THE OPPORTUNITIES AND CHALLENGES OF GNC ON A EUROPA CUBESAT

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Jupiter's moon Europa is the target of NASA's planned Europa Mission. The mission hopes to provide the most detailed view yet of the surface and subsurface of Europa and answer some fundamental questions, including whether Europa has a liquid-water ocean beneath a thick ice shelf, and if these conditions may harbor life. It is envisioned the multiple flyby mission would be only the first in a series of missions that could culminate into a surface landing mission. NASA JPL has sought proposals for CubeSats that could be carried by the main spacecraft and which would be released during the flybys. A CubeSat could significantly complement the capabilities of the multiple-flyby spacecraft. It could perform high-risk, high-payoff science missions at low altitudes. A CubeSat could provide unique science data that could not be obtained by the mothership by doing a low-altitude flyby and impact mission. A CubeSat could also perform landing site reconnaissance in preparation for a future surface lander mission. All of these capabilities depend on advances in guidance, navigation and control for use in the Jovian system. Three factors make a CubeSat concept challenging, including the high radiation in the vicinity of Europa, the low solar insolation of 50 W/m^2 and extremely low temperatures of -230 ^{o}C. Coupled with these challenges, Europa lacks an atmosphere sufficient for aero-braking. Our concept is focused on having the CubeSat separate from the mothership, 10 hours before a close flyby of Europa lasting 20 minutes. The CubeSat would use its onboard propulsion to attain altitudes of 3 to 12 km above the moon's surface travelling at 4-5 km/s. Using the onboard optical navigation techniques, the CubeSat would navigate along Europa's shadowed surface fractures to obtain detailed images of nearby features at 0.3 to 2 m/pixel. The notional spacecraft has the capacity to sample for and analyze potential plume samples, and this option could be utilized to get first answers about potential plume content. The mission concept culminates with the CubeSat impacting the Europa surface. The artificial impact plume created would be analyzed by the array of instruments onboard the Europa Mission spacecraft for material composition. Advances in GNC are required to handle the unique lighting, low temperature and high velocity conditions of the mission concept. Our early feasibility work shows a development pathway towards advancing the requisite technology towards technical feasibility.

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INTRODUCTION

Enigmatic Europa is an icy moon of Jupiter widely theorized to harbor a liquid ocean underneath a thick 15-25 km ice shell[3,7]. The moon is likely to contain more liquid water than all the Earth's oceans combined. The presence of liquid water raises prospects for finding the building blocks of life. However, liquid water has yet to be found. A few Hubble Space Telescope images suggest existence of water plumes, but this requires further detailed investigation[2].

NASA's Europa Mission would perform 40+ flybys over Europa and obtain the most detailed scientific data yet. The spacecraft would provide an unprecedented view of the icy moon's surface by achieving resolutions of up to 0.5 m/pixel. The multiple-flyby spacecraft would obtain images of fractures on Europa's surface. However, the conditions in the Jupiter system pose major space system engineering challenges. Solar insolation at the Jupiter system is nearly 27-times less than in Earth orbit. The temperature is extremely cold, reaching between -150 ^{o}C to 230 ^{o}C. A third major challenge is the high radiation due to the trapped ionized particles including electrons and protons. The Europa Mission spacecraft has requirement for handling 2 MRad in radiation exposure over a course of 40+ flybys.

All of these challenges push conventional spacecraft engineering technologies to the limits. In 2014, NASA JPL put out an opportunity to propose CubeSats that would hitch a ride aboard the Europa Mission spacecraft and be dropped in the Jupiter system. Our efforts at Arizona State University's Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory led to the design of a 3U, 5 kg CubeSat called Europa Surface and Plume 3d eXplorer (ESP-3dX). ESP-3dX would be a short, focused science mission[5] (Figure 1). ESP-3dX is designed to help address the key Planetary Science Decadal Survey[1] objective of exploring Europa to assess its habitability. Our proposed imaging investigation is specifically focused on the goals of (a) characterizing the ice shell, (b) understanding the formation of surface features (including sites of recent or current activity), (c) identifying and characterizing candidate sites for future *in situ* exploration; and (d) identifying and characterizing the source regions of potential plumes resulting from endogenic activity[2]. ESP-3dX would complement Europa Mission science and provide significant new insight into the liquid ocean hypothesis[3,7].

Figure 1. Artistic view of the Europa Surface and Plume 3d eXplorer (ESP-3dX) CubeSat concept.

ESP-3DX would be separate from the Europa Mission spacecraft on one of its closest passes, skimming 25 km above the moon's surface. The drop-off would occur nine hours earlier, with the CubeSat using its onboard propulsion to achieve an altitude of 3-12 km above Europa's surface. The entire CubeSat mission would last 10 hours and be focused on obtaining the most detailed images of Europa's surface short of landing. The mission would culminate with an impact on the moon's surface that scatters surface ice for analysis by the multiple-flyby spacecraft's suite of sensors. The CubeSat would obtain surface images of up to 0.3 m/pixel and be capable of mapping ridge to regolith scale. These high resolution images would give unprecedented insight into the existence of water plumes, detailed surface topography and candidate landing sites for a future lander mission.

In the follow section, we will present a system overview of the ESP-3dX CubeSat concept, followed by concept of operations, an overview of the Guidance, Navigation and Control challenges, discussion, conclusions and future work.

SYSTEM OVERVIEW

The proposed ESP-3dX is uniquely designed to handle the Jovian system. ESP-3dX is interplanetary CubeSat[4,6] that would work closely with its mothership to perform high-risk, high-reward science exploration. The spacecraft is 3U (34 cm × 10 cm × 10 cm) and has a mass of 5 kg. The mission will operate for 10 hours once deployed from the mothership (Figure 2, 3). The computer, attitude, and power boards utilize Aeroflex Leon 3FT. The primary science instruments onboard include a pair of ThermoScientific CID imagers and Aerospace Corporation's radiation dosimeters. The imagers would need to obtain 0.3 to 0.5 m/pixel images with a ≤ 1 pixel smear over exposure times of < 0.1 msec under the expected low brightness.

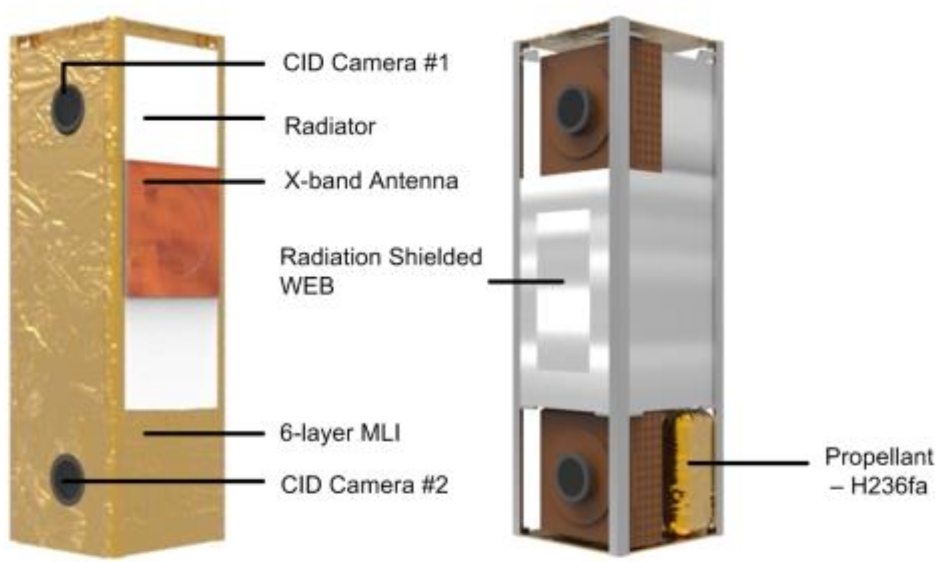

Figure 2: ESP-3dX concept external view with MLI thermal insulation (left) and without (right).

Attitude determination would be performed using a radiation hardened IMU, and CID Imagers for tracking the moon's horizon. In addition, the CID Imagers would be used to track and follow ice fractures. The attitude control system consists of a miniature 3-axis reaction wheel developed by the Aerospace Corporation. The reaction wheels, if required, would be desaturated using the onboard cold-gas propulsion system. The onboard propulsion system would have a total of delta-v of less than 6 m/s and is a cold-gas system developed by Vacco. The propellant would be a refrigerant such as HFC-236fa. The spacecraft, once deployed, operates autonomously following a preplanned trajectory, combined with visual waypoints/goal markers pre-identified by the mission planning team.

The spacecraft would consume an average of 21 W using its onboard lithium-thionyl chloride primary battery for 10 hours. The spacecraft at a minimum would include a two-way radio link with the mothership. The preference is to include a miniaturized JPL IRIS v2 X-band radio that communicates with the mothership at data rates of 2-8 MBps. JPL's X-band transponder also allows for Doppler tracking. Other options for tracking include LIDAR and optical MSRS. The mothership would remain within a 25-50 km vicinity of the CubeSat during its science mission.

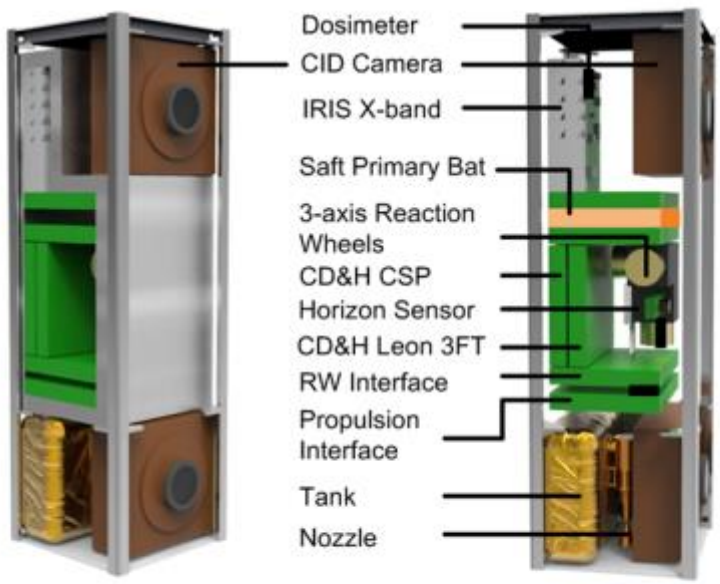

Figure 3: ESP-3dX concept internal view showing the science instruments, GNC devices, spacecraft electronics and propulsion system.

Typical CubeSats are designed for Low Earth Orbit (LEO) operations. The proposed ESP-3dX needs to meet a radiation dose of 2 MRad required of all components on the Europa flyby mission[3]. In addition, the system needs to withstand ambient temperatures of -223°C to -203° C. A third factor is the low solar insolation of 50 W/m^2. The CubeSat minimizes its power demands on Europa multiple-flyby spacecraft during transit; preliminary estimates suggest needing ~7 W continuous.

Typical CubeSats power systems are designed for LEO with photovoltaic power supplies and electronics operating within -40 °C to +60 °C and < 10 kRad TID values that are woefully inadequate for the Jovian environment. ESP-3dX exploits proven strategies from nearly 40 years of deep space spacecraft design to address these challenges. Our studies suggest that photovoltaics are not feasible due to their low power in the Jovian environment; RTGs, while providing high energy density, cannot meet a CubeSat design footprint. Instead, ESP-3dX would use Saft $LiSoCl_2$ primary batteries with their 500 Wh/kg density and heritage on the Mars Pathfinder mission. A 0.5 kg $LiSoCl_2$ battery held at 0° to 40°C could provide nearly 25 W for a 10 hour mission.

Our preliminary studies suggest the feasibility of Al 7075-T73 box for radiation shielding, provided the CubeSat is stored in the mothership's radiation-shield vault. Our preliminary SINDA-based thermal analysis suggests that a warm electronics box using MLI blanket on five faces and one face Silver Oxide radiator would require a heat load of 10-12 W to achieve desired operating temperatures of 0° to 40 °C. Ten watts would come from the operating components, including the computer, power, attitude controller and camera controller boards.

The presented CubeSat design is based on currently available electronics and systems, but requires aggressive miniaturization of electronics, sensors and actuators to meet the high radiation conditions of Europa. The electronics need to be miniaturized by about 50 % to meet the needs of the CubeSat.

CONCEPT OF OPERATIONS

We envision that ESP-3DX would separate from the main Europa spacecraft during one close flyby (~25 km) with a 3.4-3.8 km/s velocity (Figure 4). The CubeSat would be deployed 10 hours earlier using a PPOD at 0.005 m/s, before turning on its cold-gas thrusters to impart a 1.5-5 m/s velocity normal to Europa's surface. The CubeSat then uses its propulsion system retrograde, followed by cruise above Europa. Depending on the needs of the overall mission, the spacecraft could cruise at an altitude of 3-12 km. Galileo mission data shows that the highest peaks do not exceed 1 km. ESP-3dX would follow a fracture and take stereo images of its topography. Navigation would be performed by following a fracture using a combination of visual navigation and pre-set trajectory. The CubeSat's onboard X-band radio and/or the other tracking options, namely optical or LIDAR tracking system would provide real-time position relative to the mothership. However, it should be noted that inter-spacecraft ranging is a new concept and may pose some implementation challenges.

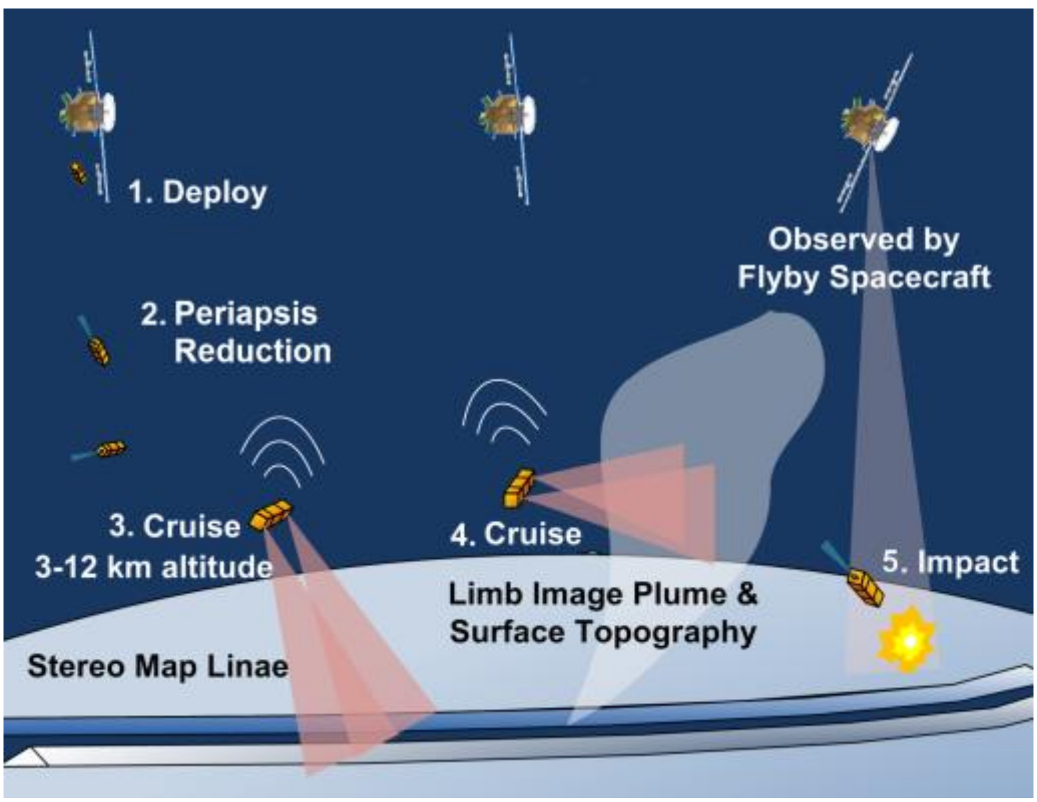

Figure 4: ESP-3dX **Concept of Operations.**

As noted earlier, the thrusters would place ESP-3dX into a steady flyby cruise altitude of 3-12 km to take close-up stereo images of key geologic features and to begin the science operations cruise. This science operations cruise lasts for 15 minutes, sufficient for transmitting 30+ stereo images. A cruise heading would be achieved using space qualified micro-reaction wheels and (possibly) custom star tracking sensor. Orbital imagery obtained during previous Europa flybys can be used to decide when to deploy.

Cruising along the ice fractures increases the probability of encountering a water plume, as the fractures are hypothesized to have been caused by Jupiter's tidal forces. The CubeSat would, if possible, obtain limb images of plumes along the moon's surface. The mission culminates with a 3.4-3.8 km/s surface impact, in view of the mothership's instruments enabling the mothership to obtain additional high-resolution images and new insights into Europa's geology and possibly surface composition.

The option to impact with the moon's surface depends on NASA planetary protection guidelines. Our current baseline design for the CubeSat fully meets planetary protection guidelines to remove any potential Earth-based contamination. However if the CubeSat is unable to meet the planetary protection guidelines, then the CubeSat would avoid impact and instead tumble in the Jovian system.

DISCUSSION

In this paper, we present a CubeSat mission concept to address important Decadal Survey science questions related to habitability[1]. This includes shedding light on the formation of linaes that are so prominent on Europa's surface. The CubeSat concept would likely shed new insight into the liquid ocean hypothesis and complement the instruments aboard the Europa Mission.

A CubeSat is one of the best tools available for attempting to answer difficult science questions in planetary science and astrobiology[5]. In the case of Europa, we have yet to observe the potential plumes in detail. Current data is from the Hubble Space Telescope and there remains deep skepticism about those observations[2]. Such high uncertainty makes the search for water plumes a high-risk science question that may not produce a "positive" outcome. Therefore, it could be more cost-effective to utilize a CubeSat that costs millions of dollars to seek answers to these questions as compared to larger, more complex probe that could cost hundreds of millions or more.

The proposed Europa CubeSat could serve as an important stepping stone towards a future landing mission. The CubeSat is relatively low-cost, and can be utilized to perform high-risk, high-reward science and detailed observation. Such spacecraft could play a critical role in identifying a suitable landing site, particularly the ability to distinguish between benign ice lakes, penitents and glaciers. There are indeed important challenges in building such CubeSats, but they are considerably less than construction of a Europa lander. Furthermore, several CubeSats may be deployed along different regions of Europa, thus providing detailed readings at multiple locations.

The proposed Europa CubeSat, if successful, would have a high science return, providing never-before seen, high-resolution images of Europa's surface, and complementary imagery and science readings from the mothership. The spacecraft would need to operate autonomously and utilize advancements and miniaturization in guidance, navigation and control to navigate towards targets of interest on Europa.

CONCLUSION

A CubeSat could significantly complement the capabilities of the Europa Mission multiple-flyby spacecraft. It could perform high-risk, high-payoff science missions not possible with the mothership alone. A CubeSat could provide unique science data that could not be obtained by the mothership. This CubeSat mission concept can also perform landing site reconnaissance in preparation for a future surface lander mission. All of these capabilities depend on advances in guidance, navigation and control for use in the Jupiter system. Three factors make a CubeSat concept extremely challenging, including the high radiation in the vicinity of Europa, the low solar insolation and the cryogenic temperatures. Current technologies for CubeSat's have been tested in Low Earth Orbit (LEO). Significant new methods of testing and verification will be required to prepare CubeSat technology for use in the Jovian system. However, the outcome from a sustained technology development effort to enable CubeSats ready for the Jovian system could deliver big-payoffs, particularly opening up exploration of the outer solar system to mother-daughter CubeSat architectures and answering important science questions on the origins and conditions required to sustain life.

ACKNOWLEDGMENTS

The authors would like to acknowledge the team members from ASU, particularly Dr. Jim Bell, Dr. Mark Robinson, Dr. Paul Scowen and Dr. Hugh Barnaby. The authors would like to also thank Dr. Alessandra Babuscia of NASA JPL for providing assistance with the communication system. The authors would like to acknowledge our collaborators from the Aerospace Corporation, Draper Laboratory, Paragon, Vacco and NASA JPL. The authors would like to thank John Baker from NASA JPL for creating the Europa CubeSat opportunity and for his encouragement.

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