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1. Solar-Powered Europa Orbiter Design Study (2007)

1.1 Introduction

The feasibility of implementing a solar-powered mission around Europa has been evaluated periodically over the last decade. Most recently, an assessment was performed as part of the 2006 Europa Explorer (EE) Study, which evaluated the practicality of implementing that mission design with large solar arrays instead of radioisotope power systems (RPS). This previous study went into some depth in considering the issues related to the use of solar arrays in the Europa orbit illumination and radiation environment. The study concluded that an all-solar option was impractical to meet the science objectives as defined in that study by the science team. This conclusion resulted from the prohibitive mass, packaging and articulation issues associated with the very large (~300 m^2) solar arrays required to accommodate frequent eclipse periods associated with the particular Europa orbit used.

Continued interest in the potential for launching a Europa mission on a foreign launch vehicle (thereby reducing NASA's total mission cost) and in exploring alternatives to using Plutonium 238 power inspired a further look at the solar-powered option. This report presents a new approach to assessing solar-powered missions: first develop a potentially viable engineering implementation and then assess the ability for that mission concept to meet Europa science objectives.

1.2 Mission Concept

The team first reviewed the 2006 study and determined the main contributors to the untenable size of the solar arrays. Solar array size derived more directly from the need to accommodate frequent eclipses as the orbit passed behind Europa than from the radiation, life and temperature degradation of the cells themselves. To meet the science objectives as defined by the 2006 Science Team, the orbit had solar eclipses of approximately 35 minutes every 2 hours. This type of orbit necessitated continuous articulation of the solar arrays to maintain illumination, requiring large gimbals and additional large reaction wheels that exacerbated spacecraft power requirements. Finally, the dynamics associated with articulation of large arrays introduced disturbances to spacecraft pointing and control that would severely compromise science measurement capability. To mitigate these issues, the team made two fundamental changes to the original mission design.

1. Fly in a continuously illuminated orbit to avoid Europa eclipse periods
2. Make use of a lower-energy trajectory to provide greater delivered mass at Europa

With these changes, the accommodation of the "floor" planning payload as defined by the 2007 Europa Explorer Science Definition Team (SDT) appeared feasible.

Whereas the 2006 Europa science orbit study experienced eclipse during roughly one third of each orbit (100 and 200 km orbits with a 10:00 pm ascending node), the 2007 study used a science orbit (shown in Figure 1) that would be continuously illuminated (100 and 200 km orbits with a 4:45 am ascending node), thus eliminating eclipsing except during passes of Europa through the shadow of Jupiter (~3.8 hr every 3.5 days).

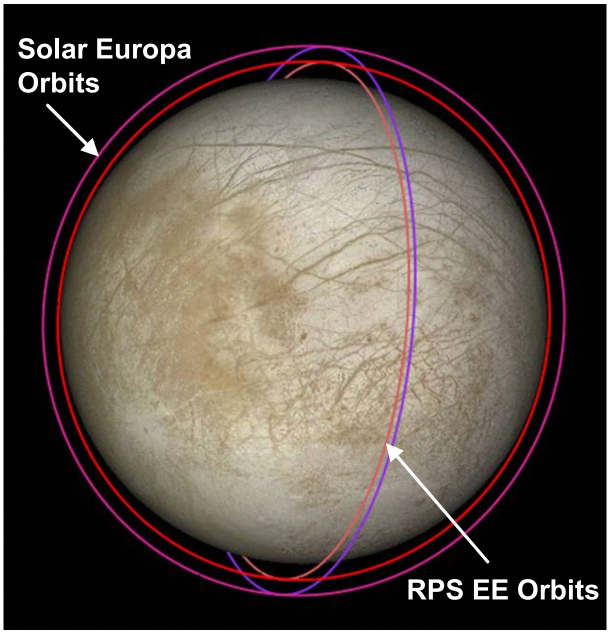

Figure 1: View of orbit along sun line
(200 km and 100 km orbits with 4:45am ascending node, 2007 EE 10:00pm orbit design shown for comparison)

This greatly decreases the amount of solar array area needed since the arrays view the sun for much longer periods of time (resulting in more power and less battery charging). Additionally, the orbit design allows the use of fixed solar arrays, eliminating the need for gimbals and the attendant power for articulation and attitude control. A detailed analysis of the design to understand pointing stability impacts was not performed.

Preliminary calculations indicated that a mission capability comparable to the 2007 EE floor science mission could be supported using a solar array of approximately 100 m^2, about 1/3 of that thought to be required by the 2006 study configuration. Additionally, preliminary mass estimates indicated that the concept might be accommodated on an Atlas V launch vehicle if a somewhat lower energy interplanetary trajectory (flight time of 9.8 years) were assumed. Given these results, the team enlisted JPL's concurrent engineering team, the Advanced Projects Design Team (Team X), for further concept development.

Results of the Team X study were promising, with a converged design (Fig. 2) emerging at the end of the session showing a mass margin of 33% for launch on an Atlas V 551. It should be noted, however, that Team X was only engaged for a single 3-hour session; so their results, though promising, should not be deemed conclusive. Given the level of maturity of this concept, a mass margin of 33% is insufficient; but the ability to use the larger-capability Delta IVH launch vehicle indicates that considerable additional margin is still available above the 33% quoted by Team X.

While launch on an Ariane was not directly addressed by the study, the Team X design as-is would show a smaller mass margin of about 24%, given the estimated capability of the Ariane 5 ECA. Considerable additional analyses for the Ariane launch vehicle would be required to determine if there is a viable mission on an Ariane.

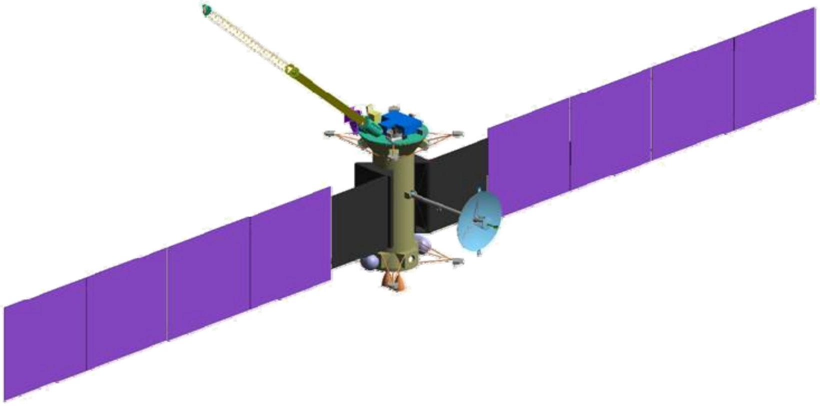

Figure 2: Potential Solar-Powered Europa Orbiter Configuration

Solar array area necessary to supply the required 731W end of mission (EOM) was determined to be ~94 m^2, about twice the area of the arrays planned for the Juno mission. The degradation factors assumed for the solar cells were the same as used in the 2006 study and have not yet been verified by the upcoming Juno solar cell test extension. (Testing is planned for EE but not yet completed). Other than power, most of the subsystem designs are based on those of the RPS-powered 2007 EE spacecraft concept study. A notable exception was the telecom subsystem, which was able to be reduced as a result of the greater available contact time associated with the revised orbit to achieve the same total data volume return. In the power subsystem the solar arrays brought the mass of the power generation components up to 468 kg, significantly heavier than the 195 kg mass of the five advanced Stirling radioisotope generators (ASRGs) used in the 2007 EE floor design. A comparison of the mission delta-Vs and masses for the EE2007 RPS-based mission concept mass and this one are shown in Tables 1 and 2, respectively. The changes resulted in a significantly heavier launch mass for the solar implementation over the 2007 EE design study (4805 kg vs. 3903 kg), but modification of the interplanetary trajectory with its consequent increase in flight time would still allow this concept to launch on a Atlas V or Delta IVH.

Table 1. delta-V Comparison.

	Solar Mission Concept		EE 2007	
Event	**Rel. Time**	**d-V (m/s)**	**Rel. Time**	**d-V (m/s)**
Launch	27-May-2015		27-May-2015	
Launch Injection Correction	15-30 days after launch	30		30
Earth Biasing	N/A	N/A		50
Deep Space Maneuver	N/A	N/A		215
Interplanetary Trajectory Correction Maneuvers	maneuvers during interplanetary cruise	20		20
Ganymede-0	3-4 hrs before JOI			
Jupiter Orbit	2-MAR-2025	1100		1050

	Solar Mission Concept		EE 2007	
Event	**Rel. Time**	**d-V (m/s)**	**Rel. Time**	**d-V (m/s)**
Insertion				
Perijove Raise Maneuver	2-4 months after JOI	70		70
Tour TCMs	~1 yr following JOI	200		150
Large maneuver cleanups	JOI through EOI	N/A*		20
Europa Endgame	Starts ~3 months before EOI	300		145
Earth Orbit Insertion	Approx. March 2026	480	4-July-2023	665
200 km Orbit	Approx. 45 days		30 days	
Orbit Change	EOI + ~ 45 d	50		40
100 km Orbit	Approx. 45 days		150 days	
Orbit Maintenance	~90 days	50	6 months	100
Reserves		N/A*		100
Total	**~ 11.25 years**	**2300**	**~8 years**	**2655**

*Reserves and cleanup included in tour delta-Vs

Table 2. Mass Comparison (*masses in kg, including contingency*).

	Solar Mission Concept	EE 2007 Floor
Instruments	100	100
Attitude Control System	70	70
Command and Data Handling	54	56
Power	320*	259
Propulsion	248	170
Structures	730*	343
Cabling	81	97
Telecom	37	67
Thermal	127	85
Radiation Monitoring	0	10
Radiation Shielding	148	133
Additional System Margin	0	135
Total Dry Mass	**1915**	**1391**
Propellant	2857	2345
LV adapter	33	33
Launch Mass	**4805**	**3903**
LV Capability	5110	4030
JPL Dry Mass Margin**	33%	35%

*Solar array structure mass carried in Structures subsystem
** Defined in JPL Design Principles as:
(Allocation –Current Best Estimate)/(Allocation)

1.3 Science Evaluation

The Team X study provided an indication of technical feasibility. Next the 2007 EE study team addressed the question of science value. The change in orbit ascending node necessarily imposes new constraints on science, giving restricted viewing angles relative to the Europa terminator, and thus restricted lighting conditions. On the other hand, measurements in some major investigation areas, such as gravity science, might actually be somewhat improved by the availability of continuous tracking allowed by the new orbit. A brief assessment of the science impacts was completed by the 2007 EE SDT co-lead as follows:

- **No negative impact, or improvement:**
    - **Gravity:** Radial and transverse velocity components are comparable, while gravity measurement objectives may be achieved more readily with continuous tracking over entire orbits. This assumes that the large solar panels would not adversely affect spacecraft stability.
    - **Radar:** Continuous downlink is an improvement to radar acquisition and downlink strategies in that it could allow radar to achieve its objectives sooner, and possibly provide an overall greater volume of radar data over the mission life.
    - **Laser altimetry:** No impact.
    - **Fields and Particles (magnetometer, particles and plasma):** No impact.
- **Modest or mixed impact:**
    - **Imaging (wide-angle camera, medium-angle camera):** At high solar incidence angles, morphology is improved; however color, albedo, and stereo all are negatively impacted.

      Color and albedo data are not optimal until >45° from the terminator, and at less than 10° they cease to be useful at all. For color, the signal-to-noise ratio (SNR) drops precipitously as the terminator is approached; and the associated technique of inferring stratigraphic information from colors only works at low phase angle (<60°), far from the terminator.

      Stereo provides no data in shadowed regions. Small-scale slopes on Europa reach 60°, but are more commonly <30°. So it is best to be more than about 30° from the terminator for stereo, which is not supported by the solar mission.

      Morphological information (shading) is optimal in a zone about 10–30° from the terminator on Europa. Closer to the terminator, images are generally too shadowed to be very useful. A canted imaging system can provide good morphological information in the solar mission.
    - **Thermal:** Time of day is not optimal for thermal measurements.

      Thermal measurements are optimal when the surface is viewed from an orbit where the surface is hottest during the day and coldest at night, so a mid-afternoon orbit is optimal. A dawn-dusk orbit will mean that temperature data and the curves used to fit them will not have as large excursions as when the orbit is optimal: the data will be noisier and the fits will be more difficult. It is possible that subtle thermal anomalies will be lost, especially in equatorial regions, but the solar mission should still be able to detect out more extreme thermal anomalies, especially at the poles (since temperature anomalies nearer the poles stand out more easily against the background thermal signature).

- **High adverse impact:**
  - **Infrared (IR) spectroscopy:** High solar incidence angles imply unacceptably low SNR, especially in the 2.7–5.0 µm range where organics have absorptions. Use of the IR spectrometer as envisioned in the planning payload is unlikely to provide the desired measurements.

    Note: Other instruments (e.g., a radar spectrometer) would need to be assessed and might be able to recover at least partial surface chemistry objectives.

Thus it appears that the constraints imposed by the continuously illuminated orbit result in a science mission that compromises the 2007 EE —SDT-defined floor science objectives. The resulting science value would need to be assessed by the full SDT.

1.4 Solar and RPS Mission Summary Comparison

Solar-powered missions have the inherent benefit of not requiring the use of radioisotope power systems and thus scarce Plutonium 238. Missions to the outer planets have successfully used RPSs for over 30 years. Limitations imposed by solar power at these distances have previously outweighed the benefits. Juno has shown that there are classes of missions to the outer planets that still might benefit from solar power. A comparison of the current RPS EE mission concept with the solar concept from this study is discussed below.

1.4.1 Concept Maturity

RPS versions of Europa missions have been extensively studied over the last decade. Assessments of solar alternatives were conducted, but extensive studies were not performed as early conclusions deemed the concepts highly impractical. This study provides insight into what potential science compromises may be necessary if a solar mission is to be considered. As was found in the 2006 EE Solar study, there are many areas in which further analysis will be required to ensure that all of the unique aspects associated with the solar implementation have been adequately addressed. The design of the solar option needs to be thoroughly evaluated through a rigorous study process to allow the penetration necessary to more fully vet the issues related to the use of solar power and the required compromises in science.

Due to the level of immaturity of the solar mission concept developed during this rapid assessment, the recommended mass/power margins should be larger than for the currently envisioned RPS mission concept. Team X cannot fully penetrate the design or the issues associated with so dramatic a design change in the short period they had to develop the concept. The resulting mass margin with an Atlas 551 (33%) is not considered sufficient given the brevity of the analysis. The option to use a Delta IVH launch vehicle mitigates the concern but would increase the cost significantly. The comparable RPS-powered science mission would use a lower cost launch vehicle and arrive at Jupiter years earlier.

1.4.2 Technical Parameters

A comparison of mission parameters is shown in Table 3.

Table 3. Mission concept key parameters.

	Solar Mission Concept	EE 2007 Floor
Total Dry Mass	1915 kg	1524 kg
Launch Mass	4805 kg	3903 kg
Launch Vehicle	Atlas V 551	Atlas V 531
Launch C3	12 km^2/s^2	14 km^2/s^2
LV Capability to C3	5110	4030
delta-V	2300 m/s	2655 m/s
Trip Time to Jupiter	9.8 yr	6 yr
^{238}Pu mass aboard	~0.019 kg (10 RHUs)*	~0.19 kg (100 RHUs) + ~4.4 kg (5 ASRGs)
Data Volume	7 Gb/day	7 Gb/day
Available Pwr. EOM	731 W	514 W

*The Solar Mission thermal design minimized the use of radioisotope heating units (RHUs), while the EE 2007 thermal design minimized required electrical power and complexity. For the Solar Mission, ^{238}Pu could be eliminated altogether by replacing RHUs with electrical heaters.

1.4.3 Implementation Uncertainty

RPSs (especially multi-mission radioisotope thermoelectric generators) provide a well-characterized power output, implementation approach and operating environment. This predictability simplifies many aspects of spacecraft design and operations, including power management, thermal management, attitude control, and orbit and trajectory flexibility. The use of the ASRG adds some uncertainty into the implementation aspects of the mission concept, but these are more easily quantified at this point in the mission concept due to the amount of study performed to date. Solar arrays introduce significant uncertainty into the design implementability including resource availability, science operations and science value.

The cell radiation deterioration modeled in this study was based on an extrapolation of data available to the 2006 EE solar team and radiation levels used in the 2006 EE Solar study. Actual cell radiation testing is currently being performed for the Juno mission, and a plan is in place to extend testing on a subset of the Juno cells to characterize the cells' response to radiation levels even higher than those predicted for the Europa mission. The results of this testing are critical to the assumptions used in solar array design for this concept. Worse-than-predicted performance would ripple through the design and could potentially take the solar option back toward infeasibility. Testing to the Europa levels is expected to be completed in the first quarter of calendar 2008.

Cursory insights into a solar mission might indicate that a solar mission would be cheaper than an RPS-powered mission. This effort did not investigate cost per se, but the tight coupling of mass to dollars for this type of radiation environment indicates that the increased mass of the solar option would drive the cost of a solar mission. The resulting cost could easily be as much or more than for an RPS-powered mission.

2. Summary

A preliminary assessment of a capability-driven, all-solar Europa mission was conducted. By addressing previously-identified design stressors, a mission concept was obtained that appears to be technically feasible within the limits of maturity. The science value of this mission was evaluated and appears to meet many of the EE2007 science objectives with several significant compromises. A true assessment would require more detailed design and further SDT evaluation to fully understand the impacts of the mission concept.

Though promising, the level of maturity of this concept leaves open many questions as to the risk, benefits and costs associated with this type of mission. The ability to meet scientifically acceptable objectives within a reasonable cost and risk posture cannot be assessed strictly using the information obtained during this brief study. Mass and power assessments along with pointing and stability analyses need further refinement. Solar cell degradation testing needs to continue to adequately understand the behavior of an array in this difficult environment. Further study of the solar-powered Europa mission would be required to more fully understand and quantify the benefits and cost associated with this choice of power source over the RPS.