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END-TO-END MISSION ANALYSIS FOR A LOW-COST, TWO-SPACECRAFT MISSION TO EUROPA

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Mission analysis results for a low-cost mission to the Jupiter moon Europa are presented. This involves a Europa orbiter and a relay spacecraft, launched by a single mid-size launch vehicle. The analysis covers the entire mission from launch to end of the science phase, including a baseline and several backups. The optimized transfer to Jupiter employs Venus-Earth-Earth-Gravity-Assist maneuvers. The launch and transfer techniques allow over 1600 kg of payload mass prior to Jupiter Orbit Insertion. Separate radiation-optimized tours in the Jupiter system are designed for each spacecraft. Finally, the actual two-month science phase is analyzed.

INTRODUCTION

This paper summarizes the mission analysis results of a feasibility study into a low-cost mission to the Jupiter moon Europa conducted at the European Space Agency. Europa is of especial scientific interest due to the possibility of an extensive water ocean beneath its ice crust.

Requirements and Specifications

The mission specifications call for launch of two spacecraft with a single Soyuz ST launch vehicle using an upgraded Fregat upper stage. The technical data of the versions available in 2009 are used as baseline[7]. A launch from Baikonur and also Kourou is considered. Launch is assumed for 2009, with backup options in the following years.

One spacecraft, the Europa orbiter, must withstand the intense radiation in the inner Jupiter system. The other, a data relay spacecraft, stays outside the inner moon system and is exposed to far lesser radiation. Communication during the science phase happens via the relay spacecraft. Both are specified as employing solar arrays at this step of the analysis. This decision may be up for revision at a later point.

TRANSFER TO JUPITER

The transfer to Jupiter shall be designed to maximize the payload delivered to Jupiter and last no longer than around 6 years.

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Transfer Trajectories

For cost reasons, only a mid-size launch vehicle is used, so the escape velocity and the sum of all deep-space maneuvers (DSMs) must be carefully minimized to nevertheless deliver a sizeable payload mass to Jupiter. Additionally, the hyperbolic arrival velocity shall be as small as possible. Fulfilling these demands mandates use of a multiple-swingby transfer. Various options were investigated. For all regarded launch years the Venus-Earth-Earth-Gravity-Assist (VEEGA) transfer constitutes the best compromise.

Baseline and Backup Transfers

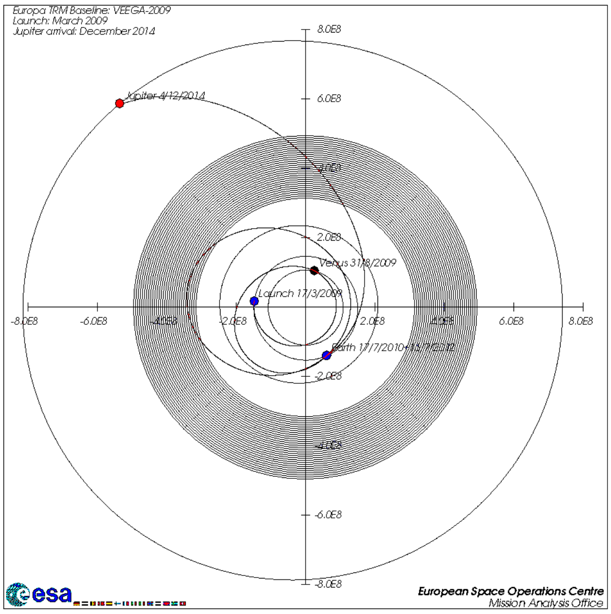

Figure 1 Earth-Jupiter Transfer for Baseline VEEGA-2009

VEEGA-2009 is retained as the baseline transfer option. This does not involve any DSMs, the required orbital energy increase is provided by the three gravity assist maneuvers. Figure 1 shows the interplanetary trajectory.

Backup options are available in the three following years, with VEEGA-2010 offering a performance comparable to VEEGA-2009, VEEGA-2011 significantly less, and VEEGA-2012 somewhat more. All backup options have a lesser Earth escape velocity than the 2009 baseline. VEEGA-2010 and -2011 require significant DSMs.

Many of the transfer trajectories analyzed were found to include relatively close flybys at major asteroids and comets, thus offering further science opportunities.

Earth Escape Techniques

The launch technique commonly applied nowadays is that the upper stage of the launch vehicle inserts the payload into the escape hyperbola. This is operationally simple but inefficient. Much of the mass in interplanetary orbit consists of the spent upper stage. A considerable increase in payload mass is obtained by using the upper stage only for insertion into a highly eccentric orbit (HEO). The upper stage is jettisoned in this bound orbit; the payload performs the escape maneuver at the next perigee pass using its onboard propulsion system.

As the spent upper stage is already jettisoned, the escape burn is more efficient and a considerable gain in mass can be achieved. The disadvantage to this more advanced technique is the increased operational complexity and risk during the extended LEOP, the need to provide larger propellant tanks and the larger radiation exposure because of the added passage through the Van Allen belts.

Further variants of the HEO-escape involve a swingby at the Moon to increase the energy of the orbit, possibly with an added Earth flyby over a year after the original escape. This again considerably raises the operational complexity, lengthens the mission duration (by up to 15 months in some cases) and may limit the launch window. Therefore we take into account only the simple HEO-escape with no additional swingbys.

Mission Performance Estimates

The characteristics of the baseline and backup transfer options are listed in Table 1. A three-week launch window is assumed in all cases. The mass performance is calculated based on the worst case occurring in the launch window. The transfer design is consistent with results obtained at JPL with the STOUR analysis tool[10] and literature[5].

Table 1
2009-2012 EARTH-JUPITER TRANSFER CHARACTERISTICS

Opportunity	2009	2010	2011	2012
Earth escape	09/3/4 – 09/3/24	10/7/19 – 10/8/8	11/9/4 – 11/9/24	12/3/21 – 12/4/10
Hyp. escape velocity [km/s]	4.08 – 4.38	2.81 – 2.97	2.62 – 2.84	2.97 – 3.13
Jupiter arrival	14/11/21 – 14/12/9	17/1/28 – 17/3/25	18/7/29 – 19/1/21	18/3/31 – 18/7/29
Hyp. arrival velocity [km/s]	5.87 – 5.99	5.92 – 6.33	5.58 – 5.70	5.62 – 6.43
Maneuver budget [m/s]	50	500	740	100
Pre-JOI mass (direct) [kg]	976	1236	1191	1365
Pre-JOI mass (HEO, K) [kg]	1678	1695	1401	1802
Pre-JOI-mass (HEO, B) [kg]	1479	1499	1265	1680
Duration [d]	2064 – 2096	2379 – 2426	2514 – 2677	2166 – 2300

In Table 1, the three rows with mass values indicate the payload mass (dry + propellant remaining at that time) before JOI for a direct escape with the Fregat upper stage and for a HEO escape following launch from Kourou (K) or Baikonur (B). In all cases, the respective minimum values observed for the three-week launch window are given. The payload mass calculation takes into account gravity losses incurred when using one 400 N thruster on each spacecraft. Analysis has shown that a similar backup option exists for 2013. After that, there is a dearth of viable transfers until at least 2018.

JUPITER TOUR DESIGN

The Jupiter tour begins with Jupiter Orbit Insertion (JOI) and ends when the two spacecraft have acquired their respective final orbits. Distinctly different tours are envisaged for the relay and orbiter spacecraft. As the orbiter shall operate in the high-radiation regime that characterizes the vicinity of Europa, it can also withstand a higher radiation load during the tour. For the computation of the radiation doses, a model based on[14] was used[6].

Conversely, the relay spacecraft is in an operational orbit between Ganymede and Callisto and does not need massive radiation shielding; the only time when it absorbs a sizeable radiation dose is at the close approach to Jupiter during JOI.

Jupiter Orbit Insertion

Jupiter Orbit Insertion consists of a large braking maneuver that inserts the spacecraft from the hyperbolic approach trajectory into an elliptical orbit around the planet. The magnitude of the maneuver, as shown in Figure 2, strongly depends on the hyperbolic arrival velocity and the target peri- and apojove radii, a low perijove and high apojove being favorable. However, lowering the perijove radius implies a close pass to Jupiter during JOI while a high apojove will increase the overall tour duration. Here, the apojove radius is limited to 250 R_J (R_J: Jupiter equatorial radius=71,492 km), the perijove radius to 5 R_J. The period of the initial bound HEO is around 6 months. A perijove-raising maneuver (PRM) is required at apojove to avoid a second low perijove pass.

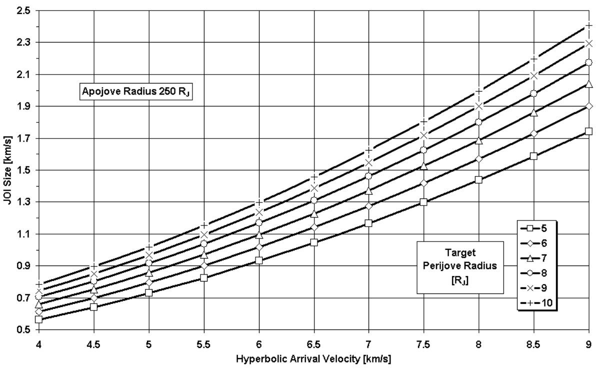

Figure 2 JOI Size as Function of Perijove Radius and V-infinity, Target Apojove 250 R_J

Alternative JOI concepts[8,12] involve a swingby at Ganymede (or possibly Callisto) just prior to JOI. This moves JOI to a larger distance from the planet, but the JOI burn can nevertheless be reduced, as the initial moon swingby removes a sizeable part of the orbital energy from the approach hyperbola. By raising the perijove the moon-swingby-augmented JOI diminishes the radiation dose at the JOI pass and also reduces or eliminates the apojove maneuver.

The disadvantage is the much-increased operational complexity, the requirement for extremely precise navigation during approach, the short time span between swingby and JOI and the overall low tolerance of this approach for errors and uncertainties. Therefore, we chose not to include this technique in the context of this mission study until it is proven to be feasible.

Differences in Tour Design

Figure 3 shows the well-known Tisserand graph with the final parts of the paths chosen for the orbiter and relay tours. The Tisserand graph here is laid out with the perijove radius in km over the orbital period in days.

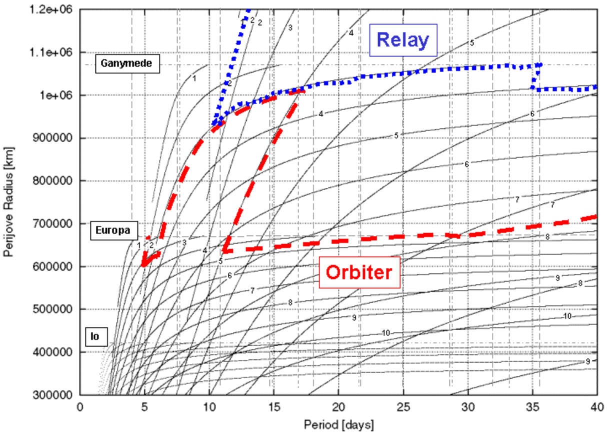

Figure 3 Tisserand Graph with Chosen Paths for Orbiter and Relay Tours

Figure 4 shows a close-up of the inner regions of the Jovian moon system with the trajectories of the orbiter and relay spacecraft tours following from the paths in Figure 3 superimposed. The orbits of the Galilean moons are shown, from Io (the small circle near the center) to Callisto. The trajectory plots start out from JOI at a radius of 5 RJ. This is closer to Io than to Europa. The plots illustrate the gradual, controlled contraction of the orbit due to a sequence of flybys at the Galilean moons. The minimum flyby altitude is conservatively limited to 200 km for safety reasons.

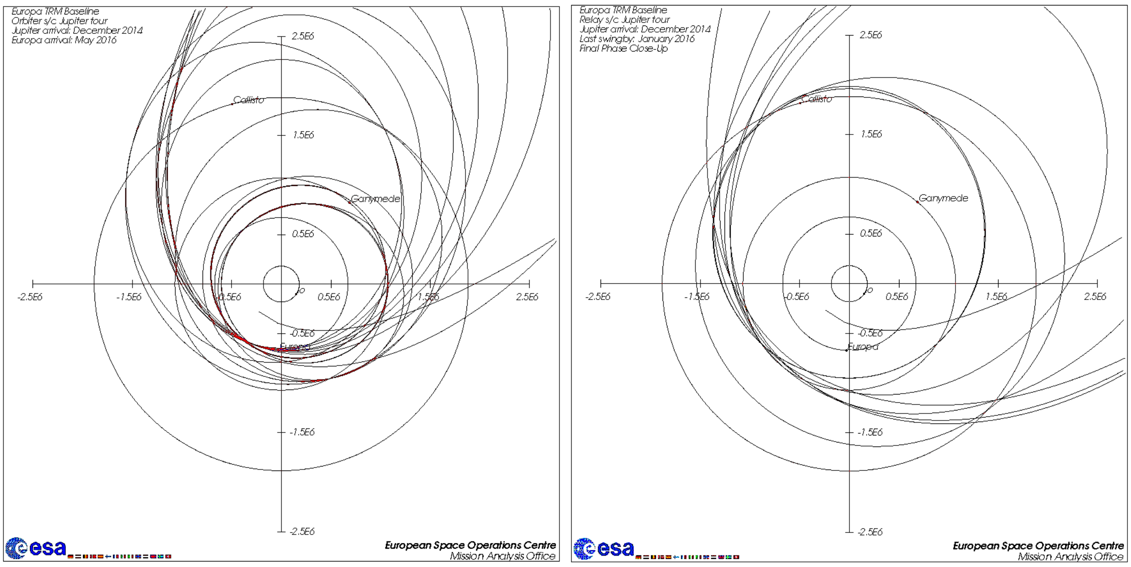

Figure 4 Close-Up View of Orbiter (L) and Relay (R) Tours

Summary of Tours

As illustrated by Figures 3 and 4, the orbiter follows an overall more aggressive tour, closer to the planet and with subsequently higher radiation exposure. The relay spacecraft remains at higher altitudes throughout (except for the JOI pass) and hardly ventures below the Ganymede orbit.

The aim of the orbiter tour is to minimize the radiation dose (although a high exposure is inevitable to a spacecraft going to Europa) while also achieving a small Europa Orbit Insertion (EOI) burn size.

Table 2
MOON ENCOUNTER TIMELINES FOR ORBITER (L) AND RELAY (R)TOUR

Encounter	Time [d]	v_{inf} / man. [km/s]	h_{flyby} [km]	T [d]	r_p [R_J]
PRM	80	0.258	-	-	-
G/1	175	7.661	200	50.5	10.3
Man	184	0.023	-	-	-
G/2	225	7.767	461	28.5	9.4
E/1	254	4.466	202	24.9	9.3
E/2	279	4.538	200	21.3	9.3
E/3	300	4.510	200	17.8	9.3
E/4	318	4.505	212	14.2	9.2
E/5	332	4.495	200	11.4	9.1
C/1	347	4.111	1051	13.4	11.0
C/2	368	4.101	1358	17.6	14.1
G/3	406	3.244	235	10.7	13.0
G/4	428	3.248	368	7.2	11.2
Man	428	0.033	-	-	-
G/5	435	3.281	383	5.9	8.8
E/6	445	3.294	200	5.0	8.5
Man	451	0.027	-	-	-
G/6	458	1.728	200	5.4	9.6
Man	468	0.039	-	-	-
EOI	488	1.600	200	-	-

Encounter	Time [d]	v_{inf} / man. [km/s]	h_{flyby} [km]	T [d]	r_p [R_J]
PRM	59	0.360	-	-	-
G/1	180	5.734	200	63.4	12.9
Man	205	0.100	-	-	-
G/2	244	4.151	200	42.9	14.3
G/3	287	4.149	1093	35.3	14.1
Man	304	0.074	-	-	-
G/4	322	3.130	1061	28.6	14.9
G/5	351	3.129	200	21.5	14.5
G/6	372	3.072	200	11.5	13.3
Man	384	0.025	-	-	-
C/1	403	1.940	200	16.7	21.0
C/2	420	1.941	200	15.5	23.6

Legend:
Time: counted from JOI
v_{inf}/man.: hyperbolic arrival velocity or maneuver
h_{flyby}: closest approach to moon at swingby
T: orbital period after swingby
r_p: Perijove radius after swingby

In our case, the final swingby prior to EOI is at Ganymede. This leads to a minimum Europa arrival velocity and corresponding EOI of 1143 m/s (see Table 3).

Conversely, other studies[8,12] achieve a considerably lower EOI maneuver size by involving an "endgame", a combination of Europa swingbys and maneuvers at apojove, which is then distinctly lower than the Ganymede orbit. This approach leads to a much lower arrival velocity and allows using the Jupiter gravitational attraction during Europa capture, thus lowering the EOI to as little as 521 m/s but adding over 350 m/s for the "endgame" apojove maneuvers[8,12]. This saves around 270 m/s with respect to our tour.

The disadvantage of the "endgame" approach is that the spacecraft spends a long time in low orbits. These are almost commensurate with that of Europa, so the spacecraft has to wait for several revolutions before it can perform the next swingby or EOI. The inevitable waiting orbits incur a massive radiation dose. The total dose absorbed during a tour including an "endgame" is typically more than twice the already considerable value of 1287 krad cited in Table 3. A recent industry study[1] performed for the European Space Agency also employs a variant of the "endgame" approach and cites an accumulated radiation dose of around 3000 krad. This inevitable downside prompted us to disregard the endgame strategy in out tour design.

Regarding the relay spacecraft tour: the aim here is to arrive at the target orbit before the Europa orbiter has reached its final orbit around Europa while also minimizing the radiation exposure to the spacecraft. A side aim for the design of both tours is to minimize the propellant consumption. The relay spacecraft ends up in an orbit between those of Ganymede and Callisto, with a semi-major axis of 1.794 million km (=25.1 R_J), a period of 15.5 d (Ganymede: 7.2 d, Callisto: 16.7 d), an eccentricity of 0.058 and an inclination with respect to the Jupiter equator plane of 12.5 degrees. The apojove radius is 26.5 R_J (Callisto orbit: 26.3 R_J), the perijove radius 23.6 R_J (Ganymede orbit: 15 R_J). The employed radiation model gives a negligible dose and electron flux for this orbit.

If the relay spacecraft is to be re-used in any future missions, the apojove should be lowered to avoid strong perturbations by Callisto. Lowering it to 25 R_J would cost an additional maneuver of 130 m/s. This is not budgeted here.

Table 3
CHARACTERISTICS OF ORBITER AND RELAY SPACECRAFT TOURS

	Orbiter	**Relay**
Total JOI [km/s] (2009 baseline)	0.913	0.912
Perijove raise maneuver (PRM) [km/s]	*0.258*	*0.360*
Δv budget between JOI and final orbit [km/s]	0.394	0.568
EOI [km/s]	1.143	-
Total Δv budget for tour [km/s]	**2.450**	**1.480**
Total tour duration (JOI to final swingby) [d]	488	420
Io swingbys	0	0
Europa swingbys	6	0
Ganymede swingbys	6	6
Callisto swingbys	2	2
Total proton dose (4 mm Al) [krad]	24	3
Total electron dose (4 mm Al) [krad]	1287	83
Total proton dose (8 mm Al) [krad]	2	1
Total electron dose (8 mm Al) [krad]	308	23
Total 1 MeV equivalent electron fluence [1/cm^2]	$3.5 \cdot 10^{14}$	$3.3 \cdot 10^{13}$

Table 3 summarizes the characteristics of the respective orbiter and relay spacecraft tours. As discussed earlier, we do not consider a Ganymede-swingby-cum-JOI approach[8,12] because of the risk. Employing this technique would reduce the JOI and eliminate the perijove raise maneuver.

Also, we chose not to take into account an “endgame” approach. This would significantly reduce the EOI, although somewhat increasing the total size of the intermediate maneuvers. Our approach is conservative. It leaves scope for savings in the maneuver budget if one is willing to accept the cost in terms of added risk and radiation.

The radiation figures are noteworthy. The orbiter receives an electron dose of 1287 krad from JOI to EOI, assuming 4 mm aluminum shielding. Conversely, the relay spacecraft is subjected to only 83 krad on its radiation-minimal tour. Also, the relay spacecraft arrives in its final orbit over two months before the orbiter performs EOI. Thus, major design requirements are fulfilled.

SCIENCE PHASE

The science phase begins when the orbiter has acquired its final orbit around Europa. It transmits telemetry and receives telecommands via the data relay satellite. This has then already acquired its operational orbit and is waiting for the orbiter.

The Europa Orbiter

A circular polar orbit is foreseen in order to maximize the surface coverage and science return. Any highly inclined orbit around Europa is subject to strong perturbations by the central planet's gravitational attraction. This leads to rapid variations of the eccentricity, which eventually lead to the spacecraft crashing on the Europa surface. The altitude and the inclination of circular orbits are the only orbital parameters with a significant influence on the lifetime. Eccentric orbits were found to have an even shorter lifetime.

An extensive parametric numerical analysis showed that for an initially circular polar orbit, the lifetime peaks at around 68 days at an orbital altitude of 125 km. A similar lifetime is observed for an initial circular altitude range between 75 and 200 km. The results obtained with our numerical analysis are consistent with those published in the literature[9,11].

For lower or higher altitudes, the expected lifetime degrades sharply. For the studied project, an initial altitude of 200 km is envisaged. A lower value might be chosen in later stages of the study, depending on the science requirements.

Reducing the inclination with respect to the Europa equator plane was found to prolong the lifetime considerably. Especially for inclinations below 70º, a marked increase becomes apparent. A circular 200 km orbit with an inclination of 45º can be expected to last for over a year. However, reducing the inclination is not taken into consideration for this mission because of the detrimental effect on the surface coverage.

Assuming a lifetime of 66 days, an electron dose of almost 2700 krad (assuming 4 mm aluminum shielding) was computed. The solar arrays will absorb an equivalent 1 MeV electron fluence of almost $9 \cdot 10^{14}$ 1/cm^2 during this period. The high radiation dose is another reason not to choose a lower inclination. It is unlikely that the spacecraft would continue to function throughout the entire science phase thus prolonged.

The plane of the polar orbit is oriented such that the spacecraft flies over the noon-midnight meridian. With this orbital layout, every point on the Europa surface can be viewed while sunlit at least seven times during the 66 day phase, most regions are covered 10 times or more, especially around the poles. The node drift on a polar orbit is negligible, as is the inclination variation during the orbital lifetime.

The noon-midnight orbit passes through the Europa shadow cone once during every orbital revolution. The eclipse duration is 47 minutes out of the 2.24 hour orbital period. Additionally, Jupiter eclipses can occur at times when the solar declination with respect to the Europa orbit is close to zero. These eclipses can last up to 2.9 hours and recur every Europa orbital period, i.e., every 3.55 days.

Terminator orbits (where the spacecraft flies over the dusk-dawn meridian) do not cross the Europa shadow cone but offer a much-degraded viewing opportunity of the illuminated surface, with sizeable areas not covered at all in the assumed 66 day lifetime. Furthermore, such orbits never pass over well-illuminated regions. Therefore, they are not chosen as baseline for this mission.

The Ground Penetrator Option

The option of deploying a ground penetrator from the 200 km science orbit was studied. The penetrator must be de-orbited with an onboard rocket engine. The burn size is at least 42 m/s for a grazing impact, 200 m/s for an impact angle of -14 degrees or more for a steeper impact. The impact velocity depends on the size of the deorbit burn. It is 1.5 km/s for a grazing impact and 1.37 km/s for an impact angle of -14 degrees.

The Relay Link

Figure 5 shows the evolution of range and range rate between the Europa orbiter and the relay spacecraft during the science phase. The range varies between 1 and 2.55 million km due to the relative motion of Europa and the relay spacecraft. Range-rate excursions reach a magnitude of 12 km/s.

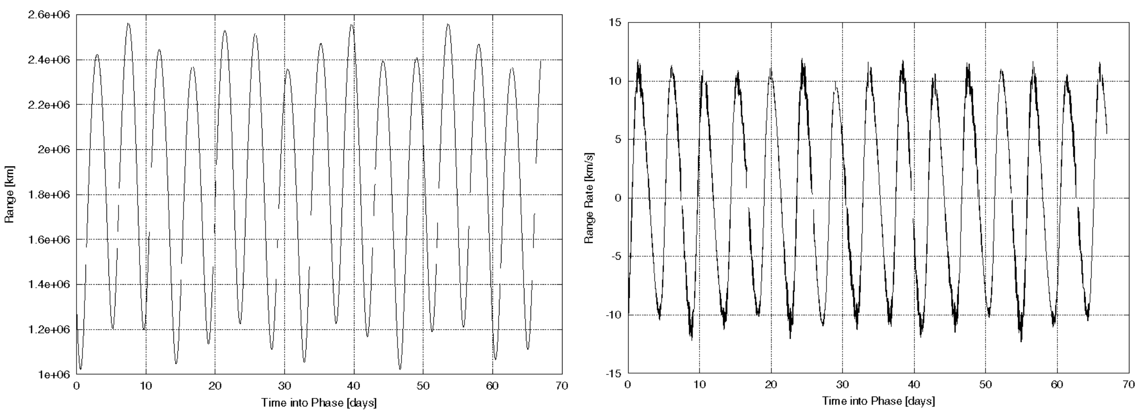

Figure 5 Range and Range-Rate between Orbiter and Relay during Science Phase

CONCLUSIONS

The results of mission analysis work into a two-spacecraft low-cost mission to Europa are summarized. The end-to-end mission analysis covers the entire mission from launch to the termination of the science phase. One of the spacecraft will go into a low orbit around Europa. The other is foreseen to remain in a radiation-safe, high orbit around Jupiter and serve as data relay.

The launch opportunities from 2009 to 2012 are regarded. All Jupiter transfer trajectories are of the VEEGA type and, with a Soyuz ST/Fregat launcher, allow a typical payload mass of over 1600 kg prior to JOI. Typical transfer durations are around 6 years.

It was found that the time frame from 2009 through 2013 is exceptional in that it offers a significant number of high-payload transfers to Jupiter that are relatively fast and lead to a low arrival velocity. After 2013, transfer conditions degrade. Opportunities similar to those found in this study do not recur before 2018 or later.

After JOI both spacecraft separately follow complex tours leading to their final orbits. For the orbiter, the tour ends with EOI. It is exposed to significant radiation doses, of which one third is incurred during its tour and two thirds in the science phase.

The orbiter's final trajectory is a 200 km circular polar noon-midnight orbit around Europa. Its lifetime there is around 66 days; the mission ends when the spacecraft crashes on Europa. This time span is sufficient for multiple observations of the entire sunlit surface.

The relay spacecraft reaches its destination some two months faster than the orbiter. The radiation dose is small during its tour and negligible in its final orbit. Possibly, the relay spacecraft can be maintained operational after the orbiter has crashed. It might then be re-used in support of the next mission.

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