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PLANETARY CUBESATS COME OF AGE

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Jet Propulsion Laboratory initiatives in developing and formulating planetary CubeSats are described. Six flight systems already complete or underway now at JPL for missions to interplanetary space, the Moon, a near-Earth asteroid, and Mars are described at the subsystem level. Key differences between interplanetary nanospacecraft and LEO CubeSats are explained, as well as JPL's adaptation of vendor components and development of system solutions to meet planetary-mission needs. Feasible technology-demonstration and science measurement objectives are described for multiple modes of planetary mission implementation. Seven planetary-science demonstration mission concepts, already proposed to NASA by Discovery-2014 PIs partnered with JPL, are described for investigations at Sun-Earth L5, Venus, NEA 1999 FG3, comet Tempel 2, Phobos, main-belt asteroid 24 Themis, and metal asteroid 16 Psyche. The JPL staff and facilities resources available to PIs for analysis, design, and development of planetary nanospacecraft are catalogued.

I. INTRODUCTION

In 2014–15 three CubeSat-related developments by JPL (Jet Propulsion Laboratory) and its partners significantly boosted the feasibility, utility, and practicality of extending the "CubeSat revolution" to the planets. JPL completed *INSPIRE*, the world's first two interplanetary CubeSats; entered Phase C/D on two 2nd-generation planetary CubeSats for a mission to Mars; entered Phase B with MSFC (NASA Marshall Space Flight Center) on CubeSats for missions to the Moon and a near-Earth asteroid; and proposed into the Discovery Program a portfolio of seven nanospacecraft concepts that would demonstrate technologies and perform science at destinations from Venus to the outer reaches of the Main Asteroid Belt.

From these development and formulation activities, a credible intersection of purpose, performance, risk, and cost is now emerging, appropriate for planetary science using nanospacecraft. This experience-based "set point" contrasts in important ways with community expectations calibrated by Earth-orbiting CubeSats.

II. STATE OF PRACTICE

This section describes six CubeSat-based interplanetary flight systems currently in the flight-project implementation pipeline: the *INSPIRE* pair already delivered (Phase D), the *MarCO* pair (Phase C/D), *Lunar Flashlight* (Phase B), and *NEAScout* (Phase B). Together this set establishes a critical benchmark for future planetary CubeSats, to anchor and validate concepts and cost estimates.

INSPIRE: system, technology, project status

The dual *INSPIRE* spacecraft (Interplanetary NanoSpacecraft Pathfinder In Relevant Environment) are the world's first interplanetary CubeSats (although, indicative of the fast-evolving nature of the CubeSat field, their launch opportunity will likely follow that of *MarCO*; see below). Intended for direct injection into Earth-escape, heliocentric orbit on a dedicated interplanetary mission, they were delivered to launch readiness in June 2014 (Figure 1).

INSPIRE has three demonstration objectives: 1) CubeSat operation, communication, and navigation far from Earth; 2) deep-space flight of key CubeSat hardware components, thereby bringing them to TRL 9 (technology readiness level); and 3) delivery of useful science by interplanetary CubeSats. These pathfinder objectives directly reduce risk for investigators aiming

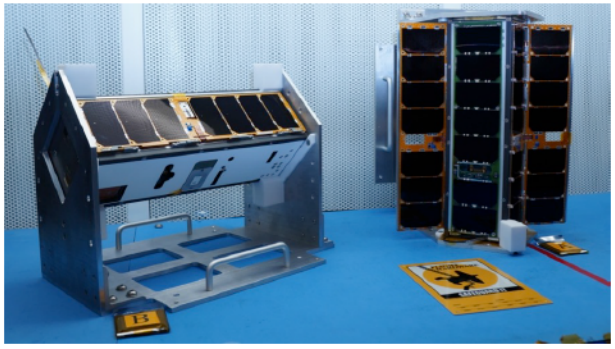

Fig. 1: INSPIRE, *the first two interplanetary CubeSats, were completed on budget and on schedule in June 2014.*

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to propose U-class planetary science missions.

The flight system comprises two identical, 3-axis-stabilized, 3U spacecraft. They combine built-to-print, commercially available, LEO-demonstrated (low-earth-orbit) subsystems (command and data handling watchdog, attitude determination, and power functions) with next-step modifications of other commercially available subsystems (cold-gas attitude control, and deep-space navigation and communications). Demonstrating integrated performance of this core hardware set in deep space establishes a common system foundation that can subsequently host special-purpose payloads for diverse deep-space investigations.

Both 3U spacecraft also host JPL's first U-class science instrument: a highly sensitive, half-U CVHM (compact vector-helium magnetometer). By measuring solar-wind fine structure, these CVHMs demonstrate directly the science utility of nanospacecraft platforms in deep space: the pair make synchronous measurements of the solar-wind magnetic field as they slowly separate, starting almost immediately upon launch but then continuing for 90 days out to 1.5M km from Earth. Instrument performance from the low-cost CubeSat bus is characterized both before and after deployment, and during long, "electrically quiet" operating periods.

MarCO: system, technology, project status

NASA's Discovery mission in Phase D now is *InSight*, a terrestrial-planet geophysics investigation that will land on Mars in September 2016. An aft-bulkhead carrier on the launch vehicle's Centaur upper stage deploys the twin *MarCO* (Mars Cube One) CubeSats (Figure 2), which then independently fly to Mars. Their mission is to relay data from InSight to Earth during the mission-critical EDL (entry, descent, and landing) phase, which lasts just minutes as the lander brakes from interplanetary speed to a soft landing.

InSight transmits EDL telemetry at 8 kbps over UHF. Overhead, *MRO* (the Mars Reconnaissance Orbiter) receives these data but cannot relay them to Earth for at least an hour because it passes out of Earth view behind Mars.

Meanwhile, the *MarCO* CubeSats fly by Mars at 3500-km altitude, supporting a direct-to-Earth (DTE) link during InSight's EDL phase. Each receives the same UHF telemetry as *MRO*; by adding framing information and then retransmitting the data to Earth, *MarCO* provides the real-time critical-event coverage that *MRO* cannot. Getting the data in real time is not mission critical, but is nonetheless highly desirable, and a powerful demonstration of CubeSat capability to augment a primary mission. Once demonstrated for *InSight*, deep-space support by nanospacecraft can be planned more routinely, introducing operations flexibility to future planetary missions.

The heart of *MarCO* is JPL's Iris v2 radio, including a UHF receiver. This software-defined, radiation-tolerant radio has up to 4 W RF output at X-band frequencies, is fully Deep-Space Network (DSN) compatible, has four receive and four transmit ports, and an external solid-state power amplifier and low-noise amplifier. Each CubeSat has a low-gain patch antenna for near-Earth communications with wide beam width, medium-gain patch array for safe-mode communications far from Earth, and high-gain reflectarray antenna for high-speed data (Figure 2). A UHF loop antenna deployed from the bottom of each spacecraft receives the *InSight* telemetry. The radio maintains an 8-kbps downlink from Mars (1.05 AU from Earth at that point).

A Blue Canyon Technologies XACT attitude-control unit includes a star tracker, gyro, coarse sun sensors, and 3-axis reaction wheels. Several modifications accommodate an additional coarse sun sensor and control of the thrusters; the software is modified for use in deep space.

A VACCO propulsion system contains eight thrusters: four canted for attitude control, and four for TCMs (trajectory correction maneuvers). The single-tank design houses all electronics, valves, and propellant (R-236FA, a cold-gas propellant used terrestrially in fire extinguishers). The XACT system commands thruster firing both for reaction-wheel desaturation and TCMs. For safety, the C&DH (control and data handling) subsystem controls propulsion subsystem power.

Driven by months-long independent flight followed by operation at 1.5 AU, *MarCO* demonstrates how to overcome some of the challenges future planetary nanospacecraft will face: higher-power heaters, interplanetary communications, and advanced

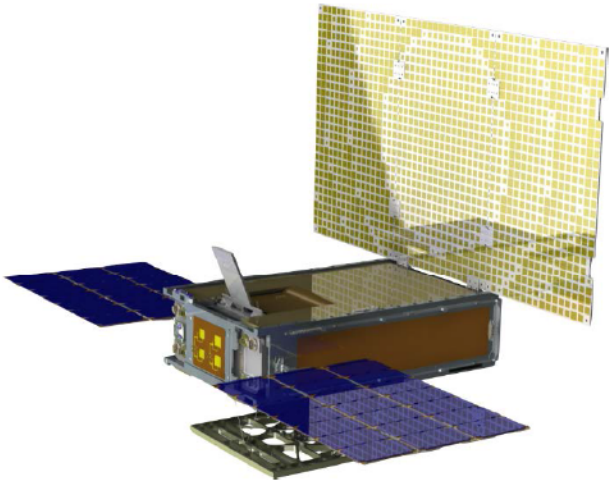


Fig. 2: MarCO, *the first two CubeSats providing operational support to a planetary mission. Large panel, high-gain reflectarray transmits 8 kbps from Mars to the 70-m DSN antenna in Madrid.*

electronics; more complex thermal management (both high and low); and heat dissipation by the U-class geometry (which has a high ratio of power to surface area).

Lunar Flashlight: system, technology, project status

Lunar Flashlight is a flight project sponsored by NASA HEOMD AES (Human Exploration and Operations Mission directorate, Advanced Exploration Systems division), implemented by a JPL-MSFC partnership led by JPL, and proposed for launch on the SLS EM-1 launch.

Future human operations in deep space would be enhanced or enabled by ISRU (in-situ resource utilization) to make propellant, air, water, and building materials. Prior science missions to the Moon, including *Lunar Prospector* and *Lunar Reconnaissance Orbiter* have found circumstantial evidence of ice in PSRs (permanently shadowed regions) at the lunar poles, but its abundance and distribution in the regolith are unknown. Consequently the existence, extent, form, origin, and behavior of potential lunar ices comprise a complex of SKGs (strategic knowledge gaps) for planning human exploration.

Lunar Flashlight seeks to discover exposed lunar surface ice deposits from low lunar orbit. Manifested to launch on the SLS (Space Launch System) EM-1 mission in 2018, it reflects sunlight into PSRs and uses a 4-band point spectrometer to observe the reflected light to detect exposed water ice (Figure 3). Repeated multi-point measurements over south-pole craters yield a map of potential surface-ice concentrations. Correlating these data with existing lunar mission data will deepen our understanding of lunar volatiles and help plan potential human missions.

The *Lunar Flashlight* design is based on the *INSPIRE* architecture that hybridizes off-the-shelf U-class hardware with new, special-purpose components. It uses JPL's radiation-tolerant Iris v2 radio; radiation-tolerant flight computer based on the LEON 3-FT processor; Blue Canyon star trackers and reaction wheels; MMA solar arrays; VACCO propulsion subsystem; and other commercially available U-class components tested by the project for use in deep space. The science instrument is a U-class 4-band point spectrometer custom-made at JPL.

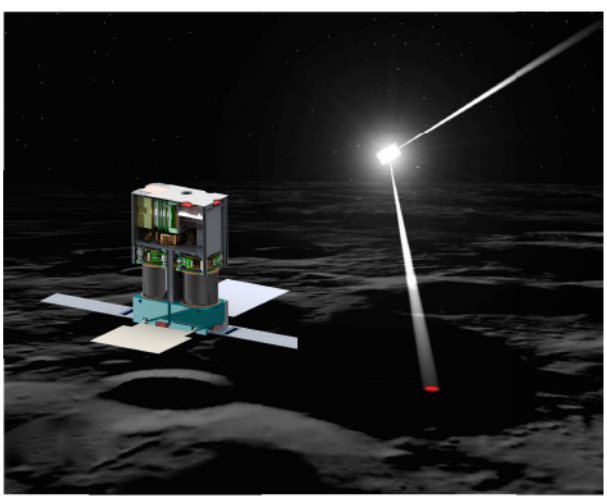


Fig. 3: Lunar Flashlight *uses reflected sunlight to determine whether water ice is exposed on the surface in permanently shadowed lunar polar craters.*

NEAScout: system, technology, project status

NEAScout is another flight project sponsored by NASA HEOMD AES, implemented by an MSFC-JPL partnership led by MSFC, and proposed for launch on the SLS EM-1 launch.

Current NASA plans include human exploration of, and operation around, an NEA (near-Earth asteroid). The local environment and surface properties of NEAs are other significant SKGs for human exploration. While there is perhaps no such thing as a "typical" NEA, robotic scouts could nonetheless survey the range of risks and challenges NEAs may pose to human explorers, advancing the science of NEAs and significantly retiring SKGs to enable confident planning.

NEAScout performs reconnaissance of an NEA (Figure 4). Also manifested to launch on the SLS EM-1 mission in 2018, it observes a small (<100 m) asteroid upon flyby, making accurate measurements of its ephemeris, shape, rotation state, spectral class, local dust and debris field, regional geomorphology, and regolith properties.

Like its sibling *Lunar Flashlight*, *NEAScout* uses the radiation-tolerant Iris v2 radio; radiation-tolerant LEON 3-FT based flight computer, Blue Canyon star

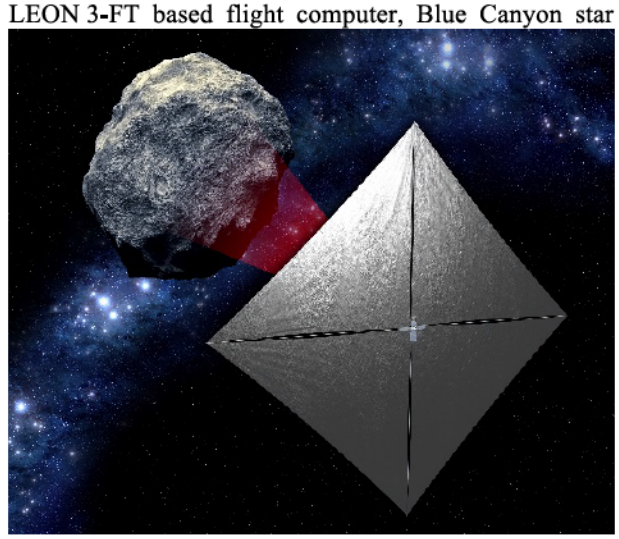


Fig. 4: NEAScout *pioneers close-up observation of asteroids and their environments during fly-by encounters, to pave the way for human exploration of such destinations.*

trackers and reaction wheels; MMA solar arrays; VACCO propulsion subsystem; and other U-class components tested by the project for use in deep space. It is propelled by an 80-m^2 solar sail. JPL provides the science-grade camera.

Lessons learned

Experience gained from these first six planetary nanospacecraft developments has already informed the next generation of U-class concepts JPL has proposed to NASA (described below). Technical differences are detailed in the next section, but a few project-level findings are:

- Planetary environments are more diverse than Earth-orbiting environments. Combined with the rarity of planetary launch opportunities, this inevitably increases expectations for success for nanospacecraft, shifting the balance from rapid, frugal "sub-Class D" development more toward experience-based space flight project practices. A hybrid approach is essential.
- Small size and rapid development alone do not avoid typical integration challenges, and in fact may exacerbate them. 3D printing is a useful prototyping technique for fit-checking, identifying, and resolving clearance, component installation, and cabling issues caused by highly constrained U-class volume.
- There is no substitute for tacit knowledge gained by a team, and facilities tailored for product development. JPL built a dedicated CubeSat Development Laboratory, staffed it with a cadre of nanospacecraft experts who carry lessons immediately into subsequent projects, and developed relationships with U-class component providers to adapt their products for stretch applications.

III. CONTRASTS BETWEEN EARTH-ORBITING AND PLANETARY APPLICATIONS

The small-spacecraft community has considerable experience operating CubeSats in LEO, and has successfully overcome many operating challenges posed by that environment. For example, ground-antenna gain can compensate for limited onboard antenna gain and radio power; and CubeSats can manage limitations of power generation and thermal dissipation by duty-cycling high-power components.

However, small spacecraft operating in deep space face considerably greater challenges (Table 1). For nanospacecraft, some of these challenges simply limit mission capabilities, while others can be overcome with

Area	*Challenges (Relative to Earth-orbiting CubeSats)*	*Solutions*
Power	• Diminishing solar power beyond 1 AU • Potentially greater power consumption from telecom and thermal subsystems	• Low-power modes and duty cycling • Large deployable solar arrays • Greater energy storage capacity
Telecom	• DTE telecom at long range with small apertures and low power, including tracking • Mother-daughter architecture requires cooperative primary mission	• On-board data compression • High-power S-Band, X-Band, and Ka-Band transponders for DTE and navigation • Low-power UHF or S-Band relay to mothership (optionally integrated with dispenser avionics package) • Deployable antennas, e.g., reflectarray • Disruption-tolerant networking (DTN)
Propulsion & Attitude Control	• Mass, Volume, and Power constraints for reaction wheels, star trackers and sun sensors • Reaction-wheel desaturation (outside geomagnetic field) • Limited volume and power for propulsion • Secondary payload safety with combustible and/or pressurized propellants	• Off-the-shelf, integrated ACS packages • Small cold-gas thrusters for reaction wheel desaturations and propulsion • Non-combustible gas with low pressure at launch temperatures • Miniaturized electric propulsion systems (in development)
Autonomy	Must operate without immediate link for long durations, including navigation and guidance (e.g., asteroid flyby or impactor) and data triage	• Onboard autonomous operations with capable processor • Affordable, small cameras • Terrain-relative navigation (TRN) • Agile-science algorithms (ASA)
Mission Duration	Long-duration cruise in deep space	• Shielded avionics compartments • Radiation-tolerant avionics with watchdog reset • Short operating life for missions in difficult environments
Mechanical & Thermal	• Dissipating avionics/transponder heat with small radiator surfaces • Providing replacement heat in low-power modes at large solar distances • Sufficient area for harnesses and fasteners	• Thermal modeling and testing, including thermal duty cycling • Area allocation for radiator and MLI surfaces • Modular architectures to facilitate integration
Mission	Potential risks to primary mission (for secondary spacecraft)	Standard non-interference deep-space dispenser with integrated avionics & telecom interface, replacement heat, inhibits, and well characterized tip-off rates

Table 1: ***Deep-space nanospacecraft*** *face multiple, unique operating challenges.*

architectural solutions that depart from LEO CubeSats. For example, limited capacity for power, attitude control, orbit control, and non-benign planetary environments simply do and will continue to impose operational or lifetime constraints. By contrast, telecommunication and autonomy challenges can be retired, respectively, by using mother-daughter relay architectures and on-board algorithms for agile science and optimal resource management.

While deep-space and LEO environments differ in many ways, radiation and thermal considerations become top drivers of design differences for U-class subsystems to function in interplanetary space. For example, radiation tolerance drives electronics "board real estate" and can exacerbate power demand. And in volume-restricted U-class configurations, even MLI (multi-layer insulation) thickness can conflict with solar-array area; early modeling is essential to allocate sufficient space for radiators and MLI. Future designs may need to move beyond aluminum brackets for conduction, to techniques like wedge locks, heat pipes, and even 3D-printed fluid loops.

In designs packed with complex functionality (e.g., at 6U class), breaking the classical, modular CubeSat stack architecture has turned out to be enabling in some cases. For example, *MarCO* uses a baseplate divided into quadrants despite its 6U "outer mold line," to facilitate tool and testing access during integration.

IV. OBJECTIVES FOR PLANETARY APPLICATIONS

Deep-space nanospacecraft offer three strategic advantages for planetary-mission investigators: 1) multiple mission modes, and thus increased opportunity cadence; 2) opportunistic technology demonstration; and 3) opportunistic (high-risk and multi-vantage) science measurements.

Multiple mission modes and increased cadence

INSPIRE, *MarCO*, *Lunar Flashlight*, and *NEAScout* exemplify the "standalone" mission mode in which a nanospacecraft flies independently to a target destination and conducts a complete investigation there. Directly analogous to traditional planetary missions, this mode imposes tough requirements on nanospacecraft for longevity and independent operations.

The other ("mother-daughter architecture") mission mode confers powerful advantages on both parent mission and nanospacecraft, because the nanospacecraft mission itself only begins once already at the investigation target, and the mother ship provides a nearby operations node.

Beyond the diverse types of investigation that the mother-daughter mode can support, the mere benefit of carriage to deep-space destinations means that every planetary mission affords a potential nanospacecraft opportunity. Planetary mission opportunities are traditionally characterized by slow cadence. Acceptance of nanospacecraft onto primary missions could eventually convert all US, European, Japanese, Indian, Russian, and Chinese planetary missions into opportunities for deep-space nanospacecraft, either for coordinated mother-daughter operations or simply for ride-along deep-space deployment onto standalone-mode investigations.

Opportunistic technology demonstration

Nanospacecraft offer unique opportunities to demonstrate advanced technologies in deep space. Traditionally, a strong bias against infusing non-heritage (i.e., high cost-risk) capabilities on cost-constrained planetary missions means that technologies are forced to fight their way onto missions from a basis of only TRL 5, and then undergo significant verification challenges to attain TRL 8 before launch. An increased cadence of opportunities to demonstrate TRL 9 (i.e., performance in the intended operating environment) with non-critical operations could be transformational for the infusion rate of advanced technologies, for both spacecraft subsystems and instruments.

The four nanospacecraft flight projects described above will demonstrate a range of subsystem and instrument technologies in deep space: small UHF relay (on *INSPIRE*); small, high-power Iris DSN transponder, compact reflectarray antenna, and U-class cold-gas TCM (on *MarCO*); radiation-tolerant LEON processor (*Lunar Flashlight* and *NEAScout*); CVHM instrument (*INSPIRE*); and U-class IR point spectrometer (*Lunar Flashlight*).

A wealth of other technology advancements awaits demonstration in planetary environments.

Power Generation and Storage

LEO-orbiting CubeSats have used a variety of solar-array configurations to package power-generation capacity into the U-class form factor for launch. As mission applications become more ambitious farther from Earth, even more innovation is required for power generation, storage, and utilization duty cycling.

MarCO uses commercially available, deployable solar arrays recently developed; even larger versions are expected to become available soon. Beyond Mars distance (~1.5 AU), and for some surface scenarios, solar power becomes impractical for small spacecraft. Although miniature radioisotope power systems (RPSs) might be attractive in theory, it is impractical to expect it: nano-RPS would be an exotic, purpose-built power source with a "long tail" of DOE (Department of Energy) infrastructure sustainment costs clearly antithetical to the original low-cost premise of deep-space nanospacecraft.

JPL has already proposed several planetary daughter nanospacecraft based on conventional primary batteries; and is developing hybrid power-storage solutions based on secondary batteries and super-capacitors for demanding U-class applications with ultra-low temperature and high-pulse-power loads.[1]

Telecommunication Technologies

There are two telecommunication challenges for planetary nanospacecraft: DTE links for the standalone mode; and inter-spacecraft relays for the mother-daughter mode or for swarm deployments.

Transmitting significant amounts of data over interplanetary distances is always aperture-limited and power-limited. For small spacecraft these challenges are amplified by the thermal challenge discussed above: limited radiator area for dissipating heat from high-power loads. JPL's X-band Iris transponder (on *INSPIRE*) enables nanospacecraft to communicate using the DSN. And the higher-power solid-state amplifier and reflectarray antenna (on *MarCO*) increases effective gain despite packaging compatible with a CubeSat dispenser.

These missions also demonstrate two UHF relay designs; in particular, *MarCO* demonstrates a deployable loop antenna that yields capability similar to the Electra Proximity Payload radio standard for surface-orbit links at Mars. JPL is developing several U-class antennas including deployable Ka-band.[2, 3]

Disruption-tolerant networking (DTN) enables internet-like functionality on space missions where communication disconnections or delays of more than a few seconds are routine. This type of networking reduces the time required for downlink planning – and its associated operations cost – by automating both prioritized data downlink and automated re-transmission of partial products. It also facilitates the automated communication required among assets for event triggering, e.g., to image transient science events from multiple perspectives or with complementary instruments on separate spacecraft. NASA has invested in DTN since 2007; it is being tested and operationally infused on the International Space Station, and was demonstrated in deep space on *EPOXI* (Extrasolar Planet Observation and Deep Impact Extended Investigation). JPL proposed DTN for the mother-daughter communication architecture of several Discovery nanospacecraft (see below).

Propulsion Technologies

The first deep-space nanospacecraft rely on U-class cold-gas propulsion already demonstrated in LEO: a refrigerant, stored as a saturated liquid and pressurized for expulsion through a set of nozzles. JPL has partnered with providers to adapt this technology for deep-space use on *INSPIRE* and *MarCO*.

JPL and others are also developing several advanced propulsion technologies for U-class planetary applications, including lightsails (as on *NEAScout*), electric propulsion,[4-6] and chemical propulsion based on both hydrazine and green propellants.

Autonomous Systems and Avionics

Operations complexity does not necessarily scale down with spacecraft size. For planetary nanospacecraft, economy therefore depends on operating with a high degree of autonomy to limit costly burdens on mothership, ground systems, or ground crews. The need for autonomy is also driven by the agility required for close-proximity interaction with targets, and rapid response to serendipitous discoveries. JPL has extensively proposed nanospacecraft autonomous guidance and navigation; semi-autonomous localization in space via accurate imaging of reference planets, asteroids, and surface features of small planetary bodies; and agile science algorithms (ASA) for science-feature recognition and prioritization.

ASA software modules enhance science return via onboard event detection and response: automated instrument operations, feature detection, and/or automated planning and scheduling. Automated instrument operations include adjusting camera exposure and sub-window settings to maximize image quality, and automatically adapting the rate of data collection and transmission to capture transient phenomena at maximum data-acquisition cadence. Feature detection within an image or multi-spectral image cube can trigger additional observations by that instrument or another (even if on a separate spacecraft); and detect objects by examining multiple images, e.g., for automated asteroid search. Onboard planning and scheduling include: 1) CPU and RAM throughput management to assure that event-triggered observations are possible; 2) geometry-aware planning to confirm that observations will occur when illumination and/or stereo-mapping constraints are met; and 3) coordinated observation planning between spacecraft with different vantage points and complementary instruments.

The *IPEX* (Intelligent Payload Experiment) CubeSat demonstrated ASA in LEO; *NEAScout* demonstrates ASA in deep space by co-adding asteroid images to increase SNR of downlinked data; autonomously adjusting payload parameters (e.g., camera exposure time); and prioritizing downlink data to maximize science return despite the limited data rate from deep space.

EDL, In-Situ Access, and Surface Mobility

Daughter spacecraft can reach environments inaccessible to a mother spacecraft due to risk or other physical constraints, or that enable "second vantage point" geometry for simultaneous, coordinated operations. Examples already proposed by JPL include

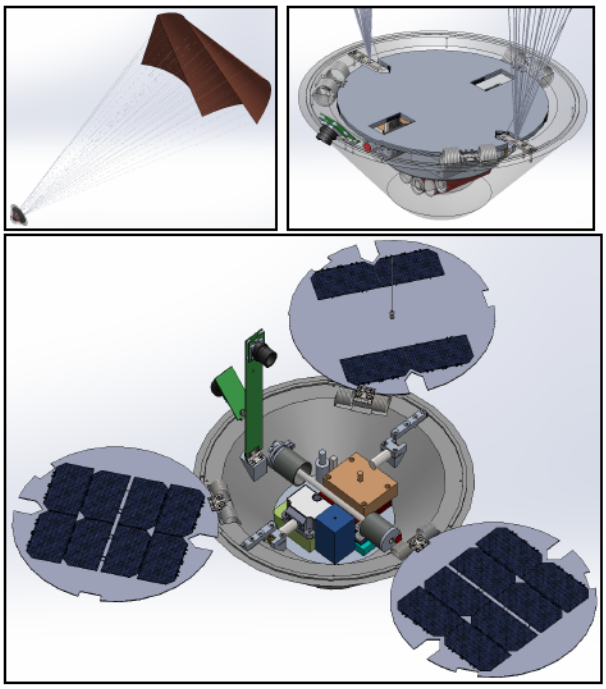


Fig. 5: ***MarsDrop****, an Aerospace Corp. – JPL collaboration, could land small instruments very close to high-value targets, using excess mass capacity on Mars-bound missions.*

decelerators and probes for planetary atmospheres, and autonomously guided close-flybys, impactors, and landers.

Together with Stanford University, JPL has a NIAC (NASA Innovative Advanced Concepts) Phase II study to develop small platforms for autonomous microgravity surface mobility.[7] Capable of hosting low-cost instruments and potentially deployable in larger numbers, such momentum-actuated hoppers could increase science return from exploring unstructured and unmapped topography, without resorting to complex landing or mobility technologies.

Together with the Aerospace Corp., JPL is also developing MarsDrop, a nanospacecraft to land ~1 kg instrument packages with tens-of-meters accuracy on Mars (Figure 5). The entry vehicle is Aerospace's REBR (ReEntry Breakup Recorder), a 30-cm diameter system that has executed three successful ~9-km/sec reentries from Earth orbit. At Mars, entry velocities would range from ~3–7 km/sec, depending on deployment from orbit or with direct entry. The 3.5-kg system has a low ballistic coefficient; a 3-m subsonic parawing deployed 5–10 km above the surface would steer to the target by lanyard actuation based on video-rate terrain-relative navigation. After impacting at up to ~20 m/sec, then deploying petals to right itself, the lander would deploy solar panels and a UHF antenna capable of 1-MB/day uplink. Batteries charged during each sol would enable night-time quiescent survival. Typical Mars-mission cruise stages have significant excess mass capacity. With MarsDrop, one or more high-priority scientific targets could be reached on every Mars opportunity.

Instruments

Miniaturized instruments not only enable science investigations using small spacecraft (see below), they are also pathfinders for significantly increasing the payload capacity of large spacecraft. U-class examples under development by JPL include the IR point spectrometer and magnetometer already mentioned, plus an IR imaging spectrometer, intelligent camera, gamma-ray spectrometer, and mass spectrometer (Table 3).

Opportunistic science measurements

Nanospacecraft can support measurements applicable to all planetary exploration disciplines. They can enable novel architectures and facilitate observational strategies that may be impractical or too risky for a primary mission or mothership.

Science Enablers

Some science objectives require distributed spatial and temporal sampling that cannot be achieved by a monolithic system architecture. Examples include diverse dynamic phenomena amenable to distributed networks (e.g., fields and particles, or volcanic activity); deep planetary-interior characterization requiring measurements at multiple sites (e.g., seismic tomography); and investigations requiring highly separated receivers for source triangulation or stereo imaging. For such investigations, simultaneous measurements at complementary sites increase the robustness of measurement interpretation.

High-Risk Measurements for High-Reward Science

A classic example would be using an expendable asset to obtain high-resolution data at a small body (e.g., spatial resolution or SNR) from an orbit altitude unsafe for a mothership. Other examples include: scouting ahead to assess risks for a mothership; reconnaissance for landing and sampling site selection; and bridging imaging scales and vantage points between what orbiters and landers can do. The scouting function, historically unavailable to planetary missions, could offer significant planning and operations flexibility. It could also significantly mitigate mission costs, e.g., for human exploration precursors. Multiple nano-scouts could assess and return information to inform advanced planning (e.g., by sorting targets and providing high-resolution imaging at the scale of crew and robots).

Alternative Low-Cost Architectures

Multi-site observations by small satellites may be a useful way to increase coverage of planetary-science targets at low cost compared to large observatories; and

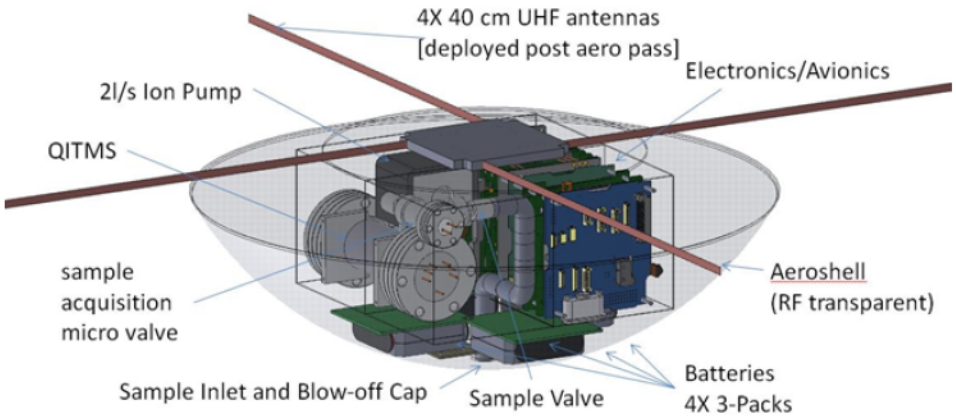


Fig. 6: Cupid's Arrow *would measure long-sought noble-gas isotope ratios upon aeropass at Venus, deployed during aerobraking phase of parent mission.*

for targeting multiple objects within a system (e.g., NEA or giant-planet systems), even potentially by tailoring sibling nanospacecraft to characteristics of various targets. Some planetary investigations may be amenable to a fractionated payload architecture (a large payload subdivided among multiple nanosats) whose individual elements are replaced over time either as needed or with higher-performance versions.

Breaking New Ground

NASA SMD (Science Mission Directorate) missions are science-driven, but their implementation – and thus their ambition – is strongly constrained by the balance between heritage capabilities and the cost risk of developing new capabilities. Nanospacecraft can open paths to revolutionary architectures for achieving more audacious science investigations in the future such as: planetary cave exploration[8]; micro-g and milli-g laboratories for material-physics experiments to support planetary accretion modeling[9]; large-scale search for methane sources on Mars[10]; purely exploratory, discovery-driven surveys of uncharted regions like Sun-Earth L4 and L5 (see below) or the solar system's interstellar frontier[11].

V. JPL DISCOVERY 2014 TDOS

The Discovery 2014 AO (Announcement of Opportunity) invited TDOs (Technology Demonstration Options) that could enable future investigations, enhance the science of the proposed mission, or both. Via JPL's proposal portfolio, seven PIs proposed nanospacecraft-based TDOs for implementation. One is based on the standalone mode; the others proposed a mother-daughter architecture. Of those, three are in situ investigations; the rest are flyby-orbiter investigations. Each has a unique set of demonstration and science objectives at a compelling destination in the solar system:

Venus

Noble-gas mass spectrometry of the well-mixed Venus atmosphere (below the homopause), upon aeropass after apoapsis release by the mothership during aerobraking (Figure 6). Determining the isotopic ratios for noble gases in Venus' atmosphere is a key objective prioritized by VEXAG (Venus Exploration Assessment Group)[12], as a key to understanding Venus' origin and as a critical puzzle piece for comparative planetology across habitable-zone planets.

Near-Earth Rubble-Pile Asteroid

Second-viewpoint and close-proximity imaging of microgravity-aggregate disruption experiments performed by the mothership at the secondary of the 1996 FG3 binary asteroid system (Figure 7). Imaging blast plumes under multiple, complementary illumination angles can help quantify ejecta volume, key to elucidating material cohesive strength. TRN in a low-gravity environment would be demonstrated, enabling close-proximity imaging of the post-disruption surface.

Jupiter-Family Comet

Controlled penetrometry of indurated cometary crust to measure surface strength of comet Tempel 2 (Figure 8). This measurement could resolve ambiguities left by *Rosetta*'s *Philae* lander, providing an important constraint for formulating a future cryogenic comet nucleus sample mission. TRN would enable dual penetrators, each with stereo imagers, to target specific sites identified by the mission science team.

Earth-Trojan Asteroids

Demonstration of nanospacecraft AutoNav (asteroid-based autonomous navigation) to decrease operations and DSN costs for interplanetary nanospacecraft exploration. Released by a host mission at Sun-Earth L2, this standalone 6U spacecraft would use AutoNav to guide itself along the weak-stability boundary to SE-L5, where it could search for putative Earth Trojan asteroids (Figure 9). Such objects are

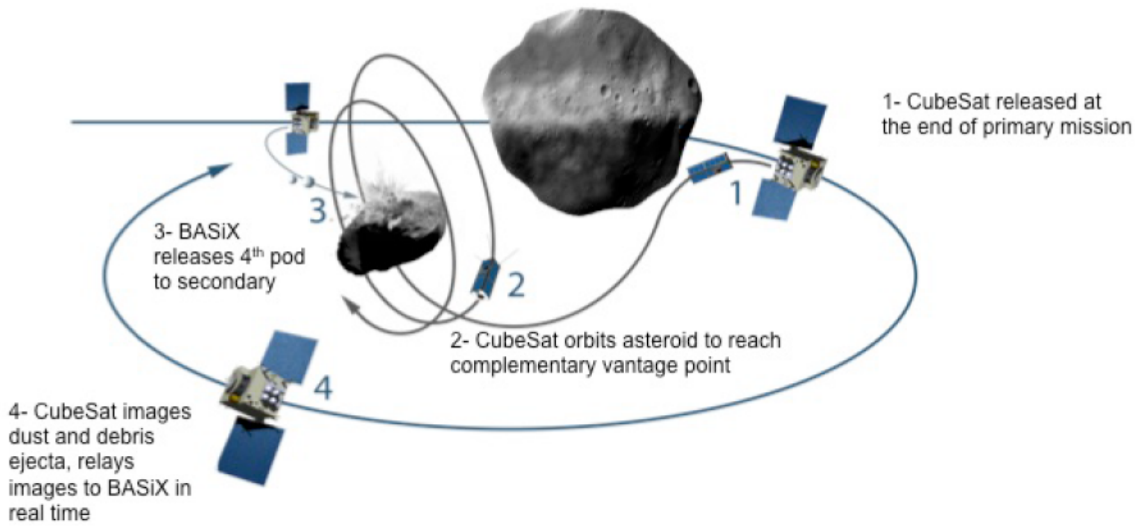


Fig. 7: ANTIX *would perform AutoNav and hovering proximity operations at 1996 FG3's secondary, witnessing a rubble-pile blast experiment up close.*

important tracers of solar-system dynamical evolution, and also potential resources for human-spaceflight ISRU. The detection investigation directly leverages *NEAScout*'s IntelliCam and concept of operations.

Phobos

Nanospacecraft soft lander demonstrates multiple technologies: cold-gas-controlled landing; boomless U-class gamma ray spectrometer; and NASA's EDS (electrodynamic dust shield)[13] (Figure 10). The mission makes high-SNR subsurface elemental composition measurements of Mars' largest moon and performs controlled experiments of dust behavior, a high-priority SKG for NASA's humans-to-Mars goal.

Main-Belt Icy Asteroid

Near infra-red (NIR) hyperspectral search for exposed surface deposits of water ice at 24 Themis, suspected parent of the mission's primary target, 238P/Read. A daughter nanospacecraft with ASA enables rapid spectral-feature extraction upon fast flyby[14], with prioritized downlink to the mothership of spectral-cube excerpts that match expected ice features (Figure 11).

Outer Main-Belt Metal Asteroid

Close-proximity magnetometry mapping of 16 Psyche, complementary to global-scale magnetic field mapping by a mothership (Figure 12). The

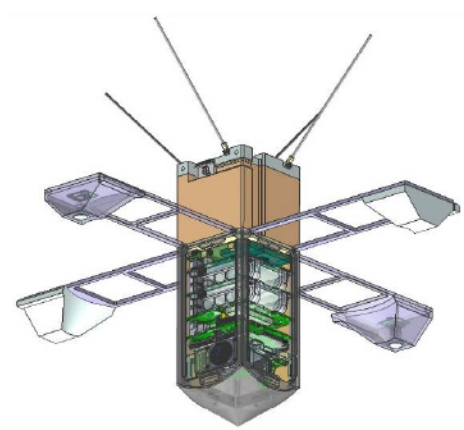


Fig. 8: ***Twin comet impactors*** *would perform the "Crème Brûlée test" at comet Tempel 2 to resolve ambiguities about surface strength left by the* Philae *lander at C-G.*

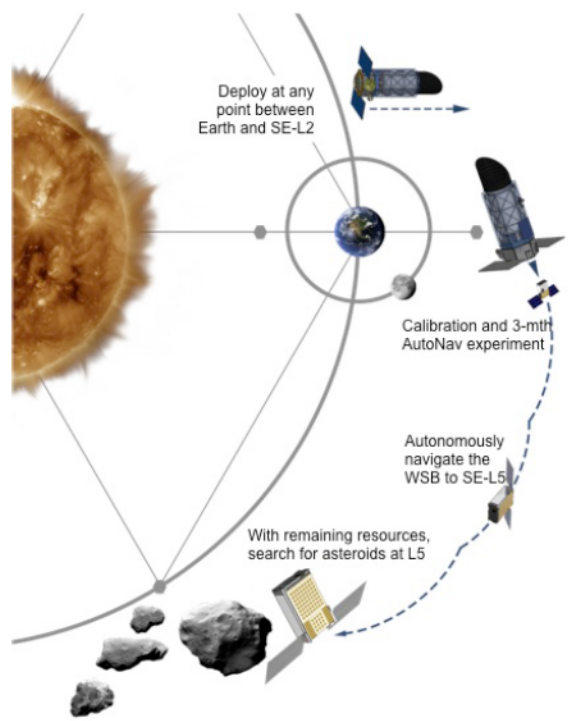


Fig. 9: Pytheas *would independently navigate on a 1000-day mission from Sun-Earth L2 to L5, to conduct a search for Earth-Trojan asteroids.*

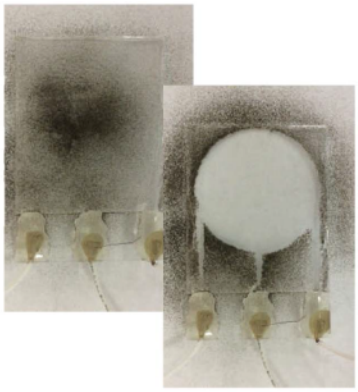


Fig. 10: Pyxis *would soft-land on Phobos* *from low orbit, to perform in situ gamma-ray spectroscopy of the moon's composition, measure dust lofting and adhesion behavior, and assess efficacy of NASA's EDS dust-removal technology.*

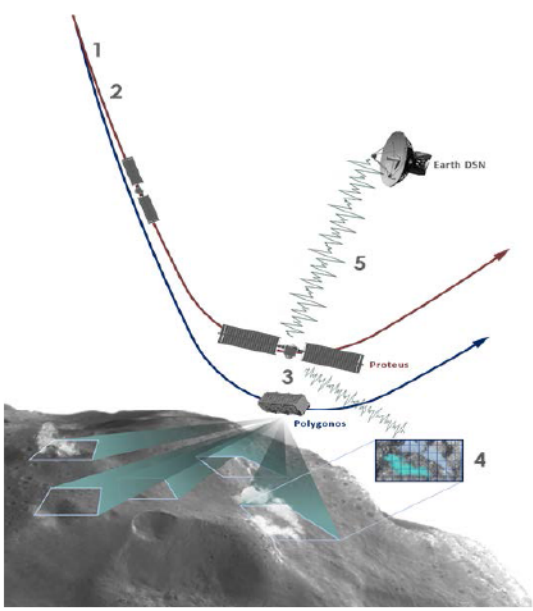
nanospacecraft investigation could detect low-amplitude, remanent fields very close to the surface, which would augment the mission's investigation of the thermal history of the solar system's largest metal asteroid, hypothesized to be the exposed core of a stripped, differentiated proto-planet.

Together this portfolio of planetary-science nanospacecraft concepts demonstrates the rich diversity of scientific and technology-demonstration objectives that could be accomplished by hosting nanospacecraft on primary missions. Each concept builds upon *INSPIRE*, *MarCO*, *Lunar Flashlight*, and *NEAScout*, the only flight-project precedents available for U-class planetary investigations. A library of common-component technical parameters (e.g., mass, power, volume, heritage) enables viable and consistent MELs (master equipment lists) and power and volume budgets; and predictable, evolutionary system performance projections for all the designs. And the programmatic basis already being documented during these pioneering flight-project developments enables credible projections of cost and schedule.

Subsystem/ Parameter	***3U Designs***	***6U-8U Designs***
Power Consumption (W, no margin)	1–4 average, 8–14 max	5 average
Energy Storage	Secondary Batteries – Li-Ion (18650)	Primary Batteries – Li-$SOCl_2$ Secondary Batteries – Li-Ion (18650)
Telecom-munication	UHF Radio and Low Gain Antenna	Iris Transponder and High Gain Antenna
Orbit & Attitude Control	Cold Gas System XACT BCT, 0.25 U	Cold Gas system XACT BCT, 0.5 U
Lifetime	Days to weeks	Up to 3 years
Mass (kg)	3–4 4–5 (with 30% margin)	6–8 8–10 (with 30% margin)
Deployer Mass (kg)	5–6 7–8 (with 30% margin)	10 13 (with 30% margin)

Table 2: *TDO portfolio system-level performance spans a wide range.*

Subsystem synergy allows lean, low mass, multi-functional flight system designs. For example, cameras are used for navigation and science imaging; bus structure provides radiation protection as well as mechanical support; the Iris transponder does both tracking and communication; and cold-gas thrusters perform both orbital maneuvers and reaction-wheel desaturations.



1. Deployed from parent mission.

2. Navigates to close flyby.

3. Collects IR spectra of surface.

4. Agile Science Algorithms identify spectral cubes indicating exposed ice.

5. Transmits highest value image cubes to parent mission.

Fig. 11: Polygonos *would perform a close flyby of 24 Themis*, *and use its U-class imaging spectrometer to map surface ice deposits.*

Table 2 summarizes salient subsystem parameters for the TDO portfolio. A standard aluminum CubeSat primary structure is used for most of the designs. Body-fixed or deployed solar arrays and batteries are sized according to destination (i.e., distance from the Sun), area/volume constraints, and power consumption requirements (with operations plans that cycle high-power components).

Small orbital maneuvers ($\Delta V < 100$ m/s) and reaction-wheel desaturations are done using VACCO cold-gas systems. Attitude control is performed primarily with the Blue Canyon Technologies attitude-control unit (star tracker, reaction wheels, inertial measurement unit, control algorithms), or relevant components from it (reaction wheels or star trackers are omitted in some designs).

For mother-daughter architectures, telecommunication using a small UHF radio and antenna achieves data rates of 100 kbps or more, depending on mothership capabilities and range. The standalone implementation returns data directly to Earth using an Iris transponder and high-gain antenna, by relaying only key data at considerably lower rates (<1 kbps).

JPL's radiation-tolerant, miniaturized Sphinx C&DH board is at the heart of most of the designs. Sphinx uses a dual-core, fault-tolerant LEON3-FT (GR712) processor that can run onboard algorithms for ASA, DTN, and optimal resource planning. The LEON architecture has been proven in space, and the Sphinx board will gain deep-space flight heritage on *NEAScout* and *Lunar Flashlight*.

VI. JPL NANOSPACECRAFT CAPABILITIES FOR PLANETARY PIs

JPL has established a portal for all types of CubeSat support, including planetary nanospacecraft, at http://www.jpl.nasa.gov/cubesat/. Tables 3 and 4 summarize, respectively, the technical capabilities (subsystems, instruments, and software) and support capabilities (formulation and development services and facilities) that JPL and its partners are using today to help proposing PIs take advantage of the nanospacecraft cost efficiencies and risk paradigm now applicable to planetary science.

Subsystems

New computer, telecommunication, and data-storage components are especially enabling. The new Sphinx computer is similar to the RAD750 but operates within the U-class architecture. U-class telecommunication technologies, including the Iris transponder and high-gain, deployable ISARA reflectarray antenna, enable navigation and telecommunication across interplanetary distances.

Instruments

In addition to the CVHM which is ready for flight, JPL is developing eight instruments smaller than 2U (Table 3). Intentionally optimized for deep-space nanospacecraft (e.g., the IntelliCam science and OpNav camera), these instruments also offer breakthrough mass and cost benefits – as well as high performance – for future primary missions.

Software

Legacy software (e.g., AMMOS and DTN), as well as a novel suite of tools, will increasingly improve onboard intelligence – and hence autonomy – to

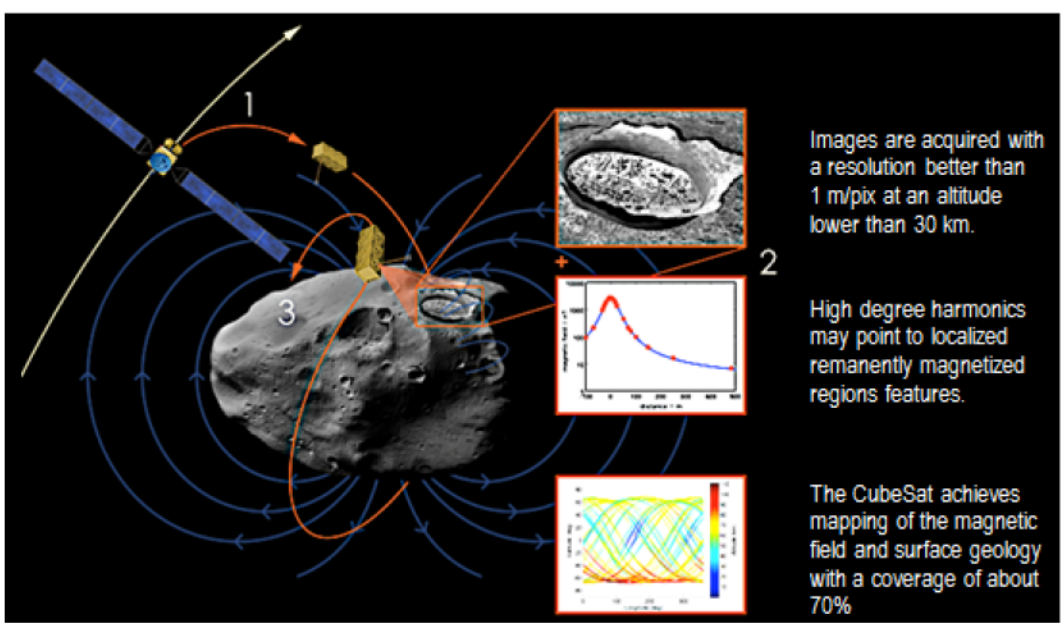


Fig. 12: ***Nanospacecraft deployed at 16 Psyche*** *would provide close-proximity imaging and magnetometry investigation of the solar system's largest metal asteroid.*

constrain operations cost and enhance science return of resource-constrained missions.

Operations services

Lifecycle nanospacecraft support services, from early formulation through development, verification, and operations, leverage legacy JPL tools and capabilities (Table 4). This includes tailored institutional processes with which mission-experienced experts balance the cost advantages of sub-Class-D payload development with the unique requirements and risk expectations of planetary missions.

Facilities

Lifecycle facilities are already designed and staffed for the unique considerations of nanospacecraft development. Team Xc leverages the traditional Team X concurrent-engineering environment and toolset to enable rapid design, cost estimating, and trade studies to help science and technology PIs quickly evaluate the potential implementation feasibility of concepts. Building 189, now renovated into JPL's institutional CubeSat Development Laboratory, is equipped for Phase D integration and test of nanospacecraft (Figure 13).

Class	Type	Name	Capability	Heritage / Infusion	Point of Contact
Nanospacecraft Subsystem	Deep Space C&DH	Sphinx	300 krad, 2×134 MIPS full duplex	Infused via *NEAScout*, *Lunar Flashlight*	John Baker
	Transponder	Iris-2	Tracking and Telecommunication beyond Earth orbit and distances > 1 AU	Infused via *MarCO*	Courtney Duncan
	Deep Space Dispenser	PDCS	COTS deployer, LEON C&DH, radio, antenna, power interface	P-POD heritage	Peter Kahn
	Deployable Antenna	ISARA Antenna	100 Mbs, fits in 3U	Infused via *MarCO* and *ISARA*	Biren Shah
Instruments	Science and OpNav Camera	Intelli-Cam	iFOV: 0.13 mrad, SNR = 5 at 50k km and H = 8	Infused via *OCO-3* and *NEAScout*	Justin Boland
	Infrared imager	SWIS	0.4–1.65 μm uncooled, up to 2.5 μm (cooled with micro-cryostat)	M3 heritage, proposed for Discovery TDO	Zakos Mouroulis
	Point IR Spectrometer	n/a	Reflectance of three water bands, passively cooled	Infused via *Lunar Flashlight*	Joseph Reiter
	Radiometer	CHARM	Microwave radiation from the 183-GHz water vapor line	Infused via *RACE*	Boon Lim
	Sub-mm wave spectrometer	WISPER	Oxygen isotope ratios for volatile formation thermometry	JPL sub-mm spectrometer (e.g., MIRO) instrument heritage	Ken Cooper
	Ground Penetrating Radar	SUPER	High- and low-frequency design for probing 20 – 200-m deep in small bodies	JPL radar instrument heritage	Yonggyu Gim
	UV Spectrometer	UVS	Reflectance imager in 100 – 250 and 250 – 600-nm range	M3 heritage	Shouleh Nikzad
	Gamma Ray Spectrometer	GRS	Ultra-bright SrI_2 scintillator, does not require boom deployment	Proposed for Discovery TDO	T. Prettyman (PSI)
	Vector Helium Magnetometer	CVHM	Measures magnetic field with < 10-pT stability	Delivered to *INSPIRE*	Neil Murphy, Carol Raymond
Software	Agile Science Algorithms	ASA	Automated gain setting, rapid feature extraction, downlink prioritization, resource management, rapid re-planning	*EO-1* mission heritage; proposed for multiple Discovery TDOs	David Thompson, Steve Chien
	Disruption Tolerant Network	DTN	Architecture and software for networks with non-continuous connectivity	Demonstrated on *EPOXI*, proposed for multiple Discovery TDOs	Jay Wyatt
	Autonomous Navigation	AutoNav	Autonomous localization and trajectory replanning	Inherited from *DS1*, *Deep Impact*; proposed for Discovery TDO	Shyam Bhaskaran
	Primitive Body Navigation Suite	PBN	Modeling of spacecraft dynamics in low-gravity environment and close proximity	Proposed for multiple Discovery TDOs	Steve Broschart
	Lightweight Real Time Operating System	Protos	< 50-kB footprint with CCSDS, sequences, and robust fault protecttion. Portable into lightweight micro controllers.	Infused via *INSPIRE* and *MarCO*.	Thomas Werne

Table 3: ***JPL and partner nanospacecraft capabilities*** *already support planetary-mission formulation by PIs.*

Class	Type	Name	Capability	Heritage / Infusion	Point of Contact
Services	Concurrent Engineering	Team Xc	End-to-end mission design and systems engineering, costing	JPL Team X heritage	Pez Zarifian
	Navigation, Operations, Ground Data System Tools	AMMOS	Telecom Forecaster Predictor (TFP)	JPL MOS heritage	Kar-Ming Cheung
	Ground Communications	DSN	Tracking and Telecommunications	JPL MOS heritage	Greg Welz
	Data Pipeline	MIPL	Automated raw data processing for archiving	Heritage from many missions (e.g., *InSight*)	Janet Fung
Facilities	CubeSat Implementation	CubeSat Development Laboratory	Implementation maker-space for clean and near-clean development	Operational Feb 2015	Pamela Clark
	Attitude Control	SmallSat Dynamics testbed	Hardware-in-the-loop testing & software development. Planar & Spherical Air Bearings. SmallSat-centric ACS simulation.	Operational Aug 2015	Laura Jones, Swathi Mohan
	Camera/Intelligent Software Testbed	IntelliCam Testbed	Camera calibration combined with Agile Science testbed	Available in 2016	Justin Boland, David Thompson
	Environmental Testing	ETL	Vibration, acoustic, shock, thermal, and thermal-vac testing for broad sizes and shapes	Used on multiple CubeSat systems and subsystems	Shannon Statham

Table 4: ***Dedicated nanospacecraft services and facilities*** *support JPL planetary nanospacecraft PIs.*

Fig. 13: ***CubeSat Development Laboratory*** *now occupies JPL Building 189.*

VII. CONCLUSION

Using four flight projects – *INSPIRE*, *MarCO*, *NEAScout*, and *Lunar Flashlight* – JPL is progressively establishing a seven-part foundation to help planetary-science PIs credibly formulate and propose nanospacecraft-enabled investigations, particularly within the context of cost-constrained primary missions: 1) a rapid approach to science scoping compatible with nanospacecraft resources; 2) a cadre of space systems engineers and scientists experienced in working with CubeSat component partners and vendors to adapt their products for deep-space use, and who are also experienced in delivering interplanetary nanospacecraft flight systems; 3) subsystem enhancements to standard vendor components that tailor and qualify them for planetary requirements; 4) flight software to operate nanospacecraft and their hosted science measurements in deep space; 5) U-class instruments capable of a wide range of measurements of interest to planetary science investigations; 6) a lessons-learned database to avoid missteps on future developments; and 7) empirical cost and schedule bases for such developments. As exemplified by novel TDOs proposed by seven Discovery PIs in 2015, this foundation is already extending the "CubeSat revolution" throughout the solar system.

VIII. ACKNOWLEDGEMENT

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IX. ACRONYMS

3D	Three-Dimensional
AES	Advanced Exploration Systems
AO	Announcement of Opportunity
ASA	Agile-Science Algorithms
C&DH	Command and Data Handling
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CVHM	Compact Vector-Helium Magnetometer
DOE	Department of Energy
DSN	Deep-Space Network
DTE	Direct-to-Earth
DTN	Disruption-Tolerant Networking
EDL	Entry, Descent, and Landing
EDS	Electrodynamic Dust Shield
EO-1	Earth Observing One
EPOXI	Extrasolar Planet Observation and Deep Impact Extended Investigation
HEOMD	Human Exploration and Operations Mission Directorate
iFOV	Instrument Field of View
INSPIRE	Interplanetary NanoSpacecraft Pathfinder In Relevant Environment
IPEX	Intelligent Payload Experiment
IR	Infra-Red
ISARA	Integrated Solar Array & Reflectarray Antenna
ISRU	In Situ Resource Utilization
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LRO	Lunar Reconnaissance Orbiter
M3	Moon Mineralogy Mapper
MarCO	Mars Cube One
MEL	Master Equipment List
MLI	Multi-Layer Insulation

MOS	Mission Operations System
MRO	Mars Reconnaissance Orbiter
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NIAC	NASA Innovative Advanced Concepts
NIR	Near Infra-Red
OCO-3	Orbiting Carbon Observatory 3
PI	Principal Investigator
PSR	Permanently Shadowed Region
RAM	Random-Access Memory
REBR	ReEntry Breakup Recorder
RF	Radio Frequency
RPS	Radioisotope Power Systems
SKG	Strategic Knowledge Gap
SLS	Space Launch System
SMD	Science Mission Directorate
SNR	Signal-to-Noise Ratio
TCM	Trajectory Correction Maneuver
TDO	Technology Demonstration Option
TFP	Telecom Forecaster Predictor
TRL	Technology Readiness Level
TRN	Terrain-Relative Navigation
UHF	Ultra-High Frequency
VEXAG	Venus Exploration Assessment Group

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