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Galileo has received approval for a two-year follow-on mission, called the Galileo Europa Mission (GEM). A three-phase tour has been designed for GEM that includes eight Europa encounters, four Callisto flybys, and two Io encounters to end the GEM in December 1999. Although science desires for the satellite encounters were of primary importance to the tour design, the flyby conditions were also necessarily selected on the basis of the gravity assist they contributed to the trajectory. The tour design was heavily influenced by the requirement to return to Io, since the radiation exposure that accompanies such a flyby may severely degrade the health of the spacecraft.

INTRODUCTION

In the Spring of 1996, before Galileo had completed even the first satellite encounter of its orbital tour,[1,2,3] the possibility of a follow-on mission for Galileo was considered. With the growing interest in the possible existence of a subsurface ocean on Europa, a concentrated study of the satellite could act as a precursor for future Europa missions. Further investigations of 10 were also of significant interest, particularly since problems with the tape recorder in October 1995, before the only close flyby of 10 in the prime mission, had prohibited the recording and playback of any remote sensing data for that encounter. Although the opportunity to return to Io was important both in terms of scientific objectives and tour design, the specific and immediate interest in Europa suggested that Europa be the primary objective of the follow-on mission. Thus, the mission was conceived as a low-cost, highly focused study of Europa, with a return to 10 following the Europa studies.

Based on preliminary studies, the Galileo flight team predicted that sufficient resources (such as power, propellant, radiation margin, health, and instrument lifetime limitations) would remain after the prime mission for as much as two additional years of productive operations. To take advantage of these resources, a tbrce-phase follow-on mission, designated as the Galileo Europa Mission (G EM), was designed to address both the Europa and 10 interests. Tbc first phase of the mission, referred to as the "Europa campaign," provides an intensive study of Europa. Its purpose is to further characterize Europa's surface, atmosphere, and internal structure, including the possible existence of a subsurface ocean, The second phase is called the "perijove reduction campaign, " or pump-down phase, since its purpose is to reduce the perijove in order to bridge the Europa study phase with the 10 encounters. Scientifically, this phase provides opportunities for mapping of the 10 torus and additional Jupiter observations. In the final phase, labeled the "lo encounter phase," the desire to return to 10 is fulfilled with two close flybys of the satellite.

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The design of the tour for GEM involved achieving acceptable science return while minimizing the usc of the consumables that arc available to the mission, For a spacecraft such as Galileo, where tbc science instruments have diverse and often conflicting requirements, the concept of maximizing the science return is itself not easily defined, since flybys that provide good conditions for 00C instrument may be unfavorable to a different instrument, Also, for Galileo, the consumables must be defined to include such resources as space on the tape recorder and downlink capability, in addition to those more readily recognized areas of power, propellant, and accumulated radiation exposure. l'bus, compromises between scientific objectives and mission operations constraints were continually necessary.

SCIENCE OBJECTIVES

For the Europa phase of the mission, the goal was to achieve a series of six to ten low altitude, light-sidc encounters. Additionally, variety in the latitude and longitude of the flybys was desirable, in order to increase the global coverage of the satellite, with latitude diversity a high priority.

For 10, given the limited number of encounters, several specific, focused objectives were proposed, in order to make efficient usc of the opportunities. Since high-resolution imaging opportunities of Io arc rare in both the prime mission and the GEM, a iow altitude (less than 1000 km), light-side encounter, preferably near regions of known volcanic activity (at iow latitudes) was specified as a priority. The iow altitude would also allow sampling of Io's atmosphere and offer good conditions for experiments designed to more fully develop the modeling of Io's gravitational field and internal structure. In addition to low altitudes, the gravitational modeling experiments would benefit even further from a very high latitude flyby. A high latitude flyby would aiso benefit investigators evaluating the supposition that Io has an intrinsic magnetic field. Onc of the original guidelines for the tour design was that the tour should include only onc Io flyby in order to minimize the radiation exposure to the spacecraft. However, for issues related to several operational constraints, that strategy was later changed to allow for repeated Io encounters (at least two targeted flybys prior to the end of the mission). (See "End-of-Mission" below.) With two 10 encounters, both the low and high latitude objectives could be accommodated. However, since the low latitude requirement was assigned a higher priority than the high latitude conditions, and the health of the vehicle following even onc 10 flyby is uncertain, duc to the potential radiation damage, the low latitude requirement is satisfied with the first 10 flyby of the GEM, with a nearly polar flyby at the second of the two 10 encounters.

Targeted flybys of the other satellites, Ganymede and Callisto, were not a scientific priority for GEM tour design. Although some modest Callisto imaging is contemplated, scientific investigations during the perijove reduction phase will focus on remote sensing of Io, Jupiter's atmosphere, and in-sitsu measurements of the Io torus, since the incremental reduction in the perijove distance provides the opportunity for mapping of that region. These studies required no specific design constraints.

MISSION OPERATIONS CONSTRAINTS

In addition to the scientific desires for the Galileo follow-on mission, constraints related to various operational considerations were also imposed, Most of these issues arc related to the two most limiting consumables of the mission, which arc propellant and radiation exposure. in order to reduce consumption of both resources, issues related to flyby conditions, mission timeline, and other navigational considerations were simultaneously investigated and evaluated in order to construct a tour that satisfies the scientific requirements while creating a flyable mission.

Propellant

Although science requirements for the satellite encounters within tbc Europa and Io phases were of primary importance to the tour design, the flyby conditions in all of the phases were also selected on the basis of the gravity assist they contributed to the trajectory. Since the design of the prime mission was not constrained to provide propellant for a follow-on mission, the use of propellant for very slight trajectory shaping was limited as much as possible in the design of the GEM tour. The dependence on gravity assists limits the number and magnitude of the deterministic maneuvers that arc required to achieve the tour, since the trajectory is primarily altered by the gravity assists of the flybys. I'bus, careful planning and accurate modeling of tbc flyby conditions are essential. Since the GEM tour design was conducted simultaneously with the prime Galileo satellite tour, predictions for the amount of propellant that would bc available for the GEM were continually updated throughout the design based on actual usage in the prime mission and improved estimates for future usc. However, as the tour design evolved, it was assumed that a small amount of AV could be used to address specific design issues.

Radiation

Encounters with Jupiter subject a spacecraft to exposure to Jupiter's intense radiation field. Since this exposure is potentially catastrophic to the health of the vehicle, large doses of radiation must bc minimized and delayed until as late in the mission as possible. I'hc level of the exposure is closely related to the spacecraft's proximity to Jupiter. The radiation levels increase as the distance decreases (within the range of distances considered in this mission). At the distance of Europa's orbit (9.2 RJ, where R_J is defined to be Jupiter's equatorial radius, 71492 km), the dosage for one perijove passage is estimated at about 10 krad (assuming 2.2 gm/cm^2 aluminum sphere shielding). Since Io orbits Jupiter at a much lower distance, approximately 5.9 R_J, the dosage from an Io encounter is significantly higher, estimated at about 40 krad. In order to limit the radiation exposure of the GEM, the Io encounters were postponed to the end of the mission, Additional requirements intended to limit and/or delay radiation damage include retaining a high perijove distance for as many orbits as possible and achieving the perijove reduction to 10 in as few orbits as possible, since the perijove reduction phase will subject the vehicle to increasingly higher levels of radiation Although the Io phase of the tour is the shortest phase, in terms of time and number of encounters, the requirement to include even one Io flyby was a significant factor in the design of the entire tour because of the radiation exposure that accompanies it.

An additional constraint, directly related to the potential radiation damage from the Io encounters, was a requirement for a relatively long orbital period following the first 10 encounter. Given knowledge of the amount of data that can be stored on the on-board tape recorder, and predictions for the data transfer rates and tracking coverage that will available near the Io encounters, tbc time required to· relay the information from the tape recorder to Earth is estimated at about 50 days. Thus, a goal of achieving a 50 day period following the first Io encounter was established, in order to provide the time to relay the data prior to the additional radiation exposure that will result from the next encounter. Since the flybys of the perijove reduction phase will also result in a decrease in period, the Europa flybys must be designed to increase the orbital period above even the 50 day post-lo goal. Thus, a requirement for the Europa campaign, that is driven entirely by the radiation associated with the 10 phase, is that the Europa flybys provide a net increase in the period from approximately 50 days at tbc end of the prime mission to more than 50 days by the start of the perijove reduction campaign.

As an additional effort to facilitate the Io data return, the time of the first 10 encounter was selected to bc near the time of opposition in the last year of the mission (October 1999). At opposition, the distance between the Earth and the spacecraft is minimized. This reduced distance produces a stronger signal at the Earth. Given the reliance on the low gain antenna, efficiently returning tbc data from every encounter is essential, in both the prime and the follow-on missions. However, since the vehicle may not survive even one 10 encounter, efficiently returning the data from that flyby, prior to the next exposure, is particularly important since the health of the vehicle will degrade even further with each subsequent encounter.

liming Issues

In addition to the timing issues involving Io, several other constraints related to time were imposed on the tour design, primarily to satisfy operational constraints. First, the end of 1999 was specified as a limit on the end of the mission, allowing for approximately two years of operations beyond the prime Galileo mission. Next, relatively long orbital periods were desirable throughout the entire GEM, not only after the Io flyby. In addition to allowing more time for data return from each encounter, long periods (on the order of 30 days or more) also reduce the demands on the operations team by providing more time for the preparation and additional work associated with each flyby. (The GEM operations team is expected to be roughly one-fifth the size of the operations team for the prime Galileo mission.) Coupled with the period limitations was a goal for the number of Europa encounters that should be included in the Europa campaign. Less than six encounters was considered unacceptable, but the existence of more than ten flybys was deemed unnecessary, if it required orbital periods of less than 30 days. Finally, due to concerns about the ability to command the spacecraft and the poor data quality that is expected near times of solar conjunction, a goal of the tour design was to avoid, if possible, targeted encounters for approximately three weeks around the times of conjunction (February 23, 1998 and April 1, 1999),

End-of-Mission

Although the two year mission duration constrains the end of the GEM, the vehicle will still be in orbit around Jupiter following the last GE M flyby. For this reason, the strategy for the end of the mission was a factor throughout the tour design. The radiation requires any 10 encounter to be postponed to the end of the mission. However, following the 10 study phase, it would be possible to usc flybys of other satellites to raise the perijove in order to reduce subsequent radiation exposure and, potentially, prolong the life of the vehicle. (Since the propellant budget for GEM does not provide sufficient AV to significantly raise the perijove, the usc of a large perijove raise maneuver after the final 10 flyby was not an option.) It was determined, however, that the increase in perijove that can be achieved with each orbit using gravity assists is small, compared with the savings in the radiation exposure, Thins, this option requires that the tour include! flybys of other satellites following the 10 phase that do not fulfill any of the specific scientific interests of the mission. The second option is to leave the vehicle in an 10 return orbit. Although this strategy subjects the vehicle to repeated, high-level radiation exposure, it places no requirements on the characteristics of the final flyby. It also leaves the vehicle in the vicinity of Io for as long as possible. Therefore, the GEM tour was designed to leave the vehicle in an Io return orbit, despite the inevitable radiation damage. This, then, provided the opportunity for two targeted Io flybys in the tour, although the health of the vehicle after the first flyby may be degraded,

Multi-Encounter Orbits

One constraint, driven almost exclusively by navigational consideration, was a limit on the number of close flybys that could be included on any single orbit of the trajectory. Each orbit was limited to include at most one targeted encounter. During the perijove reduction phase, a trajectory that includes close flybys of two satellites on the same orbit, where each flyby provides a reduction in the perijove, would reduce both the time required for the pcrijove reduction and the radiation exposure. The perijove reduction that would ordinarily be achieved in two orbits could be achieved in a single orbit with a single perijove pass. However, the existence of two close flybys on a single orbit complicates the targeting of either or both flybys. It also increases the potential for significant deviations from the desired aimpoint, particularly for the second of the two encounters. In addition, targeting both encounters would require rapid reconstruction of trajectory dispersion resulting from the first flyby and some strategy for correcting errors prior to the second flyby, particularly if impacting at the second flyby is a possibility. Since the opportunities for multiple-flyby orbits generally provide a time difference on the order of a few days between the two flybys, including a maneuver between the flybys, to accurately achieve both aimpoints, is extremely difficult. Thus, it was decided that navigating such a trajectory presents an unnecessarily dangerous operational challenge to the mission, and the one c1osc flyby pcr orbit limit was imposed.

Altitudes

As previously mentioned, one scientific objective was for low altitude flybys of Europa and Io. However, for operational, navigational, and safety reasons, lower limits for the flybys altitudes were imposed on the design. For Europa, a lower limit of 200 km was selected. For 10, the lower limit for the first flyby was set at 500 km, but a value of 300 km was specified for any subsequent encounters,

Prime Mission Attachment

A final issue considered in the tour design was the problem of attaching the GEM trajectory to the end of the prime mission. One guideline for the tour design was that the nominal flyby conditions of the prime mission should not be modified as part of the GEM design. This guideline was, however, relaxed with respect to the final aimpoint of the prime mission. That flyby is a Europa encounter at a latitude of 65°, (referred to as E 11, since it is a Europa flyby on the eleventh orbit of the prime mission)." In the early stages of the design of the GEM tour, it was determined that retaining that high latitude flyby, while still achieving Europa flybys of lower and more moderate latitudes, and then returning to Io at the end of the GEM, requires a prohibitively large maneuver, on the order of tens of meters per second, at the beginning of the GEM. Thus, the Galileo project approved the proposal that the characteristics of the E 11 flyby be changed in order to provide more flexibility in the GEM tour design, However, only changes to the geometric characteristics and small changes in the flyby time were permitted. Changes to the date of E 11 were not permitted. Although the specific conditions designed for the nominal E 1 I flyby were lost (and, in fact, none of the GEM Europa flybys achieve the high latitude provided by the nominal E 1 I), giving up that specific flyby provided a more favorable series of GEM Europa flybys than would have been possible 11'the nominal E1 1 had not been abandoned.

Although releasing the E1 l aimpoint significantly reduces the GEM attachment maneuver, an attachment cost on the order of 10 to 15 m/s was still required. Given the limited amount of propellant that is expected to be available, changes to the flyby that precedes E1 l were considered, in spite of the original guideline, ina further attempt to reduce the attachment cost. That encounter is labeled C10, since it is an encounter with Callisto on the tenth orbit of the prime mission. Onc option for C1O that would have essentially eliminated the attachment maneuver would have requireda change on the order of two to three degrees in the latitude at C 10 and a change from a nominal inbound flyby to an outbound encounter at E1 i (which would have changed the date of El 1). The nominal planning and sequencing for these two encounters cannot easily accommodate changes of this magnitude. In addition, the changes would have eliminated a ten hour solar occultation by Jupiter from the tour. Retaining this occultation was considered a high priority by the Galileo science teams, Thus, an attachment AV on the order of 10 to 15 m/s was accepted as the cost to retain as much of the nominal characteristics of the prime mission as possible.

TOUR DESIGN STRATEGY

The objective of the tour design was to satisfy all of the operational constraints discussed above with an orbital tour that provides acceptable science return. Since many of the objectives are dependent, the tour design was an iterative process that involved selecting and examining sequences of flybys both for how well they satisfied the constraints and for their value in terms of science return.

Procedure

The design of each individual tour was conducted in three stages. First, a tour design program (STOUR[§]) using a two-body conic approximation was used to select flyby conditions that are possible from the gravity assist of each successive flyby of the series. Then, an optimization routine (CATO[**,5]) was employed to adjust the flyby states (while satisfying specified flyby constraints) in order to patch together the individual legs of the trajectory while also minimizing the total AV of the tour. The models for the gravitational and other forces available in this optimization are similar to those currently in use for the navigation of the prime mission, but there arc some minor differences. Thus, in the final stage, the aimpoints generated in the second stage were used, with the current models, in order to construct the final integrated trajectory. Each resulting tour was then analyzed with respect to how well it satisfied all of the constraints and to quantify the science return available from the mission. Substantial adjustments to the tour generally required returning to the original two-body stage, while more modest changes could sometimes be accommodated within the optimization and/or targeting stages,

Perijove Reduction Strategy

As outlined in the previous section, five constraints involving time were considered in the design of the GEM tour. These objectives establish a general time frame for the tour. With the time of the first Io encounter essentially fixed (near opposition in October 1999), the first step was to work backward from the end of the mission to establish the length of time that must be reserved for the perijove reduction campaign. That would, in turn, define an upper limit for the end of the Europa study phase. At the end of the prime mission, the perijove of the trajectory is approximately 9 RJ. Achieving a close Io flyby requires reducing the perijove of the trajectory to at least that of 10's orbit (approximately 5.9 R_J). Thus, a significant perijove reduction is required to connect the first and last phases of the GEM. Given the limit of approximately twenty-two months (from the end of the prime mission in December 1997 through October 1999) for both the Europa study and the perijove reduction, one of the first objectives was to determine the number of flybys that would be required to achieve the necessary perijove reduction, Since Io's orbit is inside those of the other three satellites, any of Callisto, Ganymede, or Europa could be used to reduce the perijove. Given the desire to focus on Europa, onc option was to usc Europa to achieve the perijove reduction. Although this satisfies the scientific desire for more Europa flybys, it is not the best option for GEM, since it doesn't

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§ STOUR: Satellite Tour Design Program

** CATO: Computer Algorithm for Trajectory Optimization satisfy the timing strategy that is necessary to achieve a long post-lo period; the operational constraints outweigh the scientific benefits of the additional Europa flybys.

In general, a reduction in the perijove that results trom a gravity assist is also accompanied by a reduction in the orbital period. Since the period after the Io encounter should be close to 50 clays, the period prior to the perijove reduction phase must be larger than 50 days. Also, the perijove reduction should be achieved with as little loss of period as possible, so that the period prior to the pump-down phase is not so long that it unnecessarily reduces the number of Europa encounters. Furthermore, the pump-down should be achieved with as few reduced perijove passes as possible, in order to minimize the radiation exposure. Of the three satellites that arc available to provide the gravity assist for the perijove reduction, Callisto provides the greatest reduction in perijove with the least reduction in period for a single flyby, compared with the other satellites. (l'his is consistent with similar findings during the tour design for the Galileo prime mission.[4]) Therefore, flybys of Callisto were selected for the second phase of the GEM tour.

Timeline

After investigations of many combinations of Callisto flybys, it was determined that four Callisto flybys would be necessary to achieve the perijove reduction required to bridge the Europa study phase of the mission and the 10 encounter phase. It was also determined during this phase of the tour design that the period reduction that accompanies the perijove reduction is on the order of 50 to 60 days. Furthermore, the time required to complete the pcrijove reduction phase was estimated to be on the order of approximately 6 months. Thus, in order to place the first 10 encounter in October 1999, the perijove reduction phase would have to start early in 1999.

The next timing issue to influence the mission timeline was the objective of achieving a 50 day post-Io period. Given the significant period decrease that accompanies the perijove reduction, it is impractical to have a period inbound to the 10 encounter of 50 days. Therefore, the Io flyby itself must be used to raise the orbital period. The largest increase in period that was achieved, in the study conducted as part of the tour design, was on the order of 20 days. Thus, for a post-Io period of roughly 50 days, a goal of 30 days was established for the period inbound to the first 10 flyby. This then set the requirements for the period following the Europa campaign at approximately 80 to 90 days, given the 50 to 60 day reduction that was expected during the pump-down phase. The objective then was to select a set of Europa encounters that would yield an orbital period on the order of 80 to 90 days by the early part of 1999. At the end of the prime mission, the orbital period is approximately 50 days. Therefore, the Europa campaign would be required to increase the period by 30 to 40 days, over a time interval of approximately fourteen months.

Latitude Diversity

The next choice was in the specific characteristics of the flybys during the Europa campaign. Onc of the primary scientific objectives of tbc Europa campaign was to achieve as much latitude diversity among the Europa encounters as possible. Achieving flybys of low latitudes is generally not difficult, since confining the trajectory to the plane of all four satellites generally results in relatively low latitudes at any of the satellites. The difficult task is to achieve moderate to high flyby latitudes. To achieve a high satellite centered latitude, the Jupiter centered inclination of the trajectory must be increased. If, however, the inclination is increased too much, flybys of other satellites may not be possible because the spacecraft has been pulled too far from the plane of the other satellites.

The inclination can be increased in several ways including flybys of different satellites, repeated flybys of a single satellite, or maneuvers. Given the limited AV budget of the mission, the usc of maneuvers specifically designed to achieve high latitude flybys was not practical, since relatively large maneuvers arc required to achieve cvco modest latitudes. Callisto and Ganymede flybys were not a scientific objective of the GEM, and the inclusion of such encounters did not significantly increase the Europa flyby latitudes in the preliminary tours that were designed. Therefore, this option was also not favorable to tbc mission objectives. Thus, it was determined that the Europa campaign would, indeed, consist of a series of repeated Europa encounters (even though this was not a specific requirement of the tour design).

Repeated encounters of a single satellite may be achieved using either resonant or non-resonant transfers. Resonant trans fer paths arc defined to be transfers between two flybys of the same satellite for which the orbital period of the transfer orbit is approximately equal to N times the period of the satellite (where N is an integer). Thus, resonant transfers result in a series of flybys that either both occur inbound (or both occur outbound) of the Jupiter periapse. Non-resonant transfers arc transfers that are not resonant. In order to achieve latitude differences between successive flybys, using either resonant or non-resonant transfers, some amount of AV between the flybys is generally required, The magnitude of the AV depends on the specific characteristics of the flybys.

Using resonant transfers, the latitude can generally be incrementally changed in a single direction with little AV between successive flybys. In this way, relatively high Europa flyby latitudes could be achieved by the end of a resonant series. However, it does not solve the problem of returning the trajectory to the plane of the other satellites in order to begin the pump-down to 10. The inclination could either be reduced by a second set of resonant encounters that arc designed to incrementally decrease the latitude or through a large maneuver between the final Europa flyby and the first Callisto encounter. The time allotted for the entire Europa study phase is too short to achieve significantly high latitudes within the increasing series and then to incrementally decrease the inclination. Furthermore, the propellant budget of the mission does not accommodate the type of maneuver that is required at the end of a latitude increasing series. Thus, resonant transfers arc not the best option in terms of the operational constraints on the Europa series.

Using non-resonant transfers, a tour that achieves an acceptable level of latitude diversity was found that requires little AV between the flybys. Studies were conducted to evaluate whether including additional ΔV's would further increase the diversity, but it was determined that significant increases in the latitudes could not be achieved with the amount of propellant that is available for the mission. Thus, a tour that includes a non-resonant Europa series with small deterministic propellant requirements was accepted. Non-resonant transfers offer a second advantage over resonant transfers in that, since inbound and outbound flybys encounter Europa at a significantly different place in its orbit, the longitude and lighting conditions of successive are significantly different. Although longitude diversity was not a top priority for the Europa campaign, the non-resonant series dots offer some variety toward that objective.

Period Increase

The decision to use non-resonant transfers at Europa did, however, make the task of increasing the period to the 80 to 90 day level more difficult. Recall that one scientific objective for the Europa campaign wasa desire for light-side encounters. With resonant transfers, the period can be repeatedly increased with a series of light-side encounters; however, due to the imitations described above regarding resonant transfers, a resonant Europa series was not adoption, For non-resonant flyby s, on the other hand, a period *reducing* flyby at one of the two flybys may be necessary to achieve Iight-side flybys at both encounters. Given the general orientation of the trajectory (essentially aligned with the anti-Sun direction), inbound encounters that increase pcrijovcaredark-side flybys. Thus, the scientific desire for light-side encounters is in conflict with the requirement to increase period.

The requirement on the Europa campaign was for an increase in the period of approximately 40 days by the end of the Europa phase. A single Europa flyby can increase the period by as much as 20 days. Therefore, some flybys that reduce the period are acceptable. In fact, very long period orbits (on the order of 80 to 90 days) should be delayed until the end of the phase, if possible, since such long periods early in the mission would unnecessarily reduce the number of flybys that could be included in the time allotted for the Europa study. For this reason, the period is alternately pumped up and pumped down throughout the Europa campaign with a series of iight-side flybys. Each "pump-up" leg is designed to achieve the largest period increase available from the flyby (averaging about 17 days). On the other hand, with each period reducing flyby, the period change is designed to be as small as possible (about 13 days), while still providing relatively low flyby altitudes. In this way, although period reducing flybys arc incorporated to provide inbound, light-side encounters, a net increase in the period can be achieved with a Europa campaign that primarily includes iight-side encounters. If, however, the net increase is not large enough to meet the 80 to 90 day requirement for the period prior to the start of the perijove reduction phase, dark-side flybys can be used to provide the additional increase.

Perijove Reduction Phase

The Callisto flybys of the perijove reduction phase were selected solely on their ability to decrease the perijove while retaining the highest period possible prior to the [o encounter phase. Since the total perijove reduction that is required is approximately 3.5 R_J, and each Callisto flyby provides a reduction Of about I

R_J, four flybys are used to satisfy the perijove reduction requirements, Although the perijove reduction achieved from each of the Callisto flybys is approximately equal, the change in the period from the flybys decreases with successive flybys, The apojove distance aiso decreases in this phase, but similar to the trend in the period, the amount of reduction decreases with each subsequent Callisto encounter.

10 Encounter Phase

Many alternatives for the final phase of the tour were investigated, As previously discussed, one option that was abandoned early in the tour design was to include perijove increasing encounters following the iast [o flyby in an attempt to raise perijove above that of lo's orbit. This would have precluded additional 10 opportunities, in favor of reducing subsequent radiation exposure. But, even with the strategy of planning for repeated encounters of 10, many different alter-natives were available for the 10 encounters that end the GEM. Although even two Io encounters constitute a set of "repeated encounters," similar to the concept of repeated encounters during the Europa campaign, many of the issues that constrained the design of the Europa flybys did not exist for the design of the 10 encounters. Following the 10 flybys there was no requirement to encounter any other satellite. l'bus, the encounters could be designed to pull the spacecraft out of the plane of the other satellites. Since it is not necessary to return the spacecraft to that plane, there is no ΔV penalty associated with such a strategy. In particular, since it was decided for operational reasons to include a relatively iow latitude flyby as the first GEM Io encounter, and a polar 10 flyby as the second 10 encounter, it was necessary to significantly increase the orbital inclination and to do it in only onc orbit,

The period increase required from the first Io flyby, coupled with the requirement for flyby altitudes less than 1000 km, were the most prominent constraints on the design of this phase. Several Io series were developed that satisfied the latitude requirements with little AV between the flybys, both with resonant and non-resonant flybys. However, the period achieved after tbc first Io flyby in those tours was less than tbe 50 day desired goal. Also, the altitude of tbc second flyby was generally unacceptably high. Although minimizing propellant consumption bad a high priority, the usc of AV to increase the interval between the encounters and/or to lower the second flyby altitude was acceptable. For a ΔV of less than 10 m/s, the second flyby was moved such that the period following the first 10 encounter was about 46 days, just short of the 50 day goal, and the second flyby altitude was lowered to 300 km. The ΔV cost of achieving an even longer period was prohibitive. Thus, a compromise of expending the additional propellant to achieve at least the additional 3.5 days of data return was accepted

Although one of tile requirements for the Io phase was that onc flyby be a polar encounter, the hemisphere in which that flyby, or even the first 10 flyby of GEM, should occur was not originally specified. in the tour design, it was determined that the ΔV cost to place onc 10 flyby in each hemisphere was prohibitive, but the cost to place both encounters in either hemisphere was about equal. Therefore, the choice of hemisphere was deferred to the investigators.

GALILEO EUROPA MISSION PROFILE

Based on the issues and strategies previously discussed, several candidate tours for GEM were developed. From those options, a nominal trajectory was selected. Table 1 includes several characteristics of the flybys in that tour. The first letter (E, C, G, or 1) of the code in the first column represents the first letter of the satellite being encountered (Europa, Callisto, Ganymede, or 10). The digits indicate tbc orbit number on which the flyby occurs. (The orbit numbers for GEM arc continued from those of tbc prime mission.) An "A" following the orbit number indicates a "non-targeted encounter," where a non-targeted encounter is distinguished from a targeted flyby both by the flyby altitude and the targeting requirements for the flyby. in general, a non-targeted encounter is a distant encounter (above 10,000 km altitude) whose aimpoint will not be specifically targeted during the mission. Note that the GEM dots not officially start until December 8, 1997, which is after the E 11 encounter. However, the GEM tour design considered issues relating to dates prior to the official end of the prime mission, such as changes to tile E11 i aimpoint and changes to a maneuver near the end of the prime mission that is required to attach tile GEM to the prime tour. Therefore, this discussion includes information beginning October 18, 1997, approximately the date of the attachment maneuver.

The latitude anti west longitude included in Table 1 are specified in satellite centered true equator of date coordinates. The solar phase angle, defined as the Sun-satciiitc-spacecraft angle at the time of the flyby, indicates the lighting conditions at the encounter time: phase angles less than 90 degrees indicate light-side encounters; a flyby whose phase angle is greater than 90 degrees has closest approach on the dark-side of the satellite. Although the geometry information and the phase angles correspond to the conditions at the flyby time, other features, with different lighting conditions, may be available both inbound anti outbound to the actual closest approach. For example, the vehicle may pass relatively close to lighted parts of the satellite during the approach or departure of a dark-side flyby, making observations that require lighted characteristics possible. The Jupiter centered true anomaly is computed at the time of closest approach to the satellite, indicating whether the satellite flyby is inbound or outbound of the Jupiter periapsis.

Table l. GEM Flyby Summary

	Satellite Flyby Conditions						Jupiter-centered Osculating Elements at Apojove				
	Date (yymmdd)	Alt. (km)	Lat. (deg)	West Long. (deg)	Solar Phase (deg)	Orbit True Anomaly (deg)	Period (days)	Incl. (deg)	Perijove Distance (R_J)	Apojove Distance (R_J)	Deter-ministic AV (m/s)
C10+Apo	971018						49	0.5	9.2	99	14.7
E11	971106	2053	25.1	141	33	-24	39	0.3	9.0	84	0.0
G12A	971215	14395	-5.7	93	11	-85					
E12	971216	200	-8.7	225	i I	30	57	0.5	8.9	110	0.0
E13	980210	3556	-8.9	132	26	-30	46	0.6	8.8	95	0.0
Ei4	980329	1646	12.0	228	15	31	64	0.4	8.9	120	0.0
E15	98053 I	25i9	14.9	134	22	-31	50	0.3	8.9	100	0.0
E16	980721	1834	-25.6	226	32	28	67	0.7	8.9	124	0.0
E17	980926	3594	-42.5	139	46	-27	57	1,0	9.0	110	0.0
E18	981122	2281	41.7	220	45	25	71	0.5	9.1	129	0.2
E19	990201	1486	31.0	330	147	-18	91	0.1	9.3	154	0.0
C20	990505	1311	2.5	102	165	115	60	0.2	8.3	115	0.0
C2i	990630	1050	-0.8	74	49	-122	41	0.2	7.3	89	0.0
121A	990702	26459	0.5	136	7	1					
C22	990814	2288	-3.2	108	165	128	33	0.1	6.5	77	0.0
C23	990916	1054	-0.6	1 I 1	159	133	26	0.2	5.5	66	0.0
124	991011	500	-17.3	224	65	29	46	0.4	5.7	98	8.9
E25A	991125	10000	14.7	94	47	-8 i					
125	991126	300	-80.4	57	94	23	39	2.1	5.7	8 7	

Total Deterministic AV (m/s) = 23.8

Latitude, West Longitude: Satellite-centered true equator of date coordinates
Inclination: Jupiter-centered mean equator of date coordinates

The conic parameters: period, inclination (in Jupiter centered mean equator of date coordinates), perijove distance, and apojove distance arc osculating elements computed at the apoapsis following the encounter with which they are specified. Since these quantities arc computed after the flyby, changes in the values represent the effect of that flyby on the orbital clement, For example, since the E12 flyby is outbound, its effect on the perijove distance does not appear in an actual periapse pass until orbit 13. However, since E 13 is an inbound flyby, the actual perijove distance on orbit 13 is also influenced by that flyby. Thus, the usc of osculating perijove distances in Table I provides a more accurate representation of the effect of each individual flyby on the perijove distance than a listing of the actual perijove distances.

The period and the perijove distance are particularly important during the perijove reduction phase, where the primary objective is to reduce the perijove, while limiting the decrease in period, in order to achieve the 10 encounter on orbit 24. The period at the start of the perijove reduction phase is approximately 90 days, but the interval between the two targeted [o flybys is only 46 days, slightly less than the 50 day goal. The inclination information provides some insight into the latitude diversity among the Europa encounters. The flybys that generate the largest inclination result in high latitude flybys on the next orbit, since a Jupiter centered inclination of even one degree at the distance of Europa's orbit represents a significant out-of-plane distance.

Since the nominal GEM trajectory cannot be achieved by the gravity assists of the flybys alone, deterministic maneuvers are included in the tour to provide the additional adjustments. Each AV listed in I'able l is the magnitude of the deterministic impulse that is applied near the apoapsis following the flyby, in order to continue the nominal GEM tour. The 14.7 m/s AV listed on the top line is the magnitude of the maneuver that is required to attach the GEM to tbc prime mission. This maneuver will bc executed near the time of the apojove following the C 10 encounter of the prime mission. Following that attachment maneuver, however, less than 1 m/s of deterministic AV is required to complete the first two phases of the tour, Thus, the attachment maneuver accounts for more than sixty percent of the total 23.8 m/s deterministic propellant budget for GEM. (The deterministic cost for the prime mission orbital tour is 21 m/s.) In the final phase, an 8.9 m/s maneuver is required between the two Io encounters, to achieve the desired 125 aimpoint. Statistical maneuvers will also be required to accommodate dispersion in the trajectory that may result from improved estimates for the ephemeris data and other perturbations; however, those AV'S are not included in the table. The statistical costs associated with this tour are estimated at almost 60 m/s, based on orbit determination and maneuver execution assumptions developed by the Galileo Navigation Team. Based on those values, the spacecraft has a very high probability of completing the orbital tour. In fact, that probability has continually increased throughout the prime mission as the navigation of the prime mission continues to perform well, resulting in an increased propellant budget for the GEM.

Figure 1 is a plot of the GEM tour beginning at the apoapsis prior to E 11 and terminating December 31, 1999. Referred to as a "petal plot" because of the resemblance of the orbits to the petals of a flower, the figure shows the projection of the trajectory onto a plane normal to Jupiter's pole. The trajectory is shown in a Sun-Jupiter fixed orientation, where the direction to the Sun is toward the top of the figure. Motion occurs in a counter-clockwise direction. Plots of the orbits of 10, Europa, Ganymede, and Callisto, as well as three arcs that identify radial distance from Jupiter, in units of Jupiter's radii, arc also included on the figure. A number "n" at the apoapsis position of an orbit represents the "nth" apojove since Jupiter orbit insertion (JO I). For example, "1 I" indicates the eleventh apoapsis since JOI. It also corresponds to the number of the next encounter, E1 1. The times of the two significant maneuvers in the tour arc indicated by the butterfly symbol near the apoapses marked 11 and 25. The official start and end dates of the mission are indicated by stars. This view highlights the rotation of the tour about Jupiter's pole and the relative sizes of the individual legs of the trajectory. At the end of the prime mission, the semi-major axis of the orbit is generally aligned with the anti-Sun direction. During the first nine orbits, the tour remains in this orientation with apojove distances that arc alternately pumped up and down, as the period is incrementally increased and decreased by the Europa flybys. The actual apojove distance varies from 85 R_J after E11 to over 150 R_J following E19. Through orbits 20 to 23 the characteristics of the trajectory change significantly. The trajectory is rotated about Jupiter's pole by approximately thirty degrees, and the apojove distance is decreased from over 150 R_J prior to C20 to about 65 R_J prior to the first 10 flyby. I'hc perijove distances also decrease during the pump-down phase from 9.3 R_J on obit 20 to only 5.5 R_J on orbit 23.

Figure 2 is a plot of both the targeted and non-targeted satellite encounters from a view consistent with the petal plot, but without the trajectory. The orbits of the four satellites arc also included in the figure. This view clearly shows the alternating inbound/outbound pattern of the Europa flybys, that is the result of the non-resonant transfer strategy chosen for the Europa phase.

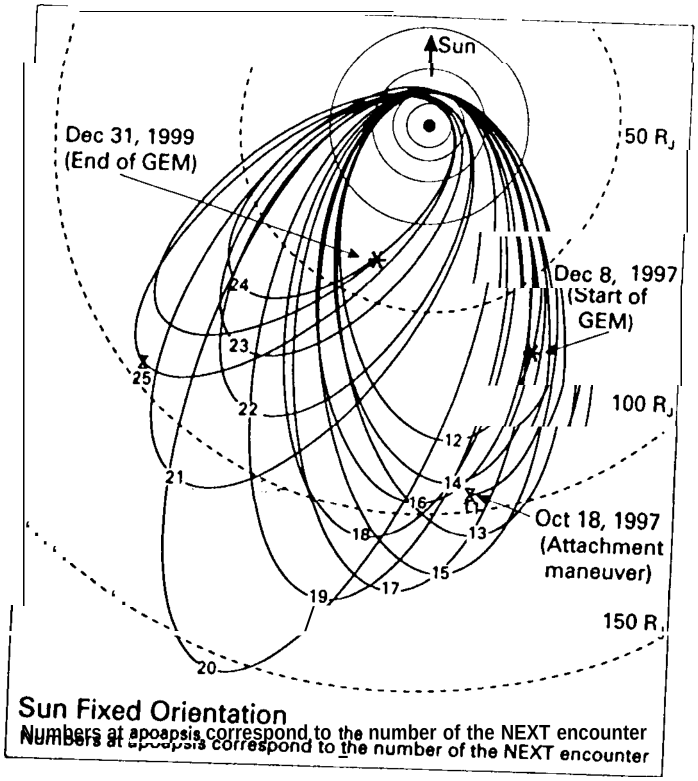

Figure 1. GEM Orbital Tour.

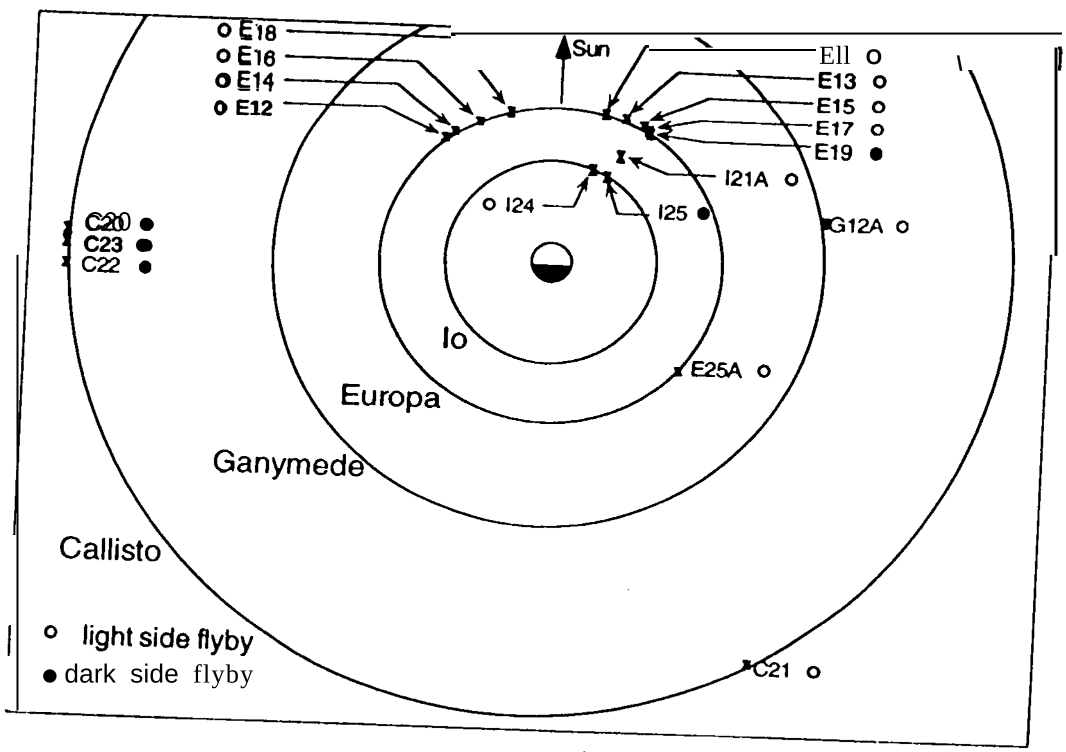

Figure 2. GEM Satellite Encounter Locations.

DETAILED GEM CHARACTERISTICS

Although the tour design considered many global constraints and objectives, each phase of the mission also had its own set of specific requirements. Thus, in addition to focusing on a different satellite within each phase, the specific flyby characteristics at those satellites also differ during each of the three phases.

Europa Campaign

The Europa campaign is roughly defined as the first 9 orbits of the GEM, including flybys E 11 through E19. During this phase, encounter altitudes from a minimum of 200 km at E12 to a maximum of approximately 3600 km at E17 are achieved. Also, significant latitude diversity among the Europa encounters, from a minimum of approximately –42 degrees at E 17 to roughly +42 degrees at E18 are available, with several different latitudes between those limits. The primary reason that this particular tour was selected, over other candidate tours, was that the level of latitude diversity available in the Europa campaign was greater than that achievable by any other tour candidate. The relative locations of the flybys are represented in the Europa aimpoint chart in Figure 3. The inner circle represents Europa as viewed by the vehicle inbound to the flyby (the B-plane, defined to be normal to the V-infinity vector of the hyperbolic path relative to Europa). The radius of the inner circle is defined as a normalized impact-radius of Europa. (Although this radius is slightly different for each flyby, the average is approximately 1652 km for the targeted Europa encounters of the GEM.) Two additional circles, with radii of two and three times the impact radius, are also included in the plot. The E4, E6, and pre-GEM E 11 flybys of the prime mission are also plotted. Most of the flybys occur at an altitude of less than two times the impact radius (or at a radius of less than three times Europa's impact radius from the center of the impact circle). Following E 11, the latitudes of the flybys follow a pattern consisting of two flybys in one hemisphere followed by two flybys in the opposite hemisphere, and so on. El 2 and E 13 are southern flybys; E 14 and E 15 occur at northern latitudes, etc. The latitude within each hemisphere increases throughout the campaign until the E 19 flyby. With that encounter, the inclination reduction required to begin the perijove reduction phase reverses the latitude increasing trend. Another difference between E 19 and the other GEM Europa encounters is that El 9 is a dark-side flyby, while all other Europa aimpoints have a phase angle less the 90°. The period following E18 was almost 20 days short of the 90 days goal for the period prior to the start of the pump-down phase, but given the limitation on the duration of the Europa campaign, only onc additional flyby could be included. Thus, although E 19 retains the non-resonant pattern of the Europa series, it was designed as a dark-side flyby in order to provide the additional period increase required prior to the perijove reduction phase.

The Europa flybys are presented from a different perspective in Figure 4, where the flyby locations are superimposed onto a map of Europa's surface. (The thin, jagged lines in the figure represent surface features on Europa.) The longitudes of the targeted GEM flybys occur essentially in two primary bands, roughly at 135 degrees west longitude for odd numbered Europa flybys (inbound encounters) and approximately 225 degrees for even numbered encounters (outbound). The exception is the E 19 flyby that occurs at a west longitude of about 330 degrees. Although this longitude is different from that of the other Europa flybys in the GEM, it is within the same band of longitude as the 136 encounter in the prime mission, which was also a dark-side, inbound encounter.

As a 200 km flyby, the E12 encounter is the lowest flyby of any satellite in both the prime and follow-on missions. This low altitude is itself a significant complication to the navigation for that leg. However, in addition to the E 12 encounter. a non-targeted flyby of Ganymede, at an altitude of' 14395 km, also occurs on orbit 12. In order to maximize the resources available for the investigation of Europa, no scientific investigations of Ganymede are planned for this flyby, but the non-targeted encounter is an important navigational consideration. Since the non-targeted G 12A flyby occurs only onc day prior to the targeted E 12 encounter on this leg, uncertainties associated with the Ganymede flyby introduce a substantial perturbation to the trajectory that must be considered during the final targeting for the E 12 encounter.

The E13 flyby of the tour occurs on February 10, 1998. The date of solar conjunction in 1998 is February 23. Thus, the E 13 flyby occurs very near the beginning of the three week interval around solar conjunction during which poor data quality is expected. For this and operational workload reasons, science gathering during this flyby will be limited to gravitational field mapping, since returning a large amount of

E13 science data prior to the E14 encounter would be difficult. In 1999, however. no encounters occur near solar conjunction (April 1, 1999).

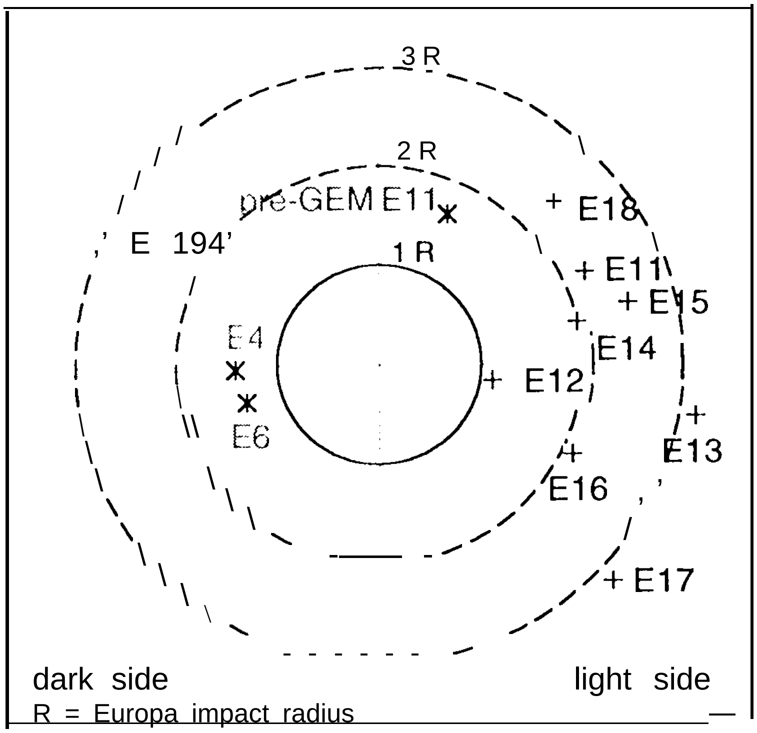

Figure 3. Europa Aimpoints.

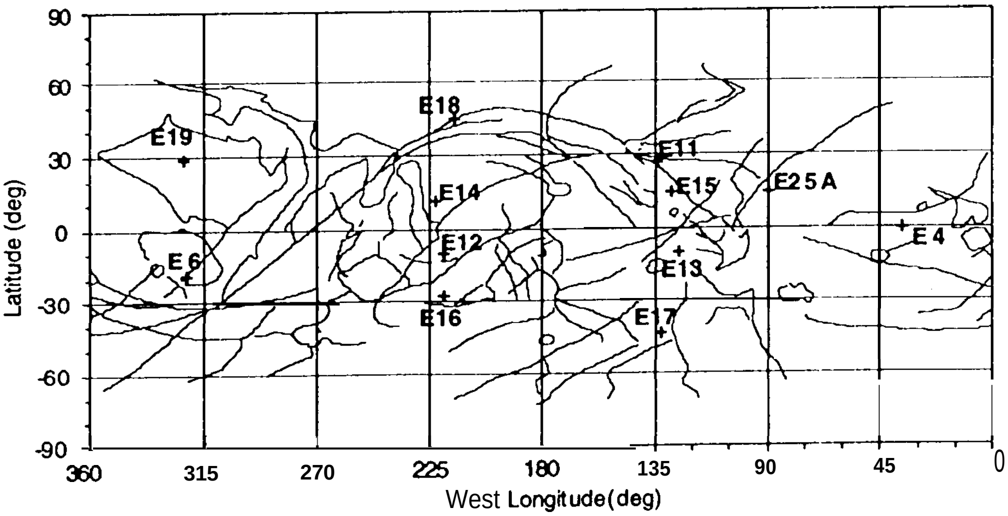

Figure 4. Europa Aimpoints Relative to Europa Surface Features.

Perijove Reduction Campaign

The perijove reduction phase, incorporating orbits 20 through 23, includes four Callisto flybys. The primary goal of this phase, in terms of the tour design, is to reduce the perijove from approximately 9.2 R_J to that of 10's orbit (5.9 R_J) in order to achieve the 10 encounter on orbit 24, The orbital period also decreases during this phase, from a high of over 90 days following E19, to 26 days following C23 (the period inbound to 124). in addition to the Callisto flybys, this phase also includes a noo-targeted Io encounter, at an altitude of 127,000 km, on orbit 21. Since this is less than half as close as the next 10 closest approach of the tour since 1995, it an exceptional scientific opportunity. Observations conducted during this encounter may be used to define the final planning for the targeted [o encounters on orbits 24 and 25 and also to refine the Io ephemeris to assist the orbit determination and final targeting for those flybys.

The radiation exposure escalates during this phase as the perijove distance decreases. Figure 5 is a plot of the estimated radiation dosage for the nominal GEM tour, based on estimates for the radiation field and the shielding on the spacecraft. (These values assume a sphere with aluminum shielding of 2.2 gm/cm^2.) The perijove distances arc also plotted on Figure 5 to highlight the correlation between the perijove and the radiation exposure. Note that Table 1 includes an osculating perijove distance, computed at apojove, in order to identify the effect of each flyby on the perijove distance. The perijove values plotted in Figure 5 arc the actual perijove distances that occur in the tour, since the radiation dosage is dependent on the actual Jupiter flyby. The slope of the radiation dosage curve increases significantly during the pcrijove reduction phase, from approximately 10 krad/rev prior to the start of the pump-down, to over 40 krad/rev by the time of the 10 encounters.

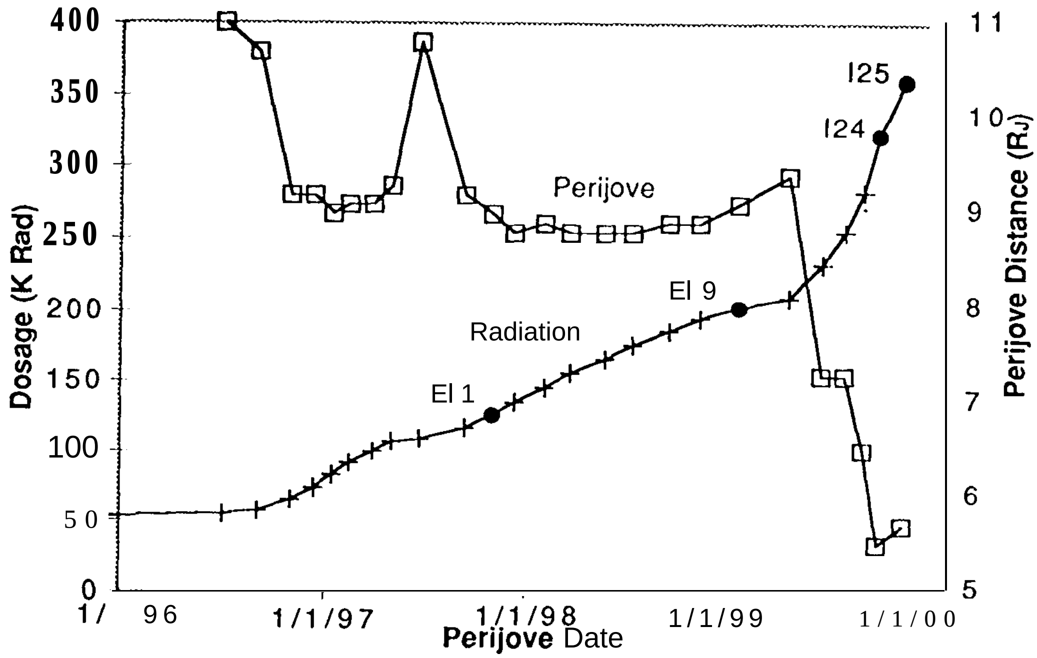

Figure 5. Radiation Dosage.

No specific value was set for an upper limit on radiation dosage for the GEM tour design. With the objective of limiting the dosage as much as possible, tours were evaluated with respect to radiation issues by comparing options relative to each other, rather than to an absolute dosage limit. While the 330 krad dosage following 124 is twice the design limit, there is significant probability that the spacecraft may yet be functional at that time. [6] The assumptions and models used to compute the dosage, as well as the capabilities of the spacecraft components to withstand the exposure, arc all under continued investigation.

Io Encounter Phase

The Io encounter phase of the tour, inclosing orbits 24 and 25, provides two close Io encounters sand one non-targeted Europa encounter. The first Io flyby was selected to be a relatively low [atitudc,light-side encounter, in order to improve the opportunities for observations of known active volcanic regions. A low altitude, nearly polar flyby was achieved at the I25 encounter, to accommodate the requirements of experiments concerned with 10's gravitational field and, potentially, the existence of an intrinsic magnetic field. Both flybys occur in the southern hemisphere. Also, both flybys arc outbound encounters. However, the 125 encounter occurs on the dark-side of 10, compared with the light-side 124 flyby. Since [25 is a near polar flyby, however, lighted parts of the body will still be visible even at the time of closest approach

Similar to orbit 12, orbit 25 also includes onc non-targeted encounter prior to the low altitude, targeted flyby on the leg. Part of the 8.9 m/s maneuver prior to 125 is the cost of constraining the altitude of the non-targeted E25A flyby to be at least 10,000 km. But, even at this altitude, E25A introduces a perturbation to the trajectory prior to the 125 encounter that must be considered during the final targeting of that series. Unlike the G12A flyby, however, resources will be devoted to Europa investigations at E25A, since the flyby provides a final opportunity for unique coverage of Europa, with a moderate phase angle sufficient for global imaging opportunities.

SUMMARY

A satellite tour for the GEM has been developed that satisfies most of the desires of the Galileo scientific community, while balancing operational constraints that result from the particularly limited resource environment that is inherent in the design of a follow-on mission. Although this mission and the Galileo prime mission share the same spacecraft, this tour provides many interesting opportunities that were not available in the prime mission and may not be available in near-term future missions. The efficient use of Galileo's resources during its prime mission has enabled a follow-on mission that includes more satellite flybys than the prime mission in a time frame that doubles the amount of operational time the spacecraft will spend in Jupiter's vicinity. The GEM mission is built on the success of the Galileo prime mission, but it stands alone in the scientific opportunities it offers.

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REFERENCES

1 O'Neil, W. J., N.E. Ausman, J.A. Gleason, M.R. Landano, J.C. Marr, R.T. Mitchell, R.J. Reichert, M.A. Smith, "Project Galileo at Jupiter," IAF 96-Q.2.01, 47th IAF Congress, Beijing, China, October 1996.
2 O'Neil, W. J., "Project Galileo – The Jupiter Mission," The Three Galileos: The Man, The Spacecraft, The Telescope," (Proceedings of the Three Galileos Conference, Padova Italy, January, 1997), Kluwer Academic Publishers, 1997. (In Preparation)
3 Johnson, T. V., "An Overview of the scientific Results of the Galileo Mission," The Three Galileos: The Man, The Spacecraft, The Telescope," (Proceedings of the Three Galileos Conference, Padova Italy, January, 1997), Kluwer Academic Publishers, 1997. (In Preparation)
4 Wolf, Aron A. and Dennis V. Byrnes, "Design of the Galileo Satellite Tour," AAS/AIAA Astrodynamics Specialist Conference, AAS 93-567, Victoria, B. C., Canada, August 16-19, 1993.
5 Byrnes, Dennis V., Larry E. Bright, "Design of High-Accuracy Multiple Flyby Trajectories Using Constrained Optimization," AAS 95-307, Halifax, Nova Scotia, Canada, August 14-17, 1995.
6 Hirst, Edward A., "Galileo Europa Mission, M1SS1ON PLAN," Jet Propulsion Laboratory, California Institute of Technology, PD 625-10, April 11, 1997.