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JPL NAVIGATION SUPPORT FOR THE JAXA AKATSUKI (PLANET-C) RETURN TO VENUS*

Mark S. Ryne†, Neil A. Mottinger†, Eunice Lau†, Maximilian Schadegg†, Cliff Helfrich†, Paul Stumpf†, and Brian Young†

This paper details the orbit determination activities undertaken at JPL in support of the Akatsuki (a.k.a. Planet-C) mission's return to Venus. The JPL navigation team's role was to provide independent navigation support as a point of comparison with the JAXA generated orbit determination solutions. Topics covered will include a mission and spacecraft overview; small forces modeling; cruise, approach, and Venus phase orbit determination results; and the international teaming arrangement. A discussion of the preparations for the Venus orbit insertion maneuver, which was successfully executed on December 7, 2015, is also covered in detail in the paper.

INTRODUCTION

The Akatsuki mission (formerly known as Planet-C and/or Venus Climate Orbiter) was developed by the Japanese Aerospace Exploration Agency (JAXA) to study the atmosphere and weather systems of Venus for a minimum of two Earth years after orbit insertion. Continuing a long-standing tradition of cooperation, JAXA invited NASA to partner with them on the Akatsuki mission. One part of the arrangement called for the NASA Jet Propulsion Laboratory (JPL) to provide navigation support, including independent orbit determination solutions that would be compared with solutions generated by JAXA.

The Akatsuki mission followed a Type II, 7-month direct interplanetary transfer orbit to Venus.[1] Along the way, three launch injection cleanup maneuvers, a main-engine test, and three approach correction maneuvers were scheduled. The Venus Orbit Insertion maneuver (VOI) was scheduled to last approximately 12 minutes using the 500-N bi-propellant main engine. Two additional maneuvers were planned following VOI to reduce the orbit period down to the planned 30-hour science orbit. This would place the spacecraft into an orbit quasi-synchronous with the atmospheric rotation.

Akatsuki missed its planned insertion into Venus orbit on December 6, 2010, due to a main engine anomaly, and entered a heliocentric orbit[2]. On-orbit and ground based testing indicated that the main engine was unusable. Consequently, JAXA formulated a plan to make a second Venus orbit insertion attempt (VOI-R1) using the mono-propellant attitude control system instead

* This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract to the National Aeronautics and Space Administration.
† Navigation Engineer, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, USA, 91109.

of the main engine. The remaining oxidizer was dumped to reduce the spacecraft mass and three maneuvers were conducted in November, 2011 to target the vehicle to vicinity of Venus in November, 2015. DSN and JPL Navigation support were suspended with the intention of resuming support sometime between late 2014 and early 2015.

TEAMING ARRANGEMENT AND JPL NAVIGATION RESPONSIBILITIES

Given that Akatsuki was a JAXA mission, the spacecraft and mission were managed and operated by a team at JAXA. JAXA also had a full navigation team, which was the primary point of contact within the Akatsuki mission for the JPL navigation team. JAXA regularly provided the JPL team with relevant spacecraft telemetry (spacecraft attitude, wheel de-saturation maneuver data, and solar panel orientation) and tracking data from the JAXA stations at Usuda (64m) and Uchinoura (34m). JAXA also provided an update to mission operations document (known as the iPOD), detailing the spacecraft, its capabilities, and the nominal mission plan. The JPL team provided JAXA weekly orbit determination solutions and real-time Doppler support. Good communication was maintained between the two navigation teams through numerous meetings during the mission. The most formal of these were the seven Technical Interchange Meetings held between November 2013 and November 2015, which occurred at Sagamihara, Japan and JPL, in Pasadena, California. There were also twelve videoconferences conducted between October 2013 and March 2015, though these were less effective in general than the face-to-face technical interchanges. In addition to the meetings, there were numerous email exchanges.

During the critical VOI-R1 period, live support was provided to JAXA from both the DSN and the JPL navigation team. A detailee from JPL was also on-site at JAXA operations to enhance communication and quickly resolve questions between the teams during VOI. JPL navigation involvement was planned to be complete at the end of March 2016

JAXA levied only two formal requirements on the JPL navigation team:

- A 3-km altitude uncertainty (3σ) just before VOI-R1
- Provide real-time three-way Doppler residuals for the VOI-R1 burn

Otherwise, its support was on a "best effort" basis – no formal requirements were levied by JAXA; this has historically been the case when JPL navigation has supported other JAXA missions (e.g., Planet-B/Nozomi, SELENE, and Hayabusa). The responsibilities of the JPL team were broadly outlined in the Technical Assistance Agreement required by the United States Department of State for work with international organizations[3]. The JPL navigation team developed a set of "assumed internal" navigation requirements, as follows:

- Provide routine weekly orbit determination solutions and as specified by JAXA
- Deliver critical orbit determination solutions for maneuver design, sequence generation, Venus approach and orbit insertion, and for post Venus orbit insertion trajectory corrections (typically when the spacecraft is out of view from Japanese domestic tracking assets)
- Include JAXA maneuver designs in the predicted burn trajectories
- Incorporate Delta Differential One-Way Range (Delta-DOR) tracking with accuracy sufficient to minimize delivery errors at Venus and to minimize the effect of un-modeled accelerations on the orbit determination process

In order to facilitate the smooth exchange of data between the teams, interface agreements were made during the planning stages of the activity, and incorporated into the iPOD. Each

navigation team had the same data with which to perform analyses, but was free to choose details such as data weights, a priori uncertainties, astrodynamic constants, etc. for use in their respective orbit determination processing.

Key deliverables from JAXA to JPL were the following: state vectors, maneuver plans, attitude plans, momentum wheel desaturation data, spacecraft orientation data, and solar array panel orientation data. All of the data were sent in text format, as defined in the iPOD document.

Key deliverables from JPL to JAXA were the following: trajectory predictions (SPICE SPK format), state vectors, state covariances, and B-plane and target mappings. All of data were sent in text format, as defined in the iPOD document.

A significant change from the 2010 support was that tracking data and calibrations would be exchanged directly between JAXA and the DSN in both directions (without JPL navigation as an intermediary). This was accomplished using tracking data and media data in TDM format. JPL navigation retained the responsibility to deliver predicted trajectories to the DSN, for use in generating antenna pointing and frequency predicts. These deliveries included "burn" and "no-burn" versions as needed.

SPACECRAFT DESCRIPTION

The total mass of the Akatsuki spacecraft was 377.1 kg at the resumption of support, of which 55.4 kg was propellant. It has a box-like shape (1.5m x 1.4m x 1.0m), three-axis stabilized by momentum wheels, with two 1.18 m^2 extended solar panel paddles that can rotate about the Y-axis axis (Figure 1). In addition to the 500-N bi-propellant main Orbital Maneuvering Engine (OME), the propulsion system also included eight 23-N mono-propellant thrusters for Reaction Control System (RCS) pitch and yaw, and four 3-N mono-propellant thrusters for RCS roll (Figure 2). The top (AT) and bottom (AB) thrusters were used for trajectory correction maneuver in this phase of the mission. Communication with Earth was enabled via a high-gain antenna (HGA), two medium-gain antennas (MGA), and two low-gain antennas (LGA).

The spacecraft was healthy, with the exception of the main engine. The trajectory was entirely within the orbit of Venus, ranging between 0.61 and 0.72 AU from the sun. Consequently, the thermal environment exceeded design specifications for many systems. Most importantly, the RCS thrusters were operating at well above their design limits, as well as now serving as the primary on-board propulsion system (operated in blow down mode). In addition, there had been continuous degradation of solar array paddles. The spacecraft was oriented with its HGA pointed to the sun to minimize the thermal impulse, which limited communications with the Earth to the MGA and degraded the precision of navigation range and delta-DOR tracking data.

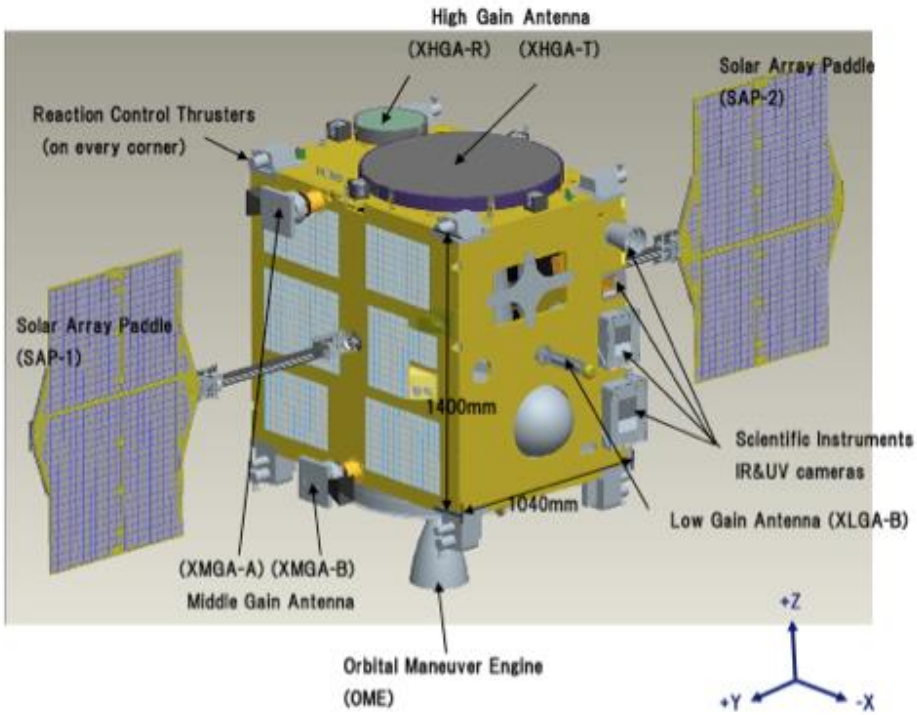


Figure 1. Akatsuki Spacecraft

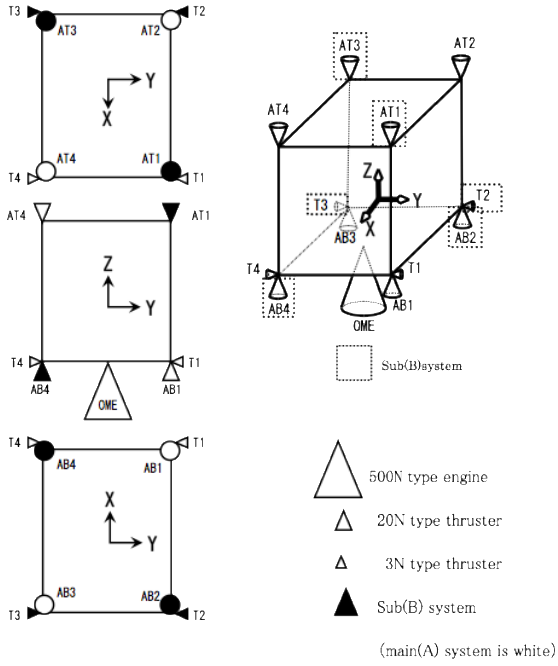


Figure 2. Akatsuki Propulsion System

TRACKING DATA AND TRACKING PERFORMANCE

The tracking campaign included Doppler, range and Delta-DOR measurements throughout the approach phase. Range and Delta-DOR data acquisition was discontinued following Venus orbit insertion (Table 1).

Table 1. DSN Tracking Plan for Akatsuki.

Timeframe	DSN Request – Doppler and Range)
Mar 2 2015 – Sep 27 2015	Three 6-8 hour 34m passes per week
Sep 28 2015 – Dec 13 2015	One 6-8 hour 34m pass per week
Dec 14 2015 – Apr 3 2016	Three 6-8 hour 34m passes per week
Maneuver Support	Two 6-8 hour 34m passes per day ± one week
TCM TT&C	One 6 hour 70m pass per maneuver
VOI-R1c TT&C	Two 6 hour 70m passes per maneuver
Timeframe	**DSN Request - Delta DOR**
Jun 8 2015 – Oct 25 2015	Two 1 hour sessions per week
Oct 26 2015 – Nov 22 2015	Four 1 hour sessions per week
Nov 23 2015 – Dec 6 2015	One 1 hour session per day

Doppler and Range Data

Two-way Doppler data was the primary tracking data type for the orbit determination process. Most maneuvers were scheduled with the JAXA Usuda tracking stations performing the uplink. On many of these occasions, the DSN would track from Canberra and provide three-way Doppler. This data was examined by the JPL navigation team to assess the status and progress of the maneuver, but not used for orbit determination. JAXA and JPL agreed to use a 60-second compression time for routine data exchange, but 10-second compression was used during maneuver support to offer more insight into the spacecraft dynamics.

JAXA and JPL utilize different ranging systems. JPL used DSN sequential ranging[4] with a cycle time of 153 seconds (high component: 5, low component: 20). JAXA employed a pseudo-noise regenerative ranging system, with a cycle time of 54 seconds.

Tracking data is commonly edited to remove “blunder points” that may occur for several reasons, including angular momentum desaturations, charged particle effects, attitude changes, HGA motion due to solar panel orientation changes, etc.

The quality of tracking data from both agencies was generally very good, with occasional noisy passes due to solar plasma in the inner solar system. Reconstructed post-fit residuals for tracking display a data sigma of 0.04 mm/s (0.002 Hz) for Doppler with a 60 second count time for both the DSN and JAXA data. The DSN and JAXA Usuda range data exhibit a noise of 0.35 m (2.5 RU) and 0.30 m respectively.

Delta-DOR Tracking

Delta-DOR was accomplished using telemetry sidebands spanning 3.7 MHz because the Akatsuki spacecraft did not have the hardware to produce DOR tones. Consequently, the

accuracy of the Delta-DOR tracking was reduced compared to what would have been possible with wider spaced tones onboard the spacecraft; precision of approximately 1.0 nanosecond was anticipated, compared to 0.06 nanoseconds if the spacecraft could produce DOR tones with 38 MHz sidebands. During in-flight checkout during 2010, it was established that actual accuracy for the DSN measurements was 0.5 nanoseconds while using the HGA. In-flight measurements on the Goldstone-Canberra and Goldstone-Madrid baselines initially showed an accuracy of 2.5 nanoseconds during the 2015 support on the MGA. Following the turn-on of the TWTA on June 17, 2015, the accuracy improved to 1.5 nanoseconds.

In addition to the DSN baselines, four experimental joint DSN-JAXA Delta-DOR observation sessions were conducted between June 16, 2015 and July 27, 2015 using the Goldstone-Canberra, Goldstone-Uchinoura, and Canberra-Uchinoura baselines. The data for the session on July 16, 2015 was processed at JPL, with good results obtained on all baselines; this data was evaluated with respect to the JPL orbit solution. The DSN baseline and the two mixed DSN-JAXA baselines all have noise sigmas on the order of 2.5 nanoseconds. The data from the mixed baselines for the final three sessions were not processed due to manpower issues related to the planning and execution of TCM1, TCM2 and TCM3.

The Delta-DOR data exhibited a noise level of 75 nanoradians (1.5 nanoseconds), as shown in Figure 3. Note that the Delta-DOR noise levels were higher relative to the 2010 support due to the use of the MGA.

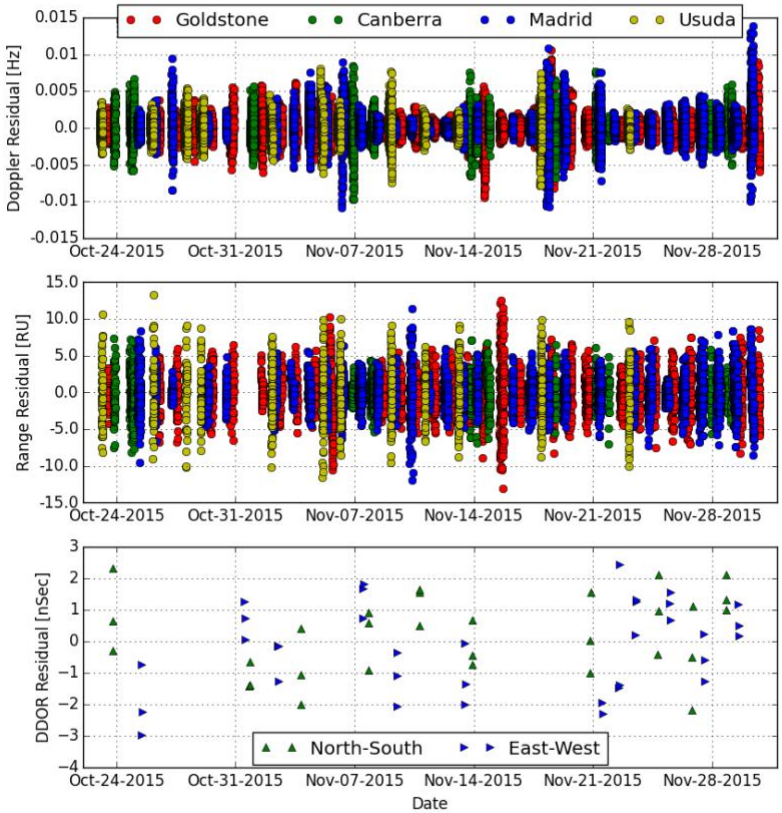


Figure 3. Doppler, Range and Delta-DOR Tracking Postfit Residuals

Data Calibrations

Each agency applied media calibrations to the Doppler, range and Delta-DOR tracking data; these calibrations account for signal path variations induced by the Earth's ionosphere and troposphere.

Range data are also calibrated for ground-based delays associated with the tracking station hardware, also for the electronic path length in the various on-board transponder path lengths. After carefully applying the on-board transponder delays, it was found that there is no bias between the DSN and the JAXA ranging systems. It is thought that the system bias (16 m) observed during the 2010 support was an artifact, resulting from reformulating the JAXA range measurements into DSN sequential range data.

Data Weights

Data weights for the various tracking data types were set in the processing as shown in **Error! Reference source not found.** below.

Table 2. Tracking Data Weights.

Data Type	Data Weight	Note
DSN and JAXA 2-Way Doppler	0.010 Hz (0.18 mm/s)	
DSN 2-Way Range	21.0 RU (3 meters, 1-Way)	
JAXA 2-Way Range	3 meters (1-Way)	
Delta-DOR on MGA	1.5 – 2.5 ns (75 – 125 nanoradians)	Recommended by JPL's VLBI processing group

DYNAMIC MODELS

Proper modeling of forces on the spacecraft, both gravitational and non-gravitational, is extremely important in an effort to deliver a spacecraft to an extraterrestrial body. Gravitational forces are well understood and well modeled, but non-gravitational forces such as solar radiation pressure, trajectory correction maneuvers (TCMs), reaction wheel desaturations (desats), and outgassing are less well understood and in general require special efforts to characterize.

Gravitation Model

In JPL's orbit determination process, both Newtonian and relativistic gravitational accelerations can be modeled. In the Akatsuki orbit determination, the Sun, Earth and Jupiter were treated with the relativistic corrections to the Newtonian point mass model; all the other planets (including Pluto) and the Moon were treated as Newtonian point masses. In addition, the oblateness of the Earth and Venus were modeled with the GGM02C[4] and MGNP180U[5] oblateness models, respectively, truncated to 20x20 potential fields. The planetary ephemeris utilized for both JAXA and JPL was DE430[6], produced by JPL's Solar System Dynamics group; it contains the mass parameters (GMs) for the planets.

Solar Radiation Pressure Model

Solar pressure was modeled using the 8-plate formulation developed during the 2010 support. This model consisted of six flat plates to represent the body of the spacecraft plus two independent plates, one for each solar array. The spacecraft body was oriented with the +Z-axis

pointed toward the sun during approach and the individual solar panels were off-pointed based on telemetry. The offset varied, and was usually less than 4.5° during approach and as much as 55° during the Venus orbital phase. Specular and diffuse coefficients for these components were well characterized from the previous support. There was some concern that the reflectivity characteristics of the vehicle had changed during the long period exposed to high temperatures but this was not found to be the case. No self-shadowing was needed due to the attitude profile used during the approach.

Small Forces Modeling

"Small forces modeling" is a term that is applied to the modeling of the cumulative delta-V effects of attitude thruster firings over one or more specified intervals of time, as well as the cumulative spacecraft mass loss due to the use of propellant in those attitude thrusters. Small forces were modeled as part of the orbit determination using JAXA reports of thruster on-time for each thruster in the spacecraft body frame.

No thrusters pointed in the spacecraft X-axis direction, and the Y-axis thrusters were always fired as balanced pairs. With the exception of alignment errors, the resultant delta-V for momentum wheel unloading was in the spacecraft Z-axis direction. For any given maneuver, the magnitude and direction were dependent on the number of unbalanced pulses. In the JPL orbit determination process, unloading time was the only parameter used from the JAXA reported momentum wheel-unloading file. Uncertainty for the RCS thrusters was reported by JAXA to be nominally 1% to 2% (1.0 N thrust (3σ) with 0.5 degree pointing error (3σ)).

The spacecraft design and construction resulted in the need for very few reaction wheel de-saturation maneuvers. Additionally, solar torques on the spacecraft body were minimized due to the HGA Sun-point attitude during approach. The observability of the unloading delta-V in Doppler data varied between 100% in the Earth line-of-sight to perpendicular to the line-of-sight; as the Sun-spacecraft-Earth geometry changed during cruise. The estimated delta-V for desat events ranged between 0.1-2.6 mm/s with the vast majority averaging about 0.5 mm/sec, predominately in the spacecraft Z-axis direction.

Routine cruise momentum wheel unloading for Akatsuki were commanded from the ground on a weekly basis with approximate execution times know well in advance. Consequently, the effect of future desats on the trajectory prediction was modeled by placing desats after the end of the tracking data arc, at the approximate execution times. Following each desat, the time was corrected (usually a few tens of seconds), generally with minimal impact on the trajectory propagation.

ORBIT DETERMINATION MODELS

Throughout the cruise phase of the mission, the JPL orbit determination results were very consistent. Shown in Table 3 are the JPL orbit determination process filter uncertainties for the Venus approach phase.

Table 3. Orbit Determination Filter A Priori Uncertainties.

Name	A Priori Uncertainty (3σ)	Parameter Type
Spacecraft state	100000 km per axis (x, y, z)	Estimated
Spacecraft velocity	1 km/s per axis	Estimated
Overall solar radiation pressure scale factor	25%	Estimated
Momentum wheel unloadings (impulsive burns)	x-axis 0.5 mm/s y-axis 0.5 mm/s z-axis 1.0 mm/s	Estimated
Maneuvers (finite burns)	thrust 10% pointing: 5.0° RA & Dec	Estimated
Per pass range bias	35.5 RU (5 m)	Stochastic
Within data arc acceleration	1.5×10^{-12} km/s^2 per spacecraft axis white noise with 2-hour update	Stochastic
DSN Station Location Error	3 cm (spin axis) 4 cm (longitude) 3 cm (Z) (correlated)	Considered
JAXA Usuda Station Location Error	4.5 cm (uncorrelated)	Considered
JAXA Uchinoura Station Location Error	6 cm (spin axis) 12 cm (longitude) 8 cm (Z) (uncorrelated)	Considered
Media (per complex) (DSN)	Troposphere wet: 4.0 cm Troposphere dry: 1.0 cm Ionosphere day: 75.0 cm Ionosphere night: 15.0 cm	Considered
Media (JAXA)	No uncertainty	Considered
Earth polar motion	1.5×10^{-8} radians per axis	Considered
UT1	3.0×10^{-4} s (10 cm)	Considered
Quasar location (RA, Dec)	4.3×10^{-8} deg	Considered

RE-TARGETING AND APPROACH PHASE

Navigation and DSN tracking support provided by JPL officially resumed on March 2, 2015. The spacecraft had completed eight orbits about the Sun since the previous VOI attempt. The spacecraft had been dynamically quiet throughout this extended cruise. The primary non-gravitational perturbations were desaturation events (desats) of the momentum wheels, which occurred approximately once per week on Fridays. The resultant velocity magnitude of these desats varied between 0.1 and 2.6 mm/sec and was primarily aligned along the spacecraft Z-axis direction. These desats also typically occurred during JAXA tracking station passes, such that the 2-way Doppler data collected facilitated the estimation of these small forces.

Several Trajectory Correction Maneuvers (TCMs) were planned during the re-targeting and approach phase, as shown in Table 4. In support of the design of each of these maneuvers, the JPL navigation team had a critical delivery schedule of orbit solutions.

Table 4. Maneuver Summary for TCM1-TCM7.

Name	Date	Reconstructed Delta-V (m/s)	Planned Delta-V (m/s)	Duration (sec)	Fuel Used (kg)	Notes
TCM1	17-JUL-2015	17.55	18.6	95.13	3.1	
TCM2	24-JUL-2015	56.30	55.34	308.63	9.0	
TCM3	31-JUL-2015	13.42	13.72	74.50	2.6	
TCM4	11-SEP-2015	1.058	1.078	6.375	0.18	
TCM5	29-OCT-2015					Cancelled
TCM6	19-NOV-2015					Cancelled
TCM7	02-DEC-2015					Cancelled

All TCMs required a slewing of the spacecraft to the burn attitude approximately 30 minutes before the maneuver execution. The spacecraft also communicated 1-way with JAXA tracking stations on the LGA during maneuvers. The orbital trajectory noting all executed cruise maneuvers is shown in Figure 4.

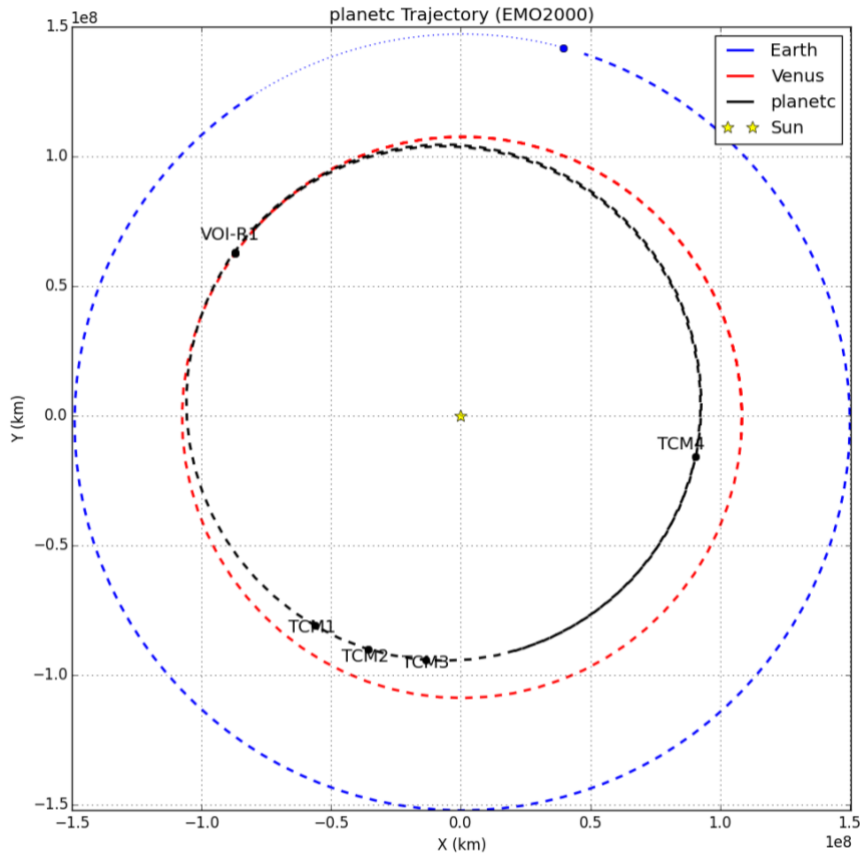


Figure 4. Sun-Centered Trajectory with Executed Maneuvers during Cruise.

TCM1-TCM3 served as the primary re-targeting maneuvers. Combined, they changed the arrival date from November 21, 2015 to December 7, 2015 and rotated the post insertion orbit from retrograde to prograde. TCM1 was executed on July 17, 2015, with a Delta-V of 17.55 m/s of the planned 18.6 m/s. This maneuver also had included a cross track component to reduce thermal input on spacecraft's positive X-axis face. TCM2 was next executed a week later on July 24, 2015 with a velocity magnitude of 56.30 m/s. This maneuver was designed to execute in the spacecraft's velocity direction and targeted arrival conditions, including the nominal altitude of 550 km. TCM3 was then executed a week later on July 31, 2015 with a velocity magnitude of 13.42 m/s and completed the targeting conditions.

These three maneuvers were executed with the Japanese Usuda tracking performing the uplink. The DSN provided simultaneous tracking support for TCM1 and TCM3 from the Canberra tracking complex (TCM2 could not be supported due to scheduling conflicts). The Canberra station acquired 3-way Doppler data during these two maneuvers. This data was used by JPL Navigation to characterize the burn performance and provide a rapid maneuver assessment in the event of a problem at the Usuda station. Figure 5 shows the 3-way Doppler data received in real-time from the Canberra DSN station during TCM3. The trajectory has the nominal TCM3 maneuver already modeled, so a small Doppler offset after the maneuver indicates that the maneuver was a success.

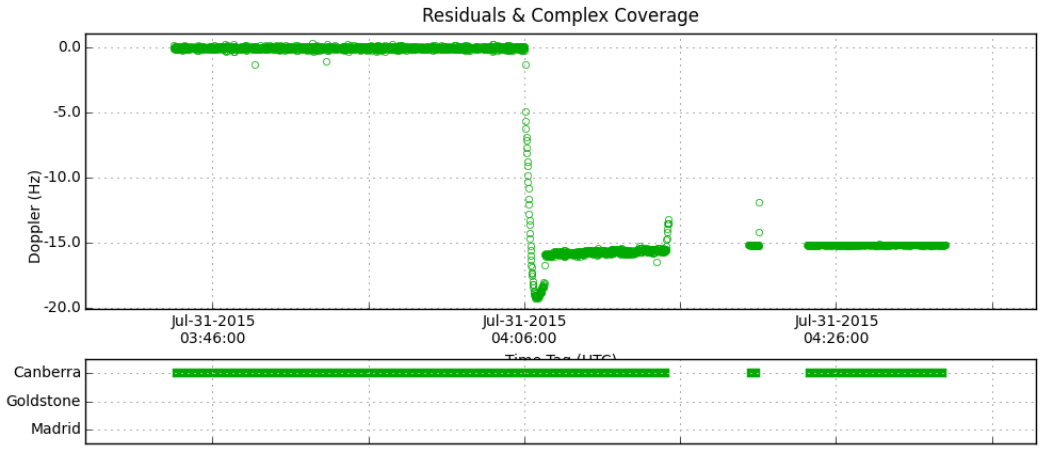


Figure 5. 3-Way Doppler Residuals Received during the Successful TCM3 Maneuver.

After TCM3, there was a quiet period while the spacecraft passed through inferior conjunction and zero declination. The solution accuracy during this time period was significantly degraded.

After this quiet period, the planned TCM4 maneuver was first cancelled, and then reinstated in order to clean up the execution errors from TCM3. This maneuver occurred on Sep 11, 2015 and had a relatively small magnitude of 1.078 m/s. Figure 6 shows the B-plane position uncertainties before and after the TCM4 maneuver. Also shown are the insertion target and the Venus hard-body radius.

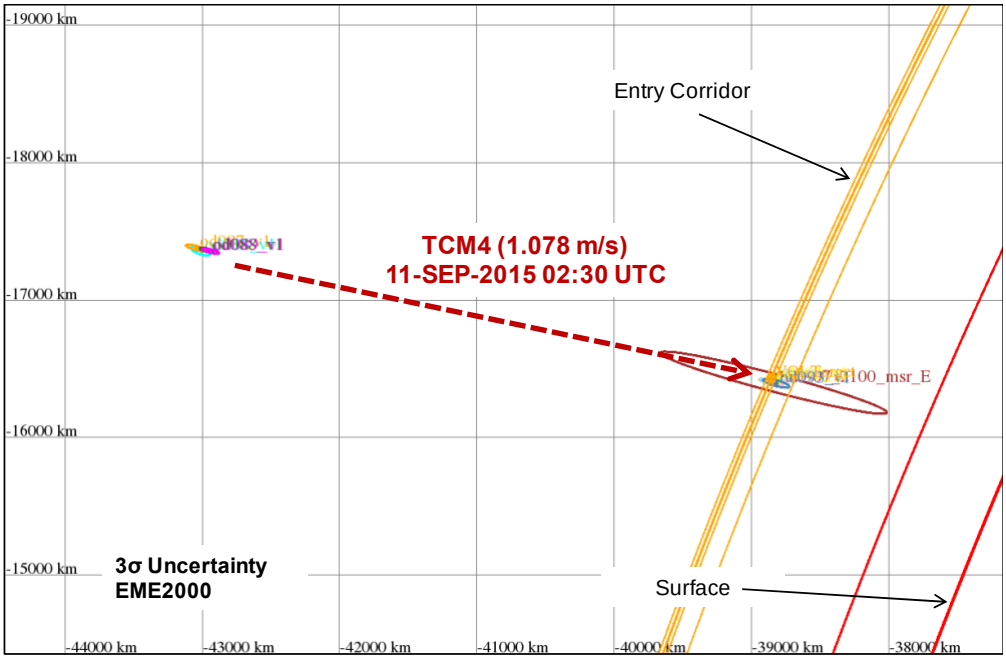


Figure 6. B-plane position uncertainties before and after TCM4 (3σ).

Ultimately, TCMs 1-4 were all successfully executed. The other clean-up maneuvers were cancelled, as JAXA deemed the spacecraft's estimated pre-insertion geometry to be acceptable. Table 5 shows the spacecraft's nominal entry target versus the estimated values before insertion. A planned Technical Interchange Meeting (TIM) between JPL and JAXA also occurred on Nov 4th, 2015, which was critical in the formulation of the navigation and tracking strategy during VOI.

Table 5. Orbit determination summary pre-VOI.

Parameter	Target	Estimated	Difference	Uncertainty (1σ)
Altitude of Periapsis (km)	550.0 ± 3.0 (1σ)	535.1	-14.9	1.5
Inclination (deg)	175.700	175.692	-7.62e-3	2.53e-3
Time of Periapsis (UTC)	07-DEC-2015 00:00:00.0	07-DEC-2015 00:01:26.8	+1:26.8	1.2

Despite the predicted periapse altitude being 15 km lower than the nominal target altitude and just below the desired entry corridor, this was deemed to be low risk, and all other TCMs leading up to VOI were cancelled. Figure 7 shows the B-plane position uncertainties for the JPL's orbit solutions upon Venus approach.

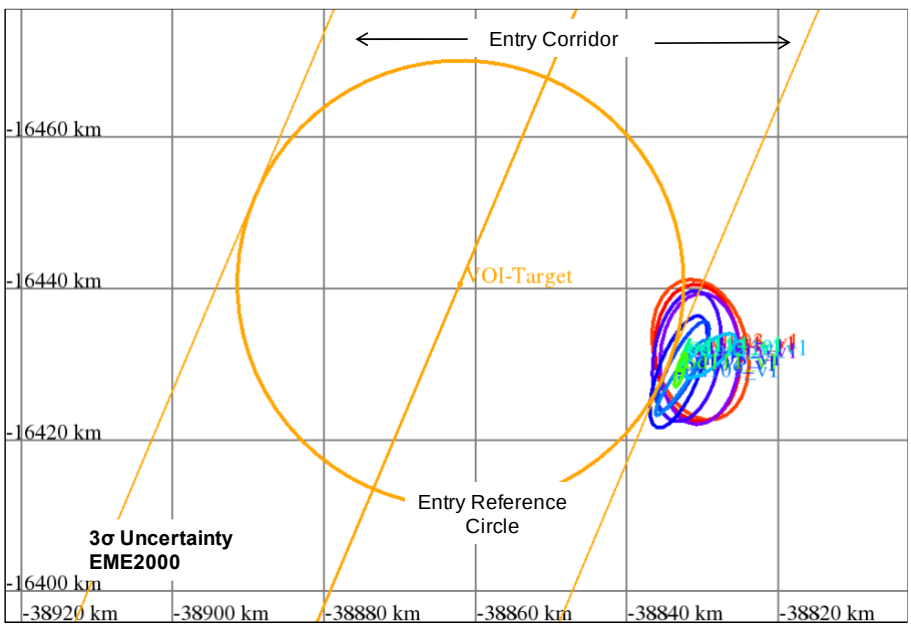


Figure 7. B-Plane Position Uncertainties Leading up to Venus Orbit Insertion (3σ).

VENUS ORBIT INSERTION PLANNING

The VOI-R1 burn was designed to achieve a post insertion orbit with a peripsis altitude of 550 km and a period of 16.6 days. The maneuver was designed to fire for approximately 20 minutes, imparting a nominal delta-V of 198.5 m/s using the AT thrusters. This would be followed by a cleanup maneuver VOI-R2 at the first periapsis, to assure that the desired orbit was achieved. Following a successful insertion, the main concern was the duration of eclipses. The spacecraft was designed to operate in a much lower orbit with shorter eclipses. Eclipses in the final orbit were much longer, and needed to be held to less than 150 minutes to prevent possible loss of the spacecraft. Consequently, several additional period control (PC) maneuvers were also needed. Figure 8 show the post-insertion planned periapsis altitude and maneuver dates.

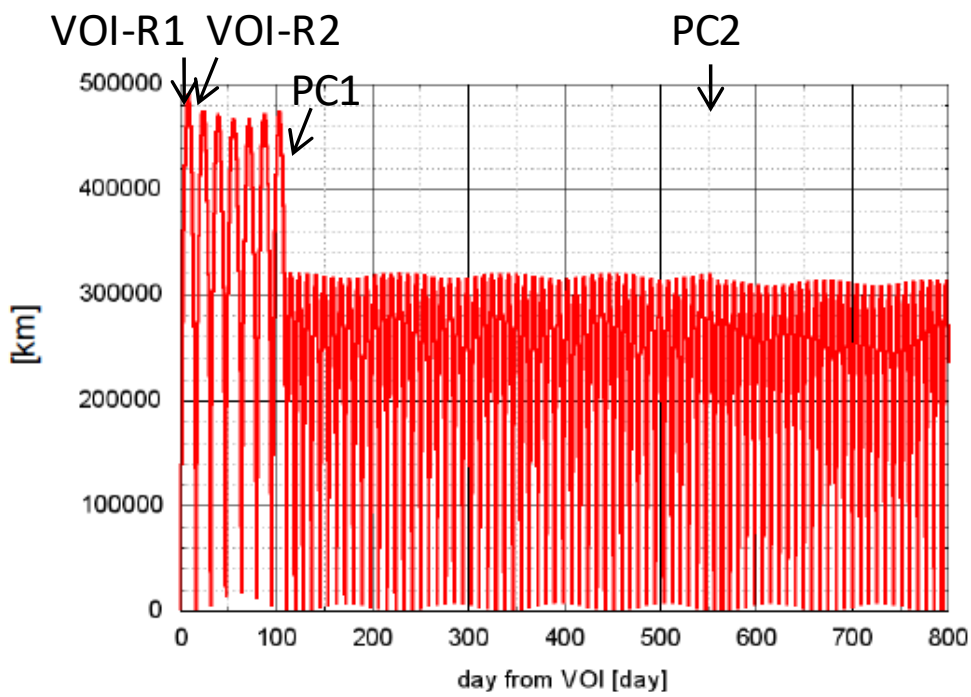
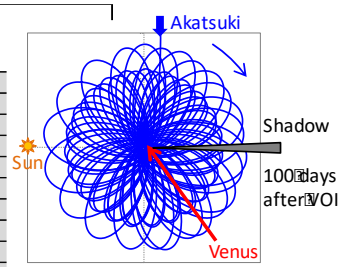


Figure 8. Planned Post Orbit-Insertion Periapsis Altitude

Provided by N. Ishii and C. Suzuki (JAXA

Much analysis was conducted by JAXA to control the eclipse duration and prepare for anomalies during the orbit insertion execution. For this reason, the maneuver was designed so that the entire burn was visible from the Earth (no occultation). Success critical for the insertion maneuver is bounded by an under-burn of 174 m/s, in which the spacecraft would escape the Venus system, and an over-burn of 206 m/s, in which the spacecraft would experience greater than 2.5 hour eclipses during apoapse. Maneuver errors between +5 to -10 percent of nominal, in addition to a small correction at VOI-R2 (during second periapsis), would also result in an acceptable short-term post-insertion trajectory. Figure 9 shows the success criteria.

VOI-R1 durion [seconds]	VOI-R1 Maneuver Amount [m/s]		Maneuver Error [%]	Umbra over 70% in area during first 100 days [minutes]	First Apoapsis [million km]	First Periapsis [km]	Remarks
	impulsive	infinite					
0	(0)	0	-100%				Escape from Venus Gravity
100	(17)	18	-91%				Escape from Venus Gravity
200	(34)	36	-82%				Escape from Venus Gravity
300	(51)	54	-73%				Escape from Venus Gravity
400	(68)	72	-64%				Escape from Venus Gravity
500	(84)	89	-55%				Escape from Venus Gravity
600	(101)	106	-46%				Escape from Venus Gravity
700	(117)	123	-38%				Escape from Venus Gravity
800	(133)	140	-29%				Escape from Venus Gravity
900	(149)	157	-21%		1.00	120,000	decay after 2 orbits
1000	(164)	174	-13%	132	0.70	10,000	
	(170)		-10%	92			
	(173)		-8%	79			
	(177)		-6%	133			
	(178)		-5%	172			Avoid long umbra by VOI-R2 (deceleration)
1100	(180)	190	-4%	188	0.55	1,500	Avoid long umbra by VOI-R2 (deceleration)
	(183)		-3%	171			Avoid long umbra by VOI-R2 (deceleration)
1125	(184)	194	-2%	164	0.52	1,000	Avoid long umbra by VOI-R2 (deceleration)
	(185)		-2%	155			Avoid long umbra by VOI-R2 (deceleration)
	(186)		-1%	148			
	(187)		-1%	140			
1145	(188)	198	-	134	0.49	700	Target at VOI-R1
	(189)		1%	127			
	(190)		1%	122			
	(191)		2%	116			
1175	(192)	202	2%	115	0.47	500	Target at VOI-R2
	(193)		3%	162			Avoid long umbra by VOI-R2 (acceleration)
1200	(195)	206	4%	191	0.45	400	Avoid long umbra by VOI-R2 (acceleration)
	(198)		5%	185			Avoid long umbra by VOI-R2 (acceleration)
1230	(200)	211	6%	173	0.42		Avoid long umbra by VOI-R2 (acceleration)
1240	(202)	213	7%	160	0.41	300	Avoid long umbra by VOI-R2 (acceleration)
	(204)		9%	148			Periapsis less than 300km
	(206)		10%	152			Periapsis less than 300km



Maneuver error (+5 to -10%)

Possible to Venus orbiter

Umbra less than 150 minutes during first 100 days after VOI-R1

28 January

MSR 49

Figure 9. Success Criteria for Venus Orbit Insertion

Provided by N.Ishii and C. Suzuki (JAXA)

In the worst-case scenario, a quick correction maneuver, VOI-R1c, was included in the orbit insertion plan as well. The VOI-R1c maneuver magnitude would be determined on an observed VOI-R1 shortfall while monitoring the real-time Doppler data and telemetry. This maneuver could be executed using the spacecraft's AB thrusters, assuming:

- The VOI-R1 maneuver is interrupted or does not execute
- The spacecraft's 3-axis attitude control is maintained (i.e. not in safe mode)
- The slew to the VOI-R1c burn attitude is nominal
- Telemetry and commanding are operational

Another fail-safe was that the entire maneuver would be visible with the burn versus no-burn pointing difference within the 70 m half-beam width for up to 18 hours. This would prevent a lost-spacecraft scenario in the event that the orbit insertion was unsuccessful. A diagram of the geometry and critical events during VOI, provided by JAXA, is shown in Figure 10 for reference.

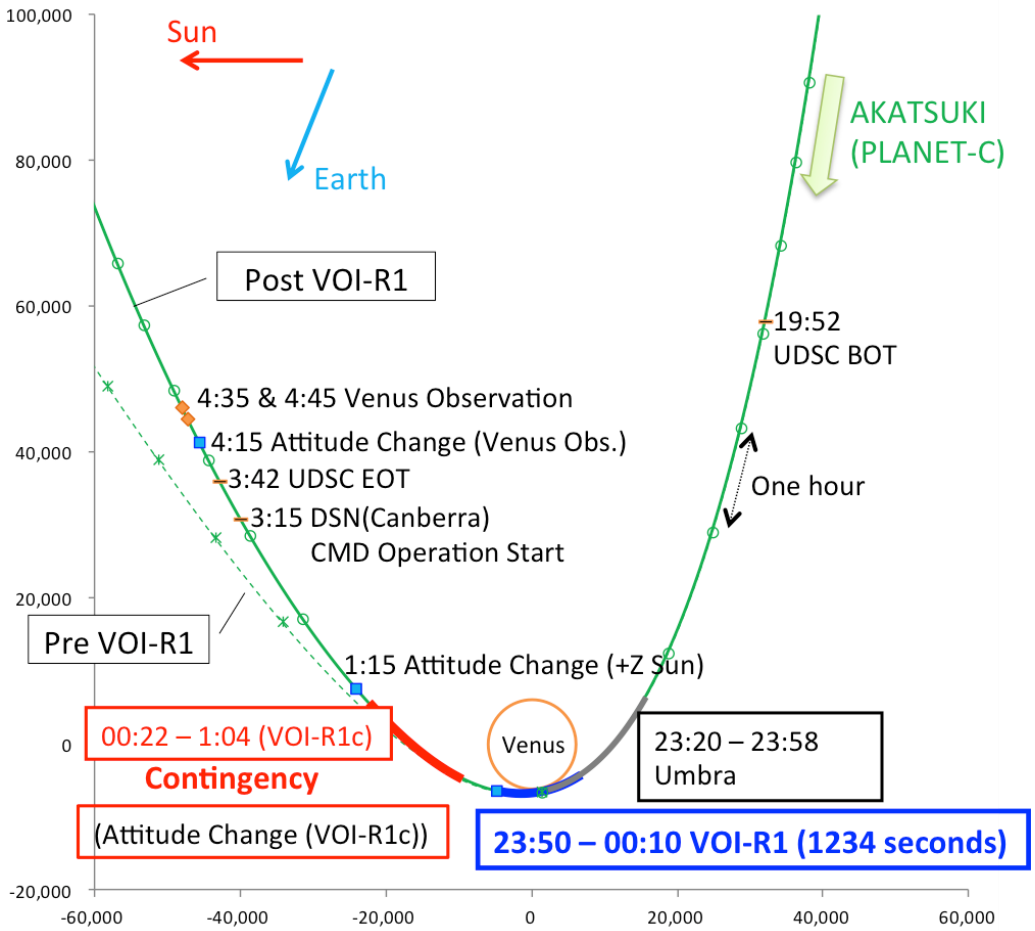


Figure 10. Venus Orbit Insertion Geometry

Provided by N. Ishii and C. Suzuki

VENUS ORBIT INSERTION RESULTS

On December 6, 2015, the spacecraft was commanded to change its attitude from positive Z-axis towards the Sun to its VOI-R1 burn attitude. The VOI-R1 burn began Dec 7, 2015 at approximately 23:50 UTC with a total duration of 1211.5 seconds. JPL had provided a liaison to monitor the VOI maneuver while at JAXA. This real-time monitoring of Doppler data, along with spacecraft telemetry, was valuable in confirming the successful execution of the orbital insertion maneuver. Overall, the VOI-R1 maneuver executed nominally, and there was no need for the VOI-R1c emergency maneuver. Figure 9 shows the real-time Doppler data from the Canberra DSS-43 with a 3-sigma maneuver execution error envelope.

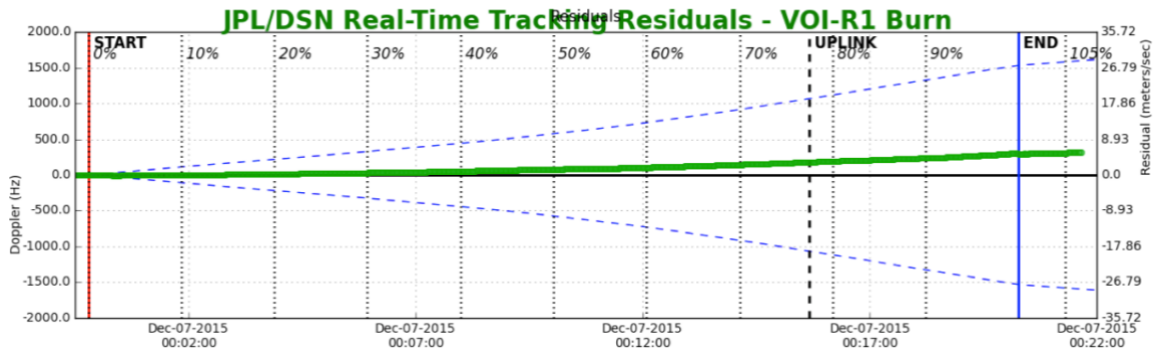


Figure 9. Real-Time 3-Way Doppler Residuals Received during the VOI-R1 Maneuver.

Reconstruction of the maneuver showed that the VOI-R1 maneuver was 4.2% over-burn with a 1.5 degree pointing error, leading to 14.0-day period versus the planned 16.6-day period. Due to this over-burn, the cleanup maneuver, VOI-R2, was re-designed to execute on this earlier periapse date.

Venus science observations began shortly after VOI, and 14 days later the VOI-R2 maneuver was performed during the periapse on Dec 20, 2015. The maneuver was again performed in view of a DSN station. Figure 10 shows the real-time Doppler data received during the burn. VOI-R2 was 0.1% under-burn with a 1.1 degree pointing error and was successful in establishing the desired 10.6-day period science orbit. Table 6 shows a summary of these VOI maneuvers.

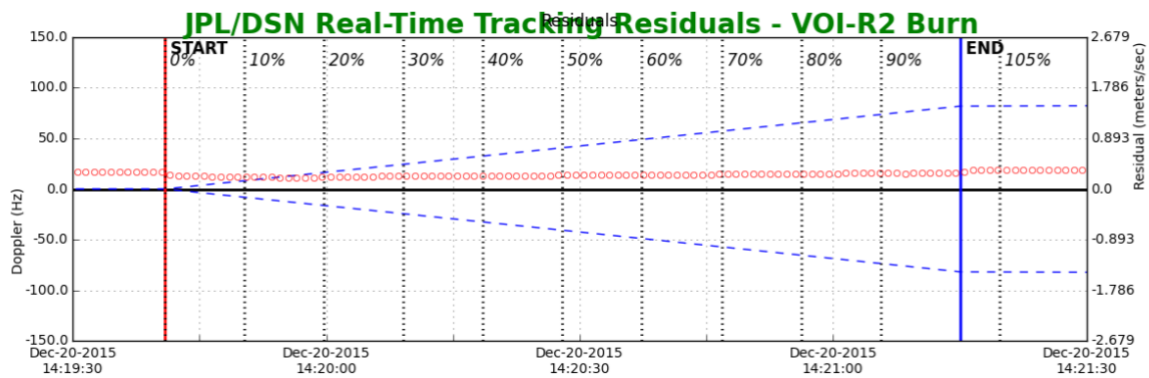


Figure 10. Real-Time 3-Way Doppler Residuals Received during the VOI-R2 Maneuver.

Table 6. Maneuver Summary for Venus Orbit Insertion and Trim.

Name	Date	Reconstructed Delta-V (m/s)	Predicted Delta-V (m/s)	Duration (sec)	Fuel Used (kg)	Notes
VOI-R1	07-DEC-2015	200.1	198.5	1234	XX	
VOI-R1c	07-DEC-2015					Cancelled
VOI-R2	20-DEC-2015	14.51	13.5	90	2.17	

POST ORBIT INSERTION RESULTS

As Akatsuki continued its science phase, it was determined that additional Phase Control (PC) maneuvers would need to be performed in order to reduce apoapsis altitude and further control eclipse duration. The first successfully occurred on Apr 4, 2016 with a nominal delta-V of 29.4 m/s. JPL navigation and DSN tracking support ceased a few days afterwards per agreement. There are two more PC maneuvers planned for later in 2017, as shown in Table 7, although JPL and DSN support for these have yet to be discussed.

Table 7. Maneuver Summary for Venus Science Phase

Name	Date	Reconstructed Delta-V (m/s)	Predicted Delta-V (m/s)	Duration (sec)	Note
PC1	04-APR-2016	2.202	2.239	15.25	Final JPL Support
PC2	10-NOV-2017	TBD	0.5		Eclipse Control
PC3	16-JUN-2017	TBD	6.0		Eclipse Control

CONCLUSION

The JAXA Akatsuki spacecraft was successfully inserted into Venus orbit after a long delay due to a main engine anomaly. JPL Navigation and the DSN provided valuable assistance to our JAXA partners and the mission is a good example of international teaming at a significant level. JPL Navigation performed orbit determination in concert with the JAXA team and all navigation requirements were met during the approach phase, which resulted in the cancellation of three correction maneuvers. JPL Navigation also provided real-time maneuver monitoring during critical maneuvers, to allow immediate corrective action in the event of problems. No such difficulties occurred and the spacecraft was successfully transferred to the final science operations orbit. Akatsuki is currently the only operating spacecraft in Venus orbit and has been acquiring unique observations of our sister planet's atmosphere for the past year including the recently announced the discovery of terrain-relative stationary atmospheric gravity waves[7].

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