that occur due to fuel impurities.

The seismic monitoring station would be inherently radiation tolerant due to the selected use of radiation hardened components and subsystems as previously discussed,. However, as external radiation levels are site specific, they would need to be assesed for a specified location and duration in order to determine whether any additional shielding would be necessary to meet the station's lifetime requirements. It is expected that the external radiation environment, not the relatively mild RPS environment, would drive the total radiation dose and any shielding requirements.

Passive Fields and Particles (PFP) Monitoring Station

The passive fields and particles monitoring station is the second deployable mini-payload concept considered in this study. It would be used to study magnetic fields and radiation levels of the target destination. As with the seismic monitoring station concept, each PFP station would be designed to be simple, low power, and lightweight, and would use a small-RPS power source.

PFP Science and Mission Objectives

Passive fields and particles monitoring stations could be deployed in Jupiter's magnetosphere, a huge region of electrically charged particles and magnetic fields surrounding the planet. Jupiter's magnetosphere resembles a smaller version of that of the Sun, and thus studying it would contribute to our knowledge of the behavior and evolution of magnetospheres in general [6].

The science goals of the passive fields and particles (F&P) monitoring station concept would be to conduct F&P experiments observing the plasma environment in Jupiter's magnetosphere. This could involve a search for evidence of subsurface liquid water on Jupiter's icy moons using magnetic field measurements, the interaction of satellites with the Jovian magnetosphere, the radiation environment of the icy satellites, and studying the structure of the satellite magnetospheres and ionospheres.

The PFP would be a simplified version of the fields and particles subsatellite concept proposed by Randolph [10] except that this monitoring station would be smaller, have no propulsion system, and would use a small APS star camera to provide attitude knowledge.

PFP Mission Architecture Overview

The PFP stations would rely on the mother vehicle for launch, deployment, and data transmission back to Earth. Because they would be designed to be small and lightweight, multiple passive fields and particles monitoring stations could potentially be carried on the mother vehicle. Deployment of the PFP would be performed by the mother spacecraft once the desired Jovian orbit had been obtained.

PFP Small-RPS Characteristics

The power source for the PFP mission would be a conceptual RPS using two GPHS fuel capsules and thermoelectric power conversion technology [4]. As conceived, it would have a mass of approximately 3 kg, and produce ~125 Wt and 6.25 We at BOL with an initial conversion efficiency of 5%. The corresponding EOM thermal and electrical power levels would be ~114 Wt and 5.2 We, respectively, at the end of a ten-year mission.

PFP Science Instruments

The payload envisioned for this mission concept would be based on the multi-mission space and solar physics micro-spacecraft [7], and would consists of an energetic particle detector, an electron and ion analyzer, and a magnetometer.

PFP Data and Communications

All data generated by the PFP would nominally be stored on a solid state recorder (SSR) until it was possible to transmit the data back to the mother vehicle using the PFP's low power communications system. The mother vehicle, assumed to possess a high power communications system, would then relay the data back to Earth for scientific analysis.

PFP Thermal

Similar to the seismic monitoring stations, passive thermal control of the PFP would be accomplished by a combination of thermal insulation, heat pipes, and louvers. Excess heat from the RPS could be used to keep critical subsystems warm, and radiators would be used to reject excess heat.

PFP Power

The PFP monitoring station would be operated in one of two mutually exclusive power modes. Mode A would be the nominal operating mode (Table 3) where all four instruments would be powered-on and either taking measurements or in hot standby (i.e., to stay warm during the long cruise phase). Sufficient electrical power would be available from the RPS unit (5.2 We at EOM) such that this mode could be sustained.

Mode B would be the nominal telecom mode, and is similar to Mode A except that the PFP communications system would be activated for transmitting or

Table 3. PFP Power Modes

Subsystem	Mode A (We)	Mode B (We)
Instruments	2.1	2.1
Energetic Particle Detector	0.3	0.3
Electron and Ion Analyzer	1.1	1.1
Magnetometer	0.3	0.3
Active Pixel Sensor Camera	0.4	0.4
Instrument Electronics Module	0.3	0.3
Avionics	0.8	0.8
Communications	(Off)	2.5
Subtotal	3.2	5.7
50% Margin	1.6	2.9
Total	4.8	8.6

receiving data from the mother vehicle. This mode would require ~8.6 We of total power, which is 3.4 We more than the EOM power output of the RPS. Thus, a supplemental battery would be required to carry the peak loads during the communications events. The precise battery size and mass would be expected to be small relative to the overall station dimensions, and would depend on the required PFP data volume and communications bandwidth.

3.10 PFP Mass

The total mass of the passive fields and monitoring system is estimated to be ~10.8 kg, including 50% contingency (Table 4). The RPS system comprises ~40% of the system mass at 4.5 kg, followed by the structure at 3.2 kg and the instruments at 2 kg. The remaining subsystems (avionics, communications and thermal) would together have a mass of ~ 1 kg.

Table 4. PFP Mass Summary

Subsystem	CBE Mass (kg)	Margin (50%) (kg)	Mass Allocation (kg)
Instruments	1.33	0.67	2.00
Energetic Particle Detector	0.30	0.15	0.45
Electron and Ion Analyzer	0.68	0.34	1.02
Magnetometer	0.29	0.14	0.43
Active Pixel Sensor Camera	0.06	0.03	0.09
Instrument Electronics Module	0.10	0.05	0.15
Avionics (incl. Power Electronics)	0.15	0.08	0.23
Power Source (2-Fuel-Capsule Derivative)	3.00	1.50	4.50
Communications	0.15	0.08	0.23
Thermal Control	0.30	0.15	0.45
Structure	2.16	1.08	3.24
Total	7.2	3.6	10.8

PFP Radiation Environment

The external radiation environment would generally dominate the total dose to the passive fields and particles monitoring station. The baseline PFP would use radiation-hardened components in order to tolerate the radiation exposure during the long cruise phase and the strong radiation environment about Jupiter. Future detailed analyses would need to be performed to assess whether additional shielding would be required to meet the lifetime requirements.

Summary and Conclusions

This study has introduced a new class of conceptual low power, long-lived deployable mini payloads that could potentially be enabled using small radioisotope power systems. One such science payload is a seismic monitoring station that would be powered by a conceptual small-RPS unit for up to 10 years using a single GPHS fuel capsule with an estimated 2.6 We (EOM) output. The technology for the seismic stations is at a moderately high state of development with the exception of the RPS. Significant design heritage would be borrowed from the MUSES-CN Nanorover, upon which both the avionics and communications subsystems are based. Therefore, it is concluded that seismic monitoring stations could potentially be capable of supporting missions as early as 2011, given the availability of the specified RPS power system. A second science payload introduced was a conceptual passive fields and particles station designed to operate about Jupiter with a nominal 10-year mission lifetime. This payload would be powered by a conceptual RPS using two GPHS fuel capsules with an estimated 5.2 We (EOM) output, and would be supplemented by a secondary battery system used to carry the peak loads during communications events. Both the seismic monitoring station and the passive fields and particles monitoring station concepts would utilize a mother vehicle for delivery to the target destination and for communications back to Earth. Based on this initial analysis, it is believed that deployable mini-payloads powered by small-RPS systems could provide an exciting new capability for the science and mission communities.

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