Maneuver Design for the Juno Mission: Inner Cruise

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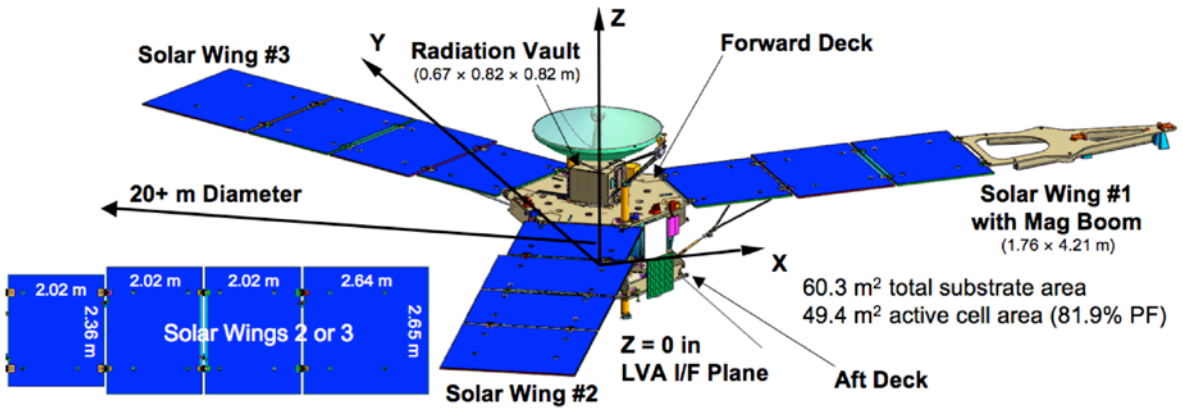
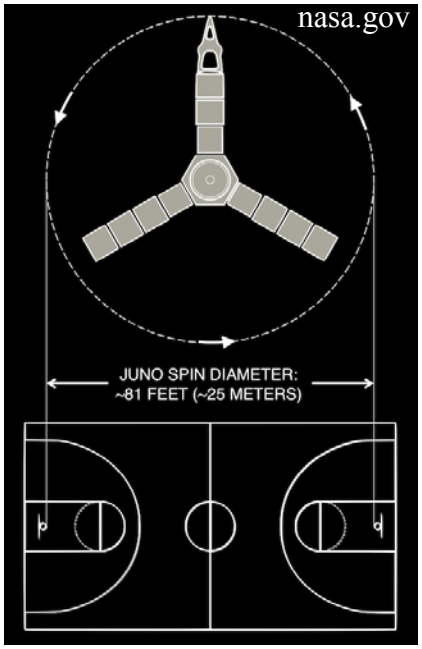
Mission Overview

- First solar-powered spacecraft to travel to the outer solar system
  - Built by Lockheed Martin
  - Mission design, navigation, and operations at JPL
- Second mission in NASA New Frontiers Program
  - PI: Dr. Scott Bolton, SwRI
- Will nominally operate at Jupiter for one year in 11-day eccentric polar orbit
  - Study Jupiter's origin and evolution through atmospheric and magnetospheric observations
  - Make detailed gravity measurements
- Mission phases:
  - "Inner Cruise"
    - Launch through Earth flyby cleanup
  - "Outer Cruise"
    - Earth flyby cleanup through Jupiter arrival

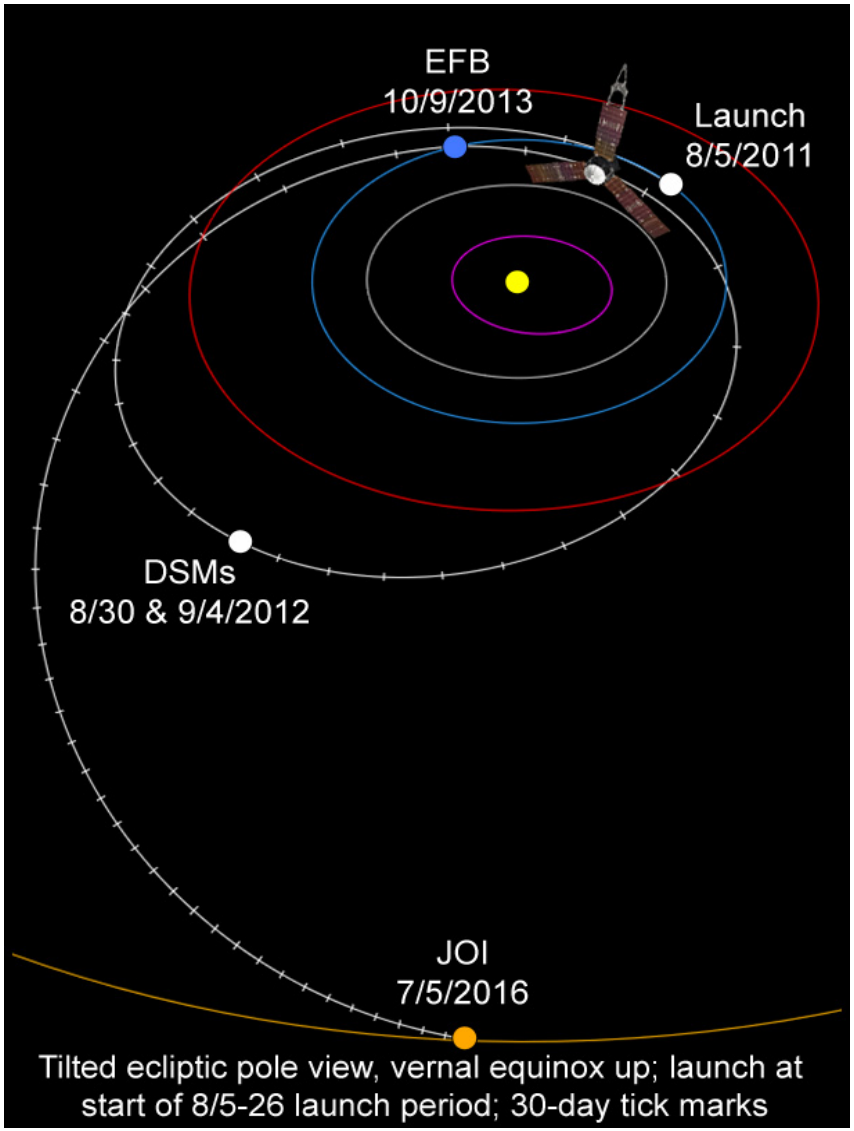
Juno Spacecraft





- Powered by three large solar panels (20+ m spin diameter)
- Spin-stabilized about +Z axis
  - High gain antenna (HGA) parallel to +Z axis
  - Main engine parallel to –Z axis
    - Thrust = 662 N
    - Isp = 318.6 seconds
- Reaction control system (RCS) consists of four rocket engine modules (REMs)
  - Forward and aft decks each house two REMs
  - Each REM consists of three, 4.5 N thrusters
    - 1 axial thruster
    - 2 lateral thrusters

Juno Reference Trajectory



- Launched into heliocentric trajectory in August 2011
- Two large Deep Space Maneuvers (DSMs) near aphelion
- Earth Gravity Assist slightly more than 2 years after launch, hence "2+ ΔV-EGA"
- Jupiter Orbit Insertion (JOI) on July 5, 2016 to capture into 107-day polar orbit
- Period Reduction Maneuver (PRM) delivers Juno to 11-day science orbit
  - 30 orbit nominal mission
  - Generates mesh along Jovian equator with 12° longitudinal spacing
- Mission ends with Jupiter impact in 2017

Maneuver Operations Strategy

- Nine TCMs (plus two contingency TCMs) planned during Juno Inner Cruise phase
  - Three deterministic, six statistical
  - One maintenance main engine flush (MEF-1)

- Spacecraft spin rate varies depending on mission phase
  - 1 rpm during interplanetary cruise
  - 2 rpm during Jupiter orbit phase, post-DSM cleanup maneuver, select pre- and post-Earth flyby (EFB) TCMs, and instrument checkout and calibration
  - 5 rpm during main engine burns

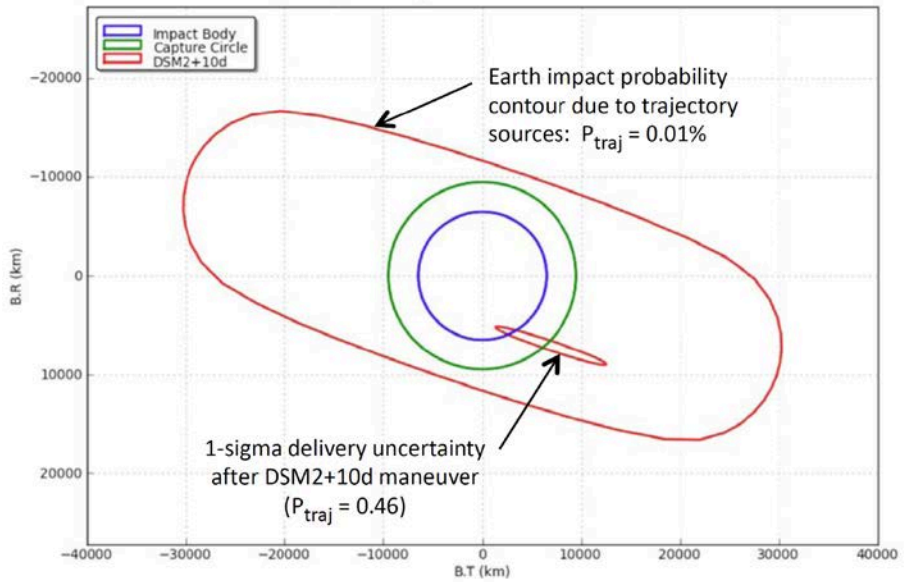
- Two Maneuver Implementation Modes:
  - Vector mode
    - Spacecraft burns at cruise attitude
    - Burn decomposed into separate – but coordinated – axial and lateral components
    - Makes use of RCS thrusters and used for all maneuvers except DSM-1 & 2, JOI, & PRM
  - Turn-burn-turn
    - Spacecraft turns to burn attitude, fires engine, and turns back to cruise attitude
    - Used for main engine burns
      - DSM-1, DSM-2, JOI, and PRM

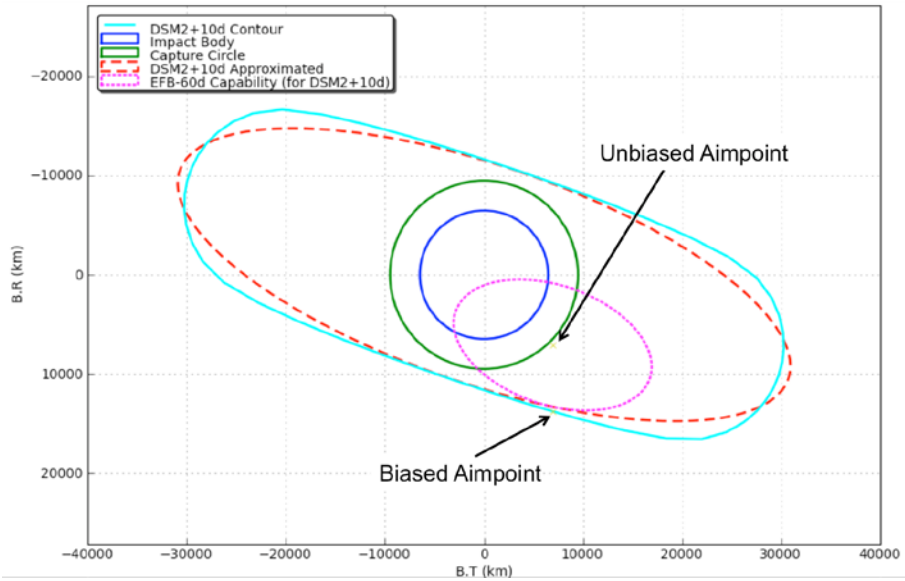
Launch and Post-Launch TCMs

- Launched August 5, 2011 from Cape Canaveral, Florida aboard an Atlas V 551
  - First day of 21-day launch period
  - Launch $C_3 = 31.10\ km^2/s^2$
- TCM-1 scheduled 20 days after launch
  - Canceled due to accurate launch injection
- TCM-2 scheduled 180 days after launch
  - Target: DSM-1 Cartesian initial state
  - Vector mode RCS burn:
    - 864 mm/s axial
      - Designed: 867 mm/s
      - $\sigma = 5.29$ mm/s
    - 843.66 mm/s lateral
      - Designed: 844 mm/s
      - $\sigma = 15.04$ mm/s

Deep Space Maneuvers

Earth Flyby Altitude Biasing Strategy





- August 5, 2011 launch date required Earth gravity assist altitude of only 560 km
  - B·R = 7,075 km
  - B·T = 6,930 km
- DSM-2 cleanup, TCM-5, executes 10 days after DSM-2
- Pre-launch analysis showed that, due to execution errors, Juno had post-TCM-5 impact probability of P_{traj} = 0.46
- P_{traj} was deemed unacceptably high by the project as it would remain unchanged for ~1 year
- "Universal" biased aimpoint selected to reduce P_{traj} below 0.01% across 21-day period
  - B·R = 14,000 km
  - B·T = 7,000 km

Deep Space Maneuvers
DSM-1 and DSM-2

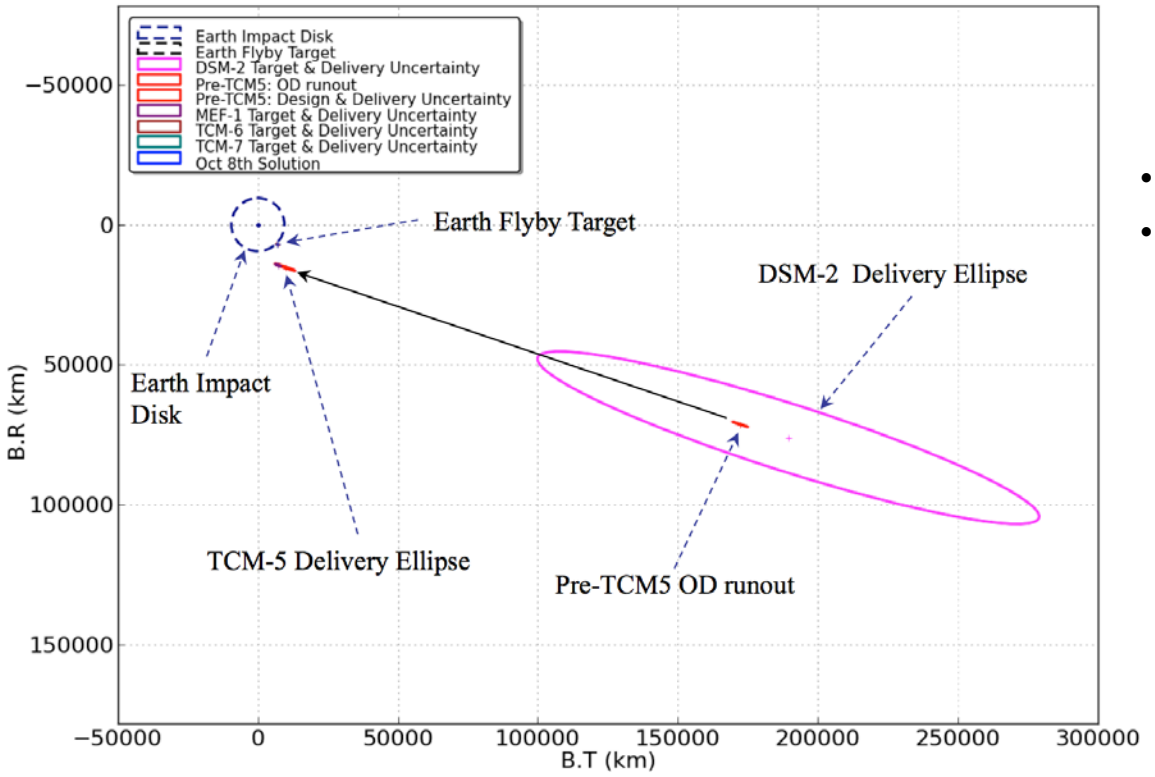
- Two deep space maneuvers executed near aphelion in late Summer 2012 to setup the Earth Flyby required to reach Jupiter
  - Divided into two burns because main engine not qualified for required single burn duration
  - Both DSMs designed several months in advance and implemented as turn-burn-turn maneuvers
  - Designed utilizing aforementioned Earth flyby altitude biasing strategy

- DSM-1: August 30, 2012
  - Target: DSM-2 Cartesian initial state
  - Main engine burn:
    - 344.284 m/s
      - Designed: 344.151 m/s
      - σ = 401.86 mm/s

- DSM-2: September 14, 2012
  - Delayed 10 days to investigate high oxidizer line temperatures/pressure observed during DSM-1
  - Target: biased Earth flyby B-plane aimpoint
  - Main engine burn:
    - 387.941 m/s
      - Designed: 387.722 m/s
      - σ = 452.65 mm/s

Deep Space Maneuvers

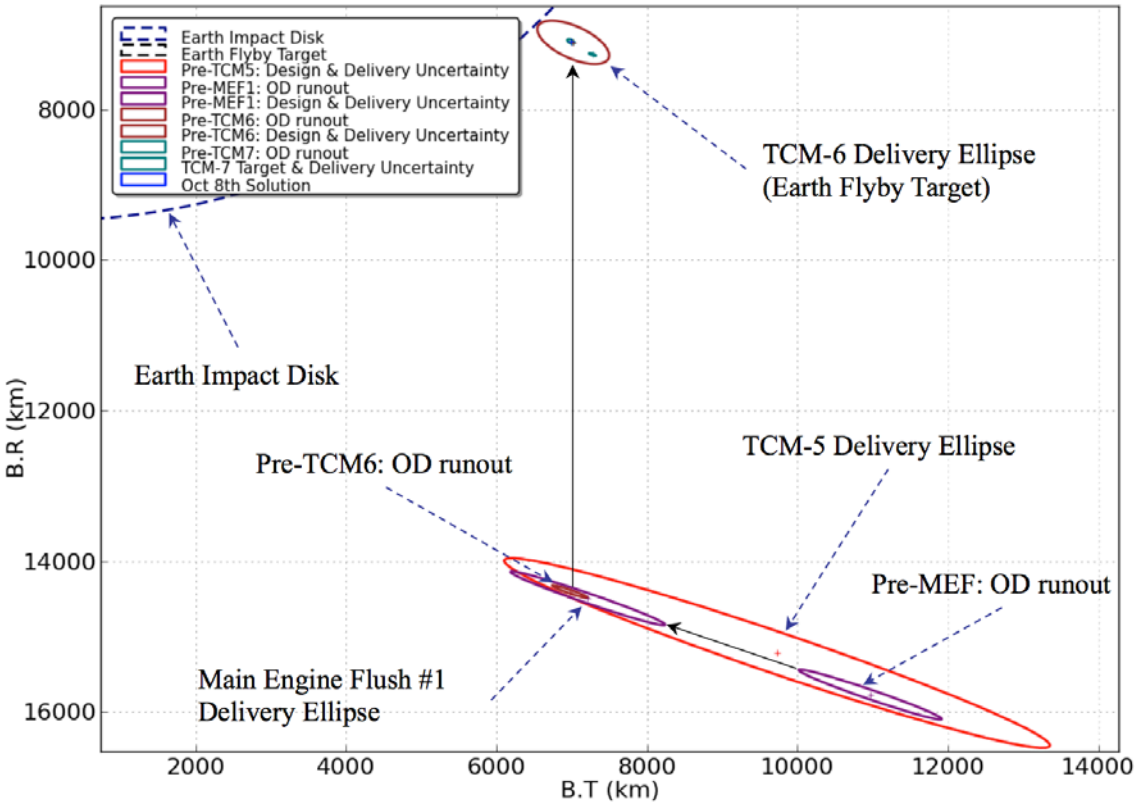
DSM Cleanup Maneuver: TCM-5



- TCM-5: October 10, 2012 (DSM-2 + 19 days)
- Target: biased Earth flyby aimpoint
  - Vector mode RCS burn:
    - 428 mm/s axial
      - Designed: 424 mm/s
      - σ = 3.12 mm/s
    - 1.714 m/s lateral
      - Designed: 1.720 m/s
      - σ = 15.17 mm/s

Pre-Earth Flyby Maneuvers

Targeting Earth Flyby: TCM-6

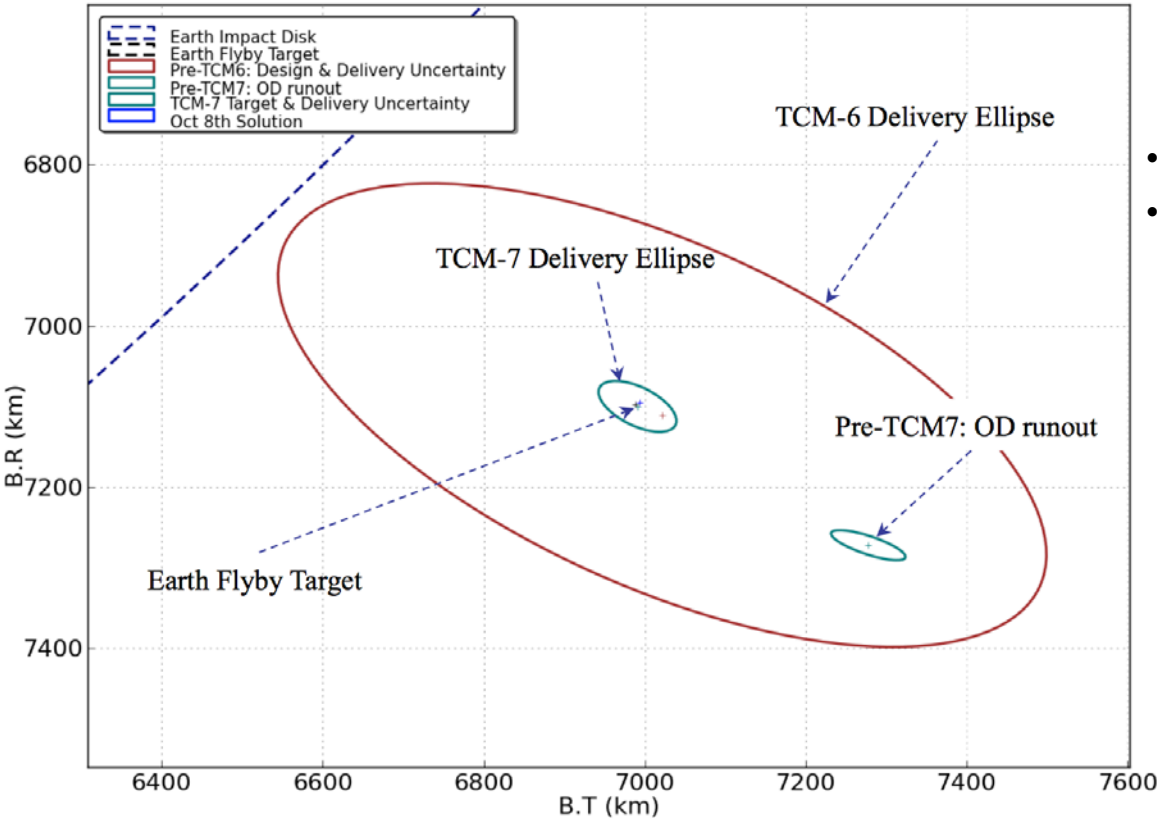


- First main engine flush (MEF-1) executed May 1, 2013
  - 5 second duration
  - 1.1 m/s

- TCM-6: August 7, 2013 (EFB - 63 days)
- Target: Earth flyby aimpoint
  - Vector mode RCS burn:
    - 1.462 m/s axial
      - Designed: 1.457 m/s
      - $\sigma = 8.50$ mm/s
    - 3.096 m/s lateral
      - Designed: 3.093 m/s
      - $\sigma = 15.56$ mm/s
- Deterministic maneuver
- Largest RCS burn to date

Pre-Earth Flyby Maneuvers

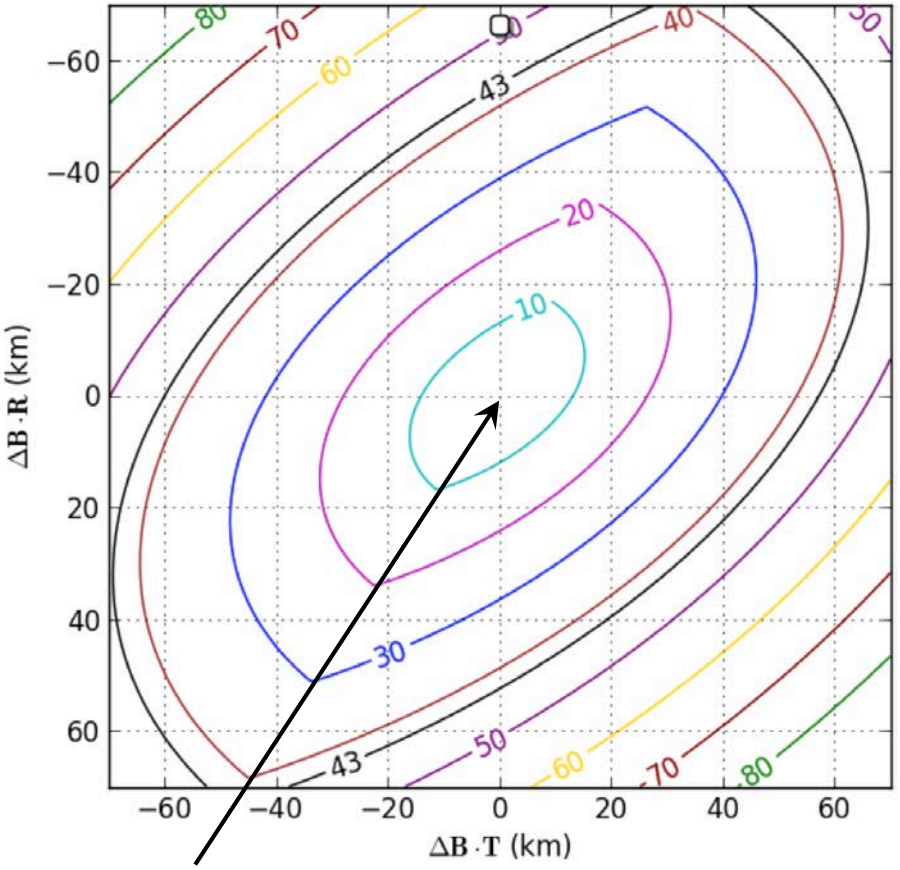
Targeting Earth Flyby: TCM-7



- TCM-7: September 9, 2013 (EFB - 30 days)
- Target: Earth flyby aimpoint (same as TCM-6)
  - Vector mode RCS burn:
    - 124 mm/s axial
      - Designed: 119 mm/s
      - $\sigma = 2.11$ mm/s
    - 52.2 mm/s lateral
      - Designed: 49.6 mm/s
      - $\sigma = 15.0$ mm/s

Pre-Earth Flyby Maneuvers

TCM-8 Cancellation Criteria

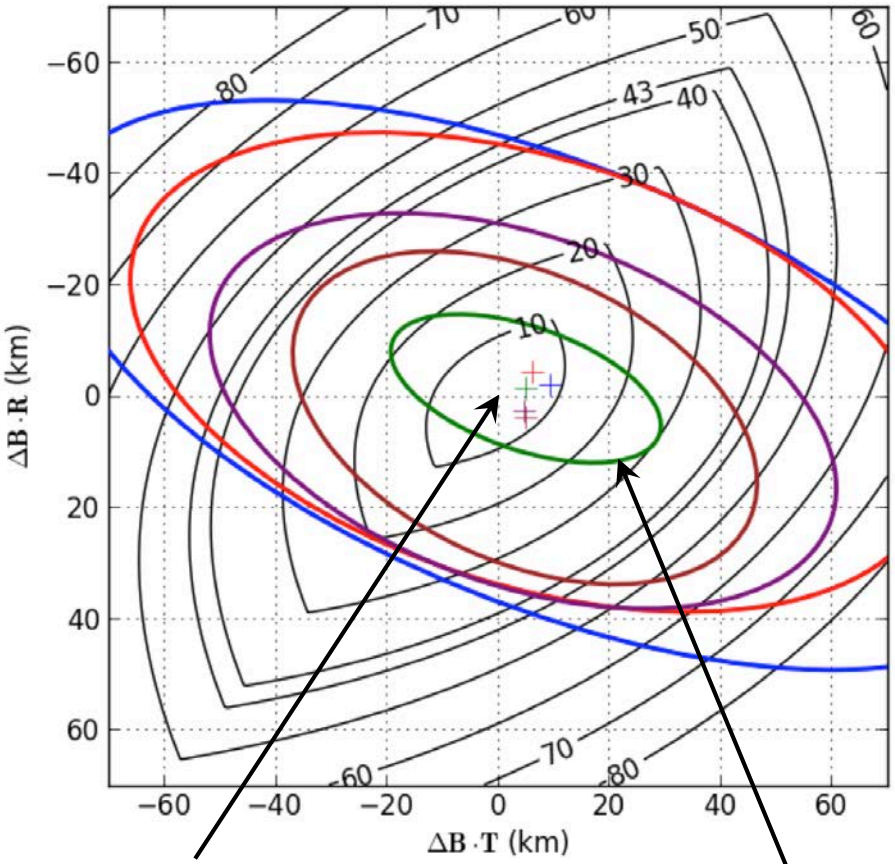


Earth Flyby Target

- TCM-8 planned 10 days prior to Earth closest approach
  - Not desirable to execute maneuver unless necessary
- Impact of cancelling TCM-8 analyzed by mapping TCM-9 propellant costs to the Earth B-plane
  - 43 kg contour represents propellant budgeted for TCM-9 ΔV99 of 23.2 m/s
- TCM-8 would be canceled if post-TCM-7 3-σ orbit determination (OD) solution was within 43-kg contour

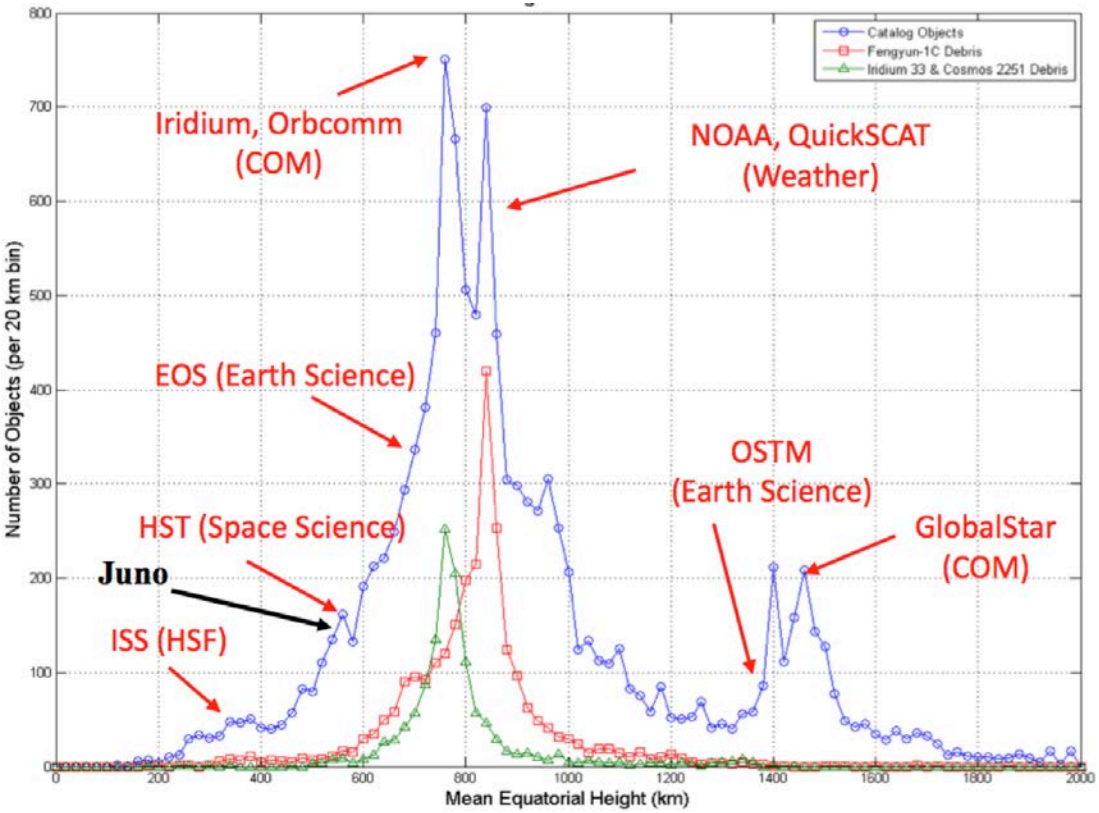
Pre-Earth Flyby Maneuvers

TCM-8 Cancellation Criteria



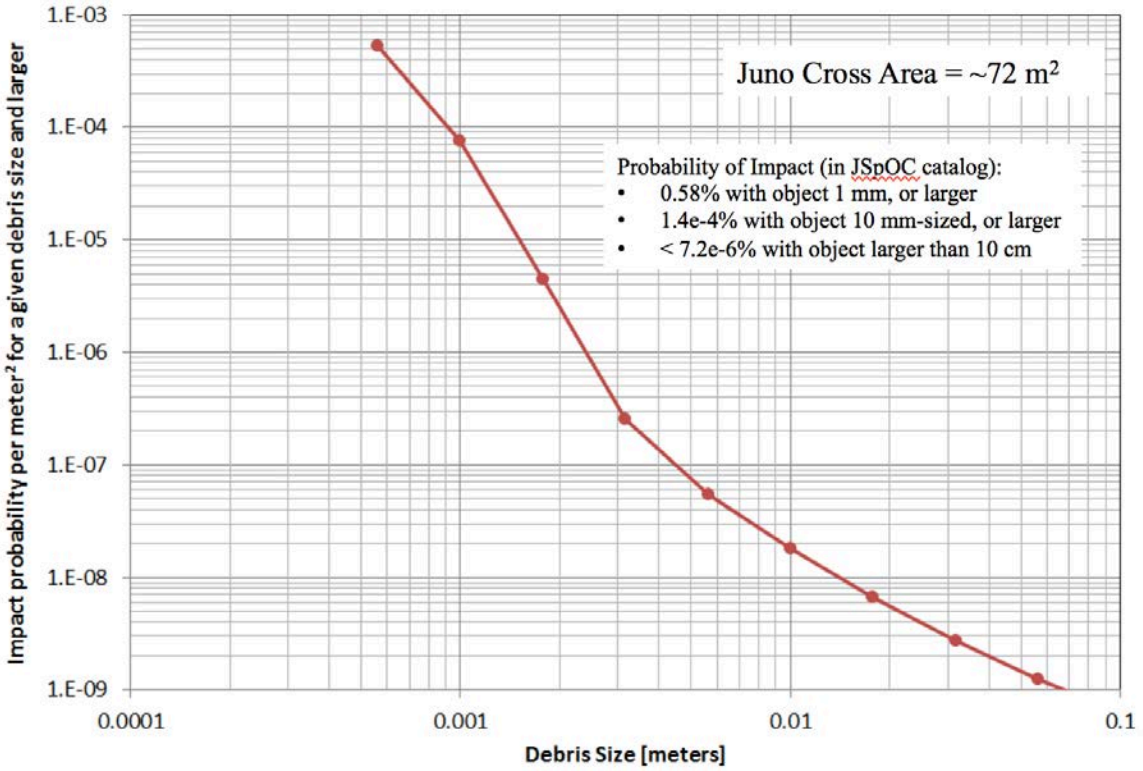
- TCM-8 planned 10 days prior to Earth closest approach
  - Not desirable to execute maneuver unless necessary
- Impact of cancelling TCM-8 analyzed by mapping TCM-9 propellant costs to the Earth B-plane
  - 43 kg contour represents propellant budgeted for TCM-9 ΔV99 of 23.2 m/s
- TCM-8 would be canceled if post-TCM-7 3-σ orbit determination (OD) solution was within 43-kg contour
- September 22, 2013 OD solution (green) was generated 17 days prior to Earth flyby
  - Error ellipse well within 43-kg propellant cost contour so **TCM-8 canceled**
  - TCM-8a contingency maneuver canceled by default

Earth Flyby
Conjunction Assessment



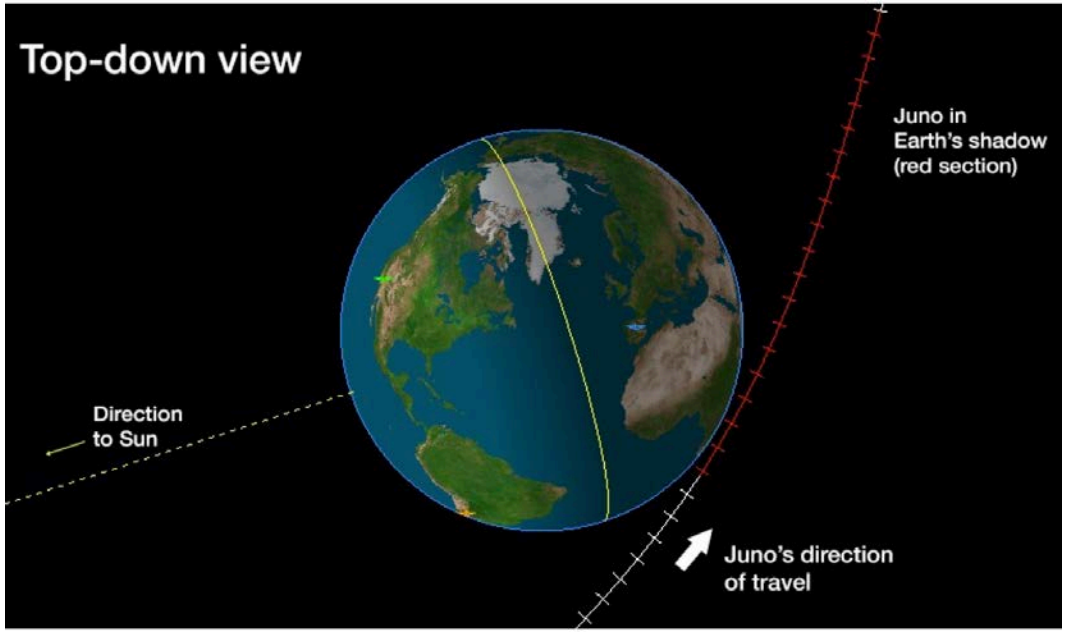
- Juno had designed EFB altitude of ~560 km

Earth Flyby
Conjunction Assessment



- Juno had designed EFB altitude of ~560 km
- Small, but nonzero chance of impacting object in JSpOC catalog (larger than 10 cm)
- Daily ephemerides/covariances delivered to CARA at GSFC for 10 days prior to EFB
- Two collision avoidance maneuvers (CAMs) pre-designed to shift time of closet approach (TCA) by approximately +/- 1 second
- Executed only if both of following satisfied:
  - Probability of impact > 0.01%
  - One of CAMs reduced probability of impact by factor of more than 100
- In the end, Juno came no closer than 26 km to any catalog object and the CAM was **canceled**

Earth Flyby
Earth Flyby Delivery

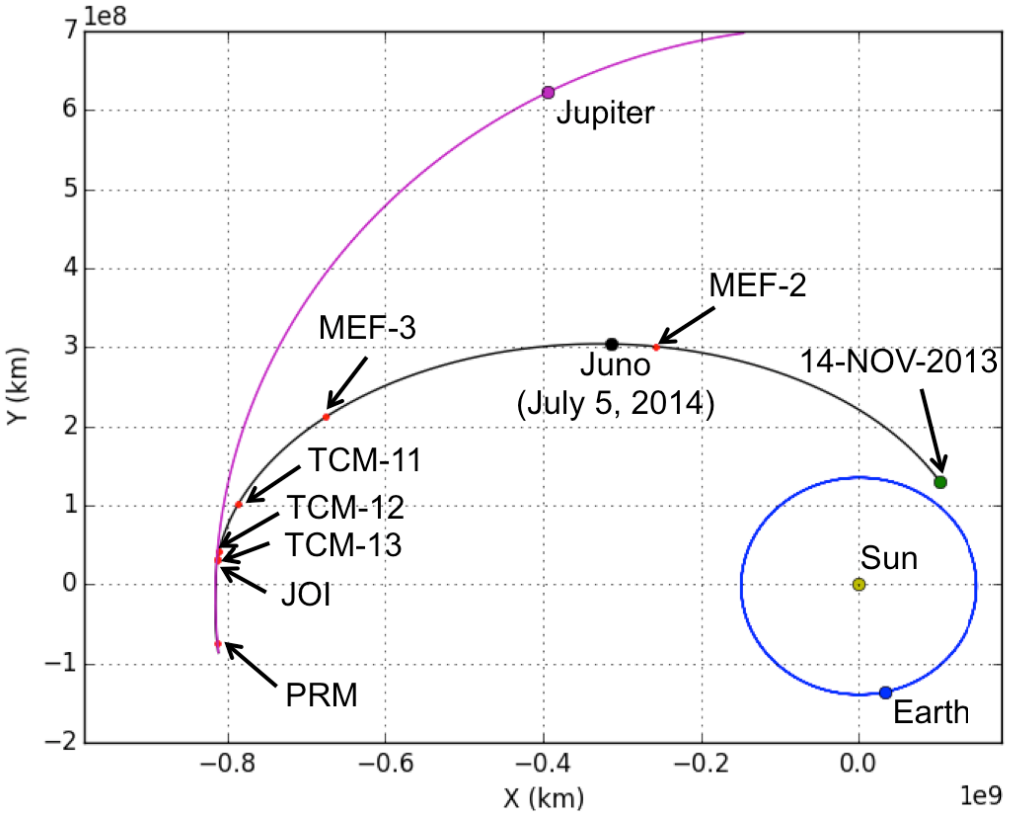


See EFB video here

- Juno completed successful Earth flyby on October 9, 2013 19:21:24 UTC
  - EFB characteristics, relative to Earth:
    - Altitude = 561 km
    - Velocity = 14.9 km/s
  - Closest approach off South African coast
  - 20 minute eclipse (only post-launch eclipse of entire mission)
- Deviation from EFB target:
  - 6 km in B-plane
  - TCA differed by 0.17 seconds
- Deviation from pre-TCM-8 OD solution:
  - 1 km in B-plane
  - TCA differed by 0.05 seconds

Post-Earth Fly and Outer Cruise

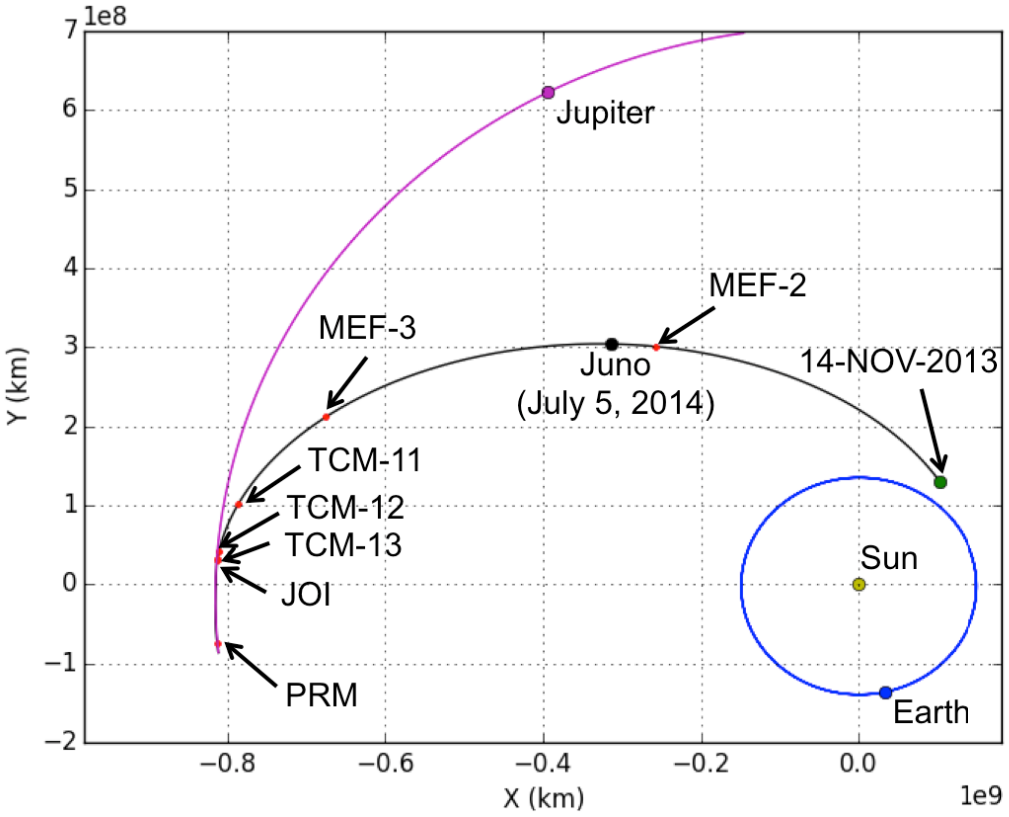
Earth Flyby Cleanup: TCM-9



- TCM-9: November 13, 2013 (EFB + 34 days)
- Target: TCM-12 Cartesian initial state (JOI – 34 days)
  - Vector mode RCS burn:
    - 1.324 m/s axial
      - Designed: 1.320 m/s
      - σ = 7.74 mm/s
    - 1.543 m/s lateral
      - Designed: 1.539 m/s
      - σ = 15.14 mm/s
- Delayed 13 days due to EFB safe mode events
  - Did not significantly impact trajectory or planned science activities

Post-Earth Fly and Outer Cruise

Outer Cruise



- TCM 10: April 9, 2014
  - Canceled due to highly accurate Earth flyby and TCM-9 execution
- MEF-2: executed May 1, 2013
  - 5 second duration
  - 1.1 m/s
- Future maneuvers:
  - MEF-3: June 2015
  - TCM-11: February 2016

Summary and Concluding Remarks

Maneuver	Epoch ET	ΔV (m/s)	ΔV99 (m/s)
TCM-1	8/25/11	-	3.9
TCM-2	2/1/12	1.2	0.5
DSM-1	8/30/12	344.3	360.1
DSM-2	9/14/12	387.9	394.8
TCM-5	10/3/12	1.8	9.2
TCM-6	8/7/13	3.4	5.5
TCM-7	9/9/13	0.1	0.4
TCM-8	9/29/13	-	0.2
EFB	10/9/13	7,300	
TCM-9	11/13/13	2.0	14.9
TCM-10	4/9/14	-	0.9

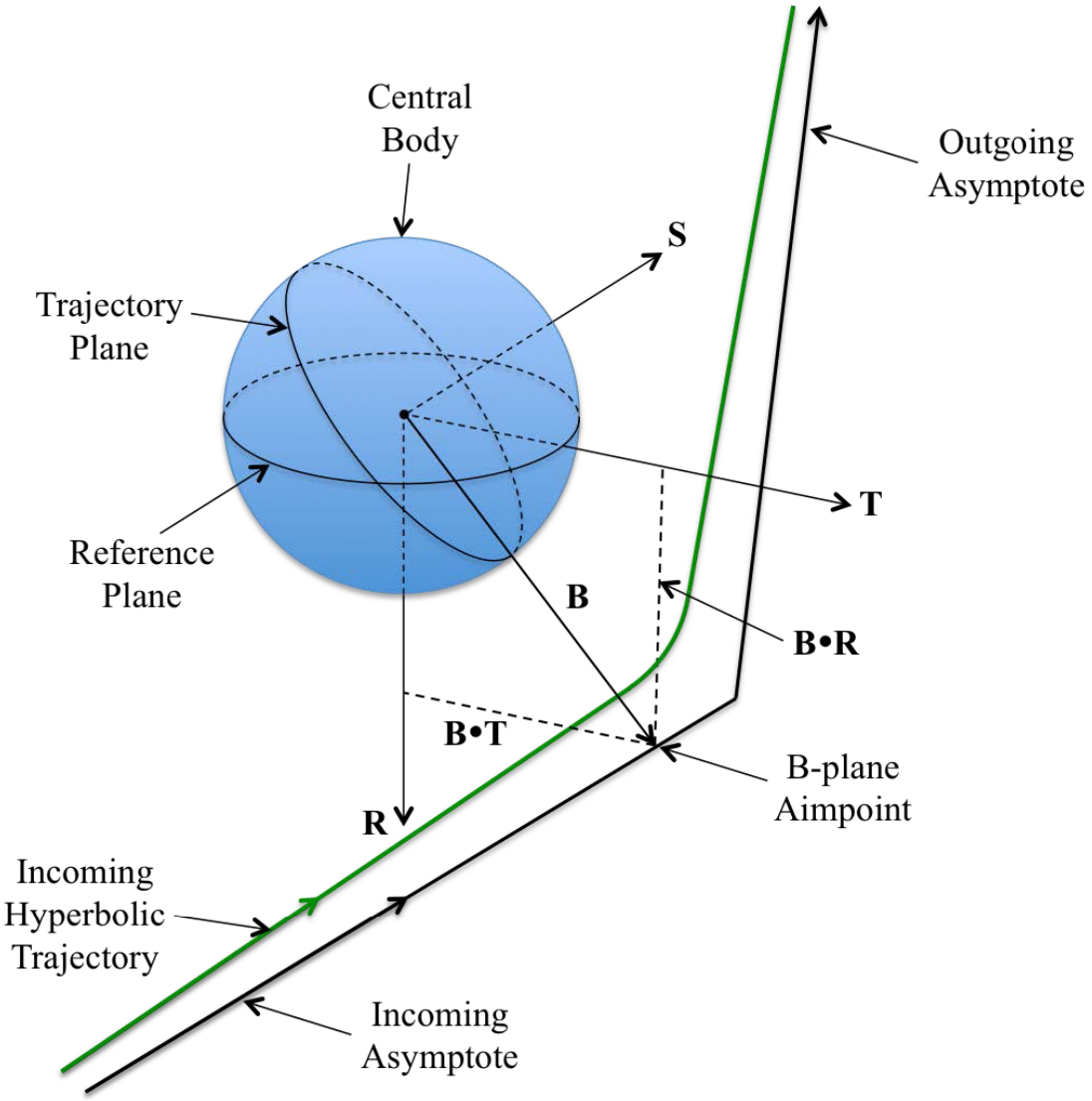
- To date, Juno has successfully executed all maneuvers nominally and as designed
  - Six pre-Earth flyby TCMs
  - One post-Earth flyby TCM
  - Two main engine flush maneuvers
- Only one maneuver, TCM-2, was larger than its pre-launch ΔV99 value
  - Explained by the cancellation of TCM-1
- From a navigation perspective, the EFB on October 9, 2013 was a complete success
- Currently, Juno continues to operate successfully in its Outer Cruise phase and is on-track for a nominal arrival at Jupiter on July 5, 2016

Acknowledgments

- Is there an “official” NASA/JPL/Cal Tech acknowledgement we need to make?

Back-up Slides

B-Plane Description



Maneuver Performance

Estimated and Designed Magnitudes

Maneuver	Est. ΔV (m/s)	Designed ΔV (m/s)	AP σ (mm/s)
TCM-2 Axial	0.864	0.867	5.29
TCM-2 Lateral	0.844	0.844	15.04
DSM-1	344.284	344.151	401.86
DSM-2	387.941	387.722	452.65
TCM-5 Axial	0.428	0.424	3.12
TCM-5 Lateral	1.714	1.720	15.17
TCM-6 Axial	1.462	1.457	8.50
TCM-6 Lateral	3.096	3.093	15.56
TCM-7 Axial	0.124	0.119	2.11
TCM-7 Lateral	0.0522	0.0496	15.00
TCM-9 Axial	1.324	1.320	7.74
TCM-9 Lateral	1.543	1.539	15.14

Maneuver Performance

Estimated and Designed Pointing – Right Ascension

Maneuver	Est. RA (deg)	Designed RA (deg)	$AP\ \sigma$ (deg)
TCM-2 Axial	51.179	51.179	0.145
TCM-2 Lateral	144.433	144.778	0.868
DSM-1	62.173	62.148	0.243
DSM-2	62.203	62.197	0.243
TCM-5 Axial	344.157	344.184	0.213
TCM-5 Lateral	74.412	74.110	1.227
TCM-6 Axial	118.333	118.338	0.205
TCM-6 Lateral	6.667	6.620	1.490
TCM-7 Axial	164.347	164.390	0.392
TCM-7 Lateral	53.873	61.012	7.794
TCM-9 Axial	264.837	264.820	0.241
TCM-9 Lateral	253.906	254.704	1.992

Maneuver Performance

Estimated and Designed Pointing – Declination

Maneuver	Est. Dec. (deg)	Designed Dec. (deg)	$AP\ \sigma$ (deg)
TCM-2 Axial	18.593	18.597	0.138
TCM-2 Lateral	16.330	16.365	0.833
DSM-1	19.456	19.501	0.229
DSM-2	19.520	19.500	0.229
TCM-5 Axial	-6.703	-6.750	0.212
TCM-5 Lateral	20.507	19.969	1.153
TCM-6 Axial	20.921	20.901	0.191
TCM-6 Lateral	39.134	39.362	1.148
TCM-7 Axial	6.669	6.665	0.389
TCM-7 Lateral	53.250	54.466	4.530
TCM-9 Axial	-37.439	-37.453	0.192
TCM-9 Lateral	54.670	54.542	1.155