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Small Probes for Orbital Return of Experiments

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The Small Probes for Orbital Return of Experiments (SPORE) flight system will provide low-cost on-orbit operation, Earth return and recovery for small payloads. The SPORE flight system design includes a service module for orbital operations and de-orbit capability, and an entry vehicle to perform entry, descent and landing. The SPORE system architecture is scalable, allowing payload sizes ranging from the CubeSat standard one-unit (1U) configuration 2U and 4U configurations. Experiments including biological science, materials science, and thermal protection system flight demonstrations are targeted applications for SPORE. The flight system can be launched as either a primary or secondary payload into low-Earth orbit or geosynchronous transfer orbit. It can also be deployed from the International Space Station. This paper describes the driving requirements for the SPORE system architecture. Conceptual designs for the service module and entry vehicle are provided, and launch vehicle and ISS interfaces are discussed. Future work leading to SPORE commercialization is described.

Nomenclature

EDL = entry, descent and landing
EELV = Evolved, Expendable Launch Vehicle
ESPA = EELV secondary payload adapter
GTO = geosynchronous transfer orbit
I_{sp} = specific impulse
ISS = International Space Station
LEO = low-Earth orbit
RCS = reaction control system
RF = radio frequency
SPORE = Small Probes for Orbital Return of Experiments

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TPS = thermal protection system
UHF = ultra-high frequency
1U = 1-Unit payload dimensions of 10 cm x 10 cm x 10 cm
2U = 2-Unit payload dimensions of 20 cm x 10 cm x 10 cm
4U = 4-Unit payload dimensions of 20 cm x 20 cm x 10 cm

I. Introduction

THE Small Probes for Orbital Return of Experiments (SPORE) flight system addresses the need for low-cost access to an on-orbit microgravity and radiation environment, enabling experiments that require safe return to an Earth-based laboratory. Through a partnership between Aurora Flight Sciences Corporation and the Georgia Institute of Technology, SPORE will provide a standardized platform for the on-orbit operation, de-orbit and recovery of experiments. Payloads targeted for flight using the SPORE platform include investigations related to thermal protection system (TPS) flight characterization, biological and life sciences, and material sciences. The SPORE development is based upon a scalable flight system architecture consisting of a service module for on-orbit operations and de-orbit maneuvering, and an entry vehicle to perform entry, descent and landing (EDL). The flight system will be capable of accommodating payload volumes ranging from the 1-unit (1U) dimensions of 10x10x10 cm to the 4U dimensions of 20x20x10 cm. SPORE will be capable of being launched as a primary or secondary payload into low-Earth orbit (LEO) or geosynchronous transfer orbit (GTO), or being deployed from the International Space Station (ISS). Landing sites at the Utah Test and Training Range and the Woomera Test Range in South Australia are being evaluated.

Missions such as the Stardust comet sample return mission[1] and the Hayabusa asteroid sample return mission[2] represent the state of the art in sample return from deep space, but with missions far beyond Earth orbit these flight systems are far too costly for routine orbital science experiments. The Dragon flight system is being developed by Space Exploration Technologies for resupply of the International Space Station. The Dragon capsule has an advertised capability to return large payloads to Earth, up to 3,000 kg of downmass from the ISS. The per-flight cost of the Dragon system is not publicly available, but it is expected to be in the $100M range. The SPORE flight system architecture enables flight experiments to be flown and returned for a fraction of the cost of these larger systems. Designed for launch as a secondary payload, the targeted mission cost utilizing the SPORE flight system is $3-5M.

As a testbed for thermal protection system validation, SPORE will provide in-flight characterization of instrumented heat shields using experimental TPS materials. The payload within the SPORE entry vehicle will consist of a data recording system that will enable the post-flight evaluation of the heat shield performance. The size of the entry probe will permit a 1:1 geometric similitude between the ground test and flight article to be maintained, allowing the same probe to be tested both on the ground and in-flight at full scale. Demonstration of TPS technologies on an affordable flight platform will advance the technology readiness levels of new TPS concepts as well as evolved applications of heritage designs. This increased maturity can be translated to reduction in TPS mass or design margins. This is an important contribution, because TPS is traditionally a significant portion of the entry mass for EDL and aerocapture missions.

SPORE is suitable for a variety of small biological payloads that support the space biology and human research programs. Microorganisms, small plants, cultured cells/tissues, or a variety of invertebrate species (e.g. fruit flies, snails and round worms) could be supported in the experimental volume and returned to Earth for post-flight analysis. Many of the recognized risks to human health in space are tested and evaluated through experiments on cultured cells and small organisms. The ability to return biological samples after exposure to the space environment is of critical importance to biologists. Access to the radiation environment in geosynchronous transfer orbit is also a priority, allowing experiments to evaluate the risks to biological systems and to test potential mitigation strategies against the detrimental effects of radiation and microgravity at the cellular level.

In the coming years, the ISS is expected to have a very limited sample return capability for biologic payloads. Currently down mass from the ISS is utilized for astronaut samples including saliva and blood samples, surface swabs taken from the ISS to check for microorganisms and allergens, and other biological experiments. The SPORE development can extend the downmass capability for biological experiments on the ISS and provide more flexible return schedules.

Materials science investigations using the SPORE flight system will enable advanced materials to be tested in the rigors of the space environment. In particular, the sensitivity of materials such as advanced composites, polymers, and microelectronics to the radiation environment and microgravity effects can be evaluated. Low-gravity materials productions tests may be performed. The advanced materials and components that will be assessed through experiments conducted on the SPORE platform will improve the performance, increase the useful life, and reduce the cost of future space operations.

SPORE conceptual development is structured to achieve the following objectives: (1) Develop requirements for the flight and ground systems, addressing TPS characterization missions, biological experiments, and materials science investigations; (2) Develop a conceptual design for the system, including mission design, service module design, and entry vehicle design; (3) Employ multi-disciplinary design optimization tools and techniques to refine the design and establish system performance.

This paper describes the SPORE conceptual design. In Section II, the SPORE design space is defined, and key requirements are identified that drive the flight system design. Section III provides an overview of the SPORE flight system, including the service module and entry vehicle (an accompanying paper on SPORE entry, descent and landing[3] provides further details). Considerations for launch vehicle and ISS interfaces are discussed in Section IV. Section V describes future work needed to advance SPORE to an operational system.

II. Driving Requirements and Mission Design

A. Requirements Definition

SPORE requirements have been defined and organized according to the flowchart shown in Figure 1. At the highest level, the SPORE mission statement captures the overarching system objective:

The SPORE system shall be a scalable platform for providing flight experiment payloads with low-cost access to the on-orbit or re-entry environment for return to Earth and recovery.

The SPORE system architecture has evolved from an earlier concept, Recovery of In-Space CubeSat Experiments[4] (RICE). While the RICE concept was targeted to provide a 1U experiment payload volume access to and return from low-Earth orbit (LEO), SPORE is designed to be scalable to accommodate 1U, 2U and 4U payload volumes for orbits ranging from LEO to geosynchronous transfer orbit (GTO). The requirement to accommodate LEO and GTO orbits is driven by both biological science and thermal protection system (TPS) flight experiments. Biological experiments may require exposure of the payload to the increased radiation environment in GTO, while TPS experiments may require the higher entry velocities and heating rates attainable for return from GTO. In addition, a key requirement for SPORE is to accommodate deployment from the ISS for Earth return. This capability is sought to provide time-critical downmass for ISS experiments.

Payload accommodation drives key design requirements for the SPORE flight system and mission design. Thermal requirements to accommodate biological payloads were developed through study of recent biological science missions, including PharmaSat[5], GeneSat-1[6], and BION-M[7,8]. SPORE will be designed to maintain biological payloads within a temperature range of 20°C – 25°C throughout launch and on-orbit operations, as well as re-entry and recovery. This temperature range is appropriate for many biological payloads including microorganisms and human tissue, however some flight experiments may require a more tightly controlled temperature range, or a different range (e.g., frozen samples from ISS). Mission-specific requirements will be defined with the experiment principal investigators. A power allocation of 5W is defined for payload operations. Health and status payload telemetry is recorded throughout all mission phases, including recovery operations.

The SPORE mission design is tailored to maintain accelerations experienced by the payload to within specified levels. Acceleration levels associated with parachute deployment and landing are required to be less than 40 Earth g's. Entry accelerations can exceed 16 g's for no more than 20 sec, and can exceed 9 g's for no more than 100 sec. These requirements are derived from the BION-M mission specification.

The maximum diameter for the 1U entry vehicle configuration is 40.64 cm (16 in). This diameter is the maximum that can currently be tested within the NASA Ames Research Center arcjet facilities. This requirement is driven by the desire to test the thermal protection system at full-scale in the arcjet facility for direct comparison with flight experiments. Entry vehicles carrying 2U or 4U payloads may have a maximum diameter of 60.96 cm (24 in). This is the maximum diameter that can be accommodated by an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring on Atlas V and Delta IV launch vehicles. Because SPORE is designed for launch as either a primary or secondary payload, the ESPA interface requirements have been adopted.

The required orbital mission duration is between one to four weeks. This mission duration is used to size consumables such as propellant utilization for attitude control. It is anticipated that the system design capability will significantly exceed the four-week maximum mission duration requirement.

Recovery of the entry vehicle within two hours of the landing is required. A radio frequency (RF) beacon will be transmitted from the entry vehicle throughout EDL to assist in recovery. While recovery of the entry vehicle is expected in much less than two hours, the requirement is applied to thermal modeling to assess the payload temperature following landing.

System-level requirements, through Level 5 in Figure 1, have been defined during the SPORE concept study. Payload and interface requirements have also been defined, since they drive the design of the system. Subsystem-level requirements (Levels 6 & 7 in Figure 1) will be defined during the preliminary design phase.

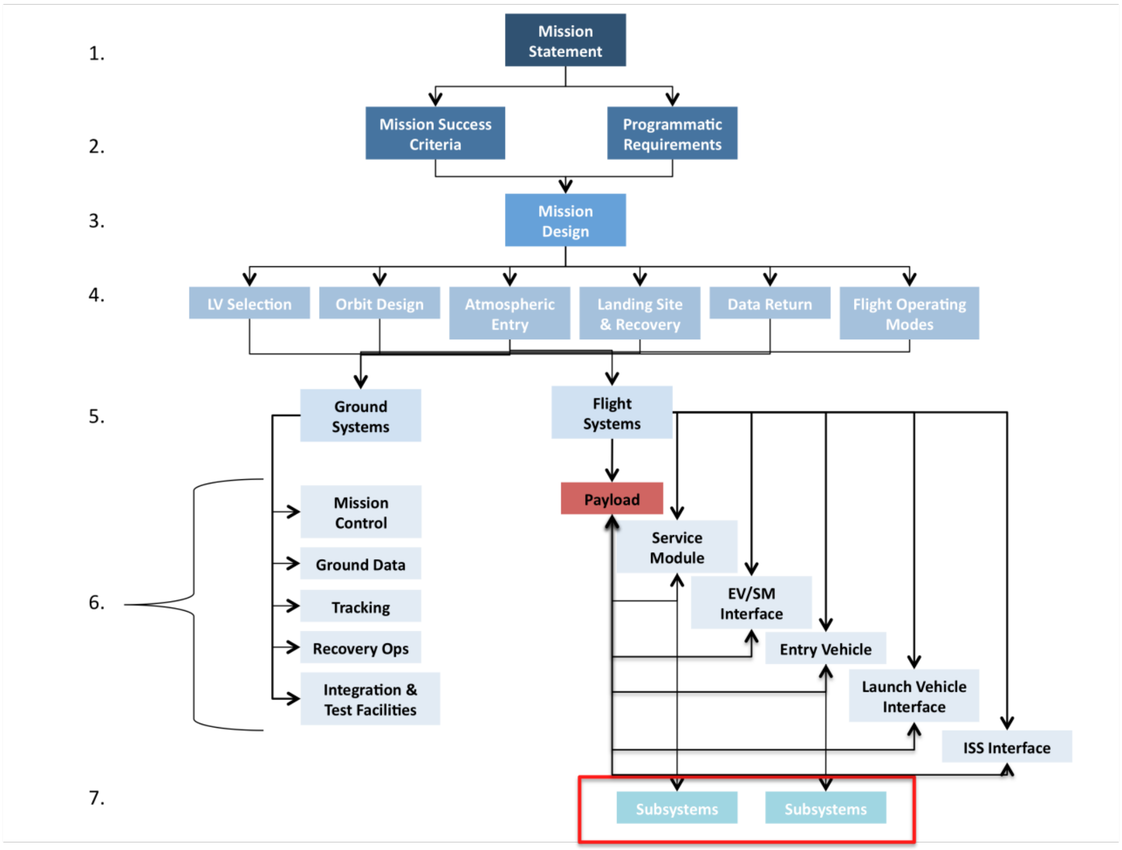

Figure 1. SPORE requirements flowdown structure.

B. Reference Orbits and Entry Conditions

Reference orbits have been defined for LEO, ISS and GTO missions, as shown in Table 1. Actual orbits may differ from the reference orbits, however, since the SPORE system may be launched as a secondary payload. Nominal entry conditions are provided in Table 2. Atmosphere-relative entry velocity and entry flight path angle are defined at an atmospheric interface altitude of 125 km, corresponding to a radius of 6,503.14 km.

The nominal entry trajectories are designed to target Woomera Test Range in Australia (31.2°S, 136.82°E). In order to reach Woomera from the GTO trajectory, a 2.5 deg inclination change is performed at apogee as part of the de-orbit burn. An alternative landing site is the Utah Test and Training Range (40.49°N, 113.64°W). Landing site selection will be based upon landing site dimensions and range safety. Preliminary landing footprints are shown in Reference 3.

Table 1. SPORE Reference Orbits for LEO, ISS and GTO

Orbital Element	**Units**	**LEO**	**ISS**	**GTO**
Apogee Altitude	km	600	355.8	35941
Perigee Altitude	km	600	351.1	167
Eccentricity	--	0	0.000349	0.73
Semi-major Axis	km	6,978.14	6,371.59	24,432.1
Inclination	deg	90	51.6	28.5

Table 2. Entry State at Atmosphere Interface

Orbital Element	**Units**	**LEO**	**ISS**	**GTO**
Radius	km	6503.14	6503.14	6503.14
Latitude	deg N	-16.65	-43.75	-36.4
Longitude	deg E	137.65	126.78	127.98
Velocity	km/s	7.780	7.572	9.964
Flight Path Angle	deg	-5.00	-2.60	-6.71
Azimuth	deg	182.9	36.3	57.8

III. Flight System Architecture

The SPORE flight system consists of a service module and entry vehicle. The service module provides on-orbit functionality, including power, attitude control, and communications of payload health and status telemetry. The service module executes the de-orbit burn and aligns the entry vehicle to zero angle-of-attack prior to release of the entry vehicle. The entry vehicle is battery-powered during EDL, and is designed to actively maintain the payload within its temperature requirements throughout EDL and recovery.

A. Service Module

The service module provides electrical power production and distribution, attitude determination and control, and telecommunications. The service module monitors health and status of the payload and all engineering subsystems, including the entry vehicle. A self pressurizing nitrous oxide propulsion system is used for thruster-only attitude control and the de-orbit burn. Subsystem descriptions are provided below.

1. Attitude Determination and Control

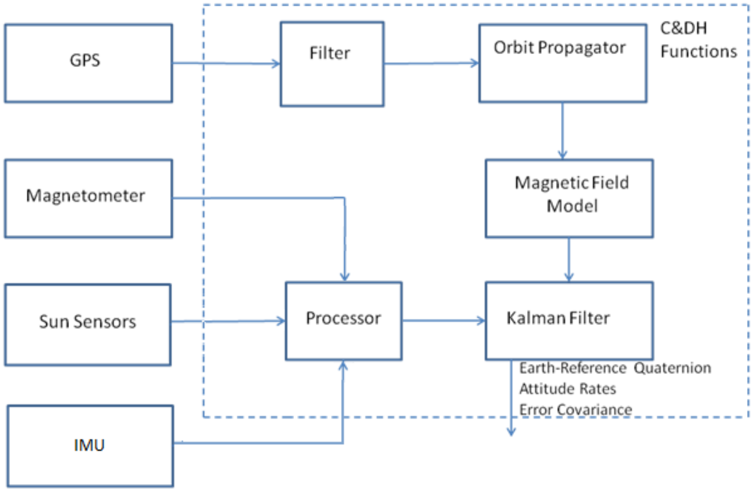

Figure 2. Attitude determination block diagram.

Service module pointing requirements are derived from three phases of the mission: on-orbit operation, de-orbit, and reentry. Nominally, while in orbit, the vehicle will point the body-mounted solar cells towards the sun. The requirement for sun pointing is ±5 deg to achieve maximum power production from the solar cells. When passing over a ground station, the vehicle must achieve an orientation that allows for a strong communications link with the ground. Telecom link budgets are calculated assuming a pointing error of up to 5 deg. When the vehicle performs the de-orbit burn, attitude control thrusters will be used to maintain the nominal attitude during the main engine firing and negate any external torque applied by the main engine. During de-orbit, the thrust vector is required to be within 1 deg of the nominal direction. The service module will orient the entry vehicle to within 1 deg of the desired attitude prior to entry vehicle separation. The service module is 3-axis stabilized in order to meet these requirements. In addition, slews are required for ground communication during tracking passes. To fully determine the 3-axis attitude of the vehicle, a combination of magnetometer, sun sensors, GPS, and an IMU will be used to obtain the vehicle's attitude and rotation rates. Output from the suite of attitude sensors will be fed into a Kalman filter for a refined attitude estimate. Figure 2 shows a basic block diagram for estimating the vehicle's attitude.

Due to the short mission lifetime, and because the vehicle must have reaction control system (RCS) thrusters to maintain attitude during the de-orbit burn, control actuation for the entire mission will be provided by RCS thrusters only. Three-axis thruster-only attitude control requires 12 thrusters in order to obtain a torque in any direction without producing a translating force.

2. *Propulsion*

The SPORE propulsion system consists of 12 thrusters for attitude control and a single de-orbit thruster. A combined nitrous oxide system has been selected to reduce system weight and complexity and eliminate the need for more volatile propellants such as hydrazine. Figure 3 shows the schematic of the propulsion system. The multi-mode N_2O micro-propulsion system is capable of providing cold gas thruster capability for low impulse applications at performance levels similar to existing cold gas systems operating on nitrogen or carbon dioxide. In addition, the system incorporates a high thrust capability via a monopropellant thruster that minimally impacts overall propulsion system volume and mass relative to a cold gas-only design. The effective I_{sp} for cold gas thrusting is 60 sec. The de-orbit thruster decomposes nitrous oxide to achieve a specific impulse of 195 s and a thrust of 60 N.

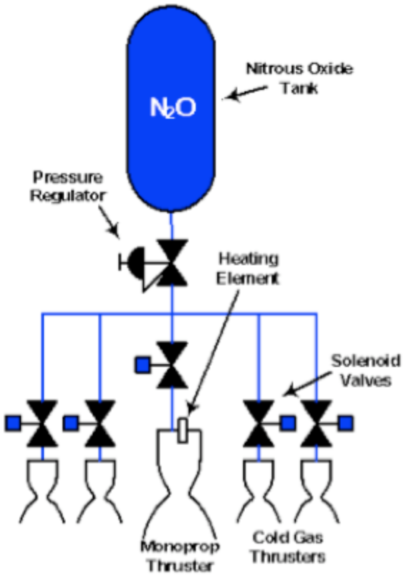

Figure 3. Propulsion block diagram.

3. *Telecommunications*

The SPORE telecommunications system will utilize UHF for uplink, and S-band for downlink. A downlink data rate of 9,600 bps is baselined for all communications passes. A micro-strip antenna is used for downlink, providing a boresight gain of 7-9 dB. An omni-directional antenna is used for uplink.

The Georgia Tech Center for Space Systems tracking station will be the primary ground station during SPORE flight operations. A Yagi antenna is used for UHF uplink, and a 3-m mesh dish with an S-band receiver is used for downlink. A minimum of 3 dB link margin is maintained for all contacts.

Data volume requirements for SPORE are modest. For LEO orbits, downlink data volumes of 20 MB per day can be accommodated. The longer pass times associated with GTO allow an average daily data volume of 260 MB to be downlinked.

4. *Electrical Power Subsystem*

Solar cells mounted on the service module top deck will provide power during on-orbit operations. The area that is available for solar cells is 0.3 m^2. A conservative efficiency of 20% for dual-junction cells is assumed. When a packing factor of 0.8 and an overall panel efficiency of 80% are applied, calculations show that the solar cells produce 52 W of power. Power budgets have been developed for three operating modes: safe mode, orbital operations, and de-orbit. Safe mode requires 16 W, orbital operations requires 22 W, and de-orbit requires 32 W of power. A 15% contingency is included in these values. Adequate power remains for battery charging in daylight operations. A 45% maximum depth of discharge requirement is applied for battery sizing.

5. *Mass Budget*

A master equipment list has been developed for SPORE flight system. Table 3 provides a mass summary for the service module at the subsystem level. The total service module dry mass is estimated to be 31.0 kg, including 15% contingency. With 12.2 kg of propellant, the service module wet mass is 43.2 kg. The entry vehicle mass varies with the configuration, ranging from 10.5 kg for the 1U configuration to 15.0 kg for the 4U configuration. Total flight system launch mass ranges from 53.7 – 58.2 kg. The SPORE launch mass is required to be less than 180 kg, based upon ESPA ring launch interface requirements.

Table 3. Service Module Mass Budget

Subsystem	**Mass Estimate (kg)**
Attitude Determination & Control	0.6
Propulsion	8.7
Telecommunications	0.7
Electrical Power Subsystem	9.0
Structures	10.4
Thermal	0.5
Command & Data Handling	1.1
Service Module Dry Mass	*31.0*
Propellant	12.2
Service Module Wet Mass	*43.2*

IV. Launch Vehicle and International Space Station Interfaces

The SPORE flight system is designed to be launched as a primary or secondary payload on an expendable launch vehicle, or deployed from the ISS.

A. Launch Vehicle Interface

The Department of Defense Space Test Program Office ESPA Planner's Guide is referenced as the primary resource for specifying launch vehicle interface requirements pertaining to the SPORE flight system[9]. The ESPA ring, fitted below the launch vehicle's primary payload, is an aluminum structure that can accommodate six secondary payloads arranged radially around the ring. Figure 4 shows the ESPA ring interface mounted underneath a primary payload, supporting six secondary satellites/payloads. The ESPA Ring is 61 cm tall, with a 157.5 cm primary payload bolt

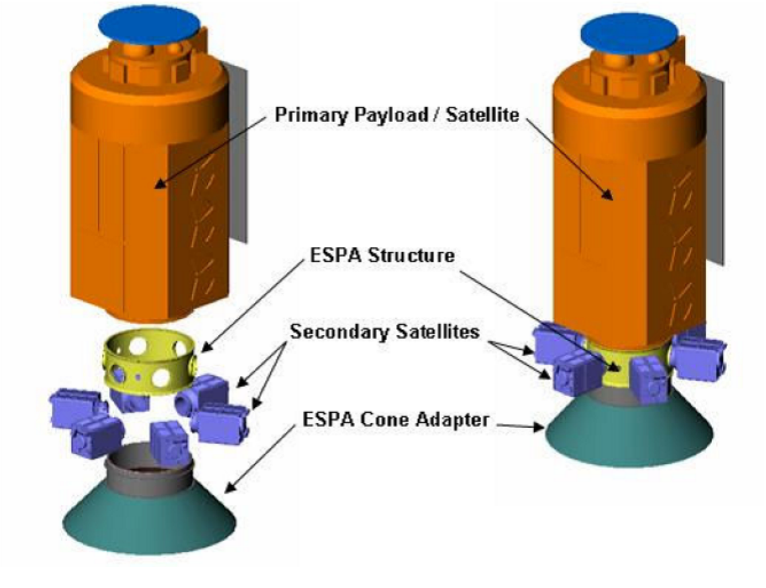

Figure 4. ESPA ring platform for secondary payloads.

circle featuring a pattern of 24 bolts, and each of the secondary payload ports around the outside of the structure is 38 cm in diameter. The separation system for the secondary payload is not included in the ring.

The maximum allowable size for a secondary payload is 61 cm x 71 cm x 90 cm. The SPORE flight system is designed to stay within this volume. The maximum secondary payload mass for the ESPA ring is 180 kg.

B. International Space Station Interface

Deployment of the SPORE flight system from the ISS may be accomplished from the Japanese Experiment Module Exposed Facility (JEM-EF). Not only does the JEM-EF robotic arm allow for tele-robotic installation of payloads on the External Facility without the need of extra vehicular activity (EVA) operations, but the associated Kibo airlock allows crewmembers to bring payloads into the pressurized ISS environment using the Kibo Main Arm to interact with/perform measurements on the payload, thus extending the range of possible experiments that may be conducted. The JEM Exposed Facility (JEM-EF), developed by JAXA, is an unpressurized pallet structure attached to the Japanese Experiment Module, Kibo. This external platform will be used for research in areas such as communications, space science, engineering, materials processing, and Earth observation. Figure 5 shows the layout of the Kibo Exposed Facility with the payload attachment points shown in red.

The Kibo EF Exposed Pallet appears to be an ideal method for deploying SPORE from the ISS. These pallets are delivered to the ISS via the JAXA HTV and are mounted on the Kibo EF using the Canadarm 2. Upon completion of experiments, the Exposed Pallets are jettisoned from the ISS. The SPORE system would be mounted inside a pallet for transit and attachment to the ISS. Following installation of samples within the payload volume, the SPORE system would be jettisoned from the ISS and the service module would initiate, acquire radio communications with the ground station, and conduct orbital operations leading to re-entry.

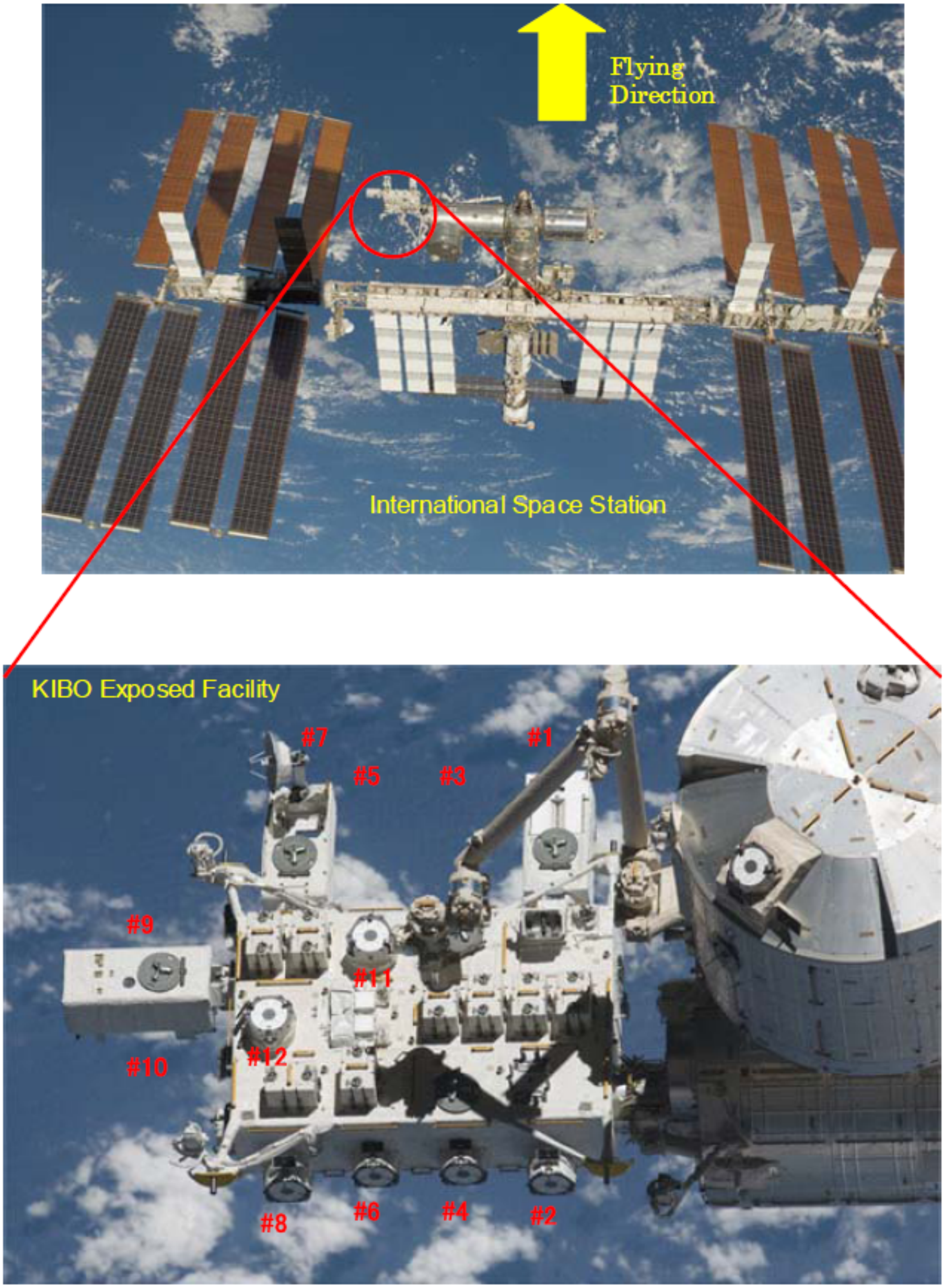

Figure 5. The KIBO Exposed Facility provides an ideal location for SPORE deployment from the ISS. Note the Exposed Pallet labeled #9.

V. Future Work

The SPORE conceptual design, funded through a Phase 1 NASA Small Business Technology Transfer (STTR) award, will be completed in February 2012. The Georgia Institute of Technology and Aurora Flight Sciences will propose a Phase 2 STTR investigation to advance the SPORE system design and conduct prototype testing.

Over a two-year period, the SPORE development team will complete the preliminary and detailed design phases. Hardware components will be selected, and prototype testing will be conducted for technology maturation and risk reduction. A service module avionics and flight software testbed will be developed, and an advanced nitrous oxide propulsion system will be tested. A full-scale entry vehicle prototype will be fabricated, and high-altitude drop tests will be conducted to assess vehicle stability, parachute deployment and performance, and the data recording system. Detailed cost estimation will be performed, and a commercialization strategy will be developed. With the completion of the Phase 2 STTR investigation, SPORE will be ready for implementation as a flight project.

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