INTERPLANETARY CUBESAT NAVIGATIONAL CHALLENGES

Tomas J. Martin-Mur(1)**, Eric D. Gustafson**(2)**, and Brian T. Young**(2)
(1) *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive,*
Pasadena, CA 91109, 1-818-393-6276, Tomas.J.MartinMur@jpl.nasa.gov
(2) *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive,*
Pasadena, CA 91109

Abstract: *CubeSats are miniaturized spacecraft of small mass that comply with a form specification so they can be launched using standardized deployers. Since the launch of the first CubeSat into Earth orbit in June of 2003, hundreds have been placed into orbit. There are currently a number of proposals to launch and operate CubeSats in deep space, including MarCO, a technology demonstration that will launch two CubeSats towards Mars using the same launch vehicle as NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) Mars lander mission. The MarCO CubeSats are designed to relay the information transmitted by the InSight UHF radio during Entry, Descent, and Landing (EDL) in real time to the antennas of the Deep Space Network (DSN) on Earth. Other CubeSat proposals intend to demonstrate the operation of small probes in deep space, investigate the lunar South Pole, and visit a near Earth object, among others. Placing a CubeSat into an interplanetary trajectory makes it even more challenging to pack the necessary power, communications, and navigation capabilities into such a small spacecraft. This paper presents some of the challenges and approaches for successfully navigating CubeSats and other small spacecraft in deep space.*

Keywords: *Interplanetary Navigation, Cubesat, MarCO.*

1. Introduction

CubeSats are miniaturized spacecraft of small mass that comply with the CubeSat Design Specification published by the CubeSat Program (Cal Poly) at the California Polytechnic State University, San Luis Obispo. Started in 1999, the CubeSat Project began as a collaborative effort between Prof. Jordi Puig-Suari at Cal Poly, and Prof. Bob Twiggs at Stanford University's Space Systems Development Laboratory (SSDL). The purpose of the program is "to provide a standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches." [1] Currently more than 100 universities, high schools, and other private and public entities are developing CubeSats for a wide number of applications. The most basic CubeSat (1U) is a 10 cm cube with a mass of up to 1.33 kg, but they are scalable in 1U increments with 2U and 3U models having been built and launched, and 6U and 12U models, some exceeding the scaled maximum mass, having been proposed.

The advantage of using a standard form specification is that it simplifies the launch interfaces so the satellites can be launched using one of a number of already available standardized CubeSat deployers. Since most CubeSats are launched as secondary payloads, the design specification has the goal of minimizing risk to the rest of launch vehicle and to the primary and other payloads. For example, restrictions are imposed on the components and parameters of the propulsion system, with most of Earth orbiting CubeSats lacking the capability to perform trajectory correction maneuvers. CubeSats, despite their size, still need to perform most of the functions required by bigger spacecraft, such as power management, thermal control, data management, attitude control, communications and navigation. Communication for Earth orbiting CubeSats can be accomplished using low gain antennas on the spacecraft and relatively small apertures in the ground, while navigation may be performed just using the tracking performed by the Joint Space Operations Center (JSpOC), or using GPS receivers. Performing the same functions in deep space requires the use of different means: even the powerful radars operated by JSpOC cannot obtain detectable returns from small spacecraft at deep space distances, and while GPS could be used up to lunar distances, even then it may require antenna sizes not practical for small spacecraft. The sensitivity and aperture size of the antennas of NASA's Deep Space Network, and similar antennas operated by other space agencies, make them suitable for use by deep space CubeSats, but significant spacecraft transmit power would be required in order to close the link and achieve the required data rates, and to reduce the amount of DSN antenna time required by the CubeSat mission. [2]

2. Interplanetary CubeSats

A number of deep space or interplanetary CubeSat flight demonstrations and missions have been proposed or at different stages of development, both at NASA and by other space agencies. [2] The goals of these missions go from demonstrating CubeSat technology and capabilities for deep space use to performing scientific research at different solar system locations and bodies. The perceived advantage of using CubeSats is that they are cheaper to build and launch than bigger spacecraft, and they can be built faster when taking advantage of standard CubeSat components and subsystems available in the marketplace. There are a number of opportunities to launch CubeSats along with bigger spacecraft, making use of excess launch capability, and there are also proposals for the CubeSats to hitch a ride with other spacecraft and to be deployed when the main spacecraft reaches its destination. The first Space Launch System (SLS) mission, Exploration Mission 1 (EM-1) – currently scheduled to launch in 2018 – will deploy 11 CubeSats after it deploys Orion into a translunar trajectory. Three of these CubeSat concepts have already been selected as of the writing of this paper: Lunar Flashlight, [3] Near-Earth Asteroid Scout, [4] and BioSentinel, [4] and other selections may include participation by non US-government partners.

2.1. INSPIRE

The first CubeSat probes built for deep space are the Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE). [6] This NASA/JPL mission addresses a tiered set of technology demonstration and education objectives, including a demonstration that CubeSats can operate, communicate, and navigate far from Earth. The flight system comprises two identical 3U CubeSats with three-axis attitude control using a star tracker and a cold-gas reaction control system. The probes use DSN-compatible IRIS v1 radios [7] for X-band communication and tracking. The IRIS radio, developed by the NASA Jet Propulsion Laboratory, is a miniaturized DSN-compatible radio capable of coherent 2-way Doppler, ranging, and Differential One-way Ranging (DOR) tones. It occupies about 0.5U, weighs about 0.5 Kg and requires about 13 W of power when receiving and transmitting. For INSPIRE, the radio will operate in X-band, but future versions of the radio could be setup for Ka-band, S-band, or UHF operations. The INSPIRE probes are equipped with dual receive / transmit patch antennas for communication with the DSN stations, limiting the distance at which the radio can communicate with the ground due the available transmit power. It is expected that a telemetry rate of 1 kbps can be demonstrated at a distance of 1.5M km. The radio performance should be sufficient to demonstrate a navigational accuracy of better than 500 km when relatively close to the Earth, and between 1000 and 2000 km at greater distances, using 2-way Doppler and range.

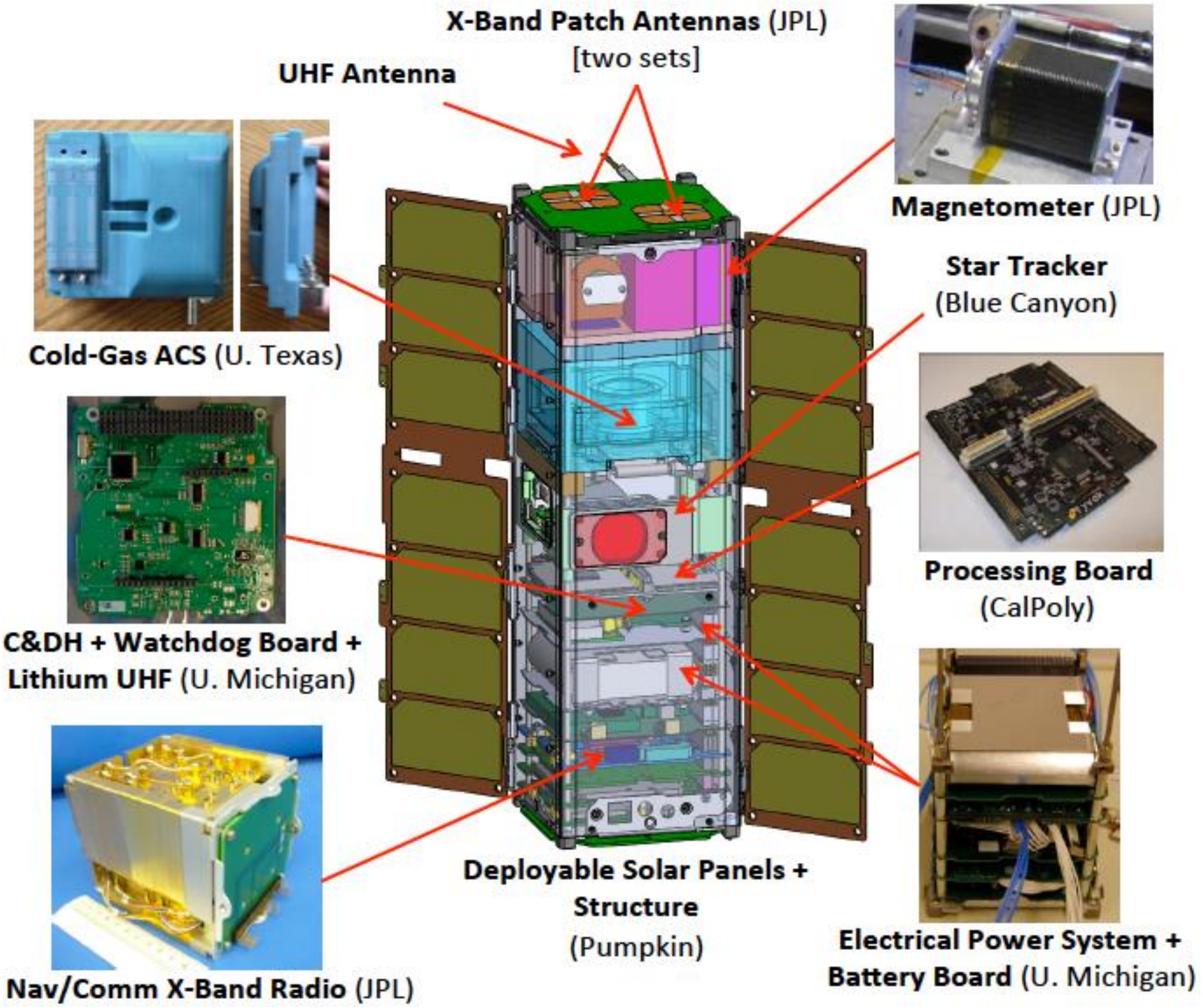

Figure 1. INSPIRE Overview (NASA/JPL)

The INSPIRE probes were completed in 2014 and are currently waiting for a suitable launch opportunity.

2.2. MarCO

Mars Cube One (MarCO) is a NASA/JPL technology demonstrator consisting of one, possibly two, 6U CubeSats that will be co-launched with NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander in March of 2016. InSight is NASA's first mission devoted to understanding the interior structure of the Red Planet. The

MarCO probes will be deployed by the Atlas V upper stage after InSight separates, and will independently fly to Mars. The probes will fly by Mars as InSight lands and are designed to demonstrate the real-time relay of the InSight UHF signal to the DSN antennas on the Earth.

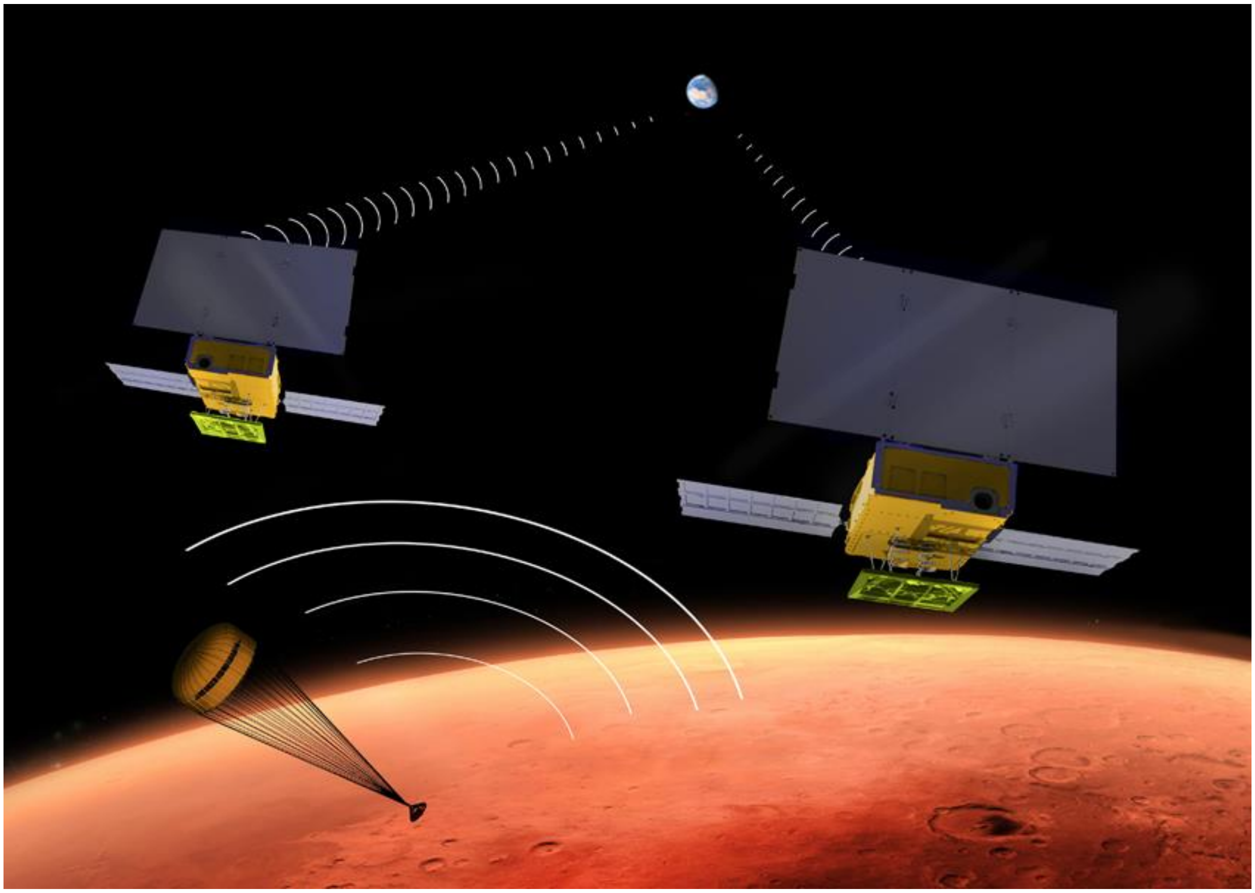

Figure 2. Artist's Concept for MarCO (NASA/JPL)

The MarCO probes will be flown independently of InSight, and success of their demonstration is not needed for InSight mission success. The probes will be equipped with a cold-gas propulsion system for attitude and trajectory control, and with an IRIS v2 radio capable of X-band receive and transmit and of UHF receive. During InSight's Entry, Descent, and Landing (EDL), the MarCO probes will receive and decode the 8 kbps UHF signal generated by InSight and transmit the decoded data to the Earth in X-band. The probes will have a deployable X-band transmit array to ensure that their signal will be strong enough to be received by the DSN 70m antenna in Madrid. Up to five Trajectory Correction Maneuvers (TCMs) are planned in order to remove the injection bias and error, ensure compliance with planetary protection requirements, and achieve the final fly by trajectory to ensure a successful EDL relay, all while maintaining a safe separation distance with respect to InSight and each other.

2.3. Lunar Flashlight

Lunar Flashlight [3] is one of the CubeSats proposed for the EM-1 SLS flight. It is a NASA/JPL, NASA/MSFC, and UCLA collaboration that intends to locate ice deposits in the Moon's permanently shadowed craters. The probe consists of a 6U CubeSat that would shine light on the Moon's surface and use its on-board spectrometer to measure the surface reflection and composition. The probe would acquire lunar orbit and perform a number of passes over the lunar South Pole to accomplish its science objective.

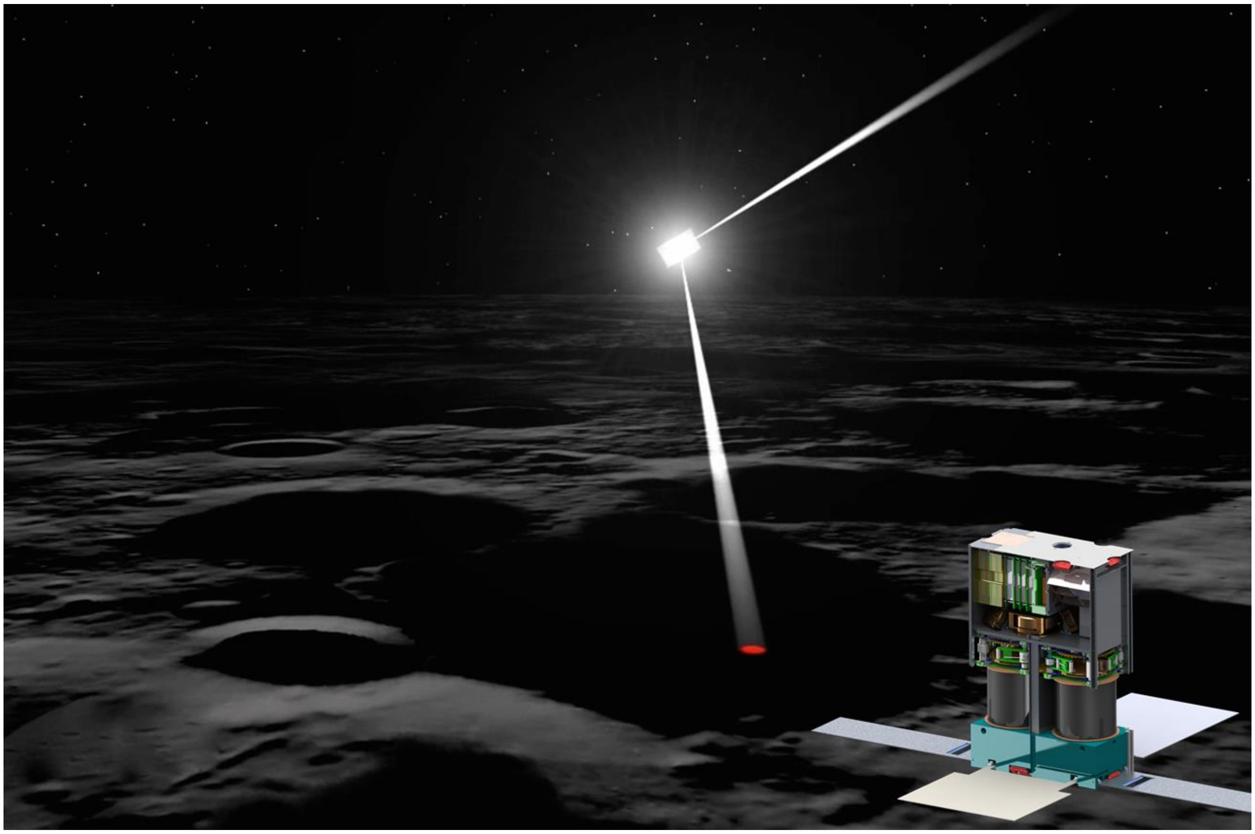

Figure 3. Artist's Concept for Lunar Flashlight (NASA/JPL)

In its current configuration, Lunar Flashlight would be equipped with an 80 m^2 solar sail to propel the probe and to reflect sunlight into permanently shadowed regions of the Moon's surface. The probe would be equipped with an IRIS v2 radio for communications and navigational tracking.

2.4. NEAScout

The Near Earth Asteroid Scout (NEAScout) [4] is a NASA/JPL/MSFC 6U CubeSat also manifested for the EM-1 SLS launch. It intends to be the first CubeSat to reach an asteroid and it would map the asteroid and demonstrate a number of innovative technologies. In its current concept, it is equipped with an 80 m^2 solar sail similar to that in Lunar Flashlight, but instead of maneuvering into a lunar orbit, it would escape from the Earth/Moon system in order to rendezvous with an asteroid for a slow flyby. The probe would also be equipped with and IRIS v2 radio for communications and navigational tracking, and would stay within 1 AU of the Earth due to be able to maintain communications with the DSN. During approach the probe would use an optical camera to assist with navigation relative to the asteroid.

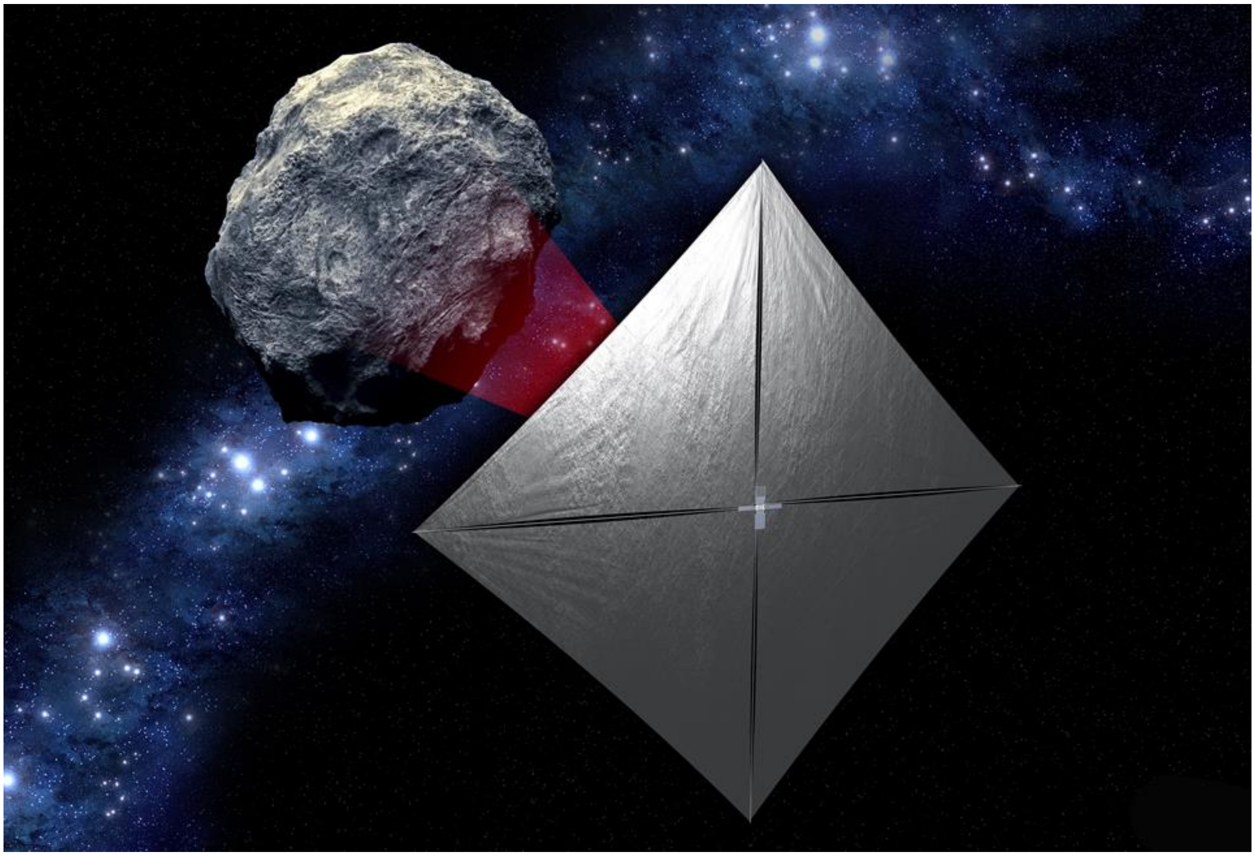

Figure 4. Artist's Concept for NEAScout (NASA/JPL)

2.5. BioSentinel

BioSentinel is a third 6U CubeSat slotted for the EM-1 SLS launch. [5] This NASA/AMES mission has as primary objective to operate a biosensor using a simple organism – yeast – to detect, measure, and correlate the impact of deep space radiation on living organisms over long durations. The probe would fly by the Moon after being deployed from the SLS upper stage and then enter a heliocentric orbit between 0.92 and 0.98 AU.

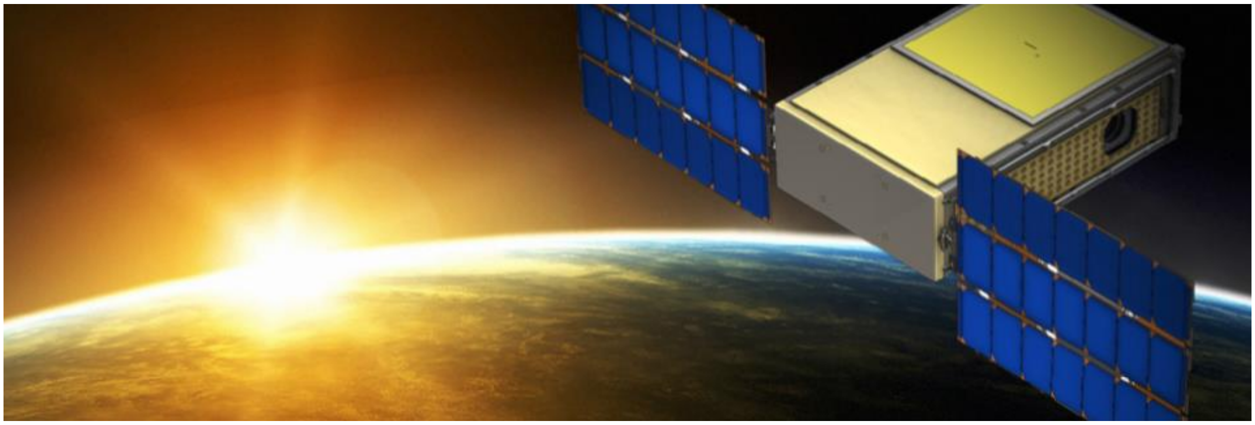

Figure 5. Artist's Concept for BioSentinel (NASA/AMES)

2.6. Other Future Interplanetary CubeSats

In addition to the five NASA interplanetary CubeSat concepts described above, there are other plans to fly CubeSats beyond Earth orbit. The SLS EM-1 mission may carry up to 8 more CubeSats into a trajectory that will fly by the Moon and could reach deep space. NASA has put out a request for proposals for CubeSats to hitch a ride with its proposed Europa mission. [8] If flown, these CubeSats could be carried by the spacecraft and be deployed in the proximity of Europa to carry out their own investigations, and would communicate with the ground through the main Europa mission spacecraft. CubeSats could also be flown along with future NASA Discovery or New Frontiers missions. ESA has also announced that CubeSats could be carried by the Asteroid Impact Mission (AIM), and other space agencies have also shown interest in using CubeSats for deep-space exploration.

3. The Challenges of Deep Space CubeSat Navigation

Flying spacecraft in general is challenging; flying small spacecraft in Earth orbit is even more challenging because of the limitations imposed by the small spacecraft mass and volume. As CubeSats push the boundaries of their capabilities, the challenges become more difficult, and the difficulties are compounded when flying a CubeSat into deep space because it is even more challenging to pack the needed power, communications, and navigation capabilities into such a small spacecraft. Deep-space communications require both a large ground antenna and a communications system in the spacecraft with sufficient receive and transmit gain and transmit power. The small size of CubeSats limits the size of the solar panels, and consequently the power that they can produce, and also the size of the communication antennas.

3.1 Energy Management

The power and energy limitations of CubeSats can make mission operations very different from those of bigger spacecraft. The size of the solar arrays and batteries is going to be smaller than those for a bigger spacecraft, but the space loss will be the same at the same distance. The fact that the CubeSat may be farther from the Sun than 1 AU means that the power that the solar arrays will be able to generate will be further reduced. Because of that, CubeSats may not be able to continuously transmit at the power levels required for interplanetary communication, and the length of tracking passes may be very limited due to energy and thermal constraints. This means that the amount of tracking data to be expected can be greatly reduced when compared with other missions, with just one hour of tracking per day expected in the case of the MarCO mission in proximity to Mars.

The radio system in an interplanetary CubeSat is going to be a very substantial fraction of the mass and power of the spacecraft, and it may be difficult to operate it for long periods of time without it becoming overheated. This radio will be a miniaturized version of the transponder used by other deep space spacecraft that must still perform all the necessary functions, but with a reduced mass and power consumption.

3.2 Propulsion

Many Earth orbiting CubeSats are not equipped with propulsion systems for trajectory control, being allowed to drift after deployment and to naturally decay. Reaching interplanetary targets is going to require adding a propulsion system to the CubeSat. As CubeSats are usually secondary payloads, they are not allowed to use pyrotechnics or hazardous materials, and limits are set on the pressure at which any fluids are kept and on the total chemical energy that they store. Waivers can be requested, but the operator of the primary payload is going to be reluctant to allow anything that may jeopardize or contaminate its own mission. This limits the kinds of propulsion systems that can be used and, consequently, the total velocity change that they can produce.

A number of propulsion systems have been proposed for interplanetary CubeSats. Solar sails are an attractive option because such sails do not involve the storage of hazardous chemicals or pressurized fluids, but its deployment and operation add considerable complexity. MarCO is planning to use a cold gas propulsion system with a capability of 755 Ns, providing in excess of 40 m/s of TCM ΔV, enough for what is needed for a Mars-bound mission. [9] The system uses as propellant R236fa, a commonly used refrigerant and fire suppressant fluid. Electric propulsion is also a very attractive candidate, since it can be inert until the probe is activated, but it also may require a substantial expenditure of energy in order to operate it to provide a substantial ΔV. Chemical propulsion, for example using hydrazine, is also being explored, but it has the disadvantage that it could jeopardize the primary payload. The novelty of all these systems, at least as related to the use on CubeSat missions, make maneuver execution errors difficult to assess and require additional conservatism in the amount of propellant that needs to be carried in order to ensure that the mission can be accomplished successfully.

3.3. Tracking

Many Earth-orbiting CubeSats lack a navigation capability and their operators rely on JSpOC radar tracking and TLEs to know where to find their spacecraft. Other Earth-orbiting CubeSats are equipped with GPS receivers that can provide fairly accurate positioning. Neither of these options are available for deep space CubeSats. Using ground antennas with big apertures and high sensitivity, such as those operated by the DSN, is an attractive option, but it is also costly and ties up expensive resources to support what are supposed to be inexpensive missions. One case in point is the CubeSats to be deployed by the SLS EM-1 mission. They may all want to be tracked by the antennas of the DSN, but two at each complex will be committed to tracking the Orion vehicle in its flight around the Moon and back to Earth, leaving the two or three other antennas in each complex to track both the 11 CubeSats and the rest of the spacecraft supported by the DSN and in view of the complex.

There are a number of times when two or more spacecraft, including CubeSats, are going to be within the beam width of a DSN antenna, so when pointing to one of them, the signal from others can also be received. This can create interference, but it can also be used to track more than one spacecraft simultaneously. An especially interesting case is that of spacecraft separating from the same upper stage. If the relative separation velocity is small, it may only be necessary to locate one of them, likely the primary spacecraft, in order to communicate with the CubeSats that accompany it. This is useful also because the CubeSats may not be able to point and transmit as soon as the primary spacecraft, since restrictions may be imposed on them, or they may need to orient themselves and recharge their batteries before they can start transmitting to the ground.

The DSN is actively pursuing strategies to allow it to more efficiently support small spacecraft [2]. Among the strategies being contemplated are to increase the use of Multiple Spacecraft per Aperture (MSPA), from its current capability of supporting two downlinks at a time to four. This will be useful for the MarCO flight demonstration as it will allow the 70m antenna in Madrid to simultaneously track InSight, NASA's Mars Reconnaissance Orbiter (MRO), and the possible two MarCO probes as Insight approaches and descends to Mars. Another strategy being studied, known as Opportunistic MSPA, is to record the full spectrum slice allocated to deep space communications on a given band, so all the signals originating from spacecraft using that band and within the ground antenna beam width could be processed, either in real time or in post processing.

Another possible method that is being explored is the tracking of CubeSats using optical means. CubeSats in the proximity of the Earth could be painted with or carry retro-reflecting materials so they could be illuminated by a powerful enough ground laser and produce a reflection that could be used to measure the range to the spacecraft or its position against the background of stars.[1] Small spacecraft could also be equipped with a small laser co-boresighted with the high gain communication antenna, so they could be tracked against the star background.[2] CubeSats carrying optical laser communication systems could use them for navigational tracking at the same distances that they will be used for communications. Other CubeSats, such as NEAScout, would use on-board optical cameras to navigate relative to their target body.

One important thing to remember is that the navigation performance requirements for CubeSats need to be commensurate with the schedules and means used to track them. As an example, the MarCO demonstration is planning to use much less tracking than that required by InSight, but the delivery requirement for MarCO is an accuracy in the hundreds of kilometers as it flies by Mars, while for InSight the delivery requirement is just a few kilometers, as the lander spacecraft needs to hit a narrow entry corridor into the atmosphere of the planet. Expecting the same kind of performance and accuracy from a CubeSat as from a main mission would necessitate spending the same level of resources, in terms of tracking means and flight dynamics operations, as required by the bigger mission.

3.4. Planetary Protection

CubeSats are usually built using commercial off-the-shelf components and are assembled in environments that do not necessarily comply with stringent cleanliness requirements. If the CubeSat mission design requires it to come close to a protected solar system body, such as Mars or Europa, planetary protection rules [10] may impose constraints on the way the mission is navigated, so as to minimize the probability of contaminating the protected body. The CubeSats being launched by the SLS EM-1 may also need to comply with the NASA recommendations for

---

[1] Slava Turyshev, personal communication

[2] Micheal Shao, personal communication

lunar missions [11], in particular the protection of the US government artifacts on the lunar surface.

In the case of the MarCO probes, the approach used to comply with NASA planetary protection requirements was to request that they be classified as launch vehicle elements, so they had to comply with a requirement of a probability of impact with Mars of less than 10^{-4} for a period of 50 years after launch. InSight itself, because it is built in a clean environment, only needs to comply with a requirement for probability of impact of 10^{-2} during cruise and approach, and that is calculated using probabilities of spacecraft failure that are combined with the probability of impact after each maneuver. In the case of MarCO, and due to the fact that the processes and components used to build the probes are significantly different from those used by established spacecraft manufactures, it is difficult to assess not only the reliability of some of the parts, but also the reliability of the whole probe once parts from different suppliers are put together. That is why, for MarCO, the probability of impact with Mars requirement needs to be fulfilled for every maneuver design, including the trajectories of the probes after they fly by Mars. That means that every maneuver during cruise has to be biased away from Mars, to avoid both a direct impact and an impact in future close returns. The final flyby target is designed not only to provide good relay geometry, but also to ensure that the probe will not impact Mars if we cannot command it again after the flyby.

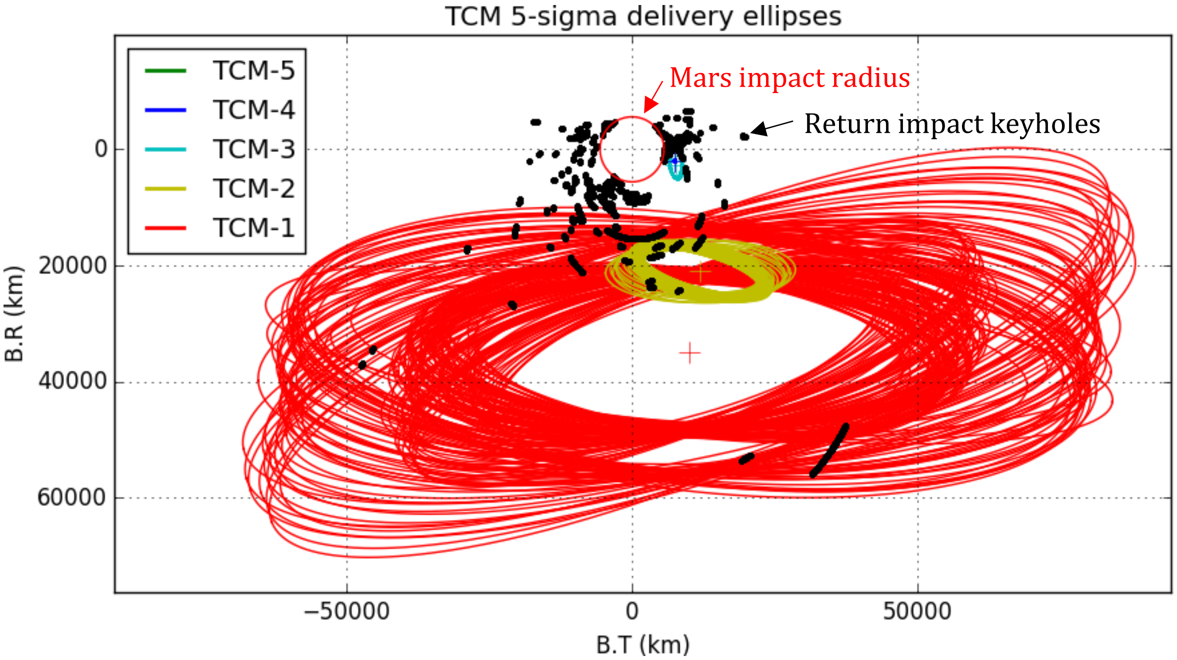

Figure 6. Example of MarCO TCM Targeting

Figures 6 and 7 show an example of the pre-launch analysis performed for the MarCO CubeSats. The figures show TCM delivery ellipses for open, middle and close of every day of the launch period in the B-plane against a map showing the Mars impact disk as a red circle and resonant return keyholes as black dots. The tentative TCM targets are selected to be at least 5-sigma from the Mars impact disk and so that the probability of ending up in a return impact keyhole is smaller than 10^{-4}. The keyholes were determined by scanning a grid in the B-plane, finding the local minimums of closest return distance and searching around those points to find the actual return keyholes. The biased TCM targets increase the size of late maneuvers and the total propellant required for cruise, and also make the delivery errors for the final maneuvers greater than what they could be if all the TCMs could have been targeted to the final flyby target.

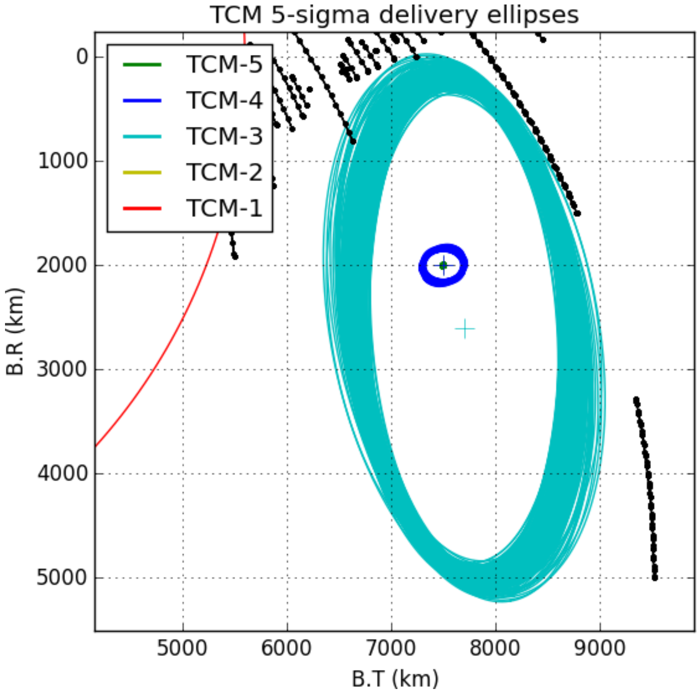

Figure 7. Close-up Example of MarCO TCM Targeting

4. Conclusion

The CubeSat paradigm is a very attractive option for low-cost interplanetary missions, but it presents some specific challenges on top of those already faced by bigger deep-space spacecraft. In particular, we have described the navigation challenges faced by CubeSats in terms of energy management, propulsion, tracking, and planetary protection, but there are also significant challenges in other areas, including thermal management and communications. While CubeSats may be cheaper to build and launch, mission operations may not necessarily be cheaper if the requirements and constraints imposed on the CubeSat mission are similar to those imposed on missions using bigger spacecraft.

5. Acknowledgment

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

6. References

[1] “CubeSat Design Specification”, revision 13, the CubeSat Program, Cal Poly San Luis Obispo, February 2014.

[2] Kar-Ming Cheung et al., “Next-Generation Ground Network Architecture for Communications and Tracking of Interplanetary Smallsats”, IPN Progress Report 42-202, August 2015.

[3] P. Banazadeh, P. Hayne, B. Cohen, and R. Staehle, “Lunar FlashLight: A CubeSat Architecture for Deep Space Exploration” Proceedings of Interplanetary Small Satellite Conference (ISSC), Pasadena, California, 2014.

[4] A. Frick, J. Castillo-Rogez, L. Johnson, and J. Dervan, “NEA Scout: A CubeSat Architecture for Near Earth Easteroid (NEA) Exploration,” Proceedings of Interplanetary Small Satellite Conference (ISSC), Pasadena, California, 2014.

[5] M. Sorgenfrei, and B. Lewis, “BioSentinel: Enabling CubeSat-Scale Biological Research Beyond Low Earth Orbit,” Proceedings of Interplanetary Small Satellite Conference (ISSC), Pasadena, California, 2014.

[6] A. Klesh, J. Baker, J. Castillo-Rogez, L. Halatek, N. Murphy, C. Raymond, et al., “INSPIRE: Interplanetary NanoSpacecraft Pathfinder In Relevant Environment,” 27th Annual AIAA/USU Small Satellite Conference, Logan, Utah, August 2013.

[7] C. Duncan, “Iris for INSPIRE CubeSat Compatible, DSN Compatible Transponder,” 27th Annual AIAA/USU Small Satellite Conference, Logan, Utah, 2013.

[8] JPL Europa CubeSat Concept Study Request for Proposals, RFP SS063014, Solicitation Number: SS-14-05, National Aeronautics and Space Administration, July 2014.

[9] C. Day, “VACCO ChEMS Micro Propulsion Systems”, CubeSat Developers’ Workshop 2015, Cal Poly, San Luis Obispo, April 2015.

[10] NASA, “Planetary Protection Provisions for Robotic Extraterrestrial Missions”, NPR 8020.12D, April 2011.

[11] “NASA’s Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts”, July 2011.