Launch Period Development for the Juno Mission to Jupiter

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The Juno mission to Jupiter is targeted to launch in 2011 and would reach the giant planet about five years later. The interplanetary trajectory is planned to include two large deep space maneuvers and an Earth gravity assist a little more than two years after launch. In this paper, we describe the development of a 21-day launch period for Juno with the objective of keeping overall launch energy and delta-V low while meeting constraints imposed on Earth departure, the deep space maneuvers' timing and geometry, and Jupiter arrival.

Nomenclature

C_3	=	launch energy (V_∞^2)
ΔV	=	delta-velocity
I_{sp}	=	specific impulse
V_∞	=	hyperbolic excess velocity

I. Introduction

THE Juno mission to Jupiter is planned for launch in 2011, reaching the giant planet in 2016. Subject to NASA approval, the interplanetary trajectory will include two large deep space maneuvers (DSMs) and an Earth gravity assist a little more than two years after launch. Upon arriving at Jupiter, the spin-stabilized, solar-powered spacecraft will establish a highly-elliptical, polar orbit with the perijove roughly 5000 km above the planet's cloud tops. From this orbit, Juno will investigate Jupiter's gravity and magnetic fields, interior structure, water abundance, and complex atmosphere. In this paper, we explore the development of a 21-day launch period for Juno with the objective of keeping overall launch energy (C_3) and deterministic ΔV low while meeting constraints imposed by spacecraft and navigation requirements.

II. Juno Mission Overview

Juno plans to employ a so-called "2+ ΔV-EGA" trajectory to reach Jupiter (Figure 1). Generically, the "EGA" stands for Earth gravity assist, and the "2+" means that the gravity assist occurs a little more than two years after launch. The "ΔV" part of the name refers to the fact that this is a V_∞-leveraging trajectory[1] with a large Deep Space Maneuver (DSM) that generally occurs near aphelion, which is roughly a year after launch. This type of trajectory is attractive for Jupiter missions because it yields short flight times (less than 6 years) without the high C_3 costs of a direct launch.[2] The trades that led to the selection of the 2+ ΔV-EGA for Juno, though, are not discussed in this paper. Juno has opted to split the DSM into two maneuvers, nominally placed two days apart. This is discussed in more detail in the next section.

Juno plans to launch in August, 2011 with the DSMs occurring sometime in the July-September 2012 timeframe, depending on the actual launch date. The Earth flyby is scheduled to occur October 12,

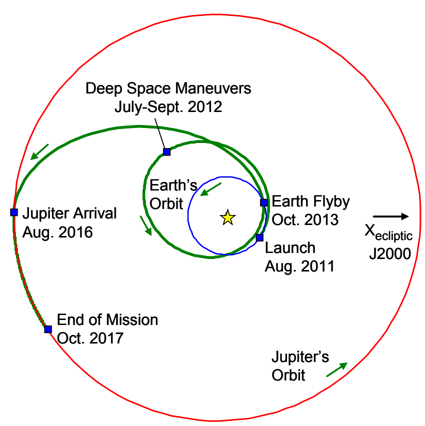

Figure 1. The Juno interplanetary trajectory.

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2013, with the precise timing being launch date dependent. Jupiter arrival is planned for August 3, 2016.

Upon arriving at Jupiter, Juno will execute a large maneuver to insert into a 78-day capture orbit. This approximately 33-minute Jupiter Orbit Insertion (JOI) burn places Juno into a polar, highly-elliptical orbit with a perijove roughly 4500 km above the 1-bar pressure level at Jupiter (see Figure 2). At the next perijove passage, on Oct. 19, 2016, Juno performs a Period Reduction Maneuver (PRM), lasting roughly 34 minutes, to reduce the orbital period to just under 11 days for the science phase of the mission. The first 11-day orbit is allocated to cleaning up any errors in the PRM execution, so the first science orbit is the second 11-day orbit. We count the capture orbit as Orbit 1, the clean-up orbit as Orbit 2, and the first primary science orbit as Orbit 3. On each science orbit, there will be a maneuver four hours after perijove to target the desired conditions at the following perijove (discussed below). This orbit trim maneuver (OTM) occurs after the primary science phase on each orbit is complete (±3 hours from perijove).

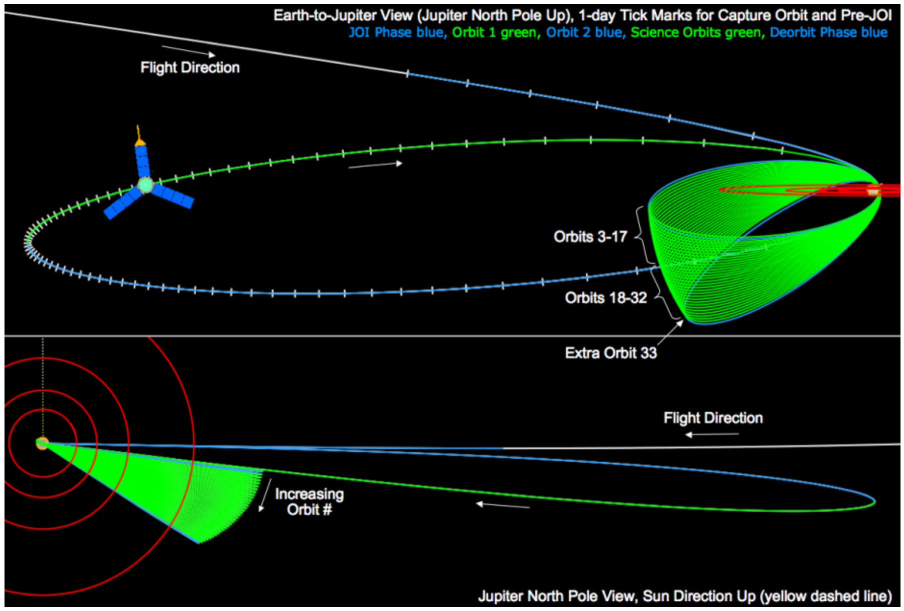

Figure 2. Overview of Juno's orbital phase. (Image credit: S. Stephens.)

The nominal science orbit has a period averaging 10.9725 days, which is designed to place the perijove-science events over the Goldstone Deep Space Network (DSN) complex in California and also to provide the desired longitude spacing at each equator crossing. Because Juno plans to do gravity science using Ka-band uplink and downlink, the gravity science intervals (±3 hours from perijove) must be over the Goldstone DSN complex since it is the only DSN site with a Ka-band uplink-capable station (DSS-25). The Jupiter view period as seen from Goldstone repeats every 0.9975 days, so the nominal science orbit period must be an integer multiple of this value to keep each perijove passage in view of Goldstone. The choice of 10.9725 days (=0.9975 days x 11) provides the required Ka-band uplink to meet the gravity science objectives. Although the average science orbit period is actually 10.9725 days, for convenience it will henceforth be referred to as the “11-day orbit.”

The chosen science orbit period also yields global coverage of the Jovian magnetic field per the magnetic field investigation requirements. The Juno science orbit has an initial perijove latitude of just over 3° with the descending node (equator crossing) following perijove only minutes later. The magnetic field science investigation requires equal spacing of the longitudes at each equator crossing to provide a global magnetic field map. With the 10.9725-day orbital period, each successive equator crossing is stepped 192° from the previous. After 15 science orbits (numbered 3 through 17), Juno will have achieved global coverage of Jupiter with 24° longitude spacing. At this point, Juno will make a slight adjustment in the period to shift the longitude of the next equator crossing by 12° from the original pattern, meaning the longitude is only 180° away from the previous orbit’s. What follows is another cycle of 15 orbits (numbered 18 through 32) that yields 24° longitude spacing, but since these longitudes are shifted 12° from the first 15 orbits, the overall spacing for the 30 science orbits is 12°.

The design of the science mission to be in a polar, highly-elliptical orbit with a low perijove serves several purposes. From a ΔV standpoint, the low perijove keeps the JOI and PRM ΔVs low. The low perijove also enables the microwave radiometer, gravity science, and magnetic field investigations to achieve the desired

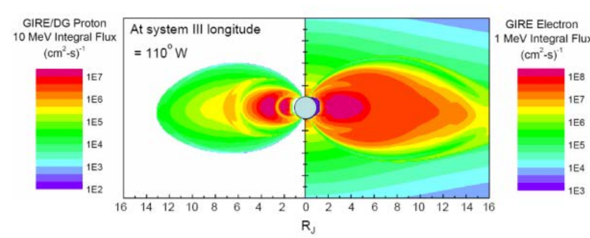

Figure 3. Contour plot showing ≥1 MeV electron and ≥10 MeV proton integral fluxes at Jupiter.[3] (Image credit: Jun and Garrett.).

resolution. However, one of the greatest benefits of this orbit is to keep the exposure to Jupiter's radiation low. Since the regions of highest-intensity radiation at Jupiter are essentially a torus (see Figure 3),[3] Juno avoids the peak radiation regions by flying inside the torus at perijove. With the perijove near the equator at the beginning of the mission, the overall radiation exposure is quite low for the first half of the 30 science orbits. However, the argument of periapsis increases approximately 0.9° per orbit, sending the latitude of perijove further from the equator. This forces the ascending node of the orbit closer to Jupiter on successive orbits (see Figure 4), and by consequence increases the radiation dose. Juno's initial approach to Jupiter is over the North Pole (indicated in Figure 2) because this approach establishes an initial perijove latitude that is about 6° closer to the equator than for the South Pole approach. In both cases, the rotation of the line of apsides causes the perijove to move away from the equator, so starting the mission closer to the equator reduces the overall radiation exposure. A 6° increase in the initial perijove latitude is equivalent to starting the mission about six orbits later because of the 0.9°/orbit rotation of the line of apsides. The South Pole approach would cause Juno to enter the high-radiation regions sooner. To mitigate this, the flight system would need to apply additional shielding, at the expense of potentially removing a science instrument to accommodate the additional shielding mass, or Juno would not be able to plan for as many science orbits. Fewer orbits means the 12°-spacing for the magnetic field investigation could not be achieved.

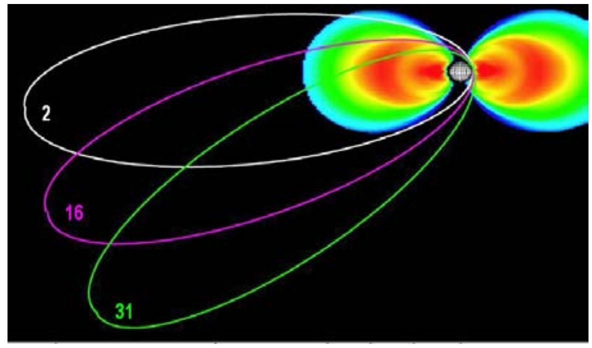

Figure 4. Juno experiences increasing radiation as the mission progresses and the line of apsides rotates. (Image credit: S. Stephens.)

Because the accumulating radiation dose puts the controllability of the spacecraft at risk as the number of orbits adds up, Juno plans to de-orbit into Jupiter following the completion of the baseline mission. Without de-orbiting, the Juno team could eventually lose control of the spacecraft, and there is a small, but non-zero, probability of impacting one of Jupiter's icy Galilean satellites (Callisto, Ganymede, and Europa).[4] These satellites are suspected of harboring liquid water oceans beneath their thick ice surfaces, and the possibility of water leads to the possibility that these satellites could support life. De-orbiting the Juno spacecraft is planned to eliminate the possibility of an unintended impact that could contaminate any sub-surface oceans.

Juno plans to allow for one extra science orbit before de-orbiting, however, to allow recovery of magnetic field data at any longitude in the event of a loss of data due to a spacecraft event during one of the science orbits. This means that Juno will have one capture orbit, one orbit to clean up maneuver execution errors from PRM, 30 nominal science orbits, and one extra science orbit, which totals 33 orbits (orbits are labeled in Figure 2). The 34th orbit is only half an orbit because the perijove is planned to be deep enough into Jupiter's interior to ensure the spacecraft is completely consumed by the atmosphere.

III. Interplanetary Trajectory Constraints

Designing Juno's reference launch period requires careful consideration of a variety of constraints. These constraints can be broken down into three main categories: 1) launch energy and timing, 2) Jupiter arrival timing and geometry, and 3) interplanetary events. We will discuss each category individually and provide the background and reasoning for each constraint.

A. Launch Constraints

One of the most important constraints in developing a launch period is the maximum allowable launch energy, or C_3. The current maximum C_3 for Juno, 30.8 km^2/s^2, was defined during the early stages of the reference trajectory development. Therefore, many of the assumptions that went into characterizing the relative merits of different C_3 limits are no longer valid. However, the process for selecting a different maximum C_3 would remain the same if the C_3 limit were to be revisited, and that process is documented here.

The ground rules for performing the launch energy comparisons were as follows. 1) Assume a fixed Jupiter arrival date of Oct. 22, 2016. JOI is to begin at 20:50 on this date. Note that the mission plan did NOT include a capture orbit at the time of this study. The spacecraft injected directly into the 11-day orbit, so JOI was roughly twice as long as in the current plan and there was no PRM. 2) Assume a single DSM and that the DSM cannot occur between Aug. 1, 2012 and Sept. 17, 2012, inclusive, to avoid solar conjunction. However, the DSM date can vary

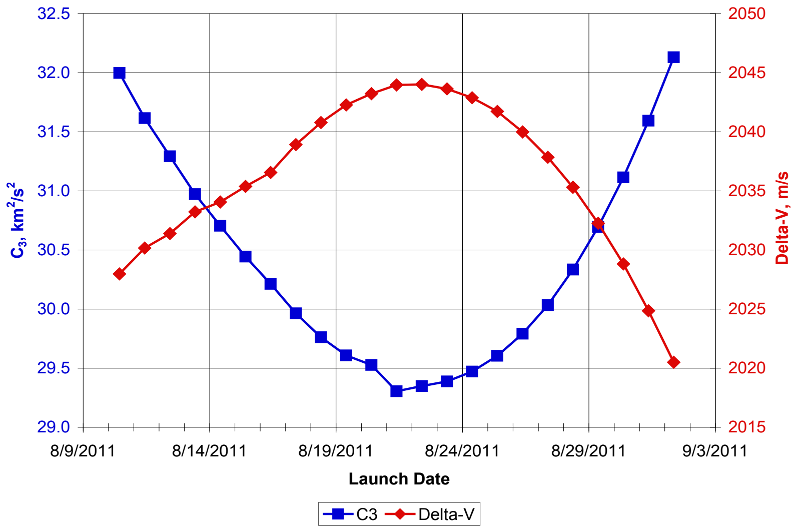

Figure 5. Launch energy and ΔV requirements (through JOI clean-up) for the unconstrained C_3 case.

over the launch period. Note that the current plan is for two DSMs. 3) Assume the Earth flyby altitude is fixed at 800 km but that the date and time can be optimized for each launch date. 4) Assume launch times for each day are consistent with the long-coast launch trajectory option. These times came from a curve fit of approximate launch times provided by the Kennedy Space Center Mission Analysis Branch of the NASA Launch Services Program.

Since determining an optimal C_3 limit becomes a mass optimization trade, some other modeling parameters must be defined. One of the most important is injected mass as a function of launch C_3. This performance relationship can be found on NASA's Launch Services Program's vehicle performance website.§ Juno is planning on launching on the Atlas V 551 launch vehicle, so that vehicle's performance curve is used in this analysis. The other major factor in computing the mass is the main engine's specific impulse, I_{sp}. This analysis assumed an I_{sp} of 317 seconds.

The ΔV-EGA trajectory has the feature such that where the launch energy is at a minimum, the DSM ΔV has a local maximum. Figure 5 shows a plot of the launch C_3 and total ΔV, accumulated through the JOI clean-up maneuver, as a function of launch day. It can be seen in the figure that the C_3 has a minimum for a launch on Aug. 21, 2011 but that the maximum ΔV occurs for that same launch date. (Note that the apparent "jump" in C_3 between Aug. 20 and Aug. 21 is due to the effect of the Moon.)

It will be shown that the overall maximum-mass launch period encompasses the minimum C_3 launch date, so the peak ΔV for this date is unavoidable. We also will show that near the first and last launch days shown in Figure 5, the C_3 could be reduced at the expense of additional ΔV. This allows a larger injected mass over the launch period, since the injected mass must be based on the maximum C_3 that is realized over the entire launch period. To obtain a 21-day launch period from the data shown in Figure 5, the C_3 would have to be 31.6 km^2/s^2 with a corresponding ΔV (through JOI clean-up) of 2044 m/s. The resulting launch mass in this case would be 3570 kg. However, if the C_3 were capped at a lower value, allowing greater launch mass, the ΔV costs for the earlier and later launch days would rise. As long as the C_3 isn't too low, the ΔV costs for the ends of the launch period could be kept to below the 2044 m/s peak in the middle. A judicious selection of a launch C_3 upper limit would increase the injection mass without costing additional ΔV.

Figure 6 shows the increases in ΔV that result from imposing various limits on the maximum allowable launch C_3. It is apparent that the ΔV for the early and late launch dates must grow to

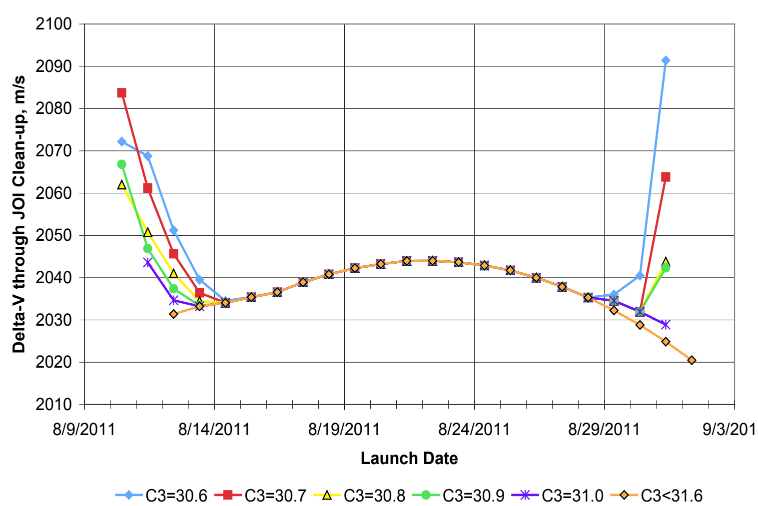

Figure 6. ΔV requirements for various C_3 limits.

§ http://elvperf.ksc.nasa.gov/elvMap/?

accommodate the reduced energy from the launch vehicle. Careful selection of the DSM dates can reduce the required DSM ΔV, and this technique was employed in producing the ΔV curves in Figure 6. The details of the DSM date selection requirements will be discussed in later sections.

Across the entire range of launch dates for each C_3 limit, it is possible to select the 21 days that provide the highest overall mass. For each maximum C_3 case, the 21 days that required the lowest ΔV were selected as the representative launch period for that C_3. Table 1 shows the injected mass, launch period start date, and ΔV requirement for nine different C_3 limits. The injected mass and ΔV were used to compute the masses given in the far right column of Table 1. Note that the highest overall mass across the launch period can be obtained with C_3=30.8 km^2/s^2. Because this C_3 yielded the maximum mass across the launch period, Juno selected 30.8 km^2/s^2 as the C_3 limit for the mission. Note that many of the assumptions and requirements have changed since the C_3 analysis was performed, and these are discussed in the next sections. However, the C_3 limit remains at 30.8 km^2/s^2.

Table 1. Mass comparison across entire the launch period for various C_3 limits.

Maximum C_3 (km^2/s^2)	Injected Mass (kg)	1st Day of Launch Period	ΔV (m/s)	Post-JOI Clean-up Mass (kg)
31.3	3590	8/12/2011	2044	1860
31.1	3605	8/12/2011	2044	1868
31.0	3610	8/12/2011	2044	1870
30.9	3615	8/12/2011	2044	1873
30.8	**3625**	8/12/2011	2044	**1878**
30.7	3630	8/11/2011	2061	1871
30.6	3635	8/11/2011	2069	1868
30.5	3645	8/11/2011	2078	1868
30.4	3650	8/11/2011	2087	1865

Even though the C_3 analysis assumed launch times that were consistent with long-coast launch trajectory option, the Juno project elected to adopt the short coast option as the baseline to address spacecraft and operational constraints. This means that the launch times on each launch date are different by many hours from what was assumed in this analysis, but this does not significantly affect the C_3 or post-launch ΔV, which is the basis for the optimal C_3-launch mass strategy discussed above. Another consequence of the selection of a maximum C_3 is to establish the maximum spacecraft launch mass of 3625 kg. This value is important not just for the spacecraft team in designing the Juno spacecraft, but also for performing mission design analyses. Since all of the major maneuvers of the mission are modeled as finite burns to account for gravity losses, the post-injection spacecraft mass has a direct bearing on the overall ΔV requirements for the mission.

B. Jupiter Arrival Constraints

As noted above, the C_3 analysis was performed before the capture orbit was included in the Juno mission plan. This capture orbit actually changed the Jupiter arrival date so that the PRM would occur on the same date as the previous JOI date. Keeping the PRM on the same day as the previous JOI allowed the rest of the orbits to retain the same timing as in the original mission plan. The selection of the previous JOI date of Oct. 19, 2016 was based on an evaluation of 15 different arrival dates and comparing the ΔV requirements (for OTMs and the de-orbit maneuver) and undesirable close approaches to the Galilean satellites. The JOI date was moved from Oct. 22, 2016 to Oct. 19, 2016 after the C_3 study was completed because it offered a lower total mission ΔV and had more-distant encounters with the Galilean satellites. In summary, following the C_3 study JOI was moved from Oct. 22, 2016 to Oct. 19, 2016 to optimize the performance of the orbital phase of the mission. Adding the 78-day capture orbit changed JOI once more to Aug. 3, 2016 with PRM occurring on Oct. 19, 2016

The selection of the current JOI date of Aug. 3, 2016 took into account the ΔV savings for breaking up JOI into two large maneuvers (JOI and PRM), which reduced the gravity losses and saved over 170 m/s. Also considered were the longitudinal variations of Jupiter's magnetic field. Because Juno will be spinning at 5 RPM during main engine burns, its communications system becomes vulnerable to magnetic field interference. Jupiter's magnetic field is stronger at some longitudes than others, so it was necessary to select JOI and PRM dates that would place the maneuvers at longitudes with low magnetic field magnitude. Of course, Jupiter's rotation period of nearly 10 hours should yield flexibility in the timing of the maneuvers, even on a fixed date. However, JOI is constrained to occur during overlapping coverage from two DSN complexes because it is a critical maneuver. The Goldstone-Canberra overlap is the longest available, so the Juno Project elected to plan JOI during that time. Even though the overlap of the two stations' coverage is significantly longer than the JOI burn itself (roughly three hours of overlap for a 33-

minute burn), many of the pre-burn events also need to occur during the overlapping coverage. This further restricts the timing of JOI. Since Juno has a polar approach to Jupiter, the longitude varies only a few degrees during the burn, so it is possible to select a JOI time that stays within the lower-magnetic field regions. The selected JOI start time of Aug. 3, 2016 00:30 has been determined to provide the low magnetic field interference the project desires. The Jupiter Orbit Insertion maneuver is constrained to have this start time for every day in the launch period.

The Period Reduction Maneuver, however, has a different set of timing requirements. This maneuver is not considered critical, so dual DSN complex coverage is not required. However, the timing of PRM can be optimized to reduce overall ΔV requirements. Since the science orbit perijoves are constrained to occur over the Goldstone complex, selecting the right PRM timing can minimize the deterministic clean-up ΔV required to establish the proper perijove timing and orbit period. However, PRM is also a main engine burn and is therefore susceptible to Jovian magnetic field interference. Fortunately, the optimal PRM time on Oct. 19, 2016 (the previous JOI date) yields a Jupiter longitude with low magnetic field magnitude. For all days in the launch period, PRM is constrained to begin at Oct. 19, 2016 18:00.

Recall from the previous section that Juno plans to fly over Jupiter's North Pole as it approaches perijove and JOI. The perijove altitude during JOI is constrained to be 4500 km above the 1 bar pressure level at Jupiter. This altitude is well inside the "hole" in the torus describing the areas of most intense radiation and also serves to keep the ΔV magnitude of JOI low. Furthermore, the JOI altitude sets up the altitude profile for the rest of the orbital mission. If JOI were performed at a much higher altitude, a perijove-lowering maneuver would be required.

C. Interplanetary Constraints

Juno's interplanetary trajectory has two main features: the DSMs and the Earth flyby. These events each have particular constraints associated with them that affect the overall design of the mission. The Earth flyby constraints are discussed first.

The Earth flyby provides approximately 7 km/s of gravity-assist ΔV. While the date and time of the Earth flyby is optimized for each launch date, the flyby altitude is fixed at 800 km. This distance is closer than Cassini's flyby altitude (1200 km), but is still comfortably above the altitude of the Space Station (~500 km). While the design of the interplanetary trajectory will force the flyby altitude to be 800 km, the actual execution of the event during operations will not be so constrained. An 800 km design allows for flexibility in the range of 100 km to 200 km in targeting following the execution of the DSMs for overall trajectory optimization and potential hazard avoidance.

Perhaps one of the most challenging tasks in designing Juno's launch period is selecting the Deep Space Maneuver dates for each launch date. The reason this is so challenging is that the selection of the DSM dates will affect the required launch C_3 as well as the mission ΔV. However, it is not as simple as choosing dates that will minimize the ΔV subject to the C_3 limit of 30.8 km^2/s^2 because there are two other constraints that limit the options available: avoiding solar conjunction and accommodating telecommunications requirements.

Recall from previous sections that Juno plans to execute the 2+ ΔV-EGA trajectory with the DSM split into two parts. The primary reason for this deals with the qualification of the main engine. If there were only a single DSM, it would be the longest burn of the entire mission by about a factor of two. Furthermore, Juno's main engine is not currently qualified for a single burn of nearly 60 minutes, the duration required for a single DSM. Re-qualifying the main engine to accommodate a burn of this duration would be a costly activity that could also impact the development schedule. Therefore, the Project opted to split the DSM into two parts (called DSM1 and DSM2). While there are an infinite number of ways to divide up the DSM, Juno will be designing the two DSMs to be equal in burn duration. This makes both burns a few seconds shorter than JOI and about one minute shorter than PRM. In addition, the plan calls for the two DSMs to execute two days apart.

In selecting the DSM dates for each launch date, it is necessary to avoid solar conjunction for the sake of having real-time visibility into the maneuver and to acquire navigation data to reconstruct the maneuvers and to design clean-up maneuvers. Juno plans to use the DSMs as rehearsals for the JOI activities, which includes sending tones on Juno's toroidal antenna. The spacecraft and the Earth will be nearly on opposite sides of the Sun during the DSMs, and solar interference can degrade the radio signal.[5,6] This degradation will reduce the quality of the radiometric navigation data, as demonstrated in Refs. 5 and 6. Juno therefore has the following requirements for the timing of the DSMs: 1) DSM timing with respect to solar conjunction ensures two days of tracking with the Sun-Earth-spacecraft (SEP) angle greater than 10° for maneuver design, and 2) maneuver execution occurs when the SEP angle is greater than 3°. These requirements are designed to ensure high-quality navigation data is available for maneuver design and that the quality of the radio signal during the maneuvers is sufficient to have visibility into the engine's performance. Note that the two days of tracking data do not immediately precede the maneuver execution because the data must first be processed and the maneuvers designed based on those trajectory estimates. Under normal circumstances, it is expected that the design cycle will take seven days after the navigation data cut-off.

Note that Juno plans to execute two DSMs separated by two days. This means that both maneuvers must execute when SEP is greater than 3°. However, the requirement on acquiring the tracking data really only affects the timing of the first maneuver because Juno plans to design both maneuvers with the same set of navigation data. While tracking data will certainly be collected and evaluated in between the two maneuvers, the nominal plan is to not re-design the second maneuver after execution of the first. Any execution errors or dispersions will be corrected in a clean-up maneuver that is nominally planned to take place ten days after DSM2. However, to design the clean-up maneuver, the navigation team will need at least two days of tracking data after DSM2 with SEP > 10°. In the cases where the DSMs would precede solar conjunction, this means that they would both have to occur *before* SEP passes below 10° because two more days of tracking data are needed after DSM2 to acquire navigation data for design of the clean-up maneuver. Therefore, when the DSMs occur before solar conjunction the *latest* execution date for DSM1 is four days before SEP = 10°. In the cases where the DSMs occur after solar conjunction, acquiring the data for DSM1 becomes the driver for how close to solar conjunction the maneuvers can occur. Since there must be two days of tracking after SEP becomes greater than 10° and the maneuver design cycle takes seven days, the *earliest* execution date for DSMs occurring after solar conjunction is 9 days after SEP = 10°.

There is a final consideration relating to solar conjunction that only affects the cases where the DSMs occur before solar conjunction. To have a robust plan in the event of contingencies, such as a failed maneuver attempt, it is desirable to allow adequate time before solar conjunction to re-try the failed burn. While there is no fixed requirement on how much time to allow, having the ability to execute a contingency DSM before solar conjunction reduces the additional ΔV needed to accomplish the baseline Juno mission. Since Juno, like all missions, will carry some contingency ΔV, designing a baseline mission that requires little additional ΔV to cover the most likely contingency cases reduces the overall mission ΔV requirement. The contingency analyses that have been conducted for the Juno mission are not discussed here, but generally allowing an additional ten days to complete all the maneuvers before SEP = 3° is desired.

The last major constraint relating to the DSM timing is due to the spacecraft configuration and the need for the ground to receive the tones sent via the toroidal antenna on the spacecraft. Because of the relative positioning of the antenna and the main engine and the off-boresight performance of the antenna, the best telecommunications link is achieved when the angle between the ΔV direction and the Earthline direction is 90°. This angle is referred to as the Earth-Look Angle (ELA). To ensure a good radio signal during the burn, the ELAs are constrained to be within ±10° of 90°. Since the first DSM would be the first use of the main engine, there is also a strong navigation desire to have visibility into the burn via 2-way Doppler. The Doppler data is of very little value if the ELA is too close to 90°, so the navigation team imposes an additional design constraint that the ELA be at least 3° away from 90°. (This navigation constraint is not a hard requirement, however.) Combining the telecom and navigation constraints yields acceptable ELAs of 80°–100° but a preferred ELA range of 80°–87° and 93°–100°.

For a given launch date and DSM date pair (hypothetically assuming a single DSM), there is an optimal DSM burn direction. Given that the entire trajectory is optimized for a particular DSM date and that the Earth, of course, is in a different location for each DSM date, there is not an easy analytical solution to ascertain what the ELA will be for given launch date-DSM date pair. Figure 7 shows the ELAs and cumulative ΔVs (through PRM clean-up) for a variety of DSM dates. (The Aug. 18, 2011 launch opportunity and a single DSM were assumed, but the ELAs change very little when there are two DSMs). Also indicated in the figure are the dates where the SEP angle is less than 10° and less than 3°. If the DSMs were executed after solar conjunction (after SEP > 10°), the ELAs would be less than 80°, which is outside the acceptable range. It is also evident that the minimum ΔV is obtained when the SEP angle is less than 10°, which means that navigation data for designing the clean-up maneuver could not be acquired until after solar conjunction if the DSMs were executed at that time.

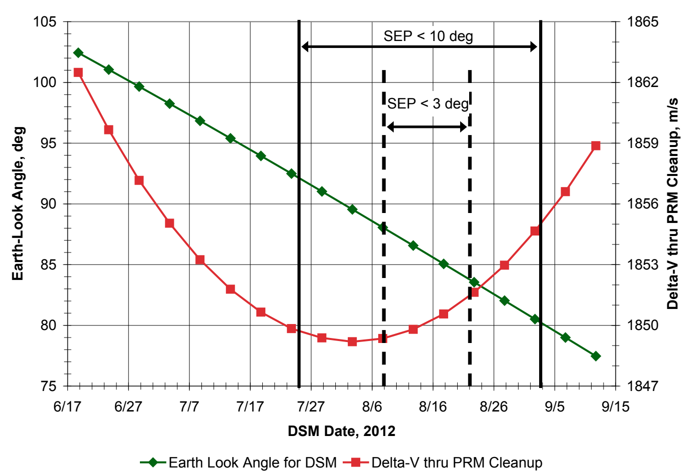

Figure 7. Earth-look angle and cumulative ΔV (through PRM clean-up) versus DSM date. The launch date was Aug. 18, 2011 and Jupiter arrival was Aug. 4, 2016 (which is not the current baseline). A single DSM was assumed.

The values in Figure 7 represent the variability of the ELA and DSM ΔV for a single launch date only (Aug. 18, 2011). Different launch dates will create a different ELA and ΔV profile. To develop the launch period, each potential launch date must be considered separately to accommodate the particular geometry and ΔV requirements of that case. For mission planning purposes, it is desirable to plan to have the DSMs on the same dates for all launch dates. It will be shown later that this is not possible for the Juno mission, but an effort should be made to keep the DSM dates the same for as many launch dates as possible, subject to the solar conjunction and ELA constraints and without forcing the required ΔV above the "peak" found near the center of the launch period.

IV. Launch Period Results

Computing the required launch C_3 and post-launch ΔV for each potential launch date would be a laborious activity if we were to run each case from launch all the way through de-orbit. Given that the JOI and PRM dates are constrained to be the same for all launch dates, we found that the ΔV required for the orbital phase and de-orbit were virtually the same for any launch opportunity. Consequently, we only integrated each of the cases evaluated in the launch period study through Perijove-4, which is the second science orbit. The accumulated ΔV used to develop the launch period therefore includes both DSMs, JOI, PRM, and the OTMs on orbits 2 and 3. Keeping in mind that only the deterministic ΔV is considered in this paper, the timing of PRM with respect to the Goldstone view period means that there is no ΔV on orbit 2 and nearly zero ΔV on orbit 3.

Recall that the Juno Project requires a 21-day launch period to provide a high probability of launch given the most likely causes for launch delays. These include adverse weather, launch vehicle readiness, and spacecraft readiness. The 23 best-performing launch dates are plotted in Figure 8, showing the required launch C_3 and post-launch ΔV, tabulated through the Perijove-3 OTM. Furthermore, the corresponding DSM1, DSM2, and DSM clean-up dates are shown in Figure 9. Finally, Figure 10 gives the Earth-look angles for the DSMs. The sharp drop in C_3 in Figure 8 between the Aug. 20 and Aug. 21 launch dates is due to the effect of the Moon. (There is no risk of impacting the Moon, however.) Note also in Figure 8 the jump in the post-launch ΔV when the DSMs change from

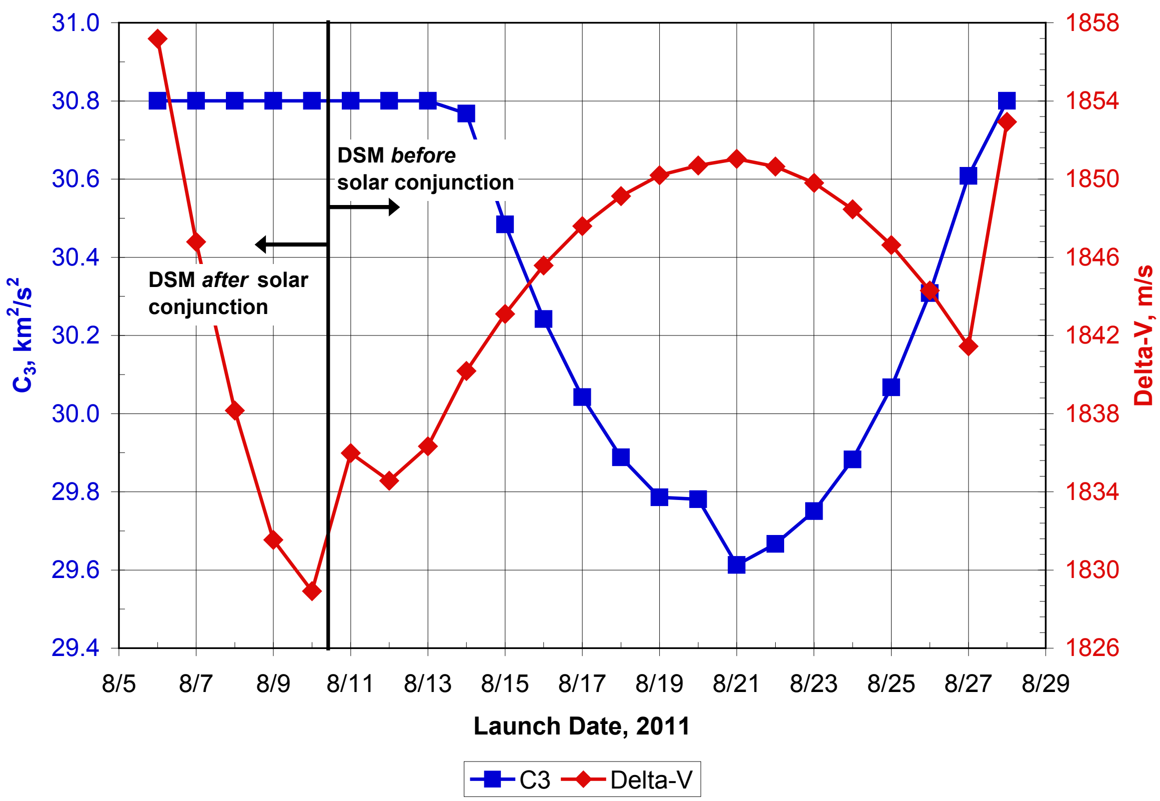

Figure 8. C_3 (in blue) and ΔV (in red) for 23 potential launch dates. The total ΔV includes DSM1, DSM2, JOI, PRM, and PRM clean-up.

being after solar conjunction (launch dates Aug. 6 – Aug. 10) to occurring before solar conjunction (Aug. 11 – Aug. 28). As a general rule, earlier launch dates require later DSM dates, and vice versa, to meet the ELA constraints and to keep the overall DSM ΔV low.

The Aug. 28 launch date differs from the others in that it requires a deterministic maneuver of about 10 m/s, occurring 30 days after launch. (The first statistical maneuver is planned for 30 days after launch, so the deterministic maneuver that is needed for the Aug. 28 launch opportunity was designed to be at the same time.) This maneuver serves to augment the energy provided by the launch vehicle, which is at the maximum (30.8 km^2/s^2) for this launch date. Without this maneuver, the trajectory would be infeasible without relaxing constraints described in the previous section. The ΔV plotted in the figure includes the post-launch maneuver on the Aug. 28 launch date. Though the Aug. 28 launch has the additional 10 m/s from the launch +30 days maneuver, the magnitudes of the DSMs are somewhat less than for many of the other launch dates. This is why the total ΔV is only 2 m/s higher than the peak ΔV near the middle of the launch period.

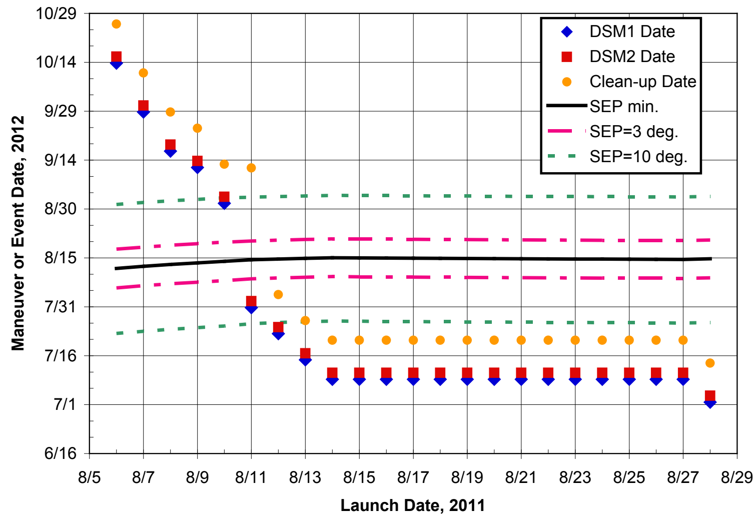

Figure 9. Dates of the DSMs and the DSM clean-up maneuver for each potential launch date. The dates when the Sun-Earth-spacecraft (SEP) angle equals 5°, 10°, and the minimum are also shown.

Figure 9 shows that the DSM dates for launch dates Aug. 14 – Aug. 27, inclusive, are the same. For each of these cases, DSM1 occurs on July 8, 2012, DSM2 is on July 10, 2012, and the DSM clean-up maneuver is planned for July 20, 2012. Since the Sun-Earth-spacecraft angle doesn't reach 3° until Aug. 9, 2012, this schedule of events allows ample margin for re-trying either of the DSMs in the event of a failed attempt. In fact, the SEP angle only reaches 10° on July 26, so there would still be opportunities for acquiring new navigation data if a re-design of one or both maneuvers were required.

Two of the potential launch dates deserve special discussion because the paradigm of how the maneuvers are designed and executed is somewhat different: Aug. 10 and Aug. 11. We will first address the Aug. 10 case. Note in Figure 9 that the two DSMs take place before the SEP angle reaches 10° following solar conjunction (maneuvers on Aug. 31 and Sept. 2, 2012, respectively). It would seem that these maneuvers were designed with data taken with SEP < 10°. However, the plan for this launch opportunity is to design these maneuvers with navigation data that was acquired *before* solar conjunction. The second DSM is placed on the date where SEP equals 10° so that good navigation data can be taken immediately following the maneuver for the design of the clean-up maneuver.

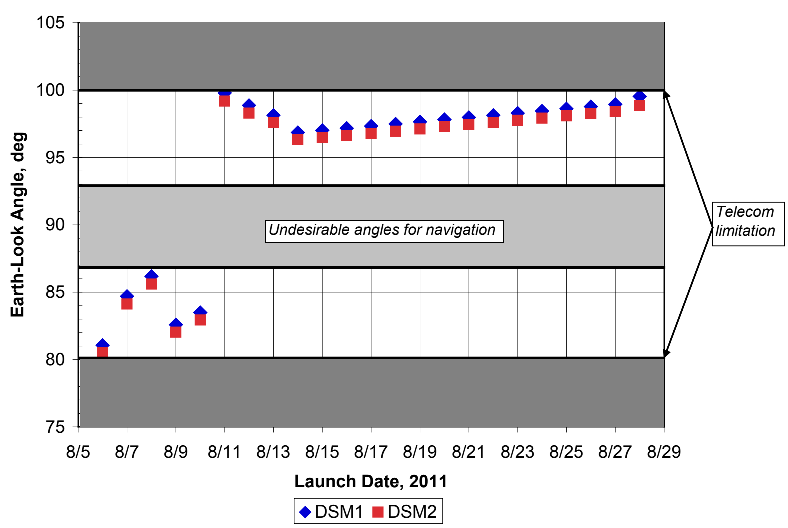

Figure 10. The Earth-look angles for each potential launch date. Launch dates with the DSMs after solar conjunction have ELAs less than 90°; those with DSMs before solar conjunction have ELAs greater than 90°.

The question, of course, is why we would choose this plan for this launch date. For the other launch opportunities where the DSMs are after solar conjunction, the maneuvers will be designed with data taken about 10 days before their actual execution. The Aug. 10 launch date presents a special problem, however, because of the Earth-look angle constraint. If DSM1 were on Sept. 11, 2012, which is 10 days after SEP=10°, the ELA would be 78.4°. Recall from the previous section that the ELA must be within ±10° of 90°, so 78.4° is outside the acceptable range. Placing the DSM *before* solar conjunction on Aug. 1, 2012, though, results in an ELA of 105°. (The Aug. 1 date has another problem in that it would not allow navigation data to be acquired with SEP ≥ 10° to design the clean-up maneuver before solar conjunction.) The selected DSM dates yield ELAs of about 83° (shown in Figure 10), which are well within the constraints.

The Aug. 10 launch date DSMs will be designed with data taken about 38 days before the maneuvers are executed, while every other launch opportunity will be designed with data acquired only about 10 days before execution. With the additional elapsed time between the navigation data cut-off and maneuver execution, the statistical ΔV for the DSM clean-up might be expected to be much higher given the greater uncertainty in the spacecraft's state at the maneuver execution time. However, note in Figure 8 that the Aug. 10 launch opportunity has the lowest deterministic ΔV requirement of any date analyzed. In fact, the required ΔV is 22 m/s below the maximum ΔV case on the Aug. 21 launch date. Also, a statistical analysis of these two launch dates indicates that there is essentially no penalty for the large gap in time between the data cutoff for maneuver design and the DSM execution for the Aug. 10 launch opportunity.

The other launch date that bears special discussion is Aug. 11. Figure 9 shows that although the DSMs for that launch opportunity occur before solar conjunction (July 30 and Aug. 1, 2012), the clean-up maneuver takes place after (Sept. 11, 2012). The Aug. 11 launch suffers from the same ELA difficulties as the Aug. 10 launch. If all three maneuvers (DSM1, DSM2, and clean-up) were to occur before solar conjunction, the ELAs would be approximately 105°; if they were to take place after, the ELAs would be about 78°. Therefore, the DSMs are planned to be as early as possible without violating the ELA constraint to allow as much time as possible for contingency attempts at executing the DSMs in the event of a delay. The ELAs for the Aug. 11 launch DSMs are only slightly less than 100° (see Figure 10).

For the Aug. 11 launch date, the clean-up maneuver is nine days after SEP reaches 10° following solar conjunction, which allows for two days of navigation data acquisition and seven days of maneuver design. This means the clean-up maneuver is 41 days after DSM2 versus 10 days after DSM2 for most of the other launch opportunities. Again, the question of the statistical ΔV impact arises because of such a delay. However, note in Figure 8 that the ΔV required for the Aug. 11 launch date is 15 m/s less than for the Aug. 21 launch (the maximum ΔV case). And as with the Aug. 10 launch, a preliminary statistical ΔV analysis of the Aug. 11 launch opportunity yields no penalty for the amount of time that elapses between the DSMs and the DSM clean-up maneuver.

The data given in Figure 8 – Figure 10 are for 23 potential launch dates. Recall from previous sections, however, that Juno only requires a 21-day launch period. Selecting the baseline launch period requires selecting the 21 days that will define the ΔV requirements that the flight system must accommodate in its design. That would suggest that the 21-day period beginning on Aug. 7, 2011 should be selected as the baseline launch period. However, if many delays occur during the launch period, having back-up opportunities available following the conclusion of the primary launch period offers additional flexibility and robustness. If, for example, the flight system were designed to accommodate the additional ΔV needed for the Aug. 6 launch, there would be ample ΔV for a 21-day launch period ending on Aug. 26 as well as two back-up opportunities on Aug. 27 and 28. While this seems like an attractive plan, doing so essentially creates a 23-day launch period, which is beyond the requirement levied by the project. Therefore, there is no justification for adding ΔV to obtain more than 21 launch days. In addition, the first day in the launch period is considered to be the most likely date on which the launch will actually occur. If Aug. 6 were the first day in the launch period, the most likely launch date would require the maximum ΔV, leaving less margin for contingency. If, on the other hand, the flight system were sized to accommodate the ΔV required for the Aug. 21 launch and the launch occurred on the first day of a launch period beginning Aug. 7, there would be an additional 3 m/s (deterministic) of ΔV to handle contingencies. Juno would have to launch on the 15th day of its launch period to reach the maximum ΔV case for the Aug. 21 launch.

Juno has therefore decided that its baseline launch period begins on Aug. 7, 2011 and ends with an opportunity on Aug. 27, 2011. The details of each launch date are given in Table 2. Note that Aug. 28 is also included in this table even though it is outside the launch period accepted by the project. In the Total ΔV column on the far right, the maximum is 1851.0 m/s for a launch on Aug. 21. The Aug. 28 launch opportunity, however, requires a mere 1.9 m/s, or 0.1%, more than the maximum. While we do not discuss the computation of the statistical ΔV in this paper, the Juno project requires that sufficient ΔV be allocated to accommodate the 99th percentile case. The so-called "ΔV-99" must allow for uncertainties in the orbit determination as well as maneuver execution errors. With a total deterministic ΔV requirement of nearly 2 km/s, it is expected that the statistical ΔV for Juno would be many 10s of m/s. In fact, the statistical ΔV is approximately 70 m/s for the 99th percentile case. This means that the 1.9 m/s additional deterministic ΔV required for the Aug. 28 launch is available at the expense of reduced probability of completing the mission, (i.e., less ΔV is available to account for orbit determination uncertainties and maneuver execution errors). Since Aug. 28 would only be considered as a back-up launch opportunity, the slight reduction in ΔV available for maneuver execution errors and orbit determination uncertainty might be acceptable.

Table 2. Summary of the Juno launch period. For each launch opportunity, the DSM and clean-up dates, the Earth-look angles, and ΔVs are given. The final date (8/28/2011) is not part of the primary launch period but is considered to be a back-up opportunity, so it is given in italics.

Launch Date	DSM1 Date	DSM2 Date	DSM Clean-up Date	DSM1 ELA (deg)	DSM2 ELA (deg)	DSM1 ΔV (m/s)	DSM2 ΔV (m/s)	Total ΔV* (m/s)
8/7/2011	9/28/2012	9/30/2012	10/10/2012	84.7	84.1	363.7	412.1	1846.8
8/8/2011	9/16/2012	9/18/2012	9/28/2012	86.2	85.6	359.8	407.1	1838.2
8/9/2011	9/11/2012	9/13/2012	9/23/2012	82.6	82.0	356.8	403.3	1831.5
8/10/2011	8/31/2012	9/2/2012	9/12/2012	83.5	82.9	355.6	401.8	1828.9
8/11/2011	7/30/2012	8/1/2012	9/11/2012	99.8	99.2	358.8	405.9	1836.0
8/12/2011	7/22/2012	7/24/2012	8/3/2012	98.9	98.3	358.2	405.1	1834.6
8/13/2011	7/14/2012	7/16/2012	7/26/2012	98.1	97.6	359.0	406.1	1836.3
8/14/2011	7/8/2012	7/10/2012	7/20/2012	96.9	96.3	360.8	408.3	1840.2
8/15/2011	7/8/2012	7/10/2012	7/20/2012	97.0	96.5	362.1	410.0	1843.1
8/16/2011	7/8/2012	7/10/2012	7/20/2012	97.2	96.6	363.2	411.5	1845.6
8/17/2011	7/8/2012	7/10/2012	7/20/2012	97.3	96.8	364.1	412.6	1847.6
8/18/2011	7/8/2012	7/10/2012	7/20/2012	97.5	96.9	364.8	413.5	1849.1
8/19/2011	7/8/2012	7/10/2012	7/20/2012	97.6	97.1	365.3	414.1	1850.2
8/20/2011	7/8/2012	7/10/2012	7/20/2012	97.8	97.3	365.5	414.4	1850.7
8/21/2011	7/8/2012	7/10/2012	7/20/2012	98.0	97.4	365.7	414.6	1851.0
8/22/2011	7/8/2012	7/10/2012	7/20/2012	98.1	97.6	365.5	414.4	1850.6
8/23/2011	7/8/2012	7/10/2012	7/20/2012	98.3	97.8	365.1	413.9	1849.8
8/24/2011	7/8/2012	7/10/2012	7/20/2012	98.5	97.9	364.5	413.1	1848.5
8/25/2011	7/8/2012	7/10/2012	7/20/2012	98.6	98.1	363.7	412.1	1846.6
8/26/2011	7/8/2012	7/10/2012	7/20/2012	98.8	98.2	362.6	410.7	1844.3
8/27/2011	7/8/2012	7/10/2012	7/20/2012	98.9	98.4	361.3	409.1	1841.4
8/28/2011	*7/1/2012*	*7/3/2012*	*7/13/2012*	*99.5*	*98.8*	*362.4*	*410.4*	*1852.9*

*Total ΔV includes DSM1, DSM2, JOI, PRM, and PRM clean-up.

V. Back-Up Launch Opportunities

Launch opportunities that match the basic features of the 2+ ΔV-EGA trajectory repeat every 13 months. The principal differences among different launch opportunities are variations in the ΔV (primarily for DSM and JOI) and in the approach direction with respect to Jupiter, which gives slightly different initial perijove latitudes. The September 2012 launch opportunity was analyzed in enough detail using the same process as described in this paper to determine that the DSM and JOI maneuvers are slightly smaller than for the current August 2011 opportunity. The initial perijove latitude is 5.3º compared to 2.9º in the baseline, which implies that the 2012 launch opportunity will have a somewhat higher radiation dosage for the same number of science orbits at Jupiter. Another feature of the 2012 launch opportunity is that there is a shorter view period at Goldstone; this results in not being able to have the full perijove ±3hr coverage for science observations.

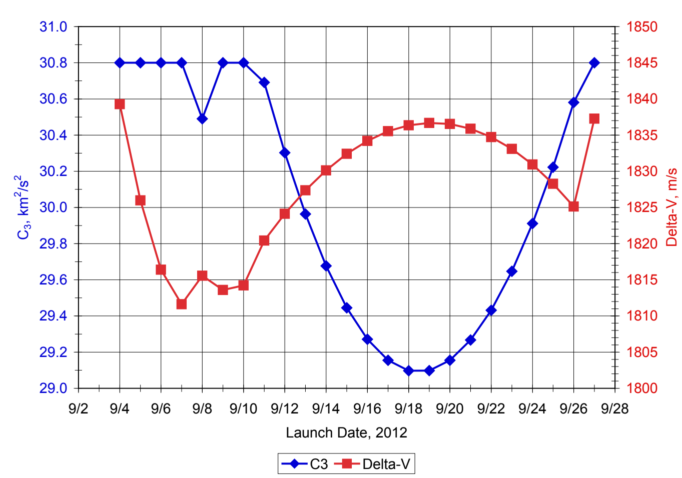

Figure 11. Launch C_3 and ΔV for 2012 2+ ΔV-EGA back-up launch opportunity. ΔV is tabulated through PRM clean-up.

Figure 11 shows the launch C_3 and post-launch ΔV for the 2012 back-up launch opportunity. This analysis assumes a single DSM and a Jupiter arrival on Sept. 6, 2012. There are 24 potential launch dates shown in the plot, so if only 21 are required to define a launch period clearly one would not include the first date (Sept. 4) or the last (Sept. 27) because of the higher ΔV required than the peak on Sept. 19. This leaves 22 potential launch dates. One might consider skipping the peak ΔV case on Sept. 19 except that the difference in required ΔV for this launch opportunity is less than 0.2 m/s more than for the next highest case (Sept. 20). This means that for the 2012 back-up, a 22-day launch period is available for the same ΔV cost as a 21-day launch period. Such a launch period would begin on Sept. 5, 2012 and continue through Sept. 26, 2012. Note that the required ΔV through PRM clean-up is only 1837 m/s, which is 14 m/s less than with the baseline case.

The ΔV shown for the 2012 launch opportunity is only tabulated through PRM clean-up, the same as we did for the baseline. However, with the baseline case we were able to assume that for each launch day the OTMs and de-orbit ΔV would be roughly the same because of the fixed JOI and PRM times. The 2012 launch opportunity, however, will have a different overall orbital mission because the JOI and PRM dates will be 13 months later. An optimization study would need to be conducted to select the best JOI and PRM dates, keeping in mind the constraints on DSN coverage, the magnetic field magnitude during the burns, any close encounters with the Galilean satellites, and overall ΔV. It is possible that the 14 m/s reduction in ΔV through PRM clean-up could be overtaken by other ΔV costs in designing the full-up reference case for the 2012 launch opportunity.

Another back-up launch opportunity that was investigated was the 2- ΔV-EGA opportunity, which falls in the October-November 2011 timeframe. Because the launch would occur only a few months later, this case might be viewed as a good back-up to the August 2011 launch opportunity if the launch were delayed due to payload or launch vehicle integration issues. The 2- ΔV-EGA trajectory has an Earth flyby less than 2 years after launch. The required C_3 for a 21-day launch period for a 2- ΔV-EGA is considerably less than for the baseline case (C_3 = 29 km^2/s^2) while the ΔV through PRM is nearly the same as the baseline (see Figure 12). If we assume, however, that this launch opportunity were to be used only as a back-up to the primary, the launch vehicle and flight system would have already been designed to accommodate a C_3 of 30.8 km^2/s^2 and the same post-launch ΔV as with the 2+ ΔV-EGA. Using the same process as described in this paper to develop a launch period with a C_3 constrained to 30.8 km^2/s^2, one can obtain a larger launch period of 33 days. The required ΔV, however, would be 1865 m/s, or 15 m/s more than for the baseline case.

The real problem with this launch opportunity, however, is that the approach angle at Jupiter results in a perijove latitude that is farther away from the equator. A North Pole approach has an initial perijove latitude of 12.0º (which would evolve through apsidal rotation to a perijove latitude value near 42º at end of nominal mission); a South Pole approach has an initial perijove latitude of -9.8º (which becomes near -40º at end of mission through apsidal rotation). Thus, these trajectories would incur a higher radiation dosage at the beginning of mission and would reach the baseline mission's maximum radiation dosage 7 to 9 orbits earlier. The solution to the problem of highly-increased radiation dosage is to change the number of orbits at Jupiter; however, this results in degraded science. In addition, if a South Pole approach were used (which has the smaller latitude magnitude), certain science instruments would not work since they will be designed with particular assumptions on the orbit normal and spin directions of the spacecraft. The project, therefore, concluded that the 2-ΔV-EGA opportunity was not a suitable back-up launch opportunity.

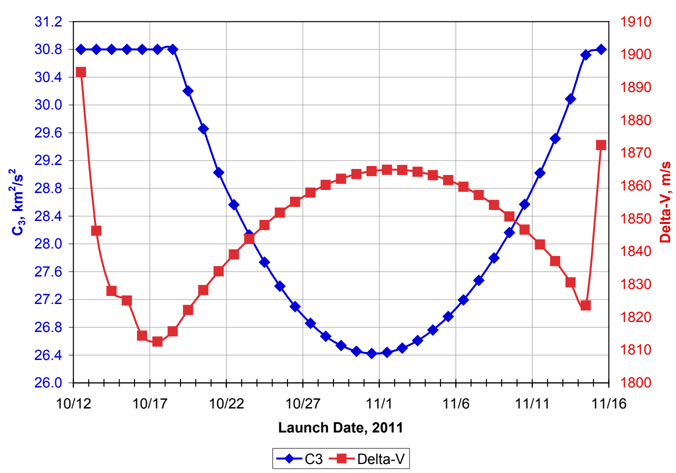

Figure 12. Launch C_3 and ΔV for 2011 2- ΔV-EGA back-up launch opportunity. ΔV is tabulated through PRM clean-up.

VI. Conclusion

Accounting for the numerous constraints on the Juno mission design, a 21-day launch period is achievable from Aug. 7, 2011 through Aug. 27, 2011, inclusive, with a back-up launch date on Aug. 28, 2011. The primary launch period requires only the ΔV needed by the "peak" case on Aug. 21, 2011. Although the timing of the Deep Space Maneuvers is significantly constrained by solar conjunction and Earth-look angle requirements, many of the DSM dates allow ample margin for possible contingencies. There is also a viable back-up launch period that is about 13 months later than the baseline (October 2012). This opportunity provides a 22-day launch period for approximately the same ΔV as the baseline with the same maximum C_3.

Acknowledgments

The authors thank Stuart Stephens for the use of his figures, John Bordi and Ian Roundhill for the navigation references, and Inoo Jun for the radiation reference. In addition, we thank Steven Matousek for his expert guidance and Sara Hatch and Julie Kangas for their contributions to the launch period analysis. The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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