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A Europa CubeSat Concept Study for Measuring Atmospheric Density and Heavy Ion Flux

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Abstract

This paper describes a mission concept study conducted for a CubeSat to be carried aboard the *Europa Clipper* and released in the Jovian system to make *in situ* measurements at Europa. It details the scientific return as well as the technical feasibility of a CubeSat designed to elucidate the linkage between Europa's atmospheric structure and the Jovian radiation environment, which generates Europa's atmosphere through sputtering and radiolytic processes. The primary goals of the mission are to make *in situ* measurements of a) H^+ , O^{n+} , and S^{n+} particles with energies ~ 8 – 100 MeV/nuc at Europa and b) atmospheric density through drag forces on the CubeSat, entitled the Deployable Atmospheric Reconnaissance CubeSat with Sputtering Ion Detector at Europa (DARCSIDE). The study demonstrates that the technology exists to enable a 3U, 4.6 kg CubeSat to detect Europa's tenuous atmosphere through drag imparted on the vehicle for ~ 300 s of flight time during a single flyby down to an altitude of 10 km above Europa's surface. By including a charged particle detector capable of detecting protons, oxygen, and sulfur ions in discrete energy bins (8–20 MeV/nuc, 20–50 MeV/nuc and 50–100 MeV/nuc), DARCSIDE can also measure the sputter-inducing charged particle flux incident on Europa's surface. In addition to providing highly complementary science to the mass spectrometer, ultraviolet, and imaging spectrographs onboard the *Europa Clipper*, the combination of the accelerometer and charged particle detector will yield important insights for the study of Europa's atmospheric constituents and densities, its surface composition, its interaction with the Jovian magnetosphere, and possibly links to its subsurface ocean through potential plume measurements.

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1. Introduction

The development of NASA's upcoming Europa Mission (henceforth the *Europa Clipper*)—a flagship mission slated for launch to the Jovian system in the 2020s (Europa Study Team, 2012; Phillips and Pappalardo, 2014)—includes extensive instrumentation to study Europa's surface and atmospheric composition, its icy shell thickness and subsurface ocean, magnetic field, and recently observed plume activity (Roth et al., 2014; Sparks et al., 2016). With the approval of a more powerful launch system—the Space Launch System (Donahue et al., 2016) instead of the previously planned Atlas V 551—and potentially a surface lander (Hand et al., 2017), the spacecraft may also be able to carry deployable CubeSats for further scientific study of Europa during one of its 45 close (~ 2700 –25 km altitude above Europa) flybys of the moon. This paper describes the results of a concept study for the Deployable Atmospheric Reconnaissance CubeSat with Sputtering Ion Detector at Europa (DARCSIDE)—a 3U, 4.6 kg CubeSat—conducted by a team of investigators at New Mexico State University to assess the potential science return of a CubeSat at Europa. The primary objective of the DARCSIDE mission will be to execute a low altitude (10 km) flyby of Europa in conjunction with a flyby of the Europa Clipper spacecraft to measure Europa's atmospheric density and heavy ion radiation environment.

The following sections briefly discuss the current state of understanding of Europa's tenuous atmosphere, followed by the key scientific objectives of the DARCSIDE mission and a discussion of DARCSIDE's synergies with the *Europa Clipper*. Section 2 details the science feasibility of the mission, which will allow the measurement of both Europa's atmospheric density and the heavy ion flux thought to be responsible for the generation of the atmosphere itself. The concept of operations and mission design are discussed in Section 3. Orbit and range determination, and a detailed description of the spacecraft payload and bus (including concerns regarding Jupiter's intense radiation environment) are provided in Section 4, along with a brief discussion of risks and potential future work needed to bring this concept study forward

to a mission concept review. The study conclusions are summarized in Section 5.

1.1. Background and Motivation

Europa's surface-bound atmosphere is dominated by molecular oxygen, which is liberated through radiolysis and sputtering interactions of ionized sulfur, oxygen, hydrogen, and charged particles with Europa's water ice surface (Johnson et al., 2009 and references therein). Other water family species produced through Europa's sputter-induced chemistry—including H_2O , OH, H_2 , O, and H (Paranicas et al., 2009)—either recombine with the surface or exceed Europa's escape velocity to make up the energetic neutral atom population in the circum-Jovian torus found at Europa's orbit (Mauk et al., 2003).

Europa's atmospheric O_2 column densities were initially inferred from particle sputtering rates (Johnson et al., 1982) prior to the first detection of Europa's atmosphere with the Hubble Space Telescope (Hall et al., 1995). A wealth of atmospheric models have since been developed, with increasing sophistication as additional trace elements such as Na, K, SO_2 , and CO_2 , which have been detected in Europa's atmosphere (Johnson, 2000) and surface (Hendrix et al., 2011), are included. However, until *in situ* measurements of Europa's bound and escaping atmospheric constituents are obtained, the exact species, source processes, and possible connections to the surface and subsurface ocean remain elusive (Vance and Goodman, 2009; Hand et al., 2009; Huybrighs et al., 2016).

The number density of ions and charged particles trapped in Jupiter's magnetosphere, which erode Europa's surface through sputtering and alter its atmospheric composition through excitation and charge exchange, presents a well-established explanation for Europa's atmospheric composition (Paranicas et al., 2009; Johnson et al., 2009). Particle sputtering models (Cassidy et al., 2013) suggest that the flux of “hot” (~ 100 s keV – MeV/nuc) ions, primarily S^+ , is responsible for the majority of H_2O liberation from the surface, while “cold” (~ 100 s eV/nuc) ions may account for the majority of O_2 in Europa's bound atmosphere. DARCSIDE will make measurements of the former

group, which will not be detected directly by the *Europa Clipper*.

Roth et al. (2014) and, more recently, Sparks et al. (2016) reported the detection of a water vapor plume over Europa's south polar region based on observations from the Hubble Space Telescope. This provides a tantalizing link to Europa's subsurface ocean, and an additional potential source process responsible for Europa's atmosphere. However, the plumes may be ephemeral in nature, and may not be present during specific (or any) *Europa Clipper* flybys; thus, we considered the possibility that they exist in our atmospheric modeling efforts, but also ensured that lack of plume activity would not compromise DARCSIDE's science return.

1.2. Key Science Questions and Objectives

The goal of the DARCSIDE CubeSat mission is to reveal the nature of Europa's atmosphere to complement measurements made by the *Europa Clipper*. This leads to the two key science questions for the mission:

1. What is the density structure of Europa's atmosphere?
2. What is the nature of the energetic particle population believed to be the mechanism through which Europa's atmosphere is generated and sustained?

The DARCSIDE scientific objectives are therefore to:

- Determine Europa's atmospheric mass density structure down to 10 km above the surface by measuring atmospheric drag imparted on the spacecraft.
- Determine the energetic particle flux at Europa with a solid-state particle telescope capable of detecting proton and ion particles with energies between 8–100 MeV/nuc throughout the flight to Europa.

Together, *in situ* measurements of Europa's atmosphere and ion flux would provide unique insight into Europa's surface composition, possible subsurface ocean activity (i.e. plumes), and a deeper understanding of the diffuse neutral atom torus found at Europa's

orbit. When compared to previous models and observations of Europa's atmosphere and neutral torus, these measurements will improve our understanding of the generation of sputter-induced, tenuous atmospheres unique to icy moons around the giant planets.

1.3. Synergies with *Europa Clipper*

DARCSIDE's science focus and instrument suite are highly complementary to those of the *Europa Clipper*. DARCSIDE will characterize Europa's vertical atmospheric mass/density structure as quantified by measured spacecraft deceleration induced by atmospheric drag. Additionally, DARCSIDE will quantify the fluxes and energies of charged particles responsible for the surface sputtering production of Europa's atmosphere by measuring H, S, and O ions with energies between 8–100 MeV/nuc with a solid-state particle telescope.

The *Europa Clipper*'s MAss SPectrometer for Planetary EXploration (MASPEX) will provide direct volatile species abundance information via ingestion and identification of those species during its close passes by Europa. The summing of those abundances and their atomic/molecular weights provides an estimate of the atmospheric density encountered. DARCSIDE's physical measurement of gas density complements the results from MASPEX, and the DARCSIDE measurements would be obtained for a lower altitude than any MASPEX observations. If DARCSIDE's drag pass occurs in conjunction with a flyby of the *Europa Clipper*, atmospheric scale height information between their two altitudes could be achieved; additionally, DARCSIDE's measurements can aid in the absolute calibration of MASPEX during the initial flyby of Europa. Conversely, the *Europa Clipper*'s single low altitude (25 km) passage could likely provide the only direct dynamic detection of Europa's atmosphere by the mission, and only if it is instrumented with appropriately sensitive accelerometers or if subsequent orbit reconstruction from tracking is feasible.

The Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument aboard NASA's *Mars Atmosphere and Volatile Evolution* (MAVEN) spacecraft is

providing volatile species number density measurements at Mars (Mahaffy et al., 2015) similar to what MASPEX is expected to provide at Europa. MAVEN has also measured the dynamic pressure and gas-drag deceleration experienced by the spacecraft with accelerometers, especially during its initial ‘deep dip’ campaigns. These simultaneous NGIMS and accelerometer measurements from Mars will provide valuable guidance for designing, collecting, and interpreting similar measurements made by the *Europa Clipper* and DARCSIDE.

The *Europa Clipper*’s Ultraviolet Spectrograph (UVS) will characterize species abundances over a greater spatial and radial extent than either MASPEX or DARCSIDE. DARCSIDE’s accelerometer measurements would complement the UVS measurements by providing an additional estimate of atmospheric density to compare with UVS measurements obtained near in time to DARCSIDE’s drag pass.

The instrument selections for the *Europa Clipper* did not include an energetic particle detector to measure the “hot” component of the heavy ion bombardment on Europa, hence the particle measurements made by DARCSIDE represent a unique data set that would add value to the *Europa Clipper*. The Mapping Imaging Spectrometer for Europa (MISE) instrument on the *Europa Clipper* will provide measurements from which Europa’s surface composition can be derived. DARCSIDE’s measured energetic particle spectra will provide quantification of the particle flux impinging upon Europa’s surface, creating the sputter-produced atmosphere. Thus, the combination of MISE and DARCSIDE measurements will constrain the rates of volatile production and the anticipated abundances of various volatiles.

2. Science Feasibility and Traceability Matrix

The atmospheric and sputtering processes described in Section 1 will be investigated in part by the *Europa Clipper* through ultraviolet and neutral mass spectrometry; however, atmospheric density and *in situ* ion flux measurements by a CubeSat can provide highly complementary science for the determination of Europa’s atmospheric composition and structure,

and its generation through sputtering. To assess the capability of a 3U CubeSat to measure the atmospheric density at Europa through an aerobraking pass, a deployable drag panel array was designed to greatly increase the effective surface area of DARCSIDE—described in more detail in Section 4.3.1. Using estimated densities of the bound and escaping (O_2 and H_2 dominated, respectively) atmosphere populations to calculate the induced drag on this solar panel array, the effectiveness of current accelerometer technology available for CubeSats for a low altitude aerobraking pass was determined and numerical simulations were used to compare DARCSIDE measurements to those expected to be made by the *Europa Clipper* under similar conditions.

A family of atmospheric density profiles (Figure 1a) was computed that considered a range of surface gas densities from McGrath et al. (2009), similar to published models used to initialize Europa’s neutral atom torus (Smyth and Marconi, 2006). Assuming a simple geometric model of Europa’s atmosphere in which a low altitude pass over Europa is approximated as a straight line symmetric about the lowest altitude tangent point, the time spent by DARCSIDE in Europa’s atmosphere ranges from tens to several hundred seconds depending on the altitude of the flyover. The corresponding atmospheric density that DARCSIDE would encounter as a function of time is shown in Figure 1b, for a target altitude of 10 km. With these basic assumptions about the flight time through Europa’s atmosphere and the number densities present in the path, techniques similar to those applied for spacecraft aerobraking within Mars’ atmosphere (e.g., Tolson et al., 2002) were used to determine the atmospheric drag felt by DARCSIDE using the following relation: $m a_z = 0.5 \rho v^2 C_z A$. Here, m is the mass of the CubeSat; a_z is the acceleration in the direction parallel to the satellite’s velocity, v ; the atmospheric mass density is given by ρ ; the effective area of the CubeSat is given by A ; and the aerodynamic drag coefficient (assumed to be ~ 2 for a flat, square surface area) is C_z . For a simulated tangent flight starting at 500 km altitude with a velocity of 4 km s^{-1} , the resulting drag profiles for a low altitude tangent height (10 km for DARCSIDE, 25 km for the *Europa Clipper*) are shown in Figure 2 for both

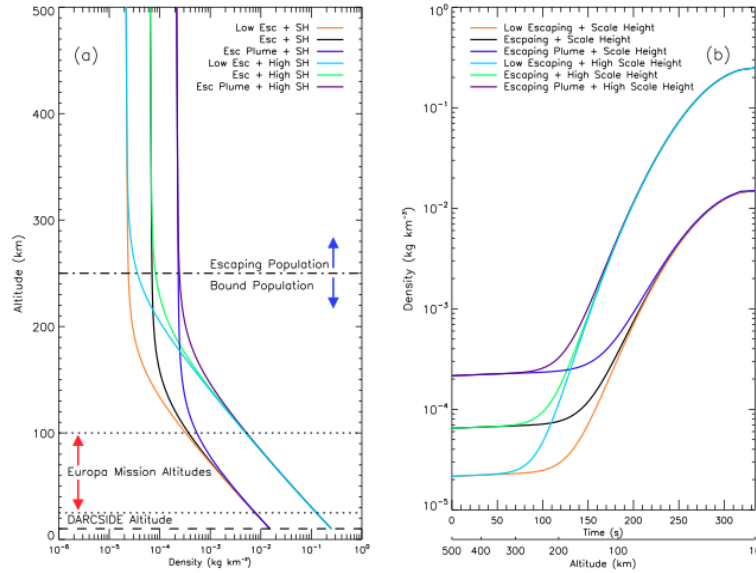


Figure 1. (a) Simple atmosphere models generated by combining a 'scale height' (SH) and 'escaping atmosphere' profile (Esc) for various surface densities and enhancement due to a plume, based on combined water-family species modeled by Smyth and Marconi (2006). The dash-dot line denotes where Europa's bound (mostly O₂; below the line) and escaping (mostly H₂; above) populations dominate the atmospheric density profiles. DARCSIDE's nominal 10 km altitude is plotted (dashed), as well as the range of altitudes for the Europa Clipper (25–100 km, dotted). (b) Mass density as a function of time and spacecraft altitude for a nominal DARCSIDE pass down to 10 km above the surface.

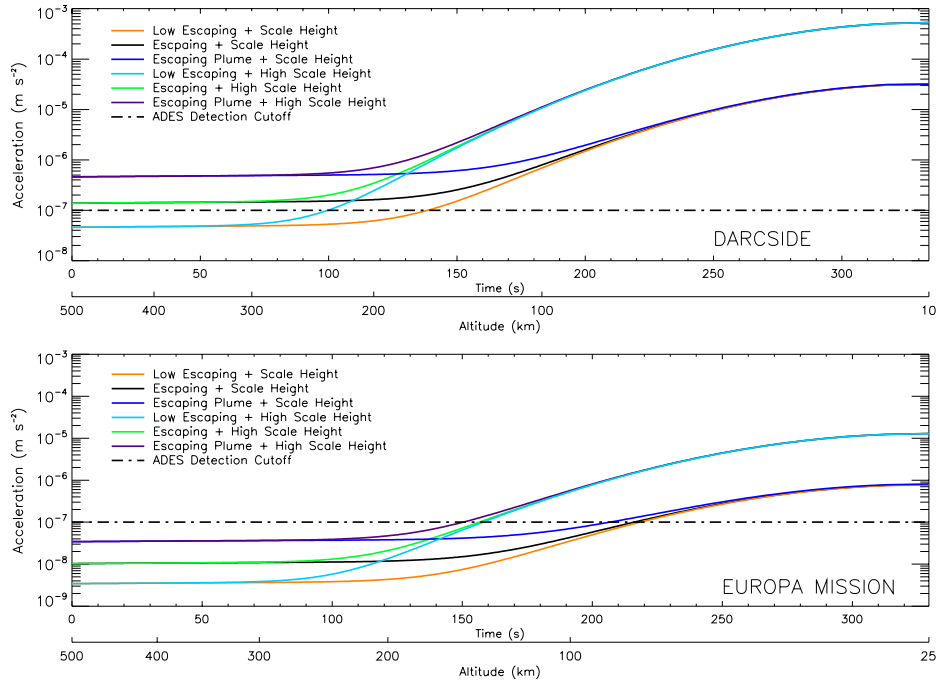


Figure 2. Modeled atmosphere-induced drag as would be measured by DARCSIDE (top) and the *Europa Clipper* (bottom), in addition to the AFRL ADES detection limit (dot-dashed black line). For various scale height and escaping atmosphere profile combinations, DARCSIDE will be able to detect a large extent of Europa's atmosphere; the *Europa Clipper*, conversely, may only be able to detect the bound portion (see Figure 1) if it were equipped with the same accelerometer (note the difference in scale on the y-axes).

spacecraft. These drag measurements are compared to the sensitivity of the Air Force Research Laboratory (AFRL) Atmospheric Drag Environment Sensor (ADES) accelerometer, which is capable of measuring atmospheric drag down to 10 nano-g (Sutton et al., 2010).

Since the large mass of the *Europa Clipper* spacecraft (~3500 kg) dominates over the surface area provided by its solar panels (~36 m²), the above equation reveals that DARCSIDE's inverse ballistic coefficient is ~13 times greater than that of the *Europa Clipper* spacecraft, thus its sensitivity to atmospheric drag is correspondingly greater (assuming that they have roughly the same aerodynamic drag coefficient for their solar arrays). As shown in Figure 2, the *Europa Clipper* can detect atmospheric densities due to Europa's bound atmospheric population close to the surface; however, it is possible for DARCSIDE to detect both the bound *and* escaping populations of Europa's atmosphere depending on the surface density (and thus composition) of the water family products light enough to escape Europa's gravity. The drag measurements close to the surface allow us to determine the surface density of the bound portions of Europa's atmosphere. A low (or no) escaping population density measurement would suggest that Europa's escaping population 'sticks'/recombines relatively well with the regolith, or is quickly ionized and swept away by the Jovian magnetosphere. Higher escaping density profile measurements would indicate that either the lower mass populations do not resurface efficiently or are not removed as effectively, or that there is enrichment due to a localized plume.

Through atmospheric density measurements, comparisons can be made between current atmosphere models, remote observations of Europa, and mass spectrometry measurements made *in situ* by the *Europa Clipper*. These measurements will help constrain the atmospheric composition, the velocity distribution of its constituents, and the extent that thermal mixing and collisions influence the particle distribution to inform atmospheric models such as those developed by Smyth and Marconi (2006). Additionally, detections of particles that make up Europa's escaping population

(see Figure 1) help us understand the neutral atom torus present at Europa's orbit, which is difficult to detect through other means.

Separate from the measurements obtained with an accelerometer during an aerobraking pass, a particle detector aboard DARCSIDE will allow measurement of the heavy ion flux incident on Europa during a low altitude flyby. The atmosphere of Europa is thought to be produced by sputtering (ion erosion) from Europa's surface by impacts of ions (predominantly H⁺, Oⁿ⁺, and Sⁿ⁺) and electrons from Jupiter's magnetosphere. Cassidy et al. (2013) modeled this process based on the information about the Jovian plasma environment at Europa obtained from the *Galileo* mission. They divided the ion population into two components—"hot" and "cold"—differentiated by particle energies, with the hot component having energies in the 100 keV/nuc to 50 MeV/nuc range. DARCSIDE will include a small, solid state particle telescope to measure the flux of the hot ion component, described further in Section 4.2.2. These charged particle flux measurements complement the atmospheric drag measurements and will constrain the theoretical picture of Europa's atmosphere by linking the production component (energetic ions) with direct atmospheric density measurements. This informs our knowledge of Europa's surface composition and its interactions with charged particles, in addition to the interactions of these particles with Europa's atmosphere.

Finally, the data provided by DARCSIDE may help to confirm plume activity through enhanced density measurements, in conjunction with simultaneous observations by the *Europa Clipper*; links to Europa's subsurface ocean; and effects that the radiation environment and Europa's atmosphere may have on potential biomarkers. The main DARCSIDE science objectives drive the mission design and instrument requirements, which are described in the Traceability Matrix in Table 1.

3. Concept of Operations and Mission Design

The DARCSIDE CubeSat would ride along on the *Europa Clipper* spacecraft and nominally be released

Table 1. DARCSIDE Science Traceability Matrix

DARCSIDE Science Question	Science Objective	Measurement	Instrument	Functional Requirements
What is the nature of Europa's atmosphere?	Determine Europa's atmospheric structure	Atmospheric drag	Accelerometer	Altitude of pass ~ 10 km Sampling rate ~ 10 Hz
	Determine hot ion flux at Europa	Elemental ion flux	Solid state particle telescope (dE/dx vs. E)	8-100 MeV/nucleon with pitch angle information

prior to the *Europa Clipper* Europa-5 pass on 25 February, 2029, which is the spacecraft's first science pass. Optionally, it may be possible to operate DARCSIDE's particle detector during this period as part of the *Europa Clipper* instrument package prior to separation. One hour after being released from the parent spacecraft, with its drag/solar panel array already having been deployed, DARCSIDE will conduct its first burn of 3.1 m/s to set the orbit for a passage above Europa at the desired altitude (10 km). During this weeklong cruise to Europa, DARCSIDE will perform two to four trajectory correction maneuvers to refine the Europa passage.

Roughly two hours before DARCSIDE enters Europa's atmosphere, it will rotate to the attitude required for the science measurements (with the deployable array orthogonal to the velocity vector), conduct instrument calibrations, and may conduct an optional burn to increase the CubeSat's speed during the pass through Europa's atmosphere. DARCSIDE uses a large deployable array of twenty rigid panels to increase the vehicle's cross-sectional area. When deployed, this system gives the vehicle a cross sectional area of nearly 0.6 m². The accelerometer and particle detector measurements will be made over the hundreds of seconds of passage through Europa's atmosphere. A 10 Hz sampling rate would provide measurements at a spatial resolution (along-track) of ~ 0.4 km, and allow the averaging of measurements to remove possible artifacts caused by spacecraft oscillation (Witers, 2006). The single science pass through Europa's atmosphere will be executed for approximately 23 minutes, during which all of the data will be relayed back to the *Europa Clipper* spacecraft. Once the Europa atmosphere pass is complete and at least one redundant data playback has occurred, DARCSIDE will

cruise to apojoove, where it will conduct a final EOM thrust ($\Delta V = 100$ m/s), placing it into a Europa avoidance orbit.

Table 2 lists the delta-V associated with each DARCSIDE maneuver from the time of deployment

Table 2. DARCSIDE Delta-V Budget

Maneuver	ΔV (m/s)
First burn	3.1
Optional burn to increase drag	200.0
Mission Termination	100.0
ADACS & TCM	30.0
Total	333.1

Note: ΔV values were generated using the Analytical Graphics Software Tool Kit.

from the *Europa Clipper* spacecraft to the end of mission. These data show that DARCSIDE needs approximately 333.1 m/s delta-V, leaving the vehicle with approximately a 2% margin based on the baseline MPS-130TM thruster unit. The selected mission termination sequence is to place DARCSIDE into an orbit that is inclined relative to Europa's orbit, and with a perijove well below that of Europa's orbit. This provides a low probability of future impact with Europa, while imposing a relatively low delta-V requirement on the mission.

The DARCSIDE concept of operations is detailed in Table 3. The times listed for spacecraft events are all in UTC time, and were calculated based on the DARCSIDE mission profile using the *Europa Clipper* baseline mission orbits as the study reference (page C-60 of the Europa Study 2012 Study Report).

Table 3. Notional DARCSIDE Concept of Operations

Event	Date and Time (UTC)
Begin <i>Europa Clipper</i> science mission; DARCSIDE separation from <i>Europa Clipper</i>	25-Feb-2029 17:45:14
First burn	25-Feb-2029 18:45:14
Cruise to Europa	25-Feb-2029 18:46:14 – 04-Mar-2029 02:26:44
Science Preparations	04-Mar-2029 02:26:44 – 04:26:44
Science pass through Europa's atmosphere	04-Mar-2029 04:26:44 – 04:49:59
Cruise to apojoove	04-Mar-2029 04:49:59 – 13-Mar-2029 03:44:14
Mission termination burn & EOM	13-Mar-2029 03:44:14

4. Technical Overview

4.1. Orbital Maneuvering

DARCSIDE will release from the parent spacecraft shortly before apojoove (Figure 3). At apojoove, DARCSIDE will perform a 3.1 m/s maneuver to lower its drag pass tangent height above Europa to 10 km. A series of Trajectory Correction Maneuvers will occur to fine-tune DARCSIDE's pass above Europa as the vehicle approaches the moon. Shortly before reaching Europa there is an optional opportunity for the vehicle

to do a substantial burn (up to 200 m/s) to increase its velocity, and in turn the drag experienced, during the pass. This optional delta-V thrust would provide an added benefit of acting as the first maneuver of a bi-elliptic orbit transfer. However, there is a tradeoff in that executing this maneuver would increase the mission complexity and have a larger impact on the delta-V budget (Table 2) available for the mission termination phase. Additionally, increasing the distance from the *Europa Clipper* spacecraft could potentially make communications more difficult.

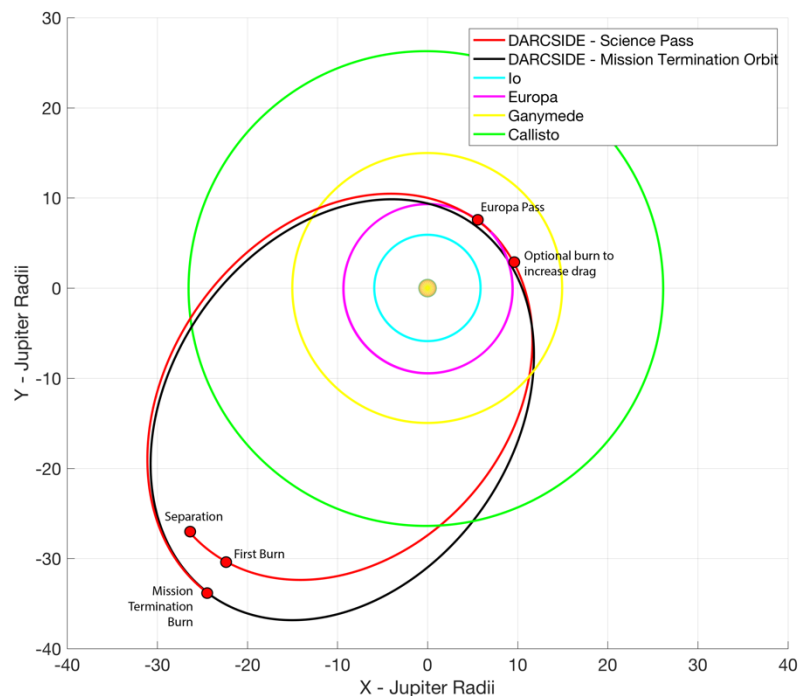


Figure 3. DARCSIDE's orbital trajectory.

As the vehicle travels away from Europa after the science low altitude drag pass, it will coast out to apojove, at which point it will conduct one final maneuver to place the vehicle into its final Europa avoidance orbit. For the baseline mission, this study lowered DARCSIDE's perijove as much as possible using the remaining fuel. Given that DARCSIDE's orbit is slightly inclined relative to that of Europa, this will leave the vehicle in a path where it is unlikely to collide with any of the Jovian moons. However, further analysis is required to quantify the likelihood of a future collision.

The entire DARCSIDE spacecraft will be spin stabilized (~ 12 rev/minute) about the long axis (the principal moment of inertia). DARCSIDE will use its optical navigation system—the micro-Advanced Stellar Compass (μ ASC; Jørgensen et al., 2001)—for attitude and orbit determination. Attitude determination will work as is typical for a star tracker, by using the visible star field to determine the orientation of the vehicle down to $1''$ at 3σ . Orbit determination will be performed by using the optical navigation system to measure the positions of Jupiter and several of its moons over time, along with uploaded ephemerides to provide detailed positions of bodies in the Jovian system (Staehle et al., 2013). Deviations in the orbit of DARCSIDE can be determined to less than 20 km by using Jupiter and Europa as targets for the optical navigation system; Figure 4 (left) shows the range of errors in orbit determination for DARCSIDE, calculated

using its distance from Europa or Jupiter (known through a combination of star tracker, ephemeris, and *Europa Clipper* data) and the $1''$ accuracy of the μ ASC as a function of DARCSIDE's flight path. Precise range measurements were determined based on Europa's angular diameter (between ~ 100 – $5300''$ over the course of the mission) as a function of distance from the moon (Figure 4, right), including the errors in orbit determination and star tracker accuracy. Through measurements of Europa during the cruise and science preparations phases of the mission, range measurements decrease to well under 1 km, making a target altitude of 10 km possible.

4.2. Instrument Payload Description

4.2.1. Accelerometer

The drag measurements illustrated in Figure 2 were compared with current CubeSat accelerometer technology, including those produced by the AFRL for low-Earth orbit atmospheric science, to assess the detectability of Europa's atmosphere. The Atmospheric Drag Environment Sensor is a miniaturized accelerometer under development for a 3U CubeSat by AFRL (Sutton et al., 2010); it has detection capability down to drag accelerations of ~ 10 nano-g ($1 \times 10^{-7} \text{ m s}^{-2}$). The accelerations detectable by the ADES system are comparable to the drag felt by DARCSIDE for all atmospheric profiles that were considered at ~ 100 –

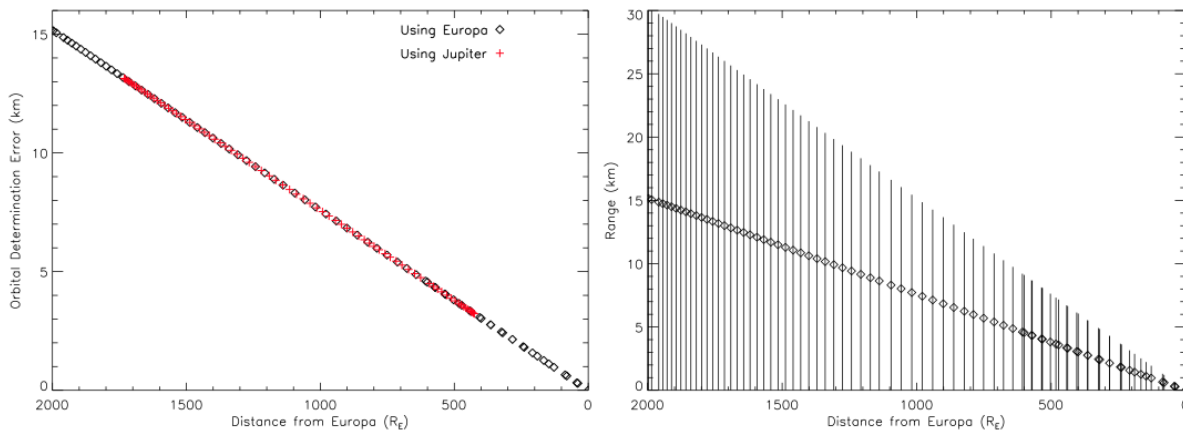


Figure 4. (Left) Error in orbit determination for DARCSIDE as set by the $1''$ accuracy limit of its optical navigation system, plotted as a function of spacecraft distance from the moon in Europa radii (1565 km). Black diamonds show errors calculated using Europa as a target; red crosses are determined by using Jupiter. (Right) DARCSIDE's possible range as a function of distance from Europa. Error bars for each point are determined using the errors in orbit determination derived from Europa's position (left panel).

150 s into the 500 km flight simulations, as shown in Figure 2 by the black dash-dotted line. Thus, the technology to measure Europa's atmospheric density with a CubeSat-sized spacecraft is already in development, and the atmospheric density ranges and their induced spacecraft decelerations for a low altitude Europa flyby exceed the detection threshold (10 nano-g) imposed by ADES.

4.2.2. Charged Particle Detector

Approximately 1U of the DARCSIDE 3U CubeSat is dedicated to the charged particle detector. The DARCSIDE particle telescope will cover the proton, sulfur and oxygen measurements in the energy bins (8–20 MeV/nuc, 20–50 MeV/nuc and 50–100 MeV/nuc). The particle detector design will be based on instruments with significant flight heritage, primarily those flown on the *Voyager* (Krimigis et al., 1977) and *Resurs-O1-N4* (Sparvoli et al., 2001) missions. Evidence that this type of detector is appropriate for use on CubeSat missions can be found in Blum et al. (2012).

The proposed detector will use the dE/dx vs. *Total E* method (Stone et al., 1977; Stillwell et al., 1979) to determine the charge (Z), mass (m), and energy (E) of particle passing through the telescope with a velocity (v). The energy loss per unit length, dE/dx , is proportional to Z^2/v^2 , and the total energy E is proportional to $1/2mv^2$. Thus, $(dE/dx)*(E)$ is dependent on Z^2m . This detection method was used by *Voyager's* Low-Energy Charged Particle Detector, including during a flyby of Jupiter (Krimigis et al., 1977). The particle telescope will be mounted with the entrance plane perpendicular to the rotational axis. As the spacecraft rotates, the view of the particle telescope will vary, thus allowing particles from various directions (pitch angles) to be sampled; particle flux will largely come from directions perpendicular to DARCSIDE's trajectory—in Jupiter's equatorial plane—as they traverse Jupiter's magnetic field lines. Calibration measurements can be taken during DARCSIDE's cruise and science preparations phases to determine particle flux throughout its orbital path from approximately 9–30 R_J , intersecting the orbits of Callisto, Ganymede, and Europa in Jupiter's equatorial plane (Figure 3). These measurements

are necessary to distinguish particles trapped in Jupiter's magnetic field from those produced by interactions with Europa's atmosphere and induced magnetic field (Krishan et al., 2009) and other spurious particles in the system; measurements of particle velocity by the telescope allows further differentiation from ionic sources, as pickup ions generated by magnetospheric-neutral interactions in Europa's atmosphere travel at roughly Europa's orbital velocity upon generation (Kivelson et al., 2009).

The particle telescope will be comprised of eight layers of silicon detectors of graduated thickness (Figure 5), based on previous studies of electron energy deposition across silicon layers and calibration

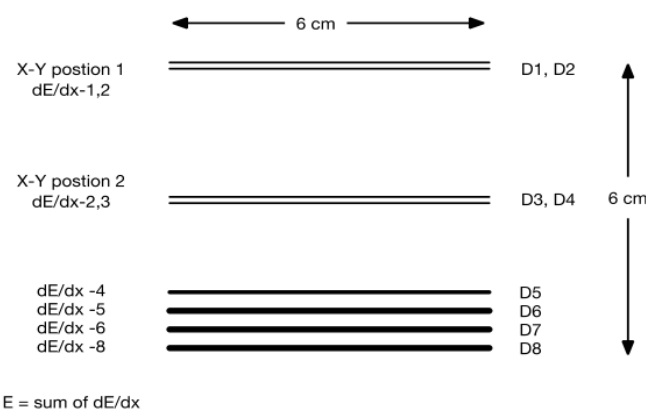


Figure 5. Schematic of the DARCSIDE particle telescope showing the position sensitive layers (D1, D2) and (D3, D4) and the energy loss layers D5–D8. The entire telescope is surrounded by an anti-coincidence detector to veto events that enter through the sides and multiple particle events. The Total E is derived through adding the energy losses in each layer. The tracking layers provide a coarse measure of the incident angle of the particle and allow for the energy loss in each layer to be normalized by the path length in that layer.

for the Electron Telescope onboard the *Voyager* spacecraft (Stone et al., 1977). The upper two double layers will be composed of silicon detectors segmented into 16 strips mounted back to back and orthogonal to one another to provide the (x,y) coordinates for a particle as it traverses the layers (Sparvoli, 2001). Coincidence/anticoincidence will be handled through a combination of aluminum shielding and detection algorithms similar to those performed by particle detectors onboard *Voyager* (Stillwell et al., 1979). From the measured coordinates, a particle's trajectory will be reconstructed and used to compensate for the path

length through each detector as a function of incident angle. The top four layers will be thin (70 μm), and the thickness of the remaining four planes will vary from 280–500 μm . With this multiplane configuration, DARCSIDE will make multiple measurements of dE/dx for each incident particle, which improves the mass resolution. The signal from each plane will be shaped, amplified, and digitized using a simple ASIC with multiple discriminators for different energy deposition thresholds. The signal will be fed to an FPGA, which will use a lookup “matrix” based on the signals from each plane, to determine the particle’s charge, mass, and energy for each event. A time tag will allow the position and attitude of the spacecraft to be extracted. This scheme will minimize the amount of data needed for transmission back to the *Europa Clipper* spacecraft.

Directional information will be recorded in 60 degree bins. It is anticipated that the particle telescope will be able to sample this distribution with an event rate of 50 Hz during the Europa atmosphere pass. The rough geometry factor for the instrument is 22 $\text{cm}^2\text{-sterad}$. Measurements of the individual charge states of the ions are not possible given the volume, mass, and power constraints of a 3U CubeSat; thus, the elemental particle flux provides a measure of the sum of the ions over all charge states.

4.3. Flight System

A summary of the baseline system totals for the DARCSIDE mission is listed in Table 4. A combination of COTS and custom components were chosen for the CubeSat’s electronic systems. These are described further in the following sections, including justification for specific parts chosen to mitigate damage from the intense Jovian radiation environment.

4.3.1. Deployable Mechanism

To maximize drag and, in turn, increase the magnitude of the atmospheric density measurements, DARCSIDE will use a large deployable array to increase the vehicle’s cross-sectional area (Figure 6). Additionally, since the vehicle requires this large surface area for maximizing the drag signal, solar cells were included on this surface to meet the higher power consumption of a rad-hard optical navigation system and allow for the spacecraft to be powered on during the cruise phase for additional calibration measurements and orbit determination. A solar array with a size of $\sim 0.6 \text{ m}^2$ should be achievable and would enable DARCSIDE to reach a power positive state; due to the large demand of the optical navigation system (1.9 W), the spacecraft can only fully operate on battery power for ~ 4 hours (Table 4). The addition of a solar array thereby allows for an extended post-release cruise period around Jupiter before DARCSIDE’s atmospheric penetration science mission begins. This permits more flexibility in mission planning, and reduces the delta-V requirements of the mission by permitting maneuvers to take place further from Europa.

The baseline deployable mechanism for DARCSIDE is a system of twenty rigid panels that stow into the area between the deployment rails of the 3U canister. When deployed, this system gives the vehicle a cross sectional area of nearly 0.6 m^2 . The baseline system was selected because it provides a fairly high degree of flexibility; the size can be readily adjusted by adding or removing panels from the array. Additionally, by using rigid panels, it is straightforward to add solar cells to the arrays. Finally, given that the baseline array is comprised of four separate sections, most failure modes should only affect part of the array, meaning that a deployment failure should not

Table 4. System Totals

	Mass	Power	Data
System Totals with 10% Contingency	4.60 kg	6.85 W	373 bits/s
Margin to Limit (Including Contingency)	-2.2%*	14.32%	68.9%
Operating Time on Batteries		4.38 h	
Solar Array Generation (When Array is Pointed at Sun) ⁺		7.5 W	

* The negative sign denotes our mass total is over the nominal 4.5 kg budget.

+ Solar array power generation is listed for the start of mission, and may decrease due to degradation of solar panels from radiation effects.

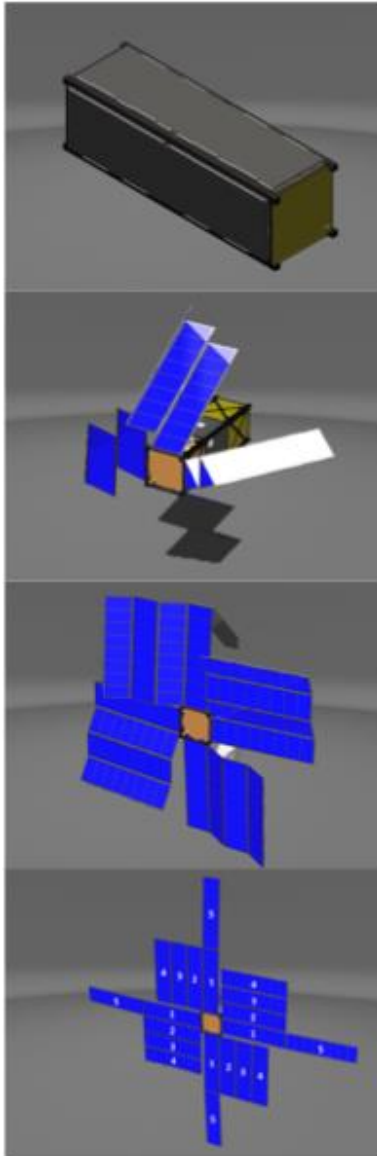


Figure 6. Deployment sequence of the 20 rigid panels on DARCSIDE.

result in mission failure provided there is a way to quantify the vehicle's cross section in the failed configuration. However, there could be potential flight stability issues if the drag is not uniformly distributed around the CubeSat's along-track motion.

The deployable mechanism will be restrained in the canister, and during deployment from the *Europa Clipper* spacecraft, by a burn wire. Once clear of the parent spacecraft, the burn wire will be cut, releasing the spring-loaded array. Panel 1 will spring up from the main body, while simultaneously panels 2, 3, and 4, accordion fold out of panel 1. Finally, once panel 5

clears the satellite body, it will spring up from behind panel 1.

4.3.2. Spacecraft Bus

The baseline DARCSIDE CubeSat system was developed with off-the-shelf components to the extent practical. This was done to provide a high level of confidence that all of the components could fit within the volume and mass constraints. The result is a spacecraft with a mass of 4.6 kg that is power positive when the solar arrays are pointed towards the Sun. The baseline design for DARCSIDE roughly breaks the vehicle down into three approximately 1U sections (Figure 7). The forward section contains the particle detector. The

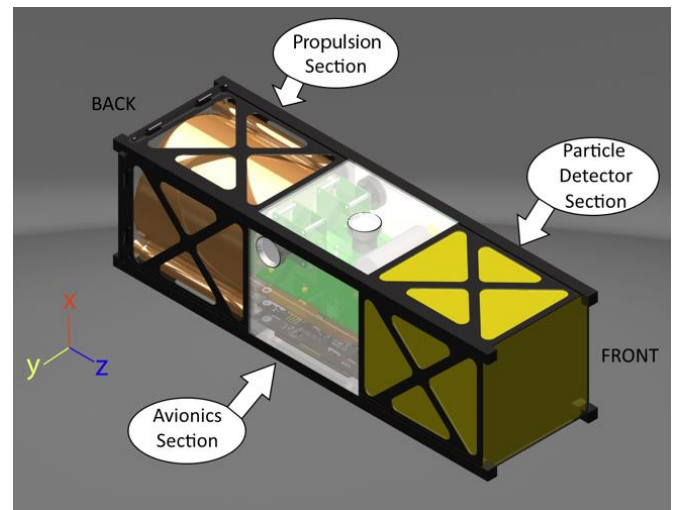


Figure 7. Modular design of a 3U CubeSat for DARCSIDE. The CubeSat body coordinate system is adopted from the Cal Poly CubeSat Design Specification (Arash, 2014). 'Front' indicates the ram direction of the spacecraft in the +z-direction; DARCSIDE will rotate about the z-axis.

middle section houses the avionics including star trackers, and the accelerometer. The aft section houses the thruster. The design is set up with the forward and aft structures being built with as low a mass as possible, which then maximizes the available mass that can be placed around the avionics section to help shield the electronics from radiation.

CubeSat Thermal Model

Figure 8 shows the approximate steady state temperature of the DARCSIDE spacecraft as a function of

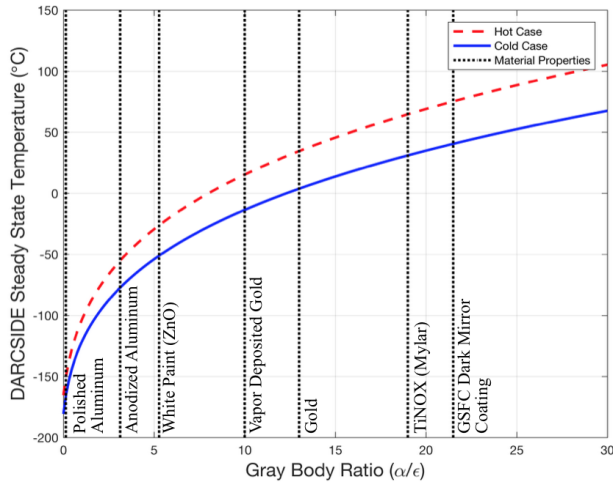


Figure 8. DARCSIDE thermal models compared to black body ratios of various surface coatings (Henninger, 1984).

the ratio of the absorptivity (α), and emissivity (ϵ) of DARCSIDE's surface coating. There are a variety of surface coatings that bracket temperature ranges appropriate for the baseline electronics, demonstrating that it is possible to obtain passive control of DARCSIDE's temperature in the Jovian environment. Our thermal model (Gilmore et al., 1999; Kreith et al., 2011) assumes a spherical spacecraft for simplicity, and includes heat input from the Sun and internal heating from DARCSIDE's electronics. The 'hot case' model includes reflected sunlight from Jupiter, corresponding to when DARCSIDE is on the planet's day-side; the 'cold case' model is applicable for when DARCSIDE is on the nightside of Jupiter. In addition to a layer of aluminum to reduce radiation dosage, the surface of the spacecraft bus can be coated with a range of materials for thermal control. Various coatings (gold, white paint, etc.) may simultaneously dissipate built up surface charging in the Jovian radiation environment (Europa Study Team, 2012).

Radiation Mitigation

The harsh Jovian radiation environment presents a substantial challenge to missions at Europa, particularly for CubeSats, which have few commercially available components able to withstand high radiation dosages. At this stage of mission planning, DARCSIDE's science objectives can be completed

during many (if not all) planned *Europa Clipper* orbits; however, neither additional shielding nor radiation vault space from the *Europa Clipper* is anticipated for ride-along CubeSats. Thus, to mitigate total ionizing dose levels during the DARCSIDE mission, it is planned to release from the *Europa Clipper* spacecraft during its first orbit. To address both radiation and thermal concerns, DARCSIDE's electronics will be encased in 1 cm of aluminum. Aluminum of this thickness will prevent penetration of $>2\text{MeV}$ electrons and $>50\text{ MeV}$ protons (Daly et al., 1996), the former being the primary concern for radiation damage during the day-long portion of DARCSIDE's flight within Europa's orbit where the radiation environment will be the most substantial (Podzolkko et al., 2009).

DARCSIDE will spend the majority of its flight time outside of Europa's orbit, thus the high-energy electron and proton flux is considerably reduced (Paranicas et al., 2009). During its science pass, DARCSIDE will receive the highest dosage of up to $\sim 15\text{ kRad/day}$ for a shield thickness of $\sim 3\text{ g/cm}^2$ (Podzolkko et al., 2009). This is well within the range of *Juno*'s electronic vault TID threshold of 25 kRad during its year-long mission (Grammier, 2009; Kayali et al., 2012), and below the 33.5 kRad specification level of *Juno*'s μASC star trackers (Guldager and Aage, 2005), which were chosen for use for DARCSIDE. Though the development of high radiation tolerance electronics is beyond the scope of this study, outfitting DARCSIDE with components similar to those onboard the *Galileo* and *Juno* missions would be required to ensure the completion of DARCSIDE's science goals. Additionally, if custom-made electronics and propulsion systems that could be built in a more convenient form factor were used, DARCSIDE's electronics and propulsion unit would be designed in a configuration whereby the fuel tank surrounds the electronics to provide an extra layer of radiation shielding.

4.3.3. Propulsion

DARCSIDE employs a chemically fueled thruster both for orbital maneuvering and attitude control. This reduces the vehicle's electrical power consumption, as a thruster should have lower power consumption than

reaction wheels, magnetorquers, or ion engines. DARCSIDE is baselined with a reduced-mass version of the Aerojet Rocketdyne MPS-130TM Propulsion Unit, which can provide around 330 m/s delta-V and 3-axis attitude control. This monopropellant unit was selected for the baseline mission over several other similar units under development primarily because it has fairly conservative specifications for its capabilities. While the MPS-130TM actually claims a lower performance than other competing units, given that the other units similar to the MPS-130TM are also still under development, selecting the more conservative option developed by a longtime manufacturer of propulsion systems is a better choice for this concept study.

4.3.4. Avionics

The baseline EPS (Electrical Power System) is based on the Clyde Space EPS and Battery systems, while the CDH (Command & Data Handling), and COM (Communication) systems are based around the Gomspace NanoMind. These systems are probably not suitable for the Jovian radiation environment in their current configuration, and were selected as being representative of the power, mass, and volume that will be consumed by DARCSIDE's avionics system. Additionally, housed in the Avionics section is the μ ASC star tracker, which is used by the Guidance Navigation & Control system for attitude and orbit determination. The μ ASC, developed by Danish Technical University, has significant flight heritage, with its predecessor (the Advanced Stellar Compass) being used onboard Juno's magnetometer experiment (Dodge et al., 2007). Finally, the avionics section also houses the accelerometer used for drag measurements and in turn atmospheric density determination.

The addition of a rad-hard optical navigation system greatly limits the available power, mass, and volume available for other electronics in DARCSIDE's avionics section. The μ ASC electronics would have to be merged with all other DARCSIDE components to allow even one camera head unit with its current volume specifications, and the added mass of the unit pushes DARCSIDE over the nominal 4.5 kg mass of a 3U mission (see Table 4); however, the inclusion of a

rad-hard star tracker is crucial to the orbit determination and ranging of the spacecraft, and thus the mission science objectives. Further development of a small star tracker with high radiation tolerance may be required for future mission studies.

Transmission and Link Budget

The study authors plan to pass periodic housekeeping data to the *Europa Clipper* spacecraft during the cruise phase as needed, using the UHF (70 cm) band. DARCSIDE will begin continuous real-time transmission approximately 30 minutes before the science pass, so that proper calibration data may be obtained for both instruments by sampling the radiation environment at Europa's orbit, and acquiring accelerometer data in the absence of Europa's atmosphere. The link budget for DARCSIDE (Figure 9) indicates that the vehicle should be able to stay in contact with the

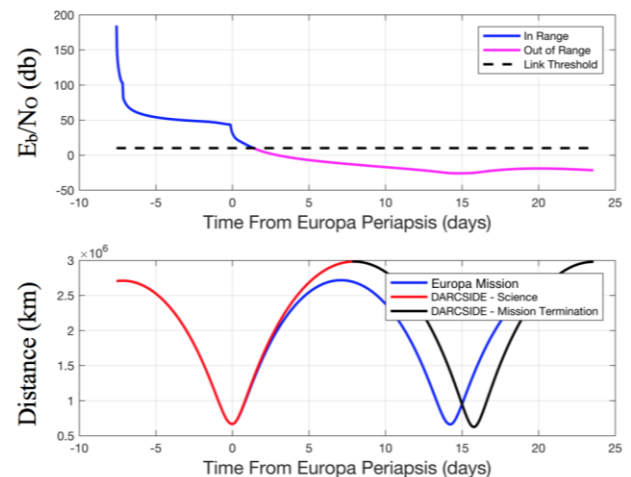


Figure 9. (Top) DARCSIDE's link budget (signal to noise ratio) as a function of flight time. (Bottom) Spacecraft distance as a function of flight time for DARCSIDE (red, black) and the *Europa Clipper* (blue).

Europa Clipper from deployment until approximately one day after the science pass is complete, with intermittent power cycles in the case of single-event upsets (Staehle et al., 2013). This is sufficient for the mission, as all science data will be transmitted well before loss of signal. Transmission of between 520 Kbits – 3.2 Mbits of data is planned, depending on the start and finish of continuous transmission to the *Europa Clipper*.

4.4. Potential Risks

There are several key areas that would need to be addressed in order to further refine this concept study and assess potential risks to the success of the mission. These include further exploring radiation shielding options of the spacecraft to ensure that the primary DARCSIDE science objectives can be completed using the proposed electronics. The volume, mass, and power constraints imposed by the addition of the μ ASC star tracker allows for only one camera unit, so loss of the star tracker due to radiation exposure is still a substantial risk. Thermal control is possible by using various surface coatings and a layer of aluminum, but these should also be applied to mitigate surface charging when possible (Europa Study Team, 2012).

The lack of a mechanism through which confirmation can be obtained that the panel array has completely deployed successfully is another potential risk to DARCSIDE'S science objectives, flight stability, and power budget. The current analysis shows that detection of Europa's atmosphere is possible if one (or even all) of DARCSIDE's panels does not deploy or unfurl properly. Drag imparted on just the spacecraft body alone, when oriented with the spin axis perpendicular to its velocity, is reduced by a factor of ~ 14 compared to the deployable array; however, this still will allow DARCSIDE to detect the bound portion of Europa's atmosphere (see Figures 1 and 2). Though this study's range analysis shows DARCSIDE will be able to safely execute a low altitude pass, stability issues due to improper deployment of its drag panels presents a potential risk to altitude and attitude determination. Further, the loss of solar panel support greatly limits spacecraft operations on battery alone, meaning instruments will have to be turned off during the cruise phase.

Finally, optimizing the cadence for accelerometer measurements will allow complete confidence in DARCSIDE's ability to execute an aerobraking pass, as *in situ* measurements of Europa's atmospheric density will be brief.

5. Conclusions and Future Work

This study demonstrated that a notional 3U CubeSat mission to Europa equipped with deployable panels and current state-of-the-art accelerometer technology can be used to measure atmospheric drag and elucidate Europa's atmospheric density structure. Combined with complementary measurements made by the *Europa Clipper*, the study will provide insight into Europa's surface composition and its atmospheric structure. Using an on-board particle detector to measure sputtering ion flux simultaneously, one can better constrain the source of Europa's tenuous atmosphere through confirmation of sputtering particle species and energies, and models of Europa's surface regolith composition (Paranicas et al., 2002). The results from DARCSIDE's two primary measurements would provide a valuable, stringent test of models that predict the production and loss of Europa's tenuous atmosphere. Additionally, a localized detection of Europa's escaping atmosphere population by DARCSIDE, with concurrent measurements by its particle telescope and instruments aboard the *Europa Clipper*, can confirm the existence of plume activity when compared to various atmospheric models (e.g. Smyth and Marconi, 2006; Shematovich et al., 2005).

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