Europa CubeSat Concept Study

Characterizing Subsurface Oceans with a CubeSat Magnetometer Payload

Feasibility Assessment, June 2015, JPL RSA 1513471

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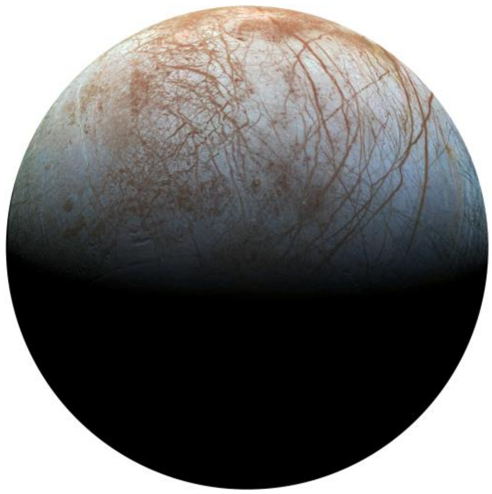
JPL Competitive Request for Proposal (RFP) No. SS06-30-14 for "Europa CubeSat Concept Study"

RSA No. 1513471



Europa CubeSat Concept Study:
Characterizing Subsurface Oceans with a CubeSat Magnetometer Payload
Feasibility Assessment

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on behalf of
The Regents of the University of Michigan

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Front cover image: “Europa Moon” (Guillebot, 2014)
Title page image: “Europa’s Stunning Surface” (Nelson, 2014)

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List of Acronyms

3U	A CubeSat (microsatellite) with dimensions 10 cm x 10 cm x 30 cm
ADCS	Attitude Determination and Control System
APL	Applied Physics Laboratory (Johns Hopkins University)
EPS	Electrical Power System
COTS	Commercial-Off-The-Shelf
GNC	Guidance, Navigation, and Control
IMU	Inertial Measurement Unit
JPL	Jet Propulsion Laboratory, Pasadena California
KPS	Kilometers Per Second
MLI	Multi-Layer Insulation
NRC	National Research Council
PIMS	Plasma Instrument for Magnetic Sounding
RFP	Request For Proposal
RSA	Research Support Agreement
SLS	Space Launch System (NASA launch craft)
S-MLI	Structural Multi-Layer Insulation
TID	Total Ionizing Dose
TRL	Technology Readiness Level
UM	University of Michigan

1 Executive Summary

With vast reserves of water and a global subsurface ocean, Europa serves as a model for potentially-habitable worlds, far outside the so-called '*Goldilocks*' zone. The opportunities to expand the horizons of planetary science and better understand potential environments for extraterrestrial life demand exploration. To this end, at the behest of JPL, the University of Michigan initiated a detailed investigation to determine the feasibility of conducting multi-frequency magnetic induction sounding of Europa's interior structure, utilizing a magnetometer payload aboard a 3U CubeSat.

Designed to accompany the Europa Clipper spacecraft, this CubeSat would complement Europa Clipper's capabilities by providing multi-period dwell times for the highest amplitude inducing fields at Europa enabling high fidelity magnetic induction sounding at multiple frequencies. Conversely, Europa Clipper enables a long dwell magnetic induction sounding mission by providing critical data on the Jovian magnetosphere and plasma conditions upstream of Europa. This symbiotic relationship makes Europa Clipper the perfect vehicle for this mission enabling considerable synergism while enhancing Europa Clipper's capabilities.

This report finds that the proposed science mission and spacecraft operations are technologically feasible using heritage instruments and technologies. Systems analyses, including spacecraft response to the Jovian thermal and radiation environments, indicate it is possible to achieve the minimum operational lifetime required to execute multi-frequency magnetic induction sounding utilizing a fluxgate magnetometer similar to that employed by the Rosetta mission. Analysis of a variety of propulsive maneuvers utilizing cold-gas propulsion systems indicate that none are able to achieve Europa proximity for sufficient duration. Subsystem design concepts for a 3U CubeSat orbiter are presented, showcasing feasibility for all elements except propulsion. The report concludes with an analysis of existing propulsion technologies capable of enabling a CubeSat probe to successfully execute the proposed mission.

2 Introduction

2.1 Commissioning the Europa CubeSat Concept Study

Europa, a world of water and ice, raises questions of profound importance to planetary evolution and the persistence of habitable worlds: How deep is Europa's subsurface ocean? How long can it persist? Is there a direct lithospheric interface with the ocean? What is the resulting salinity? These are the questions posed by the scientific community through the Decadal Survey in "Visions and Voyages for Planetary Science in the Decade 2013 - 2022" (National Academies, 2011).

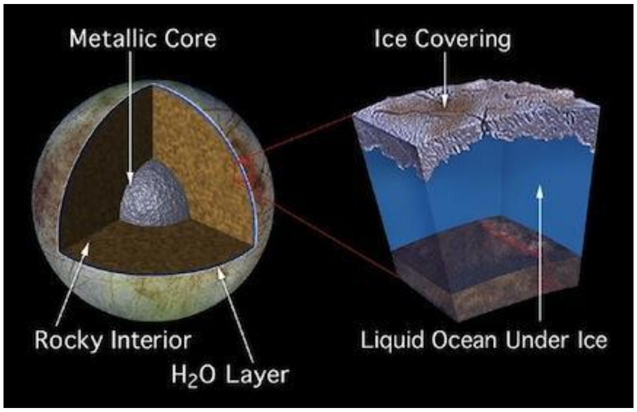

Figure 1. Suspected composition of Europa's interior, hinting at the possible conditions to support life (Scharf, 2013)

In response to JPL Competitive Request for Proposal (RFP) "Europa CubeSat Concept Study"[1] a research group from the University of Michigan (UM) submitted the proposal "Europa Clipper Concept Study: Characterizing Subsurface Oceans with a CubeSat Magnetometer Payload."[2] Selected for award under a Research Support Agreement[3], the UM research group investigated the feasibility of placing a 3U CubeSat with a magnetometer payload in Europa proximity to conduct magnetic induction sounding with the goal of answering the questions above, specifically: How deep is Europa's ocean, and what is its salinity?

This report summarizes the results of that feasibility study and presents the scientific and engineering feasibility of accomplishing the stated mission goals within JPL-imposed constraints and environmental limitations. This report does not explore the cost, scheduling, or management of such a mission. While valuable for an advanced mission concept study, such information would

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[1] See Appendix A for JPL RFP No. SS06-30-14

[2] See Appendix B for full text of original proposal "Europa Clipper Concept Study: Characterizing Subsurface Oceans with a CubeSat Magnetometer Payload"

[3] See Appendix C for Research Support Agreement 1513471

exceed client requirements, and would be difficult to address in a meaningful manner at this stage of project development.

2.2 Structure of this Report

Within this report, an overview of the science mission is presented, followed by the results of a detailed feasibility analysis. The selected mission architecture -- an orbiter -- is presented in terms of top-level requirements, traceability, concept of operations, and an overview of the engineering feasibility of each subsystem. The report concludes with a recommendation to implement the CubeSat mission, including an out-of-scope propulsion system to enable successful orbital insertion and achieve mission success.

2.3 Science Mission Overview

Discovery of a subsurface ocean through induced magnetic fields

The strongest evidence for Europa's subsurface ocean was provided by the Galileo spacecraft which revealed distortions in Jupiter's magnetosphere near Europa consistent with a strong induced magnetic dipole. The existence of a strong induced dipole requires a global spherical conductor and given the strength of the measured field, the most plausible candidate is a global subsurface ocean with conductivity, and therefore salinity, approximating that of Earth's oceans. The existence of this induced field provides an opportunity to employ magnetic induction sounding, a technique for measuring the conductivity and depth of a conductive body subject to a time varying magnetic field. In this instance, the conductive body is Europa's subsurface ocean, and the time varying field is supplied by Jupiter's strong magnetospheric field.

Magnetic Induction Sounding

The technique of magnetic induction sounding relies on Faraday's law of electromagnetic induction $\left(\nabla x E = -\frac{\partial B}{\partial t}\right)$. A time varying magnetic field produces an electric field with non-zero curl that drives eddy currents in conductors, these eddy currents in turn give rise to secondary magnetic fields whose strength and phase relationship to the inducing field are governed by the conductor's depth, thickness, and conductivity. In the case of spherical conductors, the induced fields are dipolar.

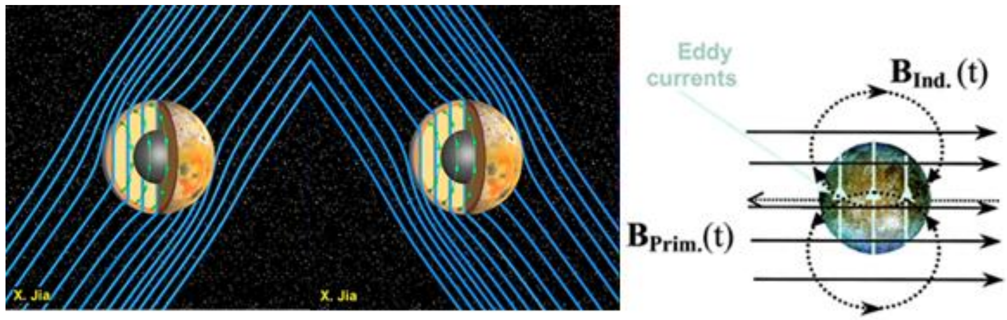


Figure 2: (a) Left: Io as a solid body conductor (Europa responds similarly), with time-varying primary field (blue), time-varying component of the primary field (black solid) & induced field (black dotted) generated by eddy currents (green) (Jia, 2011); and (b) Right: Induced field lies in equatorial plane is elliptically polarized (Khuranna 2002).

Europa is bathed in a variety of time varying fields. The largest of these oscillations is produced by Jupiter's tilted dipole which sweeps across Europa at a synodic frequency of 11.1 hours. As the name suggests, the frequency of this oscillation is the result of both Jupiter's rotational period (~10 hrs) and Europa's prograde orbit about Jupiter (~85 hours). As Europa moves through Jupiter's tilted dipole field, the direction of the primary field rotates in the Europa's body frame about Europa's spin axis (pictured in Figure 2). This produces an induced dipole whose moment co-rotates with the primary field, antiparallel to the time-varying component of the primary field.

A second major field oscillation, though substantially smaller in amplitude, arises from Europa's orbital eccentricity. As Europa moves along its orbit, its separation distance from Jupiter increases and decreases periodically, causing Europa to experience a time varying field with constant direction but varying strength, primarily along its spin axis at Europa's orbital period (~85 hrs). This induces a dipole whose moment is aligned with Europa's spin axis but periodically varies in strength in response to the temporal field gradient. While Europa is exposed to several additional time varying fields, those described above are of primary interest given their magnitude.

Multi-Frequency Induction Sounding of Europa's Subsurface Ocean

The magnetic field observations provided by Galileo, like those that will be provided by Europa Clipper, are limited in their capacity to support useful induction sounding by the short duration of observations made during a typical flyby. Time series taken over the course of minutes cannot be used to effectively characterize signals with periods from 10 to 100 hours. Furthermore, observations of a single frequency cannot be inverted to uniquely determine both the conductivity and thickness of the ocean independently. Nevertheless, if both synodic and orbital frequencies are observed for an extended period, for example two complete periods of the orbital signal (~170 hrs), the data can be used to characterize the product of conductivity and thickness independently for each frequency. This data can then be cross referenced to determine conductivity and thickness uniquely.

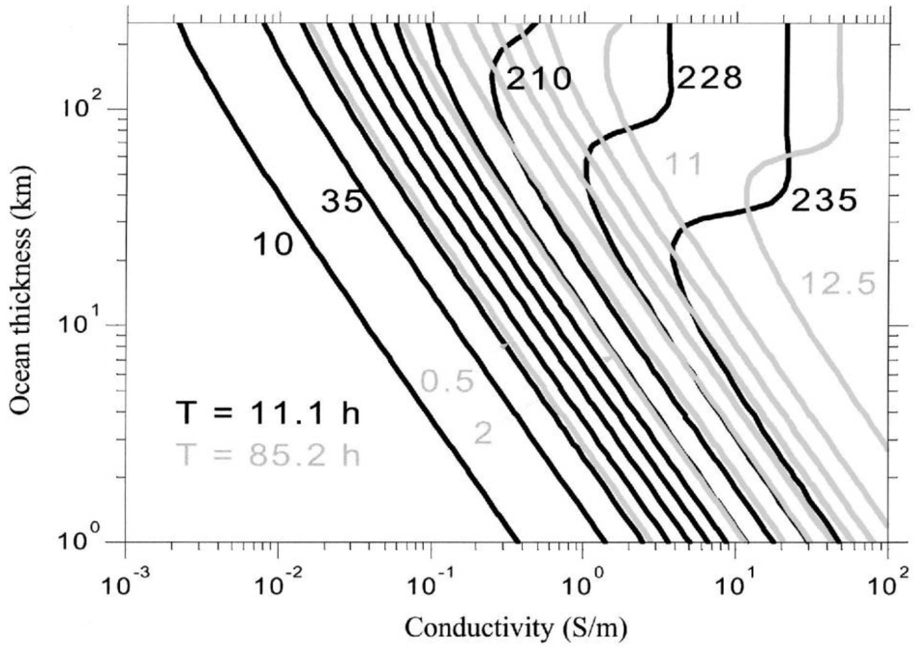


Figure 3: Contours of induced field generated by two separate frequencies of changing magnetic field (dB/dt). 11.1 hr synodic frequency in black and 85.2 hr orbital period in silver (Khurana 2002)

By plotting the amplitude and phase lag of each induced dipole, a contour plot can be created that highlights where these two frequencies agree. For example, if the CubeSat magnetometer detects an induced dipole amplitude of 235 nT at the 11.1 hr period and an amplitude of 11 nT at the 85.2 hr period, the intersection of these inductive responses can be located in Figure 6; the intersection defining the conductivity and thickness of Europa's subsurface ocean. This is the goal for which this feasibility study has been developed. In order to achieve this science goal, specific objectives must be met. These objectives are listed below.

2.4 Science Mission Objectives

The following mission objectives enable multi-frequency induction sounding through measurement of Europa's magnetic environment and are critical to uniquely determining the depth, thickness, and salinity of Europa's subsurface ocean.

Close Proximity: Remain within one Europa radius (1,560 km) of the surface to detect the induced dipoles, whose field strength is inversely proportional to the cube of the radial distance, against the background noise.

Mission Duration: Remain operational for at least two 85.2 hour periods (7.1 days) plus additional time required for subsequent comms window with Europa Clipper to ensure accurate characterization of field oscillations and guarantee the communication of the data.

Payload: Operate a magnetometer capable of resolving 0.1 nT magnetic fields at 0.1 Hz with position and attitude determination suite for the duration of the science mission, and store data for transmission to Europa Clipper.

Coordinated Observation: Coordinate observations of Europa's induced magnetic dipole with those of the Jovian magnetosphere and plasma sheet made by Europa Clipper to ensure accurate modeling of inducing fields and plasma interaction fields.

Communications: Communicate data to Europa Clipper for retransmission to Earth.

2.5 Traceability Matrix

Mission Goals and Objectives				Scientific Measurement Requirements		
Science Alignment Goals (Decadal Survey)	Europa Clipper Mission Goals	Europa CubeSat Mission Objectives	Observables	Measurement Requirements	Instruments	Data Product
What is the thickness of Europa's outer ice shell and the depth of its ocean?	Europa's Ice Shell: characterize the ice shell and any subsurface water including their heterogeneity, and the nature of surface-ice-ocean exchange.	Measure the magnetic induction signals produced by Europa as a result of both Jupiter's rotation and Europa's orbit	Magnetic field strength at spacecraft location	Measure fields of absolute magnitude 0 - 1000 nT with field strength resolution of .1 nT	Magnetometer	Chronologically ordered B-field vectors with timestamp
			Orientation of the magnetic field relative to spacecraft	Measure field orientation relative to magnetometer to within 1 deg	Magnetometer	
			Spacecraft position relative to the Jovian system	Measure spacecraft position to within 100 km	Thermopiles, Photodiodes, IMU w/ Magnetometer	Chronologically ordered position and attitude quaternion with timestamp
What is the magnitude of Europa's tidal dissipation, and how is it partitioned between the silicate interior and the ice shell?			Spacecraft attitude relative to the Jovian system	Measure spacecraft attitude relative to Europa to within 1 deg	Thermopiles, Photodiodes, IMU w/ Magnetometer	
			Time of measurement relative to previous measurements	Measure spacecraft time from deployment to better than 1 uS	Timer	Timestamp for B-field measurements and navigation

2.6 Science Mission Feasibility

Despite the straight-forward conceptual nature of the science described in the preceding sections, a number of important questions remain regarding whether the data gathered by the proposed CubeSat mission, once returned to Earth, could actually produce the desired information and achieve the science goals. Each of these questions is laid out below with a summary answer.

Can the constant and oscillating components of Jupiter's magnetospheric field be determined and subtracted from the magnetic field data set?

- Yes, observation of the Jovian magnetosphere provided by Europa Clipper in Europa's near and far field will provide the necessary data to characterize the background Jovian field at Europa's orbit.

Can the fields of interest be distinguished from plasma interaction fields?

- Yes, provided data taken within one Europa radius ensuring high signal strength and upstream plasma characterization by Europa Clipper, the plasma interaction fields can be quantitatively characterized through numerical modeling (e.g., magnetohydrodynamic models) of Europa's plasma interaction.

Can the eccentricity induced dipole (85.2 hr) be distinguished from the synodic dipole (11.1 hr)?

- Yes, using geomagnetic induction modeling techniques employed by Seufert et al. (after Parkinson 1983) a parameter space search over conductivity and thickness can be carried out using Jovian magnetospheric data to provide a field configuration match.

Do instruments exist with appropriate field strength resolution?

- Yes, recently deployed instruments such as the RPC-MAG flown by Rosetta and Deep Space 1 have more than sufficient field strength resolution to accurately characterize the induced fields at Europa.

For each of these questions, the answer is affirmative. The science goals can be met with the data set acquired by the proposed mission.

2.7 Complementary and Synergistic Observations

Coordinated observation with the Europa Clipper spacecraft, the fourth mission objective above, is crucial to mission success. Three values in particular are key and can only be observed by Europa Clipper: crustal ice depth; magnitude, direction and variability of the Jovian magnetosphere at Europa; and the magnitude and variability of magnetic fields produced by the Jovian plasma sheet. Measurements of crustal ice depth provide an upper boundary for the solution space defined by the induction sounding measurements while characterization of the Jovian magnetic field and plasma sheet allows for clear identification of Europa's induction signature against the magnetic background.

Measurement of crustal ice depth is planned for Europa Clipper's Ice Penetrating Radar. Characterization of the Jovian magnetic field and plasma sheet can be accomplished by Clipper, before or after a pass, while it is farther from Europa. In addition to characterizing the ambient Jovian environment, Magnetometer data from Clipper while it is in close proximity offer important applications. The comparison of data taken by Clipper's ICEMAG (Interior Characterization of Europa using MAGnetomerty) and orbiting CubeSat magnetometer, may be used to cross-verify each other, further validating each unique instrument.

An additional magnetometer in the vicinity of Europa will increase potential for other types of scientific discovery, like that of Cassini. Cassini's magnetometer detected oscillations created by cyclotron motion of ionized water molecules, paving the way for discovery of Enceladus' plumes (Dougherty et al., 2006). Similar magnetic oscillations could be discovered near Europa, by either CubeSat magnetometer or Europa Clipper's PIMS, indicating plume activity or atmospheric pickup ions. The synergistic operation of both CubeSat and Europa Clipper offer distinct advantages and broaden the possibilities for scientific discovery.

2.8 Study Objectives

The preceding discussion of the proposed science mission, its feasibility and benefits, motivates the four main objectives of the technical feasibility investigation as presented in the original proposal. These objectives are listed below and are addressed in detail in the Results section of this report.

1. Determine the feasibility of flying a 3U CubeSat close enough to Europa for a sufficient duration to collect the required magnetometer data either by orbiting Europa or remaining in Jupiter orbit synchronous to Europa.

2. Determine if it is possible for a CubeSat to survive the harsh Jovian environment long enough to achieve proposed mission objectives by investigating required radiation shielding and thermal management.

3. Define the requirements for a magnetometer payload to be flown by a 3U CubeSat in Europa orbit and identify plausible candidate instruments. If volume and mass allow, determine the type and nature of additional instrumentation that might reasonably be flown including possibly a dosimeter and/ or ion neutral mass spectrometer.

4. The fourth objective was dependent on the outcomes of objectives one and two:

    a) In the event that objectives one and two yield feasible results, objective four will be to refine a mission concept to accomplish the primary science goal while adhering to design constraints and Europa Clipper requirements

    b) If either objectives one or two yield an infeasible result, objective four will be to identify specific areas of research and technology development necessary to enable future CubeSat missions to Europa.

Objectives one through three each yielded feasible and highly promising results. Development of an associated mission concept, consistent with objective four, lead to selection of an orbiter as the only mission architecture suitable to the science requirements which presented substantial engineering feasibility.

It was determined that the propulsion requirements of such an orbiter violate the mission constraints provided by JPL. Specifically, no cold gas propulsion system, in use or under development, can provide the multi-kilometer-per-second delta-V required to inject an object of CubeSat mass into Europa orbit from Europa Clipper. Modifications to the mission constraints required to enable this mission are discussed and technologies needing further development are identified. These results and the resulting mission concept are presented herein.

3 Results

3.1 Study Objective 1: Achieving Europa Proximity

Determine the feasibility of flying a 3U CubeSat close enough to Europa for a sufficient duration to collect the required magnetometer data either by orbiting Europa or remaining in Jupiter orbit synchronous to Europa.

For the purposes of this study, Europa proximity is defined as a region extending from several meters below the surface up to an altitude of 1560 km above the surface (one Europa radius). This range ensures access to a region of Europa's induced dipole in which the lower frequency component has sufficient amplitude to be accurately measured.

3.1.1 Candidate Mission Architectures

Several methods, including landers, impactors, orbiters and flybys were examined. Ultimately, it was determined that the most effective method to achieve the science proximity requirements was through direct orbital insertion. The results of each method are as follows.

3.1.1.1 Lander

Evaluation of a surface mission began with a basic analysis of delta-V required to achieve sub-kilometer per second velocities relative to Europa. Projected relative velocities between Europa and the Europa Clipper spacecraft at closest approach are on the order of 4.5 kps. A propulsion system capable of canceling this relative velocity at altitude would still leave the spacecraft with ~0.2 kps relative velocity at touch-down due to gravitational acceleration. A survey of available propulsion systems appropriate for a 3U CubeSat, with respect to mass and volume, yielded no options capable of the minimally required 4.5 kps delta-V. A best case analysis revealed a maximum achievable delta-V of 10-20 meters per second utilizing existing cold-gas propulsion systems. Therefore, this report finds that soft landing for a 3U CubeSat launched from Europa Clipper is not feasible using existing technologies.

3.1.1.2 Impactor

A second surface mission concept involved an impactor, designed to embed itself in Europa's icy crust. This mission concept was also ruled out on the basis that the delta-V required to achieve survivable impact velocities, less than 1 kps, remains unachievable. Additionally, because the impactor concept requires impact survival and subsurface operation, it substantially increases the complexity of the proposed mission with respect to communication, structural integrity and thermal management.

3.1.1.3 Flyby Mission

After ruling out landers and impactors, flyby concepts were investigated. Because Europa Clipper is essentially a multi-flyby mission, a single pass flyby at velocities similar to that of Europa Clipper would not yield data with any substantial merits beyond what Europa Clipper is able to produce. To address this shortcoming, a rapid remeasurement flyby configuration using multiple spacecraft was considered. Designed to be dropped off sequentially in a *string of pearls* configuration, these spacecraft would provide a synthetic dwell time much greater than that achieved by a single spacecraft during a single pass. This architecture involved the use of three 1U CubeSats spaced evenly behind Europa Clipper to provide sequential coverage of Europa's magnetic induction signal. It was determined that to accomplish this, the furthest 1U craft would need to pass by Europa a minimum of 5.5 hours before or after Clipper. This would provide coverage of one half period of the highest frequency component of Europa's magnetic induction signal, and .06 periods of the next highest frequency component.

To test the feasibility of this concept, deployment from Europa Clipper was modeled at 1 meter per second and each 1U CubeSat was assumed to have a maximum lifetime of 2 weeks (14 days). To achieve a 5.5 hour separation with respect to Europa with a 4.5 kps relative velocity requires a spatial separation of approximately 90,000 kilometers. This in turn requires deployment of the furthest 1U craft 90,000,000 seconds (almost three years) in advance. Dropping the relative velocity to 4 kps has little effect requiring over 2.5 years advance separation. In the assumed 14 day survival time, an effective separation of only 268 seconds is achievable. Given that this is over five orders of magnitude less than the required separation for completion of our science objectives, this mission concept is deemed infeasible.

3.1.1.4 Orbiter

An orbital mission provides the possibility of long duration proximity while mitigating some of the delta-V requirements of a lander and the design requirements of an impactor. The difficulty of achieving multiple kilometer-per-second delta-V, however, led to analysis of two maneuvers to assist orbital insertion: Ganymede gravity assist and Jovian aerocapture. The results of these analyses are presented below followed by analysis of direct orbital insertion. In each case, achievable delta-V is substantially lower than the approximately 3 kps required for orbital insertion. It is, nevertheless, the conclusion of this study that a direct insertion orbiter; despite requiring mass, volume and propulsive methods in violation of mission constraints; is the most feasible option for achieving Europa proximity for the required duration.

3.1.1.5 Gravity Assist

Analysis of Clipper's model orbital data reveals multiple close approaches to Ganymede making it the most feasible target for performing a gravity assist maneuver. Clipper approaches Ganymede on four separate occasions early in the mission. This presents an opportunity to deploy a CubeSat onto a trajectory that would allow for a gravity assist maneuver using Ganymede to reduce the CubeSat's velocity relative to Europa. Further analysis of Clipper's trajectory, shows that Clipper already takes full advantage of most of the available delta-V available during each of these passes, all within 1000 km of Ganymede's surface.

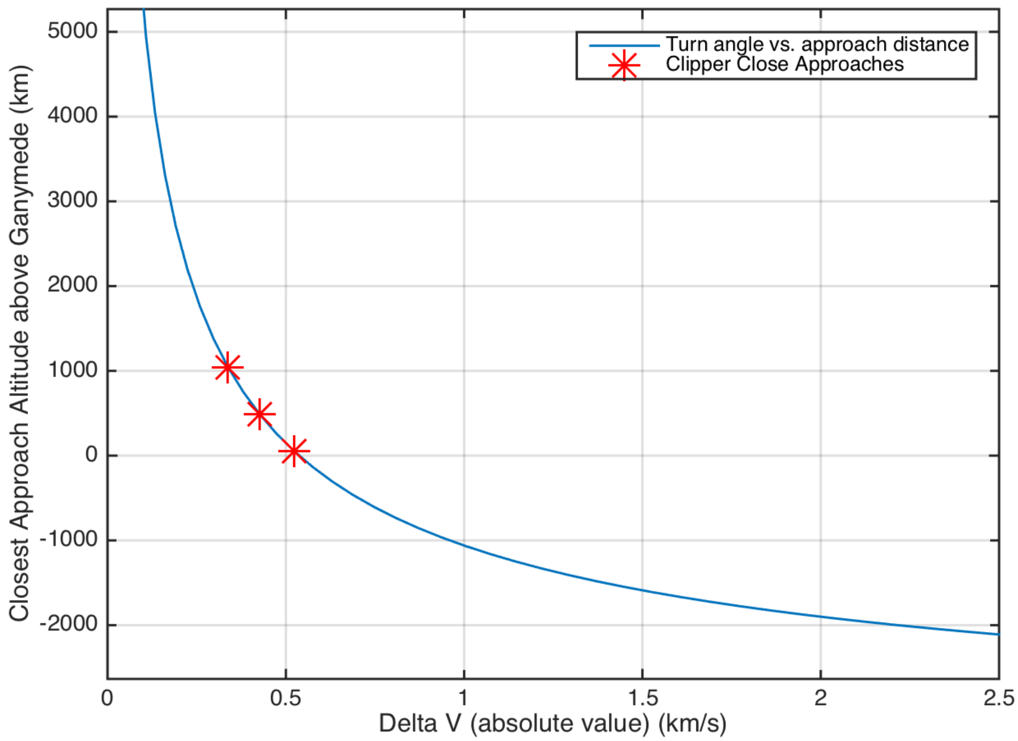


Figure 4. Plot shows delta-V available from a gravity assist maneuver at Ganymede as a function of the closest approach altitude. Marked on the plot are the four altitudes at which the Clipper spacecraft passes by Ganymede; note that two of the passes have the same altitude, so there are only three distinct points labeled on the plot.

If a CubeSat were deployed such that it passed closer to Ganymede's surface, it would gain more delta-V from the maneuver than Clipper. However, our analysis showed that the available additional delta-V from such a trajectory, during a single pass, was less than 0.2 kps, significantly less than the ~3 kps required for Europa capture. Attempting multiple sequential gravity assist maneuvers is infeasible due to the anticipated lifetime of the CubeSat and the lack of on-board propulsive capability. Finally, the inability to intercept the trajectory of any object not already in Clipper's orbital path makes gravity assist maneuvers around all such objects infeasible. Therefore, achieving sufficient delta-V for orbital insertion through a gravity assist maneuver is deemed infeasible.

3.1.1.6 Aerocapture

Investigation of aerocapture began with the assumption of a single pass high delta-V maneuver. This assumption was made because it is difficult to design a CubeSat capable of surviving the long duration mission necessary to perform multiple passes of Jupiter or its satellites. This is unusual given that most instances of aerocapture slow the spacecraft over many passes to reduce thermal and mechanical stresses. The reasons for the more common approach were highlighted by analysis of the heating experienced by the craft during a single pass aerocapture maneuver. Modeling of the heating experienced by the craft in the Jovian atmosphere, utilizing data provided by the Galileo probe, suggests the CubeSat would reach a temperature of approximately 5000 K.

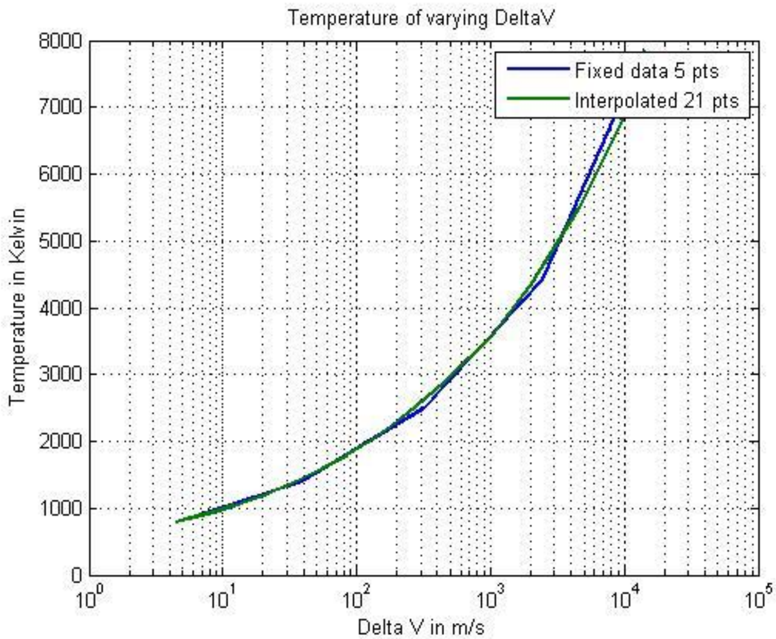


Figure 5. Spacecraft surface temperature during an aerocapture maneuver as a function of the delta-V gained from the maneuver.

This level of heating would require inclusion of an ablative heat shield, which would greatly exceed mass and volume constraints. Additionally, to achieve a trajectory that intercepts the Jovian atmosphere, the CubeSat would have to be deployed from Clipper many weeks in advance. This timeline exceeds the maximum expected lifetime of the CubeSat. Given these unavoidable obstacles, an aerocapture maneuver for orbital insertion is also deemed infeasible.

3.1.2 Direct Orbital Insertion

With aerocapture and gravity assist having been ruled out as feasible methods of achieving orbit, direct orbital insertion analysis commenced with the goal of identifying minimum success requirements. During its mission, Europa Clipper will perform approximately 45 flybys of Europa. In order to optimize its lifetime, Clipper will avoid the regions of the Jovian system where the radiation environment is most intense, while ensuring global coverage of Europa through varying pass inclinations. Each of these passes provide an opportunity to deploy an orbiter, however, the closer the pass, the lower the delta-V required to achieve orbit. Maximum allowable relative velocity, and therefore minimum required delta-V, can be bounded by calculation of circular orbital velocity at the surface of Europa, approximately 1.4 kps. This requires a minimum delta-V of approximately 3 kps. Using Europa Clipper's projected positions and velocities, released by JPL as SPICE data, possible orbits and required delta-Vs have been modeled in Matlab and STK.

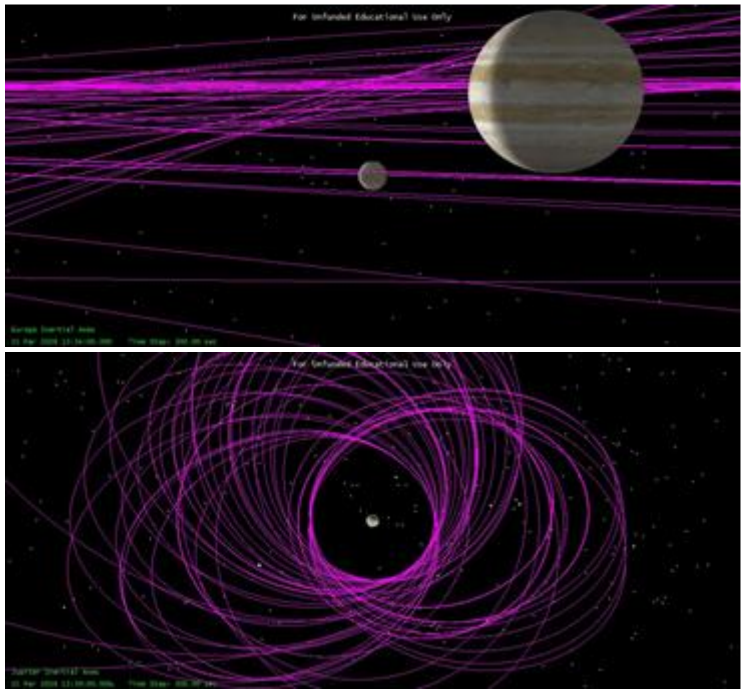


Figure 6. Trajectory of Europa Clipper in Jupiter-centric reference frame

The orbital data provided by JPL includes Clipper's position and velocity in Europa's inertial frame with five minute resolution. For the purposes of CubeSat deployment modeling, the distance from the Clipper spacecraft to Europa's center was plotted and those fly-bys under 1000 km were flagged as potential deployment opportunities. Forty-one solutions were identified with relative velocities ranging from 4.1 kps to 4.6 kps yielding a minimum required delta-V of approximately 3 kps.

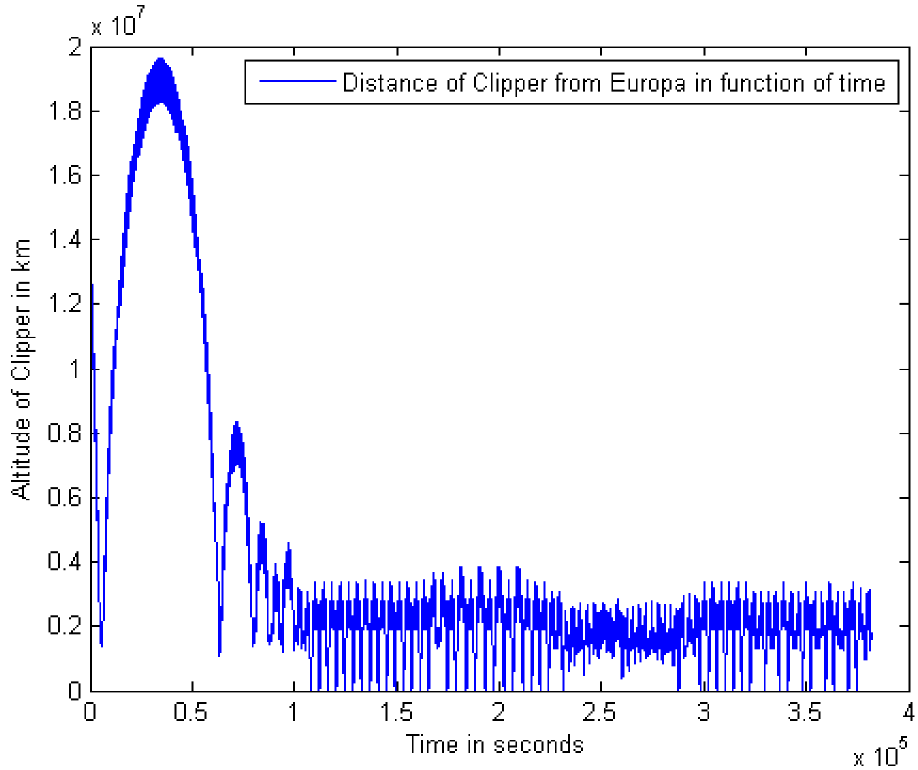


Figure 7. Distance of Clipper to the surface of Europa (km) with time. Approximately 41 flybys of the Moon by Clipper are identifiable.

In addition to circular orbits, highly elliptical orbits were considered, but none were found to be achievable. Because the maximum orbital velocity is achieved during perigee, a conservative assumption was made that Clipper is at perigee during the fly-by and therefore at maximum velocity for the considered orbit. The eccentricities of achievable orbits were computed assuming a delta-V of 20 m/s, a representative maximum value for a cold gas propulsion systems.

Table 1. Achievable eccentricities for first 10 flybys (assuming delta-V of 20 m/s)

FLYBYS (distance < 2700 km)										
Flyby	1	2	3	4	5	6	7	8	9	10
Altitude (km)	7.56E+02	2.61E+02	1.59E+02	1.36E+02	7.15E+01	4.82E+01	1.47E+02	9.80E+01	7.77E+01	6.19E+01
Inclinaison (deg)	1.43E+02	1.12E+02	1.38E+02	1.63E+02	1.71E+02	1.44E+02	1.16E+02	1.05E+02	1.26E+02	1.34E+02
r (m)	2.32E+06	1.83E+06	1.72E+06	1.70E+06	1.64E+06	1.61E+06	1.71E+06	1.66E+06	1.64E+06	1.63E+06
Velocity Clipper in Europa inertial frame (km/s)	4.33E+00	4.36E+00	4.40E+00	4.42E+00	4.43E+00	4.43E+00	4.38E+00	4.43E+00	4.45E+00	4.47E+00
Velocity Clipper in Europa inertial frame (m/s)	4.33E+03	4.36E+03	4.40E+03	4.42E+03	4.43E+03	4.43E+03	4.38E+03	4.43E+03	4.45E+03	4.47E+03
Velocity needed to be on circular orbit around Europa at r (m/s)	1.17E+03	1.32E+03	1.36E+03	1.37E+03	1.40E+03	1.41E+03	1.37E+03	1.39E+03	1.40E+03	1.40E+03
Delta V for achieving circular orbit (m/s)	3.16E+03	3.03E+03	3.04E+03	3.04E+03	3.04E+03	3.02E+03	3.02E+03	3.04E+03	3.06E+03	3.06E+03
Maximum eccentricity for elliptical or hyperbolic orbit considering Delta V = 20m/s	1.25E+01	9.71E+00	9.33E+00	9.26E+00	8.96E+00	8.81E+00	9.18E+00	9.11E+00	9.07E+00	9.04E+00
Time with the next flyby (days)	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.45E+01	1.42E+01	1.42E+01	1.42E+01

All of the eccentricities are of values greater than 1, which indicate hyperbolic orbits. Therefore achieving Europa orbit is not possible without the use of an alternative propulsion mechanism such as an intermediary propulsion module. However, if such an intermediary propulsion module can provide a delta-V on the order of 3 kps, then achieving elliptical or even circular orbits is feasible.

Assuming a propulsion system capable of providing the necessary delta-V to inject a CubeSat into circular orbit, for example, a hydrazine thruster, the orbital parameters associated with each of the identified fly-bys was computed and the first nine entries are presented Table 1. The delta-V values needed to achieve circular orbit vary from 2.7 to 3.1 kps. The achievable altitude and inclinations as well as the required delta-V for all 41 selected fly-bys are presented in Figures 8-10 below.

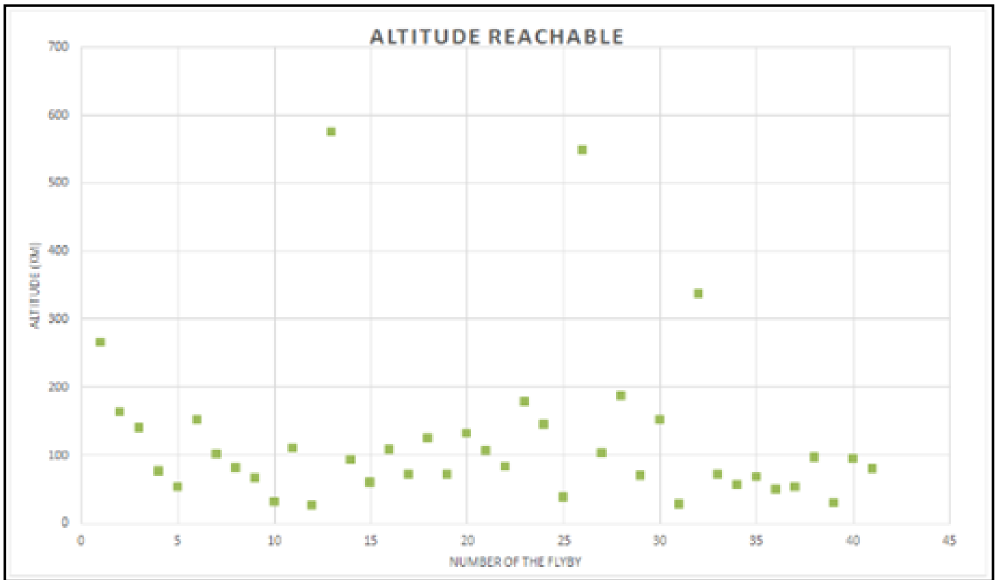


Figure 8. Altitudes reachable for each flyby

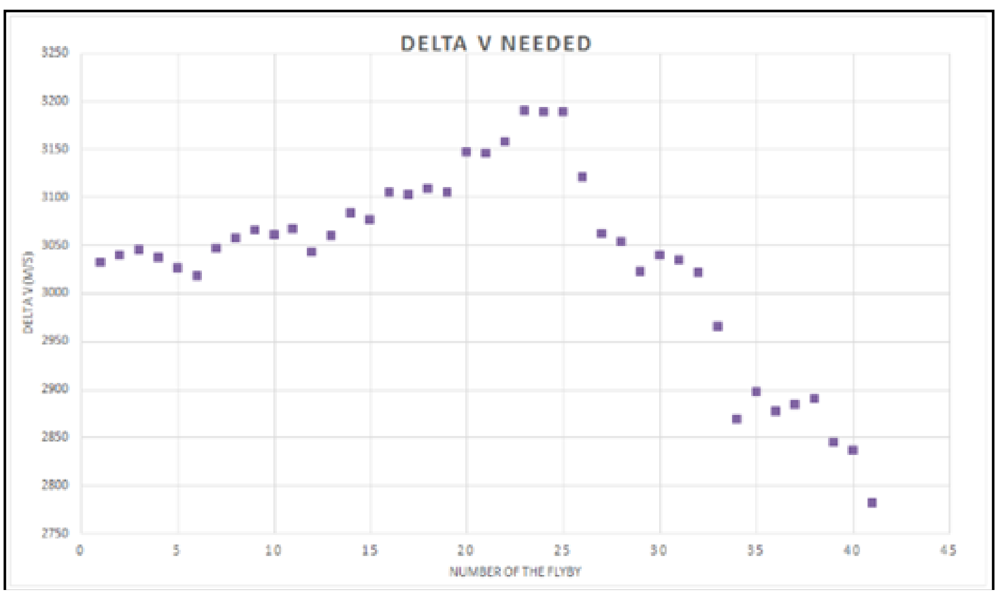


Figure 9. Delta-V needed to achieve circular orbit for each flyby.

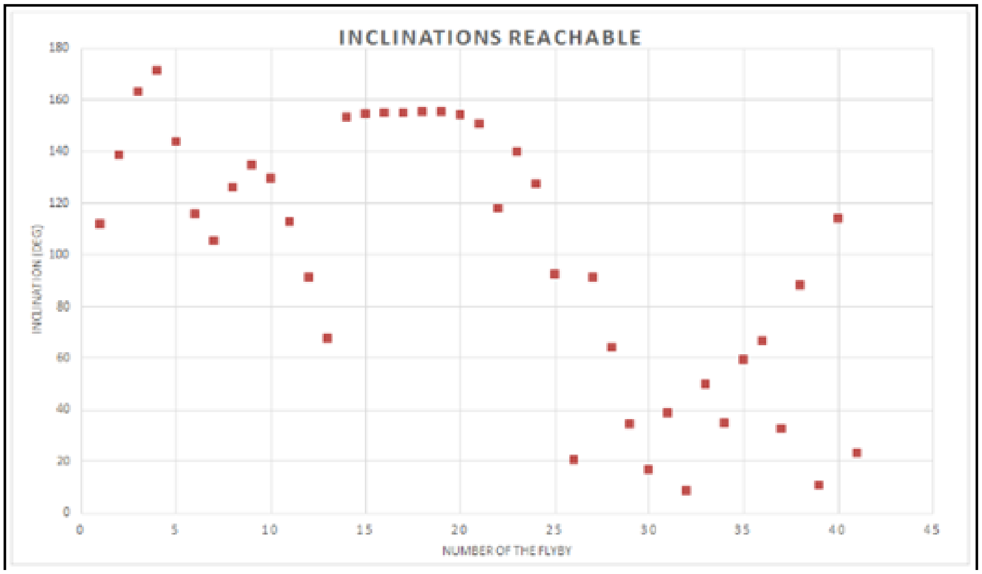


Figure 10. Inclination reachable for each fly-by.

Direct orbital insertion by propulsive delta-V maneuver represents the simplest, lowest risk option for achieving orbit. As is often the case, however, the propulsive delta-V needed to achieve orbit requires a prohibitive propellant mass and, in this case, an out-of-scope propulsion system. Such propulsion systems are discussed later in section 3.4.4.10. Nevertheless, extending the mission scope to allow for successful orbital insertion presents the best opportunity to achieve the mission goals and substantially enhance the Europa Clipper mission.

3.2 Study Objective 2: Surviving the Europa Environment

Determine if it is possible for a CubeSat to survive the harsh Jovian environment long enough to achieve proposed mission objectives by investigating required radiation shielding and thermal management.

To complete its mission, the CubeSat will need to remain within one radius of Europa's surface for at least 173 hours. In order to transmit data to Europa Clipper, the CubeSat will need to survive for approximately 15 days, an additional 187 hours. Analyses of both thermal and radiation environmental responses reveal that a 3U CubeSat can survive the journey to Europa carried aboard Clipper with only modest protection and endure the Europa orbital environment for sufficient time to complete the mission.

3.2.1 Thermal Analysis

The thermal environment in Europa orbit presents a particularly difficult design challenge given the required mission duration. With severely reduced levels of solar irradiance as compared with that experienced on Earth orbit and low levels of infrared radiation (IR) emitted by Europa and Jupiter, maintaining operational temperatures inside the CubeSat requires careful insulation and continuous heating. Key assumptions include Beginning-of-Life (BOL) and End-of-Life (EOL) absorptance as appropriate with a beta (sun/orbital plane angle) of zero. Insolation is taken as 52 w$\cdot m^{-2}$ with both Jupiter and Europa albedo flux calculated based on isotropic half sphere reflection of this insolation value. Jupiter and Europa IR fluxes are based on spherically isotropic Stefan-Boltzmann radiation utilizing mean surface temperatures for each body.

Both hot and cold cases were analyzed, using both MLI and bare aluminum, to determine the required operational temperature range and limitations on power consumption. The results of these analyses are presented in the two tables below. While each method provides only equilibrium temperatures for orbit averaged inputs, the spacecraft is unlikely to undergo significant variation outside these bounds. This is because the CubeSat's thermal time constant is much longer than the orbital period. The thermal time constant is likely to be on the order of 10^5 seconds while the orbital period is on the order of 10^4 seconds.

Calculation of Thermal Time Constant:

$$\tau = \frac{\rho \cdot C_p \cdot V}{h \cdot \mathrm{A}}$$

Where $\rho \cdot V$is the mass, $C_p$is the heat capacity, h is the coefficient of heat transfer and A is the surface area (Lienhard, 2008).

$$h = 4 \cdot \epsilon \cdot \sigma \cdot T^3$$

This order of magnitude calculation provides a useful bound on the range of internal power consumption necessary and allowable for optimal operation. Because battery performance degrades substantially below 0 C, $Q_{internal}$ is chosen to maintain spacecraft temperatures at or above this value. For an MLI blanketed CubeSat, this requires internal heat generation, and therefore power dissipation, between 0.9 and 1.4 Watts. As demonstrated by analysis of the electrical power system in section 3.4.4.3, this is feasible for a .9 kg primary battery operating for 15 days. Bare Aluminum and simple black and white paint coatings will not suffice in the cold case, given power consumption limitations.

Table 2. Cold and Hot Case for MLI Blanketed Spacecraft (Temperature is Survivable for Both)

MLI

Cold case

Surface	Area (m2)	Insolation (W	Jupiter Albedo (W	Jupiter IR (W)	Europa Albedo (W	Europa IR (W)	Radiation Heating (W)	Q_Env (W)	Q_Int (W)	Radiative Area (m2	Temperature (K)
Zenith	0.01	18.38	0.00	0.00	0.00	0.00	0.00	0.01	0.90	0.16	272.84
Nadir	0.01	18.38	0.00	0.00	1.28	0.90	0.00	0.01			
Sun	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Anti-Sun	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Ram	0.03	18.38	0.00	0.00	0.00	0.00	0.05	0.03			
Anti-Ram	0.03	18.38	0.00	0.00	0.00	0.00	0.00	0.03			
Alpha	0.05	**Epsilon**	0.02				**Total Q_Env**	0.08	**Sigma**	5.67E-08	

Assumptions: Beta = 0, BOL Alpha, Single thermal node.

Hot case

Surface	Area (m^2)	Insolation (W	Jupiter Albedo (W	Jupiter IR (W)	Europa Albedo (W	Europa IR (W)	Radiation Heating (W)	Q_Env (W)	Q_Int (W)	Radiative Area (m^2)	Temperature (K)
Zenith	0.01	18.38	0.04	0.05	0.00	0.00	0.10	0.02	1.35	0.16	307.18
Nadir	0.01	18.38	0.00	0.05	16.87	2.91	0.10	0.04			
Sun	0.03	0.00	0.00	0.00	8.44	0.00	0.10	0.03			
Anti-Sun	0.03	0.00	0.00	0.00	8.44	0.00	0.10	0.03			
Ram	0.03	18.38	0.04	0.05	8.44	0.00	0.10	0.08			
Anti-Ram	0.03	18.38	0.04	0.05	8.44	0.00	0.10	0.08			
Alpha	0.1	**Epsilon**	0.02				**Total Q_Env**	0.27	**Sigma**	5.67E-08	

Assumptions: Beta = 0, EOL Alpha, Single thermal node.

Table 3. Cold and Hot Case for Bare Aluminum (Cold Case Temperature is *NOT* Survivable)

Bare Aluminum

Cold case

Surface	Area (m^2)	Insolation (W	Jupiter Albedo (W	Jupiter IR (W)	Europa Albedo (W	Europa IR (W)	Radiation Heating (W)	Q_Env (W)	Q_Int (W)	Radiative Area (m^2)	Temperature (K)
Zenith	0.01	18.38	0.00	0.00	0.00	0.00	0.00	0.02	0.90	0.16	185.42
Nadir	0.01	18.38	0.00	0.00	1.28	0.90	0.00	0.02			
Sun	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Anti-Sun	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Ram	0.03	18.38	0.00	0.00	0.00	0.00	0.05	0.06			
Anti-Ram	0.03	18.38	0.00	0.00	0.00	0.00	0.00	0.06			
Alpha	0.09	**Epsilon**	0.1				**Total Q_Env**	0.15	**Sigma**	5.67E-08	

Assumptions: Beta = 0, BOL Alpha, Single thermal node.

Hot case

Surface	Area (m^2)	Insolation (W	Jupiter Albedo (W	Jupiter IR (W)	Europa Albedo (W	Europa IR (W)	Radiation Heating (W)	Q_Env (W)	Q_Int (W)	Radiative Area (m^2)	Temperature (K)
Zenith	0.01	18.38	0.04	0.05	0.00	0.00	0.10	0.02	1.35	0.16	279.20
Nadir	0.01	18.38	0.00	0.05	16.87	2.91	0.10	0.03			
Sun	0.03	0.00	0.00	0.00	8.44	0.00	0.10	0.03			
Anti-Sun	0.03	0.00	0.00	0.00	8.44	0.00	0.10	0.03			
Ram	0.03	18.38	0.04	0.05	8.44	0.00	0.10	0.08			
Anti-Ram	0.03	18.38	0.04	0.05	8.44	0.00	0.10	0.08			
Alpha	0.17	**Epsilon**	0.03				**Total Q_Env**	0.26	**Sigma**	5.67E-08	

Assumptions: Beta = 0, EOL Alpha, Single thermal node.

3.2.2 Radiation Analysis

Ionizing radiation represents a significant hazard for spacecraft avionics and is a frequent cause of performance loss and mission failure. Nowhere is this more challenging than the equatorial radiation belts of Jupiter, the most intense in the solar system. Europa's orbit places it precisely in the region of greatest risk making spacecraft survival particularly challenging. To address these concerns, radiation analyses for both the interplanetary transit and the 15 day nominal mission were carried out using the SPENVIS models SHIELDOSE2Q and MULASSIS. As part of this analysis, multiple shielding configurations were considered. Ultimately a 2 mm shield around a 1U volume of the spacecraft composed of 1 mm layer of aluminum outside a 1 mm layer of tantalum in a graded Z configuration was chosen for optimal performance.

Selection of spacecraft radiation shielding was constrained by available mass, volume as well as performance. Due to the nature of CubeSat missions, the shielding was required to limit total ionizing dose (TID) to less than 10 krad, the typical COTS survival threshold, over the mission lifetime. Research on heritage shielding methods yielded a graded Z configuration as the most promising given the varied composition of the radiation to which the spacecraft will be exposed: solar protons, galactic cosmic rays and high energy electrons in the Jovian radiation belts. A typical choice for graded Z shielding is aluminum and tantalum.

To explore the performance of this type of shielding, the combinations listed in Table 4 were investigated with SPENVIS, using both SHIELDOSE2Q and MULASSIS models. Results differed by an order of magnitude with SHIELDDOSE2Q predicting a much higher TID than MULASSIS. Research into the differences between the two models revealed that empirical data typically fall between the two predicted values but also suggested that MULASSIS provided superior modeling of secondary radiation. Therefore MULASSIS results are reported here. The 1 mm aluminum, 1 mm tantalum configuration yielded the best combination of performance and mass providing a substantial margin (50%) on total ionizing dose at end of life.

Table 4: TID and Shield Mass for Varying Aluminum-Tantalum Layer Depths

Aluminum (mm)	Tantalum (mm)	Interplanetary TID (krads)	Europa TID (krads)	Total Mission TID (krads)	Mass (g)
0.1	0.1	2.00	29.00	31.00	116
0.5	0.5	1.00	10.15	11.15	566
1	0.5	1.00	8.03	9.03	635
1	1	0.70	4.0	4.73	1101
3	2.5	0.30	1.01	1.31	2554
5	2	0.27	0.93	1.20	2283

Presented below are detailed breakouts of the interplanetary transit and nominal science mission.

3.2.2.1 Journey to Europa (1.9 years)

During its transit from Earth to Jupiter, Europa Clipper and its CubeSat payload are subject to several high energy radiation sources with the potential to seriously damage unshielded or delicate circuitry. The bulk of this radiation is made up of solar protons, however, galactic cosmic rays (GCR) also pose a substantial risk for the CubeSat avionics. These high energy ions are capable of causing single event upsets, latch-ups and burnouts in unshielded or sensitive circuitry. Below are the results of an analysis of the graded Z shielding discussed in the previous section using spherically concentric 1 mm layers of aluminum and tantalum. The analysis presumes a 1.9 year transit time consistent with launch aboard the SLS.

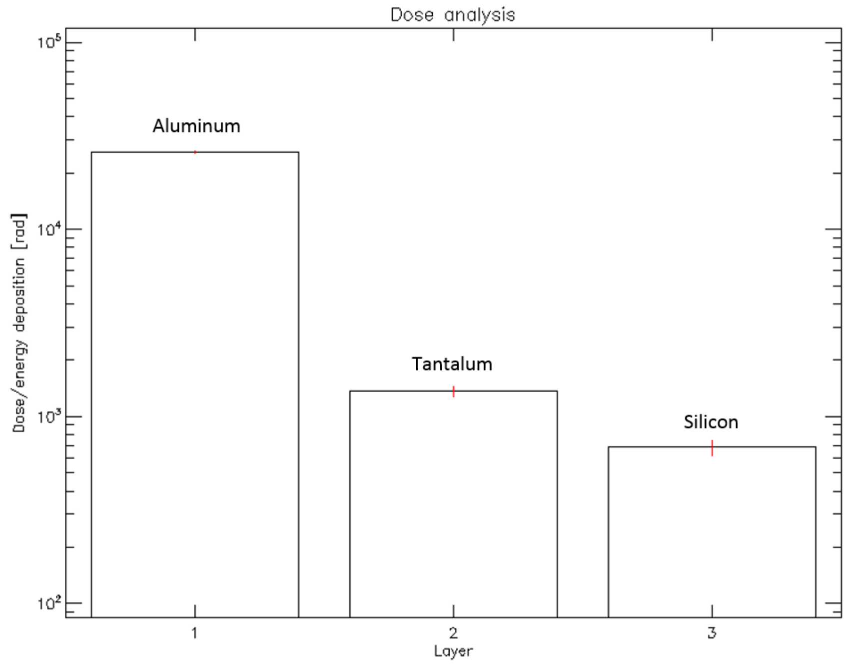


Figure 11: MULASSIS analysis: 1.9 Years Interplanetary Travel. Long Term Solar Radiation for 1 mm Al, 1 mm Ta configuration

3.2.2.2 Europa Orbit (15 day mission)

Jupiter's magnetosphere is the largest and most powerful possessed by any planet in the solar system. As a result, once Europa Clipper enters the Jovian system, solar radiation is no longer a major concern. However, Jupiter's powerful magnetosphere traps and accelerates particles ejected by Io through tidally induced volcanism, leading to the creation of radiation belts similar to Earth's Van Allen Belts but with orders of magnitude greater intensity. As such, the primary hazard during the 15 day nominal mission is the trapped particle radiation, electrons and protons, absorbed by the CubeSat during its time in the Jovian system. Figures 12 and 13 below illustrate the expected TID from each of these sources, electrons and protons respectively, assuming the same spherically concentric layers of aluminum and tantalum discussed above.

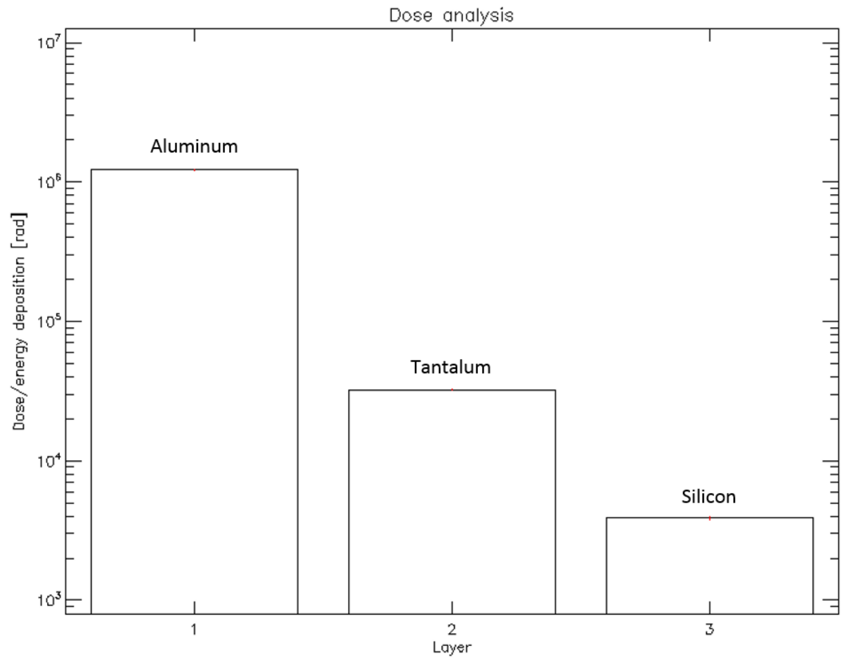


Figure 12: MULASSIS - Europa Orbit - Trapped electrons for 1 mm Al, 1 mm Ta configuration.

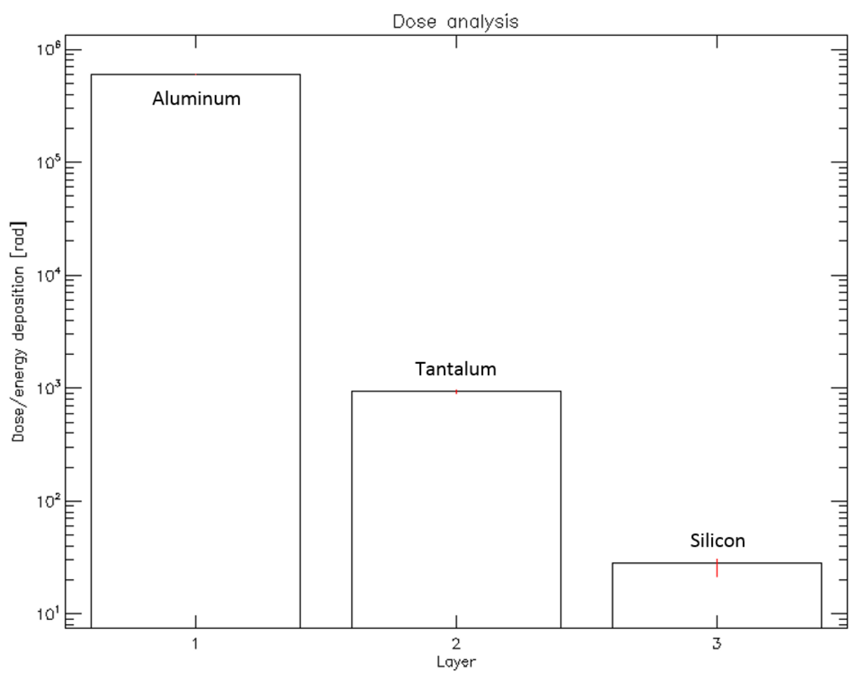
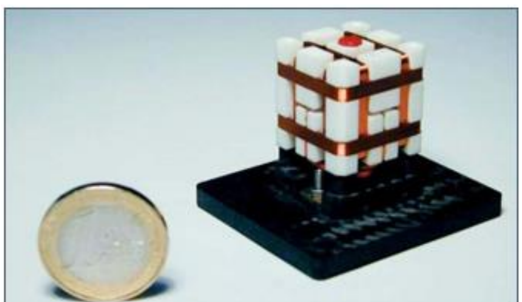


Figure 13: MULASSIS - Europa Orbit - Trapped protons for 1 mm Al, 1 mm Ta configuration

3.3 Study Objective 3: Magnetometer Payload Requirements and Candidate Instruments

Define the requirements for a magnetometer payload to be flown by a 3U CubeSat in Europa orbit and identify plausible candidate instruments. If volume and mass allow, determine the type and nature of additional instrumentation that might reasonably be flown including possibly a dosimeter and/ or ion neutral mass spectrometer.

The Europa Clipper CubeSat mission, in essence, requires placing a magnetometer in close proximity of Europa to measure the magnitude and direction of the magnetic field, with sufficient precision to enable successful analysis of the amplitude and phase of the induced components. To that end, the magnetometer must be capable of measuring the magnetic field over the full range of expected values (+/- 1000 nT) with enough resolution to enable periodic signals on the order of 1 nT to be characterized accurately, imposing a 0.1 nT (or smaller) field strength resolution. Further, the instrument must constrain to the mass, volume and power consumption limitations of a 3U CubeSat. Specifically, the requirements for payload feasibility are that the payload should account for less than 1 kg of the CubeSat's mass, less than 1U of the CubeSat's volume and less than 1 W of the CubeSat's power. The magnetometer used on Rosetta and Deep Space 1 has been identified as satisfying these requirements with respect to measurement, mass, volume and power consumption. As illustrated in Figure 14, the RPC_MAG exceeds each requirement by a considerable margin while providing substantial heritage, making it an optimal instrument for this mission.



Rosetta MAG: Tri-axial Fluxgate Magnetometer
Range: -/+ 16384 nT
Field strength resolution: 0.031 nT
Sample rate: 1-50 Hz
Data resolution: 20 bits
Sensor Volume: 25 mm cube
Power Consumption: 675 mWatts
Mass: 455 g for magnetometer and avionics
Flight Heritage: Rosetta, Deep Space 1

Figure 14. The RPC_MAG fluxgate magnetometer from the Rosetta mission. (Glassmeier, 2007).

Investigation of additional payload instruments including dosimeters and ion neutral mass spectrometers yielded no candidates of sufficiently small mass, volume and power consumption to feasibly accompany the magnetometer payload. While these instruments would have been a valuable addition to any mission, the mass and volume constraints imposed by the CubeSat form factor preclude their inclusion aboard this spacecraft.

3.4 Study Objective 4: Mission Architecture

The fourth objective was dependent on the outcomes of objectives one and two:

a) *In the event that objectives one and two yield feasible results, objective four will be to refine a mission concept to accomplish the primary science goal while adhering to design constraints and Europa Clipper requirements*

b) *If either objectives one or two yield an infeasible result, objective four will be to identify specific areas of research and technology development necessary to enable future CubeSat missions to Europa.*

Given that study objective one is not feasible within the design constraints imposed by JPL, both aspects of objective four are addressed. A mission concept employing a propulsion system in violation of JPL's design constraints is detailed, followed by a discussion of required technology development necessary for enabling future expansion of design constraints through risk reduction.

3.4.1 Mission Concept Overview

- Launch on SLS in the early 2020s and travel to Europa interfaced with Europa Clipper in an ultra-low power state
- CubeSat deployment and orbital insertion occurs during a preselected Europa flyby
- On completion of orbital insertion, CubeSat begins data collection at a nominal rate of 1 sample every 10 seconds for 171 hours
- Upon completion of primary data collection, CubeSat enters low power mode for 139 hours followed by activation of radio to receive data transmission command from Europa Clipper
- End communications link - Mission End

3.4.3 Spacecraft Functional Requirements

Environmental Requirements

- Spacecraft avionics shall at minimum tolerate exposure to 10 krads total ionizing dose
- Spacecraft avionics total ionizing dose shall be limited to no more than 10 krads
- Spacecraft avionics and battery shall operate at temperatures between 0 and 40 degrees Celsius
- Spacecraft shall maintain avionics and battery at temperatures between 0 and 40 degrees Celsius

Proximity Requirement

- Spacecraft shall orbit within one Europa Radius of the surface

Payload Requirement

- Spacecraft shall measure magnetic fields of absolute magnitude between 0 and 1000 nT with field strength resolution of 0.1 nT at a frequency greater than 0.1 hz consuming less than 1 W

Mission Duration Requirement

- Spacecraft shall collect data for 171 hours
- Spacecraft shall remain operable for 360 hours for transmission of data to Europa Clipper spacecraft

Communication Requirement

- Spacecraft shall transmit all magnetometer, attitude determination, and chronometric data to Europa Clipper spacecraft

3.4.4 Design Concept

The standalone 3U CubeSat presented in the following sections is capable of achieving all of the functional requirements outlined above with the exception of *close proximity*. For each design element, the functionality of the system will be treated *post* orbital insertion. Following discussion of the orbital spacecraft, three general approaches, each of which is in violation of mission constraints, capable of delivering the CubeSat with magnetometer to Europa orbit are discussed. What follows is a brief outline of these methods.

1. Use of advanced variants of existing propulsion systems reduced in size and power draw, capable of integration with the proposed 3U bus. Some of these advanced concepts are discussed in section 3.4.6 Future Technology Development. **- Currently infeasible**
2. Use of a secondary orbital insertion module to deliver the CubeSat into Europa orbit. **- Out of scope for the mission as designed**
3. Expansion of the 3U into a 6U design with mass and volume sufficient for integration of a rocket propulsion system capable of the required delta-V. **- Violates mission constraints**

3.4.4.1 Payload

As discussed in Study Objective 3, the magnetometer used by both Rosetta and Deep Space 1 provides an excellent fit for this mission. It exceeds all functional requirements levied on the mission payload (see comparison below) while consuming 675 mW of power in a 455 g package. This is substantially less than the minimum power consumption required to remain within an operable temperature range in both hot and cold cases and approximately 10% of total spacecraft mass.

Table 5. Comparison of Rosetta Magnetometer to Payload Functional Requirements

Specification	Functional Requirement	Rosetta/Deep Space 1 Magnetometer
Field Strength Range	+/- 1000 nT	+/- 16384 nT
Field Strength Resolution	.1 nT	.031 nT
Sampling Rate	1 Hz	1 - 50 Hz
Power Consumption	< 1 W	.675 W

3.4.4.3 Electrical Power

Given the extreme radiation and low insolation environment found in Europa orbit, solar panels were deemed infeasible for power generation. In addition to requiring significant increases in cover-glass thickness to ensure solar cell survival, increasing mass and decreasing efficiency, the power production for a mission without deployables is significantly less than that required, approximately 0.5 W. Inclusion of deployables would substantially reduce available mass reserves and levy otherwise unnecessary requirements for orbital attitude control. As such, Lithium Thionyl Chloride (Li-SOCl2) primary batteries were selected.

Lithium Thionyl Chloride offers outstanding gravimetric energy density (~440 W·hr/kg), robust low temperature operation and substantial flight heritage, including use on the Cassini-Huygens probe. Additionally, these batteries have exceptionally low self-discharge per annum, making them a suitable choice for long duration transits to the outer solar system. Analysis of available commercial off-the-shelf Li-SOCl2 cells yielded several models capable of delivering acceptable current for a nominal 15 day mission at extremely steady output voltages. Two in particular were analyzed, the Varta ER D Cell and the Saft LS33600 D Cell (Saft, 2015). Both models demonstrated broad feasibility, however, the Saft model provided significantly greater gravimetric energy density allowing for a larger cell count and yielding greater capacity margin.

Table 6 presents the expected power draw by subsystem for each phase of the mission, operational battery temperature and battery capacity remaining at end of phase. A 2% self-discharge is assumed at mission start. Distribution losses are modeled at 20% and recovered capacity is modeled as a function of temperature and current draw. Available data suggests a 13% capacity margin for a nominal 15 day mission utilizing 10 cells at 0.9 kg.

Where loads require voltages greater than that provided by the battery, point of load regulation utilizing highly integrated switched mode dc-dc converters is recommended. A wide array of integrated surface mount switched mode regulators are available on the market today enabling 80% efficient or better dc-dc conversion. Anticipation of this need was the primary driver for inclusion of the 20% distribution loss in the following power analysis.

Table 6. Power Draw by Subsystem and Mission Phase

Mission Phase	Power Draw by Subsystem								
	Propulsion (W)	ADCS (W)	CDH (W)	Payload (W)	Radio (W)	Heating (W)	Total (W)	Temperature (C)	Battery Capacity (%)
Orbital Insertion (.5 hours)	0	0.4	0.01	0	0	0.31	0.90	0	97.9%
Science Mission (171 hours)	0	0.4	0.01	0.68	0	0	1.36	20	50.8%
Post Science (158.5 hours)	0	0	0.01	0	0	0.55	0.70	-20	25.0%
Comms Window (30 hours)	0	0	0.01	0	1.4	0	1.76	20	13.5%
Mission Average Power Consumption							1.10	Capacity Margin	13.5%

Note: Orbital Insertion does not include power for a propulsion system for the reasons cited in the section *3.4.4 Design Concept*

3.4.4.4 Attitude and Position Determination

Attitude and position determination can be achieved in Europa orbit by means of a suite of small, light-weight sensors that represent a modest drain on spacecraft power resources. These include infrared sensors known as thermopiles, photodiodes, an inertial measurement unit (IMU) with an integrated magnetometer. Arrays of thermopiles can be used to detect Europa's horizon. Provided detection at two different angles this horizon sensing can supply a vector in the nadir direction. With the horizon angle for two different sectors of the moon, and the boresight angle of the thermopiles, the nadir direction can be calculated analytically. This method is shown in Figure 15 and discussed in greater detail by Nguyen (2014).

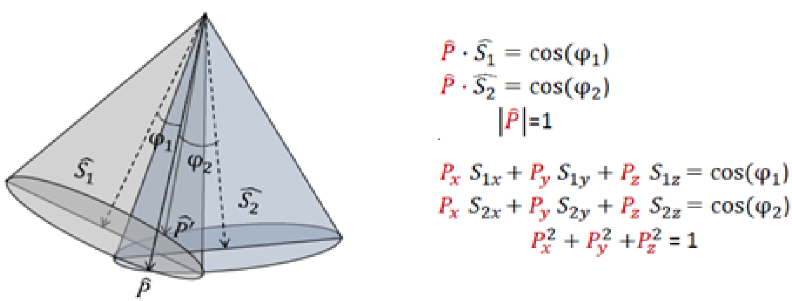


Figure 15. Analytic calculation of nadir direction based on boresight angle of two thermopiles; three equations and three unknown variables (red) (Nguyen, 2014).

As many artists have imagined, Jupiter takes up a significant portion of the night sky near Europa. More precisely, it subtends an angle of 12.2 degrees, enough to substantially modify the average temperature of an observing thermopile's field of view (FOV). This means a thermopile array can find a position vector towards Jupiter. The average temperature (T_{ave}) detected by a thermopile pointed away from Europa is estimated to be 26.0 degrees Kelvin. This calculation uses conservative values for Jupiter's emitting temperature (T_J), deep space temperature (T_S), and thermopile field of view (FOV), which are 134.0 Kelvin, 3.0 Kelvin, and 80.0 degrees respectively.

$$T_{ave} = \frac{\alpha T_s + \beta T_j}{FOV} = 26.0\ K$$

In the above formula, β is the angle subtended by Jupiter and α is the angle subtended by deep space (180- β). The difference between average temperature and Jupiter's emitting temperature is 107 Kelvin, which corresponds to an infrared wavelength of 27 micrometers (Wien's Displacement Law). This wavelength is near the high bound for common IR thermopiles, which is typically around 20 micrometers. However, because the cut-off wavelength is determined by the specific detectivity, D*, this detection limit may be extended.

$$D^* = \frac{Responsivity \times \sqrt{Area}}{Noise/\Delta f}$$

The cutoff wavelength is the point at which D* drops below half its peak value, and because there will likely be very little thermal noise in space the value of D* will increase. Furthermore, these thermopiles operate with increasing sensitivity near their center of their view. By taking advantage of this, the accuracy with which Jupiter's location is measured can be increased. The varying sensitivity is known to be Gaussian (see Figure below), and therefore predictable, so the large look angle occupied by Jupiter can be further constrained.

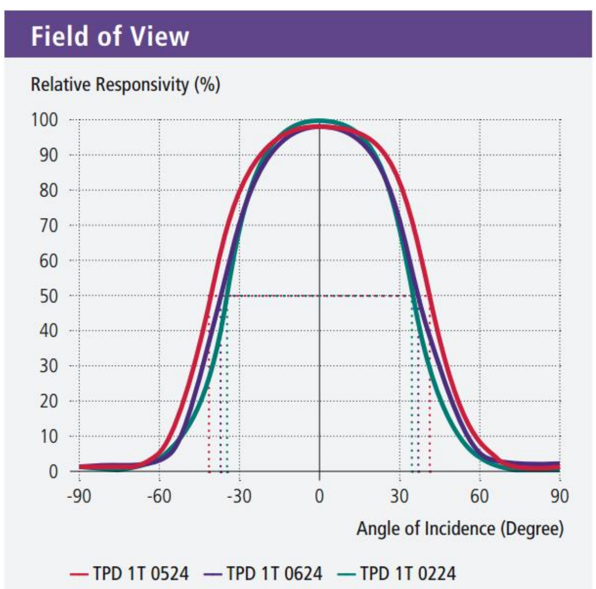


Figure 16: Excelitas TPD IR thermopile's varying sensitivity is predictably Gaussian which can increase accuracy of Jupiter's detected location (Excelitas, 2015)

Still, if future prototype testing finds this wavelength is not accurately detected by the IR thermopile array, steps to increase the detection area could also be investigated. Further discussion of technology development focused on the proposed thermopile-based position and attitude determination system can be found in section 3.4.6 Future Technology Development.

Jupiter's large magnetic dipole provides another reference location for Jupiter. Small, coin-sized, IMU-magnetometers like the ADIS16407, with significant CubeSat heritage, can easily detect Jupiter's massive dipole field. This dipole field is orders of magnitude larger than the induced signals and plasma signatures targeted by the fine-sensing fluxgate magnetometer payload. A final position vector is provided by coarse sun sensors. These sensors also carry significant CubeSat heritage but are known to degrade in a radiation rich environment. To minimize these effects, radiation hardened photodiodes such as the UVG20C may be selected.

Even if the radiation hardened photodiodes experience interruptions and are not able to accurately determine the position of the sun, the initial input of four position vectors into a Kalman filter yields an over defined solution set, capable of outputting position and attitude without functionality of all sensors. The inclusion of a star finder was initially considered in place of thermopiles. However this configuration was dropped for two reasons: First, thermopiles demand less power, mass and volume than a star tracker. Secondly, a star tracker's lens and imaging hardware are more susceptible to radiation damage.

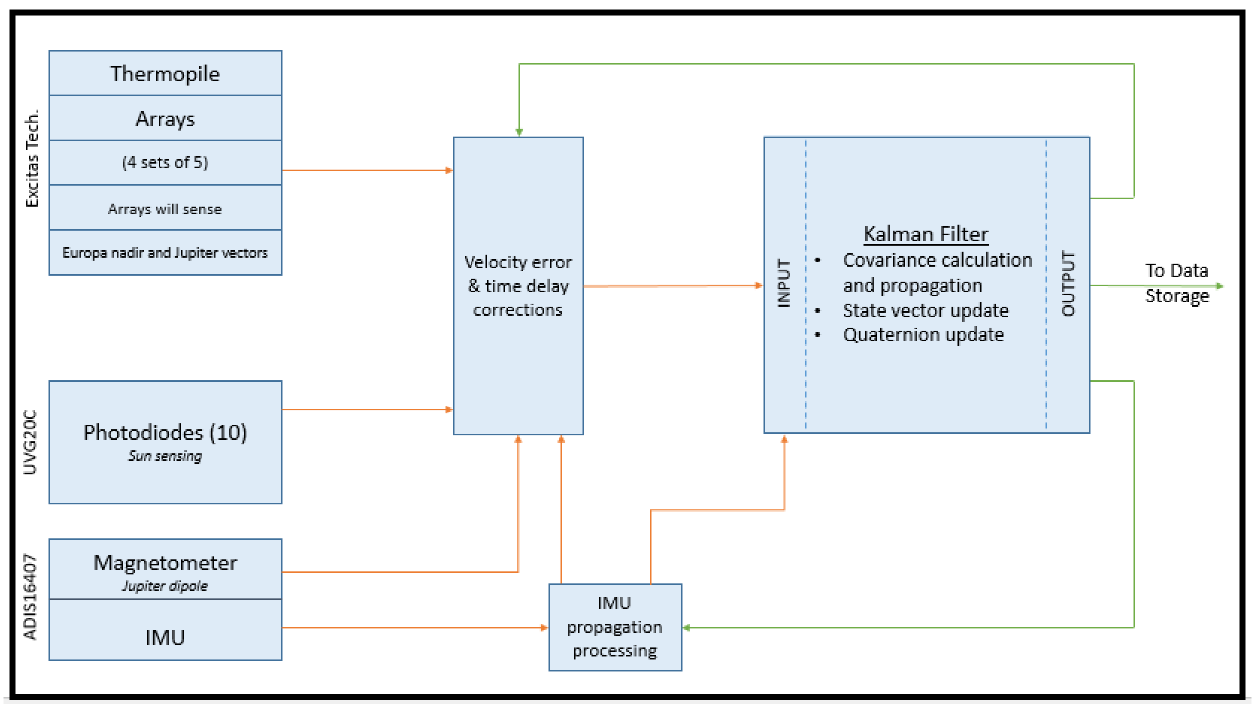


Figure 17: Attitude and position sensor inputs flow chart

3.4.4.5 Attitude Control

Size and mass constraints severely limit the options for attitude control. Additionally, any inclusion of magnetorquers or passive magnetic stabilization could have adverse effects on the CubeSat payload measurements. Fortunately, good magnetometer measurements do not require stabilization, only accurate knowledge of position and attitude. Therefore as long as rotation is kept below an operational threshold, no active attitude control is needed. The threshold being, a level of rotation for which the sensors and system discussed in the previous section are able to output accurate quaternions. The deployment from Europa Clipper and subsequent orbital insertion will likely impart some angular momentum to the CubeSat. To ensure the ensuing angular motion is sufficiently slow, the structure should be arranged so that the centers of gravity in all axes are as symmetric as possible, thereby limiting induced angular velocity.

Sensor redundancy and strategic placement is another way to improve the probability that accurate position and attitude are measured. The configuration seen in the Figure below will help ensure position vectors can acquire regardless of flight configuration with respect to Europa, Jupiter and the Sun.

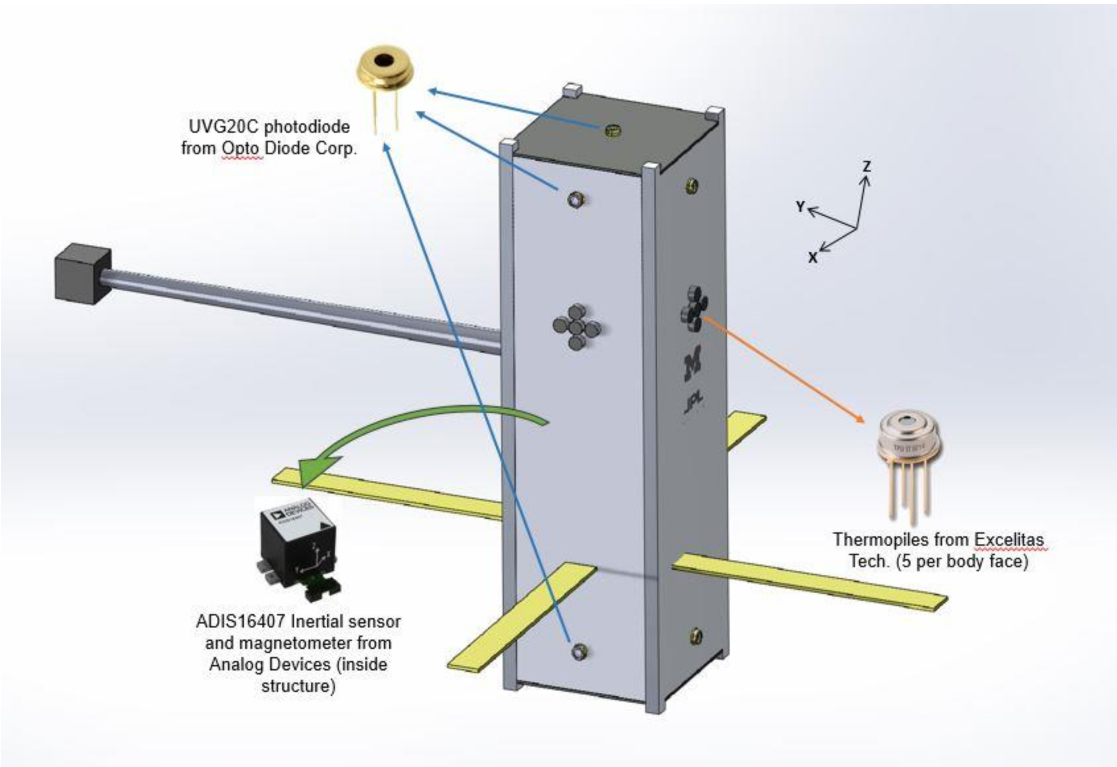


Figure 18. X and Y faces with five thermopiles each for Europa horizon nadir vector or Jupiter vector, and two photodiodes for sun vector. Each Z-face has one photodiode for sun sensing; ADIS IMU-magnetometer mounted internally for Jupiter dipole vector and inertial reference.

While this specific ADCS configuration is theoretically robust, it has not been flight qualified and thereby incurs questionable feasibility. In order to deem this subsystem fully feasible, at a minimum, ground based prototype and testing should be conducted. Alternatively, a best case scenario could achieve partial heritage in a LEO environment onboard another CubeSat. Of course, the subsystem could not be fully flight qualified beforehand as the Europa-Jupiter environment is not exactly reproducible.

3.4.4.6 Communication

Mission success is critically dependent on retrieval of the mission science data. This requires transmission of mission science data to Europa Clipper, for retransmission to Earth. Effective radio communication between the CubeSat and Clipper is certainly feasible within the given constraints of frequency range, antenna type, anticipated baud rate, and receiver gain. However, the quantity of data transmitted is directly proportional to the amount of time that the CubeSat and Clipper are within minimum effective transmission distance of one another, the uniformity of the transmitting antenna gain pattern, and the sensitivity of the receiving antenna.

The AstroDev Lithium 1a radio was selected for the purpose of feasibility analysis due to its extensive heritage as a CubeSat UHF transceiver. This highly developed and flight-qualified radio operates in the prescribed UHF band and is compatible with the ubiquitous “monopole” measuring-tape antenna. This radio requires as little as 1 W input power and weighs in at 52 grams, clearly demonstrating feasibility with respect to device mass, power, and form factor.

Given the lack of attitude control and the need to maintain a uniform radiation pattern, four synchronously driven monopole antennas were chosen to maximize gain uniformity and null definition. While the nulls can still inhibit communication when oriented directly toward Europa Clipper, the narrowness of the nulls so achieved prevent long duration or frequent occurrence of this configuration. Many heritage versions of this CubeSat antenna system are readily available, some with a maximum anticipated mass of 100 grams (ISIS, 2015) including deployment hardware. This last antenna model is presented in the mass and volume budgets, and fits within size and power constraints to provide a 3 dB peak gain transmitting antenna with +/- 37 deg beamwidth in a toroidal gain configuration. This gain pattern can be approximated by $\cos^2$ over a wide range of angles (+/- 70 deg) and so an average value of -3 dBW may be used for general calculation acknowledging that this does not accurately reflect transmission very near the nulls or gain peak. Furthermore, use of 4 synchronously driven monopoles necessitates the use of a two stage signal splitter which incurs an additional -6 dBW for an average transmit gain of -9 dBW.

Given the anticipated receiver gain of 6 dB for Clipper's antenna, and presuming that Clipper has a minimum signal detection threshold similar to that of previous deep-space missions to the outer planets (-153 dBm, -183 dBW for Galileo) (Jones, 1983), a maximum effective transmission distance can be calculated using the Friis equation:

$$P_R = \frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2}{(4 \cdot \pi \cdot R)^2}$$

Where:
P_R is power received (minimum threshold of -183 dBW)
P_T is power transmitted (-9 dBW)
G_T is the transmitter gain (-3 dBW)
G_R is the receiver gain (6 dBW)
λ is the transmission wavelength (c / f)
c is the speed of light in a vacuum in meters per second, 2.998×10^8 m/sec
R is the distance between the transmitter and receiver in meters, the quantity to be resolved
f is the frequency in hertz, here 435 MHz = 4.35×10^8 Hz

The maximum effective communication distance is approximately 38,000 km.

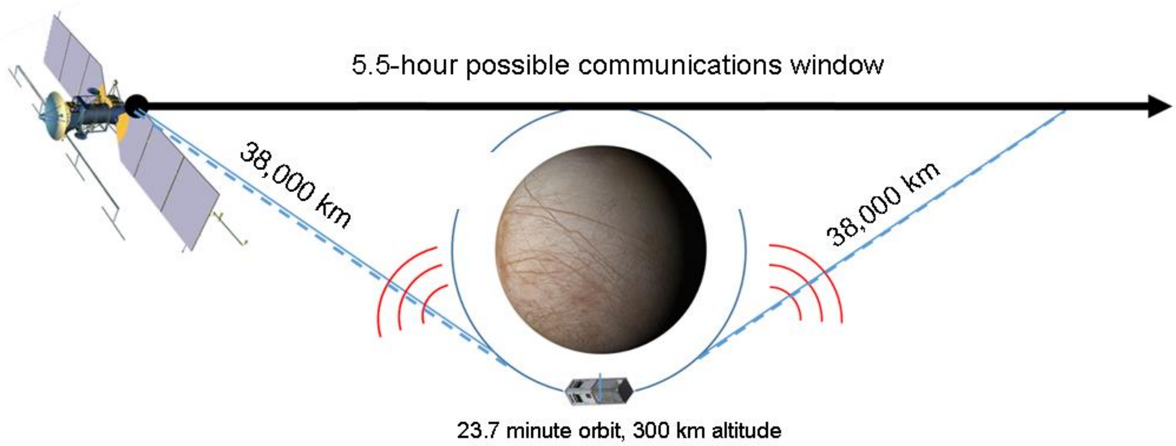


Figure 19. Threshold separation distance determines communication time window and subsequent data volume receivable

Assuming a baud rate of 9600 bps over the course of 5.5 hours (19,800 seconds), the maximum transmittable data under these conditions is 190 Megabits. By further limiting the data transfer ceiling to 50% of this value, data integrity can be made extremely robust allowing for eclipse, null pointing and retransmission of corrupted or lost data during the comms window.

Table 7. Data Parameters and Digital Resolution

Data Parameter	Bits per Sample
Latitude	16
Longitude	16
Altitude	16
Spacecraft Attitude X	16
Spacecraft Attitude Y	16
Spacecraft Attitude Z	16
Time	32
Battery Voltage	8
Magnetometer X	16
Magnetometer Y	16
Magnetometer Z	16
Total	184

With a sampling rate of 0.1 Hz, the complete dataset, at 184 bits per sample, including housekeeping data, would be 22.7 Megabits, requiring only 0.66 hours to complete transmission, leaving a nearly 5 hour margin for retransmission and error correction. Given the 190 Mbit data transfer ceiling, it is evident that complete data transfer from the CubeSat to Europa Clipper is entirely feasible.

3.4.4.7 Command and Data Handling

The selection of a flight computer is most impacted by radiation tolerance and power consumption. Single-event upsets (SEU) and latch-ups can severely damage the flight computer requiring a combination of radiation tolerance and shielding sufficient to reduce the probability of SEUs and latch-up to acceptable levels.

An example of a microcontroller with heritage as a CubeSat flight computer, which is also radiation tolerant, is the MSP430FR5739 (Texas Instruments, 2014). Recommended by JPL for the purposes of this study, this microcontroller operates at speeds of 10 Mbps read/write on input voltages from 2-3.6 V, the nominal operating range for Lithium Thionyl Chloride batteries.

3.4.4.8 Data Storage

Long term storage of both mission data and flight software require peripheral data storage. Due to their heritage in CubeSat applications, Secure Data (SD) cards were chosen. SD cards, however, are susceptible to radiation damage and bit flips, as proven by several Earth orbiting mission failures. For this reason, the spacecraft should include ruggedized SD cards which have demonstrated superior performance in high radiation environments. Furthermore, included SD cards would operate within the avionics radiation shield, further reducing exposure.

3.4.4.9 Structure

The spacecraft structure, barring inclusion of a propulsion system, is more than ample to house all proposed hardware. Figure 20 below demonstrates the feasibility of including the required hardware within the confines of a 3U CubeSat. Of particular note is the avionics radiation vault surrounded by an aluminum-tantalum bi-layer in a graded Z configuration. Other key features include the battery compartment and payload stacer boom along with two of four monopole antennas.

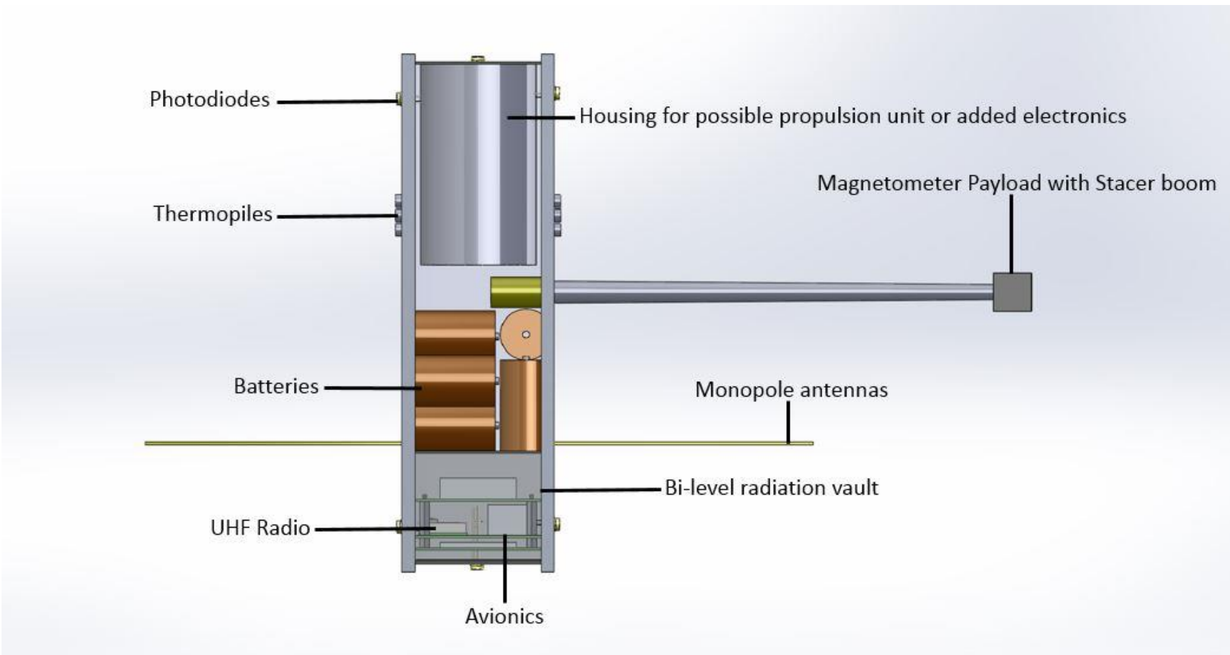


Figure 20. Mock-up of Europa CubeSat demonstrating that all necessary components can fit within a standard 3U volume

The Table below provides a summary of projected system mass. Component masses are based on given parameters where available and engineering calculations otherwise. Components such as harnessing and structural interface hardware are included only in the broadest sense as a separate listing because sizing was not performed for individual components. Such values are based on heritage data from the Michigan Exploration Laboratory (MXL).

Table 8. CubeSat Mass Budget

Component	Unit Mass (g)	Number	Total Mass (g)	Source
Payload				
Magnetometer w/ avionics	455	1	455	Documentation
EPS				
EPS board	83	1	83	COTS estimation
Batteries	90	10	900	COTS/calculations
CDH				
C&DH board	62	1	62	COTS estimation
Comms				
Antenna	25	4	100	MXL heritage
UHF transceiver	52	1	52	COTS
Structure				
Basic structure	632.6	1	632.6	Calculations
Radiation Shielding	1001.4	1	1001.4	Calculations
Stacer boom	200	1	200	COTS estimation
MLI	300	1	300	Documentation
ADCS and GNC				
Board	30	1	30	MXL heritage
Photodiodes	4	10	40	COTS
Thermopiles	4	30	120	COTS
System				
Harnessing	50	1	50	MXL heritage
Hardware	50	1	50	MXL heritage
Sub-Total			4,076	
Margin			424	
Total			4,500	

Mass Total (with 9.5% Margin) = 4.5 kg

3.4.4.10 Orbital Insertion

As discussed in section *3.4.4 Design Concept*, there are three general approaches to orbital insertion, none of which are determined or addressed by the preceding design discussion. These options include:

1. Use of advanced variants of existing propulsion systems reduced in size and power draw, capable of integration with the proposed 3U bus. Some of these advanced concepts are discussed in section 3.4.6 Future Technology Development. **- Currently infeasible**
2. Use of a secondary orbital insertion module to deliver the CubeSat into Europa orbit. **- Out of scope for the mission as designed**
3. Expansion of the 3U into a 6U design with mass and volume sufficient for integration of a rocket propulsion system capable of the required delta-V. **- Violates mission constraints**

Because advanced propulsion technologies are discussed later, they are not addressed here. The two remaining approaches to orbital insertion are essentially the same with respect to propulsion technologies and requirements, differing only in interface and mass budget accounting. In each case a high thrust propulsion system, most likely a bi-propellant rocket, is required to achieve orbit. In the case of an orbital insertion module, the rocket propulsion system is borne by a separate intermediary craft, potentially capable of deploying multiple payloads once on orbit. The advantages of such a design are the multi-functional nature of the insertion module, provided there is more than one payload to be deployed. In the case of an integrated propulsion system capable of producing the required delta-V (~3 kps), expansion of the spacecraft to a 6U, to accommodate the rocket engine and propellant, would be necessary for all existing technologies.

In either case, a chemical propulsion system is required. Existing forms of electric propulsion produce too little thrust to achieve orbit during a single Europa flyby and represent an untenable drain on the battery. An example chemical propulsion system capable of producing the required delta-V is the Aerojet R-6D. This bi-propellant rocket engine has dimensions appropriate for deployment on a CubeSat and can provide delta-V limited only by available propellant mass with a specific impulse of 294 s. Assuming a doubling of spacecraft dry mass to account for the 0.5 kg engine, 1.5 kg of propellant tanks, 0.5 kg of additional battery, 1 kg of reaction wheel assembly and 1 kg of structural interface, the R-6D can provide 3.3 kps delta-V with a total spacecraft wet mass of 28 kg. An intermediary propulsion module with an additional 4 kg of structural interface and deployment mechanisms and an additional 4.5 kg CubeSat would have a wet mass of 55 kg. For either scenario, the additional mass, 24 kg or 45 kg respectively, is a tiny fraction of the estimated 7.4 tonnes[4] of additional fuel mass required to put a spacecraft comparable in mass to Europa Clipper in orbit. The savings at launch is considerable and enables substantially more synergistic science than would otherwise be possible.

3.4.5 Feasibility Summary

This feasibility study finds that a 3U CubeSat can survive the harsh Jovian environment while remaining powered and functional for the duration of its mission. Equipped with a Rosetta-like flux-gate magnetometer, the CubeSat can conduct multi-frequency magnetic induction sounding of Europa with sufficient sensitivity to uniquely determine both the thickness and conductivity of Europa's subsurface ocean. Additionally, it has been shown that, subject to test and flight qualification, the proposed ADCS can provide the necessary attitude and position knowledge. A key finding of this report, however, is that currently available propulsion systems are not capable of achieving orbital insertion in a 3U CubeSat form factor. To achieve orbital insertion requires a propulsion system at least as massive as the CubeSat itself, either integrated in a 6U package or carried aboard an orbital insertion module. Because of this finding, the mission must be deemed infeasible until such time as the mission scope is expanded to include an orbital insertion module or a larger CubeSat with a non-cold-gas propulsion system. Major subsystem components with heritage applications are listed in Figure 21 below.

[4] This assumes that Europa Clipper has the same on orbit mass as Galileo with a propulsion system capable of the same ISP as the R-6D rocket motor.

Subsystem	Payload	EPS	Comms	CDH	Structure		GNC		
					Radiation	Thermal	Attitude	Position	Propulsion
Components	RPC-MAG Triaxial Flux-gate Magnetometer	Primary Lithium Thionyl Chloride Battery	Astrodev Lithium 1a UHF Transceiver Monopole Antenna	MSP430FR5739 Ruggedized SD Cards	Aluminum - Tantalum Bi-Layer	MLI Active and Passive Heating	Thermopiles Photodiodes IMU w/ Magnetometer	Thermopiles Photodiodes IMU w/ Magnetometer	Not specified
Heritage	Rosetta, Deep Space 1	Cassini-Huygens	CubeSat Heritage	CubeSat Heritage	Various	Various	none	none	none

Figure 21. Summary of Subsystem Feasibility; feasible (green), questionable (yellow) and infeasible (red).

3.4.6 Future Technology Development

The preceding discussion clearly indicates that most of the technologies necessary for deep-space CubeSat missions are sufficiently developed to enable orbital deployment to Europa. Guidance, navigation and control is the clear exception and represents the greatest challenge for CubeSat missions to the outer solar system. The difficulties associated with GNC fall into two categories; robust technologies for attitude and position determination (guidance and navigation) and propulsion systems capable of enabling orbital insertion and other deep-space maneuvers within CubeSat mass and power generation constraints.

The most common technology used for guidance and navigation is the star-tracker. Typical radiation tolerant star-trackers available today have imaging sensors specified to a few hundred kilorads total ionizing dose, sufficient, with appropriate shielding and radiation hardening for optical elements, to withstand the Europa radiation environment . The primary challenge to implementing these technologies are the mass and power requirements of these devices. State of the art multi-camera star-trackers account for .5 kg of spacecraft mass in a .5U volume and consume 3-5 W continuously (MIST, uASC). Even if spacecraft mass and volume allocations are sufficient, 3-5 W continuous power consumption presents an insurmountable barrier for most deep-space applications. Further development with a particular emphasis on lowering power requirements will be crucial not only to Europa CubeSat missions but all future deep-space CubeSat missions.

With regard to the particular technologies and methods for position and attitude determination described in this report, further development is required to achieve a flight qualified system, capable of providing accurate guidance and navigation with sufficient precision. Selection of optimized thermopiles and photodiodes for application in the Europa environment will play a major role in achieving a robust system. Characterization of that system in a flight-like environment will illuminate system limitations and remaining challenges. While this method clearly provides benefits with respect to mass and power, it must be noted that it is an application specific solution, requiring two bodies of sufficient temperature and angular size to function and may not be broadly applicable to deep-space CubeSat missions in alternative environments.

With respect to control, advancement in propulsion systems is paramount to the future success of deep-space CubeSat missions. Currently, Europa CubeSat concepts are limited to cold-gas propulsion systems only. A brief survey of available technologies reveals that this limitation does not stem from a lack of alternatives. Rather, it is more likely that this limitation is intended to prevent the deployment of a potentially destructive propulsion system on a secondary payload that might threaten Europa Clipper. To the extent that such concerns are warranted, further development of these technologies, including rocket and electric propulsion systems, with a focus on risk reduction, is required.

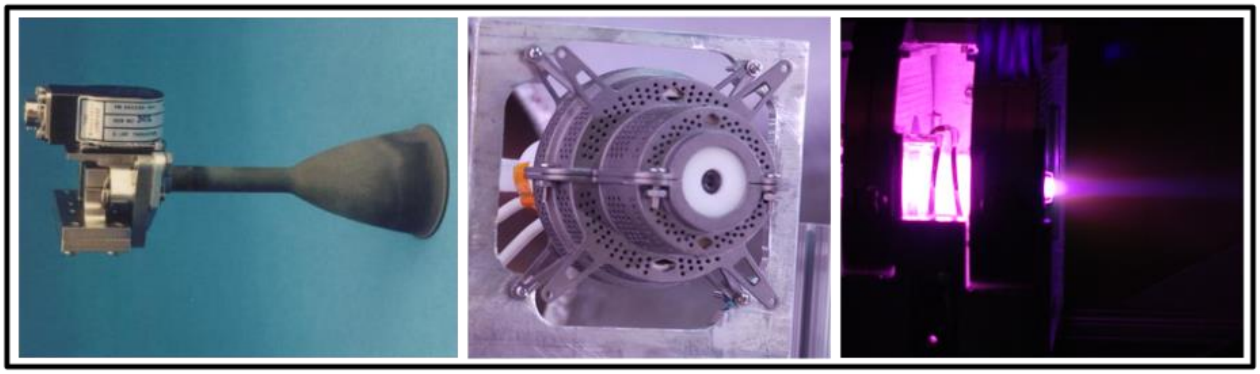


Figure 22. The Aerojet R-6D rocket engine (left) and the CAT thruster under development at the University of Michigan (center and right). Each propulsion system is capable of orbital insertion for a spacecraft exceeding 3U mass constraints.

Example propulsion systems that could be deployed to achieve the required delta-V include the Aerojet R-6D rocket engine, discussed previously, and the CubeSat Ambipolar Thruster (CAT) currently under development at the University of Michigan. These propulsion systems are displayed in Figure 22. While each of these propulsion systems is capable of producing the required delta-V neither is capable of doing so within the mass constraints of a 3U CubeSat. Both can be implemented in a 6U structural volume however, only CAT is capable of achieving orbit within 6U mass constraints. Low thrust combined with high power consumption (~10 W), however, make CAT, and similar electric propulsion systems, an infeasible option for a battery powered spacecraft. To enable future missions utilizing 3U CubeSats, rocket propulsion systems require improved specific-impulse to achieve superior delta-V with reduced propellant mass. Similarly, electric propulsion systems require substantial reductions in power consumption to enable solar powered deep-space missions.

4 Conclusion & Recommendations

The University of Michigan investigated the scientific and engineering feasibility of conducting multi-frequency magnetic induction sounding of Europa’s interior utilizing a magnetometer payload aboard a 3U CubeSat. Designed to accompany the Europa Clipper spacecraft, this CubeSat would complement Europa Clipper’s capabilities by providing multi-period dwell times for the highest amplitude inducing fields at Europa enabling high fidelity magnetic induction sounding at multiple frequencies. Invaluable to the scientific community, as expressed through the decadal survey, this data would allow for unique determination of the thickness and conductivity of Europa’s subsurface ocean, key to understanding the evolution of the Jovian system and the prevalence of potentially habitable worlds.

The proposed science mission and spacecraft operations are technologically feasible using heritage instruments and technologies. Systems analyses, including spacecraft response to the Jovian thermal and radiation environments, indicate it is possible to achieve the minimum operational lifetime required to execute multi-frequency magnetic induction sounding utilizing a fluxgate magnetometer similar to that employed by the Rosetta mission. Analysis of a variety of propulsive maneuvers utilizing cold-gas propulsion systems yielded none able to achieve Europa proximity for sufficient duration. Subsystem design concepts for a 3U CubeSat orbiter were presented, showcasing feasibility for all elements except propulsion concluding with an analysis of existing propulsion technologies capable of enabling a CubeSat probe to successfully execute the mission.

Given Europa's high scientific priority for planetary science and astrobiology, the infrequent nature of missions to the Jovian system and the opportunities for synergistic science through coordinated observation with Europa Clipper, the study authors recommend that NASA - JPL pursue this mission; whether by 6U CubeSat, orbital insertion module, or other micro-satellite architecture; allowing for required propellant mass and propulsion capabilities. The estimated opportunity cost for launching such a craft in conjunction with Europa Clipper given projected SLS launch costs is on the order of $50 Million; an insignificant sum in comparison to the $2.2 Billion cost of the Europa Clipper mission.

Beyond producing extremely valuable science, the proposed mission serves as a new paradigm for space exploration. A 6U CubeSat with a highly capable propulsion system provides a template, not only for missions to Europa, but Ganymede, Callisto and Io as well. Future missions might deploy similar spacecraft to Enceladus, Titan, Mimas, and beyond. In short, a nanosatellite with a focused, high impact payload and a propulsion system capable of orbital insertion could accomplish missions previously considered impractical, setting the stage for future achievements in deep-space exploration.

5 Acknowledgements

The Michigan research group wishes to extend heartfelt thanks to everyone who made this report a success. In particular, Professors Xianzhe Jia and Nilton Renno of the University of Michigan for their guidance, assistance, support, and encouragement throughout the process. Thank you for being our advocates and mentors!

We also thank Professor James Cutler for his continued support and supervision. A hearty shout-out goes to Professor Stephen Bougher who gave freely of his time to assist us with many orbital dynamics questions, and provided further leads. Additionally, we wish to thank Sara Samuel, a consummate librarian of engineering who helped us with questions great and small regarding the particulars of publication.

Beyond the University of Michigan, Mr. John D. Baker and Mr. Patrick Thompson of NASA JPL kindly provided assistance with our many questions. We extend our thanks to both of these gentlemen. And last but certainly not least, we thank Dr. Robert Tolson of the National Institute of Aerospace for gracious assistance through our conversations regarding aerocapture.

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7 Appendices

Appendix A - Request for Proposal

JPL
Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena CA 91109-8099

July 1, 2014

Attn: All Prospective Proposers

Subject: JPL Competitive Request for Proposal (RFP) No. SS06-30-14 for "Europa CubeSat Concept Study"

The Jet Propulsion Laboratory invites your organization to submit proposals in support of "Europa CubeSat Concept Study." The intent is to provide "A study to address a mission concept for a small CubeSat spacecraft up to 3U in size that would be carried aboard the potential Europa Clipper spacecraft, released in the Jovian system and would make measurements at Europa."

The attached RFP provides further information on proposal preparation and submission instructions, description of the selection process, and reporting requirements.

Based on your response to the RFP and the needs of JPL up to 10 proposals will be selected, successfully selected proposals will be funded as a JPL-issued Fixed-Price Research Support Agreement (RSA). RSAs are not to exceed $25,000. The Period of Performance is approximately 8 months.

This effort may lead to additional tasks in the future, however, there is no commitment at this time to fly CubeSats on the potential Europa Clipper mission.

This RFP does not commit JPL or the Government of the United States to pay any costs incurred in submitting your proposal, making studies or designs for preparing the proposal, or in procuring or subcontracting for services or supplies related to the proposal.

Provide the name of your cognizant Government Audit Agency (i.e., DCAA, etc.), if any, their phone number and point of contact, and any copy of a letter that indicates their approval.

Please note that your proposal is due at JPL no later than "August 18, 2014" 3:00 PM (PDT).

Should you have any questions, please address them to Patrick Thompson by e-mail only at the email address on the RFP cover page.

Respectfully,

Susan Scrivner,
Subcontracts Manager
Phone No.: (818) 393-0930
Fax No.: (818) 393-3027
E-mail: Susan.g.scrivner@jpl.nasa.gov

Enclosures: ***RFP consisting of:***

- ***Cover Sheet and Table of Contents***
- ***General Instructions***
- ***Technical/Management Instructions***
- ***RFP Attachment(s)***
- ***RSA Specimen Subcontract***

JPL 2839, R 12/13

RFP - Page 1 of 14

JPL
Jet Propulsion Laboratory
California Institute of Technology

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

REQUEST FOR PROPOSAL

REQUEST FOR PROPOSAL NO.: SS06-30-14

FOR:

EUROPA CUBESAT CONCEPT STUDY

PROPOSALS ARE TO BE RECEIVED AT JPL NO LATER THAN:

Date: August 18, 2014

3:00 p.m. Pacific Daylight Time

COMMUNICATIONS IN REFERENCE TO THIS RFP

It is requested that any communication in reference to this RFP be via email and directed to the attention of:

Name:	Patrick Thompson	Mail Stop:	201-203
Title:	Universities Group Supervisor	Phone:	(818) 354-2859
		Fax:	(818) 393-3027
		E-Mail	Patrick.M.Thompson@jpl.nasa.gov

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109-8099

Date of Issuance: July 1, 2014

JPL 2839, R 12/13

Jet Propulsion Laboratory
California Institute of Technology

TABLE OF CONTENTS

RFP No.: SS06-30-14

1. REQUEST FOR PROPOSAL

2. JPL anticipates awarding Research Support Agreements (RSA). **Specimen Subcontract attached to RFP. Related terms and conditions which are non-negotiable can be accessed at:** https://acquisition.jpl.nasa.gov/tc/ .

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California Institute of Technology

GENERAL INSTRUCTIONS

1.0 GENERAL REQUIREMENTS/INFORMATION

If you choose to submit more than one proposal for this effort, each proposal must be responsive to JPL's requirements, independently complete and under separate cover. JPL reserves the right to retain all proposal information submitted in response to this RFP.

This RFP does not commit the California Institute of Technology (including its operating division, JPL) or the United States Government to pay any proposal preparation or other costs related to the submission of a proposal(s). Proposers shall participate in this RFP process solely at their own risk and expense. JPL reserves the right to cancel this RFP and to reject any or all proposals.

1.1 Data

If the proposal contains data that are not to be disclosed for any purpose other than for proposal evaluation, you must place on the cover sheet of each proposal volume the following wording:

"Data contained in pages ____________ of this proposal furnished in connection with RFP No.: SS06-30-14 shall not be used or disclosed, except for evaluation purposes, provided that if a subcontract is awarded to this offeror as a result of or in connection with the submission of this proposal, JPL and the Government shall have the right to use or disclose this data to the extent provided in the subcontract. This restriction does not limit JPL's right to use or disclose any data obtained from another source without restriction."

1.2 Requests for Clarification/RFP Addenda

During the proposal preparation period, all requests for clarification and/or additional information, must be submitted by e-mail to the Subcontracts Manager referenced under "Communications in Reference to this RFP" at the bottom of the RFP cover page. When appropriate, responses to requests, as well as any JPL initiated changes, will be provided to any prospective proposer(s) as addenda to the RFP. It is the proposer's responsibility to check the RFP website weekly for addenda.

JPL anticipates responding to questions once a week by email. The last day to submit questions is Thursday, August 7, 2014 by 12 noon PDT.

1.3 Compliance with Export Control Laws and Regulations

In the performance of this RFP, JPL may exchange information or other technology which may be subject to the export control laws and regulations of the United States, including the International Traffic in Arms Regulations (ITAR), 22 C.F.R. 120-130 and the Export Administration Act Regulations (EAR), 15 C.F.R. 730-774. All proposing parties agree to fully comply with all such laws and regulations while participating in this RFP process.

1.4 Proposals via E-Mail Only

Proposals are to be submitted ***only*** as attachment to an e-mail(s) and must:

- Have a scanned signature or an e-signature.

- Be in ".pdf" file format.
- Include one file containing only a 3 page technical proposal (per Volume I), 1 page CV(s), prior work history, and a one page budget summary. This file must be less than 5 MB in total size. (Note this is the file that will be sent to the reviewers.)
- Include one file containing the entire proposal and all the supporting documentation (JPL attachments Group A). This file must be less than 15 MB in total size.
- ***Must not*** have multiple file extensions (e.g., doc.pdf). JPL IT Security system may reject multiple file extensions for suspected malicious content.
- Be sent to the Subcontracts Manager referenced under "Communications in Reference to this RFP" at the bottom of the RFP cover page.

Notify the Universities Group Supervisor referenced on the JPL RFP Cover Page if multiple e-mails are needed for a given volume of your proposal (e.g., technical/Management, Cost, or Past Performance [if any]).

If the submission of more than one e-mail is required, then ALL e-mails must be received by the time and date stated on the RFP cover sheet.

2.0 LATE E-MAIL PROPOSALS

Any proposal, portion of a proposal, or unrequested proposal revision received at JPL after the date and time specified on the cover page of this RFP will not be considered for evaluation and award, except under any of the following circumstances:

2.1 JPL determines that the proposal was late due solely to mishandling by JPL after receipt at JPL, provided that the timely receipt at JPL is evidenced by JPL records.

2.2 No acceptable proposals are received as of the proposal due date and time.

2.3 If any emergency or unanticipated event interrupts normal JPL operations so that proposals cannot be received by JPL by the date and time specified on the cover page of this RFP, and urgent JPL requirements preclude amendment of the solicitation closing date, the date and time specified for receipt of proposals will be extended to the same time of day specified in the solicitation on the first work day on which normal JPL operations resume.

3.0 SOURCE EVALUATION AND SELECTION PROCESS

The basis of source selection is predicated on the following (JPL, at its discretion, may waive minor informalities and minor irregularities in proposals received.):

3.1 Proposals will be evaluated in the areas of technical value as described in the Technical/Management Proposal Instructions of the RFP. Source selection will be based on the responsive, responsible (within the meaning of Federal Acquisition Regulation 9.1) offeror whose proposal is determined to represent the best technical and management value to JPL for the anticipated firm fixed-price amount of up to $25,000.

3.1.1 Proposals will be evaluated against the pre-set areas of evaluation outlined in the Technical/Management Proposal Instructions of the RFP.

3.1.2 JPL may, at its discretion, conduct limited communications with one or more proposer(s) for the purpose of determining whether the proposer(s) should be included

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in the competitive range. Such pre-competitive range communications may be conducted to enhance JPL understanding of proposal(s) and would be used to clarify omissions, ambiguities and uncertainties in the proposal's supplemental business/cost information. Proposers not considered within the competitive range are eliminated from further consideration and are so notified.

3.1.3 JPL may make source selection after the initial proposal evaluation or may conduct discussions with the proposers determined to be within the competitive range. The purpose of the discussions will be to assist the evaluators in fully understanding each proposal by verifying strengths and weaknesses, discussing any omissions and ambiguities, assessing the proposed personnel and examining the proposer's capabilities for performing the work.

4.0 EXCEPTIONS

No exceptions allowed: JPL has made the determination that ANY exceptions to JPL's General Provisions and/or Additional General Provisions will render your proposal unacceptable.

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TECHNICAL/MANAGEMENT PROPOSAL INSTRUCTIONS

Present and organize your proposal in accordance with the following:

1.0 MANDATORY QUALIFICATION(s)

Must be a Higher Educational Institution in the United States of America.

2.0 ELIGIBILITY OF APPLICANTS

Prospective investigators from U.S. Higher Educational Institutions, are welcome to respond to this solicitation.

3.0 SUBCONTRACT AWARDS

3.1 JPL anticipates issuing multiple RSA awards not to exceed $25,000. The Period of Performance will be approximately 8 months.

3.2 BUDGETS

A budget page is required but does not count against the three page limit and will not be used as part of the evaluation process. (For budget purposes, we recommend using a Period of Performance of September 1, 2014 – May 31, 2015.)

3.3 JPL will issue Research Support Agreements (RSA).

3.4 JPL anticipates making selection notifications on or around August 25, 2014.

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4.0 VOLUME I: TECHNICAL/MANAGEMENT PROPOSAL INSTRUCTIONS INTRODUCTORY

INSTRUCTIONS

JPL will evaluate Volume I of your proposal based on the information asked for in the below table and subsequent "Technical/Management Criteria and Factors," in respect to the degree to which your proposal meets the requirements/needs of the specified tasks herein. The degree to which the requirements/needs are met may include any number of considerations, such as the suitability of the various areas of the technical/management approach(es), the level of understanding of the requirements, the extent of insight into the technical/management challenges and their solution(s), the relevancy of corporate and/or personnel experience, etc., <u>as is appropriate for each area of evaluation</u>.

VOLUME I - TECHNICAL/MANAGEMENT EVALUATION CRITERIA AND ORGANIZATION	
TECHNICAL/MANAGEMENT CRITERIA AND THEIR WEIGHTING	
Criteria	Weighting
TECHNICAL/MANAGEMENT CRITERIA	
• Responsiveness to the technical requirements of the Tasks specified in the RFP and qualifications of the proposing team.	60%
Factors: • Understanding of the requirements • Feasibility of the proposed task • Completeness of the proposal • Cost	
• Experience and capabilities of the proposer	40%
Total Score Possible:	1,000

Proposers may submit one or multiple proposals addressing the requested task (As described below). Proposals must describe:

1) which Europa science objective(s) will be addressed from the following list
   a. Landing site reconnaissance
   b. Gravity fields
   c. Magnetic fields
   d. Atmospheric and plume Science (dust composition, gas composition, isotopic composition)
   e. Radiation Measurements
2) what kind of instrument will be used to make the measurement,
3) the scope of the study including the level of detail that will be provided,
4) the approach that will be used and
5) a brief description of the deliverable product.

The proposed study can assume that the CubeSat will be carried to the Jovian system aboard the potential Europa Clipper spacecraft and released at a desired time to flyby Europa, or go into orbit, or become an impactor or a combination thereof. The study can assume power will be provided to fully charge the CubeSat batteries prior to deployment. The study can also assume that the Europa Clipper spacecraft will have a UHF radio with an omni directional antenna with approximately 6 dB of gain for communication and that a cold-gas ACS and/or cold-gas propulsion system is allowed to be part of the CubeSat design. The proposed concept must stay within certain technical constraints including having a maximum volume of 3U and corresponding maximum mass of 4.5kg, be able to operate standalone, except for communication, from the Europa Clipper spacecraft in the harsh Jovian system radiation and thermal environment long enough to meet the mission objective.

The body of the proposal is limited to 3 pages. In addition, to these 3 pages, the proposal should include a one page CV for each investigator, full journal style reference list (including paper title), and a one page budget summary (Attachment A-19). Page limits will be strictly enforced. A page is each face of a piece of paper containing substantive, evaluable information; page size: 8 ½" x 11"; any drawings/photos are included; single spacing minimum; font size not less than 12 point; all margins 1" or greater. Additional administrative detail such as your institution cover letter or explained budget detail should be provided in a second pdf file with no page limits. Two files for each proposal are required as described in Section 1.4.

Europa Clipper is a concept under study by NASA Jet Propulsion Laboratory (JPL) and the Applied Physics Laboratory (APL), Johns Hopkins University that would conduct detailed reconnaissance of Jupiter's moon Europa and would investigate whether the icy moon could harbor conditions suitable for life. The mission would perform a detailed investigation of Europa using a highly capable, radiation-tolerant spacecraft that would perform repeated close flybys of the icy moon from a long, looping orbit around Jupiter.

The possible payload of science instruments under consideration includes radar to penetrate the frozen crust and determine the thickness of the ice shell, an infrared spectrometer to investigate the composition of Europa's surface materials, a topographic camera for high-resolution imaging of surface features, and an ion and neutral mass spectrometer to analyze the moon's trace atmosphere during flybys.

The launch could be as early as June of 2022 with an arrival in the Jovian system in 2025. The nominal Europa Clipper mission would then perform 45 flybys of Europa at altitudes varying from 2700 km to 25 km.

Additional information about the Europa Clipper mission study is available at: http://solarsystem.nasa.gov/europa/

5.0 Attachments

The section of this RFP entitled "Attachments" consists of those forms and documents containing information applicable to this RFP and must be completed and attached to your proposal.

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Attachments to the Solicitation

GROUP A – Complete and return as part of your quotation/proposal those marked with an "X"		
Various Solicitation Types:		
☐	A-1	Acknowledgment (Form JPL 2384)
☐	A-2	Cost Accounting Standards (Form JPL 2842)
☐	A-3	Government Property Questionnaire (Form JPL 0544)
☐	A-4	Acknowledgment - Commercial Items or Services (Form JPL 2384-1)
☐	A-5	Acknowledgment - CREI Contract (Form JPL 2384-3)
☐	A-6	Notice of Total Small Business Set-Aside (Form JPL 4022)
☐	A-7	Notice of Total Small Business Set-Aside – Modified (Form JPL 4023)
☒	A-8	Acknowledgment – RSA Subcontract (Form JPL 2384-A8)
☐	A-14	Past Performance (Form JPL 0358)
☐	A-15	Cost Element Breakdown (Form JPL 0549)
☐	A-16	Determination of Lowest Overall Price – Labor-Hour/Time-and-Material Proposals (Form JPL 0359)
☒	A-19	Cost Elements Breakdown (Short Form) (Form JPL 0549-1)
☐	A-20	Evidence of Adequacy of Accounting System (Form JPL 7370)
☐	A-21	Supplier Information Request (Form JPL 7255)
GROUP B – Those marked with an "X" are for use in preparing your quotation/proposal:		
Various Solicitation Types:		
☐	B-1	Waiver of Rights to Inventions (Form JPL 62-301)
☐	B-2	Reserved
☐	B-4	° Instructions for Patent Agreement for Use in Support Service Subcontracts (Form JPL 2844)
		° Patent and Copyright Agreement (Form JPL 1929)
☐	B-5	Notice of Requirement of Pre-award On-Site Equal Opportunity Compliance Review (Form JPL 3553)
☐	B-6	Subcontracting Plan Requirements (Form JPL 0294) *(If applicable, Plans must be provided with Proposal)*
☐	B-7	Security Requirements for a Classified Subcontract (Form JPL 2891)
☐	B-8	Notice of Req. for Affirmative Action to Ensure Equal Employment Oppt. (E.O. 11246) (Form JPL 2899)
☐	B-9	☐ Notice to Prospective Subcontractors of Req. for an Environ. Audit of the Lease Facilities (Form JPL 2896)
		☐ Notice to Prospective Subcontractors of Req. for an Environ. Audit of the Lease Fac.-Alt. (JPL 2896-1)
☐	B-10	Certificate of Current Cost or Pricing Data (Form JPL 2496)
☐	B-11	Stds of Conduct & Proc. for Handling Subcontr. Personnel Problems, Discipline, & Separation (JPL 4412)
☐	B-12	Unescorted Access: Subcontractor Badging Instructions and Requirements (7394)
☐	B-13	Claims for Exceptions to Cost or Pricing Data (Form JPL 2703)
☐	B-17	JPL Subcontractor Environmental, Safety, & Health Requirements (Form JPL 2885)
☐	B-18	Experience Modification Rate (EMR) / Recordable Incident Rate / Lost Time Incident Rate (Form JPL 7245)
☐	B-19	Additional General Provision—Safety and Health (If applicable; plans required before award)

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Acknowledgement – RSA Subcontracts

(RFP Attachment A-8)

(This completed acknowledgement must accompany your offer)

Offeror Information

1. Offeror Name:

   Note: *Include the full name of the firm (not just any operating division) that would be required by you to appear on a subcontract, if one were to be awarded to your firm.*

2. Offeror Address:

3. Point of Contact: Name: Phone Number:

4. Business Classification (check all that apply):

   ☒ Educational Institution Business ☐ Non-profit Organization ☐ HBCU/OMI

Terms and Conditions

5. By signing this form below the offeror accepts the General Provisions entitled "Research Support Agreement," which are found at the following website: https://acquisition.jpl.nasa.gov/tc/).

6. The submittal of a proposal/quotation certifies your organization's compliance with the requirements specified in form JPL 2892, "Certifications," attached to the General Provisions (or which may be found at: https://acquisition.jpl.nasa.gov/tc/).

Audit Information

7. a. Audit Reports. The Offeror agrees that all Government audit reports directly related to its offer(s) and subcontract, if any, are authorized to be released to JPL. ☐ Yes ☐ No

   b. Is your organization a State or Local Government or Nonprofit Organization subject to Office of Management and Budget Circular No. A-133? ☐ Yes ☐ No (If yes, the "year ending" date of the most recent report is: *(Attach a copy of the most recent report, unless previously submitted to JPL).*

Offeror Certification

The undersigned certifies that he/she is authorized to certify and to commit the Offeror regarding the information on this form and for the total offer amount submitted.

Authorized Signature: ______________________ Date: ______________

Type/Print Name: ______________________

Phone: ______________________

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RFP No: SS06-30-14

Attachment A-19

Cost Elements Breakdown – Short Form

Cost Element	Hours, Rates, Extension		
	Hours	Rate	Extension
Direct Labor (by labor category)			
		$	$
		$	$
		$	$
		$	$
		$	$
		$	$
		$	$
		$	$
		$	$
		$	$
		$	$
Total:			$
Overhead			
base		%	$
base		%	$
Total Overhead:			$
Other Direct Costs			
Material			
Material Burden		%	$
Subcontracts			
Subcontract Burden		%	$
Travel			$
Misc.			$
Total ODC:			$
General & Administrative			
G&A		%	$
Total G&A:			$
Total Cost, Profit/Fee, and Total Price			
		Total Cost:	$
	Profit/Fee:	%	$
		TOTAL PRICE:	$

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RFP No: SS06-30-14

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, CA 91109-8099

RSA No. TBD

SPECIEMEN SUBCONTRACT

RESEARCH SUPPORT AGREEMENT (RSA)

This best-efforts, fixed-price Research Support Agreement (RSA), between the Subcontractor (identified below) and the California Institute of Technology, Jet Propulsion Laboratory ("the Institute" or "JPL"), is awarded pursuant to the Prime Contract between the Institute and NASA, and shall be administered in accordance with the following provisions and are incorporated by reference and made an integral part of this Agreement:

- **JPL General Provisions (GPs) entitled "Research Support Agreement" dated 4/14.**
- **Research Support Agreement** GPs may be accessed at: https://acquisition.jpl.nasa.gov/tc/
- **ARTICLES: see below.**

Subcontractor Name and Address: TBD

For Work Described In: Article I, Statement of Work of this subcontract.

Start Date: 9/01/14 **End Date: 5/31/15**

Total Authorized Fixed Price and Advance Payment Amount: $TBD

------------------- POINTS OF CONTACT ---------------------

	Name	Email	Phone No.
Subcontractor:			
Administrative			
Principal Investigator			
JPL:			
Subcontracts Manager	Susan Scrivner	Susan.g.Scrivner@jpl.nasa.gov	818-393-0930
Technical Manager	John Baker	John.D.Baker@jpl.nasa.gov	818-354-5004

The Parties have agreed to the terms and conditions and to the effective date of this Agreement, indicated by Signature Below.

	JET PROPULSION LABORATORY	TBD
By:	(Signature)	(Signature)
	Susan Scrivner (Type/Print Name)	(Type/Print Name)
Title:	Subcontracts Manager (Type/Print Title)	(Type/Print Title)

Pursuant to JPL NASA Prime Contract No. NNN12AA01C

ARTICLES

ARTICLE I. STATEMENT OF WORK

The Subcontractor shall perform Basic Research on a best-efforts basis. "Basic Research" is research that is directed toward increasing knowledge in science. The primary aim of Basic Research is a fuller knowledge or understanding of the subject under study, rather than a practical application of that knowledge. The Subcontractor shall perform the Basic Research, which is incorporated by this reference, as described in the Subcontractor's proposal entitled: **Europa CubeSat Concept Study**, or as may be attached hereto.

The Subcontractor shall describe the results of their research in the study deliverable which shall include the mission concept, the science measurement objective(s), the instruments used to make those measurements and any associated heritage, the length of the mission, the configuration of the CubeSat spacecraft concept and identification of key features, an equipment list, the power and data resources used during the mission operations, the data volume returned during the mission, the size and mass of the spacecraft, the trajectory/flight path used for the study, how the radiation environment was mitigated in the design, how the thermal environment was mitigated in the design, any key enabling assumptions made, design challenges encountered and what was learned.

ARTICLE II. DELIVERY OR PERFORMANCE SCHEDULE

The Subcontractor shall:

(a) Submit a Report on your concept. Must be in MS Word or Power Point, on or before the "End Date" as specified on page 1 of this Agreement.

The Final Report must be submitted electronically and identified by the number assigned to this RSA (in the subject line), to the cognizant JPL Contract Technical Manager (CTM), John D. Baker (john.d.baker@jpl.nasa.gov) .

ARTICLE III. PRICE AND PAYMENT

(a) The Subcontractor shall receive the total fixed price as an advance payment in the amount authorized on the face of this RSA.

(b) In the event the Subcontractor receives notification that the Investigator named on the cover of this RSA will be changing or has changed institutions, the Subcontractor shall provide JPL written notification along with a settlement check for any unused funds from the total amount specified on the face of this RSA, within thirty (30) calendar days of receipt of such notification.

ARTICLE IV. ALTERATIONS TO THIS RSA

The following alterations have been made in this RSA:

(a) In the General Provisions applicable to this RSA, wherever the word "schedule(s)" appears in reference to the work or costs of this RSA, said references shall refer to the work referenced and price specified on the first page of this RSA. Other General Provision references to "schedule(s)" shall be deemed to refer to the "Articles" portion of this RSA.

ARTICLE V. ADDITIONAL GENERAL PROVISION(S)

The following Additional General Provision(s) is (are) incorporated by reference and made an integral part of this Agreement:

(a) Reserved

Appendix B - Proposal: Europa Clipper Concept Study

Europa Clipper Concept Study: Characterizing Subsurface Oceans with a CubeSat Magnetometer Payload

1. Statement of Work

The Europa CubeSat Concept Study aims to determine the feasibility and concepts required to place a 3U CubeSat in close range of Europa with the primary science goal of characterizing the subsurface ocean. The concept study will focus on feasibility, with heavy emphasis on the Jovian environment (radiation and thermal) and achieving constant, close proximity to Europa with a CubeSat. Integrating a magnetometer (primary instrument) and secondary instruments such as a dosimeter or ion/neutral mass spectrometer will also be studied.

2. Study Objectives

There will be four main objectives of this study:

1. Determine if it is possible for a 3U CubeSat to fly close enough to Europa for a duration required to collect high spatial/ temporal magnetometer data either by orbiting Europa or remaining in Jupiter orbit synchronous to Europa.
2. Determine if it is possible for a CubeSat to survive in the harsh Jovian environment by investigating how much radiation shielding and active heating is required for adequate lifecycle.
3. Determine the optimal magnetometer payload to be flown by a 3U CubeSat in Europa orbit. If volume/mass allows, determine the type of dosimeter and/ or ion neutral mass spectrometer to be flown in addition.
4. The fourth objective will depend on the outcomes of objectives one and two.
    a. If both one and two are deemed feasible, it will be to refine a mission to accomplish the primary science goal while adhering to design constraints and Europa Clipper requirements.
    b. If either objective one or two is deemed infeasible or highly unlikely, it will be to identify specific areas of research and technology development needed to make a future CubeSat mission to Europa possible.

3. Science Goals

According to the *2012 Europa Study Report*, the top objective of a Europa flyby mission is to characterize the ice shell and subsurface water. One way to achieve this is through a magnetic induction experiment that determines salinity and thickness of Europa's ocean by measuring the induction signature of Europa at multiple frequencies. The induction signature can quantify electrical conductivity distribution, ultimately revealing the salinity content and depth of subsurface salt-water ocean. However, attaining a convincing B field signature requires repeated measurements at similar locations throughout time. This may prove difficult with a flyby mission but could be achieved with a CubeSat in close proximity. The addition of magnetic field measurements in Europa's close vicinity to ice penetrating radar (IPR) data from Clipper could drastically increase ability to characterize subsurface liquid and ice shell. This combination of data may also aid in quantifying thermal process between ice/ ocean exchange and surface

Proposal - Page 1 of 3

structures. If volume and mass permit, the inclusion of an ion neutral mass spectrometer (INMS) and/ or dosimeter will allow the CubeSat to address the remaining two main objectives identified in the *2012 Europa Study Report* (second column of the traceability matrix).

Traceability Matrix				
Decadal Survey Questions	Europa Study Priority Objectives	CubeSat Science Goals	CubeSat Measurements	Clipper Measurements
What are the thickness of Europa's outer ice shell and the depth of it's ocean?	Europa's Ice Shell: characterize the ice shell and any subsurface water including their heterogeneity, and the nature of surface-ice-ocean exchange.	Goal 1: Using magnetic induction, determine depth and salinity content of the subsurface ocean. Determine the thickness of it's ice shell.	MAGNET-OMETER Continuous, global, coarse grain	IPR SHALLOW MODE: Vertical Depth: 3km Vertical Res: 10m
What is the magnitude of Europa's tidal dissipation, and how is it partitioned between the silicate interior and the ice shell?				IPR DEEP MODE: Vertical Depth: 30km Vertical Res: 100m
How do (Jupiter) satellites influence their own magnetospheres and those of their parent planets?				MAGNETOMETER Finer-grain, localized, discontinuous (flyby)
What fraction of the material in Jupiter's magnetosphere originates from Europa and other icy satellites?	Europa's Composition: Understand the habitability of Europa's ocean through composition and chemestry.	Goal 2: Investiage ion-surface interaction and ion-neutral interaction near Europa with in-situ measurements.	INMS*	INMS Sensitivity at least 10 particles cm-3 Flyby velocity of <7km/s Altitude 25-200 km
What are the relative roles of sublimation, molecular transport, sputtering, and active venting in generating tenuous satellite atmospheres				SWIRS Surface reflectance from 850-5000 nm with 10 nm resolution. Ability to target specific regions.
How do exogenic processes modify Europa? Possible radiation-driven chemestry?	Europa's Geology: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest local-ities.	Goal 3: Further characterize Jupiter-Europa environment/ interaction by monitoring radiation doses in close range of Europa	Dosimeter*	IPR/ TI TI with 250 m horizontal, and 20 m vertical resolution. Accuracy of 50 km either side of target.

* *Will only be considered if additional payload space allows*

CubeSat INMS data will heavily aid the INMS and Shortwave Infrared Spectrometer (SWIRS) aboard Clipper in determining the composition and geology of Europa and may also aid in characterization of ion-neutral interactions in the wake Europa and ion-surface chemistry due to water molecule sputtering. Furthermore, the inclusion of a CubeSat dosimeter could provide a means to understanding Europa's geology by examining potential radiation-driven chemistry.

4. Facilities, Experience & Team

The management team will lead select members of the Michigan eXploration Lab (MXL) and students enrolled in the Masters of Engineering in Space Engineering (MEng) in contributing to the study. The MXL has flight experience with four CubeSats. The most recent, M-Cubed2 successfully operated COVE imaging hardware developed by JPL and just delivered GRIFEX, another shared endeavor with JPL. MXL is also in the process of constructing CADRE, an NSF CubeSat with a science payload of two mass spectrometers and four energy analyzers. Members of the MXL and the MEng program are also involved with CAT and QB50. The CubeSat

Ambipolar Thruster (CAT) has undergone several successful tests after generating $97K on Kickstarter to develop a helicon wave plasma thruster. Research and test data generated by the CAT project may be particularly useful when conducting orbital simulations for this concept study. Michigan was also one of four academic institutions in the U.S.A. funded by QB50 to build a 2U CubeSat with an atomic/ molecular oxygen sensor payload. Members of the MXL and faculty/students in the MEng program have extensive experience with design tools such as: STK, GMAT, Altium, Solidworks, SPENVIS and SRIM and frequently fabricate spacecraft parts using precision milling, laser cutters and 3D printing. Students/faculty have access to and regularly use thermal vacuum chambers, 3D air bearings, and Helmholtz coils. MXL and MEng faculty/students also collaborate with members of the Space Physics Research Lab (SPRL), with extensive experience with space instrumentation. SPRL is located nearby on campus and has worked on recent NASA projects such as MSL and is leading the CYGNSS mission.

Management Team	
Principal Investigator (PI)	Dr. James Cutler
	Professor, Aerospace Engineering
	Founder MXL, Previous PI Experience
Co-Principal Investigator (Co-I)	Dr. Xianzhe Jia
	Research Scientist, AOSS
	Research Experience: Europa, Magnetic Fields
Project Manager (PM)	Casey Steuer
	PhD Student, AOSS
	MXL Member, MEng Student, CubeSat PM
Trajectory Analyst (TS)	Nathan Boll
	PhD Student, AOSS
	CYGNSS Orbital Analysis, STK Certified, GMAT Experience

5. Deliverables & Timeline

If awarded, the study will be delivered as an MS Word document meeting all objectives. Any simulations and test results related to feasibility will be included as appendixes and if deemed feasible a mission concept with details commensurate to a preliminary design review will be included. If deemed infeasible, a report highlighting quantitative improvements in CubeSat technology required for a future mission of similar scope will be substituted.

During the first five months focus will be towards feasibility and optimizing a payload. MXL and MEng students will conduct radiation and thermal analysis and lifecycle/ power studies, while flight paths and propulsion methods are simulated and evaluated. Once possible trajectories are identified we will begin researching and developing a magnetometer payload optimized to compliment the Clipper instrument suite.

Months six and seven will be spent meeting objective four. If an appropriate lifecycle and flight path can be achieved, a study similar to a PDR will be drafted. Functional requirements will be drafted utilizing the most recent Clipper requirements and CubeSat/P-POD design specifications. CubeSat subsystems including ADCS will be optimized and simulations for power generation, deployable configuration and communications will be completed.

Effort in the final month will be spent organizing work and generating a finished report. Analysis will be re-run if needed and several drafts will be read and edited before submission.

Appendix C - Research Support Agreement

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, CA 91109-8099

JPL

RSA No. 1513471

RESEARCH SUPPORT AGREEMENT (RSA)

This best-efforts, fixed-price Research Support Agreement (RSA), between the Subcontractor (identified below) and the California Institute of Technology, Jet Propulsion Laboratory ("the Institute" or "JPL"), is awarded pursuant to the Prime Contract between the Institute and NASA, and shall be administered in accordance with the following documents and ARTICLES, which are incorporated by reference and made an integral part of this Agreement (below documents can be accessed at: **https://acquisition.jpl.nasa.gov/tc/)**

- **"General Provisions (GPs) for Research Support Agreement," dated 4/14.**
- **"Subcontract Forms Set," dated 4/14.**
- **ARTICLES: see below.**

Subcontractor Name and Address: The Regents of the University of Michigan
Office of Research and Sponsored Projects
3003 South State Street
Ann Arbor, MI 48109-1274

For Work Described In: Article I, Statement of Work of this subcontract.

Start Date: 09/17/2014 **End Date:** 06/15/2015

Total Authorized Fixed Price and Advance Payment Amount: $25,000

------------------- POINTS OF CONTACT ---------------------

	Name	Email	Phone No.
Subcontractor:			
Administrative	Kathryn DeWitt	dewitt@umich.edu	734-936-1288
Principal Investigator	James Cutler	jwcutler@umich.edu	734-615-7238
JPL:			
Subcontracts Manager	Karissa Marquez	Karissa.J.Marquez@jpl.nasa.gov	818-393-0563
Technical Manager	John Baker	John.D.Baker@jpl.nasa.gov	818-354-5004

The Parties have agreed to the terms and conditions and to the effective date of this Agreement, indicated by Signature Below.

	JET PROPULSION LABORATORY	THE REGENTS OF THE UNIVERSITY OF MICHIGAN
By:	Karissa J Marquez (Signature)	(Signature)
	Karissa J. Marquez (Type/Print Name)	Peter J. Gerard, Associate Director, Grants and Contracts (Type/Print Name)
Title:	Subcontracts Manager (Type/Print Title)	(Type/Print Title)

Pursuant to JPL NASA Prime Contract No. NNN12AA01C

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ARTICLES

ARTICLE I. STATEMENT OF WORK

The Subcontractor shall perform Basic Research on a best-efforts basis. "Basic Research" is research that is directed toward increasing knowledge in science. The primary aim of Basic Research is a fuller knowledge or understanding of the subject under study, rather than a practical application of that knowledge. The Subcontractor shall perform the Basic Research, which is incorporated by this reference, as described in the Subcontractor's proposal entitled: **"Europa CubeSat Concept Study: Characterizing Subsurface Oceans with a CubeSat Magnetometer Payload"**, dated: **8/25/14** , or as may be attached hereto.

ARTICLE II. DELIVERY OR PERFORMANCE SCHEDULE

The Subcontractor shall:

(a) Submit a Final Report that briefly summarizes the status of the work described in Article 1 above, on or before the "End Date" as specified on page 1 of this Agreement.

The Final Report must be submitted electronically and identified by the number assigned to this RSA (in the subject line), to the cognizant JPL Technical Manager named on the face of this RSA.

(b) Submit any interim report(s), and a final report of subject inventions, in accordance with the General Provision entitled "Patent Rights – Retention by the Subontractor" to the cognizant JPL Subcontracts Manager named on the face of the RSA.

ARTICLE III. PRICE AND PAYMENT

(a) The Subcontractor shall receive the total fixed price as an advance payment in the amount authorized on the face of this RSA.

(b) In the event the Subcontractor receives notification that the Investigator named on the cover of this RSA will be changing or has changed institutions, the Subcontractor shall provide JPL written notification along with a settlement check for any unused funds from the total amount specified on the face of this RSA, within thirty (30) calendar days of receipt of such notification.

ARTICLE IV. ALTERATIONS TO THIS RSA

The following alterations have been made in this RSA:

(a) In the General Provisions applicable to this RSA, wherever the word "schedule(s)" appears in reference to the work or costs of this RSA, said references shall refer to the work referenced and price specified on the first page of this RSA. Other General Provision references to "schedule(s)" shall be deemed to refer to the "Articles" portion of this RSA.

ARTICLE V. ADDITIONAL GENERAL PROVISION(S)

The document entitled "Additional General Provisions Set," dated 4/14, is hereby incorporated into and made a material part of this subcontract. It is found at: https://acquisition.jpl.nasa.gov/tc/. Only the following AGPs are made a part of this subcontract:

- *Reserved.*

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