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The Europa Ocean Discovery Mission

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ABSTRACT

Since it was first proposed that tidal heating of Europa by Jupiter might lead to liquid water oceans below Europa's ice cover, there has been speculation over the possible exobiological implications of such an ocean. Liquid water is the essential ingredient for life as we know it, and the existence of a second water ocean in the Solar System would be of paramount importance for seeking the origin and existence of life beyond Earth. We present here a Discovery-class mission concept (*Europa Ocean Discovery)* to determine the existence of a liquid water ocean on Europa and to characterize Europa's surface structure.

The technical goal of the *Europa Ocean Discovery* mission is to study Europa with an orbiting spacecraft. This goal is challenging but entirely feasible within the Discovery envelope. There are four key challenges: entering Europan orbit, generating power, surviving long enough in the radiation environment to return valuable science, and complete the mission within the Discovery program's launch vehicle and budget constraints. We will present here a viable mission that meets these challenges.

Europa Ocean Discovery will carry four scientific instruments to study Europa: (1) An ice-penetrating radar sounder to probe tens of kilometers below Europa's surface; (2) A laser altimeter, to determine the height and phase of Europa's time-varying tidal bulge; (3) An X-band transponder to determine Europa's gravity field; and (4) A solid-state optical imager. These instruments will provide important information about Europa's surface, subsurface, and provide definative evidence about the existence of a Europan ocean.

2. MISSION SCIENCE

The scientific goals of NASA's exploration of the solar system are expressed in *Space Science for the 21st Century* (1995). This strategic plan poses four fundamental questions, one of which concerns the origin and existence of life in the solar system. Since liquid water is the essential ingredient for life as we know it, the existence of a second water ocean in the Solar System would be of critical importance for seeking the origin and existence of life beyond Earth. The new NASA Mission and Technology Roadmap, *Mission to the Solar System: Exploration and Discovery*, states:

> **"Europa and Titan can be used as natural biological laboratories to understand how planetary environments can lead to life.** Europa is a Moon-sized body whose surface is covered by a smooth, relatively young layer of water ice. Liquid water oceans may exist under this ice crust. Liquid water appears to be the critical ingredient for the development and sustenance of life. Internal heating of Europa may produce hydrothermal vents, similar to those on Earth known to harbor non-photosynthetic life forms. **Thus, the detection and characterization of any Europa oceans is an integral part of our search for evidence of life in the solar system."**

Space Science for the 21st Century and *Mission to the Solar System: Exploration and Discovery* reflect the consensus of the scientific community that searching for a Europan ocean is of very high scientific priority. The search for Europa's ocean and its implications for exobiology also has tremendous public interest and will stir the public's imagination as few missions can. We intend to take full advantage of this interest and bring the excitement of this mission directly to the public via television, the Internet, and educational institutions.

Since it was first proposed that tidal heating of Europa by Jupiter might lead to liquid water oceans below Europa's ice cover[1,2,3,4], there has been speculation over the possible exobiological implications of such an ocean[5,6,7]. NASA's interest in these questions culminated in November 1996 with the "Europa Ocean Conference," jointly sponsored by NASA, the National Science Foundation, and the San Juan Institute, to "explore ideas related to Europa's possible ocean, submarine volcanism, and biological activity."

The original reconnaissance by Voyager and the new results from Galileo suggest the possibility of a liquid water ocean under the Europan ice[8,9]. The density of craters on Europa's surface suggest some parts of the Europan surface may be young[10], perhaps much younger than 100 Myr old[11]. Europa's bright surface (albedo ~0.6) may be "painted" through continuous deposition of surface frost, possibly originating from a liquid interior region[2, 12]. Pull-apart features and lineaments are interpretable as brittle ice plates separating and translating atop a mobile soft ice or water layer[12]. Some current tidal heating models favor the existence of a liquid water ocean[13] as deep as 100 km beneath an ice cover typically tens of km thick but perhaps as thin as 1 km at recent faults[14]. The Galileo nominal plus extended (if approved) mission would provide important new information and constraints on Europan models[8], including clues from gravity mapping[15], but it is unlikely to determine conclusively if Europa has an ocean. In any case, Galileo will be unable to characterize the ocean or surface structure that may exist which is imperative for future missions.

The search for and characterization of an ocean via remote sensing is the prerequisite Europa mission, setting the stage for all subsequent exploration. Should our proposed mission prove an ocean exists, its characterization will be critical to the design and targeting of future missions, especially future landers. Should no ocean exist, we will nevertheless have extensively characterized a world that provides an Earth or early-Earth analogue[16], insofar as it is a primarily silicate world overlain by a layer of water.

3. MISSION OVERVIEW

The technical goal of the *Europa Ocean Discovery* mission is to study Europa with an orbiting spacecraft. This goal is challenging but entirely feasible within NASA's Discovery program envelope. There are four key challenges: entering Europan orbit; generating power; surviving long enough in the radiation environment to return valuable science and complete the mission within the Discovery program's launch vehicle and budget constraints. We have designed a viable mission that meets these challenges.

Europa Ocean Discovery utilizes a standard Venus-Earth gravity assist trajectory to reach Jupiter. The first difficult challenge is to achieve Europan orbit after arriving at the jovian system. Our solution to this problem uses the same gravity assists used for the Galileo program. Eight gravity assists at the Galilean moons, combined with 2540 m/s of delta-V over a 409-day period, can place a spacecraft into Europa orbit. The margins for error on these maneuvers are at the same level as for Galileo. Using this scenario, a dry spacecraft (including payload) with a mass as high as 522 kg (much higher than our proposed 287 kg) can be placed into Europa orbit using a Delta II 7925H.

The second challenge is to generate enough power to operate a spacecraft at Europa. 300 W, sufficient for our mission, can be produced with conventional, space-qualified, commercially flown GaAs solar arrays.

The third challenge is to survive the radiation environment at Europa long enough to fulfill the mission's science objectives. Solar panels and electronics left unshielded would have to survive an average radiation dose of 7 Mrad/month in the form of electrons and ions at Europa. In this environment GaAs solar arrays will lose less than 10% of their performance over one month. Aluminum shielding can reduce the radiation dose on the susceptible electronics to 70 krad/month. (The LANL team has used this technique on over 40 GPS spacecraft in the similar, but less intense, environment of Earth's main radiation belts for missions with comparable total external doses) Most electronics are readily available for doses up to 100 krad. Some specific components, such as the CCDs, will require especially careful shielding and further radiation hardening which is within current technology. Our radiation analysis leads us to anticipate at least a 6 week lifetime for *Europa Ocean Discovery*. A valuable advantage of the chosen gravity-assist trajectory is that the spacecraft will spend only 10 hours in the intense part of the jovian radiation environment prior to entering Europan orbit.

No single measurement technique is certain to answer the question of the existence of Europa's putative ocean. Rather, this mission relies on a set of parallel measurements (Fig. 1), each of which attacks the problem in a different but complementary way. *Europa Ocean Discovery* will carry four scientific instruments to make these measurements: (1) Ice-penetrating radar (IPR) to sound Europa's surface ice; (2) Laser altimetry, to determine the height and phase of Europa's time-varying tidal bulge; (3) An X-band transponder to determine Europa's gravity field; and (4) A solid-state optical imager to characterize the surface morphology. These instruments will provide important information about Europa's surface, subsurface, and interior whether or not an ocean is found.

Once at Europa, the spacecraft will spend one week in a 300 km altitude orbit (150 minute period), one week at 100 km, and one month at 30 km. All orbits will be polar and nearly edge-on to Earth to provide radial precision in the Doppler tracking sufficient for the gravity and altimetry experiments. The transponder will be used at 300 km and 100 km to measure the variations in the spacecraft orbit. Europa's periodic tidal bulge will distinctly perturb the spacecraft's orbit, allowing the construction of a gravity map. The magnitude of these perturbations depend on whether the tides are raised in solid ice or liquid water and the thickness of this layer. Combined with measurements of the height of the time-varying tidal bulge using the laser altimeter (to be conducted from the 30 km orbit), these measurements provide powerful constraints on possible interior models for Europa, and in particular, on the existence and characteristics of a Europan ocean. These initial measurements may by themselves answer the question of the ocean's existence (Table 2).

While still in the 300 km orbit, the optical camera will map the entire moon in two colors at 300 m resolution (Table 2). This will be the first global map of Europa. This map will: (1) Be compared to Galileo images to search for evidence of surface evolution over the 12 years between now and 2008; (2) Provide a data set for global correlation studies such as large tidal stress fractures; and (3) Provide a reference frame for radar and laser measurements to be made later in the mission.

Next the spacecraft will be lowered to an altitude of 100 km. In addition to completing a second gravity map, selective optical mapping with 50 m resolution over 10% of the surface will be conducted. This mapping will be used to refine pointing targets for the high resolution survey. Areas of suspected activity or particular geologic interest will be targeted for imaging during this week. The second gravity map will refine the gravity field coefficient determination and give a us a better determination of whether an ocean exists.

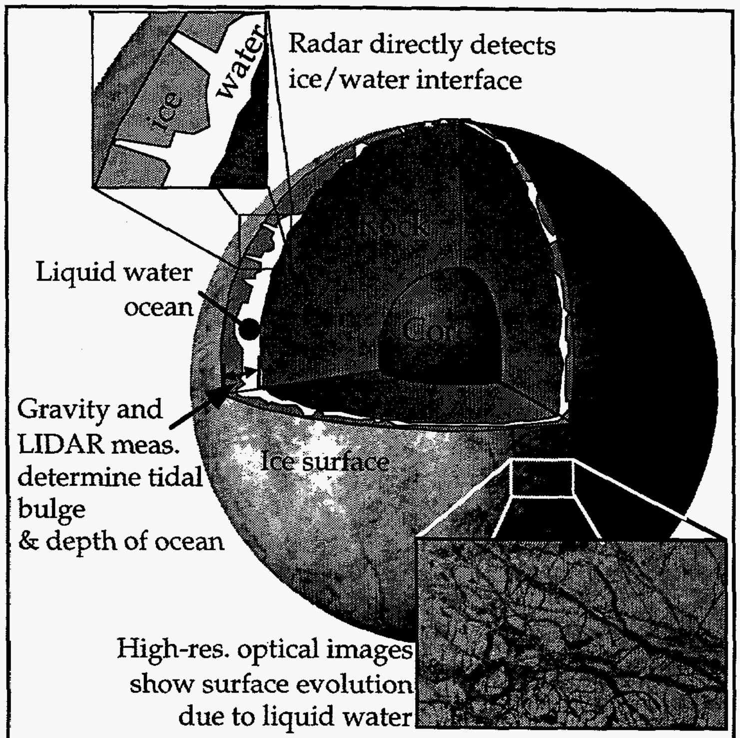


Figure 1: *Europa Ocean Discovery* measurement objectives, how they will be addressed and how they fit together.

The final orbit will be at 30 km altitude (118 minute period). At this orbit the spacecraft will complete several important studies (Fig. 1, Table 1): (1) Radar sounding of the surface ice thickness; (2) Surface topography through laser altimetry; and (3) High-resolution optical surveys.

The proposed ice-penetrating radar (IPR) system will take 3 million soundings of the Europa surface with 0.3 × 11 km spatial resolution and ~100 m range resolution. According to current models, Europa's ice layer could be as deep as 100 km but ice as thin as several km or less may be possible[14]. The IPR system will provide important information regardless of the thickness of the ice, being

Table 1: Measurement summary

Measurement	**Resolution**	**Coverage**	**Science objective addressed (time is week in Europa orbit)**
Ice Penetrating Radar	0.3×11 km spatial, 10s km depth, 100 m thickness	3 million soundings along orbit tracks	initial ice structure measurement during third week, global ice thickness map by end of sixth week, may determine existence of ocean
Gravity	k2 ± 0.003 to 0.03	global	may determine ocean existence as early as first week
Laser Altimetry	3 m topography, tidal bulge to±2m	100 million altitude determinations	may determine ocean existence during third week, topographic map by end of sixth week
Optical Imaging	300 m	global	complete global map during first week, may determine ocean existence, will display global surface features
	50 m	10%	detailed surface images for geologic and evolution studies by end of second week
	15 m	2.5%	determination of surface activity and evolution during third, fourth, fifth or sixth week

able to: (1) Detect a water/ice interface to 15-25 km depth; (2) Probe ice inhomogeneities at 90 km depth if the ocean is 100 km down; and (3) Detect an ice/rock interface to 100 km if the temperature at the interface is below 250 K. As with terrestrial radar sounding, an intensity vs. time histogram of the radar returns will be made. In these data, a thin ice surface underlain by a liquid ocean will appear very different from a thick ice layer overlying an ocean, or an ice/rock layer with no ocean. For example, a thin ice layer may have numerous distinctive radar-opaque water-filled cracks and boundaries (Fig. 1) whereas a thick layer may have fewer, larger structures at greater depths. This radar data set should produce a good model of the surface layers of Europa, thereby laying important groundwork for future lander missions.

Laser altimetry will be used in the 30 km orbit to measure the time-varying portion of the tidal bulge to +/- 2 m (1σ), as well as local surface relief. Working synergistically with the gravity measurements, the tidal bulge measurement may determine ice thickness and ocean depth. Finally, the spacecraft will also conduct a high-resolution (15 m over 2.5% of Europa's surface) optical survey in this orbit. In addition to providing the finest tests for surface evolution (Fig. 1), this data set will be critical for correlating results from the other instruments with surface features. This set of measurements--gravity, altimetry, IPR, and imaging, conducted at the three orbit altitudes described--constitute the baseline mission (Table 2).

4. MISSION SPECIFICS

4.1 Gravity Measurements

Europa Ocean Discovery will use the tides raised on Europa by Jupiter to probe Europa's interior. Because Europa's orbit around Jupiter is eccentric, the tidal bulge on the satellite rises and falls over Europa's 3.6 day period, with the radial tide's amplitude reaching its maximum at perijove. This bulge in turn modifies Europa's gravity field. These two effects may be measured through laser ranging of the satellite's shape and through gravitational perturbations of the spacecraft's orbit, respectively. As described below, the two measurements together will yield a characteristic signature if a global ocean exists on Europa.

Europa is distorted by the tide-raising potential of the jovian gravitational field. The height of the tidal bulge raised by this potential depends on Europa's surface gravity, Europa's orbital characteristics and the Love number which in turn depend on the distributions of density and elasticity within Europa [17]. When Europa reaches perijove, the tidal distortion (d) is at its maximum. For a global ocean lying beneath an ice shell tens of km thick, the Love number h_2 ~1.2 to 1.3 and d ~30 m [66]. For a solid ice shell, $h_2 \approx 0.04$ and the variation in the radial distortion drops to about 1 meter. The amplitude of the distortion varies sinusoidally with the orbital angular position Europa proceeds around its orbit. With the laser altimeter and X-band transponder we will determine Europa's global shape and the magnitude and phase of the h_2 tidal parameter.

In addition, since Europa on its elliptical orbit moves faster and slower, the location of the maximum tidal bulge librates (rocks back and forth). This leads to an along-track tidal distortion, which introduces a periodic term into the gravitational potential of the distorted satellite from which a second Love number k_2 can be determined[18,19].

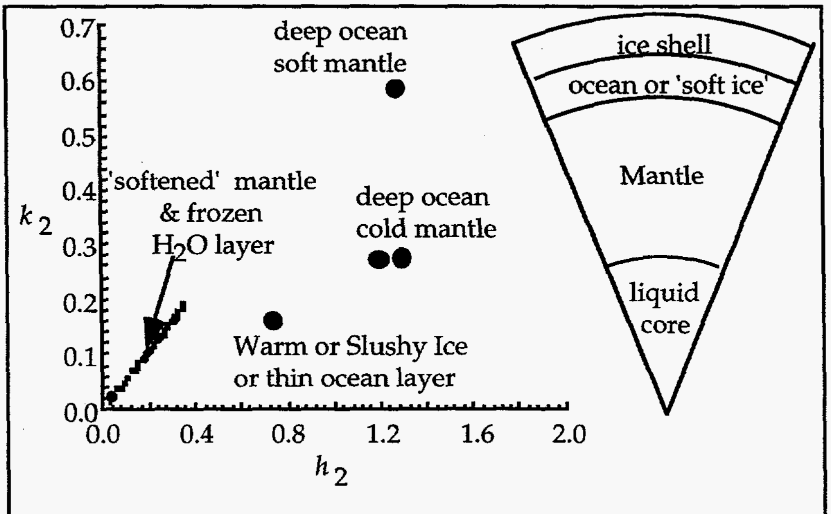


Figure 2: Love numbers h_2 versus k_2 for a variety of structure models[66]. The ratio h_2/k_2~2 for the 'frozen ocean' case while h_2/k_2~4 for a deep ocean.

The measured values of the Love numbers k_2 and h_2 may be compared to those calculated for various models of Europa's interior differing in their assumed distributions of density and elasticity (i.e., which represent different thicknesses of covering ice and underlying ocean). Typical values of k_2 and h_2 for a few representative models are shown in Fig. 2. Clearly, the measurements of shape and gravity that lead to h_2 and k_2 can be instrumental in distinguishing between various interior models. [66] Simulations suggest that the formal uncertainty in k_2 will be $\sigma(k_2) = \pm 0.003$ for a 5 day mapping from 100 km altitude. A more cautious assessment of unmodeled forces at Europa suggests we can achieve $\sigma(k_2) = \pm 0.03$ *and this is more than adequate* *to discern the presence of a global ocean..*

The gravity solution is largely insensitive to orbit orientation relative to Earth although certain geometries should be avoided, particularly a nearly face-on orbit. Moreover, an edge-on orbit senses the radial and along-track spacecraft position and that is important for the altimeter. For this reason *Europa Ocean Discovery* will orbit Europa in a polar orbit nearly edge-on to Earth.

The gravity analysis follows the same method as on the Galileo and Magellan programs. The next-generation X-band Small Deep Space Transponder being developed by Motorola will be used. This system is based on transponders currently in use for Pathfinder and MGS and to be used on Cassini.

4.2 Laser Altimetry Measurements

The laser altimeter (LIDAR) measures the round trip time of flight of laser pulses between the spacecraft and the surface of Europa. Individual Europan radii determined from the LIDAR will be used to determine the amplitude and phase lag of the time-varying tidal bulge of Europa and to characterize the topography of the surface. Topographic profiles and regional grids of topography will enable quantitative analysis of geological and geophysical processes that shaped the surface. In addition, the topography, in combination with gravity, will be used to infer the moon's internal density distribution.

Measurements will be distributed from pole to pole with an along-track spacing of 35 m. Given continuous range acquisition, the 40-Hz pulse repetition frequency over the one month nominal mission, and a 90% probability of detection, nearly 100 million precise measurements of Europa's radius are expected. (For comparison, the Clementine global topographic model consisted of only ~72,000 observations.) The expected quantity of data is sufficient for addressing problems ranging from planet-scale long-wavelength time-varying effects and static high resolution problems of a geological nature.

Considering orbit geometry and quality, 40 altimeter shots/sec with 90% success, and the anticipated coverage of Europa, we expect to estimate the magnitude of the time varying tidal bulge to ± 2 meters (1 σ), which should allow us to distinguish between the cases of a liquid ocean and solid ice shell.

4.3 Ice Penetrating Radar

Ice Penetrating Radar (IPR) offers the best hope for the direct detection of a Europan subsurface ocean from an orbiting spacecraft[20, 21]. Any abrupt transition in bulk electrical properties with a lateral dimension significant in relation to the IPR beam width will be discernible in the radar range profiles. Because the electrical properties of rock, ice, and liquid water differ greatly, detection of a discrete ice/water or ice/rock boundary beneath the ice is possible.

Based on terrestrial measurements and Europa radar sounding from Earth, Chyba, Ostro and Edwards[21], have completed a detailed theoretical study of the properties, limitations and uncertainties of radar sounding the Europan surface. This work covers many aspects of the problem and suggests that a wavelength of 6 meters is optimal for sounding the Europan ice surface. A 6 m wavelength system was chosen because: (1) This wavelength lies well beyond the wavelengths where anomalous scattering is known to occur from Earth-based observations; (2) t should be able to penetrate tens of kilometers into Europa's ice (see below); and (3) It is of shorter wavelength than most of the jovian radio noise. (The maximum equivalent noise temperature of the Jupiter magnetospheric radiation rises slowly from short wavelengths to 5×10^4 K at 6 m[24]. The noise then rises sharply to over 10^{10} K at 30 meters wavelength[32].)

The work of Chyba has been utilized to design an ice penetrating radar system to address the critical science with the spatial and range resolution and coverage required. These requirements are that we have: (1) sub-km range resolution to ensure we may detect water at depths as shallow as 1 km, which some models predict may exist under fresh faults[14]; and (2) a footprint in the ~10 km range or less, so that subsurface sounding may be correlated with prominent surface features, especially triple bands (~10-20 km wide), dark patches (up to ~30 km), large impact craters, and raised knobs (up to 35 km across; Cilix is 16 km across)[23].

To achieve the spatial resolution required we will use a 3-antenna array for the cross-track resolution (11 km). To achieve fine spatial resolution in the along-track direction, a synthetic aperture radar (or Doppler filtering) technique[31] will be employed to give us 260 m resolution in the along-track direction on the surface of Europa (the resolution 50 km deep in the ice will be about 350 m).

The proposed system will have ~100 m range resolution, a 0.3 km × 11 km footprint, and be able to detect:

- an ice/water interface 15 to 25 km below the Europa surface depending on the surface temperature.

- inhomogeneities in ice to 90 km if the ice/water interface is located 100 km below the Europan surface (warm ice attenuation prevents us from detecting the actual interface).
- an ice/rock interface to 100 km if the temperature of the ice is not above 250 K

The IPR system will produce 3 histograms of depth measurements every second on the sunlit side of Europa. This will give us 3 million depth measurements across the Europa surface with 470 m spacing along the orbital tracks. To minimize the telemetry rate while still achieving the science objectives we will use a graded thickness resolution scale with 100 meters resolution at the surface and 3 km resolution at 100 km depth.

4.4 Optical Imaging Measurements

The primary objectives of the Imaging Experiment include: (1) Very high resolution (15 m/pixel) monochrome images sampling all terrain types to search for morphological signs of geological activity that would indicate the presence of a global ocean; (2) Very high resolution (15 m/pixel) monochrome imaging to support ice penetrating radar and laser altimetry measurements by correlating surface morphology with observations; (3) High resolution (50 m/pixel) monochrome imaging to support gravity field measurements by documenting variations in surface morphology due to the interior mass distribution; (4) Global 2-color mapping of the entire surface at 300 m/pixel to complete the initial survey of Europa and provide a geological database from which inferences about a possible liquid mantle may be drawn (Galileo images have already demonstrated the value of two-color imaging for the interpretation of Europan surface features[22,23]); and (5) The determination of Europa's spin pole location to ~20 m, allowing a determination of Europa's axial moment of inertia to ~10%, and providing an additional constraint on the internal mass distribution[15].

Both this high and very high resolution imaging of selected sites and the global mapping should provide for detailed studies of Europan surface features which may be indicative of a liquid water ocean. These will include high resolution studies of Europan lineaments, pull-apart terrain, crater morphologies, and other surface features, as well as improved statistics for crater density vs. diameter curves as a function of terrain type (the latter providing information on both surface ages and viscous relaxation rate of the ice). Areas of special interest identified in the 300 m resolution images will be targeted for multiple images at higher resolution. The two color images at the global scale have been demonstrated to show clear delineation between large-scale geologic events.

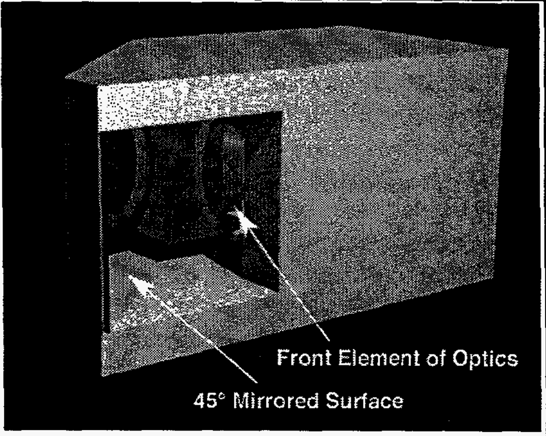


Figure 3: Optical camera with additional shielding

The *Europa Ocean Discovery* mission camera is based substantially on the Mars Descent and Mars Color Imagers (MARDI and MARCI) flying on the 1998 Mars Surveyor lander (Fig. 3). Owing to the extreme radiation environment, substantial replacement of parts will be required, but the basic design shall be identical.

The primary Imaging Experiment objectives will be carried out in phases, as the altitude of the spacecraft is reduced. The optical camera will be a basic 1k × 1k Kodak CCD array with two color filters (centered at 450 nm and 750 nm), one filter covering each half of the array. This camera will be used to take both the low- and high-resolution images, depending on the orbit. From the 300 km altitude initial orbit the spacecraft will complete the global color mapping, using both filters and employing the camera's summation mode to reduce the resolution to 300 m/pixel. High resolution monochrome imaging will be carried out from the 100 km and 30 km orbital altitudes, providing coverage of approximately 7% of the surface at 50 m/pixel in 7 days from 100 km and 2.5% of the surface at 15 m/pixel from 30 km, for 4 weeks at this altitude. This instrument is data rate constrained; the coverage described here readily allows us to address the primary science objectives.

4.5 Transit to Europa

Numerous scenarios were considered for transfer to the jovian system. The best trajectory was found to be a standard Venus-Earth gravity assist launching on Aug. 6, 2002. The trajectory takes the spacecraft past Venus on Dec. 5, 2002, Earth on Aug. 28, 2004 and arrives at Jupiter on March 24, 2007 (4 years, 7 months). With a lift coefficient (C3) of 7.75 this trajectory can launch 1220 kg to Jupiter with a Delta II 7925H and requires essentially no additional propulsive thrust (ΔV) during transit.

The following Europa orbit insertion scenario is based on the gravity assists performed by the Galileo spacecraft to reduce its orbit from 200 to 36 days. The margins of error are the same for our proposed scenario as for the Galileo mission.

Table 2: Europa Orbit Insertion Scenario

Maneuver	ΔV required (m/s)	resulting orbital period (days)	altitude (km)	Jupiter periapse (km)	Jupiter apopase (km)
Ganymede fly-by	0	—	500	9.15e5	—
Jupiter capture	899	200	9.15e5	9.15e5	1.88e7
Periapse raise	266	212	1.88e7	1.70e6	1.88e7
Callisto fly-by 1	0	66.8	723	1.57e6	7.92e6
Callisto fly-by 2	0	33.4	750	1.39e6	4.59e6
Callisto fly-by 3	0	22.3	1580	1.19e6	3.38e6
Callisto fly-by 4	0	16.1	1420	9.54e5	2.72e6
Ganymede phasing	<100	—	—	—	—
Ganymede fly-by 1	0	9.53	514	8.32e5	1.76e6
Ganymede fly-by 2	0	7.15	2219	7.06e5	1.44e6
Ganymede fly-by 3	0	6.71	18149	6.71e5	1.38e6
Europa phasing	<100	—	—	—	—
Europa capture	1069	150 minutes	300	—	—
Reduction of orbit	106	118 minutes	30		
Total	2540	—	—	—	—

On arrival at the jovian system the spacecraft will fly-by Ganymede to reduce the ΔV required for capture. A conventional propulsion burn of 899 m/s will then be used to capture around Jupiter (see table 5). The initial capture will place the spacecraft into a long elliptical Jupiter orbit with a 915,000 km periapse that is tilted 11° to the jovian equator. This orbit does not pass near Jupiter's rings, only visibly extending out to 120,000 km, minimizing impacts with particles in the jovian system. The initial orbit takes the spacecraft out past the orbits of Callisto and Ganymede again similar to Galileo's initial orbit. At the apopase of this initial 200-day orbit the spacecraft performs a short burn (266 m/s) to move the orbit periapse to the vicinity of Callisto's orbit. On the following four orbits, gravity assists at Callisto will be utilized to reduce the energy, eccentricity and inclination of the orbit. Each of these assists will be designed to place the spacecraft in a resonant trajectory that will execute M orbits for N orbits by Callisto, thus ensuring a subsequent flyby. Following the fourth Callisto gravity-assist, the spacecraft will be on a trajectory for a close fly-by of Ganymede. A phasing burn of 100 m/s may be required to match orbits with Ganymede. After three orbits with gravity assists at Ganymede and suitable phasing maneuvers (100 m/s) the spacecraft will achieve an ellipse that is tangent to the orbit of Europa with a low relative velocity. This allows us to enter a 300-km orbit ($\Delta V = 1063$ m/s) around the icy moon. Reduction of this orbit altitude to 30 km will require an additional 106 m/s of ΔV. This scenario takes 409 days and requires 2540 m/s of ΔV from entering the jovian system to entering Europa orbit. All except the first Jupiter encounter and the prime mission in Europa orbit are outside the main jovian radiation environment. This scenario places us in orbit around Europa when Earth is near its closest point to Jupiter. The insertion trajectory may be adjusted to arrive two months later which would optimixe the Earth-Jupiter alignment and be after Cassini's scheduled end-of-life.

This complete scenario has been analyzed using two-body orbital mechanics and patched conic trajectories as described in the Bate[25] and D'Amario[26]. The analysis technique is essentially the same as that employed to design the tour of the jovian moons that was carried out as part of the Galileo mission.

This scenario is the result of trade-offs which included consideration of various propulsion systems (monopropellant hydrazine, resistojet hydrazine, bipropellant, pulsed plasma and ion) and possible braking procedures (aerobraking, aerocapture, conventional propulsion, gravity assists, and all combinations of these). The method described is the best in terms of performance, cost, scheduling and risk.

4.6 Electrical power system

Electrical power for this mission will be generated through the use of GaAs solar arrays. GaAs was chosen for its high efficiency and reduced susceptibility to radiation damage. Accounting conservatively for the power required on this mission, radiation degradation, cell mismatch, sun-pointing error, meteorite damage, UV, calibration error, and IR drop, the spacecraft will need 30 square meters of solar arrays (330W, 90 kg, Fig. 4). The spacecraft will be nadir-stabilized with the solar panels mounted on 2-axes gimbals to rotate 180 degrees and track the sun.

Because the spacecraft orbit will be noon/midnight batteries will be required for darkside spacecraft operations. The energy storage capacity of these batteries will be 100 W-Hrs (this includes a 50% margin).

4.7 Guidance, navigation and control (GN&C)

The GN&C system will utilize standard hardware (heritage in brackets) including:

- reaction wheels (EOS),
- sun sensor (CRSS),

- IRU (A2100),
- Earth sensor (XTE),
- horizon crosser,
- star trackers (CRSS/XTE), and
- magnetometer (Ithaco)

Once in orbit around Europa, the instruments will require a pointing stability of ±5° to nadir with a 0.1°/sec stability to complete the science objectives. These requirements are fairly simple by today's standards.

Because of the 70-minute round-trip light travel time between Earth and Europa the spacecraft will perform coarse orbit maintenance, attitude control, telemetry cycling, power control, automatic error and upset correction, and spacecraft preservation autonomously. Non-critical functions will be controlled from Earth.

The computational power for the spacecraft will be supplied by the radiation-hard RAD6000 CPU. The processor unit will control power regulation, attitude control, telemetry and data handling.

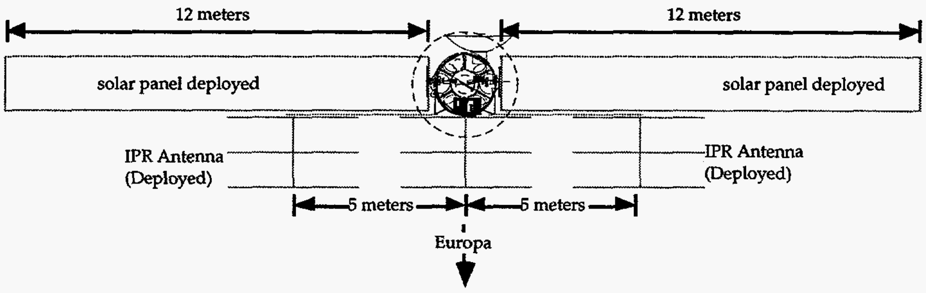


Figure 4: Schematic topview of the *Europa Ocean Discovery* spacecraft fully deployed

4.8 Propulsion

ΔV estimates are 0 m/s for mid-course corrections, 2540 m/s for the orbit insertion, and 90 m/s for orbit maintenance for a total of 2630 m/s. The propulsion system has been designed to supply 3300 m/s of ΔV.

The standard bipropellant system that will be used has an ISP of 317 sec. Primary 490 N thrusters will be used for course corrections and ΔV maneuvers. Smaller 22 N thrusters will be utilized for attitude control and for despinning the reaction wheels. The entire system is composed of off-the-shelf components. The check valves from the NTO tank will be designed to avoid the problems recently encountered on other missions with valve degradation. Non-Teflon seals or a modified propulsion system design will be used.

Depending on the thermal design, up to 35 W of heat may have to be supplied to this system to keep the propellant from freezing (the 35 W has been assumed in our design).

4.9 Thermal control

Passive control will be used wherever feasible with the second choice being electrical control. Multilayer insulation (MLI) will be used over the entire spacecraft exterior to maximize heat retention. Thermistors and electrical heaters will maintain the spacecraft temperature between 10° and 50° C at Europa. This range will be maintained during cruise phase near Venus and Earth through the use of heat pipes and radiators.

4.10 Data handling and communications

The spacecraft bus will have 10 Mbytes of memory specifically for data storage. This memory will be from Loral (radiation hard to over 1 Mrad with $<1\times10^{-12}$ errors/bit/day). In addition the RAD6000 will be used for (JPEG) compression of the optical data.

The data rate will be 8 kbps and utilize the Deep Space Network 34 meter antenna. The baseline spacecraft telemetry system has a single 5 W transmitter, 2 meter diameter dish and operates in the X-band. It is a commercial off-the-shelf system that has been used by LMC for previous missions with modifications to the dish. A cost/risk trade-off will be performed to determine if the antenna modifications should be made to the existing design or if an off-the-shelf antenna from an outside vendor will be selected. The telemetry dish is mounted on a 2-axes gimbal for tracking the Earth.

Of the 8 kbit/s, 1.5 kbit/s will be utilized by the spacecraft, 1.5 kbit/s by the laser altimetry system, 1 kbit/s by the IPR system and 4 kbit/s by the imaging system.

4.11 Spacecraft structures

The identical spacecraft structure was flown on the CRSS program. It is of composite materials to reduce mass.

4.12 Deep Space Network (DSN) and ground operations

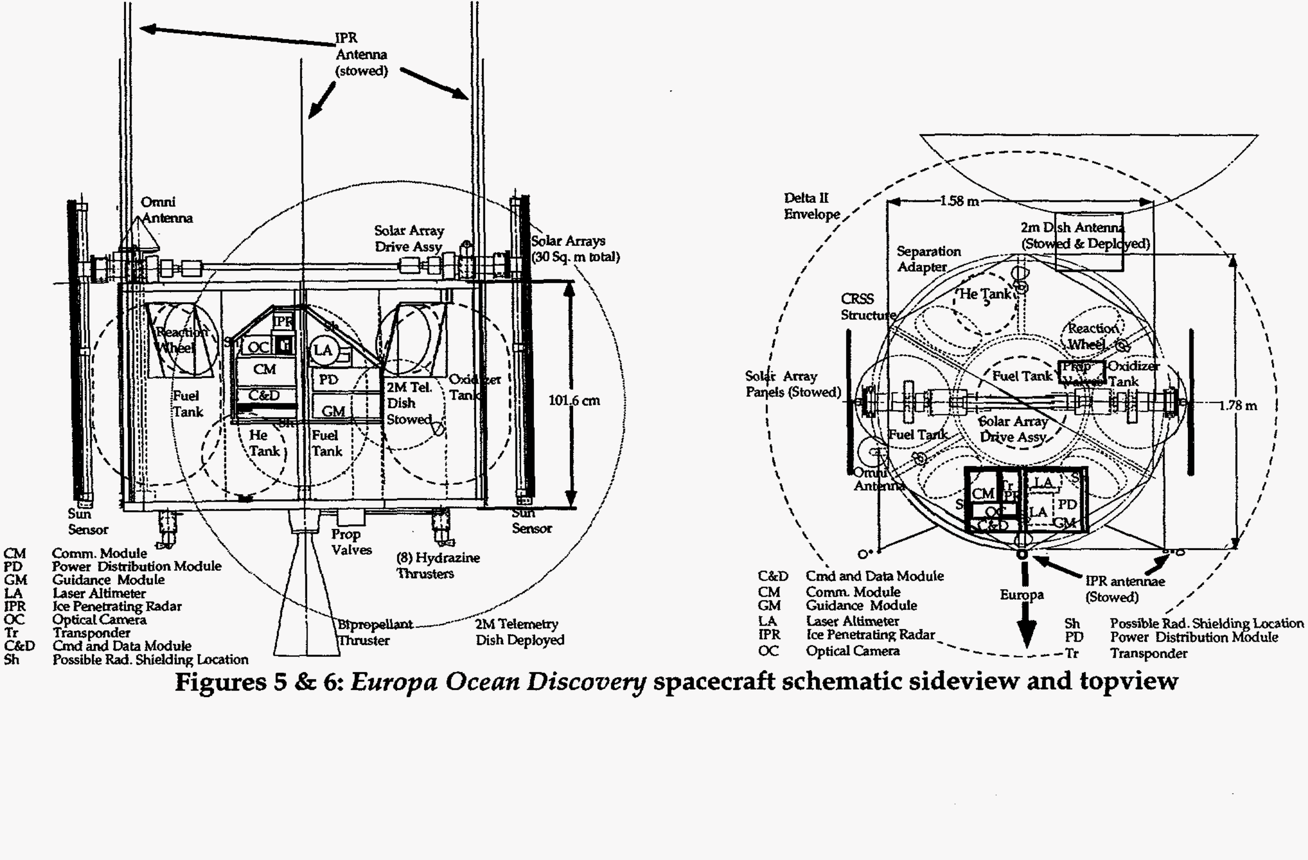
During cruise phase, the mission requires one 4-hour block of time each week with two additional 4-hour blocks at each gravity-assist event. This time will be required for spacecraft health monitoring. Once in Europan orbit the program will require at least 30% duty cycle on the 34-m DSN network for 6 weeks. However, because this telemetry is on a two-hour cycle there will not be time to realign for communications with other missions. Effectively this means *Europa Ocean Discovery* will be using 100% of the time on a particular 34 m installation. With this in mind, the telemetry duty cycle can be increased to 100% (60% effective due to eclipse) with no additional impact on the DSN.

4.13 Radiation issues

Based on Voyager[27] and Galileo measurements, the spacecraft will encounter up to 10 Mrad/month of protons, ions and electrons while in the vicinity of Europa (solar radiation will contribute another 10 krad during the mission lifetime). The protons and ions are low-energy (<1.4 MeV) and will be effectively shielded by the spacecraft without any additional shielding. Electrons with energies up to 20 MeV deposit most of the 10 Mrad/month (this will be partially shadowed by Europa due to the gyration radii of the electrons, 25 to 250 km for 2 to 20 MeV, giving us an average of 6 Mrad/month). The spacecraft will only be inside the jovian radiation environment during the first pass around Jupiter (~10 hours, 130 krad) and in orbit around Europa (6 weeks nominal). Our plan is to utilize shielding and radiation-hard components to operate successfully in this environment.

The systems susceptible to this radiation are the electronic processors, memory, CCD arrays, and solar arrays. The solar panels can not be shielded and must survive this radiation. The fluence of electron radiation at Europa will be less than 2.6×10^{14} e/cm^2/month[27]. From studies of GaAs solar cells[28] , this fluence would degrade the solar cell power production by 10% per month.

For the electronic components, our studies have found that this radiation can be effectively reduced to 60 krad/month with 0.8 inches of aluminum or its equivalent. In the design of the spacecraft (see Figs. 5 & 6) the amount of added shielding required will be minimized through modeling and placement of spacecraft components to reduce the radiation dose seen by the electronics. In the worst case (as shown in the spacecraft schematics) all of the electronics could be encased within 0.8 inches of aluminum (40 kg of shielding,



Figures 5 & 6: ***Europa Ocean Discovery*** **spacecraft schematic sideview and topview**

implemented in the current design). Additional shielding will be implemented on electronic components that can not be located in the electronics section and the radiation-soft CCDs in the optical camera and star trackers. Photons produced by stopping the energetic particles in the shielding will be stopped with a layer of high-Z material (tantalum) on the inside of the shield.

Radiation-hard electronics will also be used on this program wherever possible. For example, RAD 6000 processors and Loral memory will be used in the spacecraft bus and IPR, and radiation-hard electronics and gate-array will be used in the optical camera. These components are designed to reduce or eliminate latch-up and bit errors. For example, the RAD 6000 is tested radiation hard to over 2 Mrad and latch-up free.

4.14 Stationkeeping in Europa orbit

The orbit evolution of a close (30 to 300 km altitude) Europa satellite will be dominated, in the long term, by Jupiter's third-body gravity effects and, in the short term, by the moon's gravitational structure. The principal short-term variations in eccentricity of a close Europan orbiter will probably be controlled by the odd zonal harmonics (representing North-South asymmetries) of the gravity field. These variations in eccentricity change the altitude of the periapsis and, for close orbiters, can quickly (within a few weeks) lower the periapsis to the surface. Therefore, to maintain a stable orbit, it is necessary to adjust the orbit with propulsive maneuvers.

This problem has been studied for many years in anticipation of several proposed close lunar orbiters for our own moon (see, for example, Ridenoure[29]). Europa is nearly the same size and mass as our moon and, while there is some evidence suggesting Europa's gravitational structure will be less lumpy than our moon[30], it is prudent to include enough propellant to maintain the orbit if Europa is as asymmetrical as our moon with respect to its equator.

The "worst case" gravity-field estimate for our moon requires 1.8 m/s per day to maintain a 100-km altitude polar orbit. This corresponds to a decrease in pericenter altitude of about 4 km per day and requires corrections every 20 days for a 100 km altitude orbit and roughly every 1.5 days for a 30-km altitude orbit. Fortuitously, this is about the maximum rate of decrease (or increase) in pericenter due to the long-term Jupiter gravity effects in case the oblateness of Europa is small.

In the absence of more definitive gravity information from analysis of the Galileo close-encounter data for the Galilean satellites, the following ΔV allocation will be used for the *Europa Ocean Discovery* Mission:

- Fixed Amount of ΔV = 1.0 m/s per day = 44 m/s for 44-day close operations.
- At the 3-σ level a contingency ΔV = 1.0 m/s per day = 44 m/s for 44 days is included in ΔV budget.

We have treated Europa as if it had the same gravity field as our moon confident that this a worst-case scenario and that such treatment will be amply conservative in the system design.

4.15 Additional Mission Information

Data received from the spacecraft will have initial processing completed to check validity, aligned to a global grid, and integrated with previous data. These data will be made available immediately on a public website and to the PDS system. Global maps will be constructed subsequent to additional processing and interpretation, and then will be made public for all applications immediately upon completion.

The *Europa Ocean Discovery* education and outreach program will utilize the Internet and "Nova"-class documentaries as well as extensive educational programs to: 1) foster public interest and familiarity in the space program, 2) train and educate undergraduate and graduate students and postdoctoral fellows, 3) promote the involvement of women, underrepresented minorities, and students with disabilities in all aspects of this mission, and 4) facilitate and cultivate partnerships with the education community.

Since this mission is intended to orbit a planetary object with the possibility of some type of life or environment capable of supporting life a planetary protection plan will be required (Europa is classified as a Planetary Protection Priority C). Orbiters are classified as Category III in terms of protection from contamination of the planet. However, since the final demise of the *Europa Ocean Discovery* spacecraft will be to crash on the surface of Europa, the mission will be classified as a Category IV. Our program will follow all procedures required for planetary protection applicable to a Category IV mission.

5. SUMMARY

With the possibility of a global ocean on Europa suggested by tidal heating models and recent images returned by the Galileo spacecraft, Europa has become a prime target in the search for life beyond Earth. The first step in understanding Europa and any global ocean that may exist there would be a detailed study of the jovian moon by an orbiting spacecraft. We have presented here a Discovery-class mission concept (*Europa Ocean Discovery)* that would be capable of determining the existence of a liquid water ocean on Europa and to characterize Europa's surface structure.

We have addressed the major hurdles to a Europa orbiting spacecraft: 1) entering Europan orbit, 2) generating power, and 3) surviving long enough in the radiation environment to return valuable science. The concept we have presented not only addresses the major problems of such a mission but it would produce a tremendous science return within the Discovery program's launch vehicle and budget constraints (Table 3).

Table 3: General specifications for the spacecraft components

Component	Mass (kg)	Ave. Power (W)
Spacecraft		
GN&C	49	50.5
propulsion system	33.4 (dry) 618.2 (wet)	---
thermal control	10	35 (max)
structures	53	----
power system	117	6
communications	9.5	16
C&DH	6.1	17
radiation shields	<40	
Payload		
IPR	15.8	21.75
optical camera	0.7	5
LIDAR	1	6
Transponder	3.1	13.2 max
Total payload	26	46 max 23 ave.
TOTAL	895	170 max, 120 ave.
AVAILABLE	1220	330 max, 170 ave

Europa Ocean Discovery will carry four scientific instruments to study Europa: (1) An ice-penetrating radar sounder to probe tens of kilometers below Europa's surface; (2) A laser altimeter, to determine the height and phase of Europa's time-varying tidal bulge; (3) An X-band transponder to determine Europa's gravity field; and (4) A solid-state optical imager. The science products that would result from this mission include: 1) a global map of the surface ice thickness, 2) a determination of the exstance of a global ocean and the internal structure of Europa, 3) a 300 m resolution global optical map of the planet, and 4) a high resolution map (15 m resolution) of several percent of the surface. This mission would provide important information about Europa's surface, subsurface, as well as addressing the question of the existence of a Europan ocean.

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