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Numerical Investigation of Mapping Orbits about Jupiter's Icy Moons

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A proposed mission that would orbit Callisto, Ganymede, and Europa will require low altitude, high inclination orbits for gravity and surface mapping. The inherent instability of these orbits poses a particular challenge to gravity field mapping which requires tracking of a spacecraft unperturbed by orbit maintenance maneuvers. Analytical investigations identify conditions that allow for an uncontrolled orbit over the time scales necessary for gravity mapping, yet these are typically obtained via a Hill model with various approximations to the force models. This paper explores the dynamics of these orbits by direct propagation against an ephemeris model. Initial conditions within the context of a mapping mission's likely requirements are considered. The results complement the analytical studies and reveal additional dependencies.

INTRODUCTION

A mission that would orbit the three icy moons of Jupiter—Callisto, Ganymede, and Europa—is considering low altitude (~100 km altitude), high inclination "science orbits" about each of these moons. Upon achieving a science orbit the first goal would be to obtain a map of the gravity field of the satellite. Tracking of the spacecraft over the course of one full revolution about Jupiter can provide this with good certainty as long as the spacecraft is not performing any propulsive maneuvers. It is therefore desirable to identify the existence of orbits that require little or no maintenance for at least the duration of a Jupiter revolution.

The issue of identifying such orbits has been addressed in recent years by analytical studies[1-7] which have typically approached the problem via approximations of the physical system. The Hill approximation to the circular restricted three-body problem is

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usually invoked with force models averaged over either the orbit of the spacecraft about the satellite, the orbit of the satellite about Jupiter, or both. When the resultant potential from the averaged system is used in the Lagrange Planetary equations it is possible to obtain solutions describing frozen orbits[2], i.e., orbits for which the semi-major axis, eccentricity, inclination, and argument of periapsis are on average constant.

To gain a better understanding of the behavior of these frozen orbits over time direct integrations against an ephemeris model were performed. These integrations were extended to explore the specific range of orbital elements consistent with icy moon orbiter mission requirements.

The resulting "Time-to-Impact" plots offer mission designers an alternative perspective on the stability of a planetary satellite orbiter. They serve as a set of nomographs for the direct selection of desirable orbits via classical elements. As applied here they indicate that low-altitude orbits may exist which could satisfy mission objectives. Additionally they serve as an ephemeris-based reference with which to compare analytical results.

DESCRIPTION OF INTEGRATIONS

The integrations were conducted within the framework of JPL's Guidance, Control and Navigation section's new MONTE software system[8] which employs the DIVA integrator.[9] JUP100[10] (formerly referred to as E5) served as the ephemeris of the Jupiter system and DE405[11] was used as the ephemeris for the sun and planets. Initial states for science orbits are propagated in the satellite-centered inertial frames as defined in Ref.12.

Jupiter's gravity is represented via J_2, J_4 and J_6 zonal harmonics. The gravitational fields for Callisto, Ganymede, and Europa are problematic. Reconstructed Galileo trajectories do not yield any reliable gravitational harmonic terms for the Jovian moons above degree two. Most of the plots presented here were created with degree two coefficients only (see Appendix). The issue of modeling degree three coefficients is discussed below.

Solar radiation pressure was modeled but proved a negligible effect. No atmospheric drag was considered.

The initial states for the orbiter spacecraft were specified in classical orbital elements:

- Range at periapsis, r_p
- Eccentricity, e
- Inclination, i
- Argument of periapsis, ω
- Longitude of the ascending node, Ω
- True anomaly, ν

The integrations are run in sets. Each set samples a range of values for two specific elements of the initial state. For example a set of plots for eccentricity vs. the argument of periapsis (*e -ω)* samples a range of *e* values for a given ω. This is repeated over a range of values for *ω*—each pair of *e, ω* yielding a corresponding time-to-impact value. During each separate integration of an *e, ω* pair the initial values for r_p, *i,* Ω, are constant. The result is a three dimensional data set of (*e,ω*, time).

Two types of sets are chosen for presentation here:

- Eccentricity vs. Longitude of the Ascending Node (*e* vs Ω)
- Inclination vs. Argument of Periapsis. (*i - ω)*

Eccentricity vs. Longitude of the Ascending Node (*e* vs Ω)

Figures 2-4, and 6-8 are illustrative of *e* vs Ω plots. Initial values for eccentricity are considered in a range from 0.0001 to 0.07, and initial values for the longitude of the ascending node are sampled in five degree increments from 0º to 360º. Each plot is distinguished by an initial inclination. Argument of periapsis is chosen as +90º, per Ref.7.

Figures 2, 3, and 4 present *e* vs Ω plots for Callisto, Ganymede and Europa respectively. Ref. 12), the results are plotted in a rotating frame illustrated in Figure 1 for ease of Although the integrations are carried out in a body-centered inertial frame (defined in

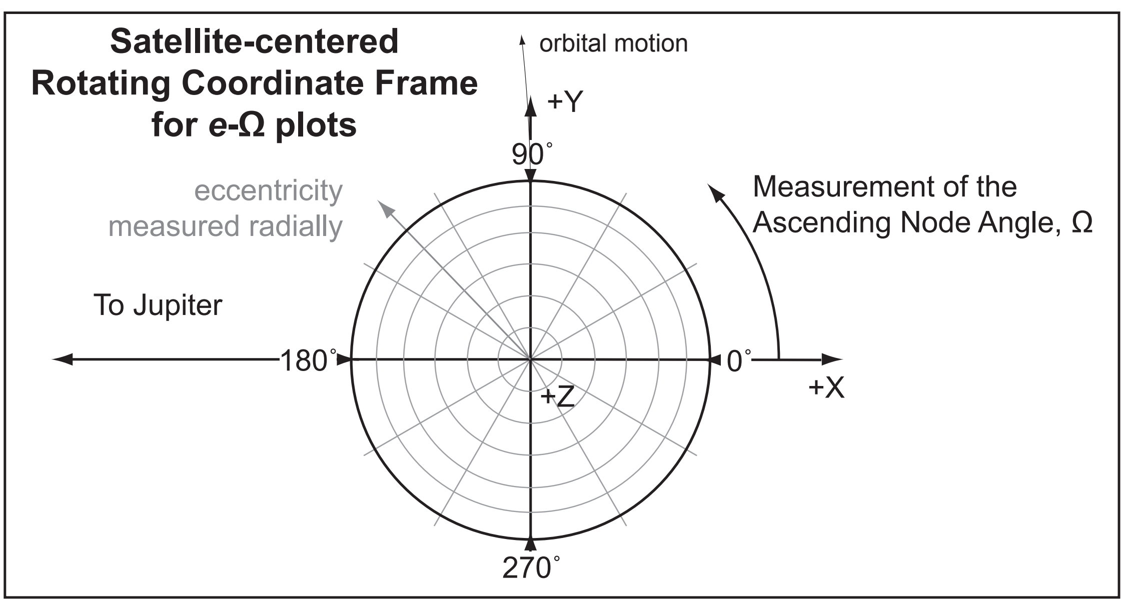
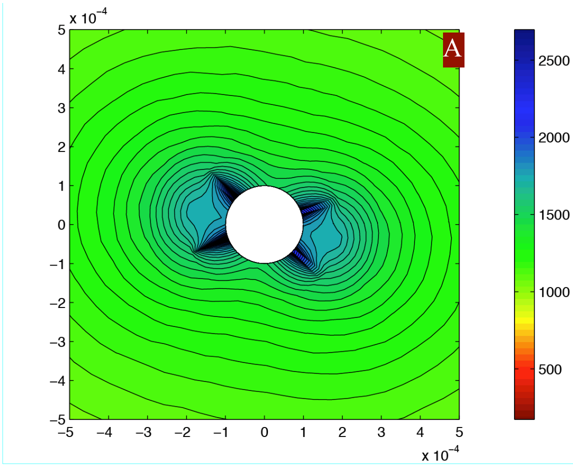
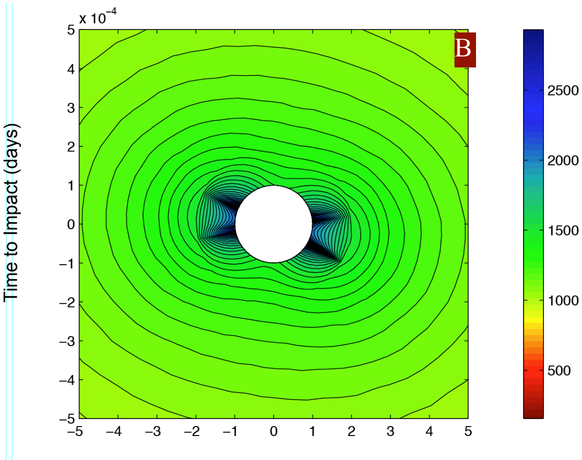


Figure 1. Synodic Frame for reading *e* vs Ω plots (Figures 2, 3, 4, 6, 7, 8).

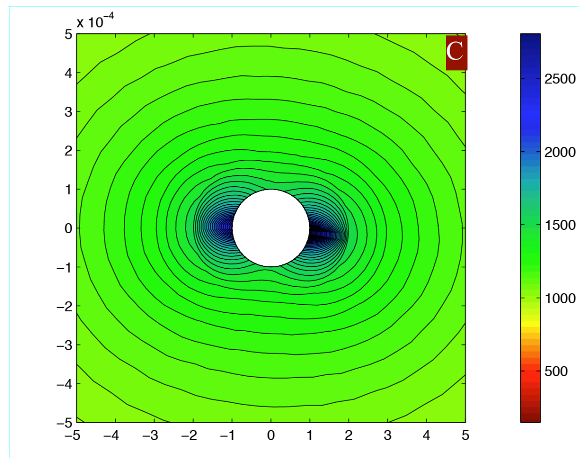


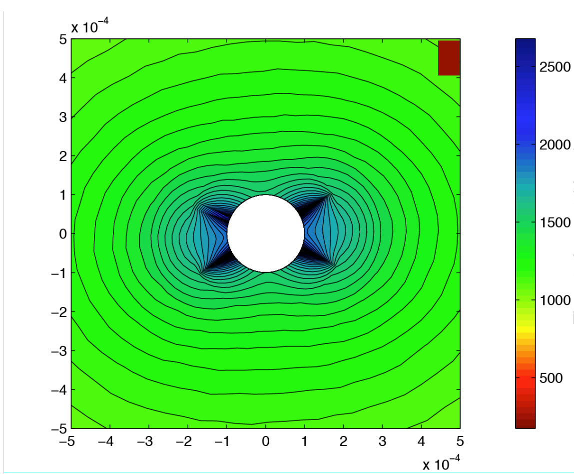


Clockwise from upper left, *e* vs Ω plots for an orbiter about Callisto.

A: 70º initial inclination.
B: 80º initial inclination
C: 90º initial inclination
D: 100º initial inclination
E: 110º initial inclination

Degree two gravity for Callisto.





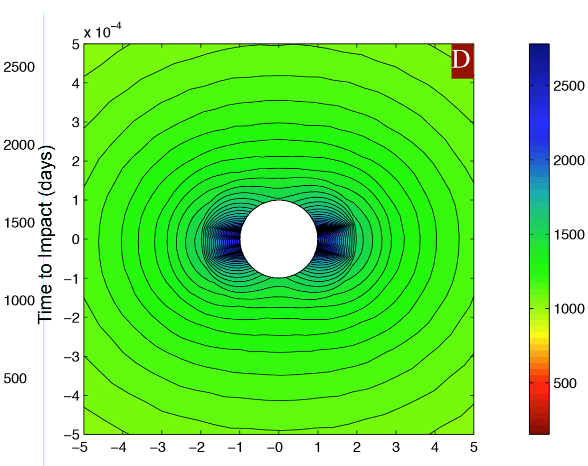
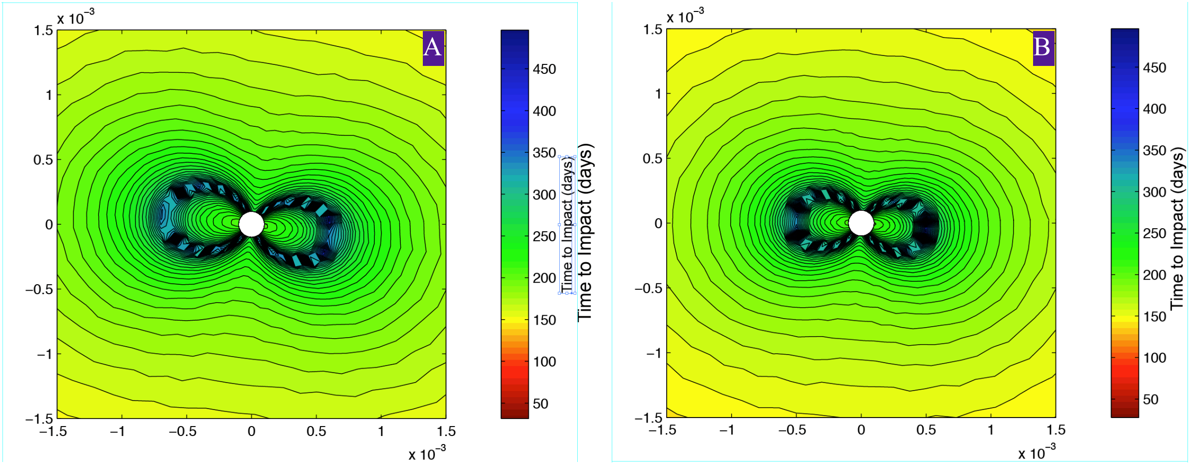


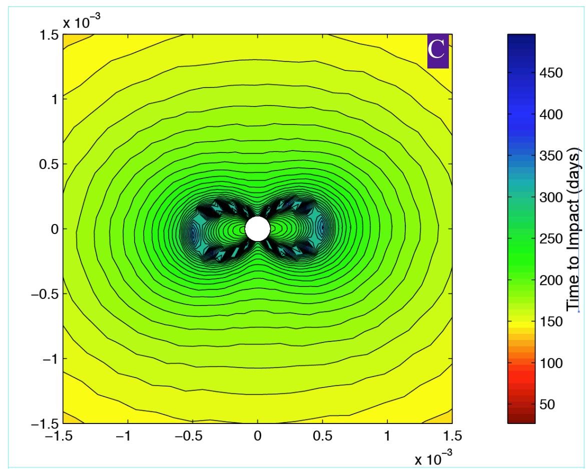
Figure 2. Callisto: Eccentricity vs. Longitude of Ascending Node. Eccentricity 0.0001 to .0005. 2nd degree gravity harmonics only. Days to Impact on color bar scale. Refer to Figure 1 for the



Clockwise from upper left, *e* vs Ω plots for an orbiter about Ganymede.

A: 70º initial inclination.
B: 80º initial inclination
C: 90º initial inclination
D: 100º initial inclination
E: 110º initial inclination

Degree two gravity for Ganymede.



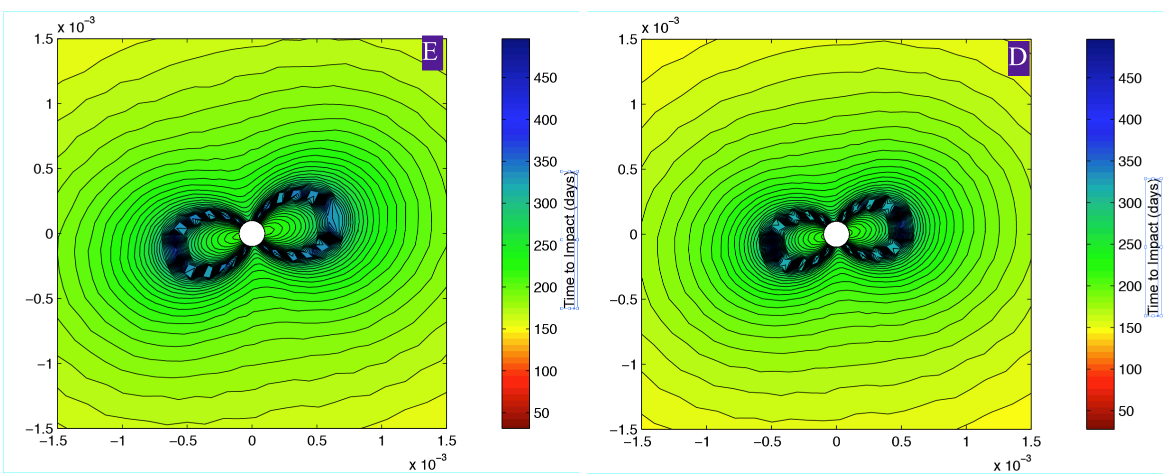
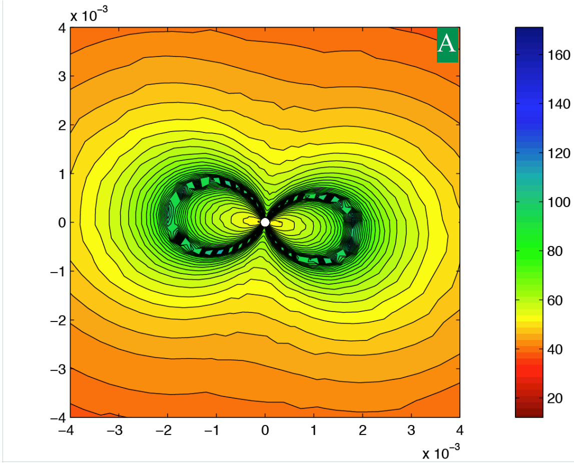
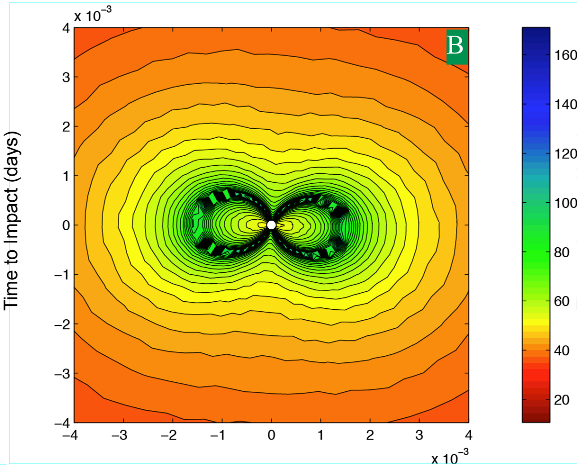


Figure 3. Ganymede: Eccentricity vs. Longitude of Ascending Node.
Eccentricity 0.0001 to .003. 2nd degree gravity harmonics only. Days to Impact on color bar scale.

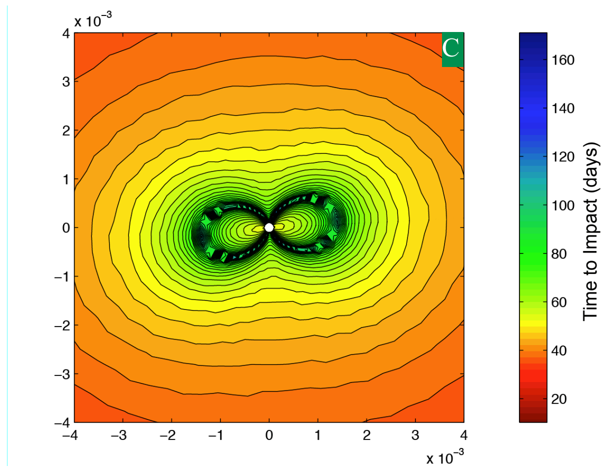


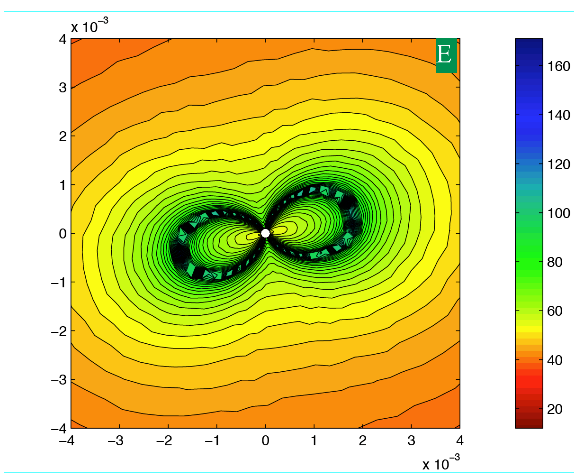


Clockwise from upper left, *e* vs Ω plots for an orbiter about Europa.

A: 70º initial inclination.
B: 80º initial inclination
C: 90º initial inclination
D: 100º initial inclination
E: 110º initial

Degree two gravity for Europa.





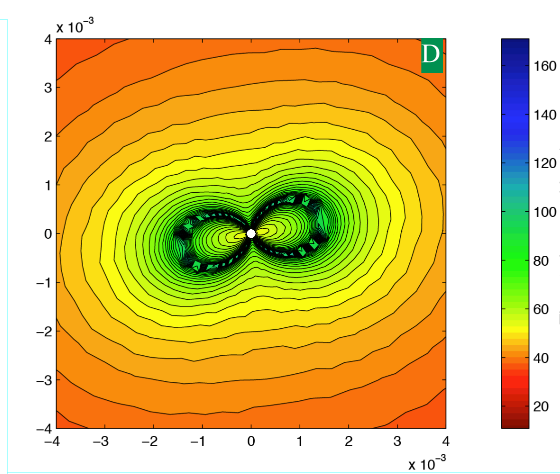


Figure 4. Europa: Eccentricity vs. Longitude of Ascending Node.
Eccentricity 0.0001 to 0.004. 2nd degree gravity harmonics only. Days to Impact on color bar scale.

comparison with analytic results. Eccentricity is measured radially and can be referenced against the tick marks on the axes. Time-to-impact is indicated via the vertical color bar scale. Only degree two gravity harmonics are modeled here. For the mission under consideration the desired science orbit durations at Callisto, Ganymede, and Europa are 120, 120, and 30 days respectively. These durations appear to be easily exceeded at Callisto and Ganymede for most all ascending nodes if the initial eccentricity is low. As would be expected at Callisto, the furthest of the three satellites from Jupiter, the lifetimes are substantially longer.

Most notably these e vs Ω plots indicate a dependency on the initial value of the longitude of the ascending node. The regions of maximum lifetime appear centered around two "preferred" node angles approximately 180º apart which in turn are dependent on the initial inclination.

When the degree two gravity harmonics are replaced with a point mass the 90º inclinations plots are aligned along the x-axis of the rotating frame.generated

For Callisto and Ganymede the highest durations at the preferred nodes are confined to low eccentricities, while for Europa the longer durations are more clearly defined tracing out a sort of figure eight shape aligned along the preferred node angles. It should be noted that for each inclination the results are invariant in time.

Inclination vs. Argument of Periapsis. (*i* vs *ω*)

The *i* vs *ω* plots (Figures 5) consider initial inclinations from 70º to 110º, while argument of periapsis is sampled in five degree increments from 0º to 360º. Each is distinguished by an initial eccentricity and an initial longitude of the ascending node. As *ω* varies, the true anomaly is adjusted so as to place the initial state in the plane of the central body's equator.

Figures 5 presents a sequence of *i* vs *ω* plots for the case of a Europa orbit with an initial eccentricity fixed at 0.001. Each plot in the sequence was generated with a different initial value for the longitude of the ascending node and the images on the right offer a reference to that value on the *e* vs Ω plots. A magnified section of the 100º inclination plot (Figure 4D) is arbitrarily chosen as the reference. The blue circle marks the position of $e = 0.001$. Starting at Ω=0º inside the figure eight ridge a yellow elliptical region of lifetimes ~ 90 days appears a slight bias to the lower values of *ω* centered around i=90º. As the value for the initial ascending node increases approaching the ridge of the figure eight (ref. right side of Figure 5) the yellow region is seen moving lower in inclination and increasing in duration. In Figure 5D at Ω = 25º the elliptical feature has developed a bounding ridge with peaks exceeding 150 days. As Ω crosses the figure eight on the right the ridge around the elliptical region on the left rapidly extends across the unstable range of inclinations and widens in the ω-axis.

Figure 5 can be seen as an extension of the plot first presented in Figure 9 of Ref.1.

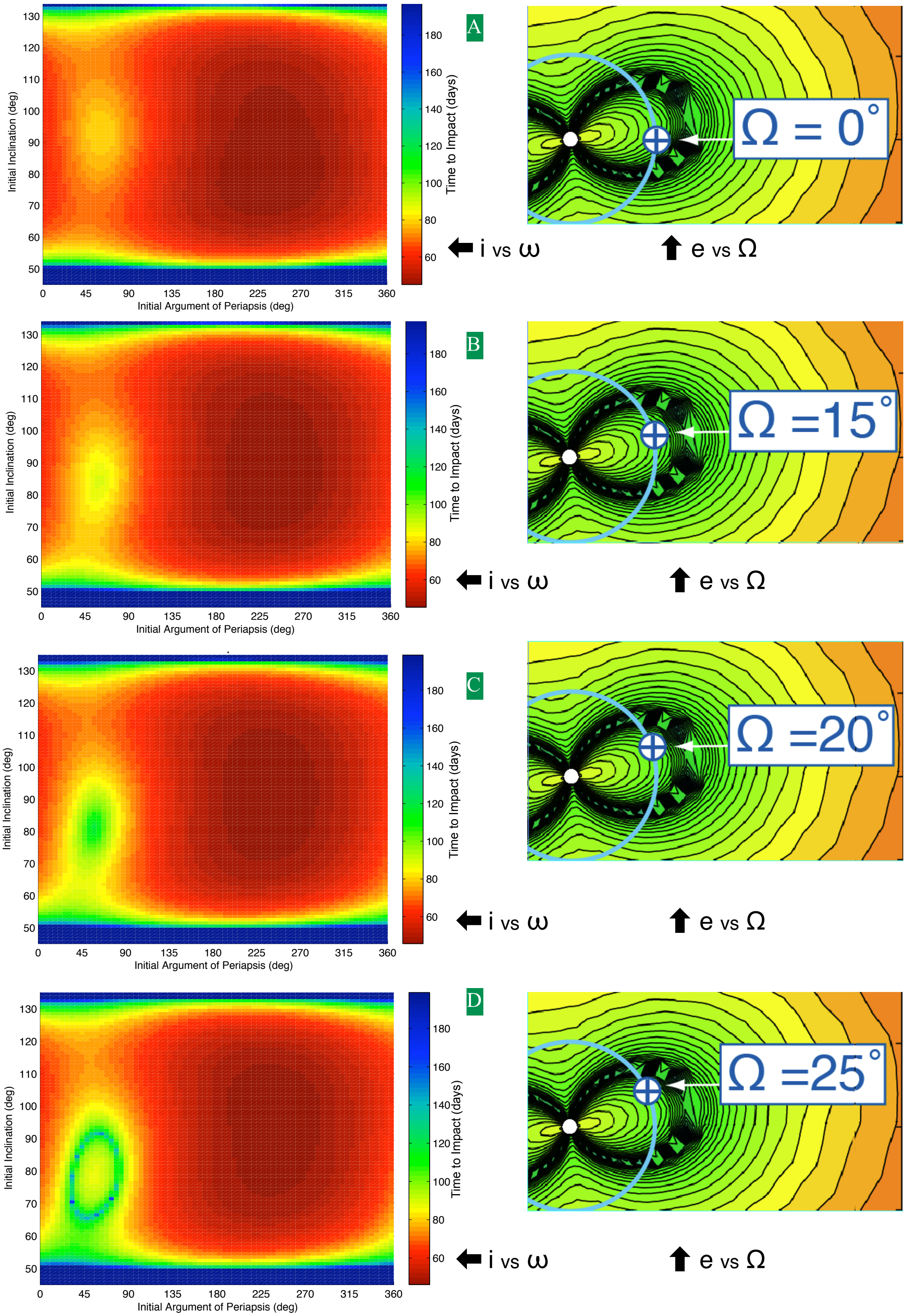


Figure 5. Initial Inclination vs Initial Argument of Periapsis for Europa orbit. e = 0.001. [Note the instability region instability extending between inclinations of 45 and 135 degrees as described in Ref. 1.]

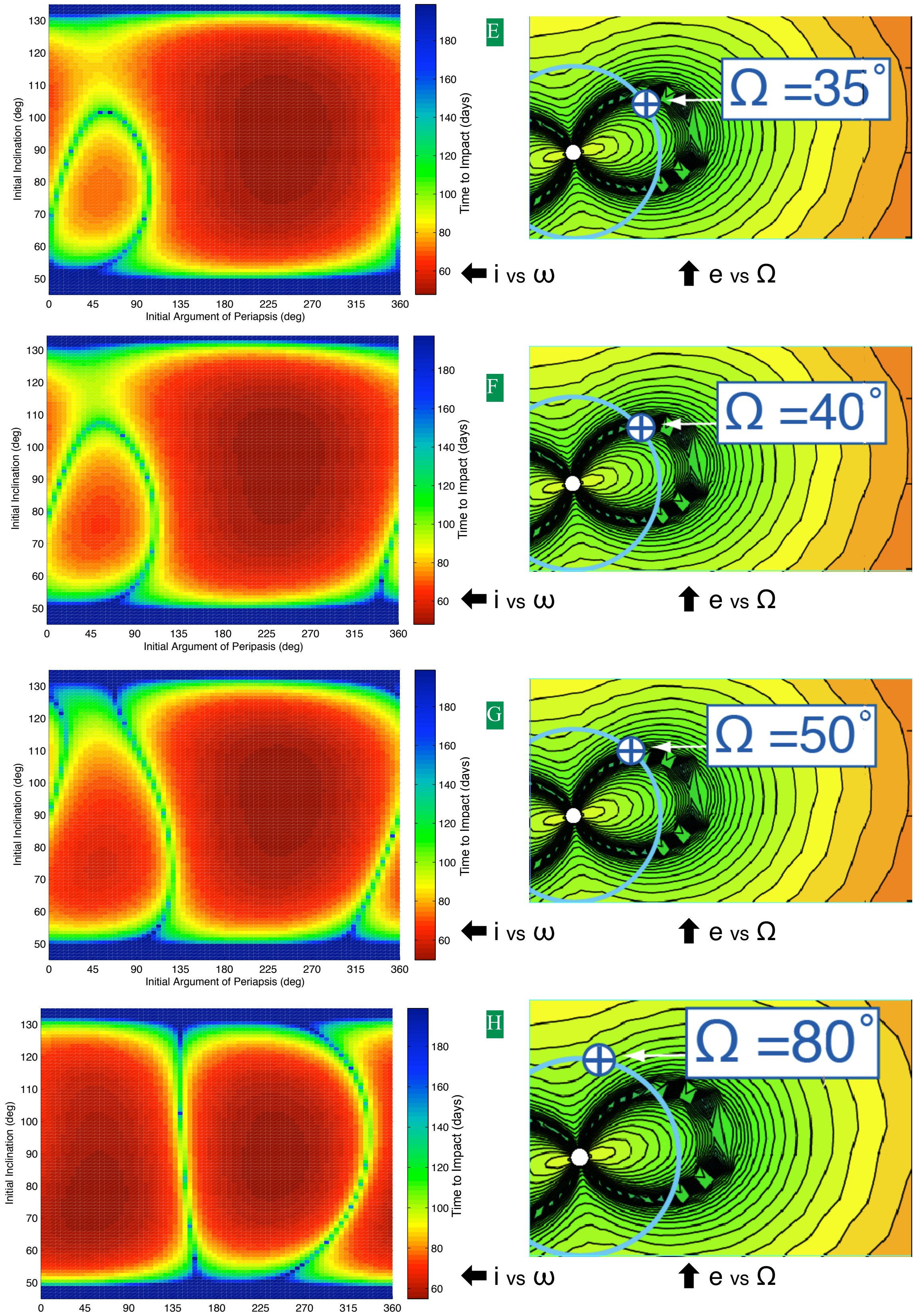


Figure 5 (cont.). Initial Inclination vs Initial Argument of Periapsis for Europa orbit. e = 0.001. [Note the instability region instability extending between inclinations of 45 and 135 degrees as described in Ref. 1.]

IMPLICATIONS OF HIGHER GRAVITY TERMS

As mentioned earlier, the harmonic coefficients describing the gravitational fields of Callisto, Ganymede, and Europa are essentially unknown above degree two–hence the high priority on gravity mapping! The spacecraft under consideration will be determining these these terms “on-the-fly” as it spirals down to a science orbit. To explore the possibilites of what might be encountered in actual gravitational fields two cases of degree three terms were postulated. For Europa William Moore of the Department of Earth and Space Sciences at UCLA has suggested[13] using the Moon and Venus as models to represent two bounding cases on the gravity field. Third degree harmonic coefficients were devised via the Kaula rule[14.] In Case 1 a “Moon-like” field is represented by scaling the Moon’s degree three set of coefficients to Europa’s degree two. Similarly Case 2 scales the Venus degree-three set of coefficients to Europa’s degree two to represent a “Venus-like” field. Analagous sets of degree three coefficients were created for Callisto and Ganymede mostly as an exercise. The appropriateness of using the same bounding cases for Callisto and Ganymede has yet to be addressed. Values for the individual coefficients are listed in the Appendix.

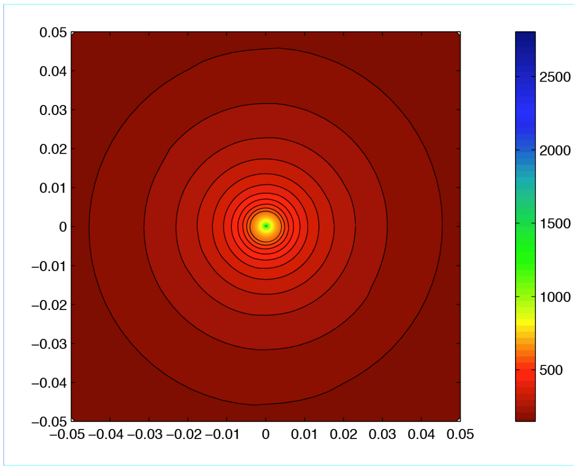
The two degree-three cases are compared with a degree-two only field for a 90º inclination orbit at Callisto, Ganymede, and Europa in Figures 6, 7, and 8. The scale of the plots for each satellite are kept equal for ease of comparison.

Callisto shows that 120 day lifetimes still appear possible in both Case 1 and Case 2 via an increase in the initial eccentricity.

Durations of 120 days are difficult to meet in the Case 1 model at Ganymede and in Case 2 lifetimes of no more than 30 days are found.

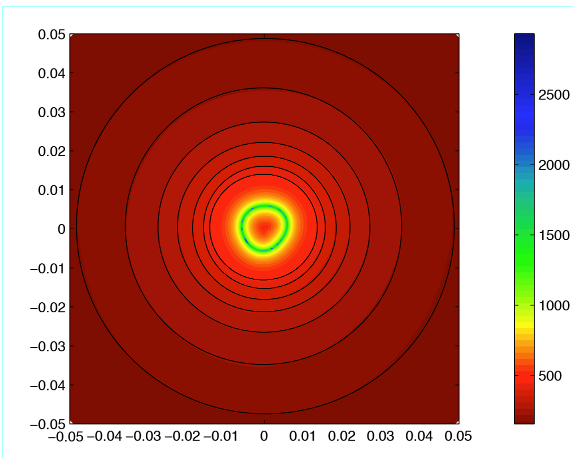
For Europa the asymmetry of the Case 1 terms and the proximity of Jupiter do not allow for orbits longer than a few days. Hopefully the actual gravity field of Europa will turn out to be a great deal more friendly! The Case 2 model showed possibilities in a range of node angles centered around either 90º or 270º with a significantly increased eccentricity of ~0.05.

Further attempts to define gravity models that could more closely approximate the actual fields that will be encountered at Callisto, Ganymede, and Europa could be prove useful.



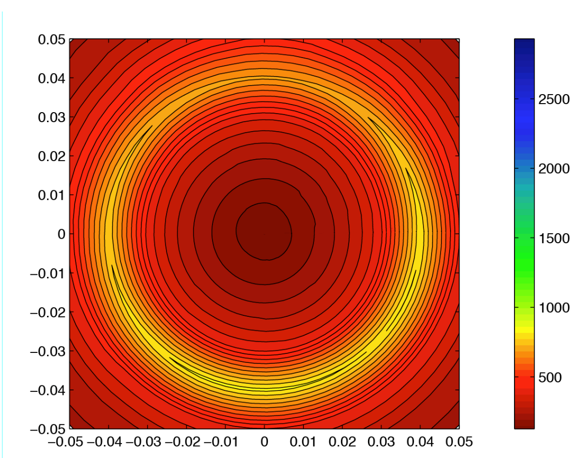
Eccentricity vs Longitude of Ascending Node
Ref. Figure 1.

Callisto: 2nd degree gravity field only no 3rd degree terms.
Lifetimes in excess of 120 days possible at low eccentricities.



Callisto: 3rd degree gravity field--Case 1

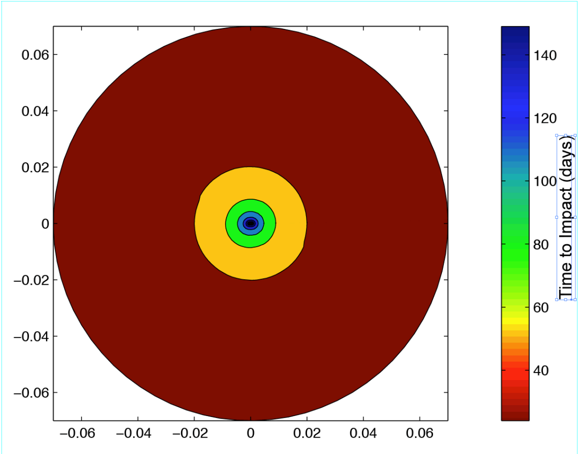
Lifetimes in excess of 120 days possible with ring of increased eccentricity ~0.006.



Callisto: 3rd degree gravity field--Case 2

Lifetimes in excess of 120 days possible within ring of increased eccentricity ~.04.

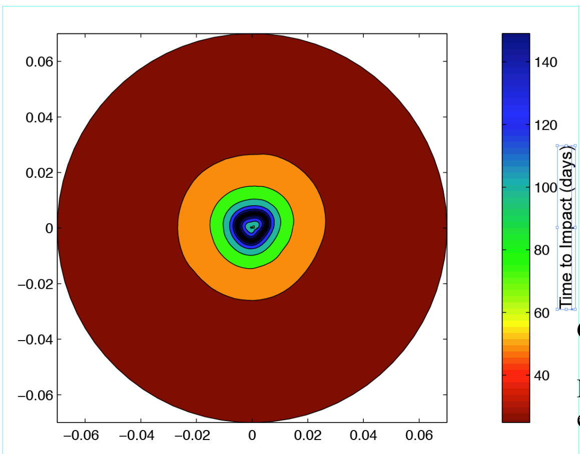
Figure 6. Comparison of degree 2 with degree 3 “test cases” for Callisto.



Eccentricity vs Longitude of Ascending Node Ref. Figure 1.

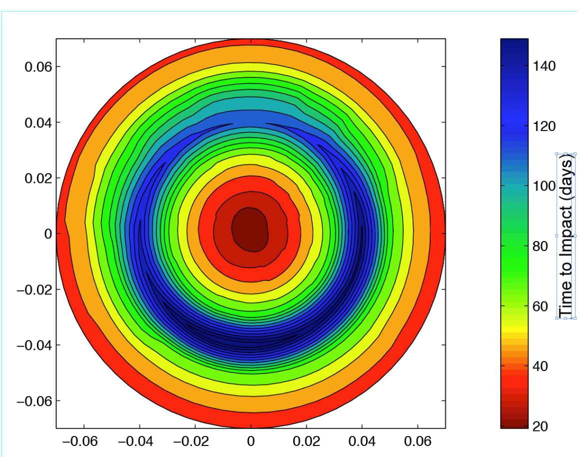
Ganymede: 2nd degree gravity field only no 3rd degree terms.

Lifetimes in excess of 120 days possible at eccentricities < 0.005



Ganymede: 3rd degree gravity field--Case 1

Lifetimes in excess of 120 days possible within eccentricity ~0.01.

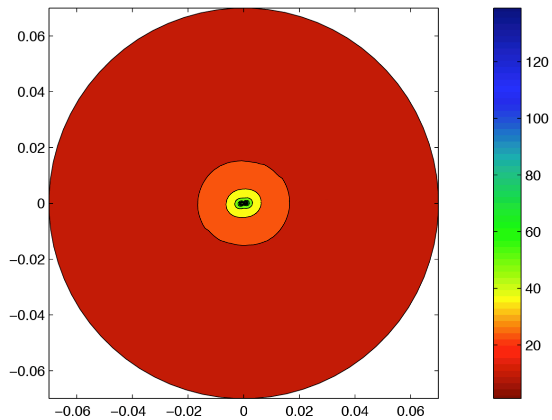


Ganymede: 3rd degree gravity field--Case 2

Lifetimes in excess of 120 days possible within eccentricity ~0.02 - 0.04.

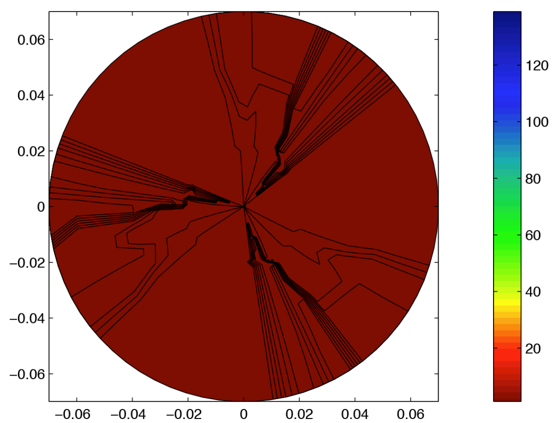
Figure 7. Comparison of degree 2 with degree 3 “test cases” for Ganymede.

Eccentricity vs Longitude of Ascending Node
Ref. Figure 1.



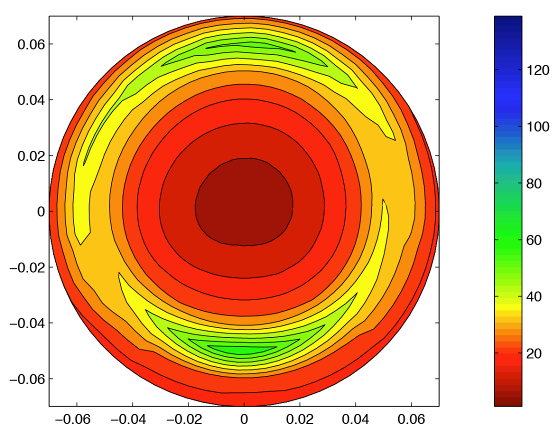
Europa: 2nd degree gravity field only no 3rd degree terms.

Compare with Figure 4C.



Europa: 3rd degree gravity field--Case 1

Time-to-impact 2 days or less.



Europa: 3rd degree gravity field--Case 2

30 day lifetimes e~0.05 and Ω ~90º, 270º

Figure 8.. Comparison of degree 2 with degree 3 “test cases” for Europa.

SUMMARY

Integrations against the ephemeris model using degree-two gravity harmonics for Callisto, Ganymede, and Europa, show specific initial states which appear stable over timeframes sufficient to satisfy mission requirements. When the gravity harmonics are expanded to include degree-three terms there are significantly different results. A means for determining the higher degree gravity harmonic terms prior to entering low-altitude high inclination orbits about these satellites needs to be identified.

ACKNOWLEDGEMENTS

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Appendix

Body specific parameters used in integrations.

Jupiter	
Equatorial radius	7.149200e+04 km
Polar radius	6.685400e+04 km
GM	1.266865378578105e+08 km^3/s^2
J_2	0.1469629738666062e-01
J_3	0.4467438166350921e-06
J_4	-0.5851427540117961e-03
J_5	0.0
J_6	0.2545010200575446e-04

* all coefficients normalized

Callisto	
Mean radius	2410.3 km
GM	7180.998 km^3/s^2
J_2 = 1.5456884E-05	
C_{21} = 6.28961381E-11	S_{21} -6.15200781E-10
C_{22} = 1.6808453E-05	S_{22} = -3.8976299E-06
J_3 = -7.574214E-07	Case 1
C_{31} = 6.28234E-06	S_{31} = 1.2928E-06
C_{32} = 3.39149E-06	S_{32} = 1.15942E-06
C_{33} = 2.93034E-06	S_{33} = -4.19264E-07
J_3 =-6.889484E-06	Case 2
C_{31} =2.030384E-05	S_{31} = 4.683017E-06
C_{32} =-7.379735E-08	S_{32} = 6.995284E-06
C_{33} =-1.625648E-06	S_{33} = 1.845828E-06

* all coefficients normalized

Ganymede	
Mean radius	2631.2 km
GM	9886.997 km^3/s^2
J_2 = 6.1436994E-05	
C_{21} =-1.2609304E-09	S_{21} = -8.9348783E-07
C_{22} =6.3943452E-05	S_{22} = -4.2976732E-06
J_3 = -2.9029E-06	Case 1
C_{31} = 2.40778E-05	S_{31} = 4.95479E-06
C_{32} = 1.29983E-05	S_{32} = 4.44362E-06
C_{33} = 1.12309E-05	S_{33} = -1.60688E-06
J_3 = -3.289356E-05	Case 2
C_{31} = 9.693988E-05	S_{31} = 2.235888E-05
C_{32} = -3.523425E-07	S_{32} = 3.339870E-05
C_{33} = -7.761589E-06	S_{33} = 8.812833E-06

* all coefficients normalized

Europa	
Mean radius	1565 km
GM	3201.0 km^3/s^2
J_2 = 1.904852E-04	
C_{21} = 1.108349E-07	S_{21} = 6.512434E-06
C_{22} = 1.993307E-04	S_{22} = -3.031719E-06
J_3 = -1.27497E-05	Case 1
C_{31} = 1.05751E-04	S_{31} = 2.17617E-05
C_{32} = 5.7089E-05	S_{32} = 1.95166E-05
C_{33} = 4.93265-05	S_{33} = -7.05749E-06
J_3 =-1.444702E-04	Case 2
C_{31} = 4.257648E-04	S_{31} = 9.820130E-05
C_{32} = -1.547506E-06	S_{32} = 1.146689E-06
C_{33} = -3.408929E-05	S_{33} = 3.408929E-05

* all coefficients normalized

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