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Exploring our Solar System with cubesats and nanosats

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ABSTRACT

The Jet Propulsion Laboratory (JPL) is NASA's lead center for robotic exploration of our solar system. We are known for our large, flagship missions, such as Voyager, which gave humanity its first close look at Jupiter and Saturn; and the Mars Rovers, which have excited millions worldwide with their daring landing exploits. Less familiar to those outside NASA may be our role in developing the Kepler mission, which has discovered more than 2000 planets around other stars; or the recently launched Soil Moisture Active Passive (SMAP) mission, one of many JPL Earth Science missions.

A recent JPL initiative has emphasized low cost missions that use rapidly evolving technology developed for cubesats and nanosats to explore our solar system. Costs are significantly lower (by one or two orders of magnitude) than for conventional JPL missions, and development time is also significantly shorter. At present 21 such cubesat flight projects are under way at the laboratory with various partners: some in flight, some in development, some in advanced formulation. Four are planned as deep space missions. To succeed in exploring deep space cubesat/nanosat missions have to address several challenges: the more severe radiation environment, communications and navigation at a distance, propulsion, and packaging of instruments that can return valuable science into a compact volume/mass envelope. Instrument technologies, including cameras, magnetometers, spectrometers, radiometers, and even radars are undergoing miniaturization to fit on these smaller platforms. Other key technologies are being matured for smallsats and nanosats in deep space, including micro-electric propulsion, compact radio (and optical) communications, and onboard data reduction. This paper will describe missions that utilize these developments including the first two deep space cubesats (INSPIRE), planned for launch in 2017; the first pair of cubesats to be sent to another planet (MARCO), manifested with the InSight Mars lander launch in March of 2016; a helicopter "drone" on Mars to extend the reach of future rovers; plans for a Lunar Flashlight mission to shine a light on the permanently shadowed craters of the Moon's poles; a Near Earth Asteroid cubesat mission; and a cubesat constellation to demonstrate time series measurements of storm systems on Earth.

From these beginnings, the potential for cubesats and nanosats to add to our knowledge of the solar system could easily grow exponentially. Imagine if every deep space mission carried one or more cubesats that could operate independently (even for a brief period) on arrival at their target body. At only incremental additional cost, such spacecraft could go closer, probe deeper, and provide science measurements that we would not risk with the host spacecraft. This paper will describe examples including a nanosat to probe the composition of Venus' atmosphere, impactors and close flybys of Europa, lunar probes, and soft landers for the moons of Mars. Low cost access to deep space also offers the potential for independent cubesat/nanosat missions – allowing us to characterize the population of near Earth asteroids for example, deploy a constellation around Venus, or take closer looks at the asteroid belt.

KEYWORDS: NASA Deep Space Missions, cubesats, nanosats

INTRODUCTION

In early 2013, a small group at JPL formed what became known as the 'cubesat kitchen cabinet', with the aim of creating an environment in which cubesats and nanosats for science could prosper at the laboratory. Science in this case of JPL means observations for Earth Science to study our planet's environment and climate, Astrophysics observations 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 the first radiometer science mission 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]. Usually NIAC studies have a time horizon decades out but it was clear that the pace of change in the world of cubesats was picking up speed, 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 largely an adhoc group, led out of JPL's Innovation Foundry. 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 has twenty-one 'live' cubesat projects, at different stages of development with our partners, but all funded. Four of these projects are deep space cubesat missions.

MISSIONS

Figure 1 illustrates exploration of our solar system using cubesats/nanosats. 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. Deep Space missions are challenging, whatever their size, and there are lots of problems to solve for deep space cubesats/nanosats, including: propulsion; communications at large distances; surviving the radiation environment; power management; attitude determination

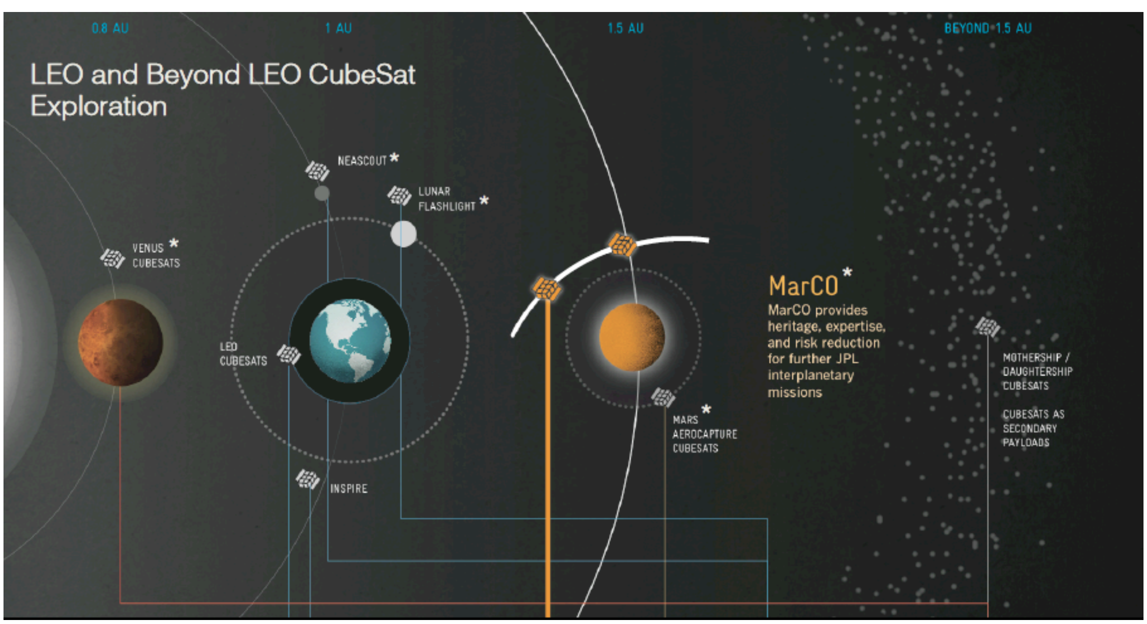

Figure 1: Exploring our solar system with cubesats

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. With INSPIRE and MarCO, the first true deep space cubesats, JPL is tackling these problems, as pathfinders for the space science community, whose interest in such missions is building rapidly[3]. The 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 prove key technologies for deep space cubesats, and demonstrate operations, communications and navigation of such missions. Each of the two spacecraft host 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 vehicle as NASA/JPL's InSight mission, but will make their way independently to Mars. These first interplanetary cubesats will execute a flyby of the red planet, during which time they will relay engineering telemetry from InSight as it lands, out of direct line of sight from Earth.

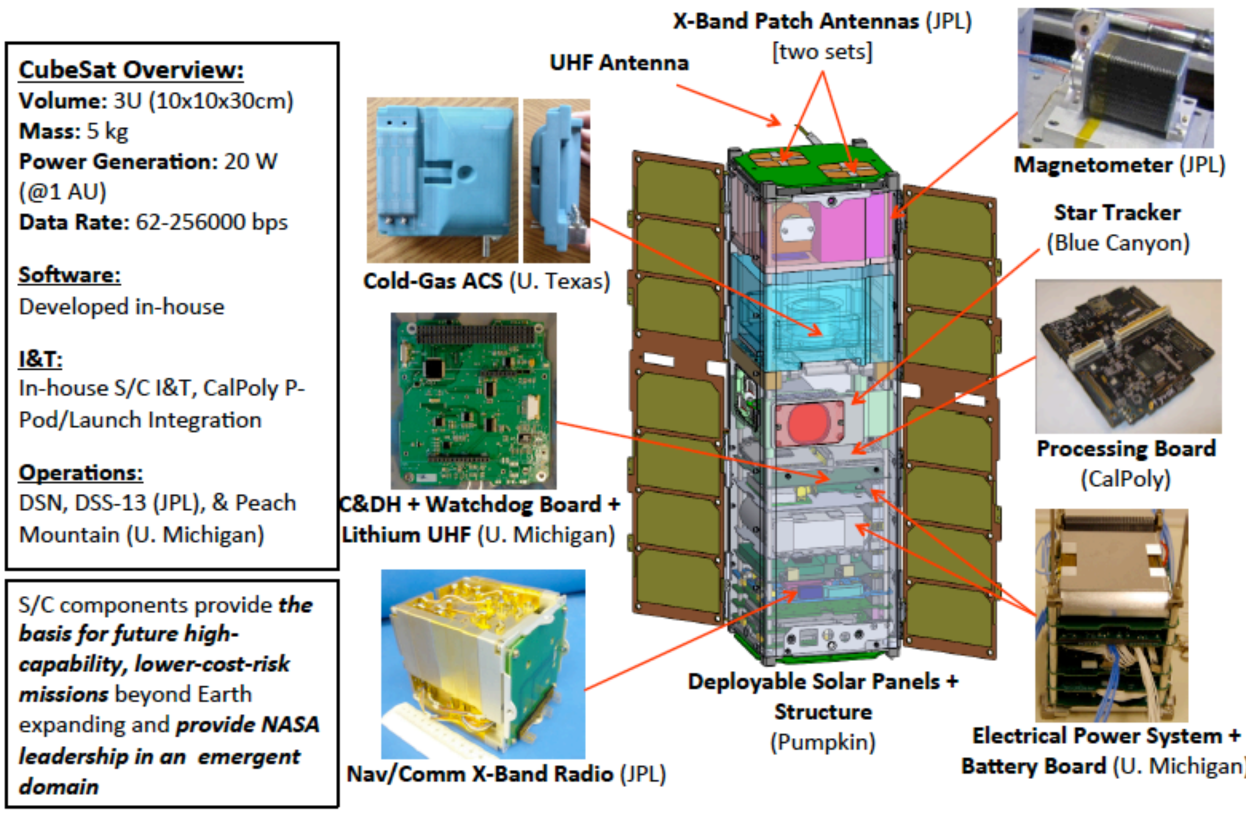

Figure 2: The InSight Spacecraft will flight prove critical technologies for deep space cubesats

Other Deep Space cubesat projects that are currently active at JPL include Lunar Flashlight[1], a mission that will utilize lasers to illuminate the permanently darkened craters of the Moon's poles, to probe the composition of the regolith there; and NEAScout[1], which will deploy a solar sail to achieve a trajectory that puts it on a path to rendezvous with a Near-Earth Asteroid.

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.

In particular, the "Cupid's Arrow" nanosat, proposed as an optional additional payload on the VERITAS Venus orbiter, enables high payoff science at a fractional additional cost. Released by the mother spacecraft after Venus orbit insertion, the nanosat uses a new, ultra-compact Quadrupole Ion Trap Mass Spectrometer (QITMS) with unrivaled sensitivity to determine atmospheric noble gas abundances and isotope ratios.

As proposed, the VERITAS mother ship carries Cupid's Arrow to Venus' orbit (Figure 3a) and it is deployed during aerobraking. The nanosat requires a relatively small nudge of 1.25 m/s of ΔV in the along-track direction to send it on its path, dipping below Venus' homopause, at less than 120 km altitude. The compact mass spectrometer then pops open a cap and ingests a sample for analysis. The nanosat exits the atmosphere and relays its measurement data via a UHF communication link to VERITAS from a range of ~1000 km. Cupid's Arrow leverages mature, flight-qualified Avionics and other subsystems developed for MarCO and INSPIRE. The total mass for Cupid's Arrow is less than 25 kg.

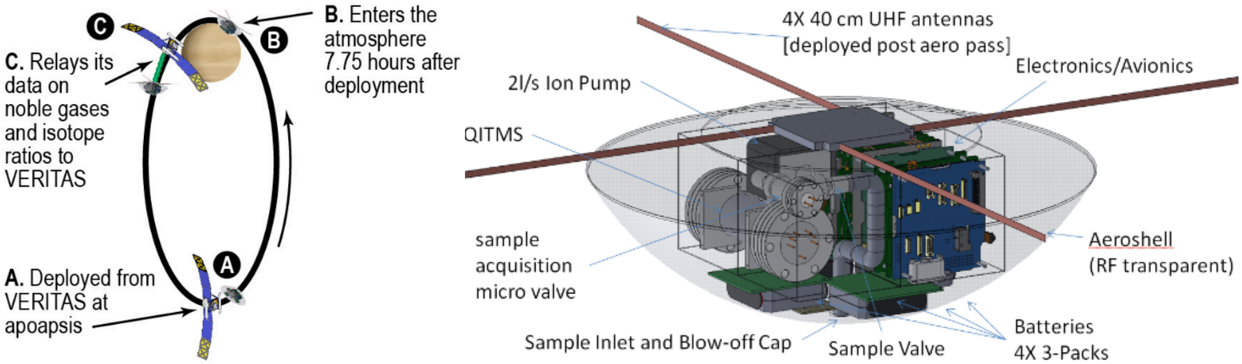

Figure 3: a) The trajectory for Cupid's Arrow is designed to sample the noble gases in Venus' atmosphere at a 120 km altitude [left]; b) Cupid's Arrow flight system configuration [right].

INSTRUMENTS

Not all instruments we need for deep space exploration can be miniaturized to fit within the constraints of a cubesat or nanosat volume. Magnetometers fit the bill, 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 an ingenuity, be made small and low-power enough, as seen in the proposed Cupid's Arrow. What other instruments can be tailored for cubesats/nanosats? It turns out to be quite a long list: optical/IR cameras; UV/Optical spectrometers; IR radiometers and spectrometers, from the Near-IR to Far-IR; microwave radiometers; Sub-mm-wave spectrometers; Gamma ray and X-ray spectrometers; short wavelength radars; GPS radio occultation; and optical communication lasers. At JPL we have initiated technology development to miniaturize each of these instrument types, 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.

KEY SPACECRAFT TECHNOLOGIES

JPL has invested in some critical spacecraft technologies (Figure 4)needed for deep space cubesats/nanosats, including: a low mass radio transponder; reflectarrays for X-band and Ka-band telecom; a compact, deployable

Figure 4: 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)

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.

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 5.

Figure 5: 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.

PROJECTING FORWARD

The "cubesat kitchen cabinet" at JPL made a projection three years ago of exponential growth in deep space cubesat/nanosat missions. So far, as seen in Figure 6, 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

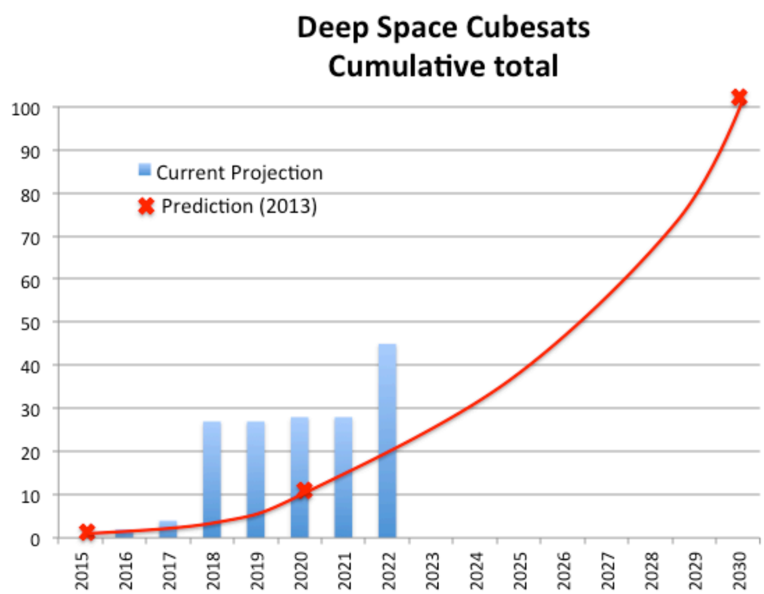

Figure 6: Projection of Exponential Growth in Deep Space Cubesats and currently planned Deep Space Cubesat Missions out through 2022.

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? We would argue that, 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. What we mean by that is summarized in Table 1 in a list of do's and don'ts for cubesat and nanosat missions of the future that explore our solar system.

Table 1: What Faster, Smarter, Cheaper does and does not mean in the context of 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 <u>all</u> planetary missions	✔	Everything has to be decadal survey-approved science	✖

SUMMARY

We have described a bright future in which low-cost planetary exploration is enabled by compact, but capable, deep space cubesat and nanosat missions. We still have a long way to go to realize that future 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 ride-along opportunities can be created on <u>all</u> planetary missions flown by NASA, ESA, and other space agencies, including the UK.

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