AAS 17-459

JUNO NAVIGATION FOR JUPITER ORBIT INSERTION*

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Juno arrived at Jupiter on 05 July 2016 UTC, achieving orbit with the execution of the Jupiter Orbit Insertion (JOI) maneuver. Thanks to a dynamically well-behaved spacecraft, the delivery of Juno to JOI was done largely with only a maneuver to setup and Earth gravity assist (EGA), an EGA, an EGA clean-up maneuver, and a JOI targeting maneuver. During the last several weeks of the approach to JOI, the dominant uncertainties in the predicted trajectory were from the Jupiter barycenter ephemeris. In this paper, we discuss the maneuver and orbit determination (OD) strategy for successfully arriving at JOI, the the challenges of calculating a correction to the Jupiter barycenter ephemeris using only radiometric data types, and how the ephemeris estimates during approach to JOI compare to a post-JOI trajectory reconstruction.

INTRODUCTION

Juno arrived at Jupiter with the successful execution of the Jupiter Orbit Insertion (JOI) maneuver on 05 July 2016 02:47:32 UTC, late in the evening of 04 July 2016, local time at the Jet Propulsion Laboratory. Successful completion of this maneuver was required to place the Juno spacecraft into an orbit about Jupiter. Thanks to the dynamically well-behaved spacecraft, very few maneuvers along with an Earth gravity assist were needed to achieve the correct JOI target. During most of the five year cruise, errors in solar radiation pressure and thruster activity (primarily for turns to maintain Earth-pointed attitude) were the dominant uncertainties in trajectory propagation. This was thanks to the relatively long time over which these small effects could propagate. However, during the last several weeks of the approach to JOI, the errors in the Jupiter barycenter ephemeris were responsible for the largest uncertainties in the predicted Juno trajectory relative to Jupiter.

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Herein, we give a brief overview of the mission from the Earth flyby through JOI. We discuss how we were able to use Doppler, range, and delta-differential one-way range (DDOR) observations in order to detect errors in the Jupiter barycenter ephemeris upon approach to JOI. This was particularly challenging in the absence of optical navigation data which could have allowed for more direct measurements of Jupiter or its moons. We compare the reconstructed Juno trajectory to the JOI target, in particular, showing how the Jupiter barycenter ephemeris updated during JOI approach was better than the nominal Jupiter barycenter ephemeris. Finally, for completeness we document the complex sequence of activities which took place during JOI. While JOI was distilled down to a relatively simple set of models, i.e., primarily via finite burn model, care had to be taken to bookkeep all of the activity accurately.

MISSION OVERVIEW

It took approximately five years for Juno to reach Jupiter after launch. All of the navigation activities during that time were in ultimately in support of targeting JOI, many of which are listed in Table 1. Launched on 05 August 2011, the Juno spacecraft travelled within the inner solar system on a heliocentric orbit for approximately two years. It flew past the Earth on 09 October 2013 with a geodetic altitude of approx. 561 km for the Earth gravity assist necessary to boost the trajectory to Jupiter. Setting up for this flyby required a large deep space maneuver (DSM), split into two parts DSM-1 & DSM-2, about one year after. The large DSM was executed near aphelion and was split into two smaller maneuvers in order to avoid having to qualify the main engine (ME) for a long burn that would be required by a single DSM.

Table 1. Selected Navigation Events for JOI Context.

Mission Event	Date	Purpose	Comments
Launch	05-Aug-2011		
DSM-1	30-Aug-2012	Maneuver targeting biased aim-point relative to Earth flyby	Deep-space maneuver, split into two parts
DSM-2	14-Sep-2012		
TCM-6	01-May-2013	Maneuver targeting Earth flyby	
TCM-7	09-Sep-2013	Maneuver targeting Earth flyby	
TCM-8	29-Sep-2013	Maneuver targeting Earth flyby	Cancelled
Earth Flyby	09-Oct-2013	Gravity assist to Jupiter	
TCM-9	13-Nov-2013	Earth Flyby Cleanup maneuver	
TCM-10	12-Apr-2014	JOI targeting maneuver	Cancelled
TCM-11	03-Feb-2016	JOI targeting maneuver	
	20-Feb-2016	Final Design of JOI Maneuver	
TCM-12	31-May-2016	Cleanup maneuver of JOI targeting	Cancelled
TCM-12a	15-Jun-2016	Contingency maneuver	Cancelled
TCM-13	25-Jun-2016	Contingency maneuver	Cancelled
JOI	05-Jul-2016	JOI maneuver	
JOI-CLN	13-Jul-2016	Clean-up maneuver of JOI	
PRM	19-Oct-2016	Period Reduction maneuver	Cancelled / Postponed
Not all thrusting related events (executed or cancelled) are shown.			

A cleanup maneuver of the EFB, TCM-9 executed on 13 November 2013, roughly a month after the EFB. This maneuver targeted JOI, but it was a very preliminary JOI target. The dominant perturbations, in terms of potential trajectory errors, were due to solar radiation pressure and thrusting from Earth re-points. However, those errors were minimal enough such that the only maneuver required to retarget JOI was TCM-11 on 03 February 2016, roughly 15 months after the previous maneuver.

Following TCM-11 on 03 February 2016, the trajectory design team produced the final reference trajectory and targets for the Jupiter orbit phase. This fed into the final design of the JOI maneuver itself, with a data-cutoff (DCO) of 20 February 2016, or about JOI – 136 days. Thanks to the accuracy of the trajectory predictions, all later maneuver opportunities scheduled to target the trajectory back to JOI were cancelled – TCM-12, -12a, and -13. This meant that only two maneuvers after EFB were needed in order put the spacecraft on the proper trajectory for JOI.

Following JOI, a much smaller JOI Clean-up (JOI-CLN) maneuver to placed the spacecraft on a capture orbit. Initially this orbit about Jupiter was to be at a 53.5-day period, followed by a later Period Reduction Maneuver (PRM) to place the spacecraft into a 14-day science orbit. An anomaly in the behavior of the main engine system led to the cancellation or postponement of PRM. At this time, the orbit period is 53.5 days and will continue to be until a final decision is made regarding a future PRM.

MEASUREMENT MODELING AND DYNAMICS

Data types used in OD included two-way coherent range, two-way coherent Doppler, and DDOR. For Doppler data, we assumed a per-pass data weight based on the post-fit RMS of each pass, with a minimum possible weight of 0.5 mm/s. Range data was weighted such that the effective weight per pass was 5-m. DDOR data was weighted at 0.06 ns. Also, a data elevation cutoff of 10 deg, and corrections for tropospheric and ionospheric media were used.

Juno is a spin-stabilized spacecraft, using the reaction control system (RCS) thrusters to correct for drift in the spin axis from off-Earth point and for the TCMs. The main engine (ME) is used for much larger burns such as those for DSMs, JOI, and PRM. During the time period of this reconstruction during which Doppler data was used, the nominal spin rate was approximately 2 rpm. There are times during which the spin rate is increased in order to provide more stability, e.g., during the JOI burn. However, there was only one-way Doppler available during JOI.

The process of removing the spin signature for Juno is similar to the procedures and scripts used for the Mars Science Laboratory (MSL) as documented in Reference 1. The details differ between the MSL process and the Juno processes in that the mass properties and antenna locations (phase centers) needed to be defined for Juno. While the numbers may change, the math and techniques used are identical. During the data arc used for orbit determination, only data from the high-gain antenna (HGA) and medium-gain antenna were (MGA) was fit. The toroidal low-gain antenna (TLGA) was used during the time period during with the spacecraft was at the JOI burn attitude. Only one-way Doppler data was available during this time and that data type was not used in the OD process. Once the spin signature had been successfully removed, the Doppler data was compressed to a 300-s count time. The software used to perform the OD function was the Mission analysis and Operation Navigation Toolkit Environment (MONTE) program[2] developed at JPL.

The dynamic models used to propagate the spacecraft trajectory included the gravitational attraction from the Sun, nine planets, and the Moon; solar radiation pressure (SRP); and thrusting activity from the spacecraft. For SRP, the spacecraft was modeled with multiple plates: a two-sided plate for the solar entire solar panel area, one-sided plate for the cap on the +Z side of the

bus, and a two-sided plate for the magnetometer boom attached at the end of one of the solar panels. Additionally, the bus itself was modeled as a cylinder. Surface optical properties (specular and diffuse reflectivity coefficients) had been calibrated based on flight experience during cruise. For the thrusting activity, small delta-Vs associated with spacecraft turns and spin rate changes were modeled as instantaneous impulsive maneuvers. Longer thrusting events, such as trajectory correction maneuvers (TCMs) and the JOI burn were modeled as finite burns with delta-V magnitude, pointing direction, and start time of the burn used as estimated parameters.

The OD filtering process estimates the initial state of the spacecraft at an epoch, plus various parameters with affect the dynamics or observational data. For our case, these parameters included the impulsive delta-Vs for turns; magnitude, direction (right ascension and declination), and start time of finite burns; and for SRP, a single scale factor applied to the total force model. As heliocentric distance was changing slowly during this time span, the SRP force was nearly constant.

Consider parameters in the orbit determination included media calibrations (troposphere & ionosphere), Earth orientation parameters (rotation and polar motion), DSN station locations, quasar locations, ephemeris of Earth/Moon barycenter, and Jupiter satellite ephemeris, and Jupiter gravity harmonics. These types of error sources do not have parameters which are improved by the reconstruction but contribute error to the precision of the estimated parameters. For additional background on the fundamentals of statistical orbit determination (e.g., linearization, measurement processing, covariance propagation, and consider parameters to name a few topics), please see Reference 3.

One quantity requiring special consideration that will be discussed later is the planetary ephemeris of Jupiter. The nominal ephemeris used for all of the planets acting on the spacecraft was the DE434 planetary ephemeris[4]. This planetary ephemeris was produced by the Solar System Dynamics group at JPL in 2015 specifically to help support Juno navigation for Jupiter orbital operations. While including historical ground based data contained in previous planetary ephemeris releases, this ephemeris included the reprocessing of data from previous flybys of Jupiter. Of particular note was the latest flyby data from the New Horizons flyby of Jupiter in 2007.

This development of the planetary ephemeris was done in conjunction with development of the satellite ephemeris for Jupiter, JUP310[5]. This satellite ephemeris was also produced by the Solar System Dynamics Group at JPL. Also of note is that JUP310 also includes models not only the satellite trajectories but also values for the Jupiter pole and gravity harmonics. While the satellite ephemeris remained fixed in the OD process, the planetary ephemeris did not. The radiometric data used to help us detect errors in the Jupiter ephemeris was not sensitive enough to also detect errors in the satellites. During approach to JOI we switched from a strategy of keeping the planetary ephemeris fixed to one which updated the Jupiter barycenter ephemeris.

ORBIT DETERMINATION AND JOI RECONSTRUCTION

Tracking Data for the OD Reconstruction

The data used for this reconstruction spanned from 13-Apr-2016 through 27-Aug-2016, while the trajectory delivered to project was limited to the time span from 22-May-2016 through 29-Jul-2016. The resulting postfit residuals for two-way Doppler, range, and DDOR are shown in Figure 1-Figure 3.

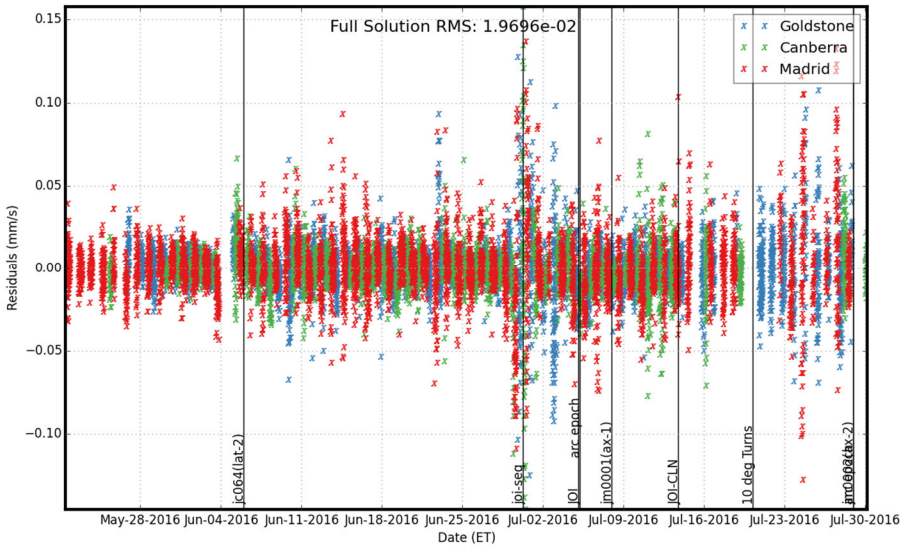

Figure 1. Two-Doppler Residuals of JOI Trajectory Reconstruction

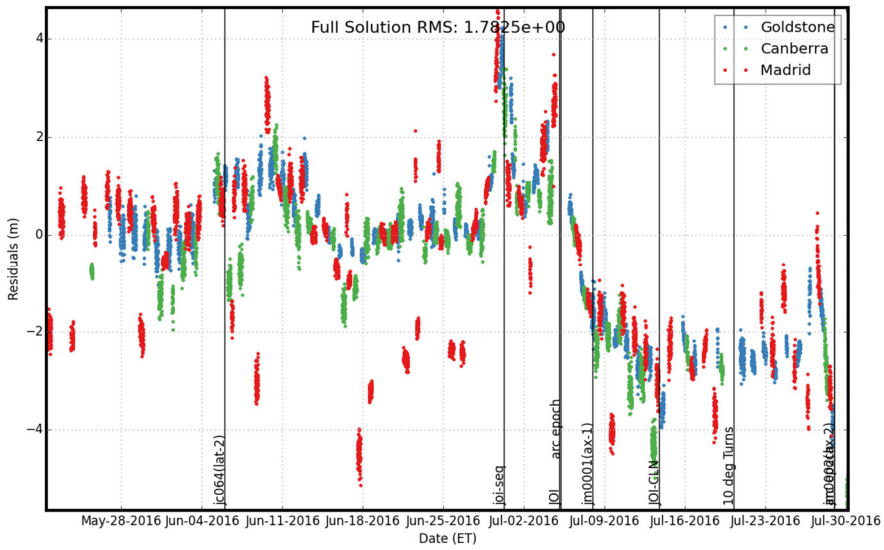

Figure 2. Range Residuals of JOI Trajectory Reconstruction

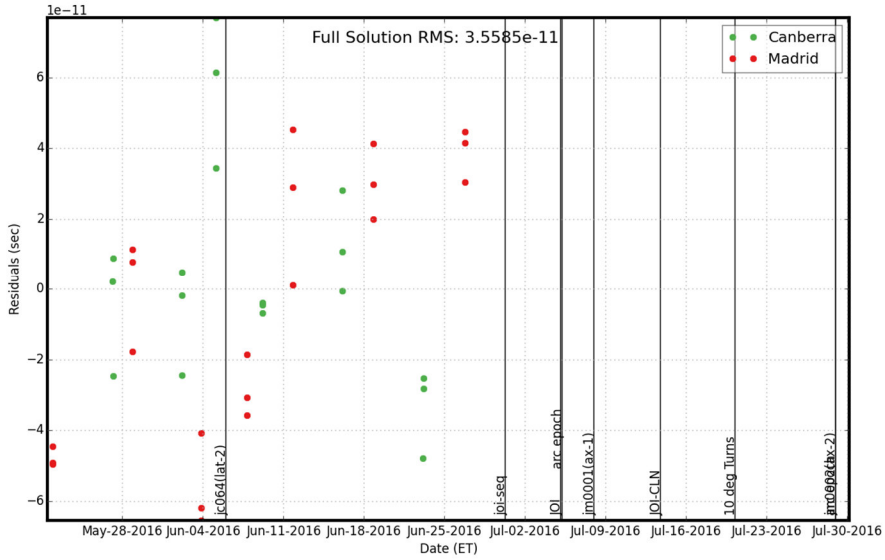

Figure 3. DDOR Residuals of JOI Trajectory Reconstruction

As was mentioned previously, only one-way Doppler was available during the bulk of the JOI activity and this data was not used in the OD process. While useful for identifying events, it was dominated by non-dynamical effects such as clock drift (e.g., due to temperature changes) and not useful for OD. There was plenty of data bracketing JOI in order to determine the trajectory before, during, and after JOI. Also, note that all of the DDOR points were obtained well before JOI.

RSC Thruster Activity

Besides the significant delta-V imparted by the ME during the JOI maneuver, there was some additional RCS thrusting which took place during the JOI activity. There events are highlighted in Table 2 to document the assumptions we made for modelling these events. Since Juno is a spin-stabilized spacecraft with no wheels, all changes in pointing or spin rate are conducted with the RCS thrusters. These thrusters are largely balanced, producing little net delta-V when executing a turn. Prior experience has given us the ability to provide reasonable predictions for the *a priori* values and uncertainties that were used to populate an impulsive delta-V model.

In all cases, the *a priori* uncertainties for the delta-V are given as 1-sigma in all three directions (spherical errors). For turns, the magnitude of this delta-V is nominally 0.0 mm/s due to the relatively balanced nature of how the thrusters are used to make a turn. However, there is some minor misalignment in the thrusters as well asymmetrical plume impingement which makes the actual delta-V something other than 0.0 mm/s, and thus it must be estimated in the OD filter. Only the size of the uncertainty varies based on the size of the turn. In contrast, the delta-V imparted by spin rate changes is somewhat unbalanced, resulting in a delta-V bias largely in the +Z-direction of the spacecraft body frame.

In the end, we found that the details of these burns were not crucial for reconstructing the JOI burn or the post-JOI trajectory used in later planning and TCM development. As there was no tracking data available during any of these events, we simply had no ability to independently separate them in the filter from JOI or from each other. The resulting estimates for these impulsive delta-Vs were determined by our initial assumptions, with the exceptions of the last two turns

listed in Table 2 (those turns were conducted while tracking data was available). The primary impact is that a small portion of the delta-V around JOI was bookkept in these nearby impulsive events rather than in the JOI maneuver. They are noted here in this paper for completeness as they do ultimately have a small effect on our reconstruction of the JOI maneuver.

Table 2. Impulsive Delta-V Around the JOI Maneuver.

Thrusting Event	Time	Turn Angle (deg)	*A priori* delta-V (mm/s)	*A priori* sigma (mms/)
Turn to MGA Attitude	JOI – 105 min	10.4	0.00	2.09
Turn to JOI burn attitude	JOI – 30 min	80.1	0.00	6.00
Spin up to 5 rpm	JOI – 20 min	0.0	5.48	0.02
Spin down to 2 rpm	JOI + 20 min	0.0	4.89	0.02
Turn to Sun-point	JOI + 20 min	91.3	0.0	6.00
Turn to Intermediate attitude	JOI + 16 hr	4.8	0.0	0.95
Turn to HGA attitude	JOI + 17 hr	5.3	0.0	1.07

Maneuver Reconstructions

As we mentioned in regards to Table 2, the reconstruction of the JOI burn during this data arc depended on assumptions made about other thrusting events during the same time period. There was not any tracking data which could separate those impulsive delta-V events near JOI from the JOI burn itself. It is under those assumptions that the results in Table 3 are given for the JOI and JOI-CLN maneuvers. Even given the large off-Earth angle for the JOI burn, the dynamics of Jupiter and the power of the tracking data are such that the JOI burn is very precisely determined, as reflected in the small uncertainties. Note that JOI is a ME maneuver; therefore it was executed in one turn-and-burn segment. JOI-CLN was an RCS maneuver and was executed in two segments while Earth-pointed – an axial and a lateral segment.

Table 3. Maneuver Reconstruction: JOI and JOI-CLN

Parameter	Design Value	Design 1-sigma	Reconstructed value	Reconstructed 1-sigma
JOI (05-Jul-2016 02:31:07 ET)				
Delta-V (m/s)	541.65	0.45	542.1054	0.0076
Right Ascension (deg)	268.46	0.49	268.4668	0.0028
Declination (deg)	62.38	0.23	62.395	0.013
JOI-CLN Axial (13-Jul-2016 17:59:53 ET)				
Delta-V (m/s)	1.5508	0.0029	1.15990	0.00011
Right Ascension (deg)	350.38	0.18	350.36	0.18
Declination (deg)	354.67	0.18	354.67	0.18
JOI-CLN Lateral (13-Jul-2016 18:08:31 ET)				
Delta-V (m/s)	4.831	0.016	4.8341	0.0037
Right Ascension (deg)	250.19	1.95	249.594	0.017
Declination (deg)	310.32	1.26	309.933	0.051

Jupiter B-Plane

One way to track the OD performance around JOI is to look at the trajectory mapped to the Jupiter B-Plane, which is a particularly useful mapping for planetary flybys. For a detailed discussion of the definition of the B-plane and its application to spacecraft navigation, see Reference 6. One feature of this approach identified during the final weeks before JOI was that care had to be taken to not map to a time where the trajectory was significantly perturbed by non-point mass effects as the B-plane formularization relies on simplified dynamical assumptions. At first, we used a mapping time equal to the perijove time from the reference trajectory (that is, around 05 July 2016 02:48). However, non-intuitive changes in both the position of the B-plane crossing and in the size of the error ellipse were noted. We found this to be due to a sensitivity of the B-plane and uncertainties to the J2 gravity harmonic. Details of that study are discussed in Reference 7. To remove this sensitivity, we changed the mapping to be at 04 July 2016, well before the influence of these non-point mass effects.

The final target for JOI was determined after an OD with DCO 20-Feb-2016. This was some time after TCM-11 which executed 03 February 2016. The location of this target and the corresponding uncertainties in the trajectory are in Figure 4, along with a history of subsequent OD solutions. The primary reason for movement observed in the B-plane (mostly in B.T) from DCO 20-Feb-2016 (green ellipse) to DCO 16-Jun-2016 (purple ellipse) was found to be due to errors in the execution of TCM-11. More specifically, these errors were not fully resolved by the tracking data available that DCO. This also explains the relatively large change in the size of the error ellipse for DCO during this same time period. From DCO 16-Jun-2016 onward, the reconstruction of TCM-11 had stabilized.

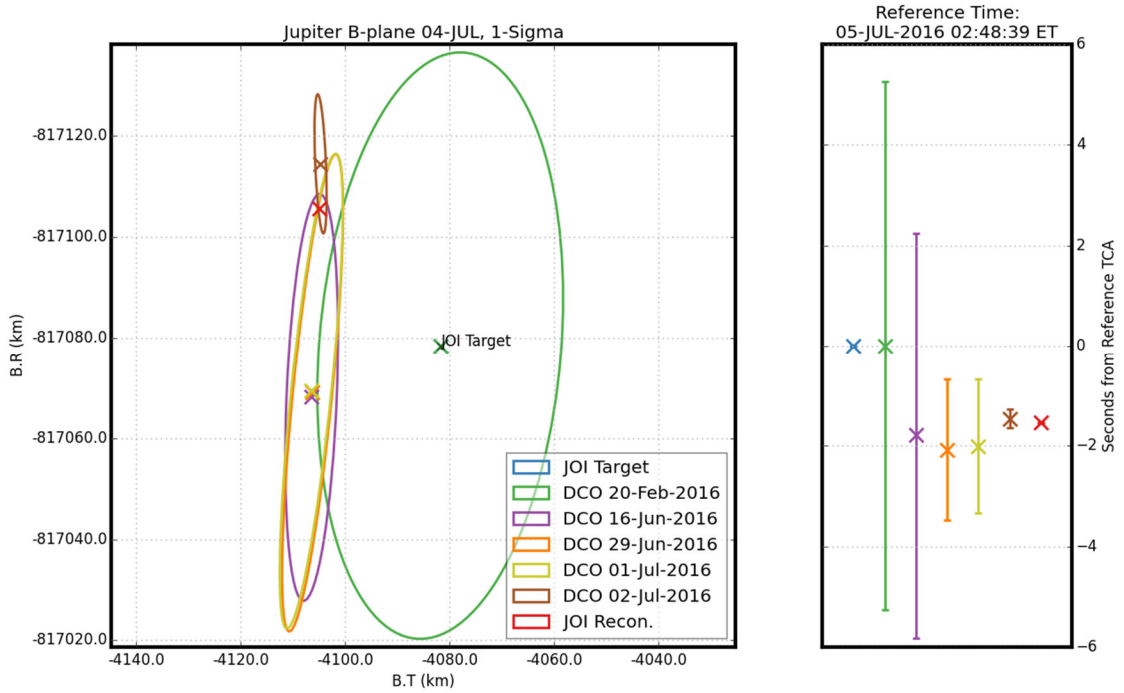

Figure 4. Jupiter B-plane and 1-sigma error ellipses for JOI. History of selected pre-JOI OD solutions compared to JOI reconstruction.

What about the relative jump from DCO 01-Jul-2016 to DCO 02-Jul-2016? This is where we modified our baseline OD solution strategy. While we had been conducting experiments with side cases which also include estimates for an update Jupiter barycenter ephemeris, we didn't consider them our preferred solution until this time. We began observing behavior which suggested that it might be due to Jupiter ephemeris error, but it was not a large enough effect to separate from other error sources. From approximately DCO 02-Jul-2016, we had increased confidence in our ability to update the ephemeris thanks to the Doppler, range and DDOR data allowing us to sense the ephemeris error as we neared Jupiter. The corresponding decrease in the size of the error ellipse, as well as TCA, was due to switching from considering the Jupiter ephemeris error (that is, not estimating it but only allowing the errors to contribute) to then including it as an estimated parameter. As noted previously, the nominal planetary ephemeris was DE434.

The movement in the B-plane from DCO 02-Jul-2016 and later was not due to the predicted spacecraft trajectory moving to a different location in a heliocentric sense. Instead, it was that the Jupiter barycenter was adjusting, thereby changing the spacecraft-Jupiter relative trajectory. And it was this change that was reflected in the B-plane. The final values for the B-plane are given in Table 4.

Table 4. Jupiter B-plane: JOI target vs. reconstructed trajectory

			TCA (ET)	Error ellipse, 1-sigma		
Label	**B.R (km)**	**B.T (km)**	**05-JUL-2016**	**Semi-major**	**Semi-minor**	**TCA**
JOI target	-817078.40	-4081.74	02:48:39.00	58.27 km	23.17 km	5.25 s
Reconstruction	-817105.64	-4104.83	02:48:37.46	0.14 km	0.04 km	< 0.01s

Jupiter Barycenter Ephemeris

An important question for navigation is: how do you know that the tracking data is properly separating errors in the Juno trajectory from errors in the Jupiter ephemeris? Given that the JOI targeting requirements were relative to Jupiter, it didn't matter as long as the Jupiter-relative trajectory was predicted correctly. However, attributing perturbations due to spacecraft dynamics versus Jupiter ephemeris does matter for longer term predictions, that is, for future maneuver and Jupiter science flybys. Allowing the Jupiter ephemeris update to be tuned for JOI could have an undesired effect or future flybys predictions. We wanted to make sure that updates to the Jupiter ephemeris based on limited data in the short term do not cause larger prediction problems much later.

In Figure 5 is the first hint of the challenge in deciding to use the updated Jupiter barycenter ephemeris as calculated from the OD. All of the plots are comparisons to DE434, shown in the heliocentric radial, transverse, and normal (RTN) frame for the Jupiter barycenter orbit. From DCO to DCO, there could be relative inconsistencies in the update. In particular, notice how the DCO 02-Jul-2016 solution (red) was closer to the DCO 04-Jul-2016 solution (green) in the radial and transverse directions, as contrasted with the OD with a DCO between these two, DCO 03-Jul-2016 (blue). There is also inconsistency in the normal directions. This level of sensitivity based on a single day of data shows both the power in the data to move the Jupiter ephemeris, but to also potentially move it in the wrong direction. The Jupiter barycenter update did not asymptotically approach a value, instead it meandered from day to day. This is one reason why we were hesitant to switch to updating the Jupiter Barycenter ephemeris as part of our baseline OD process.

Another demonstration of the sensitivity of the Jupiter barycenter ephemeris estimate to data was in looking at how the different data types could adjust the ephemeris (Figure 6. Effect of data type variation on Jupiter barycenter ephemeris, compared to DE434. Heliocentric RTN frame. DE436 (red), OD including all data (blue), and OD with delta-DOR data removed (green). Also, 1-sigma uncertainties shown for DE434 (dotted black line).). In particular, very different results were given for the Jupiter barycenter ephemeris for the same OD that only differed by using DDOR data (blue) or not using DDOR data (green). For reference, the 1-sigma uncertainties are also show in Figure 6 for DE434. The difference in the normal direction is particularly striking. It should come as no surprise that DDOR measurements were able to move the solution in the normal direction in a way that was much different from Doppler and range alone. DDOR measurements are more powerful in their ability to measure plane of sky trajectory variations than are Doppler and range. Ultimately it was determined that the DDOR measurements were critical in correctly measuring the Jupiter barycenter ephemeris error. Furthermore, using Doppler and range only while solving for an updated Jupiter barycenter ephemeris actually resulted in an answer much less accurate than the original DE434 ephemeris.

While interesting, the behavior in the B-plane as seen in Figure 4. Jupiter B-plane and 1-sigma error ellipses for JOI. History of selected pre-JOI OD solutions compared to JOI reconstruction. and in the Jupiter barycenter ephemeris comparisons in Figure 5 & Figure 6 did not warrant updating the JOI maneuver as the drift in the OD solution was not much larger than the 1-sigma error relative to the final OD used for JOI design. The monitoring of the OD in the B-plane was simply there to support the eventual cancellation of TCMs-12, -12a, and -13, as well as to support a go/no-go decision for the JOI maneuver. However, with the benefit of hindsight it was possible to compare the Jupiter barycenter ephemeris from a JOI reconstruction with an improved planetary ephemeris found separately from our OD process. Namely, DE436 was provided to us by the Solar System Dynamics group at JPL after we had completed the reconstruction of JOI. DE436 is based on mostly the same historical data as was used for DE434, except that it includes some data during the time of the first Juno perijove (referred to as PJ01). This perijove occurred on 27 August 2016, well after the JOI approach campaign and the JOI reconstruction. Figure 7 shows the Jupiter barycenter ephemeris as calculated from the JOI reconstructed OD (blue) as well as DE436 (red), both compared to the original DE434. What immediately stands out is how close the JOI reconstruction is to DE436. In light of what is in Figure 5 and in Figure 7, this shows that the OD was more accurately determining the Jupiter barycenter ephemeris beginning a few days out from JOI and continuing into the JOI reconstruction, when compared to the original DE434.

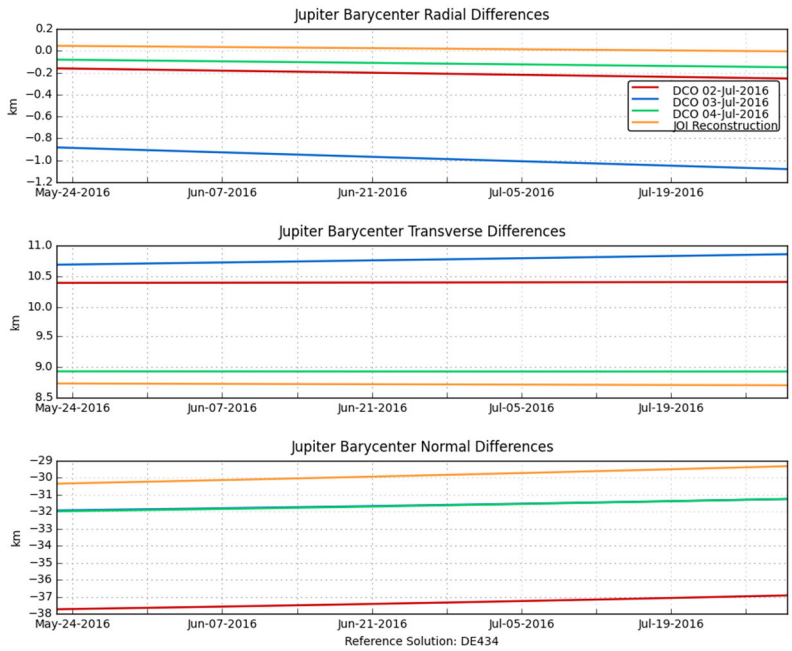

Figure 5. Final OD solutions for DCOs just prior to JOI. Jupiter barycenter ephemeris, compared to DE434, heliocentric RTN frame. 02-Jul-2016 (red), 03-Jul-2016 (blue), 04-Jul-2016 (green), and JOI reconstruction (orange).

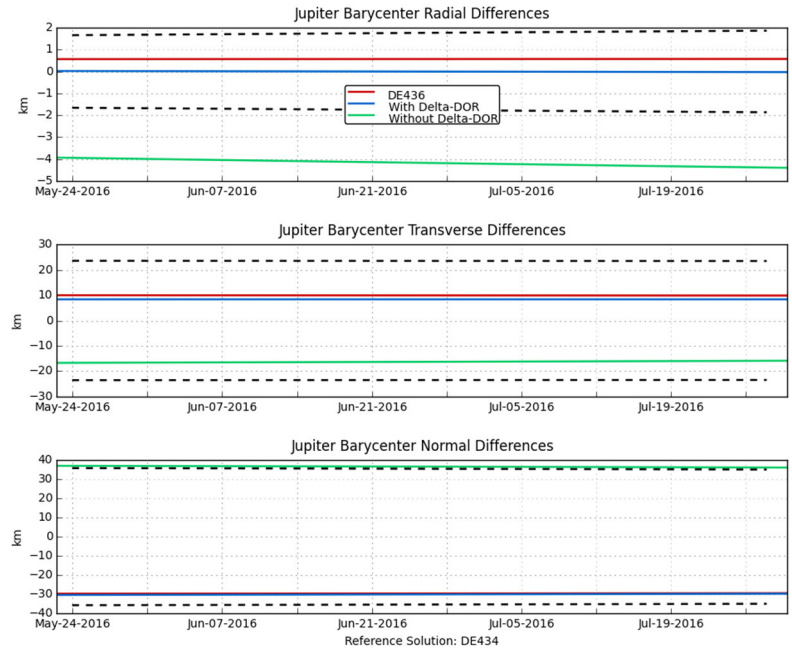

Figure 6. Effect of data type variation on Jupiter barycenter ephemeris, compared to DE434. Heliocentric RTN frame. DE436 (red), OD including all data (blue), and OD with delta-DOR data removed (green). Also, 1-sigma uncertainties shown for DE434 (dotted black line).

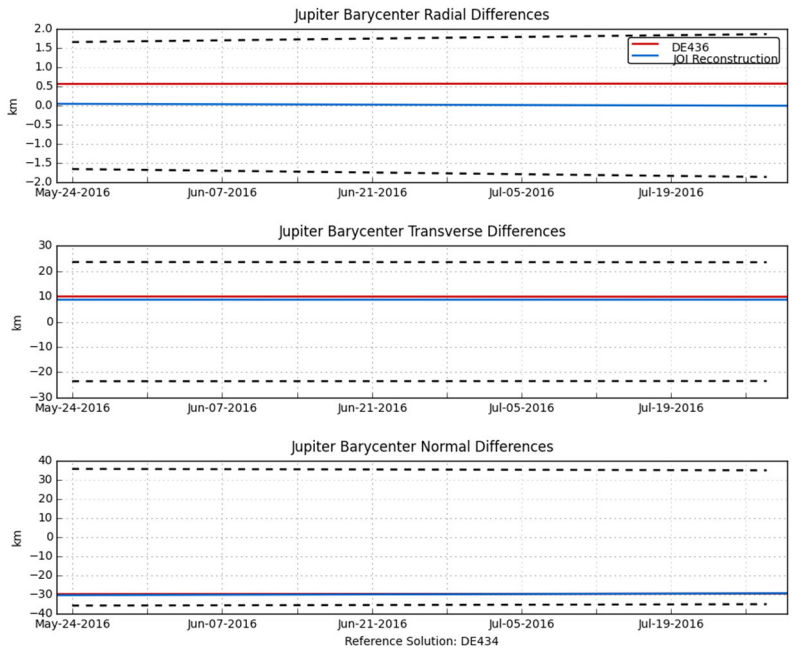

Figure 7. JOI reconstruction and DE436, both compared to DE434. Heliocentric RTN frame. DE436 (red) and JOI reconstruction (blue). Also, 1-sigma uncertainties shown for DE434 (dotted black line).

JOI ACTIVITES

The sequence of activates surrounding JOI was a complex, well-orchestrated timeline of events. All of the activities in the OD leading up to 05 July 2016 were in support of a successful JOI burn. Not only did we need to accurately target JOI, but we needed to have a high level of confidence in the trajectory prediction prior to a JOI burn go/no-go decision.

Some of details most relevant to navigation are shown in Table 5. The nominal operational state for the spacecraft is Earth-pointed, using the high-gain antenna (HGA), and spinning at a rate of 2 rpms. In this configuration, two-way Doppler and range are readily available. Also, TCMs using the RCS thrusters can be conducted while still Earth-pointed; the maneuver is decomposed into an axial and lateral component in order to achieve the desired delta-V vector.

However, in the case of JOI, the 541 m/s burn had to be performed via the more powerful ME (used for the DSMs). This required a “turn-and-burn” approach where the spacecraft was turned to align with the desired delta-V vector. In the case of JOI, this meant an off-Earth angle of 91 deg, where the delta-V was nearly orthogonal to the Earth-line. The only antenna capable of transmitting to Earth at this attitude was the toroidal low-gain antenna (TLGA), last used for the Earth flyby. Furthermore, while at this attitude and on the TLGA, only one-way data was supportable. While useful for monitoring the spacecraft and detecting key navigation events (e.g., burn start), this TLGA data was not useful for reconstructing the trajectory later in the OD process.

The primary effect on the OD processes due to this complexity amounts to a bookkeeping challenge. All of the various changes in spin-rate, antenna, or availably of two-way require addi-

tional care in managing the data before use in the OD process. That process is referred to as "despinning" the data. All of these changes affect the spin signature in different ways, complicating that procedure. However, once that process is complete, the OD process continues as if the data never had a spin signature to begin with. For the data used in OD, the spacecraft entered the JOI activity while Earth-pointed, on the HGA, spinning at 2 rpm. This was followed by a data gap (where only one-way available). Then after the JOI activity, the spacecraft was Sun-pointed, on the MGA, and spinning at 2 rpm. Two-way Doppler continued to be available as the spacecraft was turned to Earth and the switch was made to the HGA.

Table 5. JOI Activity Timeline.

Mission Event	Date	Time	Comments
Cruise State			*Earth-pointed, HGA, two-way Doppler and range data. Spin rate of 2 rpm*
End Two-way data	04-Jul-2016	23:35:14	One-way Doppler and tones only
Switch to MGA	05-Jul-2016	00:25:48	
Turn to 15 deg off Sun	05-Jul-2016	00:28:22	In same direction as later turn to JOI attitude
Turn to JOI attitude	05-Jul-2016	01:39:48	Near 90 deg off-Earth
Switch to TLGA	05-Jul-2016	01:53:16	
Spin up to 5 rpm	05-Jul-2016	02:08:03	
JOI burn start	05-Jul-2016	02:30:00	
JOI burn end (nom)	05-Jul-2016	03:04:57	Actual burn time cutoff via accelerometer
Spin down to 2 rpm	05-Jul-2016	03:07:10	
Turn to Sun-point	05-Jul-2016	03:18:46	
Switch to MGA	05-Jul-2016	03:22:47	
Coherency enabled	05-Jul-2016	03:38:14	Two-way Doppler now possible
Transmit enabled on ground	05-Jul-2016	04:38:29	
Start of two-way data	05-Jul-2016	05:30	Approx. 2 hr after JOI burn
Intermediate turn	05-Jul-2016	19:11:22	
Turn to Earth-point	05-Jul-2016	19:51:49	
Switch to HGA	05-Jul-2016	20:01:31	
All dates and times are in spacecraft event time, Universal Time Coordinated (SCET-UTC), except where noted			

SUMMARY

This was a very successful insertion into Jupiter orbit for the Juno spacecraft. From launch until JOI, a relatively small number of course corrections were needed in order to achieve the conditions necessary for a JOI maneuver. During the final months leading to the Jupiter system, only one maneuver, TCM-11, was needed in the months prior to JOI. All other statistical and contingency maneuvers were cancelled.

Furthermore, improving the knowledge in the Jupiter ephemeris during the final weeks on approach helped increase our confidence in the trajectory predictions. In hindsight, the final reconstruction of the Jupiter planetary ephemeris as determined by our OD process agreed very well with an updated planetary ephemeris, DE436, which was based on post-JOI data. A combination of Doppler, range, and DDOR data was able to reduce the uncertainty in the Jupiter ephemeris from 10s of kilometers to a few kilometers, particularly in the direction normal to the Jupiter orbit plane. It was found that all those data types were necessary – an OD lacking any one of those

data types could result in a Jupiter ephemeris significantly more in error than using the *a priori* Jupiter ephemeris, DE434.

Since JOI, Juno has been in a 53.5 day orbit about Jupiter. It continues to successfully conduct close flybys of Jupiter, collecting valuable science data. At this time, there is no decision regarding when or if a PRM will be executed to reduce the orbit period.

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

[1] Gustafson, E.D., G.L. Kruizinga, and T.J. Martin-Mur, "Mars Science Laboratory Orbit Determination Data Preprocessing", AAS 13-231, 23rd AAS/AIAA Space Flight Mechanics Meeting. Kauai, Hawaii, USA, 10-14 February 2013.

[2] Evans, S., W. Taber, T. Drain, J. Smith , H.-C. Wu, M. Guevara, R. Sunseri, and J. Evans "MONTE: The Next Generation of Mission Design & Navigation Software" The 6th International Conference on Astrodynamics Tools and Techniques (ICATT), Proceedings Darmstadt, Germany, 14-17 March 2016.

[3] Tapley, B.D., B.E. Schutz, and G.H. Born, *Statistical Orbit Determination*, Elsevier Academic Press, Burlington, MA, 2004.

[4] Park, R., W. M. Folkner, and R. A. Jacobson, "The Planetary Ephemeris DE434, IOM 392R-15-018," JPL Inter-Office Memorandum, 2015.

[5] Jacobson, R.A., JUP310 Satellite Ephemeris, NAIF

[6] Kinzer, W., "A Method of Describing Miss Distances for Lunar and Interplanetary Trajectories", JPL External Publication No. 674, 1959.

[7] Takahashi, Y., D. Farnocchia, P. F. Thompson, N. Bradley, S. Ardalan, J. Bordi, "B-Plane Mapping Uncertainty of the Juno Spacecraft Prior to the Jupiter Orbit Insertion Maneuver", AAS 17-323, 27th AAS/AIAA Spaceflight Mechanics Meeting, San Antonio, Texas, USA, 5-9 February 2017.