Planetary Protection Trajectory Analysis for the Juno Mission

AIAA Paper 2008-7368 (CL#08-2751)

Try Lam
Jennie R. Johannesen
Theresa D. Kowalkowski

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

21 August 2008

AIAA/AAS Astrodynamics Specialist Conference, Hawaii Convention Center and Hilton Hawaiian Village, Honolulu, Hawaii, 18-21 August 2008
Mission Overview

• Juno is an orbiter mission expected to launch in August 2011 (subject to receiving NASA approval for NEPA compliance)
• Uses a ΔV-EGA (2+) trajectory to reach Jupiter with arrival in August 2016
• Perform a Jupiter Orbit Insertion maneuver to capture into a 78-day orbit
• Perform a Period Reduction maneuver to reduce the orbit period down to 11 days
• Juno has a nominal science duration of 1 year at Jupiter and will perform detailed gravity measurements and explore the Jovian atmosphere and magnetosphere with a science goal of understanding Jupiter’s origin and evolution.
• Juno requires a polar, highly elliptical orbit with very low perijove altitudes (roughly 4500 km altitude) and equally spaced longitude values at equator crossings.
Planetary Protection Concerns

- Initially, the equatorial crossing near apojove 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 and cross the orbits of the Galilean satellites (Io, Europa, Ganymede, and Callisto).
- Potential impacts with the Galilean satellites may occur at these intersections (and may also be perturbed substantially by the flybys)
- Note: the nominal mission has **NO** close flybys with the Galilean satellites
Planetary Protection Concerns II

- To avoid potential impacts with the Galilean satellites, 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.
  - The Juno spacecraft is designed to have a radiation design factor of 2 at end of mission.

- **Question:** What happens if de-orbit fails or if the spacecraft fails anywhere after JOI?

- In the 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.
**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 especially with Europa.

<table>
<thead>
<tr>
<th>Key Requirements</th>
<th>Meeting the Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoidance of Galilean satellites at an acceptable probability during Juno <strong>prime mission</strong></td>
<td>Juno has no intention of encountering any Galilean satellites during its prime mission</td>
</tr>
<tr>
<td>Provide an <strong>end-of-mission plan</strong> that addresses disposition of spacecraft</td>
<td>De-orbit into Jupiter</td>
</tr>
<tr>
<td>Ensures continued <strong>avoidance of Galilean satellite impacts after the mission</strong></td>
<td>See below (focus of this presentation)</td>
</tr>
</tbody>
</table>

- With agreement from NASA, Juno has imposed a requirement such that the probability of contamination with Europa’s ocean is **less than 1 x 10^{-4}** (and 1 x 10^{-3} for the other Galilean satellites) **after 150 years.**
Planetary Protection Requirements

- The probability requirement (less than $1 \times 10^{-4}$ for Europa and $1 \times 10^{-3}$ for the other Galilean satellites) is divided between the spacecraft failure probability, the probability of being on an impacting trajectory, and the probability that the impact will contaminate the ocean.

<table>
<thead>
<tr>
<th>Body</th>
<th>Probability of impact for 150 years following a failed deorbit burn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>&lt; 5% (Goal)</td>
</tr>
<tr>
<td>Europa</td>
<td>&lt; 1.5%</td>
</tr>
<tr>
<td>Ganymede</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Callisto</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

- Must also consider satellite impacts if the spacecraft became uncontrollable any time after Jupiter orbit insertion.
Failed De-Orbit

- For the nominal mission, the Juno spacecraft would **impact into the Jovian atmosphere after about 125 years** if de-orbit fails.

- Note the effect of the apsidal rotation

---

**Periapsis altitude history**
1. Nominal Mission (in red)
2. APO-33 state propagated to Jupiter impact (in blue)

- Juno Apojove: $39 \, R_J$
- Callisto: $26 \, R_J$
- Ganymede: $15 \, R_J$
- Europa: $9 \, R_J$
- Io: $6 \, R_J$
Method and Models

- At each apoJove location, the state covariance matrix are sampled to get dispersed spacecraft states to start propagation
- Analyses includes
  - uncertainties associated with Galilean satellite states and Jupiter spherical harmonics
  - gravitational forces (Sun, 8 planets, Pluto, Moon, and Galilean satellites)
  - drag and solar radiation pressure
- Propagate trajectory from apoJove states for at least 150 years or until impact with Jupiter or one of Galilean satellites occurs
- 4000 samples per apoJove case analyzed
- Uncertainty in results:

\[
\sigma = \sqrt{Npq} / N
\]

where \(N\) is number of samples, \(p\) is estimated probability of a “hit”, and \(q = (1-p)\)
Failed De-Orbit Monte-Carlo Impact Results

<table>
<thead>
<tr>
<th></th>
<th>% Occurrence over 150 years</th>
<th>Trajectory Allocated Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Impacts</td>
<td>35.51% +/- 1.52%</td>
<td></td>
</tr>
<tr>
<td>Jupiter impacts</td>
<td>60.06% +/- 1.56%</td>
<td></td>
</tr>
<tr>
<td>Io impacts</td>
<td>2.52% +/- 0.50%</td>
<td>&lt; 5% (GOAL)</td>
</tr>
<tr>
<td>Europa impacts</td>
<td>0.81% +/- 0.28%</td>
<td>&lt; 1.5%</td>
</tr>
<tr>
<td>Ganymede impacts</td>
<td>0.78% +/- 0.28%</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Callisto impacts</td>
<td>0.33% +/- 0.18%</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

Impact results with 2-σ uncertainties
Failed De-Orbit Impact Results
(For Other Models/Assumptions)

- Analyses were done looking at different assumptions on atmospheric models, force models, and whether or not to include various sampling uncertainties.
- Impact results for these variations are similar and within their uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Atreya Atmosphere Model (baseline)</th>
<th>Edgington Atmosphere Model</th>
<th>No SRP Model</th>
<th>No Jupiter Atmosphere Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impacts Jupiter within 150 yrs</td>
<td>60.1% +/- 1.6%</td>
<td>60.0% +/- 1.6%</td>
<td>60.2% +/- 1.5%</td>
<td>59.2% +/- 1.6%</td>
</tr>
<tr>
<td>Impacts Io within 150 yrs</td>
<td>2.5% +/- 0.5%</td>
<td>2.9% +/- 0.5%</td>
<td>2.6% +/- 0.5%</td>
<td>2.7% +/- 0.5%</td>
</tr>
<tr>
<td>Impacts Europa within 150 yrs</td>
<td>0.8% +/- 0.3%</td>
<td>0.7% +/- 0.3%</td>
<td>0.8% +/- 0.3%</td>
<td>0.7% +/- 0.3%</td>
</tr>
<tr>
<td>Impacts Ganymede within 150 yrs</td>
<td>0.8% +/- 0.3%</td>
<td>0.8% +/- 0.3%</td>
<td>0.8% +/- 0.3%</td>
<td>1.1% +/- 0.3%</td>
</tr>
<tr>
<td>Impacts Callisto within 150 yrs</td>
<td>0.3% +/- 0.2%</td>
<td>0.2% +/- 0.1%</td>
<td>0.2% +/- 0.1%</td>
<td>0.1% +/- 0.1%</td>
</tr>
<tr>
<td>No Impacts within 150 yrs</td>
<td>35.5% +/- 1.5%</td>
<td>35.5% +/- 1.5%</td>
<td>35.4% +/- 1.5%</td>
<td>36.3% +/- 1.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Impacts Jupiter within 150 yrs</td>
<td>60.5% +/- 1.5%</td>
<td>61.3% +/- 1.5%</td>
<td>62.8% +/- 1.5%</td>
<td>61.6% +/- 1.5%</td>
</tr>
<tr>
<td>Impacts Io within 150 yrs</td>
<td>2.8% +/- 0.5%</td>
<td>2.8% +/- 0.5%</td>
<td>2.3% +/- 0.5%</td>
<td>2.2% +/- 0.5%</td>
</tr>
<tr>
<td>Impacts Europa within 150 yrs</td>
<td>0.6% +/- 0.2%</td>
<td>0.5% +/- 0.2%</td>
<td>0.6% +/- 0.2%</td>
<td>0.7% +/- 0.3%</td>
</tr>
<tr>
<td>Impacts Ganymede within 150 yrs</td>
<td>1.0% +/- 0.3%</td>
<td>0.8% +/- 0.3%</td>
<td>0.9% +/- 0.3%</td>
<td>0.7% +/- 0.3%</td>
</tr>
<tr>
<td>Impacts Callisto within 150 yrs</td>
<td>0.2% +/- 0.2%</td>
<td>0.3% +/- 0.2%</td>
<td>0.1% +/- 0.1%</td>
<td>0.3% +/- 0.2%</td>
</tr>
<tr>
<td>No Impacts within 150 yrs</td>
<td>35.0% +/- 1.5%</td>
<td>34.4% +/- 1.5%</td>
<td>33.3% +/- 1.5%</td>
<td>34.5% +/- 1.5%</td>
</tr>
</tbody>
</table>

Impact results with 2-σ uncertainties
Other Potential Failure Locations

- Results so far are for the failed de-orbit case only
- Must consider satellite impacts if the spacecraft became **uncontrollable any time after Jupiter orbit insertion**
- There are orbit trim maneuvers (OTMs) at PJ+4 hrs to target specific longitudes at the equator-crossing near perijove
- Each OTM alter the state of the trajectory and thus **impact probability are computed for each orbit** initiating from apojove

*First 15 orbits in blue
Second 15 orbits in green*
Impact Results for All Orbits

Requirement: Expected value < 1.5% over 150 years

Europa Results

Impact %

Orbit Number

Impact Probabilities Averaged Over All Orbits

<table>
<thead>
<tr>
<th></th>
<th>% Occurrence over 150 years</th>
<th>Trajectory Allocated Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Impacts</td>
<td>29.7% +/- 0.25%</td>
<td></td>
</tr>
<tr>
<td>Jupiter impacts</td>
<td>67.3% +/- 0.25%</td>
<td></td>
</tr>
<tr>
<td>Io impacts</td>
<td>1.74% +/- 0.07%</td>
<td>&lt; 5% (GOAL)</td>
</tr>
<tr>
<td>Europa impacts</td>
<td>0.51% +/- 0.04%</td>
<td>&lt; 1.5%</td>
</tr>
<tr>
<td>Ganymede impacts</td>
<td>0.55% +/- 0.04%</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Callisto impacts</td>
<td>0.18% +/- 0.02%</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>
Method of Reducing the Impact Results

- Much of the work presented here represents impact results by analyzing the reference trajectory.
- Some analysis has been done to examine the potential of reducing the impact probability with the Galilean satellites
  - Reduce perijove altitudes by using apoijove maneuvers
    - More complicated mission operations
  - Change orbit inclination
    - Inclination requirement of $90^\circ \pm 10^\circ$ (baseline mission: $90^\circ$ to $91^\circ$)
- None of these strategies are needed to meet planetary protection requirements and are not being pursued by project.

Include maneuvers at APO-0, 11, 18, 23, 27, and 31
Lower Perijove Altitude

- Used 3100 km as minimum allowable perijove altitude
  - acceptable for science instruments and accounts for altitude uncertainties (from navigation delivery and atmospheric density)
- Include maneuvers at apojoves 0, 11, 18, 23, 27, and 31
- Deterministically, all orbits impact Jupiter within 25 years except for Orbit 0 (78-day capture orbit) which impact Jupiter in 386 yrs.

<table>
<thead>
<tr>
<th>Orbit No.</th>
<th>Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>386</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>16</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orbit No.</th>
<th>Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>26</td>
<td>4</td>
</tr>
<tr>
<td>27</td>
<td>4</td>
</tr>
<tr>
<td>28</td>
<td>4</td>
</tr>
<tr>
<td>29</td>
<td>4</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>31</td>
<td>4</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
</tr>
<tr>
<td>33</td>
<td>4</td>
</tr>
</tbody>
</table>
• Low altitude trajectory greatly reduces Galilean satellite impacts but is not needed to meet planetary protection requirements
Other Inclinations

- Two other inclinations were investigated 85° and 95° (requirement of 90° ± 10°)
- **Initial assessment** of the failed de-orbit case for the 95° inclination case produced similar results as the low perijove altitude case
- **This option is not needed to meet planetary protection requirements**

<table>
<thead>
<tr>
<th></th>
<th>Reference Trajectory</th>
<th>Low Altitude Case</th>
<th>85° Inclination</th>
<th>95° Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Inclination</td>
<td>90°</td>
<td>90°</td>
<td>85°</td>
<td>95°</td>
</tr>
<tr>
<td>No Impact %</td>
<td>36%</td>
<td>0.0%</td>
<td>45.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Jupiter Impact %</td>
<td>60.1%</td>
<td>100%</td>
<td>49.3%</td>
<td>99.9%</td>
</tr>
<tr>
<td>Io Impact %</td>
<td>2.5%</td>
<td>0.0%</td>
<td>3.1%</td>
<td>0.08%</td>
</tr>
<tr>
<td>Europa Impact %</td>
<td>0.8%</td>
<td>0.0%</td>
<td>0.8%</td>
<td><strong>0.05%</strong></td>
</tr>
<tr>
<td>Ganymede Impact %</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.6%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Callisto Impact %</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.5%</td>
<td>0.0%</td>
</tr>
<tr>
<td>PJ33 Oblate Alt. (km)</td>
<td>6362</td>
<td>3274</td>
<td>6048</td>
<td>6272</td>
</tr>
<tr>
<td>PJ33 Inclination</td>
<td>91.0°</td>
<td>91.1°</td>
<td>86.2</td>
<td>95.8</td>
</tr>
<tr>
<td>Total Determ. DV (m/s)</td>
<td>1962.6</td>
<td>1960.3</td>
<td>1959.9</td>
<td>1960.5</td>
</tr>
</tbody>
</table>
Summary and Conclusion

• The Juno baseline reference mission **meets planetary protection requirements** for impact probabilities with the Galilean satellites.
  – Impact probability for Europa if de-orbit fails is 0.81% (< 1.5% requirement)
  – Impact probability for Europa averaged overall all orbits is ~ 0.5%
  – Impact probability for the other Galilean satellites are also met

• 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 potential changes to the reference trajectory
Then End
## Backup: Europa Impact Statistics

### 1000 Years

<table>
<thead>
<tr>
<th>Orbit No.</th>
<th>Sample Size</th>
<th>Expected Value</th>
<th>Uncertainty (2-σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0a</td>
<td>3999</td>
<td>0.25%</td>
<td>+/- 0.16%</td>
</tr>
<tr>
<td>0b</td>
<td>3998</td>
<td>0.18%</td>
<td>+/- 0.13%</td>
</tr>
</tbody>
</table>

### 150 Years

#### 150 Years

<table>
<thead>
<tr>
<th>Orbit No.</th>
<th>Sample Size</th>
<th>Expected Value</th>
<th>Uncertainty (2-σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3995</td>
<td>0.55%</td>
<td>+/- 0.23%</td>
</tr>
<tr>
<td>2</td>
<td>3996</td>
<td>0.65%</td>
<td>+/- 0.25%</td>
</tr>
<tr>
<td>3</td>
<td>3992</td>
<td>0.58%</td>
<td>+/- 0.24%</td>
</tr>
<tr>
<td>4</td>
<td>3995</td>
<td>0.10%</td>
<td>+/- 0.10%</td>
</tr>
<tr>
<td>5</td>
<td>3994</td>
<td>0.38%</td>
<td>+/- 0.19%</td>
</tr>
<tr>
<td>6</td>
<td>3989</td>
<td>0.35%</td>
<td>+/- 0.19%</td>
</tr>
<tr>
<td>7</td>
<td>3995</td>
<td>0.65%</td>
<td>+/- 0.25%</td>
</tr>
<tr>
<td>8</td>
<td>3998</td>
<td>1.15%</td>
<td>+/- 0.34%</td>
</tr>
<tr>
<td>9</td>
<td>3996</td>
<td>0.43%</td>
<td>+/- 0.21%</td>
</tr>
<tr>
<td>10</td>
<td>3992</td>
<td>0.50%</td>
<td>+/- 0.22%</td>
</tr>
<tr>
<td>11</td>
<td>3992</td>
<td>0.53%</td>
<td>+/- 0.23%</td>
</tr>
<tr>
<td>12</td>
<td>3994</td>
<td>0.53%</td>
<td>+/- 0.23%</td>
</tr>
<tr>
<td>13</td>
<td>3998</td>
<td>0.88%</td>
<td>+/- 0.29%</td>
</tr>
<tr>
<td>14</td>
<td>3993</td>
<td>0.43%</td>
<td>+/- 0.21%</td>
</tr>
<tr>
<td>15</td>
<td>3991</td>
<td>0.75%</td>
<td>+/- 0.27%</td>
</tr>
<tr>
<td>16</td>
<td>3998</td>
<td>0.78%</td>
<td>+/- 0.28%</td>
</tr>
<tr>
<td>17</td>
<td>3997</td>
<td>0.55%</td>
<td>+/- 0.23%</td>
</tr>
</tbody>
</table>

#### 150 Years

<table>
<thead>
<tr>
<th>Orbit No.</th>
<th>Sample Size</th>
<th>Expected Value</th>
<th>Uncertainty (2-σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>3993</td>
<td>0.33%</td>
<td>+/- 0.18%</td>
</tr>
<tr>
<td>19</td>
<td>3989</td>
<td>0.45%</td>
<td>+/- 0.21%</td>
</tr>
<tr>
<td>20</td>
<td>3994</td>
<td>1.00%</td>
<td>+/- 0.32%</td>
</tr>
<tr>
<td>21</td>
<td>3999</td>
<td>0.85%</td>
<td>+/- 0.29%</td>
</tr>
<tr>
<td>22</td>
<td>3990</td>
<td>0.25%</td>
<td>+/- 0.16%</td>
</tr>
<tr>
<td>23</td>
<td>3992</td>
<td>0.48%</td>
<td>+/- 0.22%</td>
</tr>
<tr>
<td>24</td>
<td>3992</td>
<td>0.15%</td>
<td>+/- 0.12%</td>
</tr>
<tr>
<td>25</td>
<td>3993</td>
<td>0.43%</td>
<td>+/- 0.21%</td>
</tr>
<tr>
<td>26</td>
<td>3993</td>
<td>0.28%</td>
<td>+/- 0.17%</td>
</tr>
<tr>
<td>27</td>
<td>3996</td>
<td>0.48%</td>
<td>+/- 0.22%</td>
</tr>
<tr>
<td>28</td>
<td>3997</td>
<td>0.75%</td>
<td>+/- 0.27%</td>
</tr>
<tr>
<td>29</td>
<td>3990</td>
<td>0.28%</td>
<td>+/- 0.17%</td>
</tr>
<tr>
<td>30</td>
<td>3990</td>
<td>0.18%</td>
<td>+/- 0.13%</td>
</tr>
<tr>
<td>31</td>
<td>3997</td>
<td>0.85%</td>
<td>+/- 0.29%</td>
</tr>
<tr>
<td>32</td>
<td>3997</td>
<td>0.85%</td>
<td>+/- 0.29%</td>
</tr>
<tr>
<td>33</td>
<td>3968</td>
<td>0.81%</td>
<td>+/- 0.28%</td>
</tr>
</tbody>
</table>