Maneuver Design for the Juno Mission: Inner Cruise

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The Juno spacecraft launched in August 2011 and, following a successful Earth flyby in October 2013, is on course for a nominal orbit insertion at Jupiter in July 2016. This paper examines the design and execution of deterministic and statistical trajectory correction maneuvers during the first approximately 27 months of post-launch operations that defined the "Inner Cruise" phase of the Juno mission. Topics of emphasis include the two deep space maneuvers, Earth flyby altitude biasing strategy, and the sequence of trajectory correction maneuvers executed in the weeks prior to the successful Earth gravity assist.

I. Introduction

The Juno spacecraft launched in 2011 and continues to operate successfully en route to a planned arrival at Jupiter in 2016. Holding the distinction as the first solar-powered probe to travel to the outer solar system, the spacecraft will nominally operate at Jupiter for approximately one year in an 11-day eccentric polar orbit to study the origin and evolution of the gas giant through atmospheric and magnetospheric observations and to make detailed gravity measurements.[1] To achieve a Jupiter-bound trajectory, the Juno reference solution allowed for a series of up to nine trajectory correction maneuvers (TCMs) – both deterministic and statistical – to guide the spacecraft through the "Inner Cruise" phase of the mission that spanned from shortly after launch until after an Earth flyby in October 2013.

This paper will examine the trajectory correction maneuvers executed and cancelled during the first approximately 27 months of operations that constituted the Inner Cruise phase of the Juno mission. Maneuver performance is considered relative to the pre-launch maneuver analysis and mission requirements. Particular attention is paid to the deep space maneuvers (DSMs), Earth flyby altitude biasing strategy, and the sequence of deterministic and statistical maneuvers executed in the weeks preceding a near-perfect Earth gravity assist that placed the Juno spacecraft on course for a rendezvous with Jupiter in 2016.

II. Mission Overview

The Juno mission is a pioneering achievement in deep space, solar-powered exploration. The design of the spacecraft, reference trajectory, and maneuver operations strategy are all carefully integrated to meet science requirements while satisfying the complex set of constraints associated with operating a suite of scientific instruments on solar power at distances of 5+ AU from the Sun.

II.A. Juno Spacecraft

As a solar powered mission to the outer solar system, the Juno spacecraft's most distinguishing feature is a trio of large, 8.9-meter long solar arrays that give it more than a 20 meter diameter. The spacecraft appears in its nominal cruise configuration in Figure 1. The spacecraft axes are defined such that the positive Z-axis points through the high gain antenna (HGA). The XY-plane is parallel with the forward and aft decks of the spacecraft bus, as well as the plane of the solar panels. Outside of planned solar array articulations to

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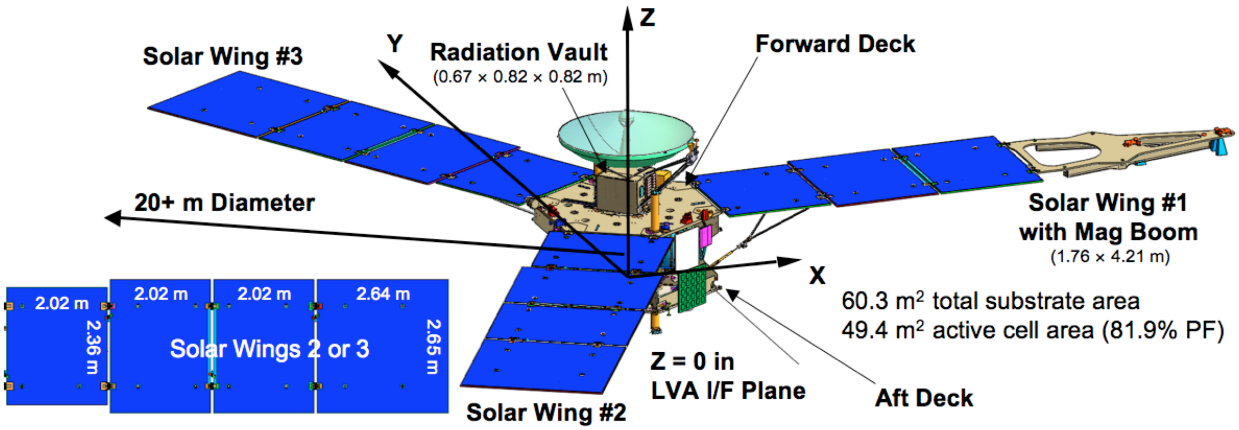
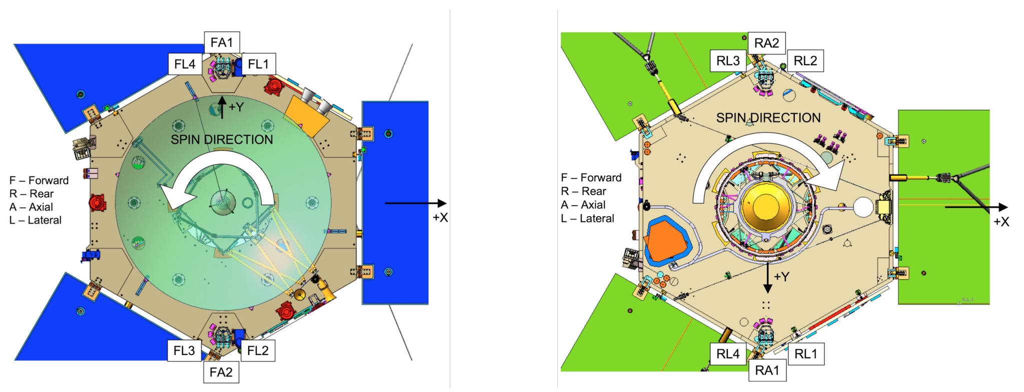


Figure 1. Isometric View of the Juno Spacecraft

minimize wobble and enable use of the HGA, the solar arrays are fixed. The mission's scientific objectives dictate that the spacecraft be spin-stabilized,[1] with spin axis coincident with the positive Z-axis (right-hand rule). Most of the science instruments point radially outward in the XY-plane, so their fields of view rotate with the spinning of the spacecraft.

Juno has a dual mode propulsion subsystem, with a bi-propellant main engine (ME) and mono-propellant reaction control system (RCS) thrusters. The main engine is mounted on the aft deck and is fixed in the negative Z-direction as depicted in Figure 2. The main engine burns are modeled with thrust and specific



(a) Forward Deck (b) Aft Deck

Figure 2. Forward and Aft Views of the Juno Spacecraft

impulse values, of 662 N and 318.6 seconds, respectively. The main engine is used for the mission's four large deterministic maneuvers: DSM-1, DSM-2, JOI, and PRM as well as three additional main engine flush (MEF) maintenance maneuvers that are required at approximately one-year intervals during "Inner Cruise."

The RCS system is comprised of four rocket engine modules (REMs), with each REM consisting of three thrusters. A REM is installed on each of the two forward thruster towers and two aft thruster towers. Both sets of thruster towers are located on opposite corners of the spacecraft, along the spacecraft Y-axis. The locations of the thrust towers on the forward and aft decks of the spacecraft bus are illustrated in Figure 2(a) and 2(b), respectively. The RCS system allows translation and rotation about all three axes with balanced thruster couplings. The much smaller RCS thrusters have a nominal thrust value of 4.5 N and are used for all non-main engine burns. Additionally, the RCS system will be used for all spin-rate changes (spin-ups, spin-downs and spin-rate maintenance), all precession turns, and active nutation damping (a fluid-filled nutation damper provides passive nutation damping). The physical orientation of the axial and lateral RCS thrusters relative to the desired thrust directions (thruster cant angles) affect their respective inefficiency factors. The axial thrusters have a 10° outward cant angle from the spacecraft Z-axis (spin axis), while the lateral thrusters are canted 5° outward from the X-axis (85° from the Y-axis), and 12.5° upward (77.5° from the Z-axis). Figure 3 illustrates the layout of the two sets of RCS thrusters mounted on the forward (upper) deck. Where "F," "L," and "A" represent "Forward," "Lateral," and "Axial," respectively. Two analogous

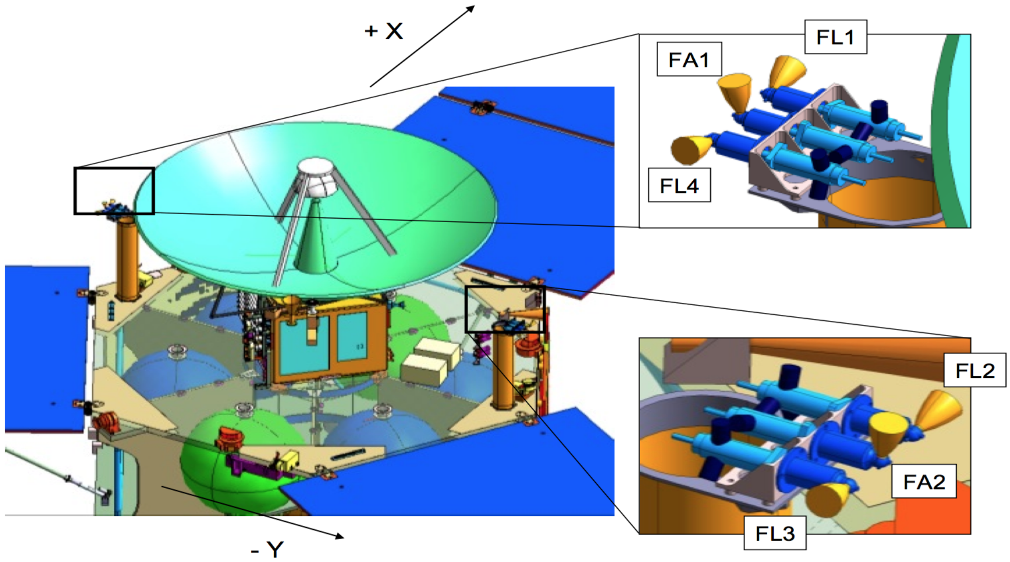


Figure 3. Forward RCS Thruster Configuration

sets of RCS thrusters are also mounted on the aft deck. The spacecraft configuration is dictated largely by instrument and power requirements which, in turn, drive the thruster placement that, ultimately, determines the maneuver operations strategy.

II.B. Reference Trajectory

Juno launched as planned into a heliocentric trajectory in August of 2011. The Juno reference trajectory is termed a "2+ ΔV-EGA" trajectory because the spacecraft leveraged an Earth gravity assist slightly more than two years after launch.[2] The Juno interplanetary trajectory from launch through Jupiter orbit insertion (JOI) is depicted in Figure 4. To set up the Earth gravity assist in October 2013 and, ultimately, enable the spacecraft to reach Jupiter, two large deep space maneuvers, DSM-1 and DSM-2 (also known as TCM-3 and TCM-4), were executed near aphelion on August 30 and September 14, 2012, respectively. To achieve the desired Earth-to-Jupiter interplanetary trajectory leg, the reference solution required an Earth flyby altitude of just 560 km. Officially, the "Inner Cruise" phase of the Juno mission spans from post-launch until the statistical clean-up maneuver following the Earth flyby.

While this paper focuses primarily on maneuver design activities during the "Inner Cruise" mission phase, it is useful to provide context by briefly discussing the latter stages of the mission as well. The "Outer Cruise" phase spans the approximately 31-month time frame between the post-flyby clean-up maneuver and arrival at Jupiter in July of 2016. This phase of the mission is designed to be entirely ballistic though several statistical TCMs are scheduled prior to reaching Jupiter. When activities commence at Jupiter, the spacecraft is initially captured into a 107-day polar orbit via the JOI burn and a period reduction maneuver (PRM) subsequently delivers it into the final 11-day science orbit. Per mission requirements, Juno will nominally complete 30 science orbits that generate a mesh along the Jovian equator with a longitudinal spacing of 12°.[3]

Successful completion of "Inner Cruise" phase of the Juno mission is crucial to enabling successful arrival and subsequent science operations at Jupiter. A robust maneuver operations strategy is critical to ensuring that the deep space maneuvers and Earth gravity assist, in particular, are achieved with sufficient precision to maintain the spacecraft on the reference trajectory.

II.C. Maneuver Operations Strategy[4]

To achieve a successful mission, the Juno spacecraft must be delivered to the proper aim points along the reference trajectory by a series of trajectory correction maneuvers without violating constraints on pointing,

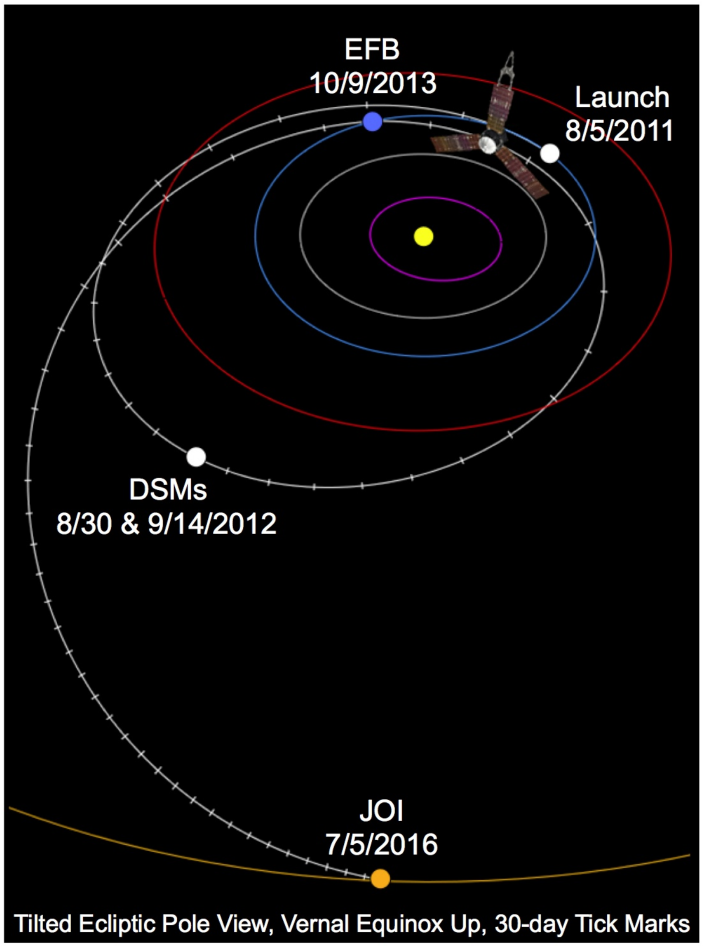


Figure 4. Juno Interplanetary Trajectory, Launch to JOI

power, etc. consistent with operating a solar powered probe in deep space. A total of nine nominal TCMs (plus two additional contingency TCMs) were planned during the "Inner Cruise" phase of the Juno mission. The TCMs are required to compensate for launch vehicle injection errors, targeting the required Earth flyby conditions, and to compensate for subsequent maneuver execution and orbit determination errors. During the Jupiter orbit phase, there is an orbit trim maneuver (OTM) planned near every perijove, with the exception of the last one, PJ-33. Near the apojove following PJ-33 (Apo-33), a deorbit maneuver is scheduled to target an impact with Jupiter that will end the mission.

For each maneuver, the magnitude and direction of the velocity change required to correct for errors in the desired aim point must be computed. These quantities are determined from an estimate of the actual arrival conditions obtained through the orbit determination and trajectory propagation processes described above. In addition, a means of estimating the statistics of the residual guidance errors due to imperfect maneuver execution is needed. These statistics are derived from estimates of the maneuver execution accuracy and the orbit determination error statistics computed as part of the orbit determination process.

II.C.1. Spacecraft Spin Rate

As discussed in Section II.A, Juno is a spinning spacecraft that rotates about its +Z axis, i.e., the axis perpendicular to the plane of the solar arrays. The spacecraft nominally rotates at 1, 2, or 5 rpm depending on the mission phase. Generally, the spin rate is nominally 1 rpm during interplanetary cruise, 2 rpm during the Jupiter orbit phase, and is increased to 5 rpm during main engine maneuvers after precessing to the burn attitude. Exceptions to the 1 rpm spin rate associated with interplanetary cruise include instrument checkout and calibration activities (including during the EFB), the post-DSM cleanup maneuver, and select pre- and post-EFB TCMs during which the spacecraft spins at 2 rpm.

II.C.2. Maneuver Implementation Modes

Taking into consideration Juno's thruster configuration and the fact that it is spinning, maneuvers are implemented in one of two modes: 1) "vector mode" or 2) "turn-burn-turn." In the vector mode strategy, the spacecraft maintains its cruise orientation and executes separate – but coordinated – axial and lateral burn components. The vector mode will be used for most of the smaller maneuvers and will make use of the RCS thrusters. The axial burn is oriented along the nominal spacecraft spin axis, i.e., in the ±Z-direction. The lateral burn is roughly perpendicular to the axial component and must be accomplished by pulsing the selected thrusters over some fraction of a spin period. A variable thruster firing arc of approximately ±30° (10 seconds at 1 rpm and 5 seconds at 2 rpm) relative to the desired lateral ΔV direction is employed for lateral burns. To minimize the thruster induced precession, the burn arc duration for the forward mounted thrusters will differ from the burn arc duration for the aft thrusters because the spacecraft center of gravity is not located precisely between the forward and aft thrusters. It should be noted that the lateral burn is not exactly perpendicular to the axial component because the lateral RCS thrusters are canted away from the X-axis and the axial thrusters are canted away from the Z-axis, due to plume impingement concerns. Therefore, the lateral part of a maneuver will provide some induced axial ΔV component as demonstrated in red in Figure 5. The effects of this burn vector decomposition are accounted for in the maneuver design process.

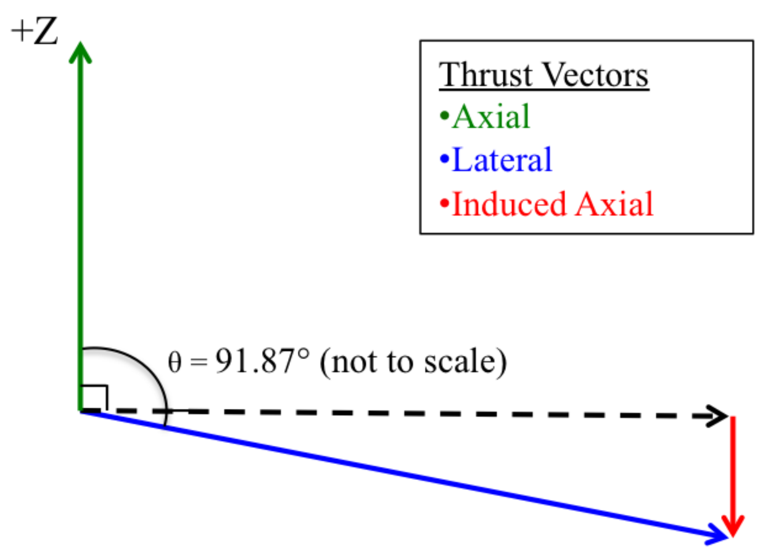


Figure 5. Vector Mode Maneuver Axial/Lateral Decomposition

In the turn-burn-turn strategy, the spacecraft slews to the appropriate maneuver attitude, performs an axial burn, and then slews back to the nominal cruise orientation. Turn-burn-turn mode is used for the main engine burns – DSMs, JOI, and the PRM – but can, in theory, also be used for larger RCS burns, such as the de-orbit burn, and JOI cleanup. For Juno, turn-burn-turn maneuvers will always be utilized to burn in the axial direction since axial burns are more efficient than pulsed lateral burns. Between the vector mode and turn-burn-turn implementations, the Juno maneuver operations strategy offers the flexibility to accommodate maneuvers of widely-varying magnitudes and is robust enough to ensure the maneuver execution precision necessary to guide Juno from launch, Earth flyby, and ultimately, a successful orbit insertion at Jupiter.

III. Launch and Post-Launch TCMs

The launch of the Juno spacecraft represented the first critical mission event and needed to be accurate to ensure that the required Earth gravity assist conditions could be met within the allotted propellant budget. To ensure that the spacecraft maintained the reference trajectory following the launch injection, two statistical launch cleanup maneuvers – TCM-1 and TCM-2 – were included in the operations schedule.

III.A. Launch

Juno launched into a heliocentric trajectory on August 5, 2011 the first day of the 21-day launch period[3] aboard an Atlas V 551 launch vehicle from Cape Canaveral, Florida. The launch was designed to insert the spacecraft into a heliocentric orbit with a period of approximately two years which, in conjunction with the deep space maneuvers, would deliver the Earth flyby conditions necessary to eventually reach Jupiter. For the August 5, 2011 launch opportunity, the targeted launch energy was $C_3 = 31.10$ km^2/s^2 and right ascension and declination of the launch asymptote targets were 57.34° and 19.63°, respectively. The launch vehicle performed very well, delivering C_3, right ascension, and declination values of 31.10 km^2/s^2, 57.34°, and 19.64°, respectively – all within 0.33-σ or less of the designed value.

III.B. Launch Cleanup Maneuvers: TCM-1 and TCM-2

To clean up launch injection errors, two statistical trajectory correction maneuvers, TCM-1 and TCM-2, were scheduled for 20 and 180 days after launch, respectively. However, the accurate launch vehicle injection resulted in the cancellation of TCM-1. TCM-2 was executed as planned 180 days after launch and targeted the Cartesian position associated with the start of the first deep space maneuver. TCM-2 was designed as a vector mode RCS burn with axial and lateral components of -864.06 mm/s and 843.76 mm/s, respectively. The Juno spacecraft's first TCM also performed favorably, yielding delivered maneuver vector mode components of -867.38 mm/s and 843.66 mm/s, respectively. Detailed comparisons of the estimated (reconstructed) and designed maneuver magnitude, right ascension, and declination values for TCM-2 and all subsequent maneuvers are included in the Appendix in Tables 2-4. The Juno mission started efficiently with a nominal launch injection, cancellation of TCM-1, and a well-executed TCM-2 to clean up launch injection errors.

IV. Deep Space Maneuvers

The Juno spacecraft was traveling close to the reference heliocentric trajectory following a successful launch injection and TCM-2 and it was the responsibility of the first two main engine burns – the two deep space maneuvers – to setup the Earth gravity assist required to eventually reach Jupiter. Given the low-altitude associated with the flyby, consideration was also given to Earth impact probability when designing the DSMs and subsequent cleanup maneuver.

IV.A. Earth Flyby Altitude Biasing Strategy

To reach Jupiter with the appropriate arrival conditions, recall that the reference trajectory includes an Earth gravity assist at an altitude of only 560 km. For the August 5, 2011 launch date, this translates to an aimpoint in the Earth B-plane of $B \cdot R$ = 7,075 km and $B \cdot T$ = 6,930 km. A description of the B-plane is provided in the Appendix. Due to the execution errors associated with the two large DSMs, if the DSM-cleanup maneuver – TCM-5 – was implemented 10 days after DSM-2, pre-launch analysis indicated that the probability of Earth impact due to trajectory sources was estimated to be $P_{traj} = 0.46$.[4] Figure 6 depicts the 1-sigma delivery ellipse for the DSM-cleanup maneuver (small red contour), centered on the Earth flyby aimpoint required to reach Jupiter for an August 5th launch. This Earth flyby aimpoint results in an unacceptably high impact probability that would remain unchanged for nearly a year – until the next scheduled statistical maneuver, TCM-6, 60 days before Earth flyby. Spacecraft failures could prevent future maneuvers from removing any trajectory errors that might result in Earth impact. To greatly lessen the risk of Earth impact, the Juno Project chose to bias the DSM aimpoint to reduce the Earth impact probability after the DSM-cleanup maneuver from an unbiased $P_{traj} = 46\%$ to a goal of $P_{traj} = 0.0001$, or 0.01% with biasing. In this strategy, the biased aimpoint is be removed with a deterministic TCM-6 maneuver. To minimize the size of this deterministic maneuver, the biased aimpoint must lie on the impact probability contour for $P_{traj} = 0.01\%$ (the large red contour in Figure 6) at a point near the unbiased Earth flyby aimpoint.

Figure 7 illustrates the resulting biasing strategy, where the maneuver capability ellipse for TCM-6 is centered on the unbiased Earth flyby aimpoint. The capability ellipse is sized to be tangent to the impact probability contour for $P_{traj} = 0.01\%$ (cyan contour). For computational ease, the (dotted red) ellipse approximates this impact probability contour. The point of tangency of the "impact probability ellipse" and

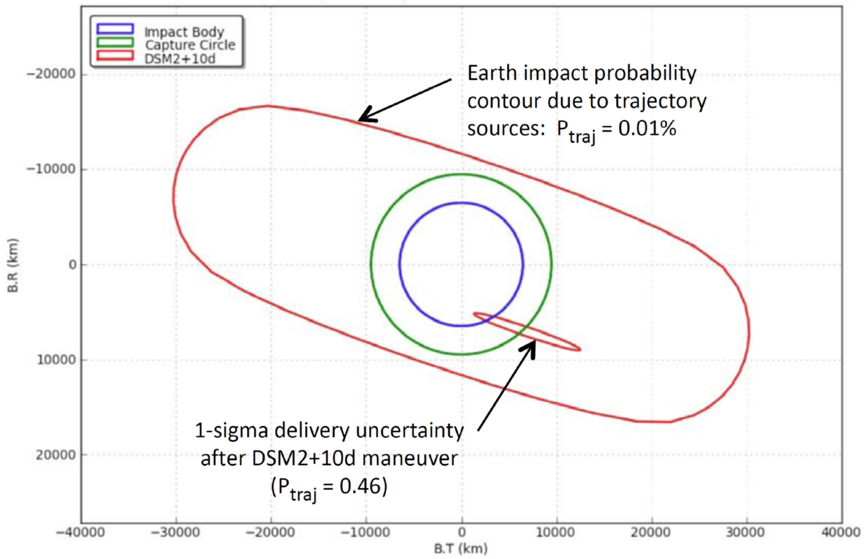


Figure 6. Unbiased DSM-cleanup Maneuver Delivery Ellipse Centered on Earth Flyby Aimpoint Required to Reach Jupiter

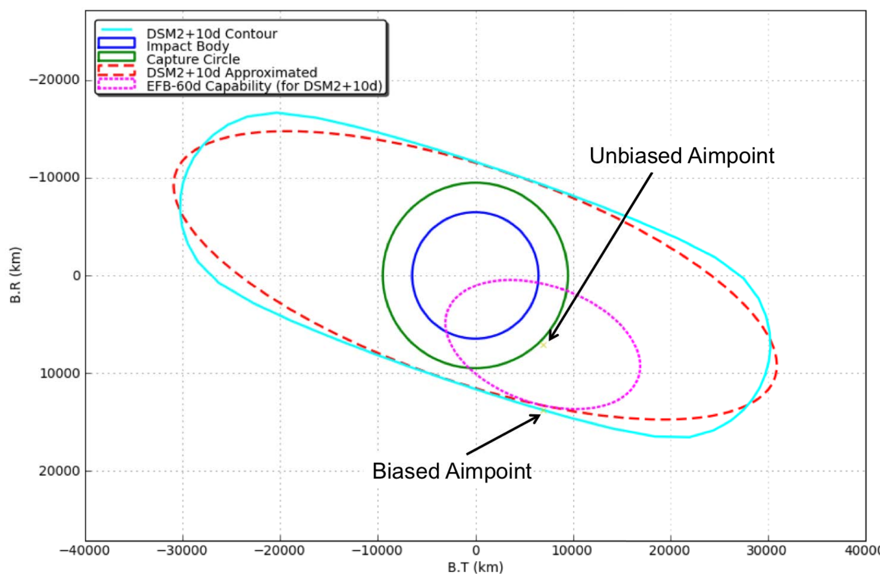


Figure 7. Earth Flyby Aimpoint Biasing Strategy

the maneuver capability ellipse is used to then locate the desired biased aimpoint on the impact probability contour. During pre-launch analysis, a "universal biased aimpoint" of $B \cdot R$ = 14,000 km and $B \cdot T$ = 7,000 km was selected because it could maintain the post-TCM-5 Earth impact probability below 0.01% across the 21-day launch period.

IV.B. Deep Space Maneuvers: DSM-3 and DSM-4

The two deep space maneuvers, DSM-1 and DSM-2 – also denoted TCM-3 and TCM-4, respectively – were designed utilizing the Earth flyby altitude biasing strategy described above. The large main engine burns were executed near apohelion in the Fall of 2012 and were divided into two burns because the main engine was not qualified to operate for the duration required to execute the DSM in a single maneuver. Both DSMs were designed several months in advance and were implemented as turn-burn-turn maneuvers. DSM-1 targeted a Cartesian position associated with the start of DSM-2 and had a designed magnitude of 344.157 m/s. The maneuver was executed on August 30, 2012 and performed nominally, delivering a ΔV of 344.284 m/s.

DSM-2 was originally designed to be executed 4 days after DSM-1, but was delayed 10 days, until September 14, 2012 as a precaution to investigate high oxidizer line temperatures and pressures observed during DSM-1. The second deep space maneuver was designed to target the biased Earth flyby aimpoint and had a designed magnitude of 387.722 m/s. DSM-2 also behaved favorably and yielded a ΔV of 387.941 m/s.

IV.C. DSM Cleanup Maneuver: TCM-5

Following the successful execution of the two deep space maneuvers, TCM-5 was executed 19 days later to target a biased Earth flyby aimpoint of $B \cdot R$ = 13,866 km and $B \cdot T$ = 5,756 km – a refinement of the pre-launch "universal biased aimpoint." TCM-5 was designed as a vector-mode RCS burn with axial and lateral components of 423.56 mm/s and 1720.38 mm/s, respectively. The maneuver was executed successfully on October 10, 2012 and delivered axial and lateral ΔVs of 427.63 mm/s and 1714.49 mm/s, respectively. The TCM-5 delivery is visualized in Figure 8 below. The large magenta ellipse illustrates the uncertainty

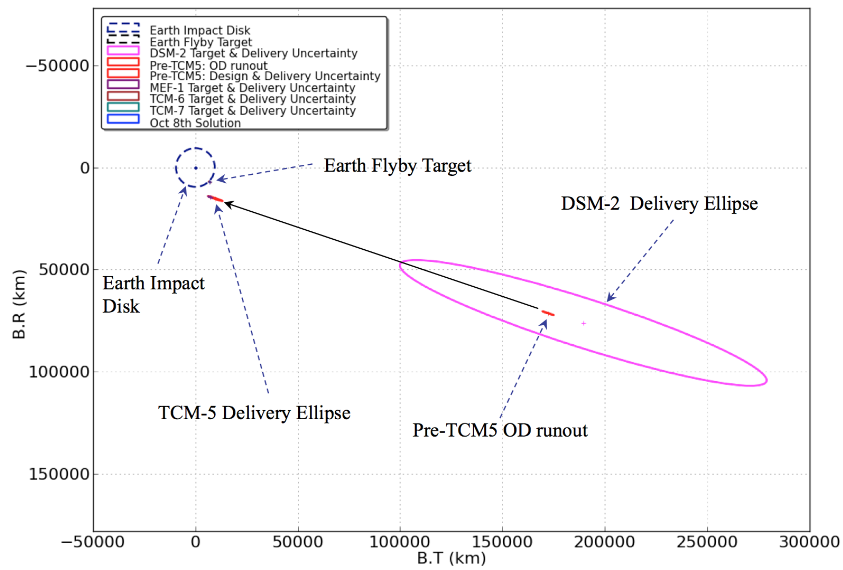


Figure 8. TCM 5 Delivery (1-sigma) in Earth B-plane

associated with the DSM-2 delivery. Note that initial DSM-2 design targeted the biased aimpoint, but the maneuver was not re-designed following the post-DSM-1 delay so the resulting delivery shifted to the right in the B-plane. The small red contours demonstrate the movement of the trajectory's aimpoint in the Earth B-plane due to TCM-5. By successfully delivering the trajectory to the biased Earth flyby aimpoint, TCM-5 ensured that the Juno spacecraft had a sufficiently low probability of impacting Earth until the next maneuver approximately 10 months later.

V. Pre-Earth Flyby Maneuvers

A successfully executed string of maneuvers including launch injection, TCM-2, two DSMs, and DSM cleanup (TCM-5) placed the Juno spacecraft close to the nominal reference trajectory as it approached the Earth flyby. However, to achieve the desired arrival conditions at Jupiter, a series of deterministic and statistical TCMs were required to move the B-plane aimpoint and, fundamentally, reduce the flyby altitude.

V.A. First Main Engine Flush Maneuver: MEF-1

Seven months after TCM-5 was implemented, the first of three main engine flush maneuvers, MEF-1, was executed on May 1, 2013. The MEF maneuvers are performed approximately once per year during the Juno interplanetary trajectory to flush the main engine propellant lines. During each MEF, the main engine burns for 5 seconds and imparts a ΔV of approximately 1.1 m/s. The flush maneuvers are passive in that they are executed at the cruise attitude and are not designed to correct known trajectory errors.

V.B. Targeting Earth Flyby: TCM 6 and TCM 7

Maneuver activities in preparation for Juno's Earth gravity assist commenced with the execution of TCM-6 on August 7, 2013 – 63 days prior to Earth flyby. TCM-6 was a deterministic maneuver to remove the Earth flyby altitude bias and target the B-plane aimpoint and time of flight consistent with an Earth periapsis altitude of 560 km. The designed axial and lateral components of TCM-6 were 1.457 m/s and 3.093 m/s, respectively, and respective estimated values of 1.462 m/s and 3.096 m/s were executed. The motion of the aimpoint in the Earth B-plane is depicted in Figure 9. The TCM-5 delivery ellipse first pictured in Figure

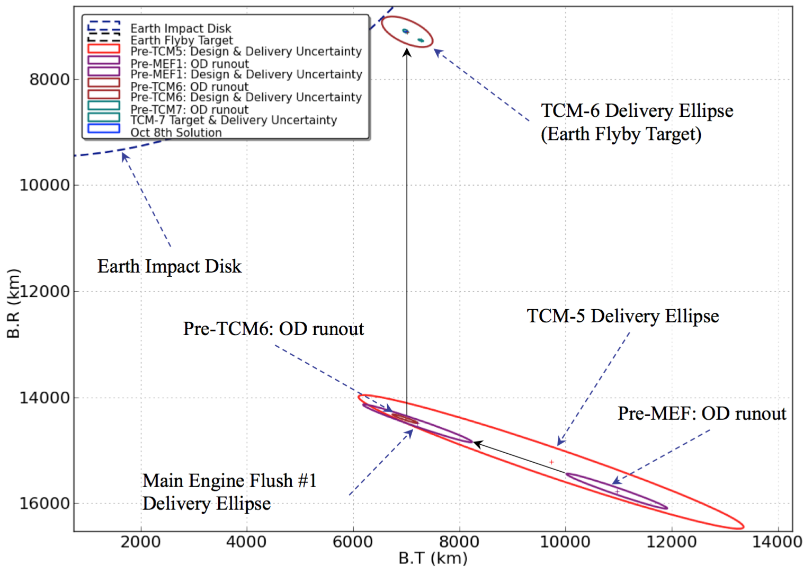


Figure 9. TCM 6 Delivery (1-sigma) in Earth B-plane

8 appears again Figure 9 in red. The first maintenance main engine flush, MEF-1, was executed between TCM-5 and TCM-6 and is illustrated in purple. From the figure, it is clear that, despite being the largest executed RCS burn to date, TCM-6 accurately moved the aimpoint from the biased location, to desired Earth flyby B-plane target.

Approximately one month after TCM-6 was executed, TCM-7 was performed on September 9 – 30 days prior Earth flyby – to further refine the Earth flyby aimpoint. TCM-7 re-targeted the Earth flyby B-plane target and, given the accurate execution of TCM-6, was quite small with a designed axial ΔV component of 119.16 mm/s and a designed lateral component of 52.19 mm/s. The effect of the delivered axial and lateral burns of 124.04 mm/s and 49.58 mm/s, respectively, is illustrated in Figure 10. In the Earth B-plane, the maneuver successfully shifted the pre-TCM-7 OD runout to the TCM-7 delivery ellipse that is essentially centered on the Earth flyby target.

V.C. TCM-8 Cancellation Criteria

Following the execution of TCM-6 and TCM-7, TCM-8 offered one final opportunity to target the desired Earth flyby aimpoint 10 days prior to closest approach. Given the critical nature of the Earth flyby and the close proximity to periapsis, preparations were also made to perform a contingency maneuver, TCM-8a, 5 days before closest approach in the event that TCM-8 was unable to execute.

Since TCM-8 was scheduled only 10 days before Earth closest approach, it was not desirable to execute the maneuver unless it was necessary. The cancellation decision hinged on the resulting propellant cost of the Earth flyby cleanup maneuver, TCM-9, if TCM-8 was not executed. To understand the relationship between post TCM-7 orbit determination (OD) solutions and TCM-9 propellant costs, the TCM-9 propellant costs were mapped to the Earth B-plane as illustrated in Figure 11. The B-plane contour lines represent constant post-flyby propellant costs for a TCM-9 executed 21 days after Earth flyby. The most important contour in the figure is the 43-kg line representing the propellant budgeted for the TCM-9 ΔV99 (2.58-σ) of 23.2 m/s. Fundamentally, the TCM-8 cancellation criteria stated that, if the 3-σ orbit determination solution prior to TCM-8 was within the 43-kg propellant cost contour, then TCM-8 would be canceled. A series of five

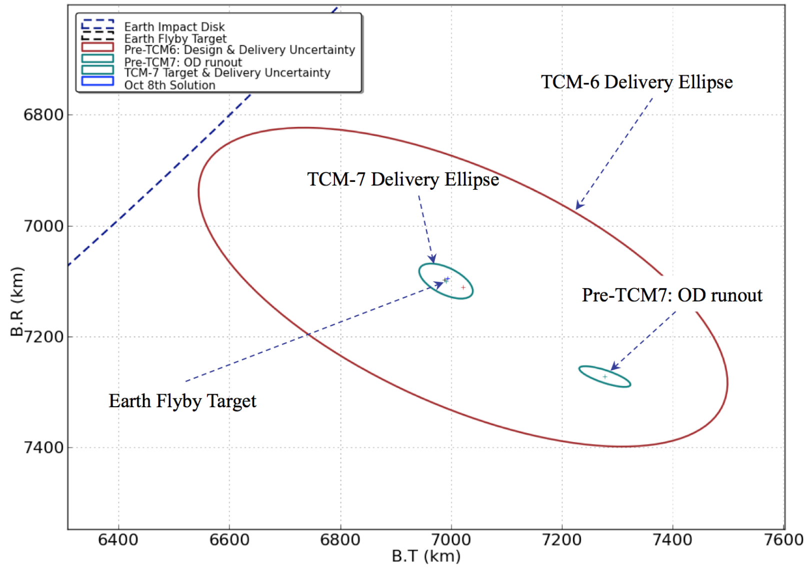


Figure 10. TCM 7 Delivery (1-sigma) in Earth B-plane

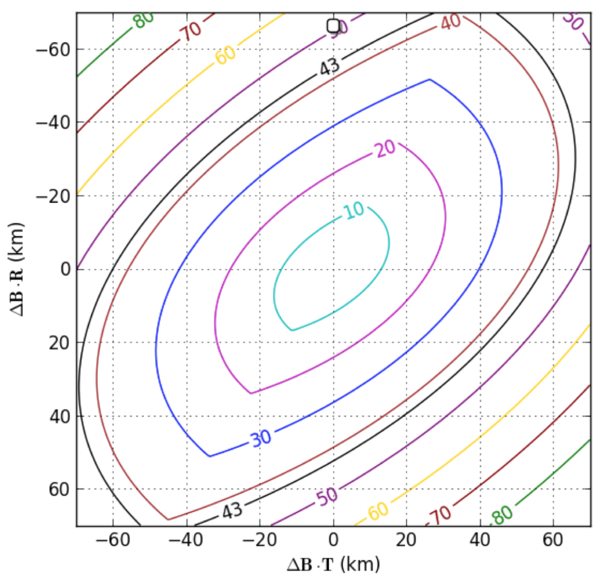


Figure 11. TCM 9 Propellant Cost Contours in kg (3-sigma)

OD solutions leading up to TCM-8 are overlaid on the TCM-9 propellant cost contours in Figure 12. The green ellipse represents the September 22, 2013 OD solution that was generated 17 days prior to Earth flyby. The fact that this error ellipse lies well within the 43-kg propellant cost contour made for a straightforward decision to cancel TCM-8 and, by default, the TCM-8a contingency maneuver.

VI. Earth Flyby

TCMs 6 and 7 were performed with sufficient accuracy to eliminate the need for TCM-8 and ensure an Earth flyby that was close enough to the B-plane target aimpoint. However, given Juno's relatively low perigee altitude of 560 km, a final pre-flyby maneuver, the collision avoidance maneuver (CAM), was available to ensure that the spacecraft maintained a safe distance from other spacecraft or debris in low Earth orbit during closest approach.

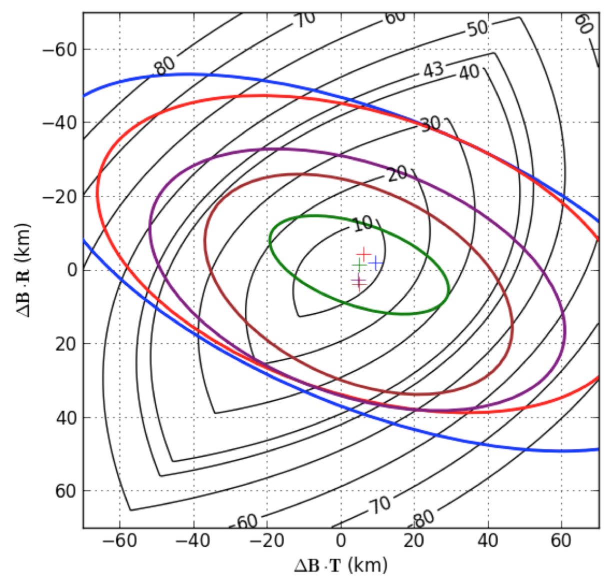


Figure 12. TCM 9 Propellant Cost Contours in kg with OD Delivery (3-sigma)

VI.A. Conjunction Assessment

The need to consider collision avoidance during the Juno mission was motivated by Figure 13 that illustrates the number of objects (active and passive) in low Earth orbit as a function of mean equatorial height above the surface of the Earth as of January 21, 2010. The number of tracked objects appear in blue and debris

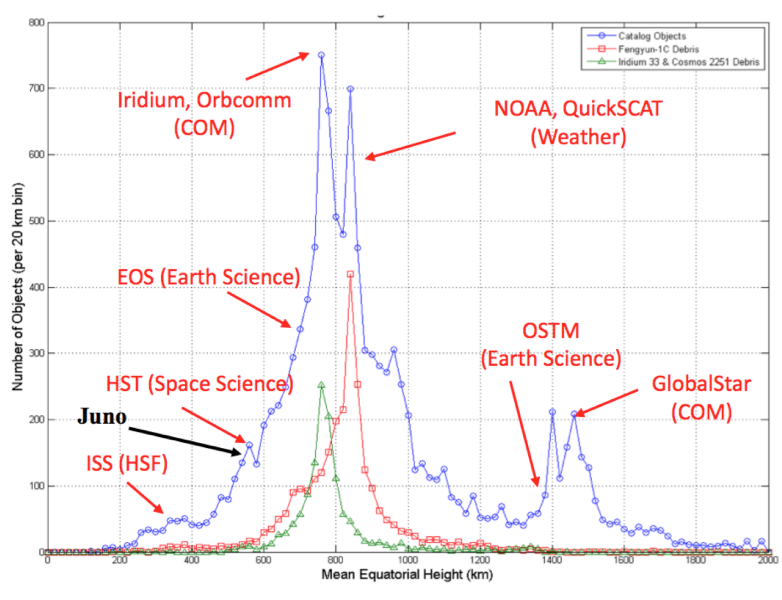


Figure 13. Distribution of Objects in Low Earth Orbit as of Jan 21, 2010

objects from the Fenyun-1C and Iridium-Cosmos explosions are shown in red and green, respectively. Juno is labeled on the plot at its closest approach altitude of 560 km, but it must, of course, necessarily traverse altitudes ≥560 km on the inbound and outbound legs of the Earth flyby. The impact probability per square meter of spacecraft cross-sectional area as a function of debris size, computed by the Orbital Debris Program Office, is presented on a log-log scale in Figure 14. With a cross-sectional area of approximately 72 m^2, the Juno spacecraft had a small, but non-zero probability of impacting an object in the JSpOC catalog (larger than 10 cm) during Earth flyby.

While it was unlikely that Juno would come close to another object during its Earth gravity assist, two collision avoidance maneuvers were designed several months in advance and loaded on the spacecraft ahead of

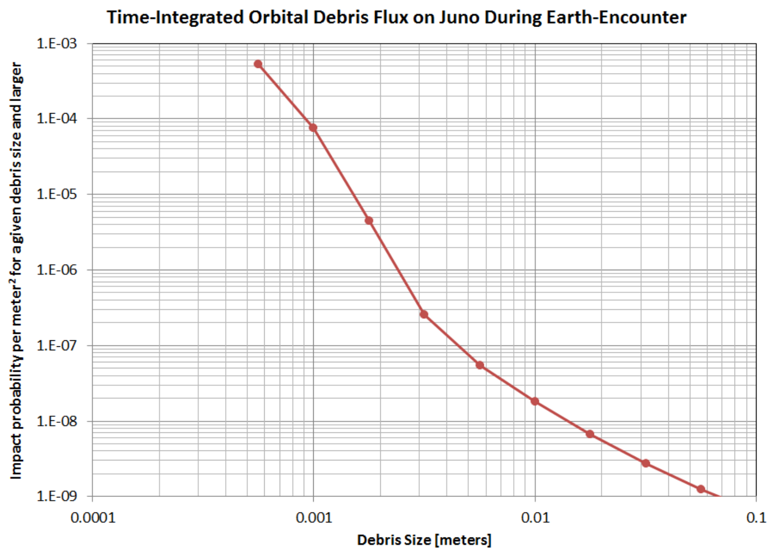


Figure 14. Time-Integrated Orbital Debris Flux on Juno During Earth Encounter (Image Credit: Nick Johnson, JSC)

time as a contingency measure. The two CAMs were axial-only RCS burns executed 12 hours prior to Earth flyby and were designed to shift closest approach by approximately ± 1 second, if necessary. In the 10 days leading up to closest approach, the Juno navigation team provided spacecraft ephemerides and associated covariance information to the Conjunction Assessment Risk Analysis (CARA) team at Goddard Space Flight Center who, in turn, analyzed closest approach distances between Juno and objects in the JSpOC catalog. Fundamentally, it was decided that a CAM would be executed only if *both* of the following two conditions were satisfied:

1. If the probability of impact with an object using the current trajectory solution is greater than 0.01%
2. If one of the CAMs reduces the probability of impact with an object by more than a factor of 100

In the end, the spacecraft came no closer than 26 km to any catalog object, it was not necessary to implement a collision avoidance maneuver.

VI.B. Earth Flyby Delivery

Without requiring either TCM-8 or a collision avoidance maneuver, Juno safely flew through Earth closest approach on October 9, 2013 and passed just off the coast of South Africa as illustrated in Figure 15. The tick marks are spaced at 1-minute intervals and the red portion of the trajectory denotes the approximately 20-minute eclipse that Juno experienced during Earth flyby – its only post-launch eclipse of the entire mission. The spacecraft's Earth flyby trajectory deviated from its target in the Earth B-plane by 6 km and achieved a time of closest approach (TCA) of 19:21:24 UTC that differed from the target epoch by only 0.17 seconds. Relative to the orbit determination solution used to cancel TCM-8, the spacecraft deviated from the prediction by only 1 km in the B-plane and 0.05 seconds in TCA. The reconstruction of the Juno Earth flyby trajectory is detailed by Thompson et al.[5]

VII. Post-Earth Flyby and "Outer Cruise"

With the completion of a highly accurate Earth flyby, the Juno spacecraft successfully passed its third major event – including launch and the deep space maneuvers – and achieved a Jupiter-bound trajectory. Following the Earth flyby, the focus of maneuver design efforts has shifted from hitting the required Earth flyby target to ensuring that the set of desired conditions are satisfied upon arrival at Jupiter in July of 2016.

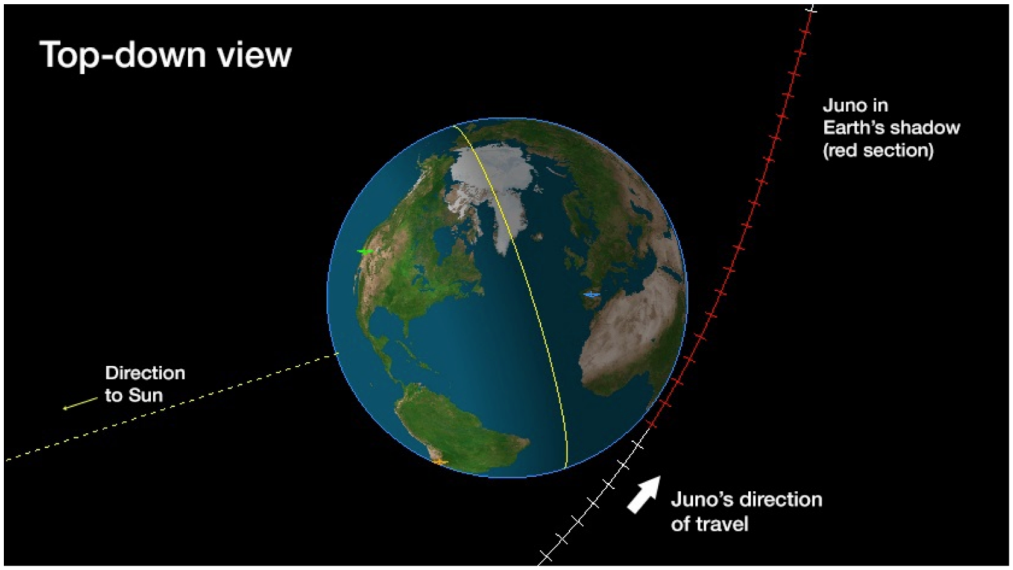


Figure 15. Reference Trajectory Near Earth Closest Approach

VII.A. Earth Flyby Cleanup: TCM 9

During pre-launch planning, the Earth flyby cleanup maneuver was initially scheduled to be executed just 10 days after closest approach. However, analysis conducted prior to Earth flyby demonstrated there was little to no ΔV penalty associated with delaying the maneuver for up to several months, so TCM-9 was moved to 21 days after closest approach. TCM-9 was delayed even further when a series of spacecraft safe mode events were triggered during the Earth flyby. It should be noted that the safe mode events had no significant impact on the Juno trajectory or the planned science activities.

The Earth flyby cleanup was executed on November 13, 2013 (34 days after closest approach) as a vector mode RCS burn targeting the Cartesian state just prior to TCM-12, a maneuver that will be executed 34 days prior to JOI. TCM-9 was designed with axial and lateral ΔV components of 1.320 m/s and 1.539 m/s, respectively and delivered axial and lateral maneuvers of 1.324 m/s and 1.543 m/s, respectively.

VII.B. Outer Cruise

With the successful execution of TCM-9, the "Inner Cruise" phase of the Juno mission was complete and the "Outer Cruise" phase that will take the spacecraft to Jupiter arrival commenced. The first outer cruise maneuver, TCM-10, was scheduled for April 2014. However, given the highly accurate Earth flyby and TCM-9 execution, the designed TCM-10 magnitude was only 5.44 mm/s – too small to be reliably executed by the RCS thrusters – and the maneuver was canceled. The "Outer Cruise" phase of the reference trajectory spanning from 1 day after TCM-9 to PRM (not part of "Outer Cruise" phase, but provided for reference) appears with maneuver locations in Figure 16. The location of the Juno spacecraft on July 5, 2014 – two years prior to JOI – is indicated with a black dot. The second maintenance main engine flush maneuver, MEF-2, was successfully executed on May 28, 2014 and MEF-3 is scheduled to take place in June 2015. Pre-JOI maneuver design activities will begin five months prior to JOI with preparations for TCM-11.

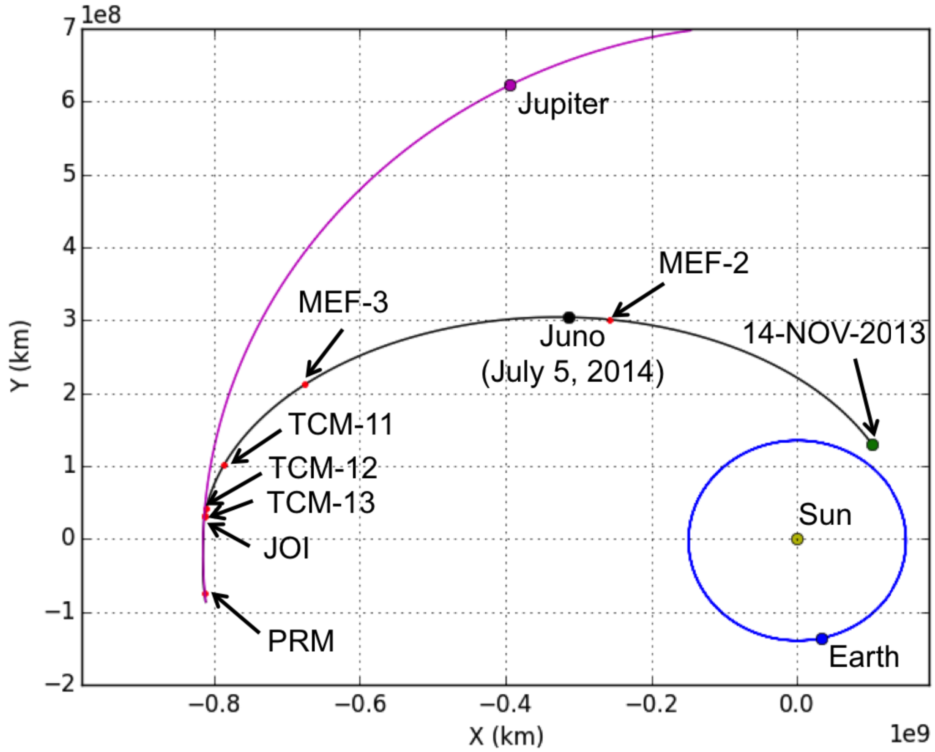


Figure 16. Reference Trajectory: Outer Cruise to PRM

VIII. Summary and Concluding Remarks

The designed and delivered maneuver ΔV components were presented in the preceding sections. For completeness, the maneuver magnitudes to date are compared with pre-launch ΔV99 magnitudes in Table 1. The epochs associated with Earth flyby (EFB) and canceled maneuvers – denoted with "-" – are included for reference. The ΔV leveraged from the Earth gravity assist is also specified. Note that only TCM-2 exceeded the pre-launch ΔV99 due to the fact that TCM-1 was canceled. It is also of interest to note the large amount of TCM-9 ΔV conserved due to the accuracy achieved during Earth flyby.

Table 1. Maneuver Magnitudes vs. Pre-Launch ΔV99

Maneuver	Epoch (ET)	ΔV (m/s)	ΔV99 (m/s)
TCM-1	08/25/11	-	3.9
TCM-2	02/01/12	1.2	0.5
DSM-1	08/30/12	344.3	360.1
DSM-2	09/14/12	387.9	395.8
TCM-5	10/03/12	1.8	1.8
TCM-6	08/07/13	3.4	3.5
TCM-7	09/09/13	0.1	0.6
TCM-8	09/29/13	-	0.3
EFB	10/09/13	7,300	
TCM-9	11/13/13	2.0	23.2
TCM-10	04/09/14	-	2.0

Through the efforts of the Juno operations team, the Juno spacecraft has successfully executed all maneuvers to date nominally and as designed. This success ultimately led to the completion of a highly accurate Earth gravity assist on October 9, 2013. Relative to the predicted trajectory, the spacecraft deviated from the prediction by only 1 km in the B-plane and 0.05 seconds in at the time of Earth closest approach. At the time of this writing, the Juno mission continues to operate successfully in its "Outer Cruise" phase and is on-track for a nominal arrival at Jupiter on July 5, 2016.

Appendix

Maneuver Performance

Table 2 compares the estimated (reconstructed) and designed ΔV magnitudes for each executed TCM. The *a priori* (AP) uncertainty is also provided.

Table 2. 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	1.539	1.543	15.14

Maneuver pointing performance in terms of right ascension and declination is detailed in Tables 3 and 4, respectively.

Table 3. Maneuver Performance: Estimated and Designed Pointing - Right Ascension

Maneuver	Est. RA (deg)	Designed RA (deg)	AP σ (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

Table 4. Maneuver Performance: Estimated and Designed Pointing - Declination

Maneuver	Est. Dec. (deg)	Designed Dec. (deg)	AP σ (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

B-Plane Description

The B-plane (body plane) provides a useful reference frame for characterizing spacecraft trajectories that are hyperbolic with respect to a central body of interest and is used extensively by the Juno navigation team for mapping orbit determination uncertainties and maneuver targeting. A graphical definition of the B-plane appears in Figure 17. The incoming trajectory (green) is hyperbolic with respect to the central body (blue).

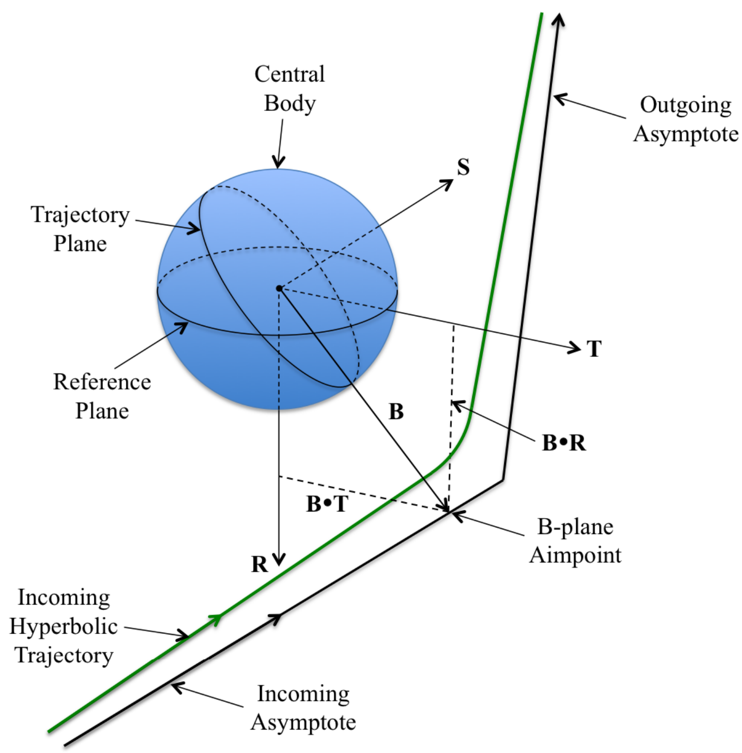


Figure 17. B-Plane Schematic

The B-plane is defined to be a plane through the center of the central body that is orthogonal to the incoming asymptote of the hyperbolic trajectory. In this definition, the vector $\boldsymbol{S}$ denotes the B-plane's surface normal direction and the vector $\boldsymbol{T}$ represents the intersection of the B-plane and a reference plane, e.g., the ecliptic, equatorial plane, etc. The orthogonal coordinate system is completed by defining $\boldsymbol{R} = \boldsymbol{S} \times \boldsymbol{T}$. The B-plane aimpoint is represented by the $\boldsymbol{B}$ vector and is often given in terms of its components, i.e., $\boldsymbol{B} \cdot \boldsymbol{R}$ and $\boldsymbol{B} \cdot \boldsymbol{T}$.

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