

# Applications of NanoSats to Planetary Exploration

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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. 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 suggested that could take advantage of these features. 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

PLANETARY exploration lacks observational strategies for characterizing the near-surface environment of planetary bodies. Most of planetary exploration to date has been achieved through remote sensing performed from orbiters and, more recently, by surface exploration and sampling. While landers may complement larger spacecraft by providing access to the surface and subsurface of planetary bodies, the information they could provide on the near-surface is limited. Besides, such missions involving one or multiple landers are expensive and risky, and, few of these architectures have been flown so far, apart from missions to Mars. Hence there is a gap in the sampling of the *in-situ* environment of most of these objects because of the lack of appropriate platforms specialized in close proximity observations. Desired investigations of environmental properties encompass high-resolution gravity fields, exosphere/atmosphere, dust dynamics, electrostatic charging, localized outgassing, etc. This is a region that could provide important information on the composition of the object, the internal structure (high-resolution fields), the presence of water (neutron detection), etc. This interface between the surface and deep space environment is also subject to large gradients over short distances and temporal variations (e.g., due to Solar wind, tidal forces). A better understanding of near-surface environments is also critical to support Human exploration by providing constraints on potential landing sites, resource availability, and risk (e.g., Wargo 2012).

For bodies with atmospheres, balloons/gondolas have been suggested as a way to provide *in situ* mobile exploration over a broad altitude range. For these objects, as well as airless bodies, we consider a new form of spacecraft that has been promising in Earth-based measurements: CubeSat-derived NanoSats, whose use for Earth's observation has boomed over the past ten years. Example flown missions include magnetic monitoring, space weather investigations, van Allen belt monitoring, lightning detection, and many others that are now being funded. These platforms have now achieved such capabilities that they are attractive to the NSF (space weather program, e.g., *RAX*, *Firefly*, *Firebird*) and NASA (O/OREOS, Earth Venture mission *CYGNES*).

The motivation for exploring the applicability/potential contribution of CubeSat-based nanosats to planetary exploration is that they have reached a high maturity level with the availability of a variety of subsystems

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and parts, while offering some flexibility, despite their small size, through the combination and manipulation of components. Hence they may enable some tailoring of an otherwise standard platform. They could, *a priori*, accommodate many of the small instruments developed to support surface exploration with nanobots (e.g., hoppers, penetrators, nanorovers).

In this paper we address the difficulties inherent to the utilization of small platforms but also highlight the unique science they could afford. First we briefly summarize the status quo for CubeSat and highlight their unique contribution to Earth science. Then we describe measurements and requirements specific to planetary exploration and discuss possible applications and measurements that may be uniquely achieved by CubeSat-derived nanosats. Then we will address a roadmap for exporting these platforms to deep space environments.

## II. CubeSats - Status Quo

CUBESATS have demonstrated unique capabilities in low-Earth orbit missions where they have the ability to selectively target and perform on narrow niches that might otherwise be a small part of a much larger mission, too expensive to be performed through “traditional design”, or demonstrate a technology that is otherwise too risky (based on cost expectations) to be carried out through other means.

As a science example, consider the comparison between the *Kepler* mission (Borucki et al. 2003) and *ExoPlanetSat*. *Kepler* has performed a wide survey to identify exoplanets crossing in front of stars throughout multiple systems. *ExoPlanetSat* (Smith et al. 2010) is performing a focused mission where a single star is targeted and observed, but at a much lower cost. In this case, in the broad sense, the science objective of identifying exoplanets is significantly impacted by the small and less capable platform. However, the targeted science objective is completely met, and at a much lower cost than a traditional solution. This risk / cost strategy allows for targeted science at lower cost, with a platform that can take advantage of greater launch availability.

Today there are greater than 50 CubeSats in orbit, with large numbers of launches expected within the next two years. This explosion of launch availability has come through support from NASA’s Educational LAUNCH of NANOSATELLITES in America, and an adoption of the CubeSat standard around the world. The standard has provided an opportunity for launch providers to carry these secondary payloads with reduced risk to the primary by encapsulating the risk. The deployment box, attached to the rocket, is certified and accepted for flight by the launch provider. The process includes basic knowledge of the internal payload (which must conform to certain standards) - mass limitation, center of mass location, volume, power-off configuration, and certain fail-safes at a minimum. This reduces risk to the primary while still allowing for flexibility and risk to be taken by the internal CubeSat, safely constrained by the certified deployment box and conforming to agreed upon restrictions.

CubeSat capability has significantly advanced as the program has matured. Today, attitude control systems are commercially available providing degree and sub-degree accuracy, power systems can provide  $\dot{\iota}$  30W of power, and onboard processing systems include FPGAs (Field-Programmable Gate Array), ARM (Advanced RISC Machine) and other microcontroller architectures. A survey of available technologies can be found in Klesh and Castillo-Rogez (2012). But a unique aspect of CubeSats is that they are constrained by volume due to the launch system - this means that though many individual capabilities are available through sub-systems, not all the sub-systems, at the bleeding edge of capability, can fit within the same spacecraft. Yet thinking “inside the box” has led to significant revolutions in design that has continued to increase the overall spacecraft functionality without increasing size.

1U, 3U and 6U platforms (10x10x10cm, 10x10x30cm, and 10x20x30cm respectively) are now standardly available. These shapes are primarily dictated by the launch availability. The *O/OREOS (Organism/Organic Exposure to Orbital Stresses)* mission qualifies as the first CubeSat-based mission with direct planetary science focus (Nicholson et al. 2011). It combines two distinct experiments on a 3U CubeSat whose goals are to monitor the behavior of micro-organisms in space and the survivability of organic molecules, two topics of great astrobiological interest (see Figure 1). But as CubeSats and NanoSats continue to show capability for science missions in low Earth orbit (LEO), there is still uncertainty on their usefulness on deep space missions, where they might be secondary vehicles attached to a mother spacecraft. Because a different carrier platform is available, it may not be necessary to remain within a traditional CubeSat formfactor, and the mission may benefit from a formfactor that varies from the box. These formfactors should be primarily driven by science applications, while at the same time, cognizant of the lessons learned from CubeSats and

the capabilities that could be provided from thinking small.

### A. Unique Contribution to Earth Science

THE risk posture adopted for most small satellites has been such that the cost is low enough to enable reflights if needed - thus, rather than guarantee mission assurance on a single vehicle, multiple flights are acceptable to complete a mission in case of individual failure. This risk posture has allowed for low cost missions. If traditional mission assurance is applied to the same platform, the cost will accordingly rise, and some of the advantage will be reduced.

Using low-cost platforms also enables new types of science, such as those where disposing of the spacecraft is an acceptable part of the mission, or where many spaceborne assets are required. The recently NASA-selected *Cyclone Global Navigation Satellite System* (CYGNSS) mission would make great use of this by flying 8 satellites to optimize the spatial and temporal sampling of tropical cyclone lifecycles. Another area of current interest is the flight of a magnetospheric constellation able to survey the structure of the field with several small spacecraft. CubeSats have already shown that these cheap flights of opportunity can provide observational opportunities that might not otherwise be available. The *RAX* mission (Bahcivan et al. 2012) demonstrated a targeted science opportunity where a ground-based radar system was able to interrogate field-aligned upper-ionospheric irregularities through a bi-static radar - in this case, the CubeSat provided a low-cost receiver for the radar which allowed the irregularities to be characterized. A solely ground-based system was not possible due to a perpendicularity requirement, and a similar large-spacecraft mission had not been previously viewed as cost-effective.

CubeSats continue to provide unique platforms for Earth science, such as proposed missions to investigate the upper atmosphere through the deployment of large (50+) numbers of probes (e.g., *Armada* and *QB50*). Other investigations have considered fractionation of the spacecraft, to allow for the replacement or upgrade of certain instruments by replacing or adding to the constellation with an additional satellite. Others have examined *ad hoc* constellation deployment through multiple launch opportunities, and the results for coverage have generally been positive.

Given the lessons learned from Earth-based investigations, it has only been natural that deep-space applications also be considered. The lessons learned from LEO operations translate well to this environment, and the components tested by CubeSats could either be used by, or will inform, planetary options.

## III. Planetary Science Requirements

PLANETARY exploration is organized around three main science themes (NRC 2012) as well as measurements supporting Human space flight. Science themes can be summarized as

- “Building New Worlds,” i.e., understand the origin of planetary bodies, planet satellite systems, or the origin of volatiles and organics in the inner Solar system.
- “Planetary Habitats,” i.e., search for and explore potentially habitable objects (past or present) and sources of volatiles and organics.
- “Working of Solar System,” i.e., characterize and understand processes that have shaped solar system bodies.

Details on science objectives relevant to each of these themes can be found for example in Castillo-Rogez et al. (2012).

Measurements to support Human Space Flight are presented as Gap Filling Activities (GFAs) meant to resolve Strategic Knowledge Gaps (SKGs) (e.g., Wargo 2012). The goals of these measurements are to collect data that can inform the strategy for Human exploration in order to reduce risk for crew, and operational risk, maximize mission performance, increase science/engineering reliability and return, and reduce the overall cost of the Human mission. Relevant observations may inform risk associated with transit (e.g., radiations), proximity operations (e.g., risk associated with descent and landing), and in situ operations.

### A. Measurement Requirements and Instruments

DETAILS on measurements and possible instruments for science and Human exploration can be found for example in Castillo-Rogez et al. (2012). Many of the measurements addressing decadal and precursor

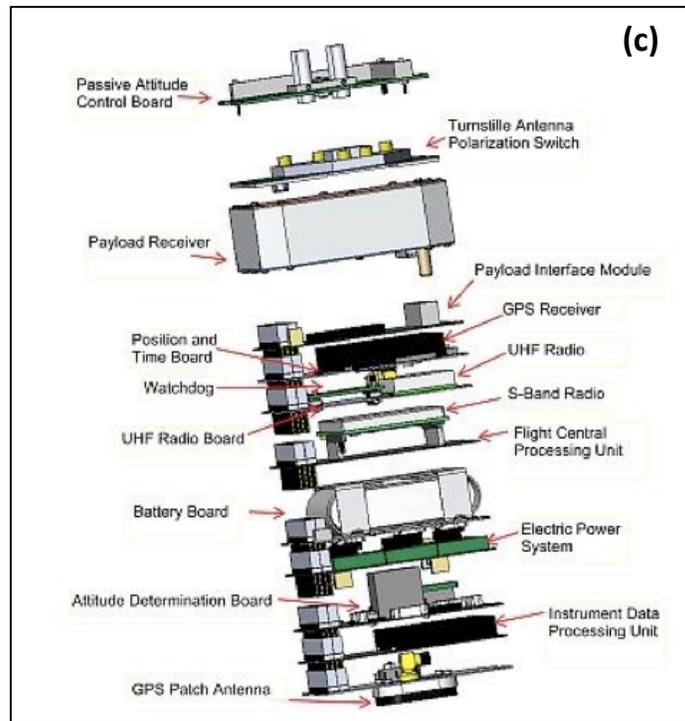
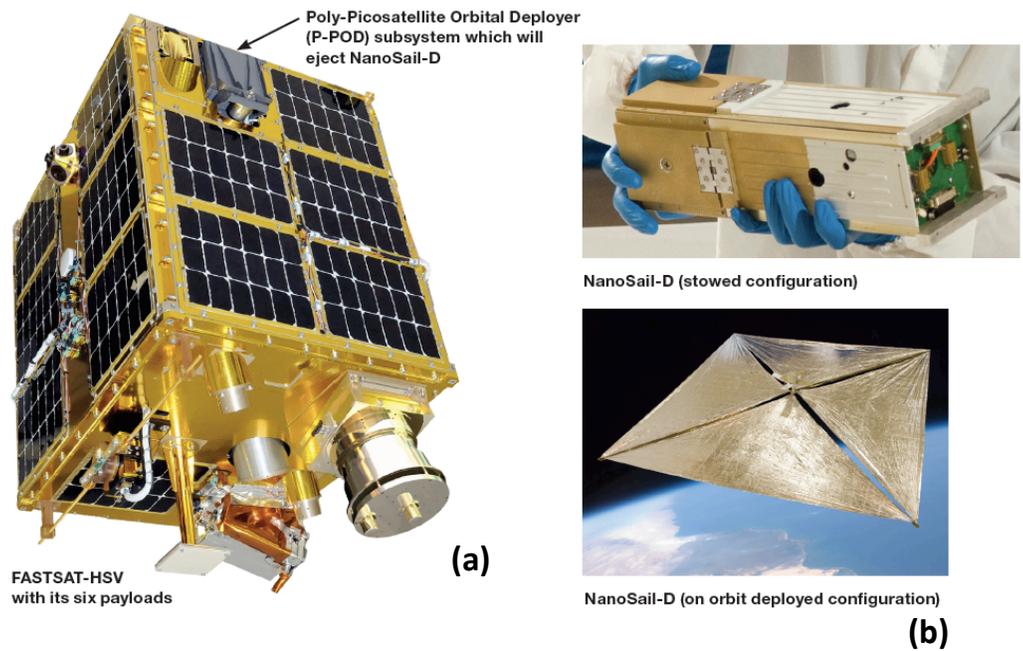


Figure 1. Illustrations of some of the terms mentioned in the text. (a) NASA's Fast, Affordable, Science and Technology Satellite (FASTSAT) payload bus which carried the NanoSail-Demonstration (Source: [http://www.nasa.gov/mission\\_pages/smallsats/fastsat/](http://www.nasa.gov/mission_pages/smallsats/fastsat/)) (b), NASA's first solar sail, as well as other satellites developed by universities and industry, such as O/OREOS (c). Representation of a typical NanoSat (spacecraft image courtesy of the University of Michigan).

science involve *in situ* (surface) exploration, characterization of the near-surface environment (e.g., atmosphere, radiations, dust, gravity field, magnetic field). Close proximity observations may provide detailed information at the regional or local scale, but they can also provide measurements that support the understanding of an object as a whole. For example, high harmonic gravity fields contain information on the departure of a body from hydrostatic equilibrium, and, correlated with topography, may provide constraints on the existence of activity inside the object. Close-proximity observations can also provide high-resolution imaging and thus give another vantage point to geological imaging complementary to that obtained with remote sensing and ground-truth observation with lander. This becomes useful reconnaissance prior to landing and again particularly important in the prospect of Human exploration in order to limit risk and operational cost. High-resolution gravity and magnetic fields express variations in internal properties that complement the global view provided by low harmonics obtained from an orbiter.

### 1. Strategic Knowledge Gap Filling Activities

- Measurements to prepare landing site reconnaissance and operation performance assessment. This includes high-resolution gravity field and topography mapping, assessment of mobility and geotechnical activities in low gravity and loose regolith. The latter may be addressed through passive observation of surface geology and regolith dynamics, or active perturbation of the surface, e.g., by sending nanobots (Pavone et al. 2013), projectiles, or thruster interaction with the surface. Propulsion-induced ejecta observation would also be necessary to help plan for crew landing. That type of information cannot be reproduced with high fidelity in Earth's labs. Surface microscopy may return important information on soil properties (grain size and shape, porosity) and a dust analyzer could also help constrain loose soil properties. These studies would help in designing strategies for anchoring and crew interaction with surface
- Measurements to characterize of the environment on Human health and performance (including transit). Measurements to assess radiation flux and understand total radiation risk link to long exposure to galactic cosmic rays (GCRs) and its biological impact; electrostatic charging and plasma fields in the proximity of the target; impact of dust levitation on crew safety and operations, as well as micrometeoroid flux. Close-proximity observations include micrometeoroid flux and dust monitoring with dust counter.
- In-Situ Resource Utilization (ISRU)/Prospecting (Moon, NEAs, Mars) The search for volatiles and other *in situ* resources might be achieved by infra-red spectroscopy and neutron spectroscopy. However ground-penetrating RADAR could provide constraints on the radial and lateral distribution of volatiles as dielectric properties are significantly affected by the presence of water and hydrated minerals (e.g., Bittelli et al. 2004). Other instruments to support the search for *in situ* resources include X-ray diffraction and fluorescence for elemental composition;

Most of these measurements need to be obtained in close proximity of the prospective targets in order to provide constraints on local conditions for landing and operations. Several platforms have been proposed to support surface exploration as part of precursor missions, such as MERLIN (Murchie et al. 2012), and nanorovers (e.g., Pavone et al. 2013). Observational strategies for characterizing the environment and high-resolution reconnaissance are missing. Depending on the target, such observations may be challenging, e.g., in the case of cluttered environments at near-Earth objects (NEOs), or in Mars' gravity environment (Phobos and Deimos).

### 2. Science

MEASUREMENTS needed to address the science themes presented in the previous section also revolve around obtaining constraints on the interior structure, surface composition, and near-surface environment of a variety of planetary bodies. These objectives benefit from observations obtained from multiple vantage points, from the global scale to specific landmarks on the surface or atmosphere. Many missions involve observations at the extent of a system to capture similarities and differences within the system. This is for example the case of the *Cassini-Huygens* mission that has obtained observations of more than 20 moons of Saturn: moonlets, medium-sized, Titan, and irregular satellites. Systematic measurement across a system can help constrain formation processes.

- Measurements that inform on the chemistry of the object, relevant to *Habitability* and *Origin Science*: these objectives involve more complex instruments to provide isotopes measurement and mineralogy, possibly in combined manner, such as Raman-LIBS (Blacksberg et al. 2012) and mass spectrometry. Of particular interest, characterization of the compositional gradient across the Solar system requires isotopic and noble gases measurements.
- Measurements informing about the evolution of the Solar system: these are primarily about characterizing the various classes of small bodies across the Solar system (e.g., wet asteroids, metallic asteroids, irregular satellites) and constraining the genetic relationships between these classes in order to track back their origin. Relevant measurements, besides chemistry, include rotational properties (high-resolution imaging), crater counting (high-resolution imaging and topography), study of multi-ring systems, study of the relationship between rings and satellites, etc.
- Observational constraints on internal state, evolution and past and current habitability potential: Interior properties are inferred from gravity (radioscience), geology (e.g., topography measurement through, e.g., altimetry techniques or stereophotoclinometry, stratigraphy through high-resolution imaging); thermal mapping. Constraints on the potential presence of a deep ocean and metallic core may come from magnetometry. Rotational dynamics and diurnal variations in gravity field bear signatures of the density and mechanical properties of the interior. While measuring such properties requires long-period measurements they can uniquely constrain interior dissipation, which in turn can inform on thermal state and porosity (Jacobson and Scheeres 2011; Rambaux and Castillo-Rogez 2012).

Study of atmospheric processes can lead to constraints on the origin of a planet; for example the extent of outgassing activity provides information on the degree of evolution telluric body interiors and can also help reconstruct climate evolution and surface environments. Similarly, magnetic measurements contain important information on the evolution and current state of planetary bodies (e.g., metallic core, induced magnetic field in a deep liquid layer). For giant planet satellites, mapping of the plasma, dust, magnetic, and gravity fields of the parent planet contributes to better understanding the environment in which some of these astrobiological targets have been evolving.

Addressing origin and habitability requires getting multiple measurements, as described above. This is the reason why flagship missions, whose payload generally includes instruments addressing field and particles, geophysics, and chemistry, have significantly improved the state of knowledge.

## B. Small Instruments

DETAILS on instruments small enough to fly on nanosats can be found in Klesh and Castillo-Rogez (2012). Many of the aforementioned instruments are available for mass less than 1 kg. This is particularly the case for geophysical measurements (dosimeter, thermoprobes, etc.). Analytical chemistry requires more significant subsystems and mechanisms for sample acquisition and preparation. It is not clear at this point, based on the current state of technology, whether the CubeSat form factor, even in 3U form, is adequate to support that type of measurement, or if significant tailoring is required. Klesh and Castillo-Rogez (2012) also pointed out that instrument volume is a major hurdle and improvement in packaging is necessary. Sampling systems for small instruments are low TRL (technology readiness level) and techniques that do not require sophisticated material sampling and processing are suitable, such as Raman/LIBS (laser-induced breakdown spectroscopy) (Blacksberg 2012), or the MALDI technique (Matrix-assisted laser desorption/ionization). Focusing the instrument capability toward the most compelling measurement identified for a given goal may also drive a next generation of low-mass/low-volume instruments. For example tunable laser spectrometer (TLS) with single channel spectrometer and laser near 2.7 microns could determine D/H and oxygen isotope ratios (e.g., upgraded version of the TLS on *Deep Space 2* would be below 1 kg, and 10 cm x 10 cm x 4 cm including electronics, Jordana Blacksberg and Chris Webster, personal communication). In any case, at this point, a large number of miniaturized instruments are in development taking advantage of microelectromechanical systems (e.g., micro-mass spectrometer by von Amerom et al. (2012)) and lab-on-a-chip technologies (e.g., Willis et al. 2012), and should emerge within the next decade.

## IV. Envisioned Contribution of CubeSat-Derived Nanosat to Planetary Science

CLOSE proximity operations are risky and costly. Mention developments for terrain reconnaissance, etc. Worked for Mars but big budget to support that type of exploration. On traditional missions there is always instrument trading and descopes, simply dealing with different constraints. With nanosats we can circumvent some of these constraints. For example, limitations on the distance to the target drives the optics size and the mass of optical remote sensing instruments, power required for RADAR, etc.; distance imposed by safety constraints, available propulsion, difficulty of navigation (e.g., *Cassini*, *Dawn*) but with nanosats we would be able to go as close as necessary, even though this may involve the loss of these assets.

### A. What new Paradigm/Framework are we Proposing to Introduce?

As an alternative, we are proposing to pursue that exploration through the utilization of cheap platforms such as CubeSat-derived nanosats. Individual platforms may be limited in performance and lifetime. However they give access to a region of the planet that is prohibitive or simply inaccessible.

**REDUNDANCY:** The performance is built on using multiple platforms for redundancy and distributed measurements at relatively low cost. The perceived risk is limited by the fact that these platforms are cheap and the loss of one or several of them does not compromise the mission, even more so if they are daughterships of a large spacecraft.

**EXPANDABLE:** They may be used for reconnaissance to limit operational risk to a lander or science reconnaissance to identify compelling sites for in situ exploration and sampling. They may also be seen as expendable assets that could play an active role in interacting with the target (Fig. 2a).

**FOCUSED AND SMART:** A CubeSat is a full craft of its own, with possible elaborate on-board data handling and advanced guidance, navigation, and control. As such they could represent smart deployable whose purpose is to accomplish a specific task complementary to the observations performed by a mothership. A CubeSat-derived deployable may access designated landmarks and possibly perform complex autonomous operations.

**DISTRIBUTED MEASUREMENTS:** Similar measurements obtained at multiple sites and close to the surface of a body enables high-resolution imaging and field mapping and may be complementary to the global view and low harmonic field obtained by a mothership.

**FRACTIONATED ARCHITECTURES:** To support objectives involving sampling multiple landing sites or objects in a system, deploying multiple assets may prove a cheap alternative to accessing all targets with the same large spacecraft. The payload on each small asset may be limited to a couple instruments for focused but systematic characterization of the targets.

**SMALL:** The very size of a NanoSat could be scientifically useful, whether, for example, by accessing regions, such as cracks, that are physically impassable for larger vehicles, or by having such low inertia that strong interaction with a magnetic field (even through the use of an onboard processor (Klesh et al. 2012a).

**A NEW STANDARD?** Another idea inherent to the utilization of CubeSat is that they would represent a standard platform. The concept of standard has been much debated in planetary science and most missions to date have involved significant tailoring. CubeSats have driven a NanoSatellite marketplace, where both subsystems and full spacecraft are available to purchase and piece together. Most components take advantage of existing standards and communication protocols which assists in building the bus like a Lego kit (however, unlike a Lego kit, integration still yields significant “large satellite” challenges, such as electromagnetic interference, thermal dissipation, and packaging). Experienced teams have also found sub-component-level designs that are “proven”, but can be manipulated to re-arrange circuit boards for a particular spacecraft, such as one with a telescope down the center requiring all boards to have a large central hole. Thus CubeSats have demonstrated the ability to work with simple payloads - where the payload is added to an existing bus - and complex experiments - where the payload and spacecraft lines merge - while maintaining flight heritage. It is now quite common to see “CubeSat compatible parts” available for purchase through major aerospace manufacturers.

**OUTLET FOR STUDENT INVOLVEMENT:** CubeSat-based experiments also provide an opportunity to involve educational institutions and train the next generation of space engineers. Student-led spacecraft development programs have been very successful and are behind most of the CubeSat-based experiments of the past decade (see Swartwout 2011 for a review), an expertise that can be leveraged for the development of deep space exploration with nanosats.

## B. Examples of Applications

**H**ERE we focus on applications that may be uniquely enabled by nanosats, i.e., exploring the low-cost, standardized platform they offer.

**RECONNAISSANCE:** CubeSat-derived nanosats may enable reconnaissance prior to landing or sampling, to support science and Human exploration purposes. As sacrificial assets, they could provide information on the surface and close proximity environment of potential Human exploration targets through high-resolution gravity and topography mapping, characterization of the dust environment, and electrostatic charging. Thus they could help identify optimal areas for robotic and crew vehicle landing following global reconnaissance of possible landing sites from an orbiter.

Nanosats could also search for compelling landing site to support specific science objectives. These scouts would complete a variety of risky tasks preparing for science and engineering activities (e.g., risk surveillance in preparation for landing, jet fly-throughs, etc.) while communicating observations back to the mother spacecraft, waiting at a safe distance. Indeed, sampling and in situ analysis involve a number of risks especially when dealing with objects as versatile as small-bodies. Also, the volatile-rich material that one would like to sample at a comet may be present in discrete locations (e.g., Tempel 1, Castillo-Rogez et al. 2012). It would be required to identify the most scientifically significant sample areas while helping with risk mitigation. With future Decadal Science missions, like the *Cryogenic Comet Nucleus Sample Return* (NRC 2011), requiring the mother spacecraft to explore more dangerous environments than have previously been attempted, use of these probes could significantly reduce mission risk and increase science return. Other high-risk targets include, for example, planetary rings (Hedman et al. 2012), Enceladus' jets, etc.

**SEARCH FOR HUMAN EXPLORATION TARGETS/MULTIPLE SCIENCE TARGETS** A number of science and exploration objectives are best addressed by accessing multiple targets. This is the case when searching for Human exploration targets. For example Elvis et al. (2012) have suggested the deployment of swarms of tens to hundreds of small satellites, each targeting a different object, hence increasing the probability to find a target that meets the criteria defining suitable Human exploration targets. Certain science measurements also involve sampling the diversity of objects within a system, for example both Phobos and Deimos to better understand the origin of the Martian system (e.g., Klesh and Castillo-Rogez 2012), or multiple satellites within a giant planet system (Castillo-Rogez 2012).

Multiple assets may also be deployed at various sides at a given objects, to characterize specific landmarks (e.g., multiple geological sites).

**INTERACTION WITH SURFACE:** Nanosat may be used as projectiles to disrupt the surface, recorded by mothership and help characterize the mechanical properties of regolith. This would be particularly useful as low-gravity environments are difficult and expensive to simulate, hence soil characterization is an important objective of precursor missions. Taking advantage of their smartness, nanosats may also provide direct constraints on the response of regolith to thrusters and help retire the risk inherent to the landing of a crew vehicle.

**HIGH-RESOLUTION FIELD MAPPING:** A constellation of nanosats may be deployed in giant planet systems to characterize their magnetosphere, measure gravity field, with a high-spatial and temporal resolution, and lead to constraints on geophysical properties (e.g., interior structure) and dynamics (e.g., perturbation in the rotational properties).

**ENVIRONMENT CHARACTERIZATION:** specifically the characterization of the interaction of a body with its environment, e.g., solar wind, plasma, magnetic field, radiations, of particular interest to the study of astrobiological targets. This requires near-surface measurements, for example to characterize the products of surface sputtering in a tenuous atmosphere difficult to characterize from an orbiter, but directly sampled by a nanosat.

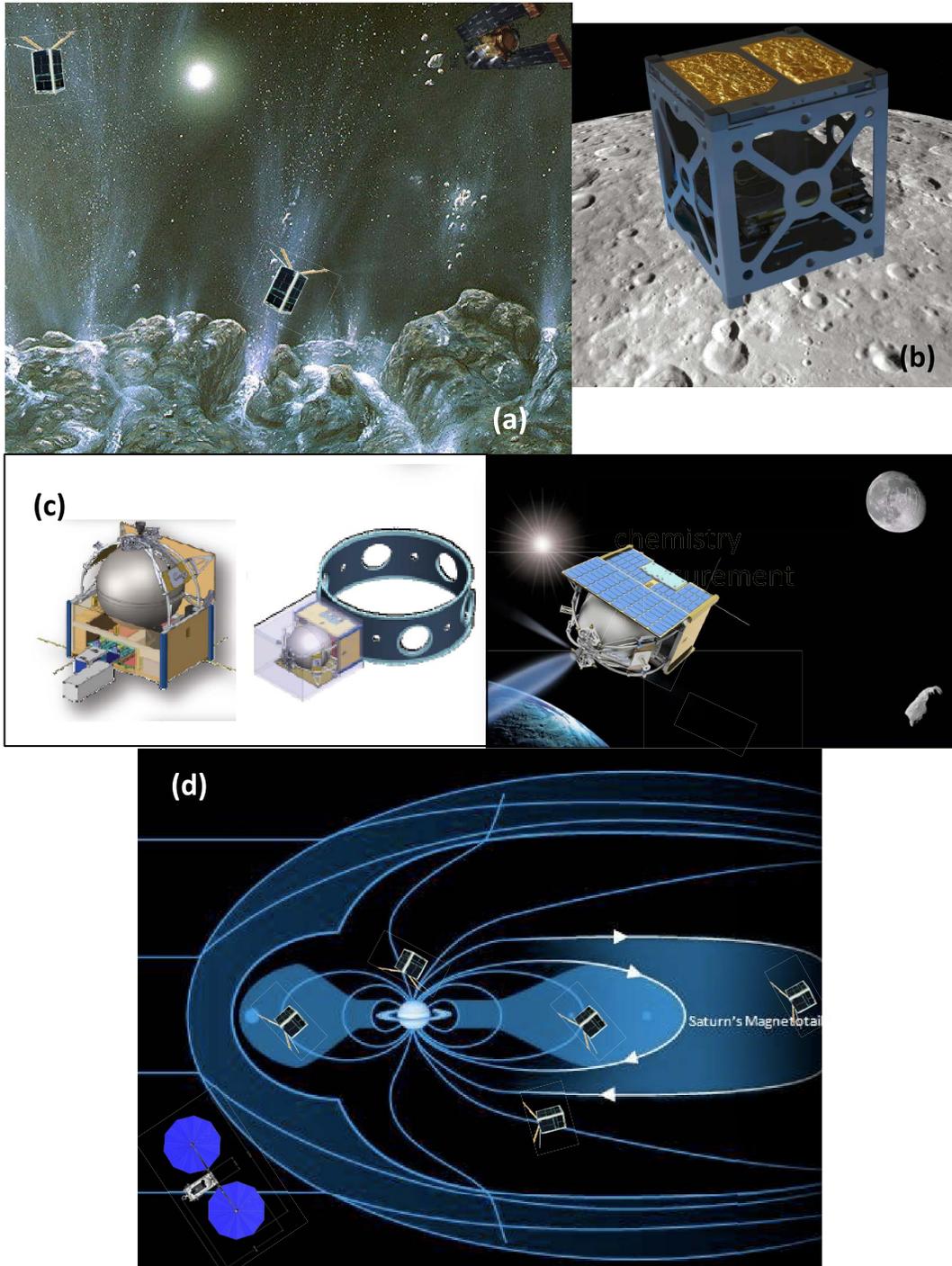


Figure 2. Illustration of possible applications envisioned for CubeSat-derived nanosats: (a) for high-risk/high-science measurements, for example by sampling cometary jets at the surface; (b) for high-resolution imaging, gravity measurements, or search for volatiles, as reconnaissance prior to robotic or Human exploration (Credit: *Flexure Engineering* <http://www.lunar-cubes.com/>); (c) in fractionated architectures where multiple assets targets a diversity of objects, instead of one large spacecraft going from one object to the other, e.g., to search for Human exploration targets, sample the diversity of bodies forming a system, etc. This particular figure depicts the *Planet HitchHiker* mission concept (Worden 2011) in which an ESPA ring (*Evolved Expendable Launch Vehicle* (EELV) Secondary Payload Adapter) would carry and deploy six 3 U CubeSats at Near Earth objects; (d) illustration of distributed measurement of a large planet gravity field where the nanosats get close enough to the planet to sense high-degree harmonics.

### C. Where to Put the Limit on Size?

THE traditional CubeSat is limited only by its launch volume - once separated from the P-POD (Poly Picosatellite Orbital Deployer) or other deployer, booms, instruments, or other parts may be extended. But the small size offers additional advantages - in Earth orbit, the low inertia of the vehicle allows it to be easily controlled through passive magnetic systems, and it is so small that a processor running complicated code and using a lot of power can actually create a torque large enough to spin the spacecraft (Klesh et al. 2012a). The size also provides a great packing factor - by having redundant spacecraft, higher risk postures per spacecraft may be taken, leading to overall potential low mission risk at reduced cost.

There is an inherent limit to the type of measurement that could be achieved with nanosats though, depending on the requirements on measurement accuracy, pointing and integration time, data volume, degree of autonomy, etc. that imply massive subsystems. Many instruments have been constructed without strict sizing requirements, leading to their infeasible use on a small platform, and certain instrument technologies may simply not be easily sized down (e.g., mass spectrometry). Also, lifetime (e.g., in cryogenic or high radiation environments) is likely a major limitation and may limit data acquisition with the accuracy needed to meet certain objectives.

Planetary exploration and Earth observation differ in their main goals in that successive planetary missions target different (types of) objects with generally little knowledge about these alien worlds prior to launch. On the other hand Earth observation missions are primarily meant to monitor over the long term processes that have been known for decades. However both fields also get the best science from obtaining observations on a variety of processes, i.e., systems science, and from multiple vantage points.

While small spacecraft or chipsats may bring risk reduction through massive redundancy, the operational expense to utilize the number of spacecraft can expand dramatically - consider, for instance, the frequency allocation required for a fractionated system. Solutions may exist, but could be operationally complicated. Such restrictions or complications on the number of spacecraft that could be simultaneously utilized must be considered, especially in the deep space regime where control is already limited.

### D. Possible Architectures

SEVERAL architectures could be considered for the planetary science NanoSat, each providing benefits and Scapability, but imposing requirements as well:

PRIMARY PROPULSION / PRIMARY SPACECRAFT: Providing a NanoSat with basic propulsion ( $\geq 100\text{m/s}$ ) is quickly becoming realizable as 10m solar sails (Klesh et al. 2012b) and electric propulsion (Marrese-Reading et al. 2010, Hrubby et al. 2012) systems are miniaturized and reach the marketplace. These systems would allow a NanoSat to be delivered to Earth orbit (likely Geostationary Earth Orbit (GEO) or escape orbit), from where it could depart and head to the Moon, Sun-Earth Lagrange points, asteroids, or even Mars, within interesting ( $\leq 5$  year) timelines (Klesh et al. 2012b, Hrubby et al. 2012, Staehle et al. 2012, Strange et al. 2012). These systems would be self-contained, with direct-to-Earth communication systems, while being able to operate in clusters or constellations.

MOTHERSHIP-DAUGHTERSHIP: The ability to deploy a NanoSat from a larger mothership would provide quite a few advantages to the NanoSat: The smaller vehicle could remain shielded during the cruise to the target of interest; the mothership could provide a communication relay, reducing power requirements on the NanoSat; the mothership could provide charging during cruise; the mothership could pull high-powered processing off-board from the NanoSat; and the mothership could provide navigation assistance. But the NanoSat would also provide benefits: a relative-navigation beacon; a low-cost observer from a new vantage point; a disposable asset for proximity / dangerous investigations ref. to Deep Impact; for localization, etc.). Some of this arrangements would depend upon the role of the NanoSat: (a) independent investigator (i.e., only required a ride to the target), (b) cooperative asset (i.e., NanoSat could fulfill secondary science objectives, or (c) collaborative (i.e., primary science objectives would not be met without the use of a NanoSat in conjunction with the mothership).

FORMATION / CONSTELLATION: With appropriate risk posture, NanoSats could remain at low cost even for large science missions. Large groups of NanoSats, flying in proximity to each other, could provide sparse arrays or distributed sensing of a single target, such as the observation of the structure of Earth's magnetotail.

FRACTIONATED SPACE: Since NanoSats can be limited in power per spacecraft, but still have large science requirements for data, DARPA and others have considered fractionated space concepts, where a suite of instruments might fly on several NanoSats in a constellation, and a single NanoSat, in close proximity to the others, would not have an instrument and instead act as a communication relay back to Earth. This splitting of functionality would retain the usefulness and cost of a small platform while meeting requirements. This strategy would offer the additional benefit of allowing for future instruments to be added to the formation as desired (whether for an upgrade or to replace a broken asset).

## V. Exporting CubeSats to Deep Space - Challenges and Roadmap

CUBESAT-derived NanoSats would hit significant challenges as they begin to work in deep space:

SURVIVABILITY: Radiation tolerance on CubeSats has always been hit-or-miss. The general strategy has been to use commercial parts, and reset or relaunch as needed. In the protected environment of low-Earth orbit, this has generally worked well. But as science missions require certain lifetime guarantees, radiation tolerance has become more of an issue. Away from LEO (and aside from the radiation belts, Jupiter or other high-radiation areas), the total ionizing dose generally decreases while the high energy particle flux increases. Thus, shielding alone, while useful, will not preserve the spacecraft. With fewer launch options available for deep space regions, relaunch may not be as feasible (though carrying multiple NanoSats onboard would be another way to accept the failure of a few vehicles). Examination of providing radiation tolerance in certain components, understanding when reset is acceptable, and investigating annealing processes would be required as NanoSats depart from Earth.

COMMUNICATIONS: Transferring data and commands to and from Earth becomes much more difficult as the range to the spacecraft increases. Power, pointing accuracy, modulation schemes and data rates could all affect how this data is transferred. As the *Voyager* spacecraft has shown, incredible distances can be overcome through creative solutions. However existing small radios have typically been raising data throughput, not investigating a reduction in signal-to-noise to receive data at farther distances. In addition, ground resources to receive the data have not yet been identified for the typical low-operation-cost market of NanoSats. If instead the vehicle is to use a mothership as a relay, communications equipment would need to be developed for spacecraft-to-spacecraft communications, possibly through an *Electra* radio, which has become a useful asset at Mars.

NAVIGATION: Without GPS (Global Positioning System), two-line-elements, Earth-horizon sensors, or other useful assets around the Earth, the position determination and navigation of deep-space NanoSats would be of significant challenge. Star trackers are becoming available in a small platform, but often have a difficult time seeing planets or asteroids. Clocks are generally poor compared to the ultra-stable oscillator flown by larger spacecraft leading to poor radio tracking. LMRST-Sat (Duncan et al. 2010) promises to provide a two-way radio solution that would interact with ground assets to provide position information, but few other options are yet available. However it is also worth investigating the actual navigational requirements - many large missions might require meter-scale accuracy, but a great deal of science might still be accomplished at greater than 1 kilometer accuracy - this could significantly reduce the navigational challenge.

ATTITUDE CONTROL: Without a magnetic field to “push” on, attitude control becomes more challenging. Reaction wheels would still need a method for desaturating, while the constrained volume of a NanoSat does not allow for the typical cold-gas solution to last very long (which may be acceptable for potentially short missions). Here, the low inertia of a NanoSat would make solar-radiation-pressure a possible acceptable alternative for reaction wheel desaturation. Other schemes, such as using small EP (electric propulsion) thrusters, may also prove useful.

PROPULSION: If the previous challenges are all met, than independent propulsion of a NanoSat may be achievable. However, giving a low-cost asset propulsion is also problematic to a mothership - in case of problem, the propulsive NanoSat could impact the mothership and induces significant risk. Risk tolerance and acceptability is a challenge that must be examined for any NanoSat, but it is of particular importance when propulsion is added. As solar sails, EP and chemical systems become small enough for that type of platform, examination of risk acceptance must be reconsidered - indeed, the first CubeSats were not allowed

to have propulsive elements when departing from a launch vehicle (though this was more of a consideration of pressurized or energy storage that was considered an additional hazard, rather than a risk of re-impact).

It is interesting to note that only the first three challenges require demonstration in deep space to fully test the system readiness. Attitude control without use of a magnetic field could still be demonstrated in LEO, and solar-radiation-pressure attitude control could be tested in GEO. Cold-gas and EP systems are already being planned for LEO, and solar sails could also be tested in GEO. For a full systems test, Survivability, Communications, and Navigation should be tested in a deep space environment.

## VI. Conclusions

THIS paper provides initial discussion on the challenges of NanoSpacecraft operating in deep space, including how the differences that may be required from traditional CubeSats. Unlike Earth-bound CubeSats which rely on a strict formfactor driven by launch availability, NanoSpacecraft traveling interplanetary may be of a different size, constructed with lessons learned from their CubeSat brethren. Science applications should determine the requirements in these designs, leading to supplemental and primary science opportunities built by smaller institutions at reduced cost. These focused missions would revolutionize access to new worlds and environments - if risk and requirements are adequately matched to the mission.

Initial science applications that look promising include distributed measurements for field mapping and very high-resolution surface imaging. Especially the use of these small spacecraft as “disposal-craft,” i.e., in high-risk, high-science environment, where the reward of their use would more than make up for the low cost. A great deal of additional study is needed, both at individual centers and throughout the community, to discuss what type of exploration is desirable with NanoSats while preserving the low-cost advantage they appear to offer. Identifying the unique factors of “thinking small,” both from a formfactor and a risk/cost perspective is instrumental. This involves discussions between the technology provider and the scientist - if an option is available to fly a payload at 10% of the cost, but at 80% capability, is it worth it? To fit high science standards into the box, we’ll need to think out of the box.

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