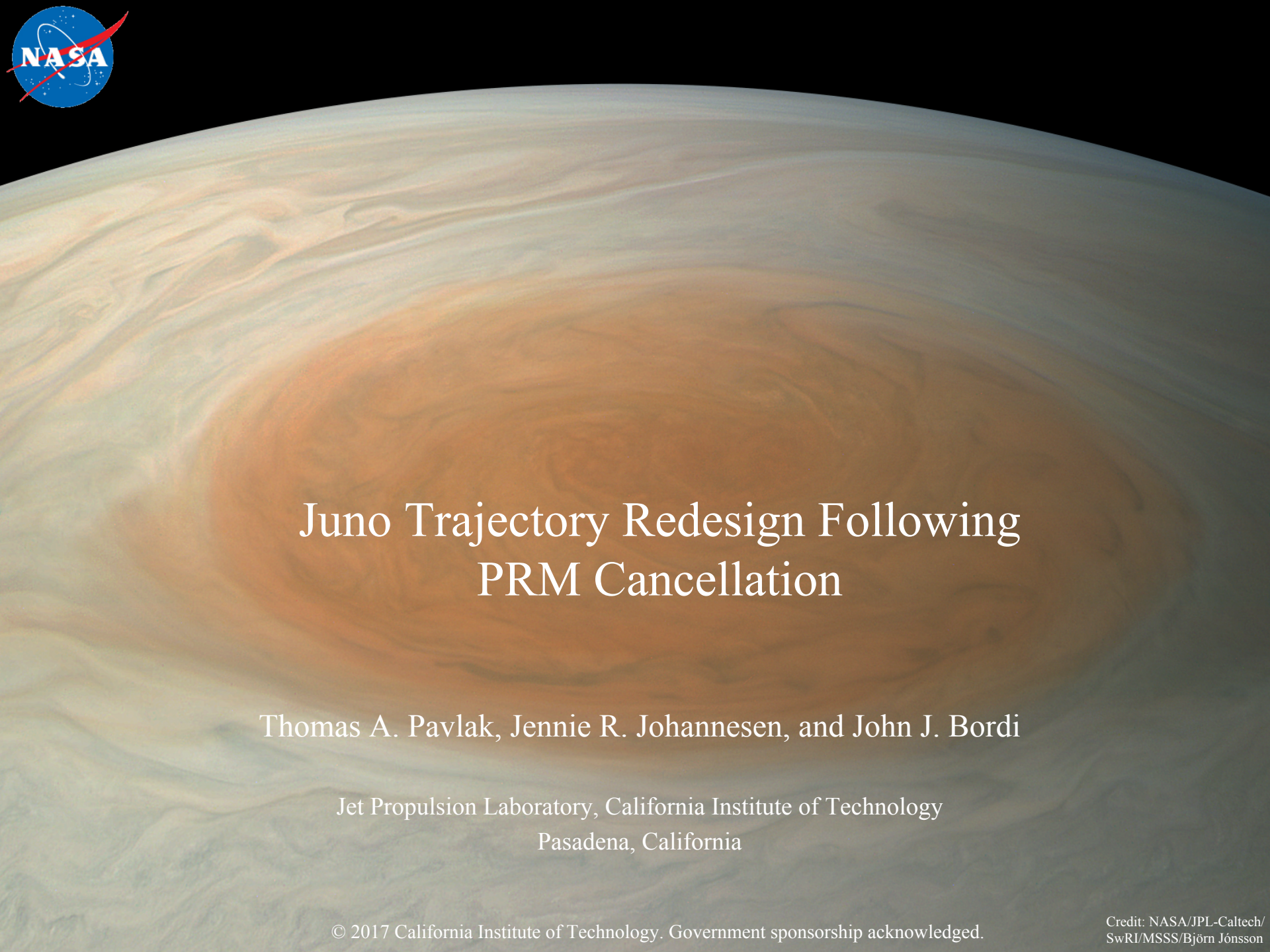


Juno Trajectory Redesign Following PRM Cancellation

Thomas A. Pavlak, Jennie R. Johannesen, and John J. Bordi

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

Credit: NASA/JPL-Caltech/
SwRI/MSSS/Björn Jónsson

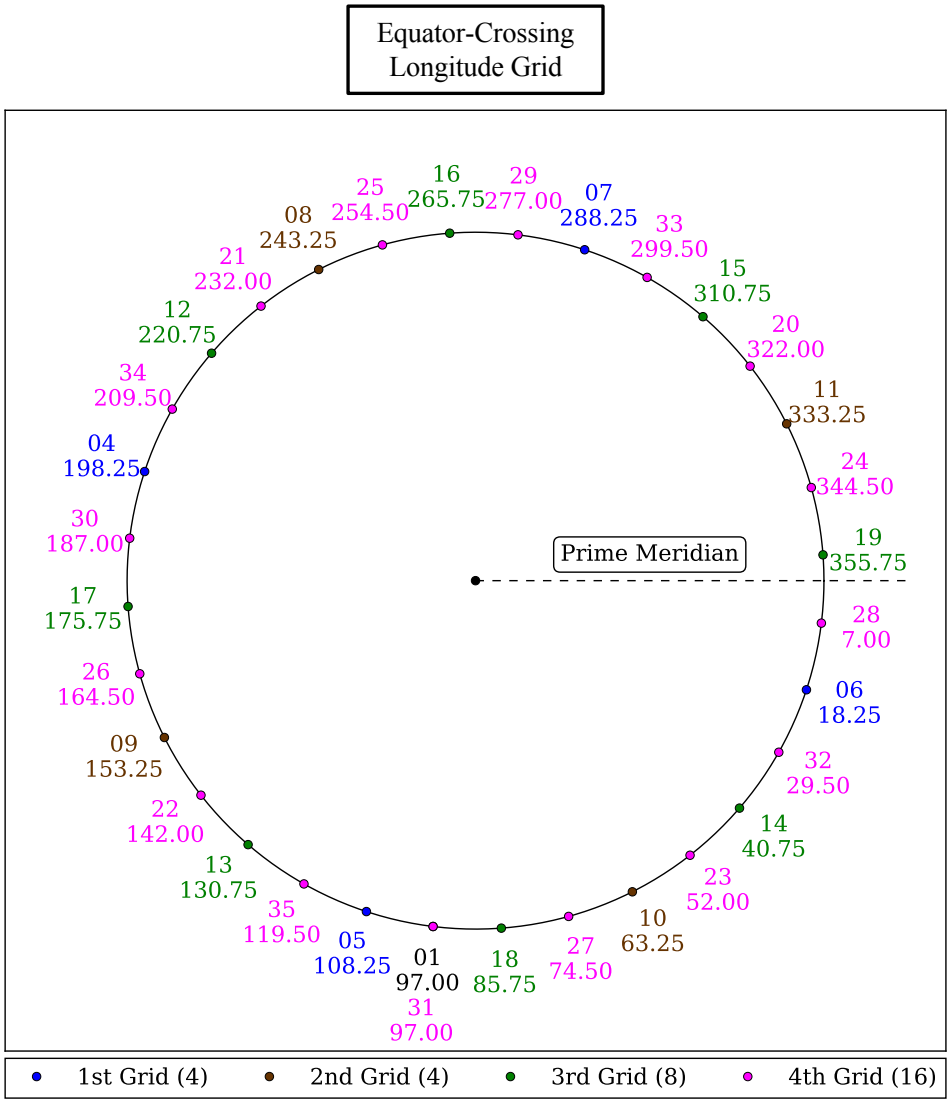
Juno Reference Trajectory Background

- Interplanetary cruise phase:
  - Launch in August 2011
  - Earth gravity assist in October 2013
  - Jupiter Orbit Insertion on July 5, 2016

- Pre-launch Jupiter operations plan:
  - JOI used to insert into 107-day capture orbit
  - Period Reduction Maneuver (PRM) on October 19, 2016 to achieve 11-day science orbits

- Reference trajectory update following Earth flyby:
  - No safe mode entries between launch and Earth flyby
  - Jupiter operations plan reassessed following three safe mode entries shortly after Earth flyby
  - 18-month trade study resulted in updated reference trajectory approved in March 2015
    - Two 53.5-day capture orbits
    - PRM to achieve 14-day science orbits (still on October 19, 2016)

14-day Science Orbit Characteristics

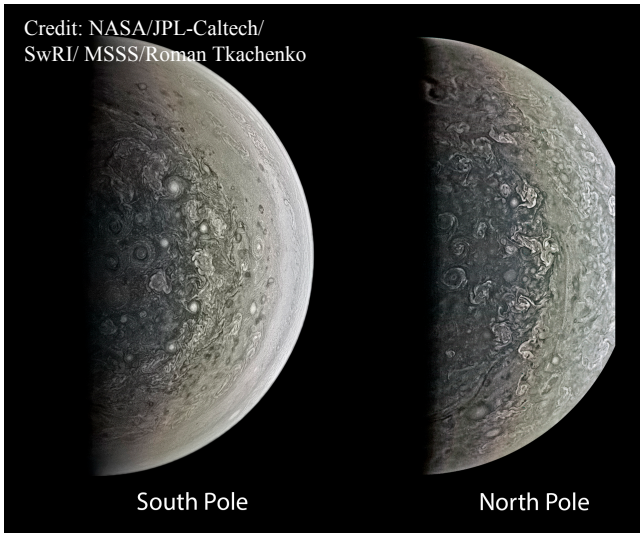


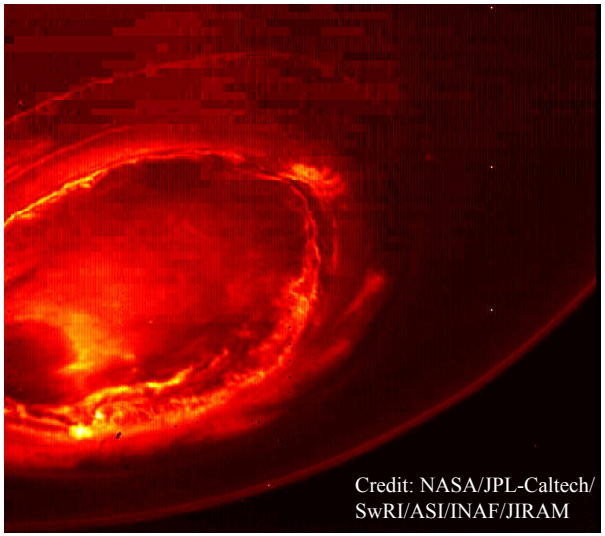
- Orbital period syncs with 7-day workweek
- Evenly-space equator-crossing longitude grid
  - 32 science passes (11.25-deg spacing)
  - Four successively finer “sub-grids”
- Deorbit burn to impact Jupiter in February 2018
  - To satisfy planetary protection requirements

Capture Orbit Operations

- JOI on July 5, 2016 to insert into 53.5-day capture orbit
  - JOI and subsequent clean-up maneuver were successful

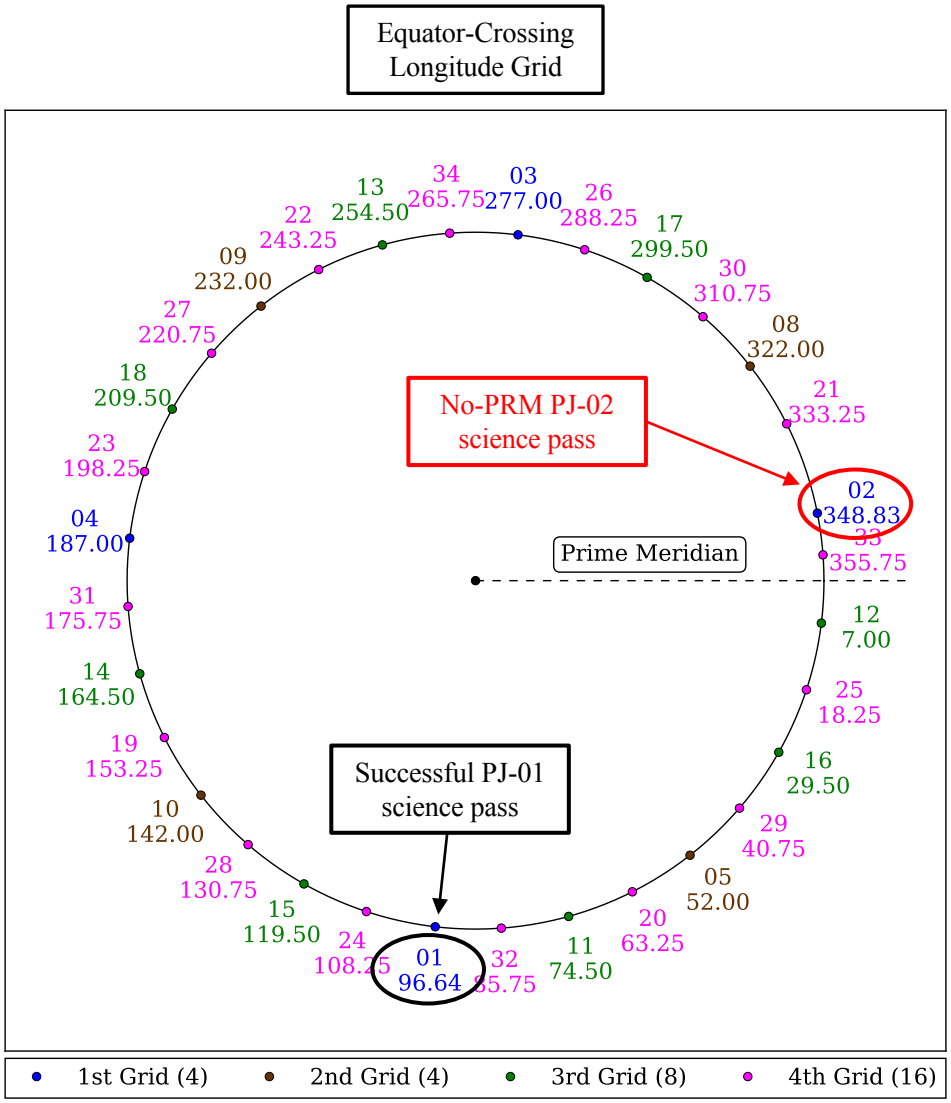
- First science perijove on August 27, 2016 (PJ-01)
  - Instruments performed nominally and exciting new science was obtained





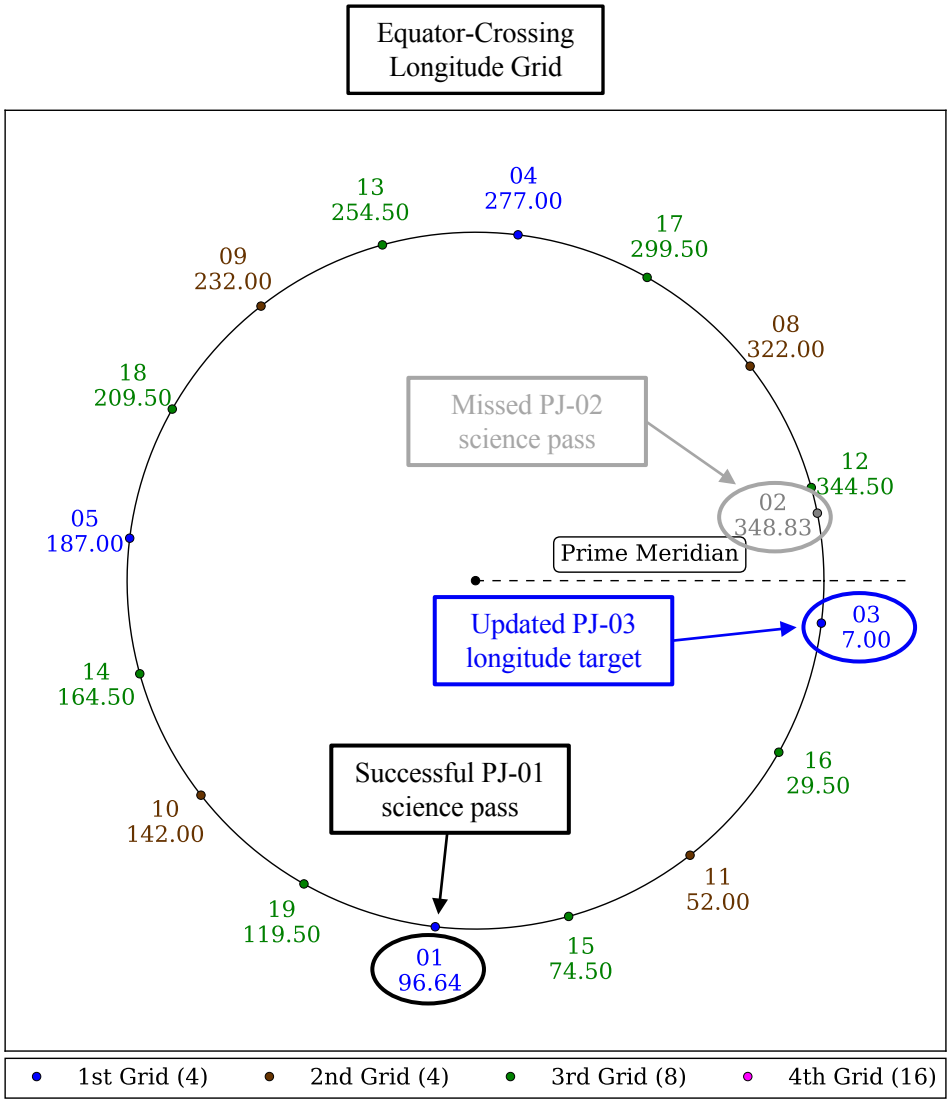
- PRM scheduled on October 19, 2016 to reduce orbital period to 14 days
  - Initially, PRM preparation proceeded nominally
  - 1 week prior to PRM, “sticky” latch valves detected in main engine propulsion system
  - PRM delayed pending main engine investigation

PRM Delay
Contingency Trajectory



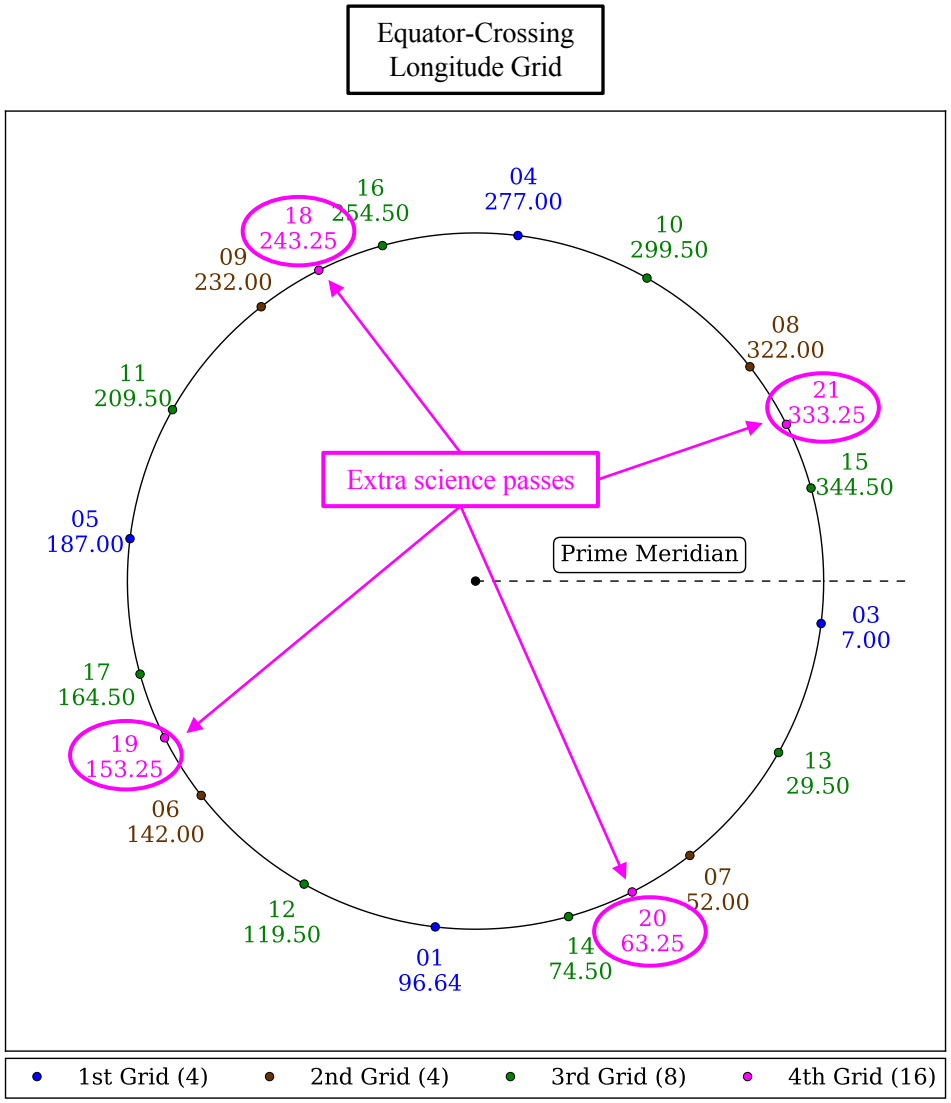
- Project transitioned to contingency reference trajectory developed months prior to PRM
  - Assumed PRM at PJ-06
- Re-aligned longitude grid using no-PRM PJ-02 equator-crossing
  - Fits reasonably well into evenly-spaced grid
  - Leveraged successful PJ-01 perijove pass

PJ02 Safe Mode Entry
Contingency Trajectory



- Spacecraft entered safe mode ~13.5 hours prior to PJ-02 science pass
  - Instruments turned off; no science collected
- As a result, a second contingency trajectory was built to shift PJ-03 and all subsequent longitudes
  - Avoid leaving a “hole” in the grid
  - Reduce OTM-02 Delta-V
  - Still assumed PRM at PJ-06
- Longitude grid incomplete due to operational time constraints
  - Only required to support short-term PJ-03 targeting/mission planning

Stop-Gap Reference Trajectory Design



- Reference trajectory required to support longer-term science, operations, and navigation during ongoing main engine anomaly investigation
- Stop-Gap reference trajectory released one week after delayed PRM
  - Remains in 53-day orbits (no PRM)
  - Includes 16 science passes + 4 extra passes
- Trajectory impacts Jupiter at PJ-22 in early November 2019
  - Avoid entering solar eclipse prior to PJ-23
  - Impact required to satisfy Galilean satellite planetary protection requirements

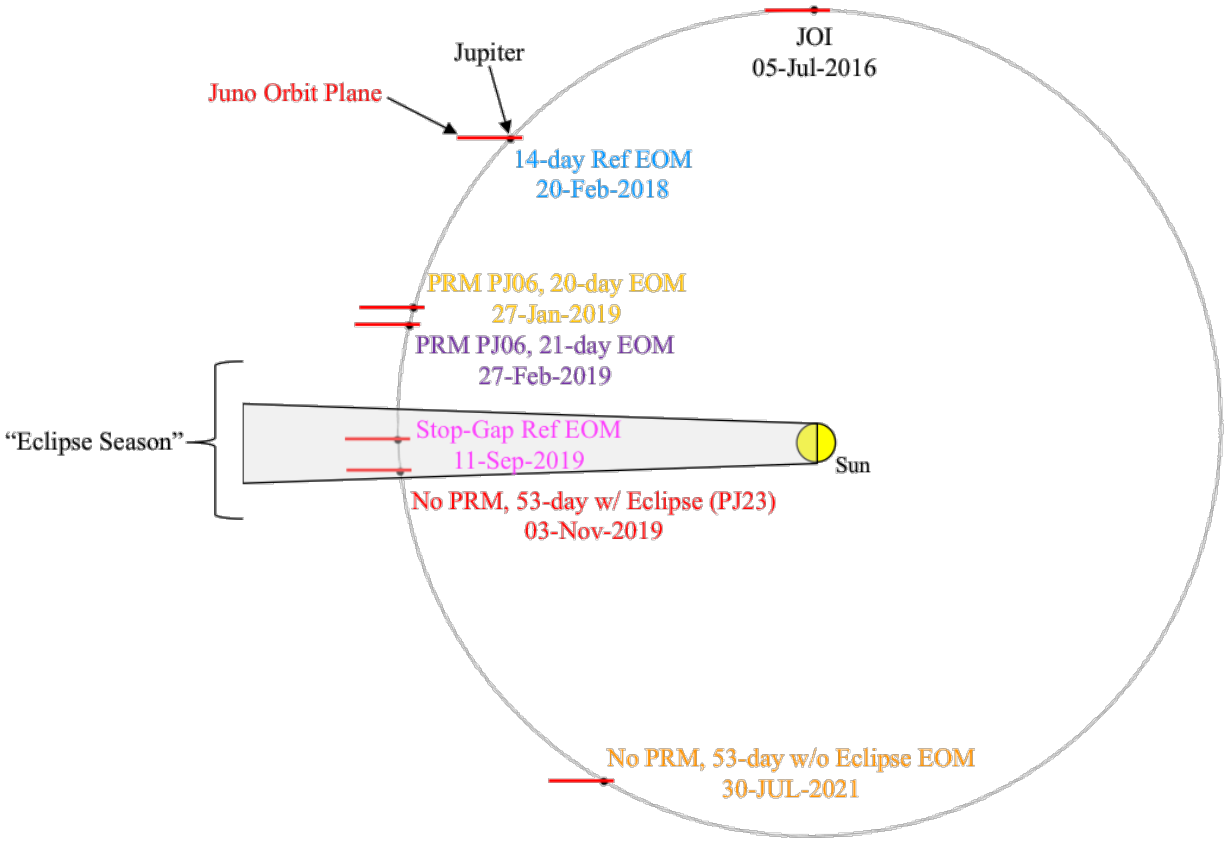
Trajectory Design Trade Study

- Design options:
  - PRM Epoch:
    - PJ-05 (March 27, 2017)
    - PJ-06 (May 19, 2017)
    - PJ-07 (July 11, 2017)
    - PJ-08 (September 1, 2017)
    - PJ-10 (December 16, 2017)
  - Orbit period:
    - 20-, 21-, 24-, 27-, 53-, 54-day orbits considered
    - A blow-down PRM could not deliver an orbit period < 18 days
  - 15-20 trajectory combinations evaluated

- Mission constraints:
  - 32-perijove, evenly-spaced longitude grid (successively finer “sub-grids” preferred)
  - Perijove passes must be visible by Goldstone DSN complex
  - Inclination = 90 deg +/- 10 deg
  - 3500 km < perijove altitude < 8000 km
  - No solar eclipses of any duration

Solar Eclipse Geometry

View from North Ecliptic Pole

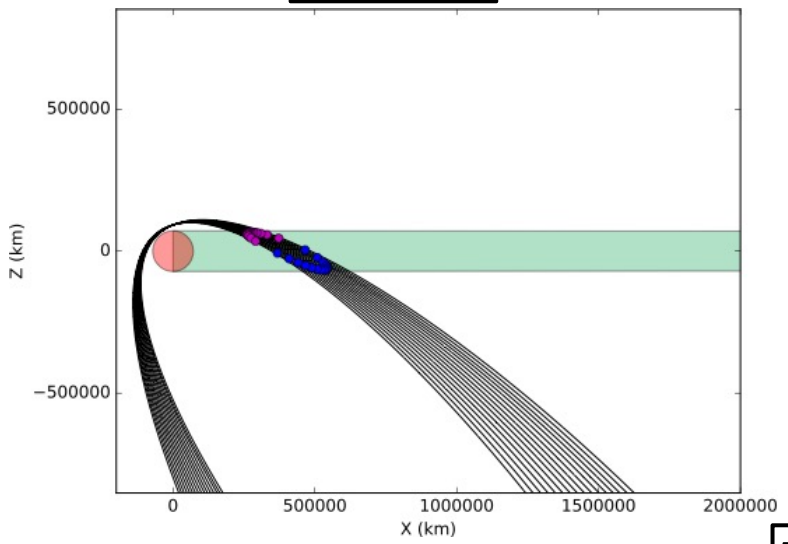


- Depending on orbital period, solar eclipses are possible from Summer 2019 to Spring 2020
  - Juno only qualified for 19-minute eclipse (Earth flyby)
  - Virtually any eclipse will likely be mission-ending
  - Any trajectory option must avoid eclipse or end prior to "eclipse season"
  - Dictates which PRM epoch/orbital period combinations are feasible

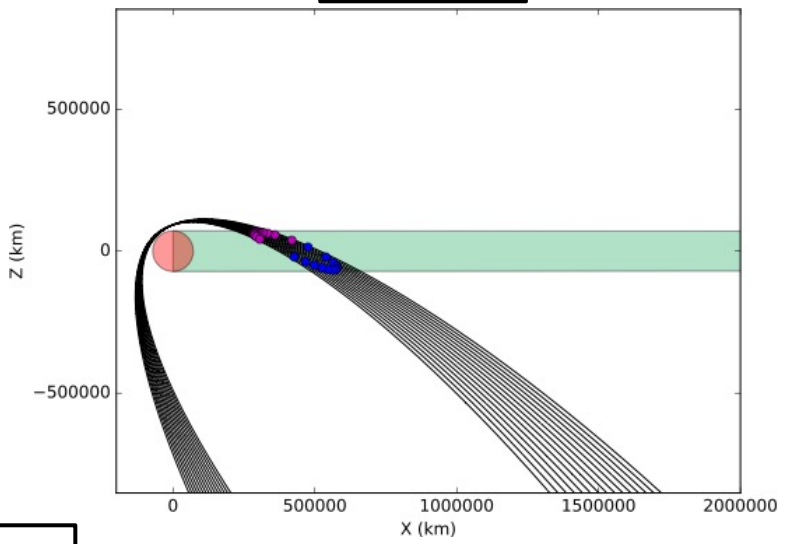
Solar Eclipse Geometry

Sun-Jupiter Rotating Frame, XZ-Projection

20-day Orbits

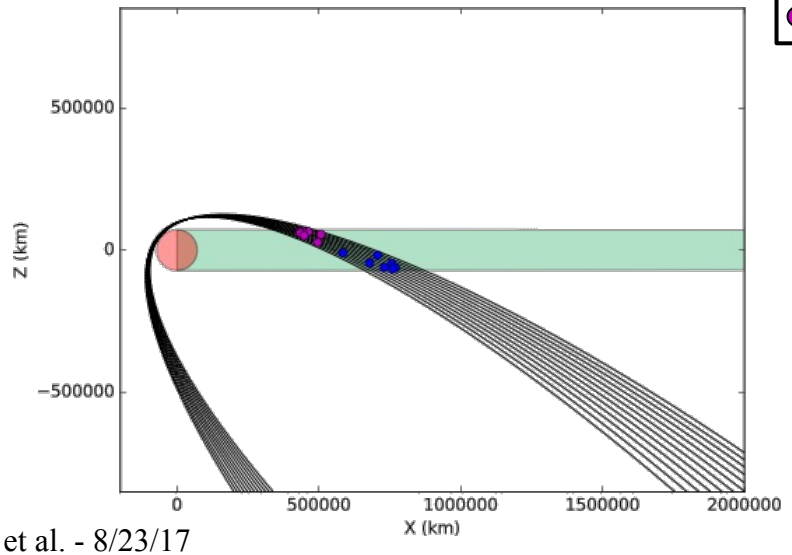


21-day Orbits

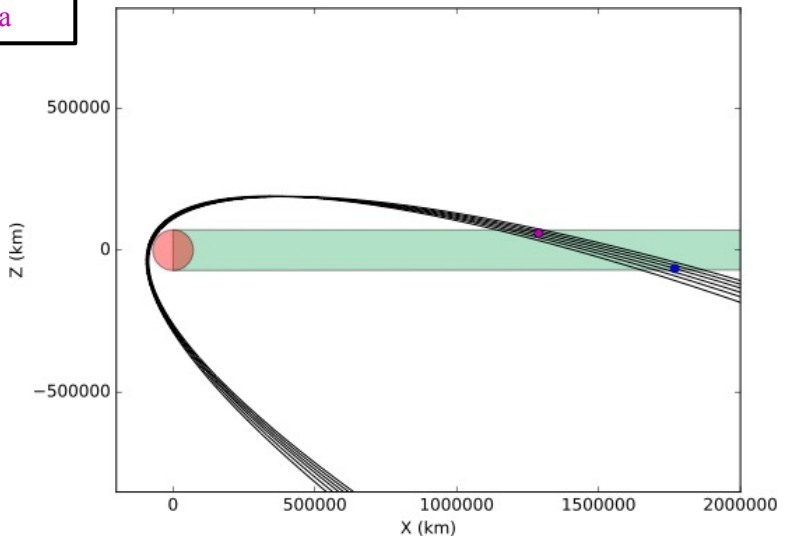


Umbral cone
Enter umbra
Exit umbra

27-day Orbits



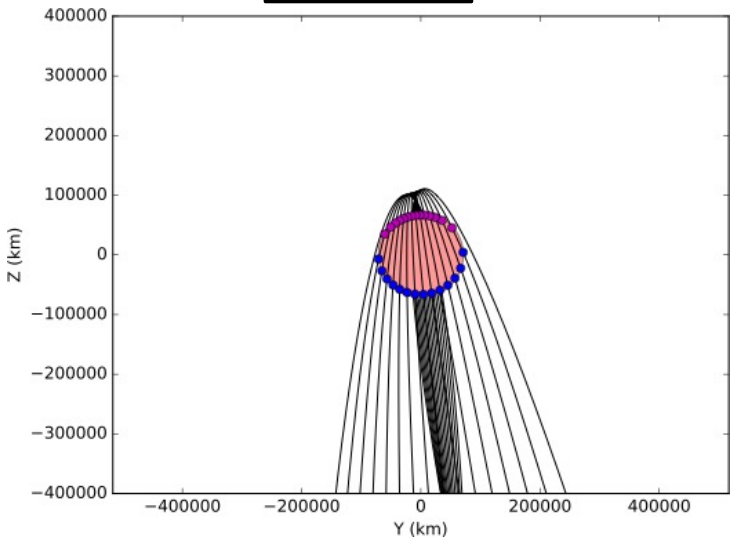
53-day Orbits



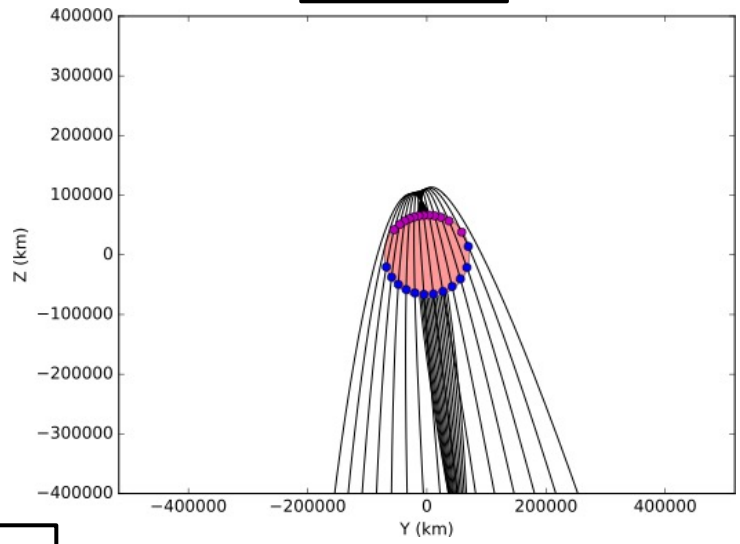
Solar Eclipse Geometry

Sun-Jupiter Rotating Frame, YZ-Projection

20-day Orbits

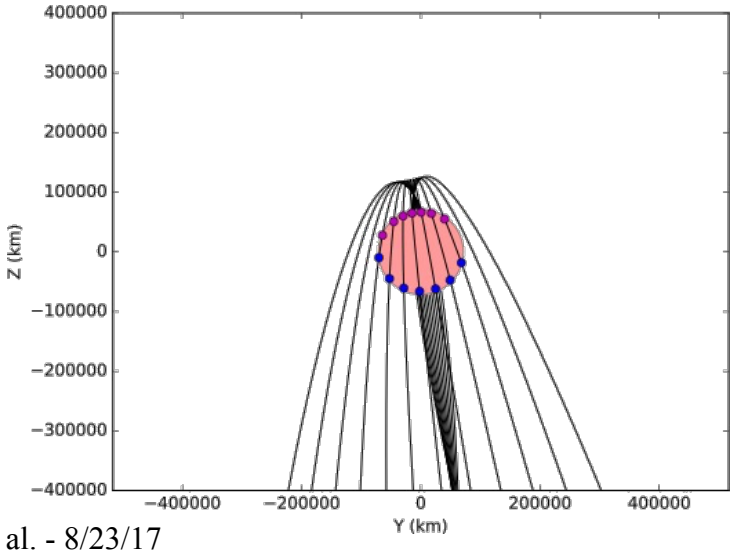


21-day Orbits

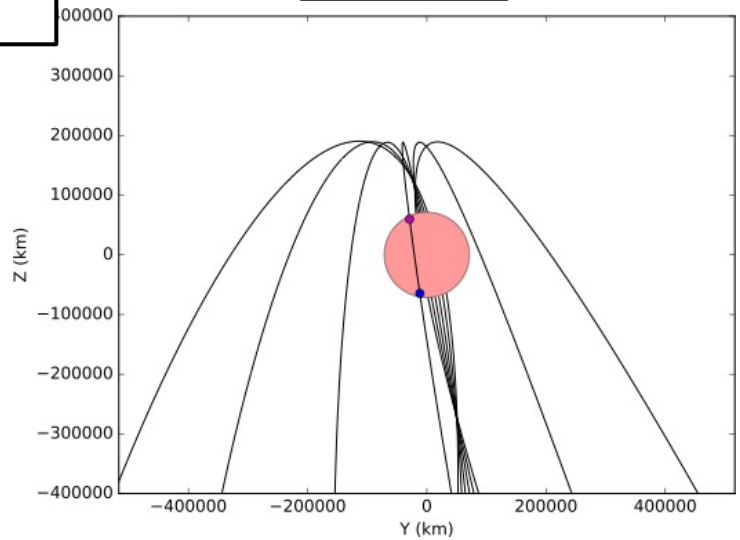


Umbral cone
Enter umbra
Exit umbra

27-day Orbits

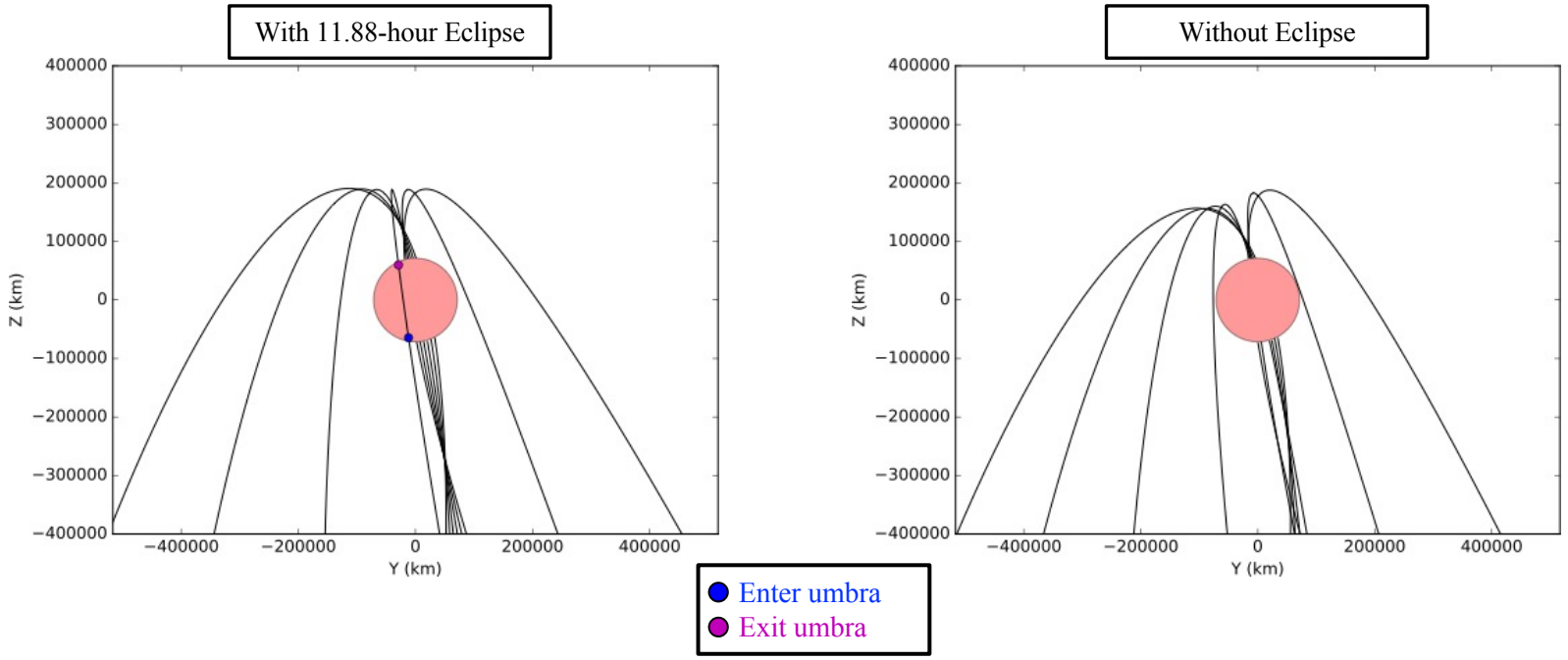


53-day Orbits



Eclipse Avoidance Strategy

53-day Science Orbit



- For the 53-day candidate reference trajectory, *complete* eclipse avoidance possible
  - Pre-PJ-22 apojove maneuvers to control inclination/nodal drift rate
  - Large, 50-60 m/s, APO-22 maneuver to change orbit plane and "step over" umbral cone

- No viable eclipse avoidance strategy for orbital periods < 53 days
  - Insufficient Delta-V to shift many perijove passes out of umbral cone
  - Satellite flybys briefly considered, but did not provide sufficient flyby gravity assist

Trajectory Options Summary

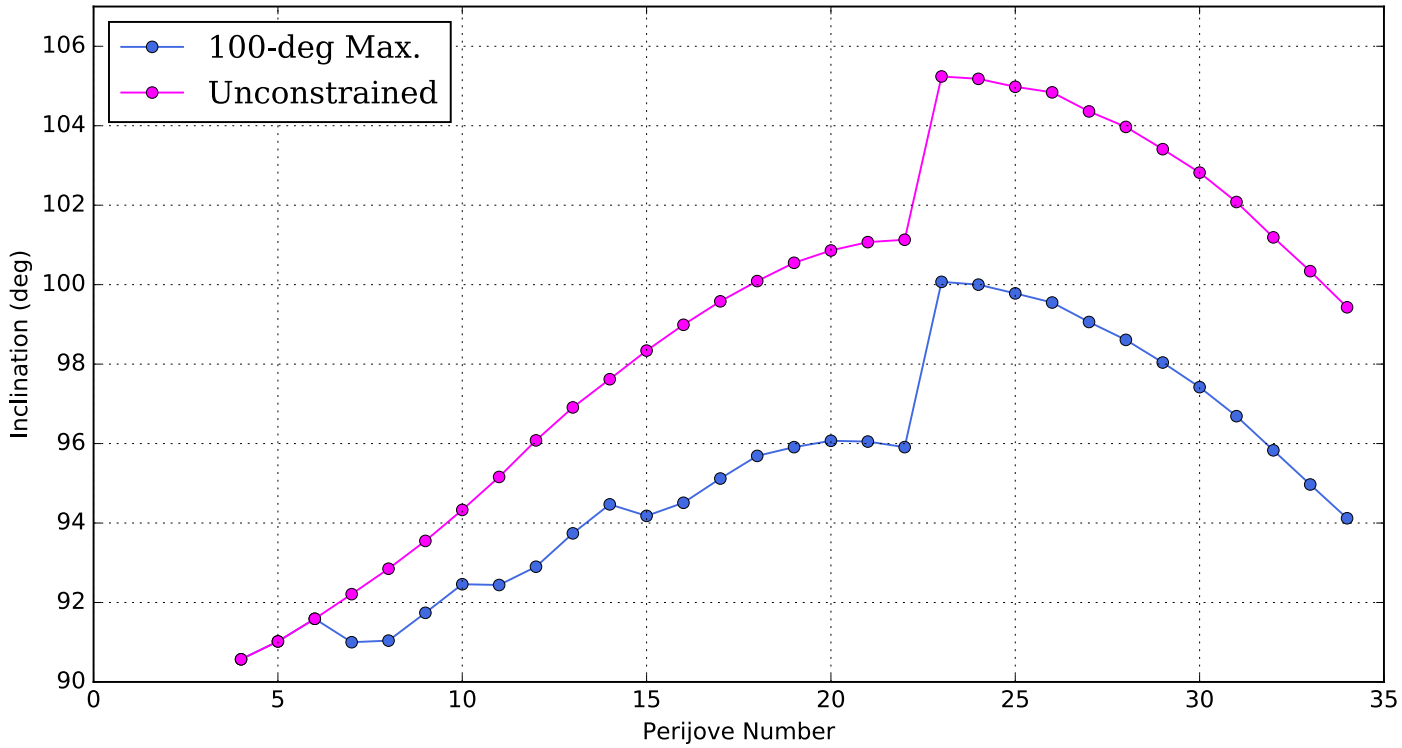
Period (days)	PRM Date	W. Lon. Shift (deg)	Max. Inc. (deg)	End of Mission	Pre-Eclipse Science PJs	Avail. DV Mean (m/s)
14	PJ02 (10/19/16)	270	90.6	2/20/18	70	169
20	PJ06 (5/19/17)	90	93.6	1/27/19	42	232
21	PJ06 (5/19/17)	236.25	93.8	1/27/19	40	233
	PJ07 (7/11/17)	236.25	94.3	3/31/19	38	218
53	N/A	270	98.0	9/11/19	20	336
	N/A	270	105.5	7/30/21	Avoids*	124

*Includes 53.0 m/s eclipse avoidance maneuver at APO-22

- Ultimately, two candidate reference trajectories were selected:
  1. PRM at PJ-07 with 21-day orbits
  2. 53-day orbits (No PRM)

- In February 2017, NASA Headquarters approved the Juno project's proposal to stay in 53-day orbits
  - Several topics, specific to 53-day orbits, left to consider:
    1. Accommodating solar conjunction
    2. Maintain inclination within mission requirements
    3. Maintain perijove altitude within mission requirements

53-day Reference Trajectory
Maximum Inclination

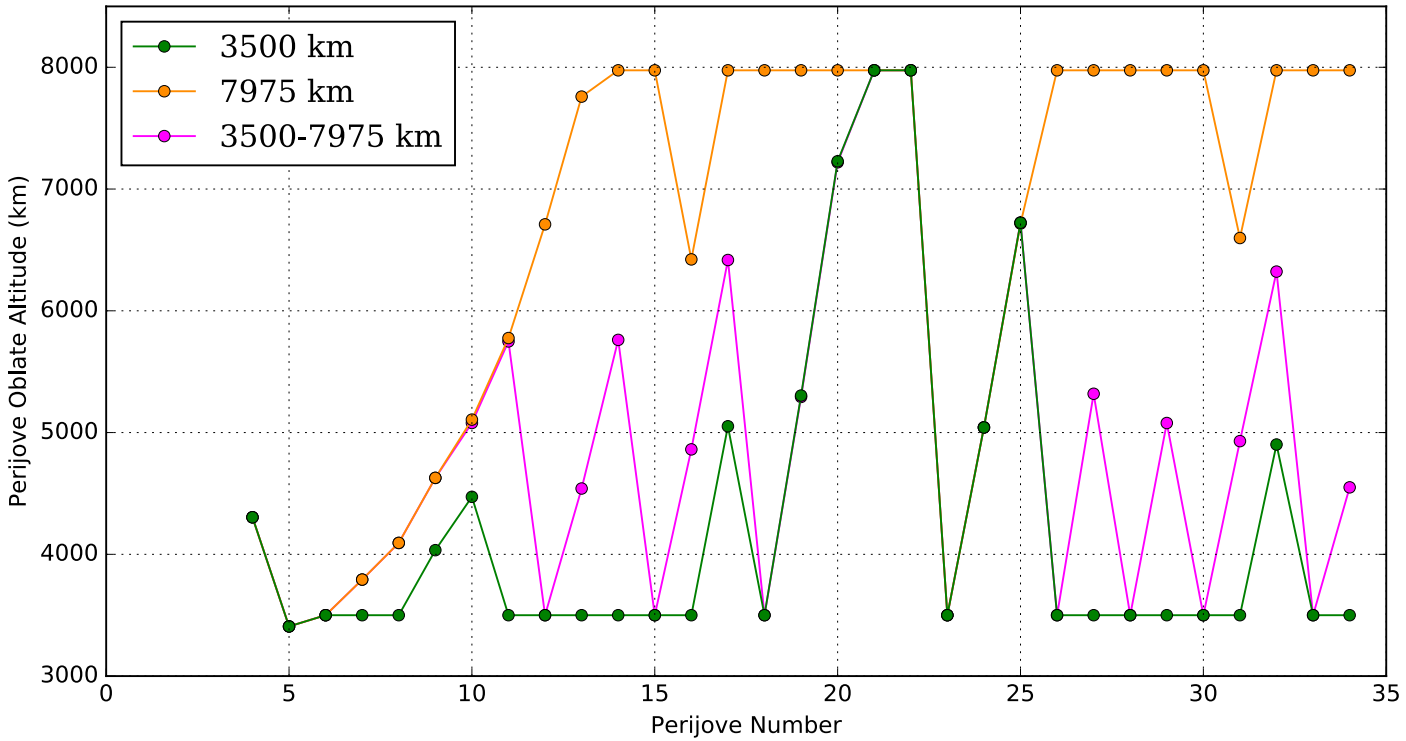


- Third-body gravitational effects dramatically increase inclination through eclipse season
  - Frequent, large apojove maneuvers required to maintain inclination within 90 deg +/- 10 deg
  - Without inclination constraints, inclination reaches maximum of 105.5 deg

- Project decided to relax inclination constraint since it did not significantly impact science, simplified operations, and saved nearly 60 m/s in Delta-V

53-day Reference Trajectory

Perijove Altitude

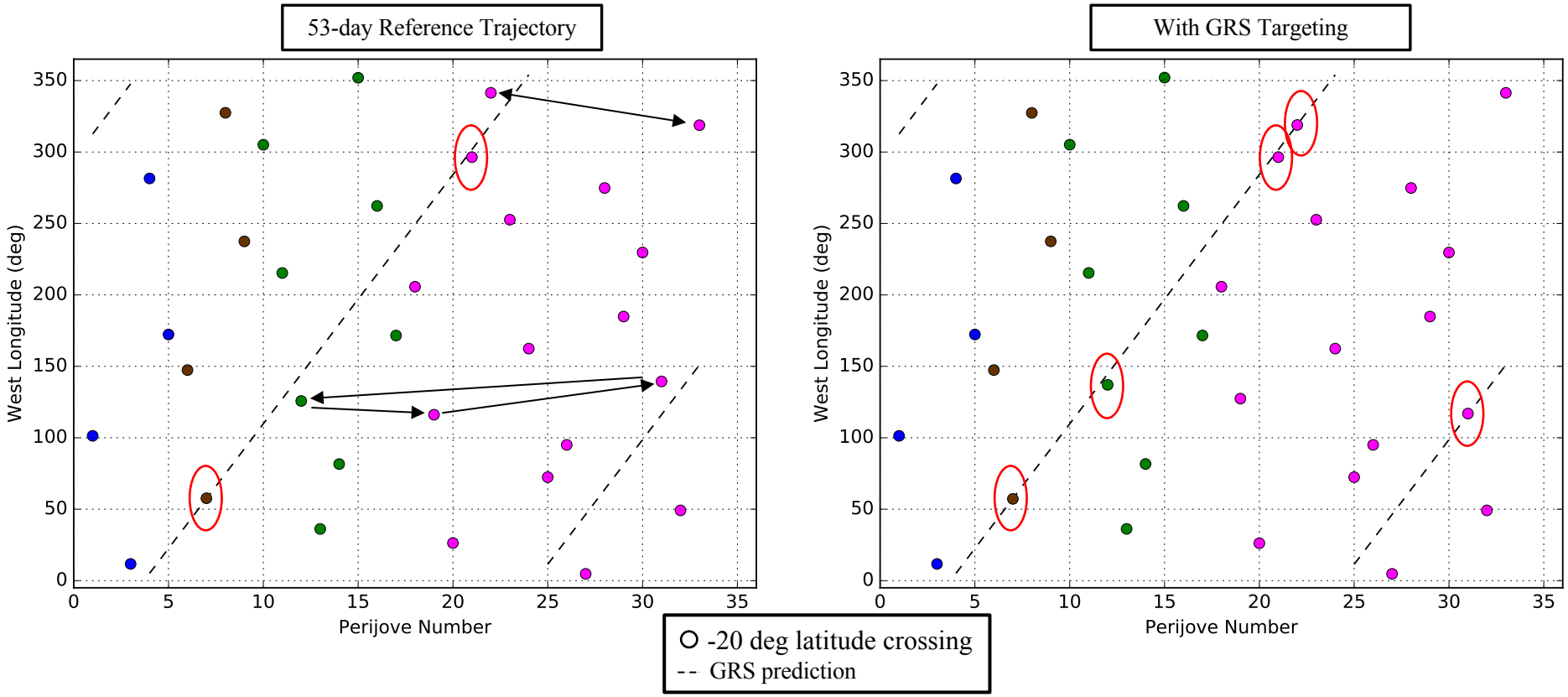


- Three strategies developed to main 3500 km < perijove altitude < 8000 km
  - Options must accommodate solar conjunction every ~7.5 orbits (closely aligned with apses)

- Ultimately, strategy was selected to maintain perijove altitude near 3500-km (when possible)
  - Perijove altitude increases around conjunction and prior to APO-22 eclipse avoidance maneuver

Future Trajectory Design Considerations

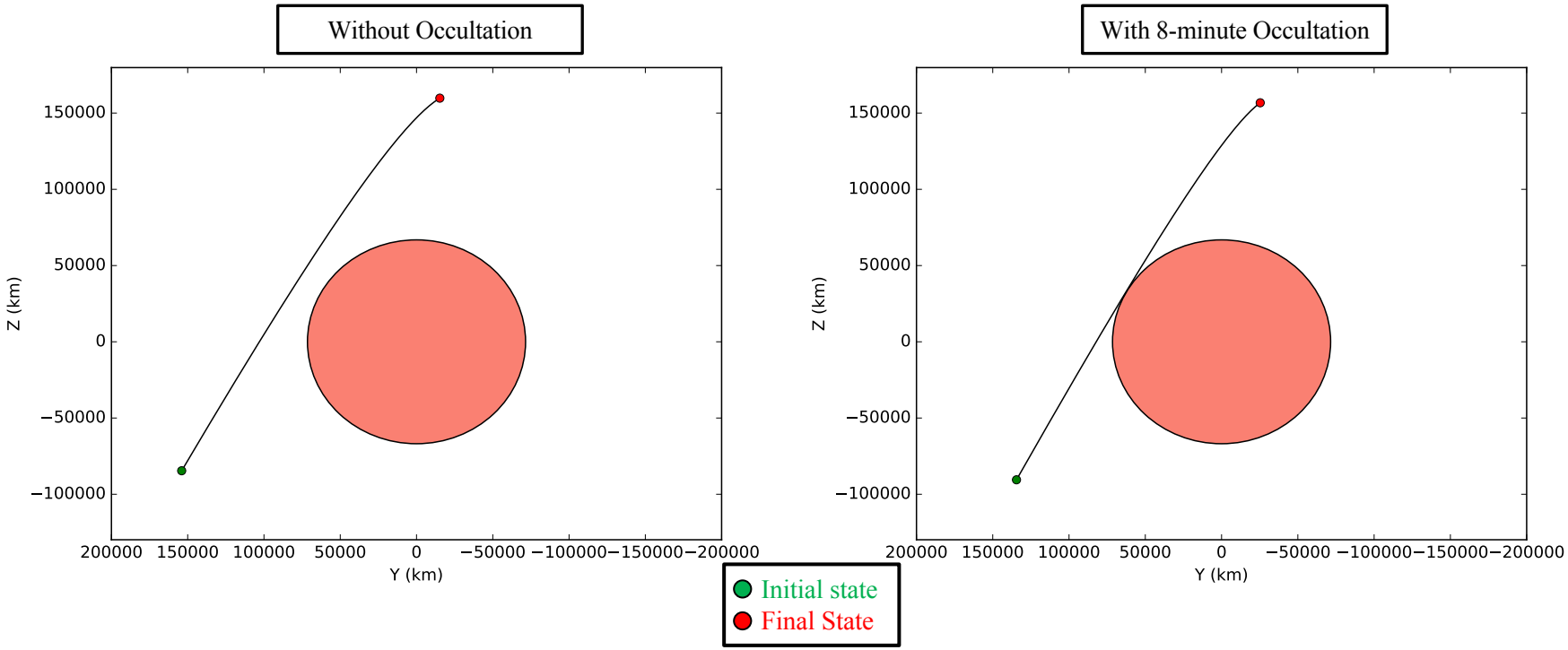
Great Red Spot (GRS) Targeting Strategy



- Juno's 53-day reference trajectory naturally includes GRS flyovers at PJ-07 and PJ-21
- Simple graphical technique developed to identify "longitude swaps" to generate additional future GRS flyover opportunities
  - Analysis of PJ-07 GRS science data will help determine utility of potential future GRS passes

Future Trajectory Design Considerations

Occultation Targeting Strategy (Earth-Jupiter Rotating Frame)



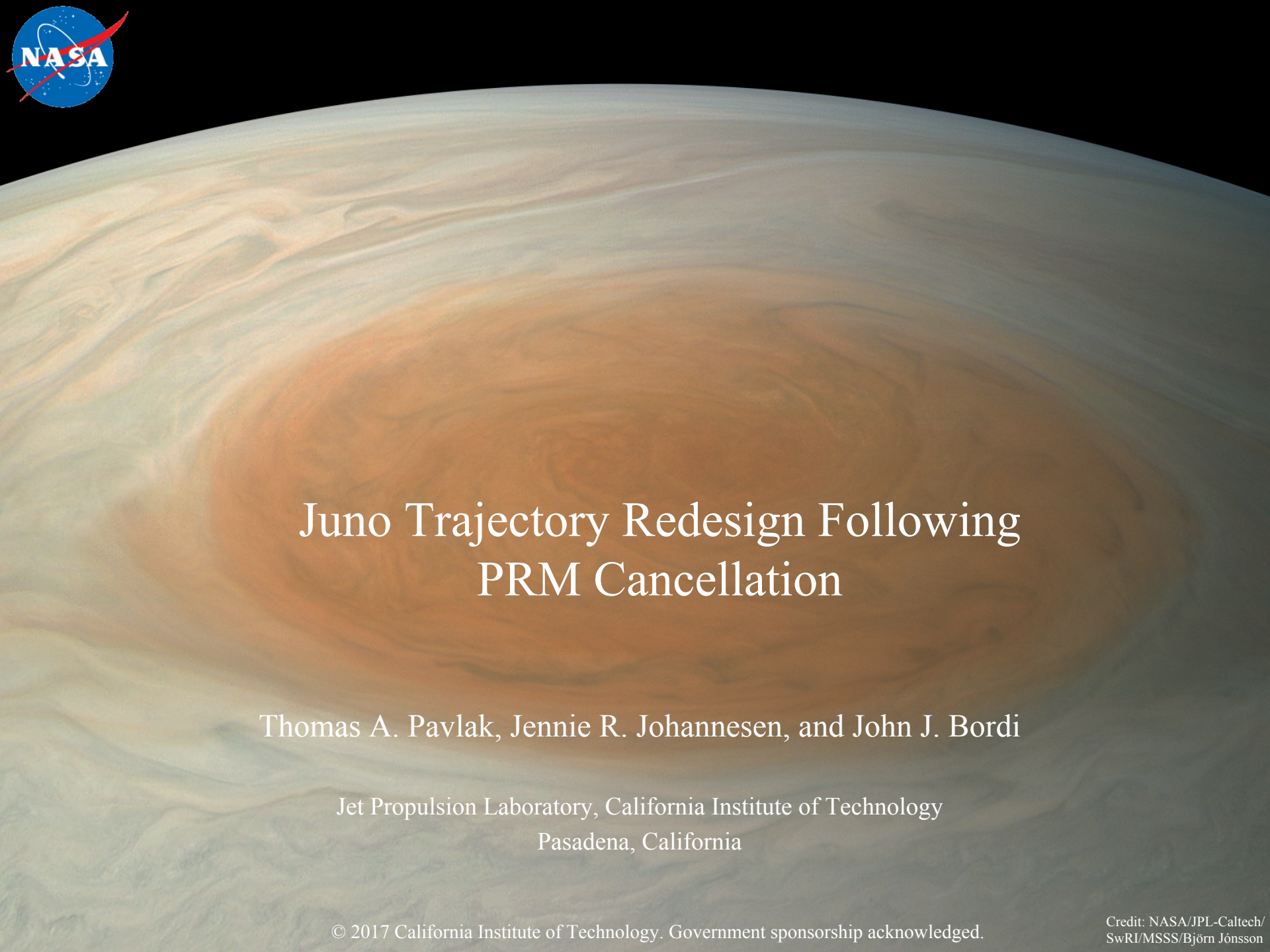
- Juno Science Team interested in making radiometric observations through Jupiter's atmosphere
  - Best opportunity inbound to PJ-23 (November 3, 2019)
  - Increasing APO-22 eclipse avoidance maneuver by ~15 m/s can generate 8-minute occultation
  - Occultation duration is directly correlated with APO-22 Delta-V

Concluding Remarks

- The Juno project faced multiple challenges following the scheduled PRM execution in October 2016:
  - Main engine pressurization anomaly
  - Decision to delay PRM
  - PJ-02 safe mode entry

- Fortunately, the Juno Navigation Team spent months prior to PRM developing robust design and analysis tools and anomaly-response strategies
  - Enabled rapid, short-term anomaly response following PRM delay and PJ-02 safe mode entry
  - Allowed consideration of many wide-ranging options during trajectory design trade study

- Today, Juno spacecraft is healthy and has been operating nominally along its current 53-day reference trajectory since March 2017
  - Completed 6 out of 32 planned science passes
  - Next event: PJ-08 science pass on September 1, 2017



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Back-up Slides

Solar Eclipse Geometry

Umbral Eclipses for Various Orbit Periods

Period (days)	Number of Eclipses	First Eclipse	Final Eclipse	Eclipse Duration (hrs)		
				Min.	Max.	Mean
20	14	25-Jul-2019	07-Apr-2020	0.93	3.50	2.64
21	12	25-Jul-2019	15-Mar-2020	0.77	3.74	2.84
27	7	31-Aug-2019	09-Feb-2020	1.32	5.12	3.89
53	1	02-Nov-2019	02-Nov-2019	11.88	11.88	11.88