Cadmus: A Europa Lander Concept

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Abstract— The Cadmus mission responds to the need for a Europa surface exploration mission in the 2021 time frame that complements and extends the science performed by the Jupiter Icy Moons Orbiter (JIMO) and Galileo spacecraft. Cadmus will help prepare for future subsurface and sample return missions. Europa is one of the most intriguing outer solar system planetary bodies due to the compelling evidence that there exists an ocean of salty water approximately 20 km beneath the surface. This liquid water could make Europa a haven for life. The search for life in the solar system, and the resources necessary to support extraterrestrial life has been identified by the NASA Office of Space Science (OSS) as an important area of study. The Cadmus mission will investigate the habitability of Europa from the surface in order to determine the likelihood that life exists on the moon. By studying the crustal dynamics of the moon, the Cadmus mission will assess the extent to which there exists a flux of water and ice between the possible subsurface ocean and the surface. Cadmus will investigate the presence of nutrients and signs of energy resources in the crustal ice, and will also assess the environmental suitability of the Europa environment to the evolution and sustainability of life. The mission architecture includes two landers that will land on the surface independently and utilize a high degree of autonomy for reduced mission operations cost and complexity.

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1. INTRODUCTION

Named after the Cadmus of Greek mythology who went in search of his sister Europa, this proposed mission will journey to Europa in search of ground truth regarding the habitability of one of the most likely environment for extraterrestrial life in the solar system.

Because Europa is believed to have an abundance of liquid and frozen water, it is one of the most interesting bodies in the solar system. Galileo spacecraft flybys returned valuable spectroscopic, gravimetric, radiometric, and imagery data that gave us our first close-up glimpse of the Jovian satellite. Currently, plans are underway to send JIMO to the Jovian system to collect radar and laser mapping data as well as more detailed spectroscopy measurements from orbits around Europa, Ganymede, and Callisto. The next step in determining whether life has ever existed or currently exists on Europa requires direct measurements from the surface of the moon. This is done not only to provide "ground truth" for data collected far above the surface, but to obtain data at much higher resolution than orbiters can offer and to obtain types of data impossible for orbiters to gather.

The Cadmus mission concept assumes project initiation in 2015 and that the spacecraft must be launched by the end of the calendar year 2021. Additionally, the total mission cost including the launch vehicle has been capped at $1 billion (Fiscal Year 2016 $). Based on these constraints the Cadmus mission has been designed to perform a focused investigation of the habitability of Europa. This science theme has been identified by the JIMO Science Definition Team, the OSS Strategic Plan, as well as previous studies [1] as a very important aspect of Europa for study by future missions.

2. APPROACH AND BASELINE ARCHITECTURE

The Cadmus design team initiated this activity by defining the science requirements anticipated from a Europa surface mission in the 2021 timeframe. Detailed discussion with students in the Department of Geological Sciences at Brown University allowed iteration between science desires and implementation realities. This iteration also provided a multi-organizational design component to this study. Measurement requirements and baseline mission architecture flowed directly from these science objectives.

Through research and calculation, the Cadmus design team identified the optimal architecture to meet the science requirements within project cost and schedule constraints. The baseline Cadmus architecture includes two identical surface landers and one common cruise module providing propulsion on the interplanetary trip. All three of these components are delivered to the interplanetary trajectory by a single launch vehicle. A two lander mission allows exploration of more than one surface location. Much more about the nature of the moon can be derived from comparison and contrast of the two landers' data than if the data came from only one source. The successes of the Viking and Mars Exploration Rover (MER) missions confirm the wisdom of this approach.

Many aspects of previously successful spacecraft and landers were included in the Cadmus design to improve reliability; many critical hardware components are redundant for the same purpose. The multiple lander architecture provides redundancy, and allows the science performance floor to be met even if there is a failure on one.

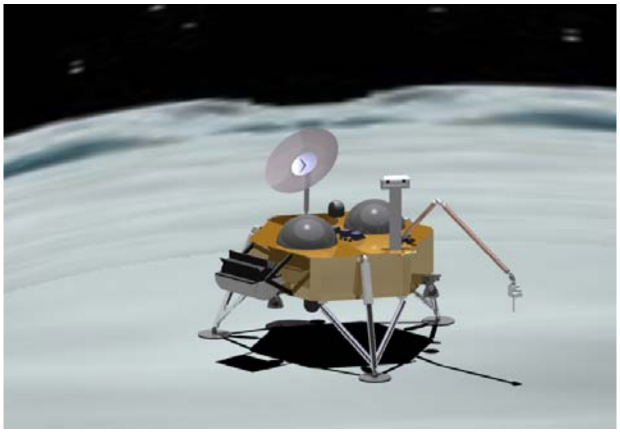

Figure 1. A Cadmus Lander on the surface of Europa.

A trade study revealed a chemical propulsion system to be the best propulsion option from a combined cost and complexity standpoint. The amount of propellant needed was kept low by inclusion of gravity assist maneuvers in the interplanetary and Jupiter system trajectories. Evaluation of different spacecraft power options led to the selection of Radioisotope Thermoelectric Generators (RTGs) for primary power and lithium ion batteries for secondary power.

3. SCIENCE RATIONALE AND TRACEABILITY

Goals and Relation to Past and Future Missions

The Cadmus mission will extend the science of JIMO and Galileo as well as provide a critical link between those missions and future Europa subsurface missions. The science theme of the Cadmus mission is the habitability of the Europa environment. The Cadmus mission has been specifically designed to obtain as much information as possible about habitability of the Europa environment for life. Previous studies confirm the wisdom of this approach to the scientific exploration of Europa [1]. The Cadmus mission establishes a sound scientific basis for the planning of future Europa science missions. As such, Cadmus is a vital step between remote sensing missions (JIMO, Galileo) and future surface and subsurface (Cryobot [2]) life detection missions. Table I shows the relation of Cadmus to past and future missions.

Objective 1: Survey the dynamics of the icy crust of Europa

Cadmus will provide an in-situ platform for the direct measurement of Europa's tidal and seismic activity, and will provide validation of the JIMO geological measurements. This objective relates to the study of the habitability of Europa by determining the extent to which there is an exchange of icy material between the surface and subsurface. Because of the possible existence of a liquid-water ocean housing extraterrestrial life as much as 20 km beneath the surface of Europa, the transport of material from the subsurface to the surface must be understood. These measurements will enable the Cadmus science team to infer the habitability of the subsurface environment.

	Mission:	*Galileo*	*JIMO*	***Cadmus***	*Future Missions*
	Mission Type:	Flyby	Orbiter	**Lander**	Rover, Cryobot, Sample Return
Science Investigations	1) Europa structural dynamics investigation	Gravimetric and radiometric data, low resolution imagery	Radar and laser mapping, gravimetric data, medium resolution mapping	**Local high resolution surface imagery (panoramic); multi site seismographic data.**	Multiple surface high resolution imagery, direct exploration of subsurface.
	2) Nutrient/Energy Resources in Surface Ice	Some spectroscopic imagery	Point spectroscopy from orbit for determination of constituents of top 1mm to 1 cm of surface	**Direct GCMS/Raman Spectrometer and aqueous chemistry lab analysis of samples up to 20 cm depth (samples unaltered by radiation)**	Surface and ice column constituency analysis
	3) Environmental conditions	None	Radiation sensors, remote sensing spectroscopy	**Direct measurement of surface environmental conditions, and direct analysis of near surface ice.**	Multiple site surveys, subsurface ocean exploration?

Table I. Cadmus relationship to past and future missions.

Objective 2: Assess the presence of potential energy and nutrient sources.

Cadmus will look for signs of geothermal energy in the subsurface environment, as well as evidence of compounds that can support known forms of life. In order for life to exist, water as well as sources of energy and nutrients must be present. Because of Europa's distance from the sun and the extreme depth of the liquid ocean (the most likely place for life to evolve and flourish on Europa), sources of energy other than solar energy must be identified.

Cadmus will provide in-situ composition analysis of the near-surface material greater than 10 cm deep to analyze samples largely unaffected by the radiation environment. The remote sensing instrumentation carried by JIMO and Galileo are capable of performing spectroscopy of the surface, providing composition information on only the top 1 mm to 1 cm of the surface material, a highly irradiated environment.

Objective 3: Assess the suitability of the Europa environment to support life.

Cadmus will study the physical properties of the surface material directly, which is not possible from a purely orbital mission such as JIMO and Galileo. Most importantly, Cadmus will prepare for future astrobiology missions that will search directly for signs of life in the Europa system by defining the surface environmental conditions, thereby bounding the types of life they expect to exist on Europa.

4. MEASUREMENTS REQUIRED

The Cadmus mission measurement requirements will enable a more detailed understanding of Europa, its resources, and its potential for harboring life.

Imagery

Landing site context imagery will provide information about the type of site at which Cadmus has landed. This will allow the science team to determine if the surface material being analyzed has been part of a subsurface ocean, and if so, how recently an upwelling event took place. A 360-degree panoramic camera similar to those utilized on the Mars Exploration Rover (MER) mission will provide this imagery. Additionally, a descent imager will be used to allow the science team to compare the landing site with JIMO and Galileo imagery providing a global context.

Spectroscopy

Three types of spectroscopy measurements will be utilized to accomplish the mission science goals. Elemental analysis will be utilized to determine the constituents of the ice. Elements of interest are those that are indicative of energy resources in the subsurface environment (e.g. sulfur as a sign of geothermal activity), as well as those elements that could provide nutrients to life, such as phosphates and nitrates. Additionally, molecular analyses will be performed. Specifically, potential byproducts of life will be sought, such as complex carbon compounds. Finally, remote spectroscopy will be utilized to analyze the surface composition of the area immediately surrounding the lander.

Seismology

Seismology measurements of Europa allow tides and quakes to be observed. It is theorized that these events occur regularly on a scale consistent with the tidal period of Europa (3.55 days). This information will provide improved temporal resolution over previous measurements, as well as allow ground truth of JIMO's radar altimetry experimental results.

Environment

Measurements of the Europa environment will be taken in order to help assess the suitability for life, as well as to assist the science team in understanding what forms of life may be present on Europa. Measurements of radiation, temperature, and solar flux will be taken. Additionally, the surface material will be analyzed to determine its pH and salinity.

5. INSTRUMENTATION

The Cadmus mission utilizes a suite of instruments with flight proven heritage [3] and operational testing in analogous environmental conditions.

All Cadmus instruments are directly traceable to the stated scientific objectives, as shown in Table II. This table shows how each science objective determines a set of mission requirements and instrument requirements and in turn a data product requirement for our mission. Cadmus' scientific mission consists of a suite of nine instrument packages, with eight having spaceflight mission heritage. Every instrument will achieve a Technology Readiness Level (TRL) of at least eight by the end of Phase C, meaning that the actual system is completed and has been "flight qualified" through testing and demonstration.

Gas Chromatograph Mass Spectrometer (GCMS)

The GCMS provides high spectral resolution elemental analysis of subsurface samples essential to the mission objectives of Cadmus. It has extensive heritage in planetary surface missions and will undergo thorough testing in environmental conditions similar to that of Europa. The GCMS consists of six identical, single-use chambers - three for analyzing samples and three for reference. Each sample chamber will have a sealable chute at its top for deposit of the sample by the corer.

Science Objective	**Mission Requirement**	**Instrument Requirement**	**Baseline Data Product Requirement (Per Lander)**
Survey the dynamics of the icy crust of Europa	Two Landers	Seismometer	> 2 weeks of measurements without other instruments/mechanisms operating = 1.2 Gbit
	Landing at one or more sites of recent upwelling	Pancam	20 Images (1024x2048) =240 Mbit
Identify potential energy and nutrient resources	In-situ sampling of crustal ice; drill for sample extraction	Mass Spectrometer	3 samples to ~2 ppb resolution- = 6 Mbit
	Landing at one or more sites of recent upwelling	Raman Spectrometer	3 Samples to ~2 ppb resolution= 6 Mbit
Assess the suitability of the crustal ice to supporting life	In-situ sampling of crustal ice; drill for sample extraction	Aqueous Chemistry Lab	3 samples = 3 Mbit
	Multiple samples per site	Point spectrometer	30 images (512x512) = 120 Mbit
		Environmental Sensors	Full Readout every hour during mission ops = 120 Mbit

Table II. Science Traceability Matrix.

Descent Imager

The descent imager provides high resolution context imagery for choosing and verifying a landing site for the Cadmus mission. The imager will also provide the capability for active hazard avoidance for the spacecraft during landing [4].

Panoramic Camera

Cadmus' panoramic camera provides high spatial resolution context imagery to meet the mission science objectives. The pancam consists of two cameras to provide stereoscopic imagery, and will rest atop an extendable mast on the lander. The cameras have four filters for red, green, blue, and near-IR images. For context imagery, the three visible spectrum images will be overlaid to produce a full color image.

Ultrasonic Corer

The ultrasonic corer (USC) allows the lander to collect subsurface samples for analysis by the GCMS using much less force and power than conventional coring methods. It has thorough ground testing through JPL's Field Integration Design and Operations (FIDO) technology test bed. The USC utilizes a piezoelectric actuator to make the corer similar to a jackhammer. As a result, the corer does not get dulled or need to be replaced like a conventional drill bit. The corer will be located on the lander arm, and will drill to a depth of 20 cm and remove a sample core of 1 cm in diameter. The estimated surface hardness of Europa, which is similar to that of basalt, will allow a drilling speed of 1 cm / hour.

Aqueous Chemistry Lab (ACL)

The ACL is a flight proven instrument that allows Cadmus to analyze the subsurface environment. The ACL consists of three single-use chambers that will analyze the chemical properties, including ion concentration, pH, redox potential, conductivity, and salinity of collected samples.

Near-Infrared Spectrometer (NIR)

The NIR provides remote sensing and mineral detection of the Europan surface for site context. The NIR will operate using images taken by the pancam using its NIR filters. For every pixel in the Pancam image, the NIR will produce a full spectrographic analysis based on the reflectivity in that pixel.

Raman spectrometer (RS)

The RS provides molecular analysis and identification of minerals and organic substances within surface and subsurface material. The RS will have a two-part configuration, with the spectrometer residing within the spacecraft bus and a probe head taking in-situ measurements of Europan material from the lander arm. The probe will be placed directly on the surface for analysis.

Seismometer

The three-axis seismometer allows investigation of Europan internal structure and dynamics, as well as ground truthing of radar mapping performed by previous missions. The seismometer is sensitive to frequencies between 0.02 Hz and 50 Hz, spanning a significant portion of the frequency range predicted by acoustic theory of cracking of Europa's icy shell.

Environmental Sensors

The environmental sensors suite consists of three instruments: a thermal mapper, an insolation sensor, and a radiation sensor array. The thermal mapper measures temperature with a set of IR sensors and is similar to the mapper used on the Rosetta mission. The insolation sensor consists of a silicon photovoltaic detector, which determines the intensity of visible-wavelength sunlight at the surface. Lastly, the radiation sensor array measures the flux of high-energy charged particles at the lander's location, doing so through application of high-resistivity silicon wafers.

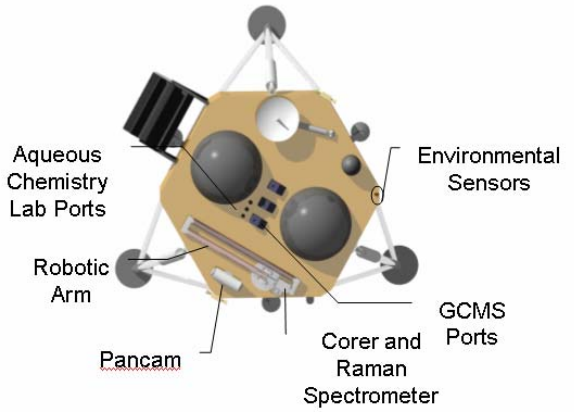

Figure 2. Cadmus Lander Instrumentation.

6. MISSION IMPLEMENTATION

Mission Design

The Cadmus mission begins on November 26, 2021 with a launch from KSC aboard an Atlas V 551 launch vehicle. The launch vehicle delivers the spacecraft, composed of a propulsion module and two identical landers, to an interplanetary trajectory with a C_3 of 16.4 km^2/s^2 [5]. As shown in Figure 3 (generated by Jaqar Space Engineering's Swing-by-Calculator), the spacecraft completes a Venus-Mars-Venus Earth flyby maneuver and arrives at the Jupiter system in June of 2025 [6]. As the spacecraft enters the Jupiter system, it performs a Ganymede Gravity Assist (GGA) and enters a highly elliptical orbit around Jupiter.

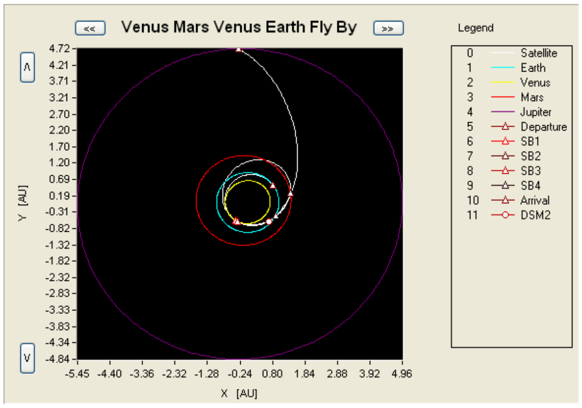

Figure 3. Interplanetary trajectory

The spacecraft then performs Perijove Raise Maneuvers (PJR), including Europa Gravity Assists (EGA), which, as shown in Figure 4, slowly raise the periapsis of the orbit to be tangent with Europa's orbit[7].

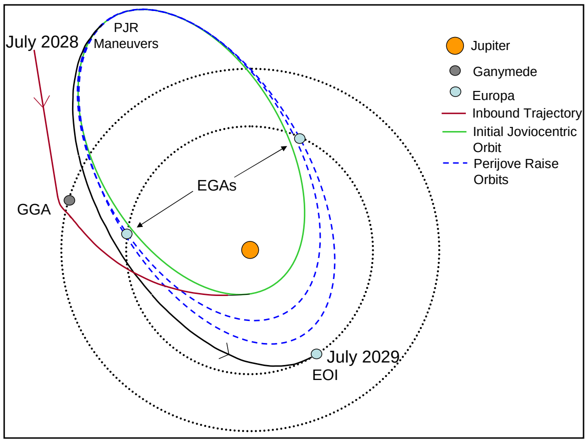

Figure 4. Jupiter System Trajectory.

The Cadmus landing site selection team will analyze Europa surface data from the JIMO mission. This data is used to augment the descent imager data in selecting suitable landing sites. While in the Jovian system, the landers separate from the propulsion module and independently perform Europa Orbit Insertion (EOI) maneuvers to arrive in 100 km circular orbits around Europa. The subsystems are checked to ensure proper functioning and the first lander initiates its descent to the Europan surface.

Data from the first landing is analyzed and knowledge gained is applied toward the second landing. This adaptive landing scenario helps to ensure a successful mission. Each lander descends using a chemical propulsion system. The lander covers approximately 400 km (ground track) during landing, which takes 10-12 minutes. So as not to land on ice that was in the path of the propulsion products, the lander turns off its main propulsion system 3.4 meters above the surface. The lander at this point has zero vertical velocity and 5 m/s of horizontal velocity. The lander drifts horizontally as it falls, and the attitude control thrusters are used as translational thrusters to null the remaining horizontal velocity before touchdown. Each lander is equipped with an autonomous hazard avoidance system that can command short bursts from the main thrusters to keep the lander afloat above surface hazards. The lander has enough propellant for 60 sec. of hovering in this fashion. The lander then impacts the surface with a nominal vertical velocity of 3 m/s. To cushion the lander from this impact, the lander legs feature crushable aluminum honeycomb shock absorbers. The honeycomb is sized to endure impact velocities of 4 m/s. Critical events communication during landing will be enabled through the use of the low gain antenna, which will transmit approximately 10 bits per second of telemetry data. The ΔV schedules are shown in Table III.

Once on the surface, the lander deploys the pancam and takes two pictures, which are sent back to Earth along with all other diagnostics as a test of the lander's health. Next, coring begins for sample extraction and analysis. The corer takes three samples at autonomously selected locations.

The mission operations team has the ability, however, to analyze the initial pancam pictures and send new locations for the second and third corings. When all three core samples have been completely analyzed, the seismometers are activated. All data except for the seismology readings is returned to Earth within 10 days of landing. This is referred to as Phase One of the mission. During Phase Two, the seismometers will then continuously gather and return seismology data to Earth for the remaining life of the lander, which is expected to be limited to approximately four weeks by the harsh radiation environment.

Cruise Stage ΔV	
Maneuver	ΔV (m/s)
Venus-Mars-Venus-Earth and Deep Space Maneuvers	763
Jupiter Orbit Insertion	320
Perijove Raise Maneuver	1100
Margin (10%)	218
Total ΔV	**2401**

Lander ΔV	
Maneuver	ΔV (m/s)
Europa Orbit Insertion	520
Landing	1680
Hover (60 sec.)	80
Margin (10%)	228
Total ΔV	**2508**

Table III. ΔV Schedules.

Cruise Stage

Propulsion—An all-chemical storable bipropellant propulsion system is used on the propulsion module and consists of two main thrusters using monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO) pressurized with helium. These thrusters provide up to 445 N each to provide a satisfactory thrust-to-weight ratio throughout the cruise stage. The propulsion module has its own spherical MMH, NTO, and helium pressurant tanks centrally located to minimize center-of-mass translations as propellant is used.

All tanks are titanium-lined composite over-wrapped. All tanks have a safety factor of two. This system provides the propulsion module with low risk and complexity.

Attitude Determination, Control, and Navigation— The cruise stage is 3-axis stabilized through use of 12 attitude control thrusters on the propulsion module. Redundant star trackers and Sun sensors will be used for attitude determination. Each lander has an Inertial Measurement Unit (IMU).

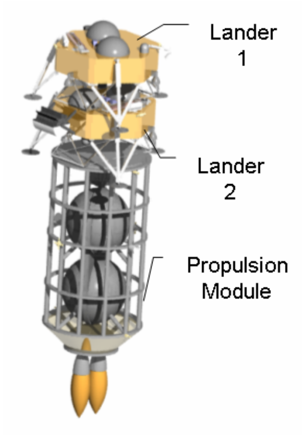

Figure 5. Cadmus Cruise Stage Configuration.

Only one IMU is used at any given time during the cruise phase. The IMU is capable of propagating attitude when information from the star trackers and/or the sun sensors is unavailable. The star trackers have 10 mm thick aluminum shutters that close for protection when the spacecraft is in the high radiation environment of the Jupiter system. The shutter of the star tracker in use opens periodically for roll-axis determination.

Command & Data Handling (C&DH)—All command and data handling operations for the propulsion module are controlled by only one of the two lander C&DH systems. The other C&DH system functions as a backup.

Thermal Control—The cruise stage must endure the heat of the solar radiation at Venus during the flybys and also the cold of the Jupiter system. Multilayer insulation (MLI) covers the propellant and pressurant tanks. Heat from the lander RTGs is used to keep temperature critical components on the cruise stage warm. Radioisotope heater units (RHUs) will be used on thrusters to minimize power drain on the RTGs. A heat shield is employed between the main thruster and the rest of the cruise stage.

Propulsion module			2163 kg
	Subsystems	362 kg	
	Propellant	1801 kg	
Lander (x2)			559 kg
	Science Payload	19 kg	
	Lander Subsystems	230 kg	
	Lander Propellant	310 kg	
Bioshield			192 kg
Lander Adapters			58 kg
Launch Vehicle Adapter			91 kg
Boosted Mass			**3622 kg**

Table III. Spacecraft Mass Breakdown.

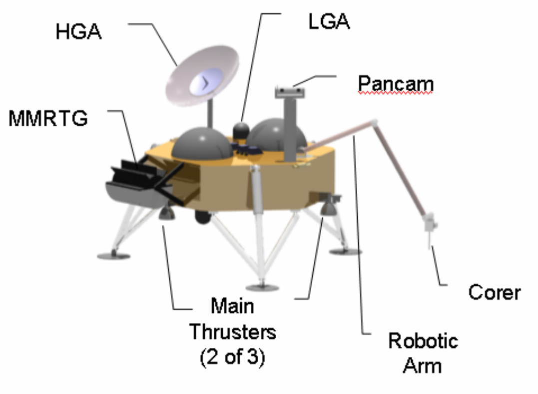

Figure 6. Lander Configuration.

Power—Power to all cruise stage electrical items is provided by the two lander RTGs. The cruise stage has its own power control unit, converters, regulators, and wiring, as well as a Pyro Initiation Unit (PIU) to detonate pyros and separate the landers from the propulsion module prior to Europa Orbit Insertion. Advances made during the JIMO mission in radiation-hardened electronics will be used in the development of power system components.

Lander

Propulsion—The lander propulsion system uses the same helium pressure-fed MMH/NTO bipropellant combination as the propulsion module, allowing a single propulsion procurement for the mission. All tanks are spherical titanium-lined composite overwrapped pressure vessels to keep propulsion system mass low. Following the successful example of Viking, the lander has three main engines. These are fired for the EOI maneuver and during descent to Europa's surface. Together the engines may be throttled to provide a lander thrust-to-weight ratio of one for temporary hover capability near the surface.

Attitude Determination and Control—A radiation-hardened hemispherical resonator gyro IMU [8] provides attitude determination during periods in the cruise phase when data from the star and/or Sun sensors is unavailable. This IMU also propagates lander attitude after the lander separates from the propulsion module. The three main engine thrusters on the lander are offset from the lander center of mass and also may throttle and gimbal to ensure sufficient pitch and yaw control during all lander maneuvers. Four small thrusters facilitate roll control.

Landing Guidance—While in its 100 km parking orbit about Europa, the lander takes several surface images per orbit with its descent imager and transmits them back to Earth for use in landing site confirmation. The lander also uses this descent imager in its landing sequence as a tool to determine velocity with respect to the ground. During descent, a laser altimeter supplies continuous altitude information. Starting five kilometers above the surface, four-beam terminal-descent and landing radar provides an additional and precise method of determining velocity with respect to the surface. Robust hazard avoidance and autonomous touchdown site selection are provided by advanced flight software.

C&DH—The lander C&DH subsystem contains a RAD750-class processor for processing commands and telemetry data, Input/Output serial buses for interfacing with other subsystems, and nonvolatile memory (NVM) data storage devices to store telemetry and science data. All components are radiation-hardened and/or have sufficient shielding. In the event of communications difficulties during the science phase of the mission, embedded command sequences and algorithms allow the lander to perform surface science independently of ground personnel.

Thermal—The requirements that the lander be able to operate on Europa at surface temperatures as low as 70 K and additionally be able to endure solar intensity variations from Venus to the Jupiter system demand a sophisticated thermal control system. Passive techniques such as insulating gold paint on the lander body and aerogel insulation layers inside the body help reduce required power and complexity in thermal control. Thermal switches direct portions of the approximately 380 W of heat produced by the RTG either inside the lander body to keep electronics warm or outside to radiators.

Power—One Multi-Mission RTG supplies power to each lander and also for propulsion module components during cruise. Two lithium-ion batteries complement the lander RTGs and provide secondary power to the lander. They support portions of the cruise phase requiring high power, such as maneuvers and periodic high-gain communications sessions. Each has three times more power than needed to satisfy power demands through the descent and landing phase, during which the power draw is at its highest for the entire mission.

Phase	Power (W)
Launch	187.6
Cruise (Min.)	148.4
Cruise (Max.)	387.5
Descent and Landing	370.8
Surface Operations (Min.)	56.8
Surface Operations (Max.)	180.6

Table IV. Cruise Stage and Lander Power Breakdowns.

Structures—Aluminum forms the basic skeleton of the lander bus to create a lightweight support structure. This structure also supplies significant radiation protection to internal components. Aluminum honeycomb sandwiched between aluminum face sheets provides light and stiff body panels.
Three legs give the lander the ability to perform a stable soft-landing. The design is based on that of the successful Viking lander, and is also used on the 2007 Phoenix mission. The legs are fully deployed before launch to eliminate the complexity of deployment.

Shielding—Aluminum shielding protects the science payload and vulnerable electronics from radiation. Over the course of the mission, the expected total radiation dosage behind 100 mils of aluminum would be approximately 4 Mrad, with about half occurring in the encounter phase. Sensitive electronics will be grouped within one "vault" with shielding sufficiently thick to limit radiation dosage to below maximum allowable levels.

Launch Vehicle

The Cadmus mission launch vehicle, the flight-proven Lockheed Martin Atlas V 551, is capable of delivering the spacecraft into a Venus-bound heliocentric trajectory with the desired Earth Escape Energy (C_3). A wide range of expendable launch vehicles (ELVS) and their capabilities were evaluated. The intermediate launch vehicle class was selected because of its capability of launching the desired boosted mass of 3622 kg, not including an additional 30% allowable growth margin, with a C_3 of 16.4 km^2/s^2. Within this category, the Lockheed Martin Atlas V 551 launch vehicle best meets the required performance. Lockheed Martin has demonstrated continued success with the Atlas family of launch vehicles [5].

Communications Approach

Uplink and Downlink—All uplink and downlink communications are direct between Earth and the landers; the absence of relays reduces complexity and eliminates the possibility of mission failure due to reliance on separate space hardware for data return. High-gain communications are in the K_A-band, with uplink at approximately 34.5 GHz and downlink at 32 GHz. The high gain antenna will consist of an advanced, inflatable antenna, which is capable of tripling it's area using a compressed gas inflatable structure. Operations are still enabled even if this new technology does not function properly.

Low-gain communications are in the X-band, with uplink near 7.19 GHz and downlink at 8.45 GHz. These bands and frequencies were selected to fall within those supported by the DSN and also based on transponder/transceiver capabilities and achievable rates. A much higher data rate is achievable with K_A-band than other supported bands, making it the best choice for high-gain communications, but the mass and power savings available with X-band transceivers make X-band more attractive for low-gain communications. Mission data rates for High Gain are shown in Tables V and VI for Phase One and Phase Two of the mission.

Parameter	Value
Science data volume CBE	500 Mb
Approximate transmission time available	4.0 days
Minimum required data rate	1.43 kbps
Uninflated HGA provided data rate	1.70 kbps
Inflated HGA provided data rate	11 kbps

Table V. Phase 1 Data Volumes & Rates.

Parameter	Value
Science data volume CBE	1800 Mb
Approximate transmission time available	8.1 days
Minimum required data rate	2.58 kbps
Inflated HGA provided data rate	11 kbps
Percent returnable by uninflated HGA	*66%*

Table VI. Phase 2 Data Volumes & Rates.

Through most of the cruise phase beacon-tone monitoring is used, meaning the active computer on board analyzes telemetry data to assess the health of spacecraft components and then summarizes the overall spacecraft status with a single-frequency tone it transmits to Earth, rather than modulating the telemetry data onto a downlinked carrier signal. The frequency of the tone received immediately tells ground personnel whether the spacecraft performance is nominal or degraded, and how urgently full-scale communications are needed. Beacon-tone monitoring eliminates the need for constant human monitoring of telemetry, thus significantly reducing operations cost. Also, the tones are detectable by Earth dishes much smaller than the DSN 34 m dishes, so communications costs may be lessened. DSN 34 m diameter antennas are employed periodically during the cruise phase (~1 time per month) to receive telemetry and to uplink any necessary command sequences or software updates to the spacecraft. The 70 m DSN dishes are employed throughout the encounter phase and surface operations to ensure reception of telemetry and science data [9].

A signal-to-noise ratio of 9.8 dB or higher shall be maintained in all communications activities to provide a 3 dB link margin over the 6.8 dB necessary for a sufficiently high probability of signal decoding. Coding is used to prevent errors in data transmission and shall adhere to the Consultative Committee for Space Data Systems (CCSDS) standard. The coding scheme to be employed shall be a turbo code of appropriate rate and block size to achieve higher performance in achieving the desired bit error rate than concatenated and Reed-Solomon codes while maintaining lower coding complexity than many predecessor spacecraft.

Critical Events Coverage—Key telemetry values are transmitted in real time to Earth during all critical events, including launch, Venus flybys, trajectory correction maneuvers, Jupiter orbit insertion, perijove-raise burns, and separation of landers from propulsion module, Europa orbit insertion, descent, and landing. This is to aid in the determination of causes for any anomalies during these higher-risk instances. In addition, *all* telemetry data during a critical event shall be stored in onboard memory for later transmission to Earth. DSN resources serve as the ground component of the link during each critical event. On the spacecraft, both the high-gain and low-gain antennas are available for communications during all cruise phase critical events. During launch and landing, the hemispherical LGAs are used since the HGA on each lander is restrained.

Mission Operations

The Cadmus mission operations plan utilizes a low-cost approach while maintaining high efficiency and competency. The high degree of spacecraft autonomy ensures a small operations team and low operations cost. The use of beacon tone monitoring reduces DSN use and a relatively short science mission minimizes operations complexity. A Flight Operations officer will be on duty at JPL during all periods to monitor the beacon tone and ensure nominal spacecraft operation. Spacecraft navigation, spacecraft and payload status, and instrument health will also be closely monitored. The flight team will be contacted at the first sign of irregular data. The flight team will consist of a Spacecraft Team, Navigation and Control Team, Descent and Landing Team, and a Surface Science Team. All mission data will be archived independently by the Science Team at JPL. After calibration and validation, the datasets will be delivered to the Planetary Data System at JPL. The efficient mission operations approach allows more of the project budget to be directed towards spacecraft engineering and science.

Technology Development

The most significant risk associated with the technology readiness of this mission concerns the high radiation environment on Europa. Although most of the instruments and hardware are flight proven, many of them have not flown in such high radiation levels. To mitigate this risk, heritage components were taken from the JIMO mission that will have successfully operated in the Jupiter system before the Cadmus PDR. Knowledge gained from JIMO regarding radiation hardening and radiation shielding will also be applied to non-environmentally qualified components. One of the components that has not flown prior to the Cadmus mission is the Hybrid Inflatable Antenna, which allows the mission to fly a lower mass antenna. Significant testing will bring this component up to flight qualified level prior to PDR. Additionally, Cadmus components will be subjected to rigorous radiation and environmental testing using JPL's testing facilities.

Priority	Element	Mitigation Strategy	Impact	Likelihood
1	Cruise Propulsion Failure	Use of reliable bipropellant storable propulsion system with significant flight heritage.	High	Low
2	Communication System Failure	Redundant systems; hybrid inflatable antenna operates even if inflation does not occur.	Moderate	Low
3	Sample Extraction Arm Failure	Robust mechanisms designed without single string failure	High	Low
4	Landing System Failure	Use of reliable bipropellant storable propulsion system with significant flight heritage; advanced active landing system utilizing descent imager and radar; multiple landers	Moderate	Low
5	Radiation Environment exceeds expected levels	Use of JIMO data for accurate determination of radiation environment; advanced electronics and shielding with JIMO heritage	Moderate	Low

Table VII. Risk Management and Mitigation.

Planetary Protection

Although Cadmus is not directly searching for life, the theme of assessing the habitability of Europa, will likely earn this mission a planetary protection category of IV-B. Possibly the best form of planetary protection against the majority of bioburdens will be the high radiation levels the landers will experience in the Jupiter system before reaching the Europan surface. Despite this protection inherent in the mission, every effort will be made to ensure that a minimal number of organisms are present on the spacecraft as it leaves Earth.

To reduce the number of viable organisms on the spacecraft, heat resistant components will be subjected to dry heat microbial reduction, through bakeout at a temperature of 125^{o}C for a period of 50 hours. This method of microbial reduction is the most effective method known for killing organisms such as Deinococcus radiodurans, known to be radiation resistant. The number of accountable surfaces will be minimized using HEPA filters which can remove 99.97% of all particles greater than $3x10^{-7}$m in size. Any non-sealed components which are not heat tolerant will be prepared using alcohol wipes. Furthermore, the spacecraft components will be assembled in a Class 100,000 clean room to reduce the chance of contamination. To ensure the cleanliness of the spacecraft after decontamination, a sterilized bioshield made of coated, woven fiberglass bonded to a composite support structure will be placed around the landers. The bioshield will be jettisoned after the spacecraft leaves the Earth's atmosphere.

Planetary protection must also be considered for the propulsion module. Although it does not go into orbit around Europa, its final orbit around Jupiter does cross the path of Europa. Care will be taken to determine a final orbit for the propulsion module for which the probability of impact on Europa is less than 10^{-4} over the subsequent 50 years.

Management

The Cadmus management organizational structure ensures that experts at the appropriate institutions or partner corporations address all aspects of the mission. The principal investigator (PI) is directly responsible to NASA and is ultimately responsible for ensuring that the project stays on schedule and within cost constraints. The Cadmus mission architecture has been designed to ensure minimal risk at every level of design. Flight proven hardware with significant heritage was selected, and redundant systems were included where possible. A summary of the top five risk elements is shown in Table VII.

Cost

The Cadmus mission design meets all requirements while coming in under the $1 billion cost cap. A summary of the cost by mission phase is shown in Figure 7. The total mission cost is $950 million FY2016. This includes $200M for the launch vehicle, and $225M of reserves (30% of Non-LV costs). The Cadmus mission was costed utilizing parametric cost models and by analogy to past missions.

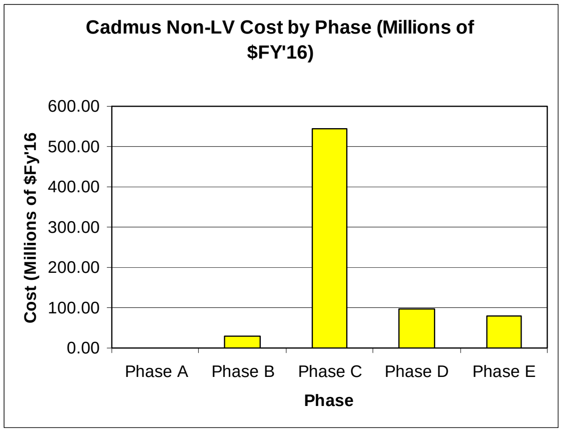

Figure 7. Cadmus Non-LV Cost by Phase.

7. CONCLUSIONS

Due to the possible presence of a subsurface salty ocean, and the potential for inhabitation by extraterrestrial life, Europa is one of the most compelling objects in the solar system. JIMO will perform extensive visual and radar mapping of Europa. However, the most important questions about life and the presence of energy and nutrients on and under the Europa crust cannot be answered until spacecraft are put on the surface, explore the subsurface, and return samples to Earth.

Therefore, Cadmus fills a critical need for a link between future subsurface exploring or sample return missions and current orbital remote sensing instruments. Cadmus addresses this need with a redundant two-lander architecture that is capable of assessing the constituency of the surface, measuring the Europa crustal dynamics, and making measurements of the suitability of the Europa crust to the presence of life. The Cadmus mission utilizes a high level of autonomy and simplified mission operations in order to reduce mission complexity. By providing a cost-effective, highly reliable, and low risk mission architecture, Cadmus will ensure a successful step towards extensive robotic exploration of the outer solar system.

There remains much work to be done before a next-generation Europa mission can be accomplished. The mission architecture presented could be improved using advanced design algorithms and methods. The instrument suite, while made up of instruments used previously on other missions, must be flight qualified in a high radiation environment.

REFERENCES

[1] Tamppari, Johnson, et al. (2000) *Europa Lander Studies May, 2000 and July, 2000.* JPL

[2] Zimmerman, et al. *Cryobot: An ice penetrating robotic vehicle for Mars and Europa.* IEEE 2001 Aerospace Conference , March 10, 2001.

[3] Phoenix Mars Lander
htp://phoenix.lpl.arizona.edu/
Last date visited: March 31, 2004

[4] Howard, et al. *Intelligent landing hazard assessment and avoidance for safe spacecraft landing*. AIAA Space 2003, September 23, 2003.

[5] NASA Expendable Launch Vehicle Performance Estimation Website
http://elvperf.ksc.nasa.gov/elvMap/index.html
Last Date Visited: March 31, 2004.

[6] Petropoulos, A.E., et al. *Trajectories to Jupiter Via Gravity Assists from Venus, Earth, and Mars*. Purdue, University.

[7] Sweetser, Maddock, Johannesen, et al. *Trajectory Design for a Europa Orbiter Mission: A Plethora of Astrodynamic Challenges.* AAS 97-174.

[8] Konefat, E. H., et al. *Enabling Technology for NASA's Europa Orbiter Mission*. American Astronomical Society AAS 01-001. February 4, 2001.

[9]Sherwood, et al. *Lessons Learned During Implementation and Early Operations of the DS1 Beacon Monitor Experiment.* NASA Center for AeroSpace Information, 1998.

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