Planetary Protection Trajectory Analysis for the Juno Mission

Try Lam[1], Jennie R. Johannesen[2], and Theresa D. Kowalkowski [3]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

Juno is an orbiter mission expected to launch in 2011 to Jupiter. Juno's science orbit is a highly eccentric orbit with a period of about 11 days and a nominal duration of one year. Initially, the equatorial crossing near apojove occurs outside Callisto's orbit, but as the mission evolves the apsidal rotation causes this distance to move much closer to Jupiter. This motion could lead to potential impacts with the Galilean satellites as the ascending node crosses the satellite orbits. In this paper, we describe the method to estimate impact probabilities with the satellites and investigate ways of reducing the probabilities for the Juno mission.

Nomenclature

C_3	=	launch energy (V_∞^2)
C_D	=	coefficient of drag
ΔV	=	delta-velocity
σ	=	standard deviation
V_∞	=	hyperbolic excess velocity

I. Introduction

JUNO is an orbiter mission expected to launch in 2011 to go to Jupiter for a nominal science duration of one year. Juno will perform detailed gravity measurements at Jupiter and explore the Jovian atmosphere and magnetosphere with a science goal of understanding Jupiter's origin and evolution. The science investigation will be accomplished by polar measurements and from close perijove passages at Jupiter. Juno's orbit is a highly eccentric polar orbit with the closest approach at roughly 4500 km altitude above the Jupiter 1-bar pressure level and an apoapsis of 39 Jovian radii (RJ), where RJ is taken as the equatorial radius, 71,492 km. Initially, the equatorial crossing near apojove (APO) occurs outside Callisto's orbit, but as the mission evolves the apsidal rotation (about 0.95° per orbit) causes this distance to move much closer to Jupiter. To avoid potential impacts with the Galilean satellites (Io, Europa, Ganymede, and Callisto) Juno plans to de-orbit into Jupiter's atmosphere after 33 orbits. This is particularly important since the increasing radiation dose puts the controllability of the spacecraft at risk toward the end of the mission. In this paper, we describe the method used in estimating impact probabilities with the Galilean satellites, key results, and methods of reducing the impact probabilities for the Juno mission.

II. Juno Mission Overview

Juno plans to launch in August, 2011, from Cape Canaveral, Florida, on an Atlas V 551 launch vehicle. Two large Deep Space Maneuvers (DSM) would be performed near aphelion setting up the Juno spacecraft for a gravity assist with Earth on October 12, 2013, a little over 2 years from launch. The selected trajectory is called a "2+ ΔV-EGA" trajectory and enables Juno to arrive at Jupiter on August 3, 2016, roughly 5 years in flight time.

Upon arriving at Jupiter, Juno would perform a Jupiter Orbit Insertion (JOI) maneuver to capture into a 78-day orbit. This initial capture orbit would be a highly eccentric polar orbit with perijove (PJ) at roughly 4500 km. Another maneuver, the Period Reduction Maneuver (PRM), would be performed at the next perijove pass on October 19, 2016 to reduce the orbit period to near 11 days (actual average orbit period is 10.9725 days) to begin Juno's one year at Jupiter. An orbit is defined to start and end at apojove and is numbered according to the perijove

[1] Staff Engineer; Guidance, Navigation, & Control; M/S 301-121; Member AIAA.
[2] Juno Mission Design and Navigation Manager; Guidance, Navigation, & Control; M/S 301-360; Member AIAA.
[3] Senior Engineer; Guidance, Navigation, & Control; M/S 301-150; Member AIAA.

between the apojoves. The primary science observation would begin on the second 11-day orbit (PJ-3). The chosen 11-day science orbit period yields global coverage of the Jovian magnetic field by providing equal spacing of the longitudes at each equatorial crossing. Orbit Trim Maneuvers (OTMs) are made 4 hours after each science perijove to meet the longitude spacing requirements. A plot of the trajectory with Juno's large capture orbit and 33 smaller 11-day orbits is shown in Fig. 1.

The Juno science orbit, with its highly-elliptical polar orbit and low perijove, would enable the science investigations to achieve their desired resolution. From an engineering perspective, the low perijove altitude helps to reduce the required JOI and PRM ΔVs and the polar orbit profile minimizes the exposure to Jupiter's strong radiation by initially avoiding the higher radiation areas. In figures 1 and 2 we see the rotation of the line of asides on successive orbits, approximately 0.95° per orbit. The latitude of perijove ranges from 3°N at Jupiter arrival to 34°N at PJ-33. The apsidal rotation increases Juno's radiation exposure as a greater portion of the orbit is exposed to the higher radiation levels; this is especially significant in the latter part of the mission.

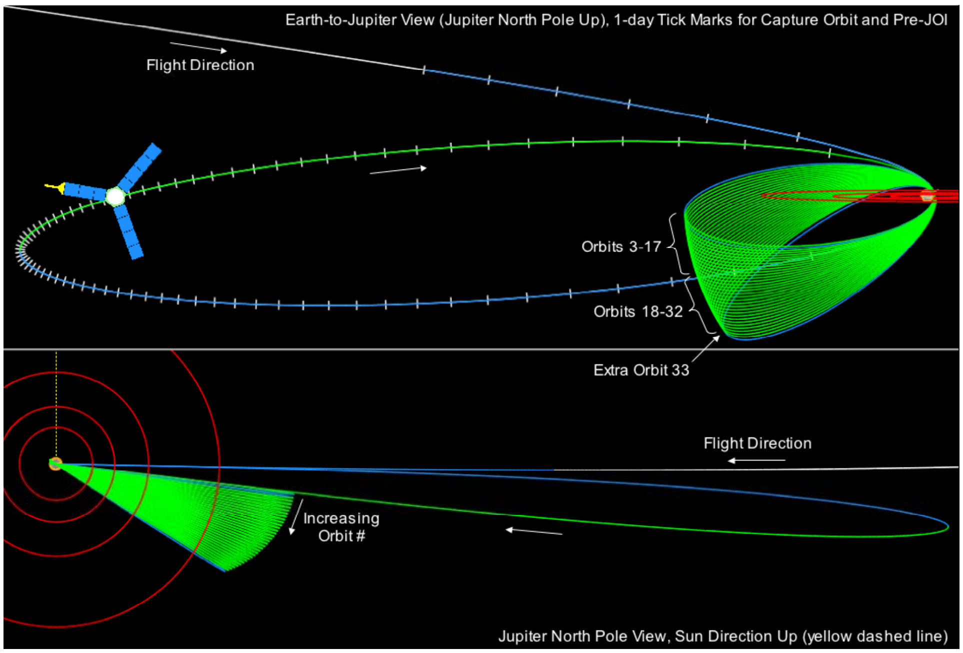

Figure 1. Juno nominal trajectory showing the larger 78-day capture orbit and the 33 11-day orbits. The top portion of the figure shows the apsidal rotation.

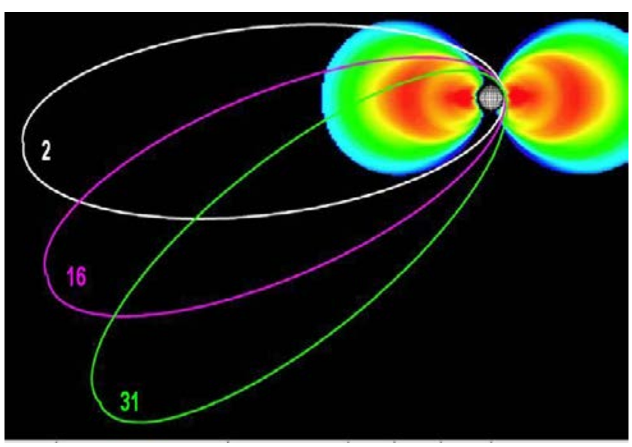

Figure 2. Juno encounters higher radiation as the mission evolves. Figure shows Orbits 2, 16, and 31 and Jupiter's radiation field. The apsidal rotation causes successive orbits to be exposed to more radiation.

The rotation of apsides has a dramatic effect on planetary protection. As the apsidal rotation moves the ascending node from outside Callisto's orbit to near Europa's orbit after 33 orbits, potential impacts with the Galilean satellites may occur. Figure 3 shows a plot of Juno's distance from Jupiter at each ascending node starting after PRM and ending after the last perijove passage. In addition, the orbit radii of the four Galilean satellites are plotted. From the plot we see that the initial distance is approximately 37 Jovian radii and at the end of the nominal mission the distance is approximately 9 RJ, which is near the vicinity of Europa. Every intersection between the radius of the satellites and Juno's equatorial crossing could lead to a potential close approach between the spacecraft and the satellite. For example, there are potential encounters with Callisto around orbit 10 and 11, Ganymede around orbit 22 and 23, and Europa around orbit 32 and 33, all of which Juno is required to avoid. Fortunately, for the nominal mission the closet approach to any satellite is greater than 100,000 km.

To ensure that no potential impacts with the Galilean satellites will occur Juno plans to de-orbit into the Jupiter atmosphere after 33 orbits and prior to solar conjunction on October 26, 2017. This is especially important since the increasing radiation dose puts the controllability of the spacecraft at risk toward the end of the mission. If the spacecraft does not de-orbit, it is likely that the spacecraft would become uncontrollable at some future time. Coupled with the apsidal rotation, the lack of controllability of the spacecraft leads to a small probability of impacting one of the Galilean satellites.

A more detailed description on the Juno mission can be found in Ref. 1.

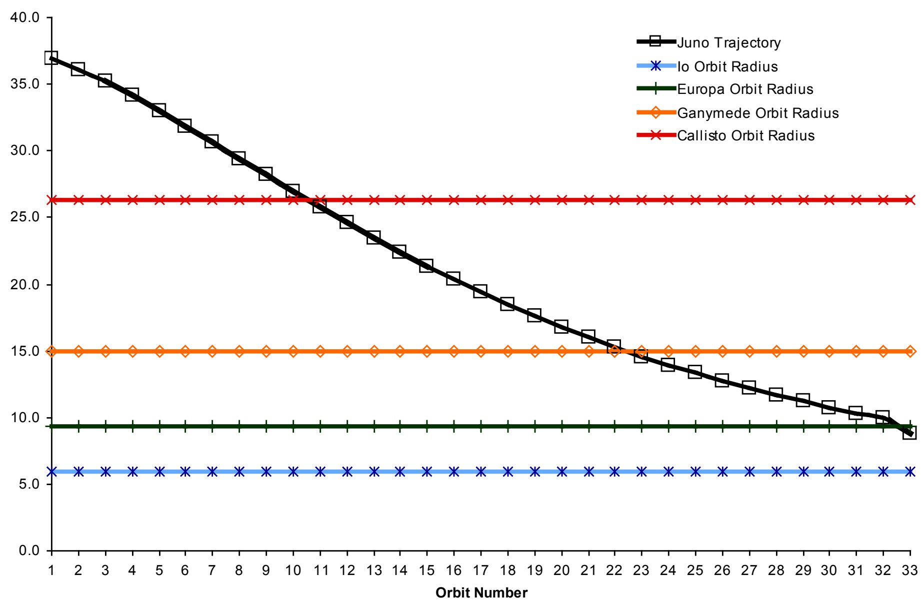

Figure 3. Ascending node distance versus orbit number. In addition, the orbit radii of Io, Europa, Ganymede, and Callisto are plotted.

III. Planetary Protection Requirements

Due to the required preservation of potential biological and/or organic materials on the icy moons of Jupiter, Juno faces some stringent planetary protection requirements. The Juno mission has been assigned a Planetary Protection Categorization II by the NASA Planetary Protection Officer (PPO)[2], implying that the mission is to a body of significant interest but where there is a small chance of contamination by the spacecraft that may jeopardize future explorations. The requirements are to:

1) document avoidance of the Galilean satellites (Io, Europa, Ganymede, and Callisto) at an acceptable probability (less than 1×10^{-4} for Europa, less than 1×10^{-3} for the others) during Juno prime mission;
2) provide an end-of-mission plan that will address the disposition of the spacecraft and ensure continued avoidance of Galilean satellite impacts after the mission has completed its observations.

As mentioned previously, Juno has no intention of encountering any Galilean satellites during its prime mission; thus, meeting the first requirement is easily shown by analysis, and a baseline reference mission can be selected to ensure that no close satellite encounters will occur. To address the second requirement, Juno plans to perform a maneuver on the last apojove to de-orbit the spacecraft on October 16, 2017 into Jupiter's atmosphere with impact occurring before solar conjunction. If the de-orbit goes as planned, then planetary protection requirements will be met, but what happens if de-orbit fails? The requirements state that Juno must ensure continued avoidance of Galilean satellite impacts even after the 1-year science mission. In addition, one must consider the satellite impacts that might result if the spacecraft became uncontrollable any time after Jupiter orbit insertion.

To comply with the impact probability requirement, Juno has imposed a requirement such that the impact probability with Europa is less than 1×10^{-4} after 150 years (the most stringent requirement) which is allocated to different aspects of planetary protection (spacecraft reliability, probability of contamination given a non-sterile impact given a limited bioburden response because of the high radiation environment, and the probability of impact given failure to de-orbit)[3]. The last area is the subject of this paper and pertains to the trajectory analyzed in a Monte Carlo fashion without the de-orbit burn (and without additional orbit trim maneuvers if the spacecraft should become uncontrollable at any time in the mission). Specifically, the allocated requirements on the trajectory design are as follows:

1) The Juno trajectory design shall be such that the probability of Europa impact for the 150 years following a failed de-orbit burn attempt is less than 1.5*%*.
2) The Juno trajectory design shall be such that the probability of Ganymede impact for the 150 years following a failed de-orbit burn attempt is less than 5%.
3) The Juno trajectory design shall be such that the probability of Callisto impact for the 150 years following a failed de-orbit burn attempt is less than 5%.
4) The Juno trajectory design should be such that the probability of Io impact for the 150 years following a failed de-orbit burn attempt is less than 5%.

If de-orbit does not occur, the apsidal rotation would cause the orbit to rotate a complete cycle in inertial space over a period of about 12 years (see Fig. 4). This assumes that the orbit stays nearly polar and that the eccentricity and semi-major axis do not change. During this period the potential for encounters with the Galilean satellites exists as the equatorial crossing intersects the satellites' orbits. Long-term propagations are analyzed to determine impact probabilities if de-orbit does not occur. In addition, OTMs after perijove, although small, introduce more failure modes because they alter the orbit states that may lead to different impact probabilities. Thus, we analyze the impact probabilities for the Galilean satellites for all failure modes in the mission after JOI.

IV. Impact Probabilities with the Galilean Satellites

Estimation of the impact probabilities for each of the Galilean satellites are made by performing Monte-Carlo trajectory propagations sampling the spacecraft state uncertainties, satellite ephemeris uncertainties, and Jupiter's spherical harmonics uncertainties at various apojove locations after a maneuver following JOI. Nearly all simulations performed for this paper were done using JPL's Mission analysis and Operational Navigation Toolkit Environment (MONTE) software. Numerical propagations were performed for at least 150 years, which requires a lot of computational effort for large sample sizes. To reduce computation time the analyses were performed using the JPL supercomputers.

A. Ephemeris, Planetary, and Physical Models

The planetary ephemeris used is DE414[4]. For the Jovian satellite ephemeris JUP230[5] is used for any deterministic results that do not require any Monte-Carlo analysis, for example, the design of the reference trajectory. The JUP100[6] analytical ephemeris, also known as the Lieske's Galilean satellite theory E5 ephemeris[7], is used for most of the results presented here in this paper. The analytical JUP100 is preferred for very long-term propagations over the integrated JUP230 ephemeris because it better conserves the general geometry (orbital elements) of the satellites. The error buildup with JUP230 makes it unreliable for state determination of the Galilean satellites after approximately 2100. To account for uncertainties in JUP100 we sample the uncertainties in the initial input values which leads to the generation of the analytical Galilean ephemerides.

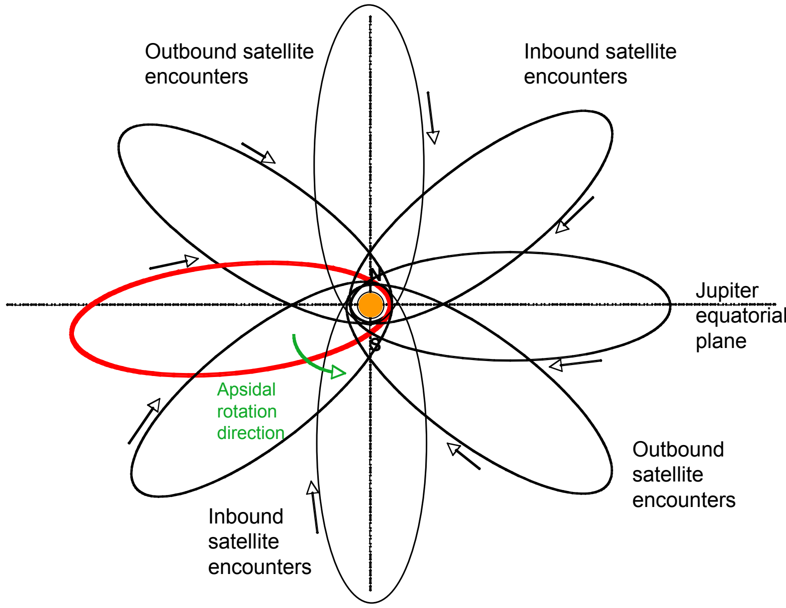

Figure 4. Full cycle of the apsidal rotation is shown in the direction opposite to orbit normal, roughly from the +X ecliptic direction looking at Jupiter. Initial orbit orientation is shown in red and the black arrows show the direction of the orbit. The apsidal rotation is in the counterclockwise direction.

The reference Jupiter gravity field used in this paper includes the zonal up to degree 6 and C22 and S22 of the un-normalized gravity field derived from the JUP230 ephemeris solution and are listed below in Table 1. In addition, the 1-σ uncertainty values are listed in the table. In the Monte-Carlo simulations the uncertainties in the gravity spherical harmonics terms are from sampling the JUP230 dynamical parameters (GMs, planet harmonics, pole) covariance.

For the atmospheric model, we have adopted a model provided by Sushil Atreya from the University of Michigan[8]. The density profile used in the analysis is listed in Table 2. The atmospheric model provided by Atreya is for an equatorial profile and Juno project investigators are currently working on updating to a more accurate model for higher latitudes.

In addition to the ephemeris model, the gravity model, and the atmospheric model, solar radiation pressure (SRP) is modeled.

B. Spacecraft Model

The Juno spacecraft is modeled as a cube bus with a total area of 10 m^2. Early analyses included modeling the 45 m^2 solar panels, but was removed to make the results more conservative and to account for uncertainties in the spacecraft's final attitude and variations in the attitude. The coefficient of drag (C_D) of the spacecraft used in the analysis is 2.

Table 1. Jupiter Gravity Field.

	Value	Uncertainty (1-sigma)
J2 x 10^6	14696.430	0.21
J3 x 10^6	-0.640	0.90
J4 x 10^6	-587.140	1.68
J5 x 10^6	0.000	--
J6 x 10^6	34.250	5.22
C22 x 10^6	0.0065	0.0075
S22 x 10^6	-0.0125	0.0093

Table 2. Atreya Jupiter Atmospheric Model.

Altitude (km)	Density (kg/m³)	Altitude (km)	Density (kg/m³)	Altitude (km)	Density (kg/m³)
0	0.1460600	225	8.9002E-06	1300	3.8086E-14
10	0.1107900	250	3.6896E-06	1400	1.9854E-14
20	0.0791140	300	6.7526E-07	1500	1.1564E-14
30	0.0517170	400	2.8930E-08	1600	7.1506E-15
40	0.0312030	500	1.8464E-09	1700	4.4283E-15
50	0.0173380	600	2.0856E-10	1800	2.7466E-15
75	0.0041073	700	3.3508E-11	1900	1.7062E-15
100	0.0011373	800	6.9349E-12	2000	1.0615E-15
125	4.0106E-04	900	1.6590E-12	2500	1.0011E-16
150	1.4901E-04	1000	4.9975E-13	3000	9.6857E-18
175	5.5443E-05	1100	1.8524E-13	3500	9.6669E-19
200	2.1955E-05	1200	7.9521E-14	4000	9.9473E-20

C. Spacecraft State

The initial spacecraft state for each propagation is initiated from the apojove location. This is chosen because the rate-of-change of the spacecraft state at the apojove is much slower. Table 3 shows what happens to each apojove state if propagated for up to 150 years assuming no spacecraft state uncertainties or ephemeris uncertainties. Propagation was performed using DE414 and JUP230. Although a majority of the cases impact Jupiter within the 150 years, some do not. For example, if the spacecraft fails in Orbit 5 and cannot be recovered, then the spacecraft will remain in orbit around Jupiter for at least 150 years.

Spacecraft state uncertainties are provided by the navigation team mapped to the apojove locations. The main orbit determination estimates are dominated by the maneuver execution errors[9].

Every maneuver introduces a failure mode and Monte-Carlo simulations to estimate the impact probabilities are made at each of these modes. Orbits 2 to 31 have OTMs, thus, we perform an analysis at each of these orbits. For APO-0 two analyses are performed, one to account for the state uncertainties after JOI and another for the JOI cleanup maneuver which is performed 7 days after JOI. The final planned maneuver is the de-orbit maneuver and where the majority of the analyses was focused. It is also the de-orbit maneuver which ensures that Juno meets the planetary protection requirement.

Table 3. Deterministic Propagation of Apojove States to Determine Orbit Lifetime (maximum propagation duration of 150 years).

Orbit No.	Lifetime (years)	Impacted Body	Orbit No.	Lifetime (years)	Impacted Body
0	***150***	---	**17**	29	Jupiter
1	34	Jupiter	**18**	23	Jupiter
2	35	Jupiter	**19**	17	Jupiter
3	29	Jupiter	**20**	23	Jupiter
4	22	Jupiter	**21**	53	Jupiter
5	***150***	---	**22**	65	Jupiter
6	***150***	---	**23**	***150***	---
7	17	Jupiter	**24**	5	Jupiter
8	67	Jupiter	**25**	16	Jupiter
9	64	Jupiter	**26**	***150***	---
10	***150***	---	**27**	36	Jupiter
11	11	Jupiter	**28**	***150***	---
12	70	Jupiter	**29**	127	Jupiter
13	***150***	---	**30**	21	Jupiter
14	***150***	---	**31**	53	Jupiter
15	6	Jupiter	**32**	54	Jupiter
16	29	Jupiter	**33**	111	Jupiter

D. Failed De-Orbit Impact Results

Numerical simulations with 4000 samples were performed to estimate the impact probabilities with the Galilean satellites for the APO-33 state. Figure 5 shows the estimated impact and non-impacting probability results with Jupiter and the satellites for up to 300 years. Table 4 list the tabular results with the 2-σ uncertainties. From the figure and table we note that the requirement of an impact probability with Europa less than 1.5% after 150 years is met with a 95% confidence (2-σ) level. Impact results of being less than 5% after 150 years for Io, Ganymede, and Callisto are also met. The σ is computed assuming uncorrelated Poisson distribution of the impact results, and is a function of the Monte-Carlo sample size and the number of impacts. A sample size of 4000 was found to be large enough to provide consistent results for various Monte-Carlo runs and small enough for computation practicality.

The results on Fig. 5 and Table 4 are for a set of default assumptions which includes the Jupiter gravity field in Table 1 and its uncertainties, the Atreya atmospheric model, SRP, DE414 planetary ephemeris, and JUP100 satellite ephemeris and its uncertainties. Results are expected to vary based on variations in the models. Table 5 shows impact results for other assumptions in the models with the Atreya model as the baseline. We note that the variations in the results are small and all cases meet the planetary protection requirements.

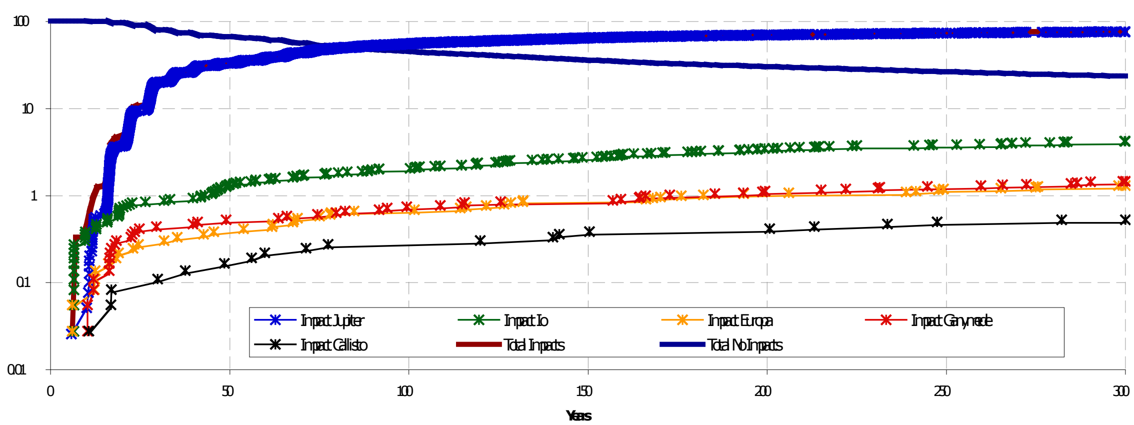

Figure 5. Impact and non-impact result if de-orbit fails with state propagated from APO-33 for up to 300 years.

E. Impact Results for All Orbits

In addition to just looking at impact probabilities for the de-orbit case a complete analysis was performed for all failure modes along the nominal mission while in orbit around Jupiter. Similar to the de-orbit case the sample sizes are 4000. Instead of providing the results for all failure modes this paper will only present the average results for all cases (Table 6) and the Europa impact results after 150 years (Fig. 6). The Europa impact requirement represents the most stringent requirement of less than 1.5% after 150 years. Table 6 shows that on average the impact results with the satellites meet the planetary protection requirements, with Io and Europa being the closest to violating. Figure 6 shows Europa impact results after 150 years for all the failure modes with the 2-σ uncertainty bars. Orbit 8 represents the highest impact probability while Orbits 0, 4, 24, and 30 have very low values of less than 0.2%. Note that Orbit 32 is not included because Orbit 33 is an extra orbit with no longitudinal science requirement and no maneuver is performed.

Table 4. Impact and non-impact results if de-orbit fails with state propagated from APO-33 for 50, 100, 150, and 300 years with 2-σ uncertainties.

	50 years	100 years	150 years	300 years
No Impacts	66.13% +/- 1.50%	44.78% +/- 1.58%	35.51% +/- 1.52%	23.26% +/- 1.34%
Jupiter Impacts	31.65% +/- 1.48%	51.81% +/- 1.59%	60.06% +/- 1.56%	69.91% +/- 1.46%
Io Impacts	1.23% +/- 0.35%	1.86% +/- 0.43%	2.52% +/- 0.50%	3.83% +/- 0.61%
Europa Impacts	0.35% +/- 0.19%	0.60% +/- 0.25%	0.81% +/- 0.28%	1.18% +/- 0.34%
Ganymede Impacts	0.48% +/- 0.22%	0.68% +/- 0.26%	0.78% +/- 0.28%	1.34% +/- 0.36%
Callisto Impacts	0.15% +/- 0.12%	0.25% +/- 0.16%	0.33% +/- 0.18%	0.48% +/- 0.22%

Table 5. Results if de-orbit fails with state propagated from APO-33 for 150 years for Various Models with 2-σ uncertainties.

	Atreya Atmosphere Model (baseline)	Edgington Atmosphere Model	No SRP Model	No Jupiter Atmosphere Model
Impacts Jupiter within 150 yrs	60.1% +/- 1.6%	60.0% +/- 1.6%	60.2% +/- 1.5%	59.2% +/- 1.6%
Impacts Io within 150 yrs	2.5% +/- 0.5%	2.9% +/- 0.5%	2.6% +/- 0.5%	2.7% +/- 0.5%
Impacts Europa within 150 yrs	0.8% +/- 0.3%	0.7% +/- 0.3%	0.8% +/- 0.3%	0.7% +/- 0.3%
Impacts Ganymede within 150 yrs	0.8% +/- 0.3%	0.8% +/- 0.3%	0.8% +/- 0.3%	1.1% +/- 0.3%
Impacts Callisto within 150 yrs	0.3% +/- 0.2%	0.2% +/- 0.1%	0.2% +/- 0.1%	0.1% +/- 0.1%
No Impacts within 150 yrs	35.5% +/- 1.5%	35.5% +/- 1.5%	35.4% +/- 1.5%	36.3% +/- 1.5%
	No Sampling of Jupiter Harmonics	**No Jupiter Satellite State Uncertainties**	**No Sampling of Jupiter Harmonics and Satellite State Uncertainties**	**No Sampling of Jupiter Harmonics, Satellite State Uncertainties, and no SRP**
Impacts Jupiter within 150 yrs	60.5% +/- 1.5%	61.3% +/- 1.5%	62.8% +/- 1.5%	61.6% +/- 1.5%
Impacts Io within 150 yrs	2.8% +/- 0.5%	2.8% +/- 0.5%	2.3% +/- 0.5%	2.2% +/- 0.5%
Impacts Europa within 150 yrs	0.6% +/- 0.2%	0.5% +/- 0.2%	0.6% +/- 0.2%	0.7% +/- 0.3%
Impacts Ganymede within 150 yrs	1.0% +/- 0.3%	0.8% +/- 0.3%	0.9% +/- 0.3%	0.7% +/- 0.3%
Impacts Callisto within 150 yrs	0.2% +/- 0.2%	0.3% +/- 0.2%	0.1% +/- 0.1%	0.3% +/- 0.2%
No Impacts within 150 yrs	35.0% +/- 1.5%	34.4% +/- 1.5%	33.3% +/- 1.5%	34.5% +/- 1.5%

Table 6. Average Results for All Failure Modes with 2-σ Uncertainties.

Event	% Occurrence
No Impacts	29.7% +/- 0.25%
Impact Jupiter	67.3% +/- 0.25%
Impacts Io	1.7% +/- 0.07%
Impacts Europa	0.5% +/- 0.04%
Impacts Ganymede	0.6% +/- 0.04%
Impacts Callisto	0.2% +/- 0.02%

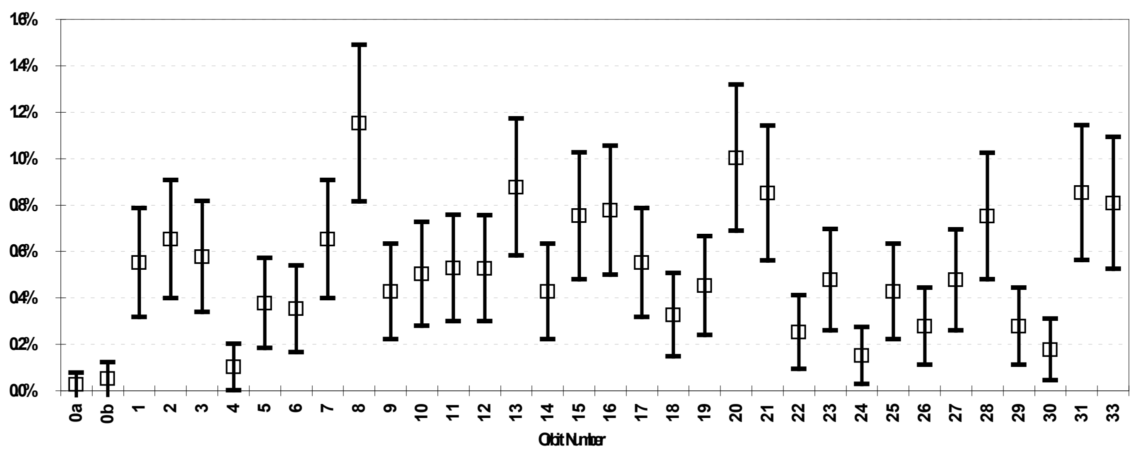

Figure 6. Europa Impact Results at Various Spacecraft Failure Modes with 2-σ Uncertainty Bars. Orbit 8 represents the highest impact probability while Orbits 0, 4, 24, and 30 have very low values.

V. Method of Reducing Impact Probabilities

Much of the work presented in this paper represents impact results of the Galilean satellites by post-analyzing a reference trajectory. Some analyses have been done to examine the potential of reducing the impact probability with the satellites by performing maneuvers on selected apoapses to keep the perijove altitudes low throughout the mission or by changing the inclination of the orbits.

A. Lowering Perijove Altitude

Analyses were performed to examine the potential of reducing the impact probability with the Galilean satellites by executing maneuvers on selected apoapses to keep the perijove altitude "low" throughout the mission. The altitude of 3100 km was set as the lower altitude bound which through an analysis not described here was deemed safe for Juno science instruments and for the spacecraft itself while accounting for altitude uncertainties, including atmospheric density and navigation uncertainties. The design strategy for such a mission is to space the apojove maneuvers far enough apart such that there is not too much operational complexity from the additional maneuvers, but frequently enough to keep the perijove altitude between 3100 km and 3500 km throughout much of the mission. Another desire is to keep each maneuver less than 10 m/s to use a vector mode maneuver implementation rather than one which includes precession maneuvers before and after the maneuver.

For this lower perijove-altitude profile the trajectories propagated without Monte Carlo treatment impacted Jupiter within 4 to 22 years, even without a de-orbit maneuver. See Table 7 for the deterministic impact time with Jupiter. On average, considering again all failure modes, the number of impacts with Jupiter increases to 89.2%, as compared to the 67.3% reported in Table 6. This increase in the number of impacts with Jupiter naturally decreases the number of potential impacts with the Galilean satellites.

Figure 7 shows the perijove-altitude profile of the lower-altitude trajectory with Europa impact probabilities for each of the failure modes. The altitude is kept at a range between 3100 km and 3500 km after Orbit 7 (when the minimum perijove altitude is reached). The letters after the orbit numbers on the x-axis of Fig. 7 are to account for the multiple failure modes in that orbit, e.g., results for Orbit 11 uses the state covariance assuming the OTM after PJ-11 failed and the results for Orbit 11a uses the covariance assuming that the apojove maneuver at APO-11 failed. Note that for Orbit 13, 14, 22, 25, 27a, and 28 to 33 there are no impacts with Europa after 150 years. In general, the impact percentages are significantly lower than the reference trajectory without apojove maneuvers; the maximum is 0.35% at Orbit 19 while the average is less than 0.1% for all cases. Apojove maneuvers, in addition to the APO-33 de-orbit maneuvers, are located on Orbit 0, 11, 18, 23, 27, and 31. Similarly, for the other satellites, the average impact occurrence or probability with Io is 0.4% while Ganymede and Callisto were 0.1%.

Although very promising for planetary protection, this trajectory option would require additional maneuvers, which would complicate activities during operations. Juno does not intend to utilize this strategy for further reducing impact probabilities; however, it is an option if a change to the reference trajectory causes Juno to not meet the requirement without such a strategy.

Table 7. Deterministic Propagation of Apojove States to Determine Orbit Lifetime for the Lower-Perijove Altitude Trajectory Case (maximum propagation duration of 150 years).

Orbit No.	Lifetime (years)	Impacted Body	Orbit No.	Lifetime (years)	Impacted Body
0	***150***	---	**17**	21	Jupiter
1	11	Jupiter	**18**	10	Jupiter
2	11	Jupiter	**19**	10	Jupiter
3	11	Jupiter	**20**	16	Jupiter
4	16	Jupiter	**21**	16	Jupiter
5	15	Jupiter	**22**	5	Jupiter
6	11	Jupiter	**23**	10	Jupiter
7	11	Jupiter	**24**	7	Jupiter
8	5	Jupiter	**25**	4	Jupiter
9	11	Jupiter	**26**	4	Jupiter
10	11	Jupiter	**27**	4	Jupiter
11	11	Jupiter	**28**	4	Jupiter
12	11	Jupiter	**29**	4	Jupiter
13	16	Jupiter	**30**	4	Jupiter
14	11	Jupiter	**31**	4	Jupiter
15	22	Jupiter	**32**	4	Jupiter
16	11	Jupiter	**33**	4	Jupiter

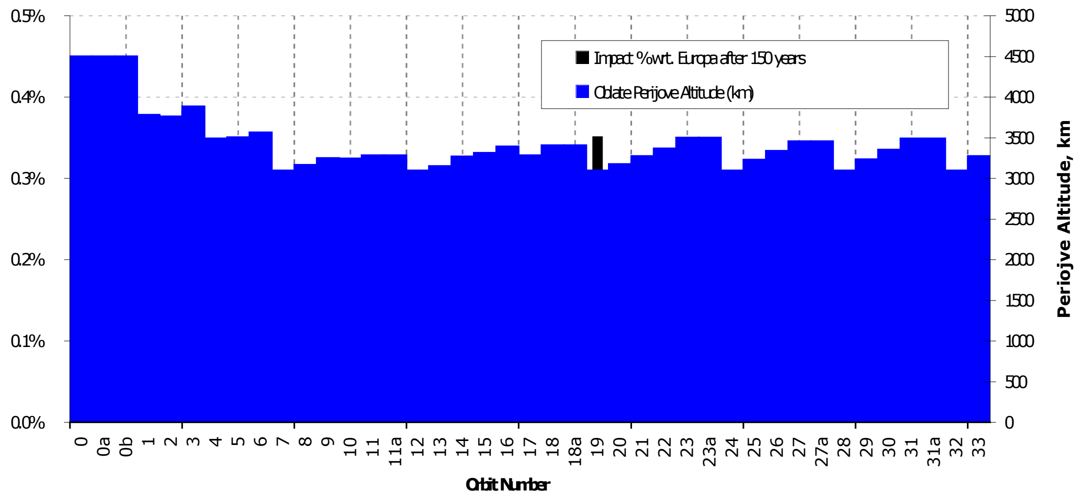

Figure 7. Europa Impact Results at Various Spacecraft Failure Modes for the Lower Altitude Trajectory with Perijove Altitude Profile. Apojove maneuvers are located on Orbits 0, 11, 18, 23, 27, and 31, in addition to the de-orbit maneuver.

B. Other Inclinations

The effects of orbital inclinations on the impact probability results has also been investigated. End-to-end trajectories with initial inclinations of 85° and 95° were created and impact results were investigated for the failed de-orbit case. The new trajectories were created in a similar way as the baseline mission: the launch date, DSM, JOI, and PRM dates are identical. Targeted longitudes at equatorial crossings were also the same. A full-up navigation analysis was not performed for these cases and as a result the same state uncertainties used for the baseline reference mission for APO-33 was assumed here.

An initial inclination of 95° is found to greatly reduce the number of impacts with the Galilean satellites. The trajectory naturally impacts Jupiter in 5.5 years when propagated from APO-33 without a de-orbit maneuver. For the 85° case the differences in the impact results with the Galilean satellites was minor compared to the baseline mission. See Table 8 for a short comparison of the impact results and overall mission ΔV between the baseline mission (90° initial inclination), the lower altitude case describe in the subsection above, and the 85° and 95° cases. From Table 8 it is clear that both the lower altitude case and the 95° inclination case have significantly low impact probabilities with the Galilean satellites, which seems to be absorbed by Jupiter. Although the results of the 95° case does not offer zero percent impacts with Europa (or Io), it does offer a simpler operational plan than the lower altitude case because it does not require any additional maneuvers. At this time the Juno project does not plan to utilize an orbit profile with any inclination other than 90°.

Table 8. Statistical Impact Results and Total Mission Delta-V Results if De-Orbit Fails Propagated from APO-33 for 150 years for Various Trajectory Cases with 2-σ uncertainties.

	Reference Trajectory	Low Altitude Case	85 Deg Inclination Case	95 Deg Inclination Case
Initial Inclination (deg)	**90**	**90**	**85**	**95**
Impact Probability (Apo-33)				
Jupiter	60.1% +/- 1.6%	100%	49.3% +/-1.6%	99.9% +/- 0.1%
Io	2.5% +/- 0.5%	0%	3.1% +/- 0.5%	0.08% +/- 0.09%
Europa	0.8% +/- 0.3%	0%	0.8% +/- 0.3%	0.05% +/- 0.07%
Ganymede	0.8% +/- 0.3%	0%	0.6% +/- 0.2%	0%
Callisto	0.3% +/- 0.2%	0%	0.5% +/- 0.2%	0%
Total Mission Delta-V (m/s)	1962.6	1960.3	1959.9	1960.5

VI. Conclusion

The baseline reference mission meets planetary protection requirements as stated by the Juno project for impact probabilities with the Galilean satellites. Methods of reducing the impact probabilities such as reducing the perijove altitude or changing the orbit inclination have been shown to greatly reduce the impact probabilities. These are options that Juno could pursue if necessary due to a change to the reference trajectory.

Acknowledgments

The authors would like to thank Stuart Stephens for use of his figures. Dennis Byrnes and Doug Bernard have provided valuable guidance for the analysis process. The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] Kowalkowski, T. D., Johannesen, J. R., and Lam, T., "Launch Period Development of the Juno Mission to Jupiter," *AIAA/AAS Astrodynamics Specialist Conference*, AIAA-2008-7368, Aug. 2008.

[2] NASA Memo D-38972 from NASA Planetary Protection Officer Dr. C. Conley to Dr. R. Grammier regarding Juno Planetary Protection Categorization, Dec. 28, 2006.

[3] "Juno Planetary Protection Plan", L. E. Newlin, Initial Release, JPL D-34003, Apr. 9, 2008.

[4] "JPL Planetary Ephemeris DE414", E.M. Standish, IOM 343R-06-002, Apr. 21, 2006.

[5] Jacobson, R. A., 2003, JUP230 orbit solution, ftp://ssd.jpl.nasa.gov/pub/eph/satellites/nio/jup230.long.txt.

[6] Jacobson, R. A., 2003, JUP100 orbit solution, ftp://ssd.jpl.nasa.gov/pub/eph/satellites/nio/jup100.txt.

[7] Lieske, J. H., "Galilean satellite ephemeredes E5," Astronomy and Asrophysics Supplements, Vol. 129, pp. 205-217, 1998.

[8] Personal conversation

[9] "Juno Navigation Plan", J. Bordi, Preliminary Release, JPL D-35557, Mar. 24, 2008.