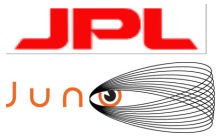

Planetary Protection Trajectory Analysis for the Juno Mission

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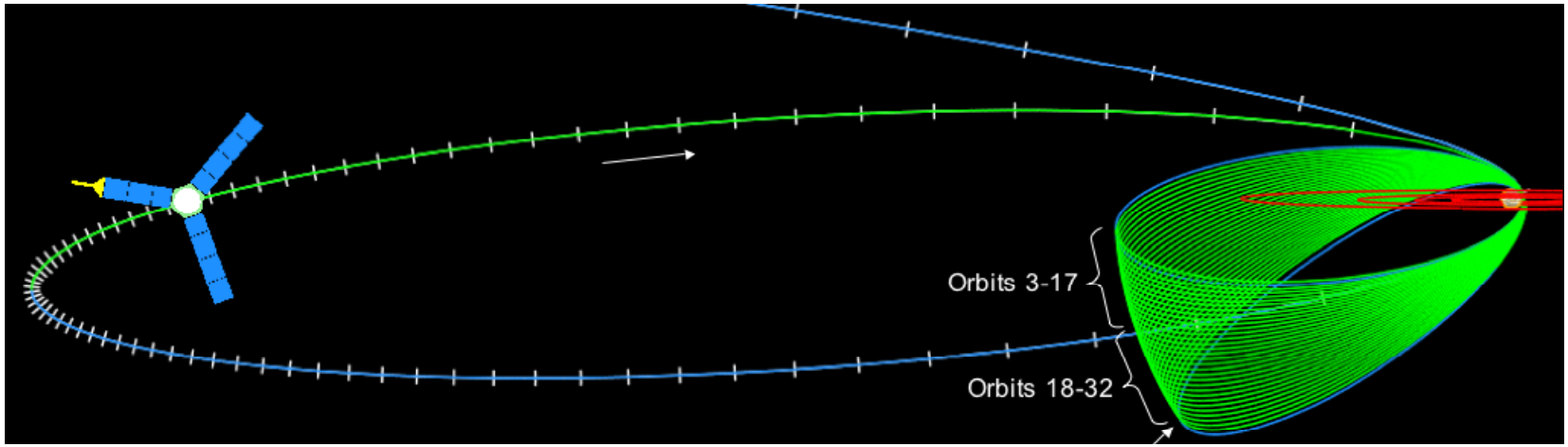
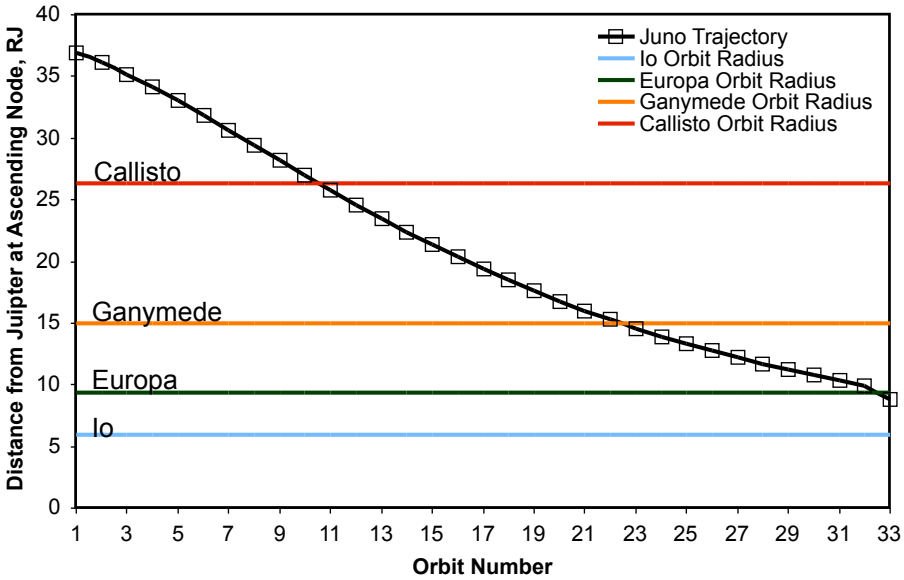
Mission Overview

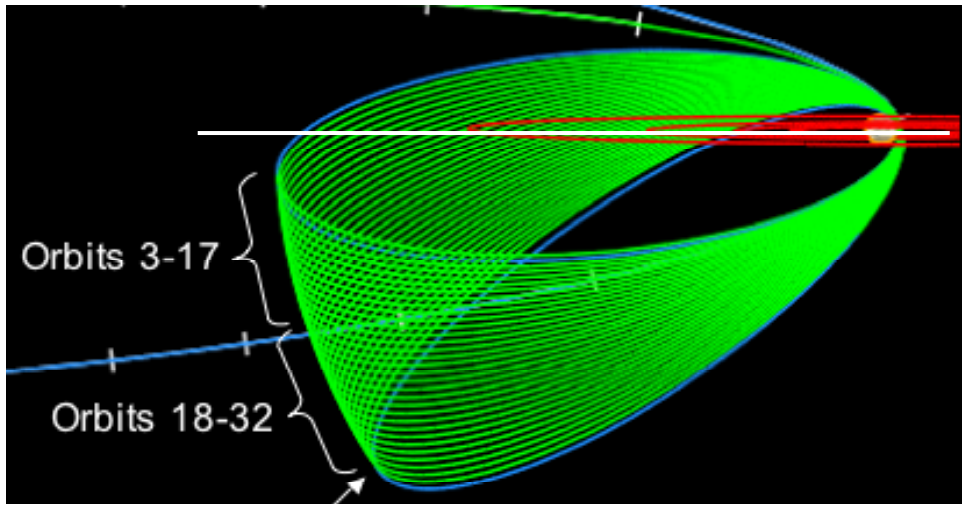
- Juno is an orbiter mission expected to launch in August 2011 (**subject to receiving NASA approval for NEPA compliance**)
- Uses a **ΔV-EGA (2+) trajectory** to reach Jupiter with arrival in August 2016
- Perform a Jupiter Orbit Insertion maneuver to capture into a 78-day orbit
- Perform a Period Reduction 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

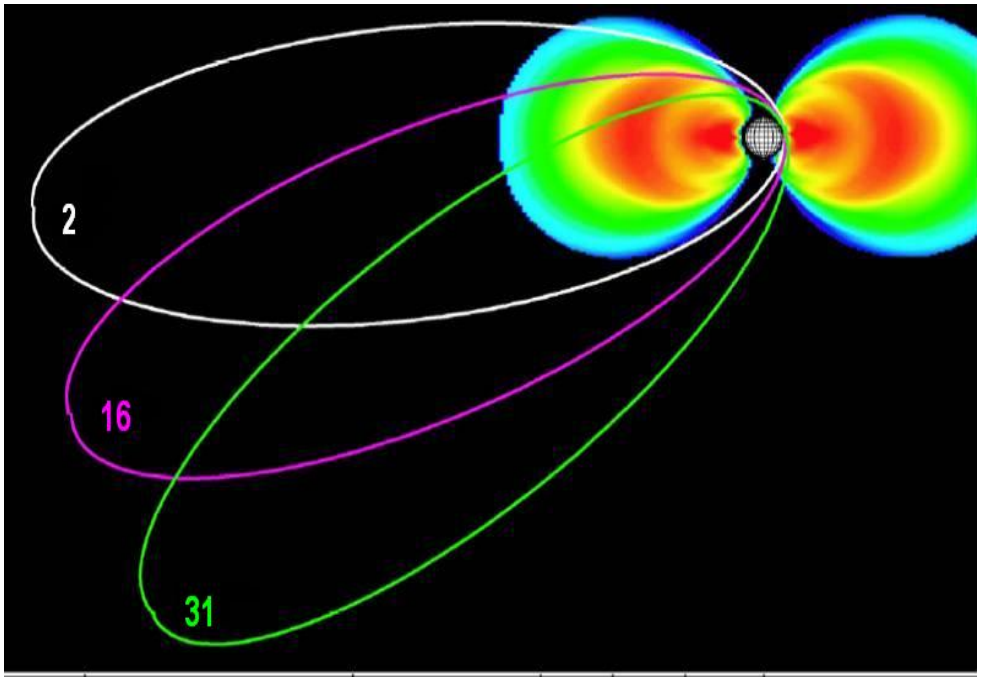
- Initially, the equatorial crossing near apojove occurs outside Callisto's orbit, but as the mission evolves **the apsidal rotation (about 0.95° per orbit) causes this distance to move much closer to Jupiter and cross the orbits of the Galilean satellites (Io, Europa, Ganymede, and Callisto).**
- Potential 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 an 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.

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

- 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

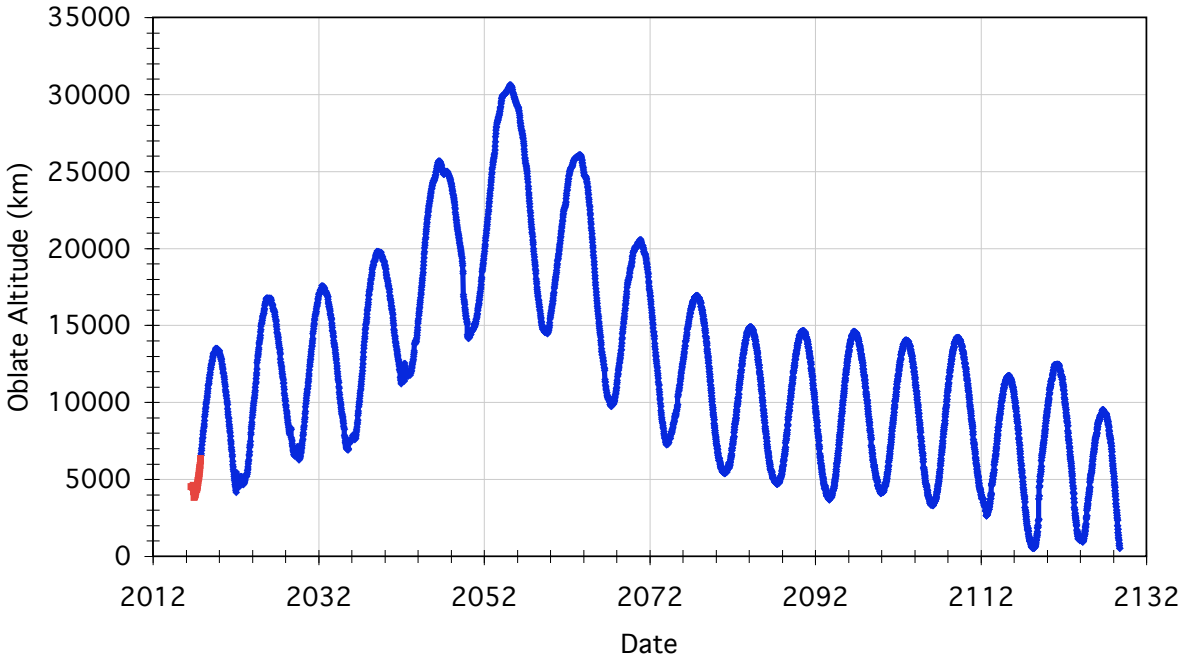
- The probability requirement (**less than 1 x 10^{-4}** for Europa and 1 x 10^{-3} for the other Galilean satellites) is divided between the spacecraft failure probability, the probability of being on an impacting trajectory, and the probability that the impact will contaminate the ocean

Trajectory Allocated Requirement	
Body	**Probability of impact for 150 years following a failed deorbit burn**
Io	< 5% (Goal)
Europa	**< 1.5%**
Ganymede	< 5%
Callisto	< 5%

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

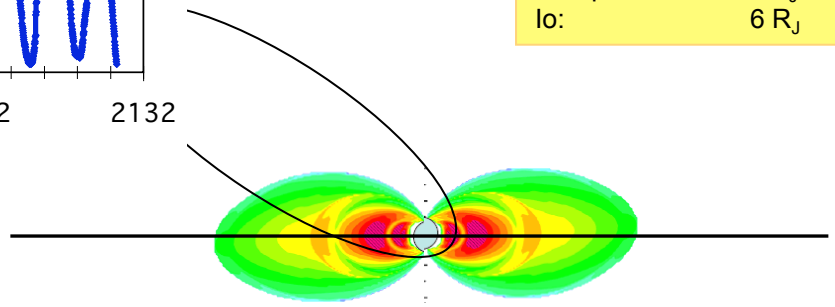
Failed De-Orbit

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



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



Direction of apsidal rotation

Orbit direction

- Note the effect of the apsidal rotation

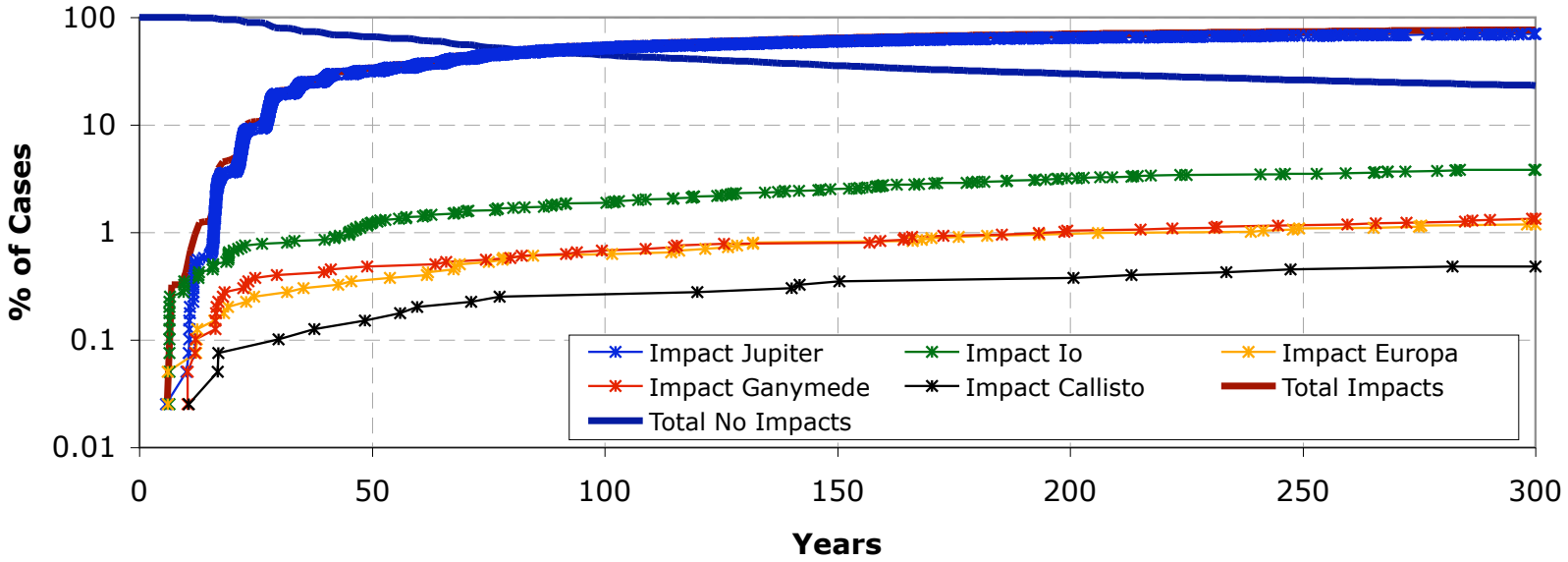
Method and Models

- 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



	% Occurrence over 150 years	Trajectory Allocated Requirement
No Impacts	35.51% +/- 1.52%	
Jupiter impacts	60.06% +/- 1.56%	
Io impacts	2.52% +/- 0.50%	< 5% (GOAL)
Europa impacts	0.81% +/- 0.28%	< 1.5%
Ganymede impacts	0.78% +/- 0.28%	< 5%
Callisto impacts	0.33% +/- 0.18%	< 5%

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

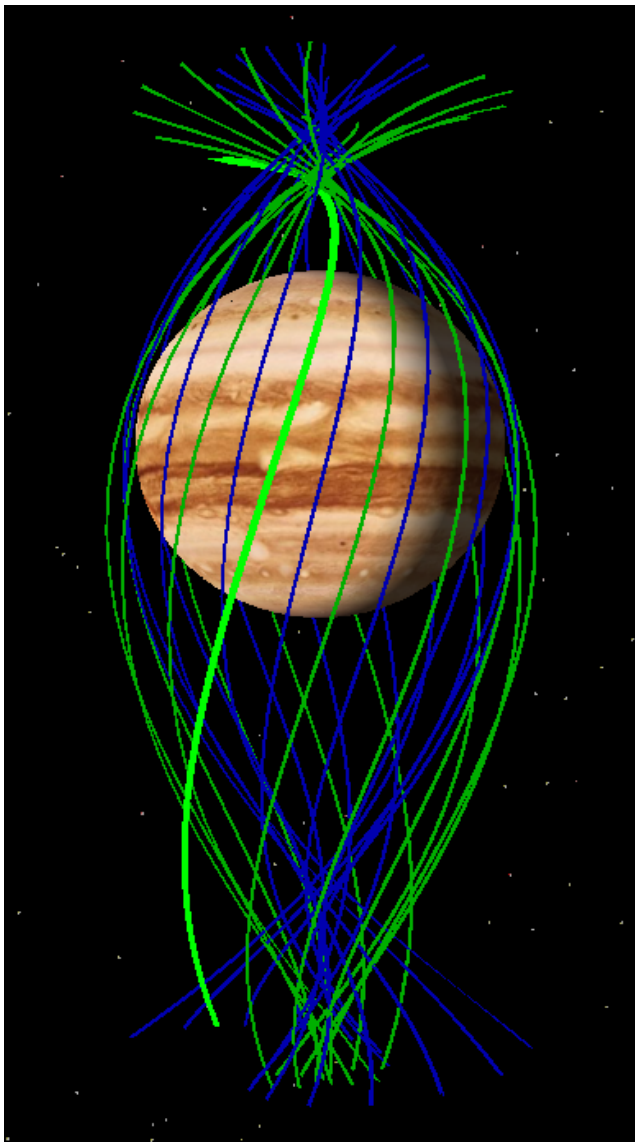
	Atreya Atmosphere Model (baseline)	Edgington Atmosphere Model	No SRP Model	No Jupiter Atmosphere Model
Impacts Jupiter within 150 yrs	60.1% +/- 1.6%	60.0% +/- 1.6%	60.2% +/- 1.5%	59.2% +/- 1.6%
Impacts Io within 150 yrs	2.5% +/- 0.5%	2.9% +/- 0.5%	2.6% +/- 0.5%	2.7% +/- 0.5%
Impacts Europa within 150 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%

Impact results with 2-σ uncertainties

Other Potential Failure Locations

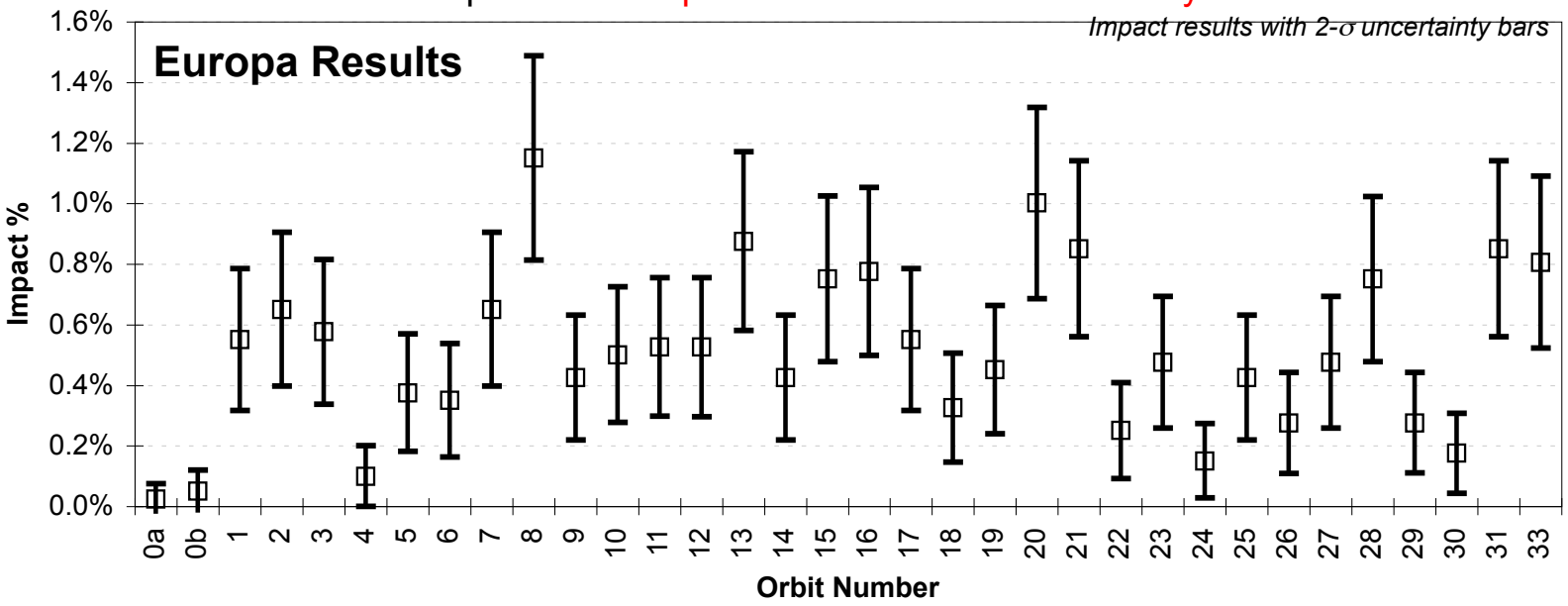
- Results so far are for the failed de-orbit case only
- Must consider satellite impacts if the spacecraft became **uncontrollable any time after Jupiter orbit insertion**
- There are orbit trim maneuvers (OTMs) at PJ+4 hrs to target specific longitudes at the equator-crossing near perijove
- Each OTM 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



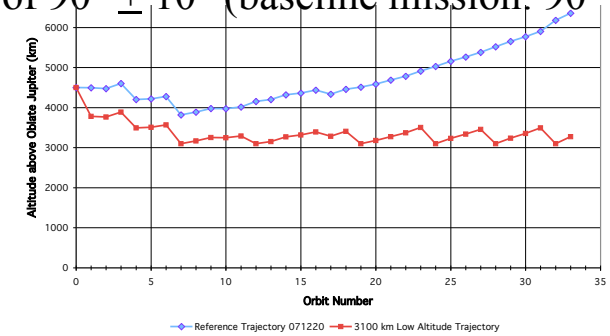
Impact Probabilities Averaged Over All Orbits

	% Occurrence over 150 years	Trajectory Allocated Requirement
No Impacts	29.7% +/- 0.25%	
Jupiter impacts	67.3% +/- 0.25%	
Io impacts	1.74% +/- 0.07%	< 5% (GOAL)
Europa impacts	0.51% +/- 0.04%	< 1.5%
Ganymede impacts	0.55% +/- 0.04%	< 5%
Callisto impacts	0.18% +/- 0.02%	< 5%

Impact results with 2-σ uncertainties

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 apojove maneuvers
    - More complicated mission operations
  - Change orbit inclination
    - Inclination requirement of 90° ± 10° (baseline mission: 90° to 91°)
- **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

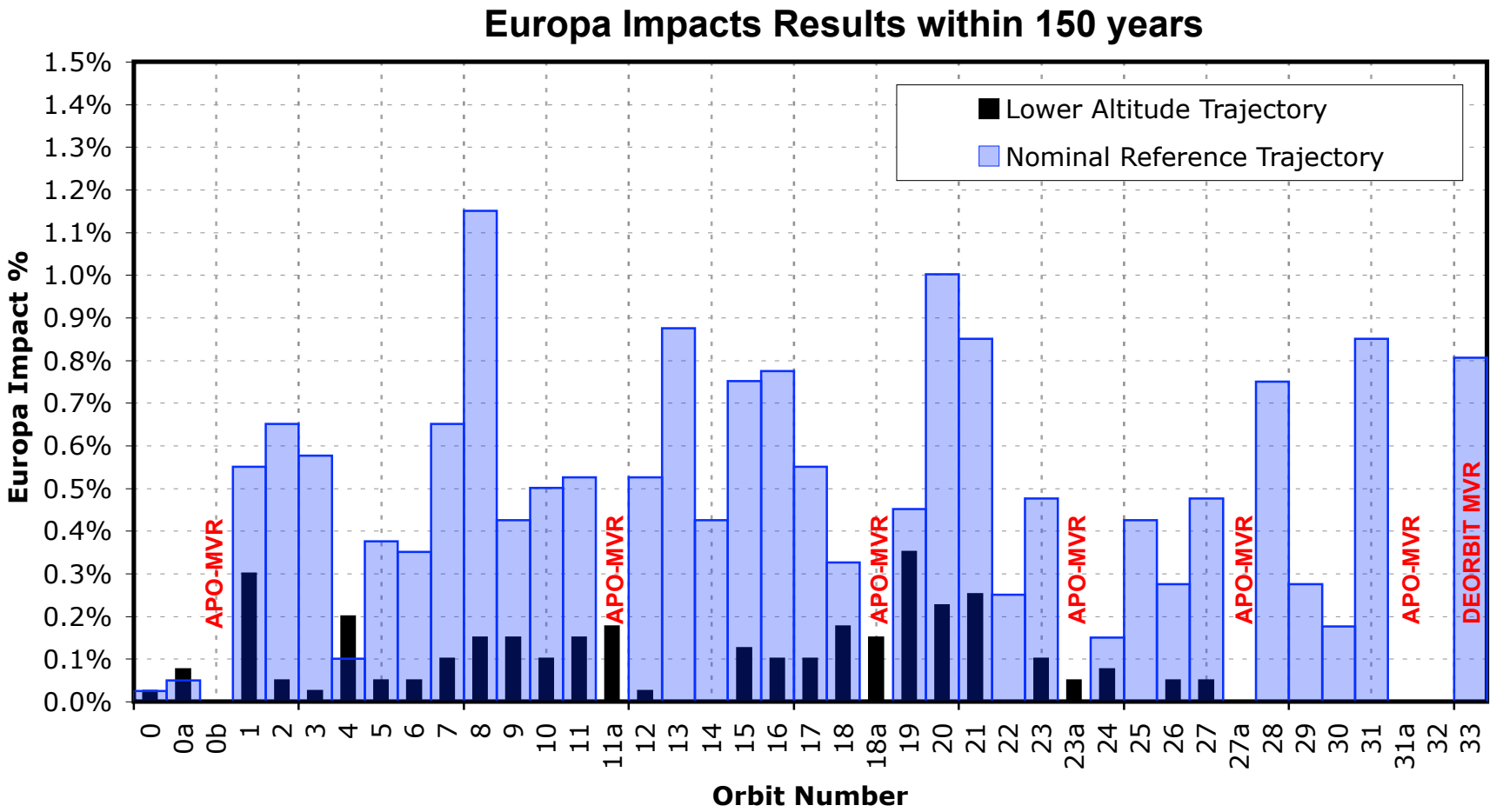
- Used 3100 km as minimum allowable perijove altitude
  - acceptable for science instruments and accounts for altitude uncertainties (from navigation delivery and atmospheric density)
- Include maneuvers at apojoves 0, 11, 18, 23, 27, and 31
- Deterministically, **all orbits impact Jupiter within 25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

Orbit No.	Lifetime (years)
0	*386*
1	11
2	11
3	11
4	16
5	15
6	11
7	11
8	5
9	11
10	11
11	11
12	11
13	16
14	11
15	22
16	11

Orbit No.	Lifetime (years)
17	21
18	10
19	10
20	16
21	16
22	5
23	10
24	7
25	4
26	4
27	4
28	4
29	4
30	4
31	4
32	4
33	4

Lower Perijove Altitude Impact Results

- 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

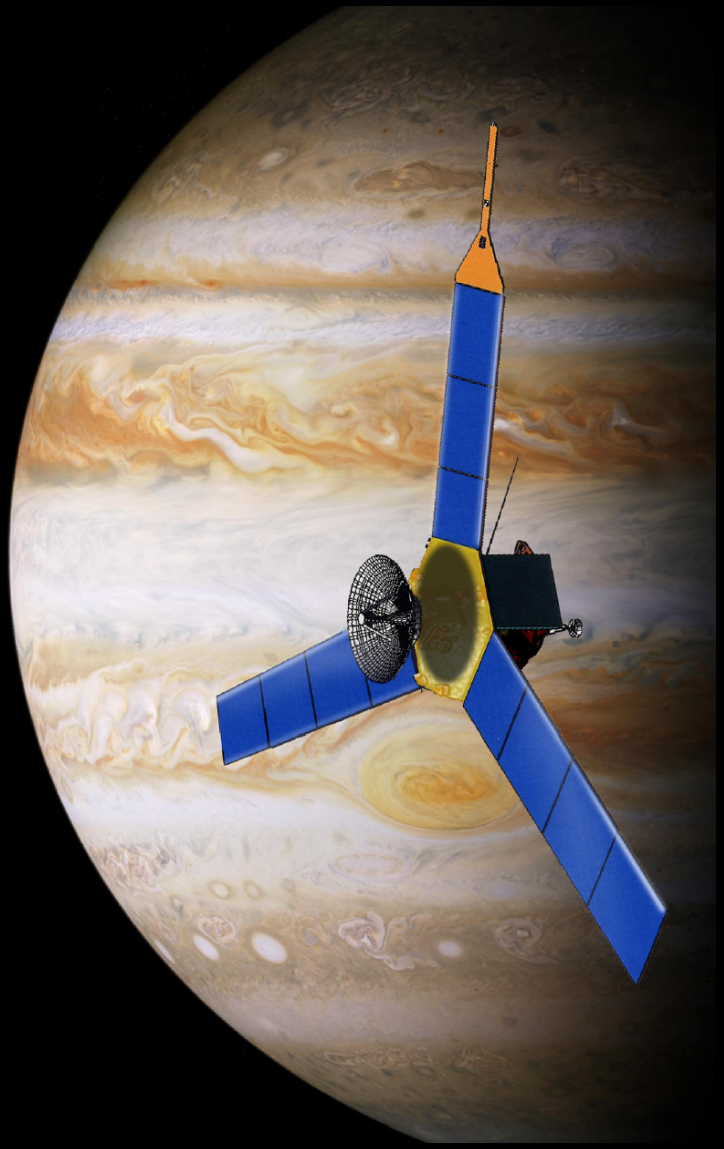
	Reference Trajectory	Low Altitude Case	85º Inclination Case	95º Inclination Case
Initial Inclination	90º	90º	85º	95º
No Impact %	36%	0.0%	45.7%	0.0%
Jupiter Impact %	60.1%	100%	49.3%	99.9%
Io Impact %	2.5%	0.0%	3.1%	0.08%
Europa Impact %	0.8%	0.0%	0.8%	0.05%
Ganymede Impact %	0.3%	0.0%	0.6%	0.0%
Callisto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

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				
Orbit No.	Sample Size	Expected Value		Uncertainty (2-σ)
0a	3999	0.25%	+/-	0.16%
0b	3998	0.18%	+/-	0.13%

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

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