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NANO-SATELLITE SECONDARY SPACECRAFT ON DEEP SPACE MISSIONS

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NanoSat technology has opened Earth orbit to extremely low-cost science missions through a common interface that provides greater launch accessibility. They have also been used on interplanetary missions, but these missions have used one-off components and architectures so that the return on investment has been limited. A natural question is the role that CubeSat-derived NanoSats could play to increase the science return of deep space missions. We do not consider single instrument nano-satellites as likely to complete entire Discovery-class missions alone, but believe that nano-satellites could augment larger missions to significantly increase science return. The key advantages offered by these mini-spacecrafts over previous planetary probes is the common availability of advanced subsystems that open the door to a large variety of science experiments, including new guidance, navigation and control capabilities. In this paper, multiple NanoSat science applications are investigated, primarily for high risk / high return science areas. We also address the significant challenges and questions that remain as obstacles to the use of nano-satellites in deep space missions. Finally, we provide some thoughts on a development roadmap toward interplanetary usage of NanoSpacecraft.

I. INTRODUCTION

The last decade of planetary exploration has seen the development of a variety of small platforms for close proximity or in situ survey of a variety of objects. Indeed, in situ observations provide access to constraints on chemistry, especially content in volatiles and organics, and soil properties that are otherwise difficult to approach with remote sensing techniques. Until recently, two types of deployable daughterships had been considered: (a) static landers (e.g., penetrators and soft landers like *Rosetta*'s *Philae*) and (b) mobile platforms, such as hoppers, tumble weeds, and rovers in the specific case of Mars. Differences in environmental properties between planetary bodies, especially gravity regime, soil properties, and temperature, make it difficult to design generic platforms that can enable a variety of measurements at a broad range of objects without requiring large tailoring. In particular, mobility becomes increasingly difficult, or prohibitively expensive, with increasing gravity. Yet, science return scales with spatial coverage and the capability of a platform to access high science areas as well as the subsurface [1].

In this paper we introduce an alternative approach for in situ and close proximity observations that aims to address the aforementioned limitations by enabling extensive mobility of a small instrument payload through the distribution of multiple small, disposable crafts across the surface, providing access to a variety of terrains and for a broad range of contexts. This study explores the availability of NanoSats, e.g., fully autonomous spacecrafts, as smart instrumented daughterships of larger missions to target distributed high science areas, guide the mothership through dangerous regions, or sacrifice themselves while they perform reconnaissance of potentially dangerous areas.

The idea comes from the observation that NanoSatellites, typically in the form of CubeSats, have transformed low-Earth orbit mission opportunities. A limited LEO mission is now feasible for several million dollars, with increased launch opportunities and a standardized platform. This has allowed universities, traditional aerospace companies, and NASA centers to carry out educational, technological demonstrator, and science missions at a fraction of a large mission cost, but in a constrained manner. Learning to handle the inherent platform and programmatic constraints has been an ongoing challenge for the community, but one that is now yielding impressive results with science missions addressing space weather, exoplanet surveys, and atmospheric composition. The O/OREOS mission hlaunched in November 2010 is the first mission with the objective to support the objectives of NASA Astrobiology Institute. This spacecraft carries two experiments, one involving organics, and the other one organic molecules, in order to test the stability of that material in space environment. This mission falls under NASA's *Astrobiology Small Payload Program* that was called only once, back in 2007, but re-

sulted in the collection of a large number of ideas, ranging from astrobiology experiments to testing in reduced gravity.

More recently, NASA's Institute for Advanced Concepts (NIAC) went farther in the exploration of science enabled by small spacecrafts with the selection of a project investigating *Interplanetary CubeSats* [2]. This concept revolves around using CubeSats as primary spacecrafts for the exploration of small bodies, the Sun, and Mars. While that project has identified a number of challenges (e.g., telecommunication, long-term survival, etc.) that will require a maturation process in line with the scope of the NIAC program, they open the door to exciting promises for cheaper, high science return missions (increased science return per dollar).

We have recognized that there are lessons to be learned from the development and utilization of CubeSats in LEO that are applicable to the use of NanoSats on interplanetary missions, either as daughterships or as primary spacecrafts. In the following sections, we compare and contrast the advantages and limitations of using NanoSats as daughtership against other forms of daughterships proposed to date (Section 2), in the frame of the science objectives of the 2013-2022 Planetary Science Decadal Survey [PSDS,[3]] as well as precursor measurements required in preparation for the Human exploration of asteroids and the Martian system. We then discuss the technologies required to bring the current generation of CubeSats to the degree of maturation required for deep space exploration and propose some prioritization (Roadmap - Section 3).

II. CURRENT GENERATION OF SMALL PLATFORMS

The application of *in situ* daughtership platforms to planetary bodies beyond the Moon started in the early 90's (many primary spacecraft missions performed *in situ* science prior to this) with the hopper *PROP-F* on the Russian mission *Phobos 2*. In 1997, one of the first US daughterships for planetary exploration, the *Huygens* lander on-board the Cassini spacecraft, was launched. With its 318 kg and six elaborate experiments, Huygens qualifies as an extreme form of daughtership, but certainly tailored to the complexity offered by the large moon Titan. This was followed in 1999 by the *Deep Space 2* twin penetrators that carried an Evolved Water Experiment and Soil Conductivity Experiment*. These missions catalyzed the development of technologies enabling miniaturized instrumentation. Other recent missions and concepts involving small daughterships are: the Japanese missions *Lunar-A* (seismometer, heat flow probe, tiltmeter), *Hayabusa* and *Minerva* (camera+contact sensors), the penetrators concepts developed by the United Kingdom Consortium to be used as part of the concepts *Moonline/LunarNet/LunarEx* and Europa lander [4], the lander *MASCOT* (DLR) as part of the JAXA-led *Hayabusa-2* mission (currently under development), and European lander *Philae* as part of the *Rosetta* mission en route to the comet 67 P (see Figure 1).

For the purpose of the present study, we focus on smaller platforms that may complement large, flagship missions, but are also expected to open a new edge for exploration as part of smaller scale missions. As discussed in detail in[1] the science emphasized in the PSDS and strategic knowledge gaps identified for the Human exploration of asteroids and Mars' moons require approaching the compositional diversity and physical diversity of planetary surfaces. The current challenge posed by this type of science is the need to sample and characterize material representative of the bulk of the objects. This means accessing regions where fresh material has been excavated, for example by impact, seismic shaking, landslides, etc. or directly access source of material such as outgassing, All this requires fine mobility for accessing discrete and narrow areas and/or extreme terrains (e.g., crater rims, volcanic regions).

We present the advantages and limitations of various platforms based after the following criteria (Table 1): extent of mobility, technological constraints, maturity (readiness level) and heritage, and affordable payload mass. However, in general, these missions compare well in terms of affordable payload. The extent of science return expected for each platform is rather a function of the extent of their mobility, both in terms of spatial coverage and the degree of precision with which these platforms can access discrete and narrow areas, as well as pointing accuracy and stability (e.g., for measurements requiring long integration times). For example, static platforms like penetrators are ideal for seismometry, which requires high stability and strong mechanical coupling with the ground in order to allow long-term seismic monitoring. On the other hand, as noted above, capturing the chemical and physical diversity of planetary surfaces requires large spatial coverage and fine mobility. Hoppers and rovers to some extent address this need, although the degree of coverage achievable with a single element is a direct function of its lifetime, which is going to be limited depending on distance to the Sun and whether Radioisotope Heater Units are used.

Similarly, field and particle mapping (e.g., gravity and magnetic fields, plasma, radiations, dust, etc.) requires global coverage. The knowledge of these properties is of critical importance for the preparation of the Human exploration of small bodies, and requires global scale observation, best approached with an orbiter. In the

*These penetrators were not delivered as their carrier, the *Mars Polar Lander* mission, failed

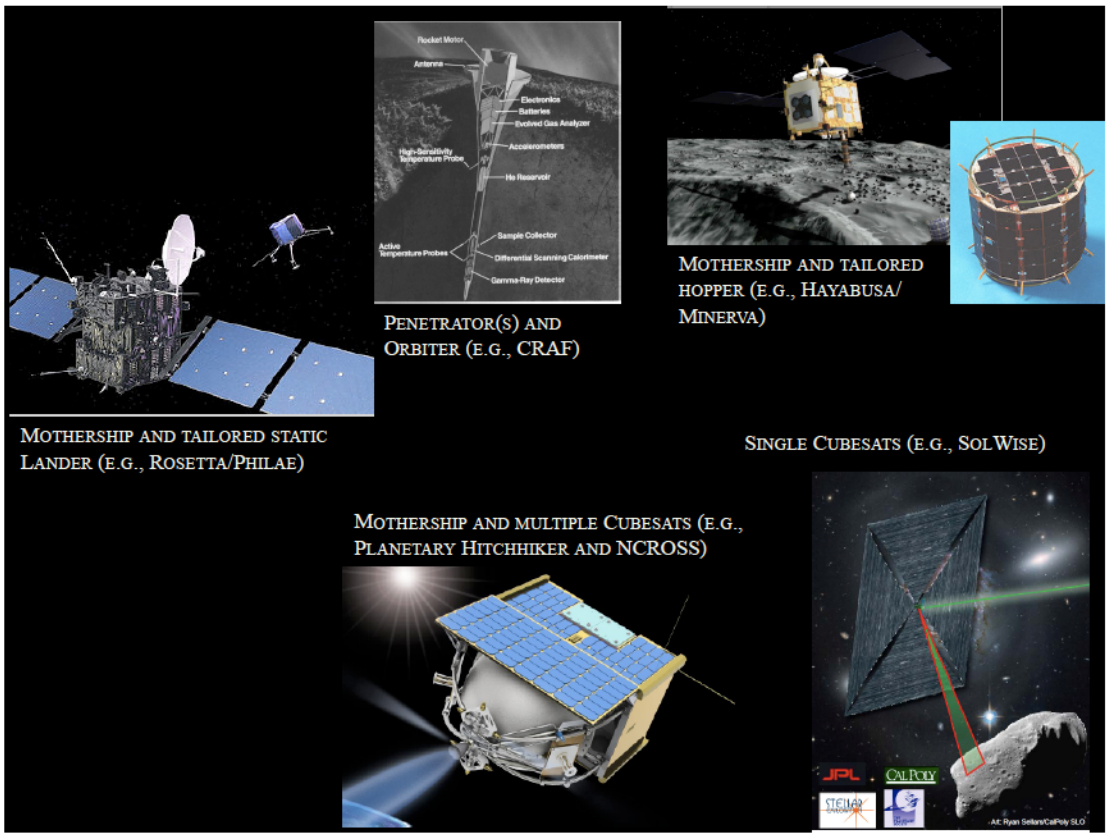

Fig. 1: Examples of small platforms that have been flown or have been suggested in mission concepts for the past two decades. First implemented on the *Hayabusa* mission, the use of hoppers has been considered for many years for small body missions [5,6,7,8] with several terrestrial designs [9,10], typically with external actuators. The *Minerva* roiver, designed for the *Hayabusa* mission, is unique because it contains an internal torquing mechanism that provides a hopping motion while remaining sealed to the environment during operations [11]. Cubesats as instruments on hitchhiking missions have been recently proposed (e.g., NASA Ames' *NCROSS*, *Planetary Hitchhiker*).

case of low-gravity bodies, mapping these fields requires close-proximity operations in challenging environments with complex orbital mechanics, dust dynamics, and an uncertain surface. This may be an area where small flying elements, like Cubesats, may prove the most useful.

III. USING CUBESATS AS INSTRUMENTS

CubeSats have become a popular and cost-effective means of reaching low-Earth orbit through the adoption of the CubeSat standard. First developed by a partnership between Stanford University and California Polytechnic - San Luis Obispo, this standard has uniquely catalyzed a revolution in nano-spacecraft. By containing the risk to the launch vehicle and primary payload within a container, the so-called Poly-Pico-Satellite-Orbital-Deployer (P-POD), nanosats are able to use space previously allocated to ballast. Recently, the NASA CubeSat Launch Initiative has begun to provide launch allocations at a low-cost or free price to universities and government institutions, enabling more launches than ever before. Though the standard, and the CubeSat movement, have only been around for 10 years, the launch rate is accelerating rapidly, and over 50 U's (10x10x10cm units) are expected to launch in 2012, with constellations of CubeSats expected in the near future.

These small spacecraft have typically fallen into several mission class areas: educational, technology demonstrator, and science, with the respective evolution of each class taking subsequently longer as requirements have grown more complex. Science advances have been

PLATFORM	PENETRATORS	SOFT LANDERS	HOPPERS	THRUSTER-DRIVEN HOPPERS	ROVERS (wheeled)	CUBESATS
Degree of Mobility	Static	Static	Fine, Short range (meters to 10s of meters)	Gross, Long range	Fine, Short range	Fine, Long range (¿100m capability)
Mass (kg)	30-40	Scales with payload	<5	Scales with payload, desired range, and lifetime	< 5 kg (small bodies)	1.5-10
Payload Mass (kg)	<5	10	2-3	5-10	5-10	0.5-4
Target Requirement	> 100 milli-g, hard surface	< 100 milli-g, any surface	> 100 milli-g, any surface, but tailoring required	> 100 milli-g, low dust required	> 100 milli-g, low dust required	Any
Deployment	Complex	Simple release (spring)	Simple release	Complex	Complex	Simple (P-POD/spring)
Operational Requirements	Alignment < 1 deg.	Pointing control required for proper orientation	Pointing control required for proper orientation	Must be able to rotate in flight	Must have traction	Autonomous navigation required
Risk	Deployment	Landing/Poor mechanical coupling with surface	Landing, stability in dynamic environment	Deployment, dust	Low TRL for small bodies	Low TRL in deep space
Maturity and Heritage	High - UK Consortium, *CRAF*, DS-2	High, *Philae*	Medium, Minerva (Itokawa)	Medium, CHopper	Low (Muses-CN)	NCROSS Thumpers
Expected Lifetime	Months	Months	Days	Weeks	Weeks	Days
Autonomy	Passive	Backroom team	Required	Backroom team	Backroom team	Required
Main Advantage	Access to the subsurface, long-integration time measurements and monitoring (e.g., surface tracking with beacon, seismometry), little req. on comm.	High TRL, scalable	Flexibility, low cost, fine GNC	Large payload and/or batteries	Fine mobility	Fine GNC, access to extreme terrains, cheap
Main Drawback	Deployment mechanism is complex and sink of mass	Stability on low gravity bodies is unclear	Limited lifetime	interaction with small bodies regolith is source of risk, deployment complex	Historically higher cost/Risk; Ttoo much tailoring required for individual surfaces	Low TRL for deep space

Table 1: Key characteristics of the main types of in situ elements proposed, requirements, and advantages/drawbacks. Information is based on specs published by the UK Consortium for Penetrators, NASA Institute for Advanced Concepts, Draper Labs, and the *Rosetta/Philae Project.*

Typical Parameter	1U	3U	6U
Mass	1.5 kg	4.5 kg	10 kg
Volume (Before Deployment)	10x10x10cm	10x10x30cm	10x20x30cm
Solar Arrays	Fixed (few deployable)	Fixed Deployable and Articulated	Fixed Deployable and Articulated
Power	~3 W oa fixed	~8W oa fixed ~25W oa deployed	~14W oa fixed ~35W oa deployed
Battery	2200mAh	4400mAh (0.2U)	4400mAh (0.2U)
Antenna	Monopole / Dipole	Dipole, Turnstile, Patch 0.5m dish (1U)	Dipole, Turnstile, Patch 0.5m dish (1U)
Comms	UHF / VHF	S-Band, UHF/VHF	S-Band, UHF/VHF
Data Rates	9600 kbps	3Mbps demo'd	3Mbps demo'd
Attitude Control	~10 deg control (passive)	1-10 deg (torquer) ~0.1-1 deg (RW) (0.5U) ~2 arcsec (piezo) (2U) "Dart" drag control	1-10 deg (torquer) ~0.1-1 deg (RW) (0.5U) ~2 arcsec (piezo) (2U) SRP control
Attitude Determination	~3-4 deg (gyro, sun, mag)	<1 deg (star tracker (0.25U)) ~2 arcsec with tracker (1 U)	<1 deg (star tracker (0.25U)) ~2 arcsec with tracker (1 U)
C&DH	RISC, ARM Some Linux-based	RISC, ARM, Linux, FPGAs	Rad-hard (SpaceMicro, etc) RISC, ARM, Linux, FPGAs
Propulsion	None	Cold Gas, EP, Solar Sail (<100 m/s)	Cold Gas, EP, Solar Sail (< 1000 km/s)
Deployables	Antenna	Antenna, Panels, Tethers, Boom (0.5m), Solar Sail (5m)	Antenna, Panels, Tethers, Boom (1m), Solar Sail
Demonstrated Lifetime	Few years	9 years+	To be flown in 2012
Instruments	1 board, camera (0.8U notional)	0.5-2U typical – passive, cameras, telescopes	Up to 5U typical

Fig. 2: Table summarizing the current state of performance of the different CubeSat form factors developed to date.

achieved using this small platform, as in the NASA Ames O/OREOS mission (astrobiology) [12] and the University of Michigan's RAX mission (space weather) [13].

The RAX mission in particular provides an example of a CubeSat assisting in the investigation of an area previously unexplored. RAX, or the Radio Aurora Explorer, is a bi-static radar mission built to explore magnetic field-aligned irregularities in the ionosphere. A radar transmitter on Earth's surface transmits a coded pulse, which scatters off the irregularities. This scatter is collected by RAX, passing overhead, and used to characterize the irregularities. Due to a perpendicularity requirement on the scatter, this mission is unachievable by a traditional radar system, and it requires a dedicated receiver in space. By taking advantage of the low-cost nature of RAX, the mission was designed, constructed and operated within 2 years, and under 1 million dollars (RAX was funded by a grant from the National Science Foundation). Almost more impressively, the team launched a second, upgraded, RAX spacecraft less than 11 months after the first encountered an on-orbit anomaly [13]. Recently, RAX "successfully took the first-ever measurement of naturally occurring auroral turbulence recorded using a nanosatellite radar receiver" [sr.com/news/releases/032212.html]. This turbulence was a direct result of a recent geomagnetic storm.

Other science missions have included NSF's *Firefly*, examining terrestrial gamma ray flashes and their link to lightning, [14], Montana State's *Explorer 1 Prime* - Flight Unit Two, which flew an original Van Allen geiger counter to measure variations in the location and inten-

sity of energetic electrons trapped in the Van Allen radiation belts [15], and MIT's *ExoPlanetSat*, the first CubeSat to look for exoplanets using an ultra-stable (2-3 arc second pointing accuracy) platform [16]. Many more CubeSat missions are now being designed and prepped for flight, providing individual investigators a low-cost option to achieve novel science at a quick cadence.

RAX, and other CubeSats, have not only achieved great science, but they have demonstrated that small spacecraft can be used to create collaborative science, unachievable by either a larger instrument (the ground transmitter in the case of RAX), or the smaller spacecraft alone. Along with the other characteristics that make CubeSats unique, these lessons can also be applied to deep space missions, where the use of small daughter-ship NanoSats can enhance a primary mission through collaboration and/or wide distribution.

III.I. Science Applications and Instrument Availability

The availability of smart, guided instruments with access to planetary surfaces offers the potential for a whole new class of science experiments. These applications include (and are not limited to)

(i) Imaging and remote sensing: very high-resolution geological, compositional, and field mapping (e.g., magnetic and gravity fields), survey of surface dynamics, e.g., dust levitation, search for outgassing activity and signs of exospheric activity, etc.

(ii) Direct surface sampling: soil mechanics (e.g., adapting a penetrometer), soil microscopy, fine chemistry (such as isotopic and elemental composition), surface tracking with beacon, seismometry, etc.

NanoSats do not have the traditional separation between instrument and spacecraft that larger vehicles have. In fact, NanoSats, including CubeSats, can be thought of as instruments with a few spacecraft parts attached to the outside. This allows great flexibility in the customization and construction of these small vehicles, often motivated by the strict mass and volume constraints imposed by the primary spacecraft (CubeSats are limited to 10x10x10cm per unit, and under approximately 1.5 kg in mass). Technical details on the current state of the art are presented in Figure 2. Should these vehicles grow too large, they begin to violate their "ignorable" nature, and primary spacecraft might have to change configuration to accommodate them.

Even though the spacecraft are, in many respects, tiny, many existing instruments already fit within this form-factor. The current generation of miniaturized instruments covers a variety of applications (see Fig. 3). Instrument technology has been evolving toward smaller detectors and sensors. The traditional 1U payload package for a 3U CubeSat can, a priori, accommodate many of these instruments, including radiation monitors, accelerometers, imagers, seismometers, the APXS, and spectrometers. Still, optical remote sensing and analytical instruments still require further development in order to decrease their mass and power consumption below 2 kg and 5 W. An overview of the power versus mass for a variety of high-TRL instruments is presented in Figures 4 and 5. The more massive instruments correspond to analytical instruments that require some processing of the sample and long integration times, such as mass spectrometry, X-ray spectroscopy, etc. On the other hand, geophysical/geological instruments (accelerometers, tiltmeters, panoramic cameras) are found well below 500 g. The more power hungry are those instruments that require some form of heat, illumination, or communication (like beacon, thermoprobe, etc.) Hence many instruments of these instrument do require more power than is typically available in the 1U form-factor, which might necessitate low duty-cycles or deployable panels.

Of lower technology readiness level, mechanisms for sampling material for in situ analysis are lagging behind. Sampling depends on material properties that may drastically vary from one surface to another (e.g., extreme fine dust, sticky organics material – different adhesion properties). Also low gravity and electrostatic charging makes it difficult to sample at small bodies, while icy material sampling requires prior melting and suction mechanisms. This keeps analytical techniques out of reach for the time being but the portfolio of NASA's instrument programs indicate that this gap could be closed before the end of the decade. An open question is the appropriate size for a secondary NanoSat spacecraft supporting interplanetary missions. Though instruments are available in a small form-factor, supporting electronics, sufficiently designed to handle the deep space environment, along with communications and propulsion need to be appropriately designed for the science or technology application on hand.

III.II. Technology Roadmap

The development of an interplanetary capable NanoSat could follow one of two paths - CubeSats have traditionally been a technology driven platform (what can we get to space in a 10 cm x 10 cm x 10 cm box? Fig. 2) and have proven small space can produce real science. We propose that rather than following the same path for interplanetary NanoSats, lessons learned from CubeSats should be combined with science applications that can take advantage of the small size - *the interplanetary NanoSat should be driven by science applications*

INSTRUMENT	GEOPHYSICS	CHEMISTRY	HABITABILITY	HERITAGE	MASS (ESTIMATED)
Seismometer	●		○	OPTIMISM/Mars 96/InSIGHT	50-500 g
PanCam	●	○	○	CIVA/Rosetta; Phobos 11	100-1000 g
Radiation dose	●		○	RADOM/Chandrayaan-1	100g
Gravimeter	●		○	GRAS/Phobos 11	250g
Tiltometer	●		○	Huygens	250g
Optical microscope	●	●	○	Beagle-2; Phobos 11	100-300g
Magnetometer	●	○	○	MMO Bepi Colombo	770g
XRF	○	●	○	APXS/Rosetta	640g
Immuno-arrays		○	●	SOLID	(1000g)
Laser-ablation MS	○	●	○	LASMA/Phobos 11	1000g
INMS	●	●	○	MANAGA/Phobos	1000g
IR close-up spectrometer	●	●	●	CIVA/Rosetta MicrOmega/ExoMars	(1000g)
Raman spectroscopy	○	●	●	RAMAN-LIBS/ExoMars[1]	1100g[2]
LIBS	○	●	○	RAMAN-LIBS/ExoMars[1]	1100g[2]
XRD[3]	●	○		XRD/ExoMars	1200g
XRS	○	●	●	No prototype	(2000g)
ATR spectroscopy	○	●	●	MIMA/ExoMars[1] for FTS analyzer	(2000g)
IR spectroscopy	●	●	○	No direct prototype; technique well established	(2000g)
Wet chemistry set		●	●	Urey	2000g
GCMS	○	●	●	GAP/Phobos 11; COSAC/ Rosetta	(5000g)

Fig. 3: Review of instruments with heritage or in development (Technological Readiness Level greater than 4) as a function of key science themes.

and designed by engineers and scientists collaborating.

Typical CubeSat characteristics that must be taken forward include:

- **Low Mass / Low Inertia** Payloads that have low mass and inertia can be ignored for some major analyses in larger spacecraft design as they have little to no impact on structure, thermal design, or configuration. In fact, some payloads may even act as ballast replacements (assuming their center of mass and geometry is well defined).

- **Low Risk to Primary** Any payload of significant risk to the primary spacecraft or primary science is at risk of being descoped, especially if the payload is of secondary importance. With the low-budget, low-risk methodology imposed on planetary missions, items of significant risk are specifically targeted for removal to assure mission success. This risk is often "bought down" through compromises in budget or schedule, which would invalidate the reason to include small secondary NanoSats to begin with.

- **Targeted Science** CubeSat constraints typically require that there is one instrument per spacecraft, which can make for creative solutions that are optimized for the mission. The attempt to include multiple payloads, or make the standard "just a little bit bigger" may create complicated secondary vehicles which cannot be afforded.

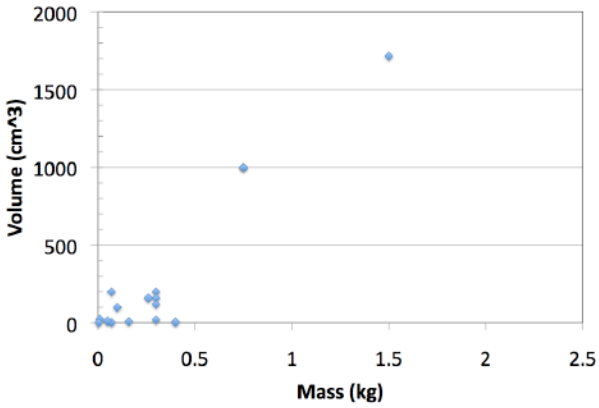

Fig. 4: Volume versus mass for some high heritage instruments.

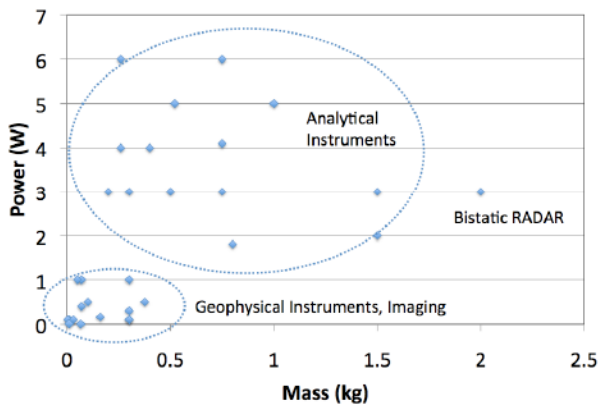

Fig. 5: Power versus mass for some high heritage instruments.

- **Creative Design** The opportunity for low cost and obtainable launch access has led to creative designs for missions that know a second opportunity is obtainable. Unfortunately, it is likely that multiple opportunities may not be the case for interplanetary NanoSats, but the ability to include multiple craft of different architectures may still allow for novel designs. Rather than include only a single NanoSat on a mission, constraining the target size to be the minimal possible for science applications would provide multiple opportunities on the same vehicle to approach the same investigation in several different manners.

These characteristics can be used to develop a standard - perhaps not for every interplanetary mission - but one that can be slightly customized for each flight opportunity, while retaining important characteristics to allow for multi-mission use if applicable.

In addition to common characteristics, some technology development would be useful to support these missions, in a loose order of importance..

1. **Rad-tolerant Mission Operation Strategies and Mainboard Computer** The deep space environment is not friendly to processors or electronic components. Jupiter is so threatening that JUNO's avionics are built within tank ([17]). Thus protection from radiation for secondary spacecraft is important, especially as travel to interesting destinations can often cover years. Rad-tolerance has already been considered for CubeSat missions, generally through the use of watchdog systems, automatic reboots, and the use of individual rad-hard parts. But the fundamental unit of a CubeSat, the command and data handling board, has few products that are ready for deep-space flight. Several solutions may exist: 1) Reduce overall exposure by shielding the NanoSat's deployment module, 2) Determine rad-sensitive and critical parts based on previous deep-space mission experience and develop a generic flight computer or daughterboard which supports these type of operations, 3) Develop rad-tolerant operation strategies and software (e.g., automatic reset every 2 days to clear latch-ups, memory and cache checking software).

2. **Laser Communications or Reliable Miniaturized Relay Communications** Laser communications may soon be available for both large and small spacecraft[2], but will rely on accurate pointing and ground station availability on Earth. The first interplanetary NanoSat missions will likely rely on relay communication with a mothership (e.g., *Hayabusa* and *Minerva* at Itokawa, *Ikaros* and subsatellite cameras like *DCAM-1* / *DCAM-2*). The CubeSat community has developed many low speed radios applicable for LEO flight, yet frequency stability due to oscillator drift and protocol differences often require ground station tweaks to optimize the received signal strength. Further development of a simple, small and solid radio, built from CubeSat heritage and deep-space experience, could quickly and easily close the link.

3. **Miniaturized Instrument Development** Some instruments, as shown in Figure 3, do exist that fit within a CubeSat formfactor, and would be applicable for interplanetary NanoSats. As rides become scarce, there is greater impetus to take instruments with novel methods that size them within an available vehicle. With growing cer-

tainty that interplanetary NanoSats would be useful, it behooves the instrument community to decide "how good is good enough" to obtain compelling science, and develop instruments accordingly; not instruments that compete directly with a Flagship-class instrument, but ones that can perform important complementary science at a tenth of the size. Important instrument development areas include imaging and spectrographic microscopy, a NanoSat-class USO or transponder, onboard data processing, radiation sensors, dust collectors and many others.

4. **NanoSat Propulsion Demonstration** Though the mothership may drop off the NanoSats at interesting targets, it is likely they will need to move to change their location, even if it is to descend to an interesting spot. Had *Minerva* contained a small propulsive module, it may not have missed Itokawa during deployment[18]. CubeSat propulsion is now under development (and a target of the recent NASA Office of the Chief Technologist Edison call), but a small system has yet to be repeatedly and reliably demonstrated on multiple missions, nor has navigation or maneuvering software been flown, allowing for precise orbit planning. Both for CubeSats and interplanetary NanoSats, this is an opportunity to open up new areas of exploration. Electric Propulsion, Cold-Gas, Hydrazine and Solar-Sail propulsive elements are now available, and should be further developed for easy implementation and use.

5. **Deep-Space Deployment** The deployment module for deep-space may not look entirely like the currently used P-POD on LEO missions. An umbilical may be required for health monitoring or battery maintenance during the long flight, which must then be separated before deployment. The P-POD may need to be shielded to minimize constraints on the secondary spacecraft. And if multiple vehicles are to be deployed (even from multiple P-PODs), there must be assurance that they will not impact each other or the mother spacecraft. A set of design studies, with reference mission architectures, should be considered to develop a next-generation P-POD that is flexible enough for use on multiple vehicles, but maintains the minimal risk posture that so characterizes the existing launch vehicle P-PODs.

6. **NanoSat Surface Mobility** Many of the science applications would benefit from the use of surface mobility. *Minerva*, one of the first NanoSats to see use, employed a novel internal torquer allowing for hopping across an asteroid's surface. Likewise, tumbling, rolling, hovering or other mechanisms should be developed that might see multiple use - reaction wheel in flight, internal torquer on the ground. Such developments will allow for distributed sampling, or greater exploration across a planetary surface.

7. **NanoSat Sample Return / Atmospheric Re-Entry Mechanism** Returning samples from LEO or beyond requires the survival of some part of the vehicle through the atmosphere. Balutes, parachutes, and even ablative packaging have been proposed to allow for CubeSat sample return. Such technologies may be useful in the deployment of interplanetary NanoSats to foreign worlds with unfamiliar atmospheres, allowing these "disposal-sats" to be used in a high risk / high science return endeavor.

8. **Sample Collection and Caching Mechanism** Once surface mobility is enabled, it is likely that the collection of samples would be of high priority. An interplanetary NanoSat swarm spread across the surface of a small body could sample and cache multiple points, ready for pickup at the next opportunity. Basic mechanisms in a small platform supporting these goals may support future missions, including Comet surface sample return.

9. **Miniaturized RHU Development** RHUs may be used to support the use of NanoSats in the outer solar system, beyond the useful range of solar power. Either as heaters, or combined with small heat exchangers to produce power, development of these kind of power systems would enable the interplanetary NanoSat to move beyond primary batteries to an extended mission of useful science.

Each of these technologies is likely achievable, and many only require creative implementation of available products. Indeed, NASA Ames has proposed the *Planetary Hitchhiker* architecture use CubeSats for small-body investigations, and both *Hayabusa* and *Ikaros* have shown the usefulness of secondary NanoSats. Further development of these technologies would extend CubeSat use in LEO, would enable interplanetary NanoSats to depart on their own from Earth orbit (which seems possible even now, e.g.,[2]), and would support the novel use of interplanetary NanoSats as secondary spacecraft at other worlds and destinations.

IV. CONCLUSION

The capability of CubeSat to return science meeting the highest standards has been demonstrated through

multiple recent and ongoing missions. The performance of these platforms keep progressing, for example in terms of attitude control, access to multiple propulsion options, etc. while preserving low-cost approach with appropriate risk. With growing interest for sampling the surface of a variety of objects across the Solar system, it is the right time to start devising science applications for CubeSats beyond LEO, possibly in the frame of Discovery, New Frontiers and other large missions. Many instruments are now available that fit within a NanoSpacecraft platform, and these can be leveraged to enable a new type of exploration - one with low-cost, disposable probes to perform high-risk / high science return missions. A great deal of work still has yet to be completed to ready NanoSpacecraft to participate on larger missions, including a large amount of technological development. By pursuing these technologies now, with testing available in LEO using CubeSats, we can prepare the investigations of tomorrow with the lessons of today. It is however important to keep in mind that further development of CubeSat-based NanoSats without coordination with the scientific community and the inclusion of expected science applications may well doom the endeavor from the start. CubeSats have shown great science return, yet are still often relegated to only educational tools and toys. Rather than design the science to fit in the technology, design the technology to support the application, with lessons learned from both engineers and scientists.

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V. ACRONYMS

CHopper Comet Hopper mission concept proposed to NASA's *Discovery* Program

DLR German Aerospace Center

DS-2 Deep Space 2 Mission (NASA Millenium Program) (failed)

GNC Guidance, Navigation, and Control

LEO Low-Earth Orbit

NCROSS NEA Close Rendezvous and OperationS Satellite mission concept

NIAC NASA Institute for Advanced Concepts

NRC National Research Council

NSF National Science Foundation

O/OREOS *Organism/Organic Exposure to Orbital Stresses* Mission (ongoing)

P-POD Poly- PicoSatellite Orbital Deployer

PSDS Planetary Science Decadal Survey

RHU Radioisotope Heater Unit

TRL Technology Readiness Level

UHF Ultra High Frequency

USO Ultra Stable Oscillator

VHF Very High Frequency

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