DEEP SPACE NANOSATS – POSITIONED FOR EXPONENTIAL GROWTH

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ABSTRACT

We are poised at the beginning of a new era in solar system exploration, in which cubesats and nanosats can potentially play a big role. In 2012 a small group of like-minded enthusiasts at JPL predicted exponential growth in deep space cubesats with at least 10 exploring our solar system by 2020, and a 100 by 2030.

Since then, JPL has built and flight-qualified the two INSPIRE spacecraft as pathfinders for future deep space cubesat missions, and the two MARCO spacecraft were assembled and tested in time to make the initial Insight launch opportunity in 2016 – now under consideration for the next available window. We have ongoing studies for lunar exploration and asteroid rendezvous missions, a Venus atmosphere sampler, and other concepts have been proposed to NASA. The Europa mission has 10 academic institutes under contract to study cubesats that would ride along with the main spacecraft to enable it to get closer to the surface of Jupiter's most intriguing moon. Last year, ESA announced that its AIM asteroid probe will carry a small number of cubesats, when it launches in 2020. In the commercial world, Deep Space Industries are planning to host multiple cubesats in a mission to a Near Earth Asteroid. The prospects for near-term growth look reasonably healthy.

This paper will provide an overview of deep space and LEO cubesat developments at JPL, and discuss the foundation they will provide for the growing community of interplanetary cubesat pioneers over the coming decade and a half.

1. INTRODUCTION

JPL's 'cubesat kitchen cabinet', was formed in early 2013 with the aim of creating fertile ground for science cubesat and nanosat missions at the laboratory. At JPL science means observations for Earth Science to study our planet's environment and climate, for Astrophysics to explore the origins of the Universe and how stars form, Heliophysics measurements to study the interaction of the Earth and the Sun, and Planetary Science to study our neighbors in the solar system. At the time the group was formed, we had just two active cubesat projects in development – IPEX [1] and CHARM [1] (later re-named RACE), and had successfully flown just one cubesat, MCubed/COVE-2 [1] (a re-flight of a prior mission from 2011 that experienced an on-orbit anomaly shortly after deployment). IPEX and MCubed/COVE-2 were technology demonstration missions, while RACE, lost during the Antares Orb-3 launch explosion, would have been our first science cubesat, using a mm-wave radiometer to measure liquid water path and precipitable water vapor. The potential for cubesat/nanosat missions to enable science return was evident from a number of internal studies we conducted, and NASA's Innovative Advanced Concept (NIAC) program had funded a groundbreaking study of deep space cubesats led by Rob Staehle of JPL [2]. NIAC studies usually have a time horizon of decades but it was clear that the pace of change in the world of cubesats was accelerating, bringing what was thought to be a distant future in much closer. Surveying the cubesat community of the time, it seemed obvious that cubesats and nanosats in Low Earth Orbit were

primed for exponential growth and that the potential was there for deep space cubesats/nanosats to take off in similar fashion.

The cubesat kitchen cabinet is led out of JPL's Innovation Foundry, and is largely an adhoc group. Membership comprises managers at the lab who are of course enthusiastic about cubesats and nanosats, but also knowledgeable about missions in a NASA context, and in a position to make decisions (or strongly influence them) about the laboratory's investments, promote good ideas, fund studies, and steer people with good ideas towards the right funding opportunity or partnership for that opportunity. As a measure of our success, at the time of writing, JPL is involved in twenty-three 'live' cubesat projects, at different stages of development with our partners, but all funded. Five of these projects are deep space cubesat missions, and there is evidence of growing interest within the science community ([3], [4], [5]) to explore our solar system using deep space cubesats, as illustrated in Figure 1.

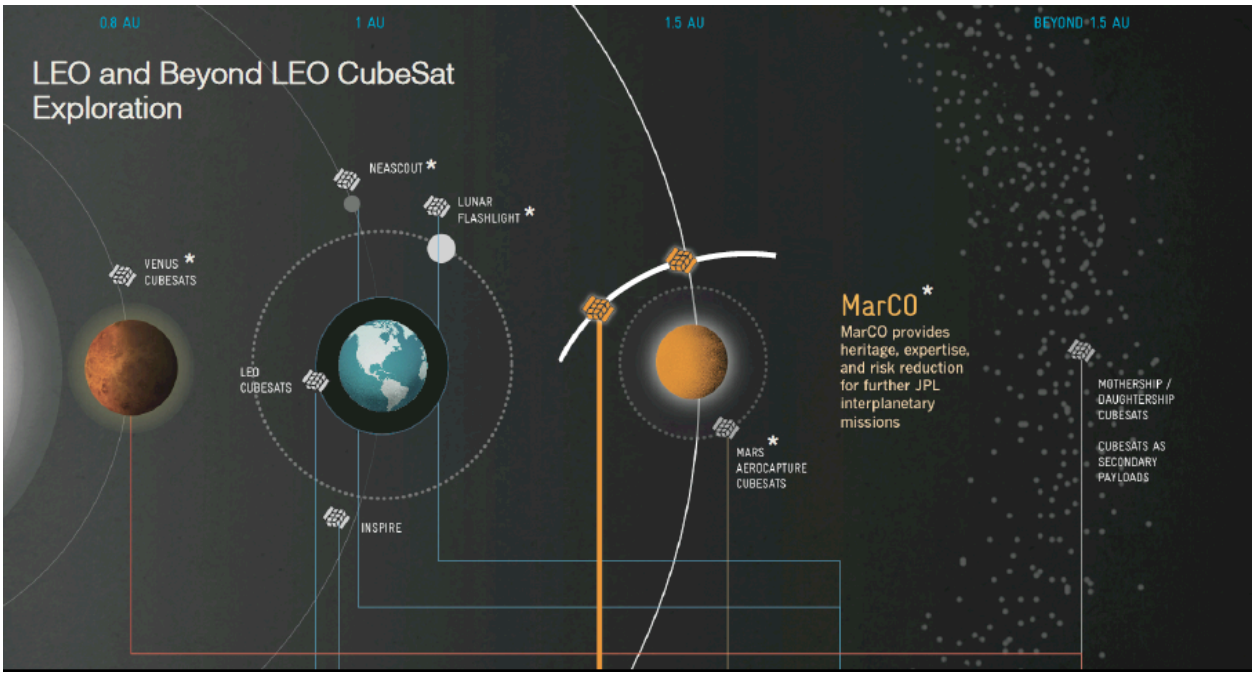

Figure 1: Exploring our solar system with cubesats and nanosats

So what do we need for exponential growth in deep space cubesat/nanosat missions? The most positive step towards realizing this future would be if all space agencies engaged in planetary exploration agreed to allocate real estate and mass for one or more cubesats, nanosats or microsats as ride-along payloads on each of their future medium- to flagship-class planetary missions. Another significant development is the advent of low-cost launch capabilities that can propel a nanosat or microsat on an Earth escape trajectory with a reasonable C3, so the spacecraft can navigate independently to its destination. Micro-Electric Propulsion (MEP) units that can deliver up to 2 km/s of Delta-V are coming soon. Communications standards and navigation approaches are in development. We are also seeing science-capable instruments that fit within volumes ranging from 1U to 4U. Currently we can field simple cameras, magnetometers, mm-wave radiometers, and of course radio science. In the very near future we expect to see: insitu instruments such as mass spectrometers; optical/NIR spectrometers; and even short wavelength radars demonstrated in Earth orbit. Self-assembling telescopes in which multiple cubesats combine to form a larger aperture are on the horizon [6]. Bandwidth of course is limited so onboard data processing/reduction also has to become the norm, not the exception.

2. DESTINATIONS

Where can we reasonably expect to explore in our solar system with nanosats? Figure 1 illustrates the regions that are most easily reached. The inner solar system is considered accessible to both free-flying and mother-daughter configuration cubesats/nanosats, while the outer solar system is currently compatible with just the mother-daughter configuration. Without a suitable, compact radioisotope power system, Deep Space nanosats heading out to Jupiter and beyond will have to hitch a ride along with their host spacecraft, run on energy stored in batteries after their release from their storage/hibernation container, and relay data back to Earth through the mother spacecraft.

In recent decades, several Deep Space missions have used a gravity assist maneuver at Venus to provide a boost in velocity to propel them on their way to their primary mission target. These missions include Galileo (Jupiter) MESSENGER (Mercury), Cassini (Saturn), and Solar Probe (The Sun). Venus gravity assists have become an arrow in the mission designer's quiver that is pulled out whenever we need to save time, money or propellant to get where we want to go. Now imagine that every time a mission executes a gravity assist at Venus, it could drop off a small nanosat probe that could sample and analyze part of Venus' atmosphere, relaying the data back to Earth via the vehicle that dropped it off. As we shall see below, straight shot, independent trajectories to Venus are also possible for nanosats. And with its thick atmosphere Venus is a good target to demonstrate aerocapture with a nanosat, placing into orbit around our sister planet.

Closer to home, the Moon is an attractive destination for nanosats, since it can be reached in a relatively short time, and communication distances are manageable. Near Earth Asteroids (between 0.98 and 1.3 AU distant from the Sun) are another rich target set, with their number estimated at over 14,000, and ~1000 of them larger than 1 km in diameter. Due to cost, it is unlikely that we will ever visit more than a very few with a NASA Discovery-class mission like NEAR Shoemaker [7], or the Japanese Hayabusa missions [8]. But if we could reach these asteroids with nanosats, it will be possible to examine hundreds of them close up within a generation, at a price tag comparable with that of a single Discovery mission.

Launch windows for energy-efficient Mars transfers occur at intervals of about 26 months, and in recent times, most windows have one or more spacecraft inserted onto a trajectory towards the red planet. Nanosats could ride along as ballast to make up the launch mass on larger Mars missions, or make their way there as free-flying spacecraft. With a few km/s of Delta-V capability free-flying nanosats could be placed into orbit around Mars, opening up the potential for science from orbit, and adding to the communications and navigation infrastructure.

The main asteroid belt, situated between 2.2 and 3.2 astronomical units (AU) away from the Sun, contains between 0.7 and 1.7 million objects with a diameter > 1 km. Thus far, spacecraft en route to the outer planets have given us a closer glimpse of only a handful; and the Dawn mission [9] has provided detailed examination of just two of the largest: Ceres and Vesta. This is definitely rich hunting ground for nanosat missions – the asteroid belt is close enough to the Sun that solar power generation is practical, and close enough to Earth that communication distances are manageable. It can take a long time to get out to the main asteroid belt though – Dawn arrived at its first target, Vesta, nearly four years after launch – so reliability and longevity will need to be demonstrated over several years if nanosat missions to the main belt are to succeed.

There are also more than 5000 known comets, whose orbits have taken them close enough to the Sun to be visible from Earth. Again, our spacecraft have visited less than a dozen: Halley's comet, 21P/Giacobini–Zinner, 26P/Grigg–Skjellerup, 107P/Wilson–Harrington, 19P/Borrelly, 81P/Wild, 9P/Tempel, 103P/Hartley, 2P/Encke, and 67P/Churyumov–Gerasimenko. That leaves plenty of possibilities for nanosat mission flybys and encounters of future comets. We know enough about comet trajectories to plan and quickly execute flyby missions, but rendezvous missions take a little

longer and will require a higher standard of reliability: ESA's flagship Rosetta mission took 10 years to catch up with comet 67P/Churyumov–Gerasimenko and match trajectories [10]. Such long mission durations are not unusual when we plan missions to chase the so-called 'short-period' comets.

3. THE FIRST DEEP SPACE NANOSAT MISSIONS

To successfully investigate the multitude of targets available in the solar system, there are many problems to solve for deep space cubesats/nanosats. These include: propulsion; communications at large distances; surviving the radiation environment; power management; attitude determination and control, thermal balancing; energy storage; proximity operations; autonomy; mission assurance and reliability; multi-mission ground operations; planetary protection; hazard avoidance; and flight software standards. The first nanosat missions to venture into deep space will blaze a trail for others to follow in solving some of these challenges.

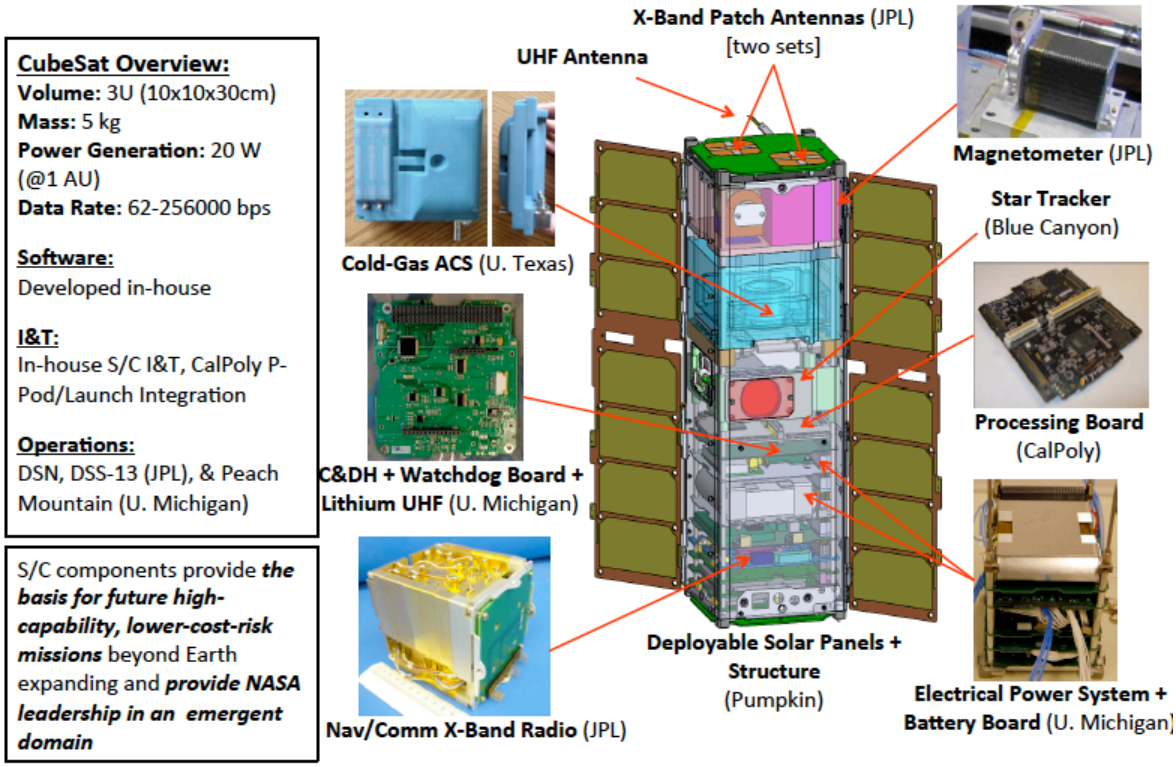

Figure 2: INSPIRE will flight demonstrate critical technologies for deep space cubesats

3.1 INSPIRE and MarCO

JPL has developed two missions - INSPIRE and MarCO, the first true deep space cubesats – that are intended as pathfinders for the space science community. Both INSPIRE (Interplanetary NanoSpacecraft Pathfinder In Relevant Environment) spacecraft are already assembled, integrated and flight-qualified, awaiting only a ride on an Earth escape trajectory. INSPIRE (Figure 2) will flight demonstrate key technologies for deep space cubesats in the cislunar environment, and also demonstrate operations, communications and navigation of such missions [11]. Each of the two INSPIRE spacecraft hosts a compact magnetometer, to characterize the Sun's magnetic field. The MarCO (Mars Cube One) pair of spacecraft are scheduled to launch on the same rocket as NASA/JPL's InSight mission, but will make their way independently to Mars [12]. These first interplanetary cubesats will execute a flyby of the red planet (Figure 3), during which time they will

relay engineering telemetry from InSight as it lands, when it will be out of direct line of sight from Earth.

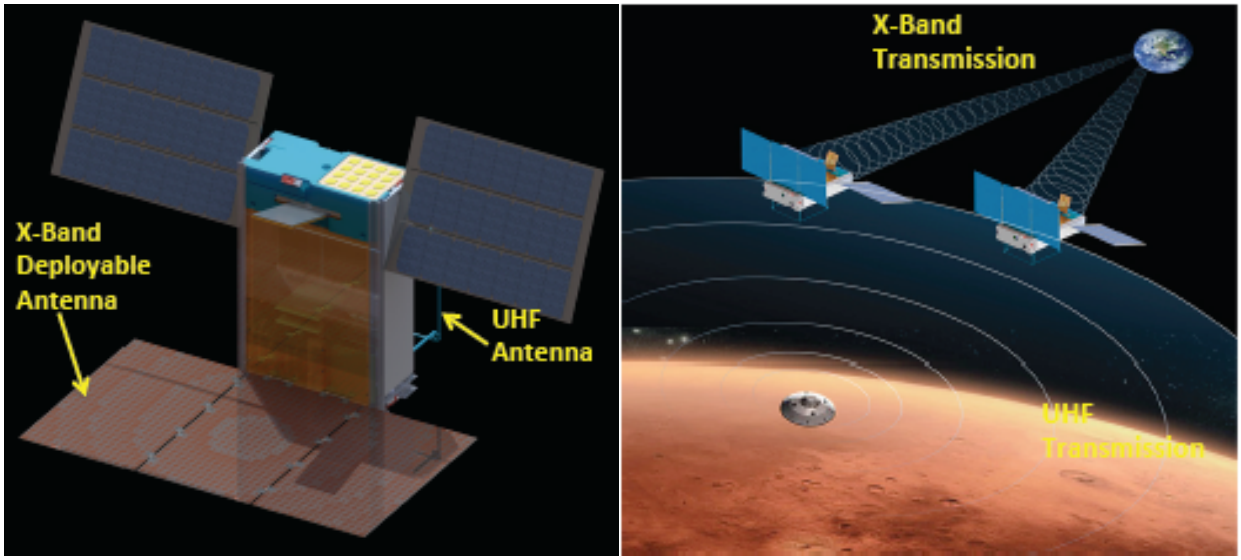

Figure 3: The two MarCO cubesats will flyby Mars and relay UHF telemetry received from the Insight lander directly back to Earth using an X-band communications link.

3.1 Other Deep Space nanosats

Another deep space cubesat project currently under development at JPL is Lunar Flashlight [13], a mission that will use lasers to illuminate the permanently darkened craters of the Moon's poles, to probe the composition of the regolith. Lunar Flashlight will be the first planetary CubeSat mission to utilize green propulsion, and the first mission to employ lasers to look for water ice [14]. It will probably be the first cubesat mission ever to use a laser for remote sensing, a feat made possible by its close approach orbit at the Moon. A fourth active project is the Near Earth Asteroid Scout [15], which will deploy a solar sail to achieve a trajectory that puts it on a path to rendezvous with a Near-Earth Asteroid. JPL is partnered with Marshall Space Flight Center on both Lunar Flashlight and NEA Scout.

Figure 4: Lunar Flashlight (left) and NEA Scout (right) cubesat missions

LunarIceCube (Figure 5) is a cubesat project led by Morehead State University [16], with significant contributions from Goddard Space Flight Center and Busek Corporation. The Principal Investigator is Pam Clark of JPL. LunarIceCube will use a compact broadband IR instrument (BIRCHES) to investigate the origin of volatiles on the Moon, their distribution, and ongoing processes at the lunar surface. To operate the IR spectrometer at its required temperature of 120 K,

the mission will demonstrate the first use of a tactical cryocooler on a cubesat platform. Like Lunar Flashlight and NEA Scout, the spacecraft will be dropped off near the Moon on the SLS EM1 flight planned for 2018 [17], but will then thread its way into a close lunar orbit using Busek's breakthrough low-thrust propulsion system for cubesats [18].

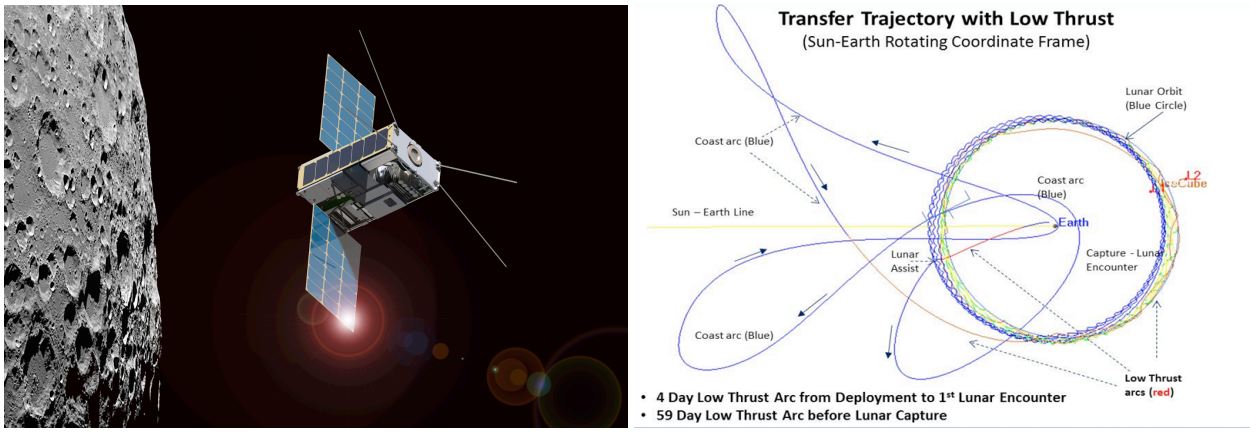

Figure 5: LunarIceCube and the elaborate low-thrust trajectory that will place it into its mapping orbit at the Moon

Also selected for the EM1 flight opportunity is the CuSP solar observatory, which will carry JPL's Vector Helium Magnetometer instrument [19].

4. THE NEXT WAVE OF DEEP SPACE NANOSAT MISSIONS

The genie is now out of the bottle: many deep space nanosat mission concepts are currently under study for future flight opportunities. Here we describe just a few of them.

4.1 Europa

In October 2014, JPL selected proposals from 10 universities to study CubeSat concepts that could enhance the Europa mission currently planned for a 2022 launch opportunity by NASA [20]. As illustrated in Figure 6, such cubesats would be carried to Jupiter by the host spacecraft, and then

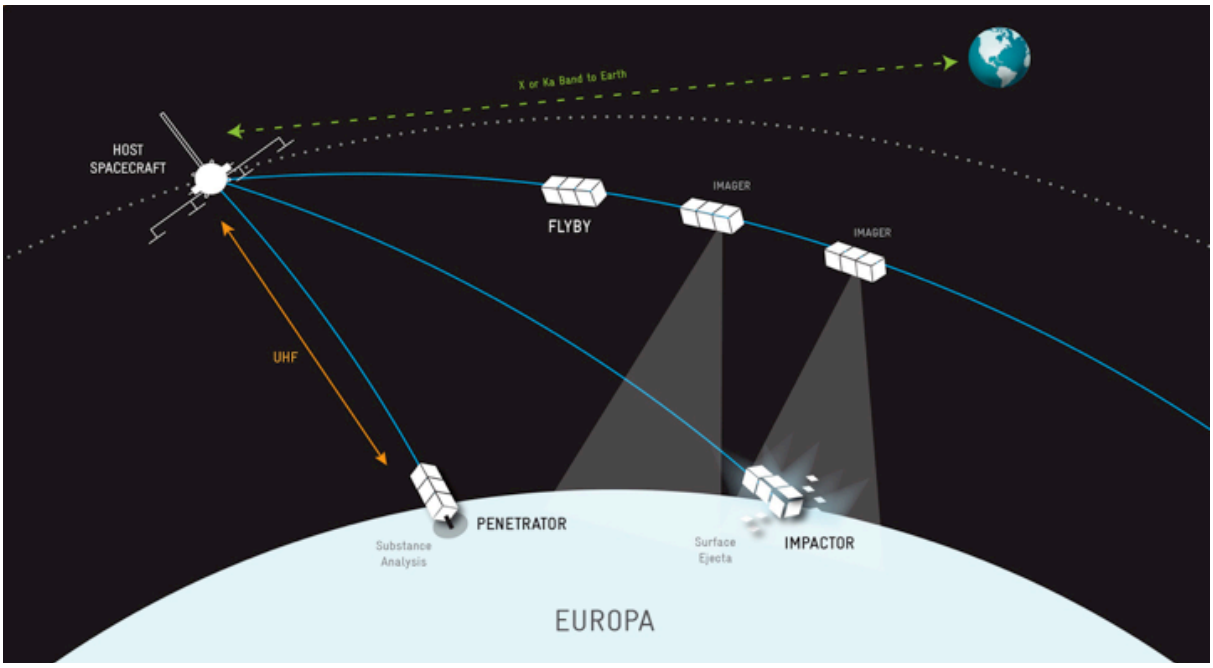

Figure 6: Illustration of how cubesats could be deployed from the Europa Clipper mission

released on approach to Europa to execute their assigned mission. In this mother-daughter architecture, the cubesat elements can approach much closer to the surface of Europa than the primary spacecraft, enabling unique science observations. As an example, one cubesat under study by the University if Michigan would use multi-frequency magnetic induction sounding from a compact magnetometer to characterize the subsurface ocean of Europa [21].

4.2 MarsDROP

A recent study conducted jointly by JPL and the Aerospace Corporation looked at micro-landers that could be carried to Mars as secondary payload(s) on spacecraft bound for Mars [22]. In the study, each lander (Figure 7) consists of a 30 cm diameter probe, carrying a ~1kg scientific payload. The concept built on the success of Aerospace's small Earth Reentry Breakup Recorder (REBR) vehicle to design a low mass/low ballistic coefficient entry system that allows for subsonic deployment of a steerable parawing glider, capable of up to 10 min and more than 10 km of guided flight, which would impact the surface with a 3:1 glide ratio at ~20.5 m/s. The MarsDROP concept would enable scientists to reach areas of Mars that are inaccessible to larger landed missions.

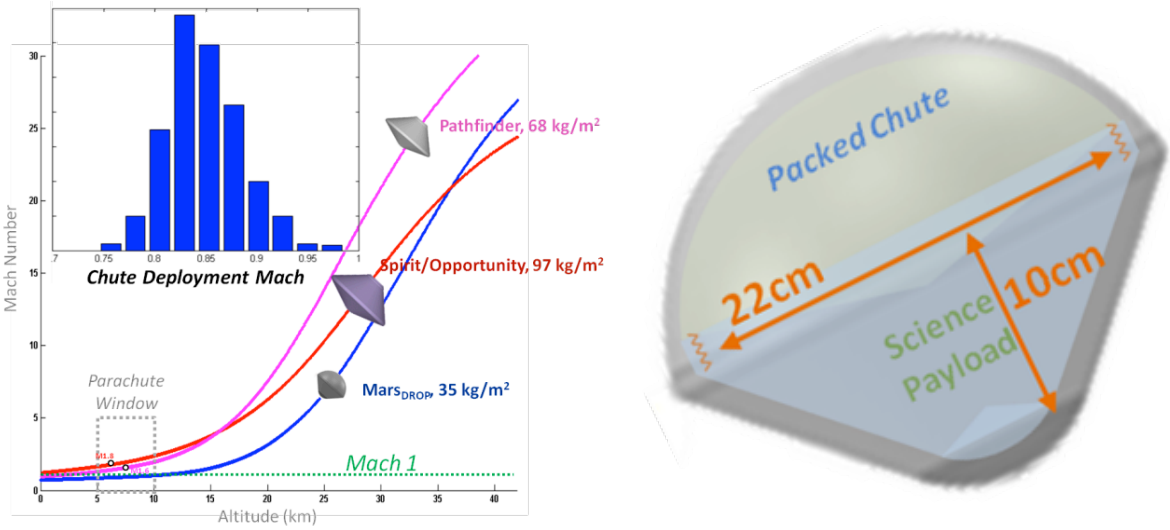

Figure 7: MarsDROP MicroProbe concept

4.3 Discovery Technology Demonstrations

JPL recently proposed seven cubesat/nanosat missions as technology demonstrations to augment larger missions proposed to NASA's Discovery program [4]. Each cubesat or nanosat was carried in a mother-daughter configuration to its destination in the solar system, which ranged from Venus to main belt asteroids, a Jovian comet, and Phobos [5]. Each provided a unique capability that augmented the science of the companion (mother) Discovery mission. Some were flybys of the target body to offer a closer look than could be risked with the main spacecraft, others provided insitu measurements.

One forward-looking mission concept submitted to the recent Discovery call proposed to achieve *all* of its science using cubesats. The NANOSWARM mission concept [23] positions a fleet of cubesats in orbit around the Moon to address science questions on: space weathering; the origins of planetary magnetism; the origins, distributions, and migration processes of surface water on airless bodies; and the physics of small-scale magnetospheres. The NANOSWARM concept uses a novel "mother-with-many-children" architecture to place its cubesat armada into a low, circular, polar lunar orbit. The mother ship releases some cubesats on impact trajectories into the hearts of lunar magnetic anomalies to measure magnetic fields and proton fluxes, in real time, up until the last tens of milliseconds. A second set of cubesats would then be released into a polar orbit with a periapsis over the South Pole, to measure neutron fluxes.

4.4 Venus Nano-Probe

A recent study at JPL examined a free-flyer nanosat probe, launched directly from Earth towards Venus [24]. The probe targets very high priority science at Venus - the need to measure the relative abundances of Neon, Argon, Helium, Krypton and other noble gases to understand how Venus' atmosphere formed and has evolved. To be truly representative of the noble gases and their isotopic ratios, a sample of the atmosphere has to be acquired where the atmosphere is well-mixed: at an altitude below the homopause, which for Venus is around 120 km.

The study came up with a novel, low-cost, Smallsat architecture for a conceptual standalone mission that would sample the noble gases and their isotopic ratios at Venus. Sampling is achieved by a compact, ion-trap mass spectrometer incorporated into a small (60 cm diameter) probe that skims through the atmosphere, targeting a closest approach altitude above the surface below the nominal 120 km. Following acquisition, the gas sample is analyzed over a period of ~60 minutes.

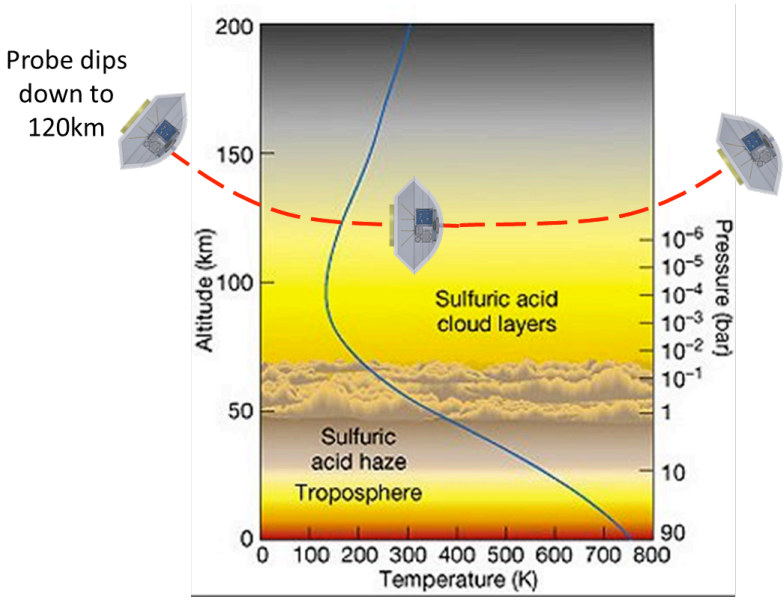

Figure 8: Venus atmospheric sampling probe would skim through the atmosphere to sample the noble gases below the homopause at ~120 km altitude above the surface

The Venus probe and carrier spacecraft are assumed to launch together on a Type II trajectory towards Venus, on a dedicated Pegasus launch vehicle developed by Orbital Sciences Corporation, with a STAR27H motor used as a kick stage. The probe and carrier spacecraft both moth make extensive use of nano-spacecraft components and their combined mass is estimated at less than 55 kg. The compact mass spectrometer instrument mass is estimated at 8 kg. En route to Venus the carrier spacecraft would execute pre-planned TCM maneuvers for a total Delta-V of about a hundred m/s. On approach, the carrier spacecraft would spin up to rotate at ~10 rpm, then release the probe on its path to skim through the atmosphere. The carrier spacecraft would then execute a small maneuver (with a few m/s of Delta-V) to fly past Venus above the atmosphere. Following the probe skim-through and data analysis, results are returned to Earth via a UHF/X-Band relay, similar to that developed for MarCO.

4.5 Other Opportunities

NASA has commissioned several nanosat concept studies which could ride along as secondary payloads on the Asteroid Redirect Mission [25], including contributions from two asteroid mining companies: Planetary Resources and Deep Space Industries. Five CubeSat concepts are being studied as secondary payloads to accompany ESA's proposed Asteroid Impact Mission [26]. SSTL in the UK are developing a partnership with ESA for a lunar communications pathfinder to enable

nanosat missions [27]. Looking far ahead into the future, Russian billionaire Yuri Milner just announced $100M of funding for interstellar nanosats to Alpha Centauri [28].

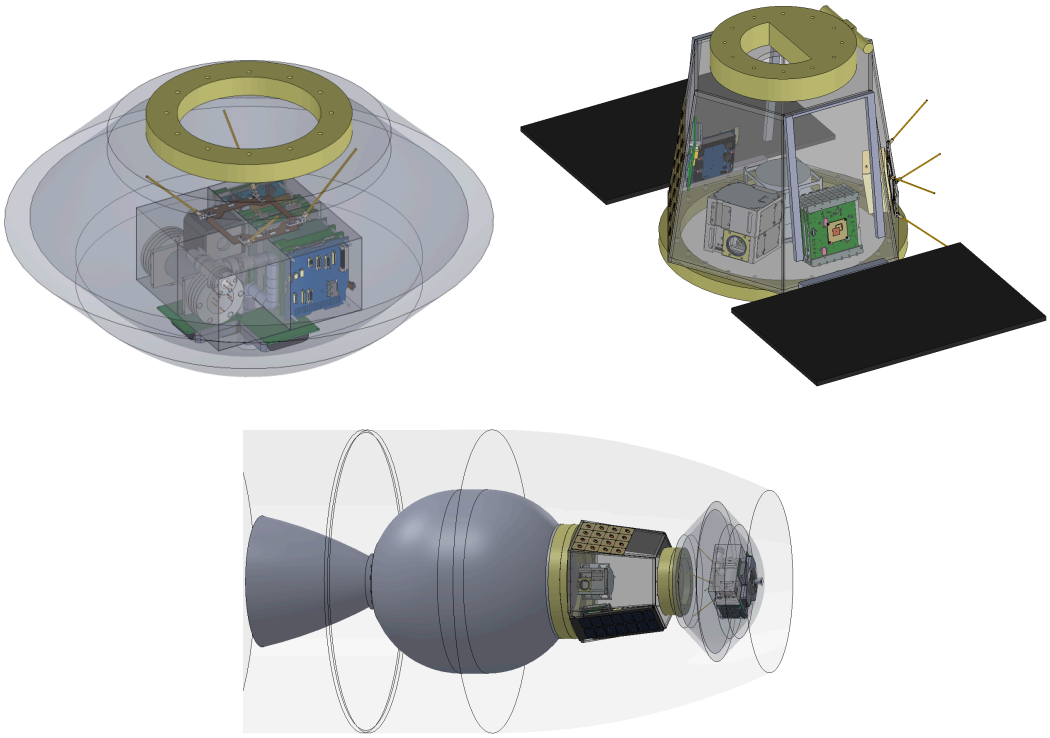

Figure 9: a) Compact Venus probe concept with a 4U QITMS mass spectrometer and nanosat avionics (top left); b) carrier spacecraft with eHawk solar arrays shown deployed (top right); c) Carrier spacecraft + probe configuration, mounted on STAR27H motor, within the Pegasus XL launch shroud envelope (bottom).

5. INSTRUMENTS

For a JPL nanosat science mission, there's no point in arriving at an exotic destination in the solar system if you can't make useful, science-grade measurements when you get there. But not all the instruments we need for deep space exploration can be miniaturized to fit within the constraints of a cubesat or nanosat volume. Magnetometers can be made to fit, as seen on INSPIRE, radios can be miniaturized to enable radio science investigations, as seen on both INSPIRE and MarCO, and insitu instruments can, with some effort and ingenuity, be made small and low-power enough, as seen in the proposed Venus probe. What other instruments can be tailored for cubesats/nanosats? For a first cut at this we turn to a survey of Earth Observation instruments that was generated in 2012 [29], and recently updated to reflect the progress made by instrument developers in 2016 [30]. It turns out to be quite a long list (Table 1): including optical/IR cameras; UV/Optical spectrometers; IR radiometers and spectrometers, from the Near-IR to Far-IR; microwave radiometers; Sub-mm-wave spectrometers; short wavelength radars; GPS radio occultation; and optical communication lasers that can be used for occultation. Cubesat versions of Synthetic Aperture Radars (SARs) – which conventional wisdom has requiring huge apertures and kWs of power to operate from orbit – are under study ([31], [32]). It is evident that substantial progress has been made in advancing the feasibility of several instruments classes since 2012. For planetary science investigations we should also add compact Gamma ray and X-ray spectrometers to the list. The NANOSWARM proposal included a miniaturized neutron spectrometer and a solar wind ion sensor [23]. The community has invested significantly in technology development to miniaturize such instruments, an effort which we are now seeing pay off as instrument concepts mature to the point where we can incorporate them in cubesat/nanosat missions for science.

Table 1: Feasibility of cubesat-sized instruments for Earth observation. 2012 assessment from [29] and updated 2016 assessment from [30]

Instrument Class	2012 Assessment	2016 Assessment	Justification
Atmospheric Chemistry Instruments	Problematic	Feasible	PICASSO, IR Sounders
Atmos Temp and Humidity Sounders	Feasible	Feasible	3-D Winds
Cloud profile and rain radars	Infeasible	Feasible	JPL RainCube Demo
Earth Radiation budget radiometers	Feasible	Feasible	SERB, RAVAN
Gravity instruments	Feasible	Feasible	Mini-MAGGIE concept
Hi-resolution optical imagers	Infeasible	Feasible	Planetlabs
Imaging microwave radars	Infeasible	Problematic	Several concepts exist
Imaging multi-spectral radiometers (Vis/IR)	Problematic	Feasible	AstroDigital, M-Cubed
Imaging multi-spectral radiometers (uwave)	Problematic	Feasible	TEMPEST-D
Lidars	Infeasible	Problematic	DIAL laser occultation
Lightning Imagers	Feasible	Feasible	FireFly
Magnetic Fields	Feasible	Feasible	INSPIRE
Multiple direction/polarization radiometers	Problematic	Feasible	HARP polarimeter
Ocean color instruments	Feasible	Feasible	SeaHawk
Precision orbit	Feasible	Feasible	Can-X 4 and 5
Radar altimeters	Infeasible	Feasible	Bistatic GEO-LEO
Scatterometers	Infeasible	Feasible	GPS reflections

6. SPACECRAFT TECHNOLOGIES

JPL and others within NASA are investing in some critical spacecraft technologies (Figure 10) with high payoff for deep space cubesats/nanosats, including: a low mass radio transponder; reflectarrays for X-band and Ka-band telecom; a compact, deployable Ka-band 0.5 m diameter reflector antenna; Micro-Electric Propulsion (MEP) that can provide up to 1 km/s of Delta-V; the design of a Deep Space P-POD to deploy cubesats on mother-daughter configuration missions; and onboard data reduction and data handling to significantly reduce science data volumes.

Figure 10: Examples of JPL spacecraft technology development for cubesats/nanosats, and the corresponding mission they will be demonstrated on. From left to right – the deep space transponder (INSPIRE and MarCO), micro-electric spray propulsion (TBD), compact, deployable 0.5 m diameter reflector (RainCube), and onboard data reduction board (M-Cubed/COVE-2)

Other technology developments that will greatly enhance or enable deep space nanosat missions [5] include: low-power modes and duty cycling; efficient, lightweight solar arrays; greater energy storage capacity; on-board data compression; delay-tolerant networking; autonomous operations; terrain relative navigation; radiation-tolerant avionics; and multi-layer structures for more efficient packaging and improved thermal balancing. For spacecraft technology developers, nanosat missions offer attractive, fast-track opportunities to demonstrate technology readiness.

Looking ahead, compact radioisotope power systems may eventually open up the outer solar system to free-flying nanosat missions ([33], [34]). A successful demonstration of aerocapture would go a long way towards enhancing the feasibility and capability of independent nanosat missions to Venus and Mars. Long-duration nanosat missions will continue to be flagged as high-risk until reliability can be demonstrated over several years.

7. INFRASTRUCTURE

To support the current and projected surge in deep space cubesats/nanosats, JPL has also invested in improvements to our infrastructure as illustrated in Figure 11.

Figure 11: From left to right: Communication and Navigation protocols using the Deep Space Network; Team Xc for fast formulation of cubesat/nanosat mission/spacecraft concepts such as MarCO and Cupid's Arrow; the Cubesat Development Lab for cubesat development, integration and test.

8. LAUNCH VEHICLES

The Venus probe concept described above used a Pegasus XL launch vehicle, with a final stage STAR27H motor to achieve escape velocity with sufficient C3 to send it on its way to Venus. NASA recently awarded contracts to three launch service providers: Firefly, Rocketlabs and Virgin Galactic to develop launch vehicles that give small satellites easier access to low Earth orbit [35]. Assuming those launch vehicles all succeed in that objective, a useful next step would be to see whether they could accommodate deep space trajectories for nanosats.

9. PROJECTING FORWARD

The "cubesat kitchen cabinet" at JPL made a projection just over three years ago of exponential growth in deep space cubesat/nanosat missions. So far, as seen in Figure 12, based on the current projection of planned missions from NASA, ESA, and commercial entities, our prediction appears to be on track. Of course, these plans are fluid – as anyone involved in the space business for an extended period knows: launch manifests can change overnight. So, having seen the pace of developments in deep space cubesats/nanosats accelerate over the last few years, what is the secret to ensuring this projection of exponential growth becomes reality? To adapt a famous saying from NASA's past by former Administrator Dan Goldin, they need to be executed Faster, *Smarter* and Cheaper than conventional space missions. The ingredients for that are summarized in Table 2 in a list of do's and don'ts for cubesat and nanosat missions of the future that explore our solar system.

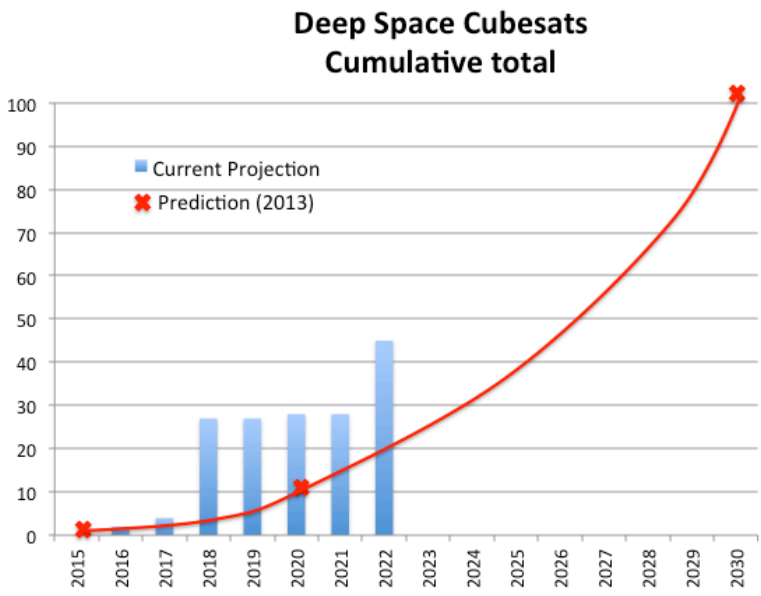

Figure 12: Projection of Exponential Growth in Deep Space Cubesats and currently planned Deep Space Cubesat Missions out through 2022.

10. SUMMARY

The future for low-cost planetary exploration looks bright using compact, but capable, deep space cubesat and nanosat missions. We are clearly at the bottom of the growth curve but the pace of change in this area is accelerating, and a lot of innovation is happening across the community. The two factors that will have the most influence on this future from *outside* the cubesat/nanosat community are whether launch costs can be kept low (and in particular whether dedicated, low cost launch vehicles make it to market), and whether ride-along opportunities can be created on all planetary missions flown by NASA, ESA, and other space agencies.

Table 2: Checklist of Do's and Don'ts for exponential growth in deep space cubesat/nanosat missions.

Short (1-2 year) development cycles	✔	Lengthy (8-15 year) development cycles with extended Phase A	✖
Take advantage of today's incredible advances in instrument miniaturization	✔	Only use heritage instruments	✖
Take advantage of today's incredible advances in software	✔	Don't fly current-generation microprocessors. Insist all science processing be done on ground	✖
Cubesat form factor encourages use of modular subsystems	✔	Design everything to meet a specific set of mission requirements	✖
Keep launch costs low	✔	Dedicated launches on rockets designed primarily for 1000s of kg GEO comsats	✖
Create ride-along opportunities on all planetary missions	✔	Everything has to be decadal survey-approved science	✖

11. ACKNOWLEDGMENTS

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