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 $C_3 = 31.10 \text{ km}^2/\text{s}^2$

- 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
  - $B \cdot R = 7,075 \text{ km}$
  - $B \cdot T = 6,930 \text{ km}$

- 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 $P_{\text{traj}} = 0.46$

- $P_{\text{traj}}$ was deemed unacceptably high by the project as it would remain unchanged for $\sim 1$ year

- “Universal” biased aimpoint selected to reduce $P_{\text{traj}}$ below 0.01% across 21-day period
  - $B \cdot R = 14,000 \text{ km}$
  - $B \cdot T = 7,000 \text{ km}$
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
    - $\sigma = 401.86$ 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
    - $\sigma = 452.65$ 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
      - $\sigma = 3.12$ mm/s
    - 1.714 m/s lateral
      - Designed: 1.720 m/s
      - $\sigma = 15.17$ 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

- 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
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- 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
• 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

- 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

See EFB video [here](#)
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
      - $\sigma = 7.74$ mm/s
    - 1.543 m/s lateral
      - Designed: 1.539 m/s
      - $\sigma = 15.14$ 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

- 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 $\Delta V_{99}$ 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

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Epoch ET</th>
<th>$\Delta V$ (m/s)</th>
<th>$\Delta V_{99}$ (m/s)</th>
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<tr>
<td>TCM-1</td>
<td>8/25/11</td>
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<td>DSM-1</td>
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Acknowledgments

- Is there an “official” NASA/JPL/Cal Tech acknowledgement we need to make?
B-Plane Description
# Maneuver Performance

Estimated and Designed Magnitudes

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Est. $\Delta V$ (m/s)</th>
<th>Designed $\Delta V$ (m/s)</th>
<th>$AP$</th>
<th>$\sigma$ (mm/s)</th>
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<td>TCM-2 Lateral</td>
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<td>DSM-1</td>
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## Maneuver Performance

*Estimated and Designed Pointing – Right Ascension*

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<tr>
<th>Maneuver</th>
<th>Est. RA (deg)</th>
<th>Designed RA (deg)</th>
<th>$AP$</th>
<th>$\sigma$ (deg)</th>
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## Maneuver Performance

Estimated and Designed Pointing – Declination

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<th>Designed Dec. (deg)</th>
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