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NAVIGATION SUPPORT AT JPL FOR THE JAXA AKATSUKI (PLANET-C) VENUS ORBITER MISSION*

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This paper details the orbit determination activities undertaken at JPL in support of the Japanese Aerospace Exploration Agency's (JAXA) Akatsuki (a.k.a. Planet-C and/or Venus Climate Orbiter) mission. 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 include a mission and spacecraft overview, dynamic forces modeling, cruise and approach orbit determination results, and the international teaming arrangement. Significant discussion is dedicated to the events surrounding recovery from the unsuccessful Venus orbit insertion maneuver.

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 independent orbit determination solutions that would be compared with solutions generated by JAXA.

MISSION OVERVIEW

The nickname "Akatsuki" means "dawn" or "daybreak" in Japanese. This nickname for the mission was chosen by the project team for several reasons. "'Akatsuki' means 'dawn' when Venus shines most brightly as the first graying of dawn appears in the east sky just prior to sunrise. Akatsuki is scheduled to arrive at Venus, which beautifully shines as the 'morning bright star' at dawn, in the winter of 2010. The name also reflects the purpose of the Planet-C project to

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newly create planetary meteorology by exploring Venus. The word ‘Akatsuki’, which indicates the start of a day, implies not only a beautiful scenic image, but also the power of achieving a goal, thus the name carries the thoughts and determination toward the success of the mission.”[1]

The Akatsuki mission followed a Type II, 7-month direct interplanetary transfer orbit to Venus (Figure 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 main engine. Two additional maneuvers were planned following VOI to reduce the orbit period down to the planned 30-hour science orbit.

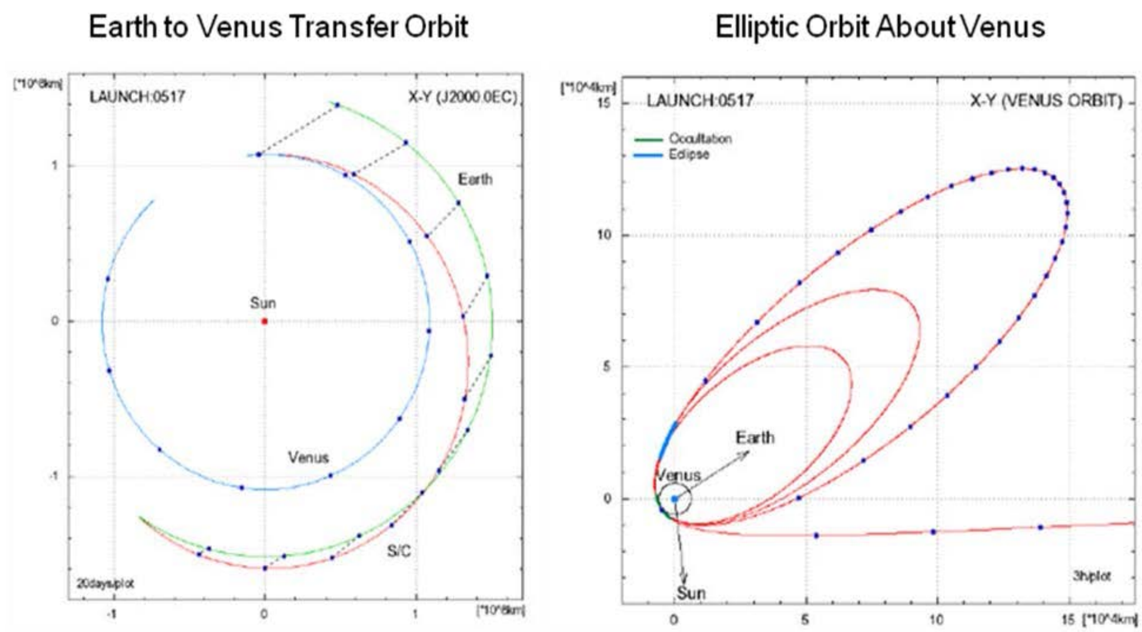

Figure 1. Akatsuki Trajectory

SPACECRAFT DESCRIPTION

The total mass of the Akatsuki spacecraft was 517.9 kg at launch, of which 196.7 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 2). 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. Communication with Earth was enabled via a high-gain antenna (HGA), two medium-gain antennas (MGA), and two low-gain antennas (LGA).

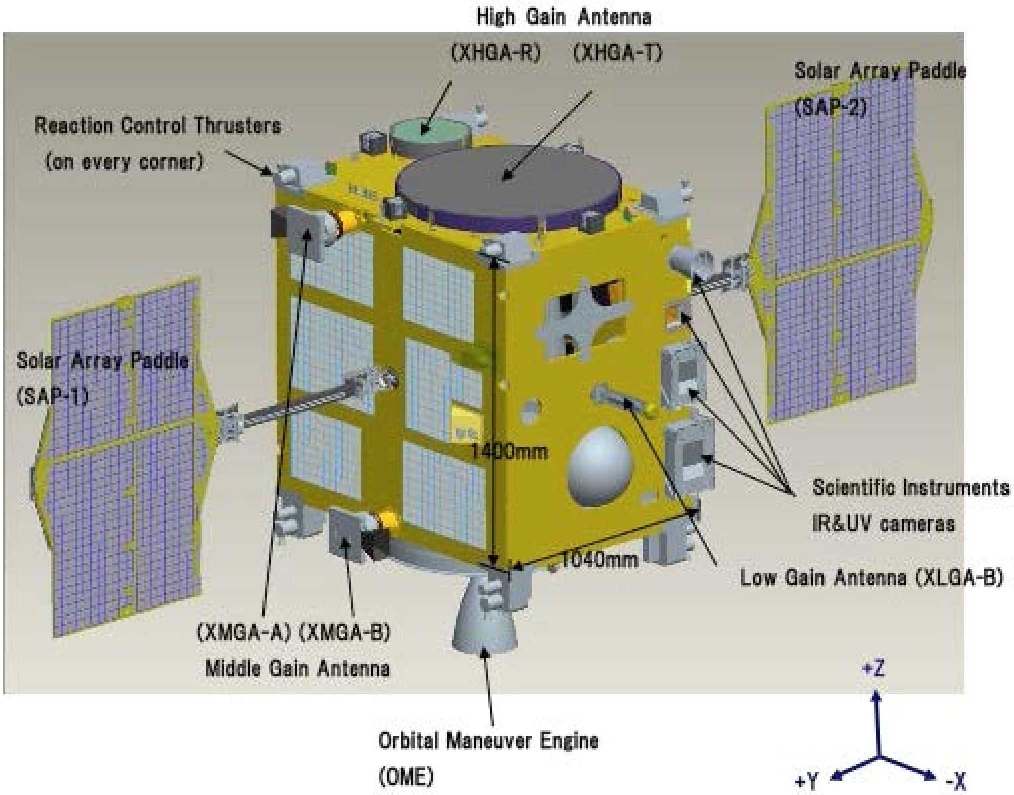

Figure 2. Akatsuki Spacecraft

TEAMING ARRANGEMENT AND JPL 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 and Uchinoura. JAXA also provided a document (known as the iPOD) detailing the spacecraft, its capabilities, and the nominal mission plan. The JPL team provided JAXA with Deep Space Network (DSN) tracking data and weekly orbit determination solutions. Good communication was maintained between the two navigation teams through numerous meetings during the mission. The most formal of these were the Technical Interchange Meetings which occurred at Sagamihara in March 2010 and October 2010 and at JPL in July 2010. There were also 18 weekly videoconferences conducted between February and September 2010, though these were less effective in general than the face-to-face technical interchanges. In addition to the meetings, there were many email exchanges.

During the critical VOI 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 within eight days after the VOI had been accomplished.

Formally, the JPL navigation team's 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, Hayabusa). The responsibilities of the JPL team were broadly outlined in the Technical Assistance Agreement[2] required by the United States Department of State for work with international organizations. The JPL navigation team developed a set of "assumed internal" navigation requirements, as follows:

- deliver trajectory files to the DSN as needed for tracking predicts generation
- provide routine weekly orbit determination solutions and as specified by JAXA
- deliver critical orbit determination solutions during launch and initial acquisition (at L+8.5 hours to support an orbit trim maneuver at L+14 hours), for maneuver design, sequence generation, Venus approach, and 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
- orbit determination accuracy sufficient to maintain contact with the spacecraft to the DSN and JAXA for the duration of the mission and following maneuvers (.032 degree 3 sigma pointing accuracy and 2000 Hz range rate accuracy)
- exchange media calibrated tracking data with JAXA.

In order to facilitate the smooth exchange of data between the teams, a number of interface agreements were made during the planning stages of the activity, well prior to launch. For example, agreements were established as to which files would be sent from JAXA to JPL and what the formats of those files would be, and vice versa. Where these files were not standard interface files (e.g., DSN interfaces or CCSDS standards) scripting was performed to process the files into a format that could be used by the JPL navigation software. It was agreed that tracking data would be exchanged using the DSN's TRK-2-18 Orbit Data File format, which is a format that has historically been used for the exchange of tracking data between NASA and JAXA. Additionally, it was agreed that media calibrations would be applied by the agency that supplied the tracking data.

Key deliverables from JAXA to JPL were the following: tracking data (DSN TRK-2-18 format), state vectors, maneuver plans, attitude plans, momentum wheel desaturation data, spacecraft orientation data, and solar array panel orientation data. All but the tracking data were sent in text format, as defined in the iPOD document.

Key deliverables from JPL to JAXA were the following: tracking data (DSN TRK-2-18 format), Delta-DOR data (DSN TRK-2-18 format), trajectory predictions (SPICE SPK format), state vectors, state covariances, and B-plane mapping. All but the tracking data were sent in text format, as defined in the iPOD document.

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 the orbit determination filter.

Key deliverables from JPL Navigation to the DSN consisted of trajectory predictions sufficient to produce antenna pointing and frequency predicts. These deliveries included "burn" and "no-burn" versions as needed. While this is essential under normal circumstances, a very special instance of this delivery path was executed in the wake of the failure of the Akatsuki VOI maneuver, where several "partial burn" ephemerides were made available to the DSN.

SOFTWARE

The JPL navigation team opted to use the same version of the navigation software as that used by the JPL Hayabusa navigation team, which was also supported by JPL in a "shadow" capacity. Recall that the Hayabusa Earth Return was scheduled only a few weeks after the Akatsuki launch. This decision was largely driven by the fact that on the JAXA side, the same team was supporting both Hayabusa and Akatsuki, and the same interface files/formats were already being exchanged between the two agencies.

JPL NAVIGATION TEAM COMPOSITION

JPL utilizes a multimission navigation team approach, where there is a minimum number of team members "full time" on a mission, and various support staff are added/subtracted according to the needs of the mission and the mission phases. For Akatsuki, there was a Navigation Team Chief who was essentially full time throughout the mission. The Team Chief was supplemented for most of the mission by a half time orbit determination engineer, a fractional time maneuver engineer, and a fractional time Delta-DOR engineer. At various points in the mission (primarily pre-launch/launch/initial acquisition and the approach to Venus Orbit Insertion (VOI), this baseline team was supplemented by additional orbit determination engineers, additional maneuver engineers, systems administrators, and tracking data technicians. The minimum team size was about 1 (Team Chief only) up to a maximum of about 5, with an average of approximately 2.25 full time equivalents.

During the 6-week Approach phase, JPL navigators staffed five shifts per week for the first four weeks, one per day for the fifth week, two shifts per day for the sixth and final week, which included the scheduled VOI.

LAUNCH

The spacecraft launched on 20-May-2010 at 21:58 UTC on an H-IIA rocket from the Tanegashima Space Center in Japan on a 7-month trip to Venus. This was the first hyperbolic Earth departing trajectory attempted using the H-IIA. The launch had originally been scheduled a few days earlier, on May 17, 2010 (UTC), however, at T-5 minutes, the JAXA team announced that the launch had to be scrubbed due to poor weather conditions (low clouds, fog, and showers). The launch scrub after fueling started mandated a 3-day turnaround period. In addition to the Akatsuki spacecraft, the H-IIA launcher also injected the IKAROS solar sail demonstration and the UNITEC-1 university consortium spacecraft; all three spacecraft were placed on Venus transfer orbits. Three other small university-developed piggyback payloads were launched into Earth orbit as well.

In preparation for the launch, JAXA provided JPL with launch injection states and an injection covariance matrix for each day in the launch period. These materials were used by the JPL navigation team to derive dispersed launch trajectories, which were used for initial acquisition planning by the DSN and operational orbit determination by JPL navigation. JPL navigation also arranged for United States Strategic Command (USSTRATCOM) tracking during the launch event; in the event of a non-nominal launch injection, the radar tracking is desirable. For this service, it was necessary to provide the trajectories of all of the HII-A payloads to USSTRATCOM.

Initial acquisition was successful by the DSN approximately 3 hours after launch (21-May-2010 1:01 UTC) using the Goldstone DSS-15 and DSS-24 antennas. The first two-way data was acquired at 01:35 UTC.

Post-launch, three maneuvers were planned at L+12 hours, L+7 days and L+14 days for cleanup of the launch injection errors (which were about 1.5σ).

TRACKING CAMPAIGN

The tracking campaign included range, Doppler, and Delta-DOR measurements throughout the mission (Table 1).

Table 1. Tracking Plan for Akatsuki.

Phase	**From**	**To**	**DSN Request (Doppler/Range)**
Launch	Launch	L + 3 days	Continuous
Early Cruise	L + 4 days	L + 13 days	8 hours per day
Early Cruise	L + 14 days	L + 44 days	4 hours per day
Non-Grav Cal	L + 45 days	L + 80 days	6 hours per day
Quiet Cruise	L + 81 days	L + 109 days	16 hours per week
Approach	VOI - 38 days	VOI - 4 days	8 hours per day
VOI	VOI - 3 days	VOI + 19 hours	Continuous
Post VOI	VOI + 1 day	VOI + 7 days	6 hours per day
Phase	**From**	**To**	**DSN Request (Delta DOR)**
Post Launch	L + 9 days	L + 44 days	Goldstone/Canberra once per week
Non-Grav Cal	L + 45 days	L + 80 days	Goldstone/Canberra once per day
Quiet Cruise	L + 81 days	L + 109 days	Goldstone/Canberra once per week
Approach	VOI - 38 days	VOI - 1 day	Goldstone/Canberra and Goldstone/Madrid, two per day
Phase	**From**	**To**	**JAXA Request (Doppler/Range)**
Launch/Cruise	Launch	L + VOI - 7 days	32 hours per week

VOI Phase	VOI - 7 days	VOI + 7 days	8 hours per day x two stations

Doppler and Range Data

The Doppler data utilized in the orbit determination process was restricted to two-way X-band Doppler data only (not one-way or three-way). JAXA and JPL agreed to use a 60 second compression time for the data. Each agency used a different time reference for the tracking data. Timetags in the JPL data were provided in seconds past 2000, and timetags in the JAXA data were initially provided in seconds past 1950. JAXA later altered changed their delivery specification to use the seconds past 2000 reference to be consistent with the JPL format.

JAXA and JPL utilize different ranging systems. JPL's ranging is the DSN Sequential Ranging[3] (high component 5, low component 20, cycle time 103 seconds). JAXA's ranging is the pseudo-nose system (high component 0, low component 24, cycle time 39 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.

Reconstructed post-fit residuals display a data sigma of 0.05 mm/s (0.003 Hz) for Doppler with a 60 second count time and 0.11 m (0.8 RU) for range tracking data (see Figure 3).

Delta-DOR Tracking

Delta-DOR was accomplished using telemetry sidebands spanning 3.7 MHz because the Akatsuki spacecraft was not able 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, it was established that actual accuracy for the DSN measurements was 0.5 nanoseconds. For the first 109 days of the mission, only one DSN baseline could be used for Delta-DOR, i.e., the Goldstone-Canberra baseline given the Southern outgoing asymptote. For the final 38 dates prior to the orbit insertion, it was possible to use both DSN baselines (i.e., Goldstone-Canberra and Goldstone-Madrid) for the Delta-DOR tracking. Baseline diversity increases the accuracy (and value) of the Delta-DOR data type, yielding both components of angular position during the tracking campaign; good data were obtained on 103 of the scheduled scans.

In addition to the DSN baselines, 3 experimental joint DSN-JAXA Delta-DOR observation sessions were conducted between 30-Jul-2010 and 10-Aug-2010 using the Goldstone-Canberra, Goldstone-Uchinoura, and Canberra-Uchinoura baselines. The data from the mixed baselines for the first two sessions were not processed given that the spacecraft had been on the MGA and thus noisier, however, these sessions helped to establish the operational feasibility of the mixed baseline technique. The data for the session on 10-Aug-2010 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 noise sigma is 0.5 nanoseconds, and the mixed DSN-JAXA baselines have a baseline noise sigma of 3 nanoseconds. These mixed baseline data have a higher noise level due to the short mutual visibility between Goldstone and Uchinoura, and the consequently poor geometry. Subsequently, a total of 3 quasi-operational joint DSN-JAXA Delta-DOR observation sessions were conducted between 28-Nov-2010 and 02-Dec-2010, with the mixed baseline results now similar to the DSN measurements.

Reconstructed post-fit residuals display a data sigma of 3.4 nanoseconds for Delta-DOR tracking data (see Figure 3).

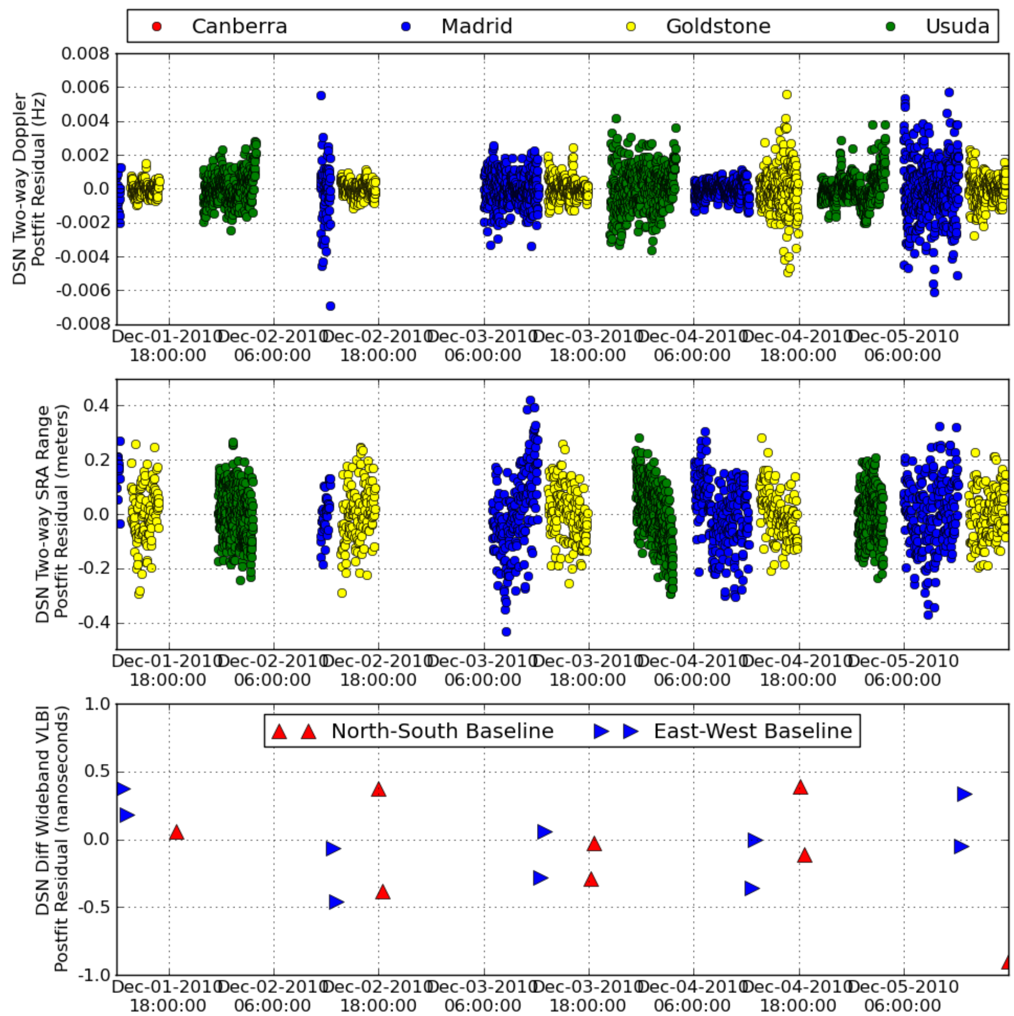

Figure 3. Doppler, Range and Delta-DOR Tracking Residuals (Postfit)

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 calibrated for ground based delays during first order radiometric processing, but must be further processed by the navigation team to account for onboard transponder delays. For DSN range data, transponder delays were calculated as 3387.06 RU, 3403.95 RU, and 3393.39 RU for the HGA, MGA and LGA respectively. The transponder delay for JAXA range data was 2856.12 RU; it is different from the DSN range transponder delays due to the different ranging implementation at each agency.

In addition, the JPL navigation team had to apply constant biases to the JAXA range data computed observables; these biases, which are a function of the tracking station hardware, were 92.7 RU for Uchinoura and 48.8 RU for Usuda. JAXA also applied a similar bias to their range data computed observables to make it consistent with the JPL range.

Data Weights

Data weights for the various tracking data types were set in the processing as shown in Table 2 below.

Table 2. Tracking Data Weights.

Data Type	Data Weight	Note
DSN 2-Way Doppler	0.005 Hz (0.09 mm/s)	
JAXA 2-Way Doppler Uchinoura	0.014 Hz (0.25 mm/s)	
JAXA 2-Way Doppler Usuda	0.010 Hz (0.2 mm/s)	
DSN 2-Way Range	14.2 RU (2 meters, 1-Way)	
JAXA 2-Way Range	14.2 RU (2 meters, 1-Way)	
Delta-DOR on HGA	1.0 ns (50 nanoradians)	Recommended by JPL's VLBI processing group
Delta-DOR on MGA	1.4 ns (70 nanoradians)	Recommended by JPL's VLBI processing group

CRUISE

The cruise period to Venus was generally quiescent, with communications via HGA and light staffing. There was sparse DSN tracking including Delta-DOR from 05-Aug-2010, but long JAXA tracking passes on most days. During this time there was regular exchange of media calibrated tracking data, orbit determination solutions, and telemetry based products between JPL and JAXA.

A calibration of dynamic forces acting on the spacecraft was conducted in late July and early August 2010. This calibration period requires that there be no thrusting events, no attitude changes, and no solar panel orientation changes. This "quiet" period was required in order to collect and analyze data that allows the best possible modeling of the solar pressure perturbations and trending of the momentum management system. Occasionally there were also instrument calibrations or zodiacal light observations during late cruise.

One major calibration during cruise was an in-flight test of the OME, with the intention of obtaining main engine performance data in preparation for VOI. The 13-second duration maneuver, named APH-1, was not intended to correct trajectory injection errors. The maneuver was conducted on 28-Jun-2010, though due to the test design, the results were not directly applicable to the VOI. The results of the APH-1 test were significantly different than expected, with an actual magnitude of 12.152 m/s compared to 11.661 m/s planned (thrust error of 0.491 m/s), right ascension +5 degrees relative to plan, and declination -2.25 degrees compared to plan.

There was an attitude anomaly on 06-Sep-2010 through 07-Sep-2010 during a camera calibration that caused a loss of communications to Earth for 24 hours, but there was no apparent impact on the spacecraft health or trajectory. This anomaly was caused by a failure to switch to the LGA during the calibration.

APPROACH PHASE

The "approach phase" was defined to begin on 01-Nov-2010. At this point staffing levels increased to support the increased level of activity. A number of maneuvers were planned during the approach phase (see Table 3), all of which were nominally designed by the JAXA navigation team to occur while the spacecraft was in view from Japanese tracking stations. In support of the design of each of these maneuvers, the JPL navigation team had a critical delivery schedule of orbit solutions. For most of the approach phase, the required delivery times were approximately 3 to 4 days prior to the scheduled maneuver, however, as the VOI approached, the interval between the delivery time and the event time reduced dramatically.

Table 3. Approach Phase Maneuver Schedule.

Name	Date	Magnitude (m/s)	ΔM (kg)	Note
TRM-1	VOI - 29 days	3.3	0.96	Target VOI
(TRM-1c)	VOI - 22 days	0.1	N/A	
TRM-2	VOI - 15 days	1.0	N/A	
(TRM-2c)	VOI - 8 days	0.1	N/A	
TRM-3	VOI - 6 days	1.0	N/A	
VOI -1	Venus Periapsis	704.6	107.32	Period: 96 hr, Apoapsis altitude: 186,500 km
(VOI-1c)	VOI + 22 hours	10	N/A	Correction if needed
APV-1	VOI + 2 days	56.1	7.51	Periapsis Raise if needed (500 - 600 km)
APV-1 B/U	VOI + 3 days	56.1	7.51	Periapsis Raise if needed (500 - 600 km)
VOI-2	VOI + 4 days	99.4	12.97	Period: 48 hr, Apoapsis altitude: 112,500 km
(APV-2)	VOI + 5 days	1.0	N/A	Periapsis Raise if needed (500 - 600 km)
VOI-3	VOI + 6 days	100.1	12.64	Period 30 hr, 500 km x 78,600 km

As events unfolded, ultimately the TRM-3 maneuver was the last of these maneuvers that was successfully executed.

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 DE423[6], produced by JPL's Solar System Dynamics group; it contains the mass parameters (GMs) for the planets.

Solar Radiation Pressure Model

The largest orbit determination error source for Akatsuki was ultimately reduced to solar radiation pressure (SRP). Significant effort was put into developing and refining a detailed solar pressure model, which further improved the orbit determination accuracy. This effort was necessary in order to reduce the magnitude of modeling errors that ultimately produce a less accurate estimate of the true trajectory.

The SRP model evolved over the course of the cruise and the various orbit solutions. For the first few post-launch orbit solutions there was no solar pressure estimate. Starting about two weeks after launch, a simple 4-plate model was used incorporating 3 plates for the bus and 1 plate for the solar arrays. The 4-plate model incorporated specular/diffuse coefficients derived by examining the iPOD information. The spacecraft attitude was always sun pointing. By 09-Jul-2010 a 7-plate model had been developed which included 6 plates for the bus but still used a single plate for the solar arrays; the coefficients were again derived from the iPOD and the attitude was Sun pointing. Within one solution of building 7-plate model, the coefficients were updated based on estimates from the orbit determination data arc 22-May-2010 through 07-Jul-2010. In the last two weeks when the 7-plate model was used, a "scale factor" was developed. About two months prior to the VOI, the 8-plate model was developed; this model was used for the remainder of the mission because it captured the spacecraft dynamics well (better filter convergence and smaller stochastic accelerations than the lower fidelity 4-plate and 7-plate models). In this final iteration of the model, eight one-sided rectangular flat plates were used to model the spacecraft. Six of these plates were for the bus, arranged as a box. The single plate which had been used to model the solar arrays was split into two independent plates, one for each solar array. The attitude of the spacecraft in the model was upgraded such that it was no longer merely Sun-pointing; spacecraft bus attitude data and orientation angles for each solar panel relative to the bus were received weekly from JAXA. Specular and diffuse coefficients were estimated for each plate via the orbit determination process (see Table 4). Additional coefficient information was derived based on JPL's extensive experience modeling SRP for orbit determination. No self-shadowing was modeled.

Table 4. 8-Plate Akatsuki Spacecraft Model.

Name	Area (m^2)	Specular Coefficient	Diffuse Coefficient
+X Plate	1.686	0.239	0.168
-X Plate	1.686	0.159	0.208
+Y Plate	2.370	0.348	0.372
-Y Plate	2.370	0.306	0.329
+Z Plate	1.823	0.100	0.180
-Z Plate	1.823	0.102	0.300
Solar Panel #1	1.180	0.084	0.178
Solar Panel #2	1.180	0.084	0.178

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, 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)), though a "contingency" uncertainty was larger by at least a factor of 2.

The spacecraft design and construction resulted in the need for very few reaction wheel desaturation maneuvers. Because the spacecraft nominal orientation during cruise was with the HGA on Earth-point, the +Z-axis was pointed to Earth. Thus the momentum wheel unloading delta-V was 100% in the Earth line-of-sight and therefore highly observable in two-way Doppler data, with the exception of alignment errors (note that zero was used for the nominal values for X-axis and Y-axis components of the momentum wheel unloading delta-V). However, there was rarely any two-way Doppler for these events. Consequently, the nominal value for the momentum wheel unloading was determined by observing the pass through Doppler shift of the next two-way Doppler pass after the unloading. These maneuvers were generally small (mean of 0.4 mm/sec) when they did occur (once or twice per week depending on the spacecraft activity).

ORBIT DETERMINATION RESULTS / PLANNING FOR VENUS ORBIT INSERTION

Throughout the cruise phase of the mission, the JPL orbit determination results were very consistent. Comparisons with JAXA state vectors showed good agreement near the end of the data arcs, on average approximately 7 km in position and 2 cm/s in velocity. Shown in Table 5 are the orbit determination filter uncertainties utilized in the JPL orbit determination process.

Table 5. 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
Specular reflectivity	20% per plate	Estimated
Diffuse reflectivity	20% per plate	Estimated
Overall scale factor	25%	Estimated
Momentum wheel unloadings (impulsive burns)	x-axis 1 mm/s y-axis 2 mm/s z-axis 2 mm/s	Estimated
Per pass range bias	35.5 RU (5 m)	Stochastic
Within data arc acceleration	5.0×10^{-12} km/s^2 per spacecraft axis white noise with 8 hour update	Stochastic
Post data arc acceleration - momentum wheel offloading	10^{-12} km/s^2 spacecraft Z-axis 0.4×10^{-12} km/s^2 spacecraft X, Y-axis white noise with weekly update	Stochastic
Post data arc acceleration - solar pressure	10^{-12} km/s^2 spacecraft Z-axis 3×10^{-12} km/s^2 spacecraft X, Y-axis white noise constant acceleration from end of data arc	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

Beginning one month out from VOI, the three TRM maneuvers were executed to achieve the desired Venus B-Plane target. These maneuvers were relatively small and the good orbit determination results allowed for accurate planning (Figure 4). The final TRM-3 maneuver resulted in a predicted B-Plane offset from the target of about 20 km and a timing error of less than 1 second.

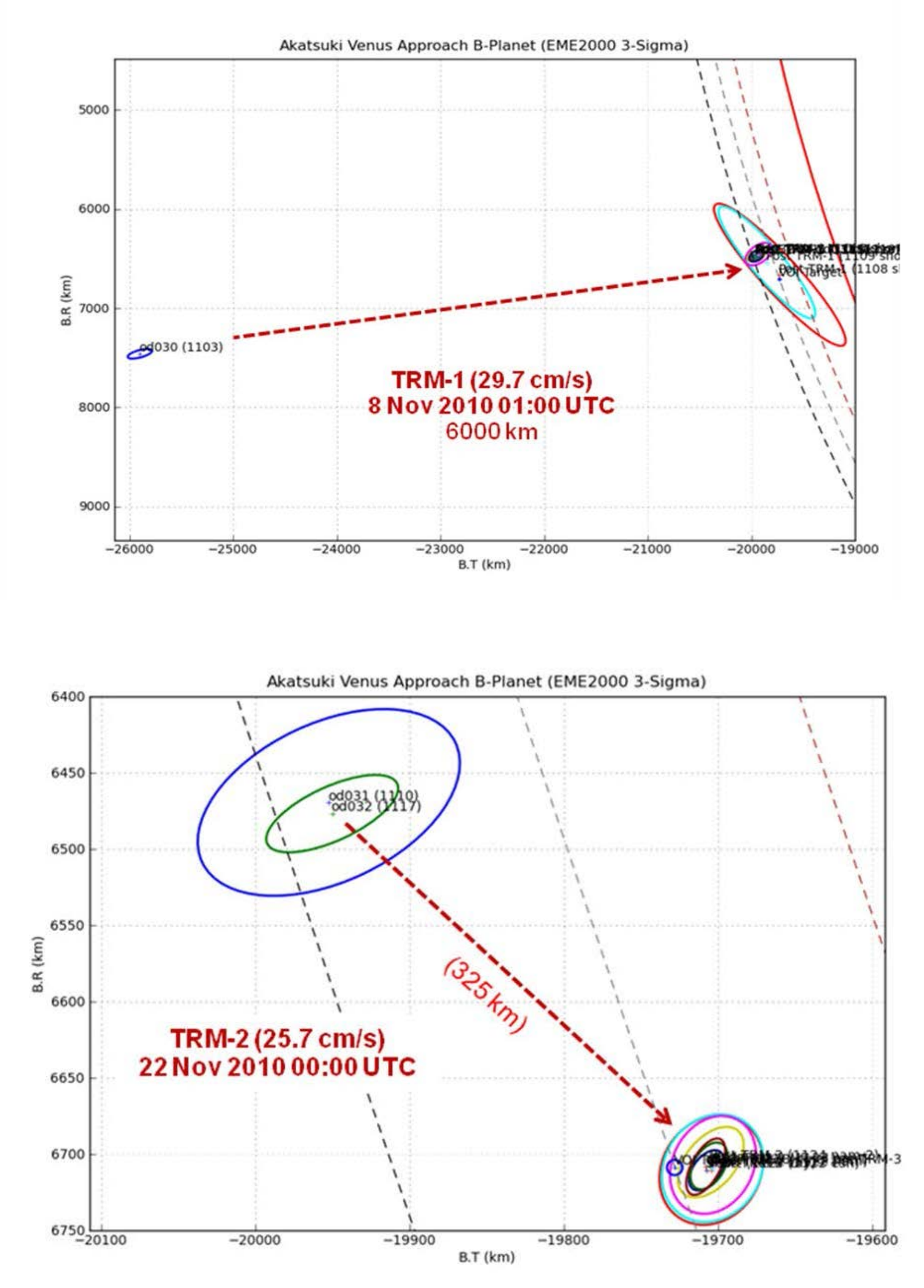

Figure 4. TRM-1 and TRM-2 Orbit Determination Deliveries from JPL (plotted on Venus B-Plane).

Orbit determination solutions were very stable during the approach phase and the desired pre-VOI trajectory was achieved following TRM-2. The TRM-3 maneuver, though not needed, was conducted as a demonstration of terminal approach targeting (Figure 5). JPL state vectors, corresponding the preliminary and final maneuver design, were delivered to JAXA at three and two days prior to the VOI burn respectivley. The final state vector delivery to JAXA had an altitude of periapsis of 547.0 km (3.0 km low) with a three-sigma uncertainty of 4.8 km. The estimated time of periapsis was 06-DEC-2010 23:59:59.75 UTC (0.25 seconds early) with a three-sigma uncertainty of 1.97 seconds.

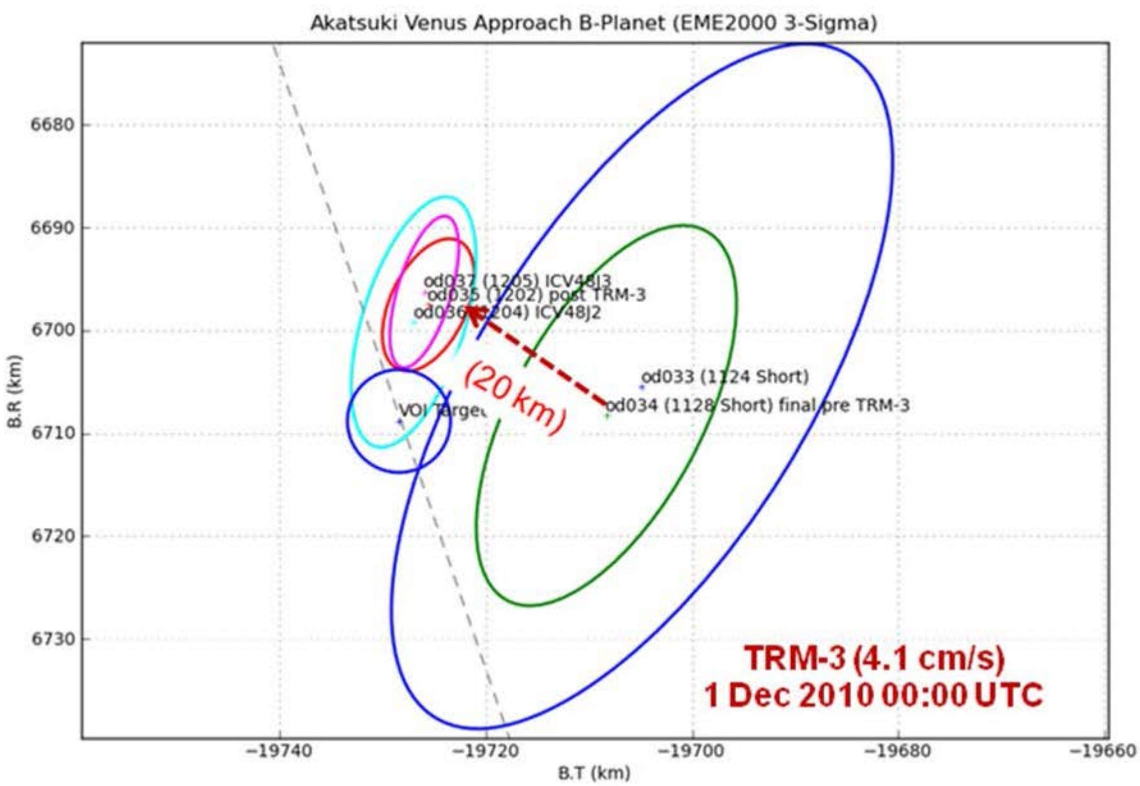

Figure 5. TRM-3 Orbit Determination Deliveries from JPL (plotted on Venus B-Plane).

The details of the VOI-1 maneuver included:

- VOI-1 (preliminary design)
    - Epoch: 06-DEC-2010 23:49:00 UTC
    - ΔV = 704.7 m/s
    - Δm = 110.8 kg
    - Duration: 718 seconds (11:58 minutes)
    - First 90 seconds of maneuver is visible from Usuda prior to Venus occultation entry

- VOI-1 target
  - Time of Periapsis: 07-DEC-2010 00:00 UTC
  - Altitude of Periapsis: 550 km
  - Inclination: 155.0º (Earth Mean Equator and Equinox of J2000)

A collision avoidance study using the Akatsuki trajectory and the European Space Agency's Venus Express trajectory was also conducted in preparation for the VOI. The period of study extended from post-Venus approach through the attainment of the Akatsuki science orbit about a week after VOI. The results of this study were negative, with the closest approach during the interval being around 11,000 km.

UNSUCCESSFUL VOI

As discussed above, the spacecraft performed very well throughout cruise and approach, with great stability and few problems. However, a major anomaly occurred on 06-Dec-2010 as the spacecraft attempted to enter Venus orbit. The main engine failed to complete the VOI maneuver required to slow the craft enough to be captured by the gravity of Venus. The decisive actions of JPL navigation played a major role in helping the DSN regain and maintain contact after the anomaly and as well as enabling JAXA to reestablish control of the spacecraft.

Chronology

The Akatuski VOI maneuver began on time at 23:49 UTC on 06-Dec-2010. By design, tracking during the 704.6 m/s VOI maneuver was performed exclusively by the JAXA Usuda 64m ground station; although the DSN antennas at Canberra were in view, their support had not been requested. The JPL navigation team stayed in communication through their detailee at JAXA and through a live (one-way) video feed from the JAXA operations room. In the nominal burn plan, the main engine would fire for 718 seconds total. The first 90 seconds could be seen from Earth, but the remainder of the burn would occur when the spacecraft was occulted by Venus. The exit from occultation was nominally expected 11 minutes after the completion of the maneuver with the spacecraft communicating on its MGA. Concurrent with the JAXA VOI prime shift, the JPL team was on duty to provide a trajectory update after VOI-1.

The VOI burn started on time per plan, and the reaction at JAXA was positive. Engineers confirmed ignition of the OME thruster before Akatsuki passed behind Venus, which was expected to block communications signals from the spacecraft for 22 minutes. The first 90 seconds while the spacecraft was in view were apparently nominal; however, the spacecraft did not resume communications at the specified time following the occultation. After about 1 hour, the flight project declared a spacecraft emergency. The DSN responded by making arrangements for emergency tracking coverage, and JPL Navigation was tasked to provide rapid post-insertion burn orbit determination.

Shortly thereafter, Usuda established weak and intermittent contact (07-Dec-2010, 01:28 UTC). Little useful engineering telemetry could be acquired because the spacecraft was in a 10-minute spin, indicative of a safe mode condition, with telemetry at a very low data rate (8 or 16 bps, about 30 seconds of telemetry per revolution). Over the following 10 hours, communications were gained and lost numerous times, then more ominously lost for a period of about 2 hours.

Using pre-prepared azimuth/elevation plots of topocentric burn vs. no-burn trajectory differences (Figure 6), JPL navigation investigated how long predicts using the nominal VOI burn might provide adequate station pointing for downlink acquisition in the event of a truncated burn. At the time there was still substantial uncertainty about the actual burn performance (e.g., duration, direction, mass flow), which compounded the orbit determination challenge. Making assumptions about how much of the burn had occurred nominally, an under-burn was selected such that pointing would degrade to the point that the signal would be lost at approximately the same time contact was actually lost (estimated at 55% of the burn).

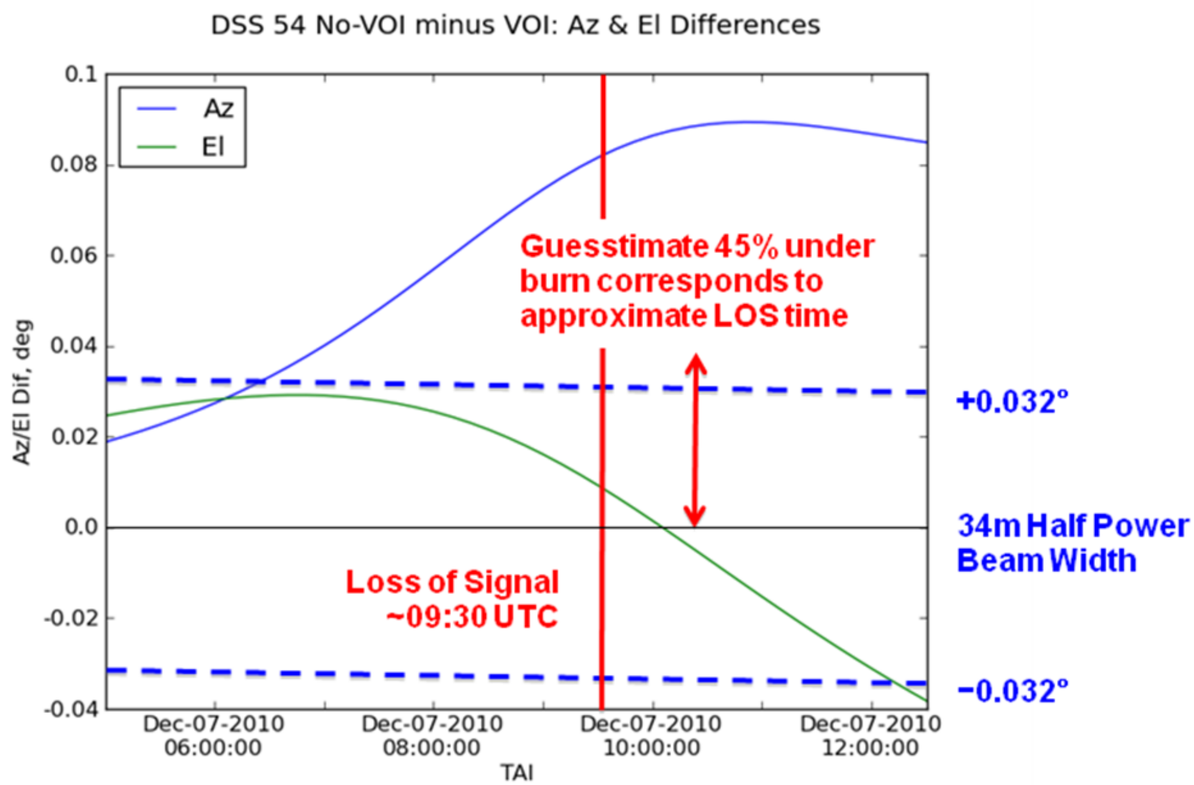

Figure 6. Pre-prepared Azimuth/Elevation Plot of Topocentric Burn vs. No-burn Trajectory.

The JPL navigation team created a trajectory predict based on this presumed partial burn and provided it to the DSN, which used the new predicts to attempt re-contact with the spacecraft over Madrid's 70m DSS-63 antenna. The signal was immediately detected at 07-Dec-2010 11:20 UTC using this new predict and snippets of telemetry were received. This enabled the JAXA controllers to de-spin the spacecraft and establish 2-way communications with the ground. A decision was made by JPL navigation to use the same trajectory for Goldstone predicts. Later the initial analysis was improved upon by generating a number of trajectories assuming various maneuver under burns (see Figure 7).

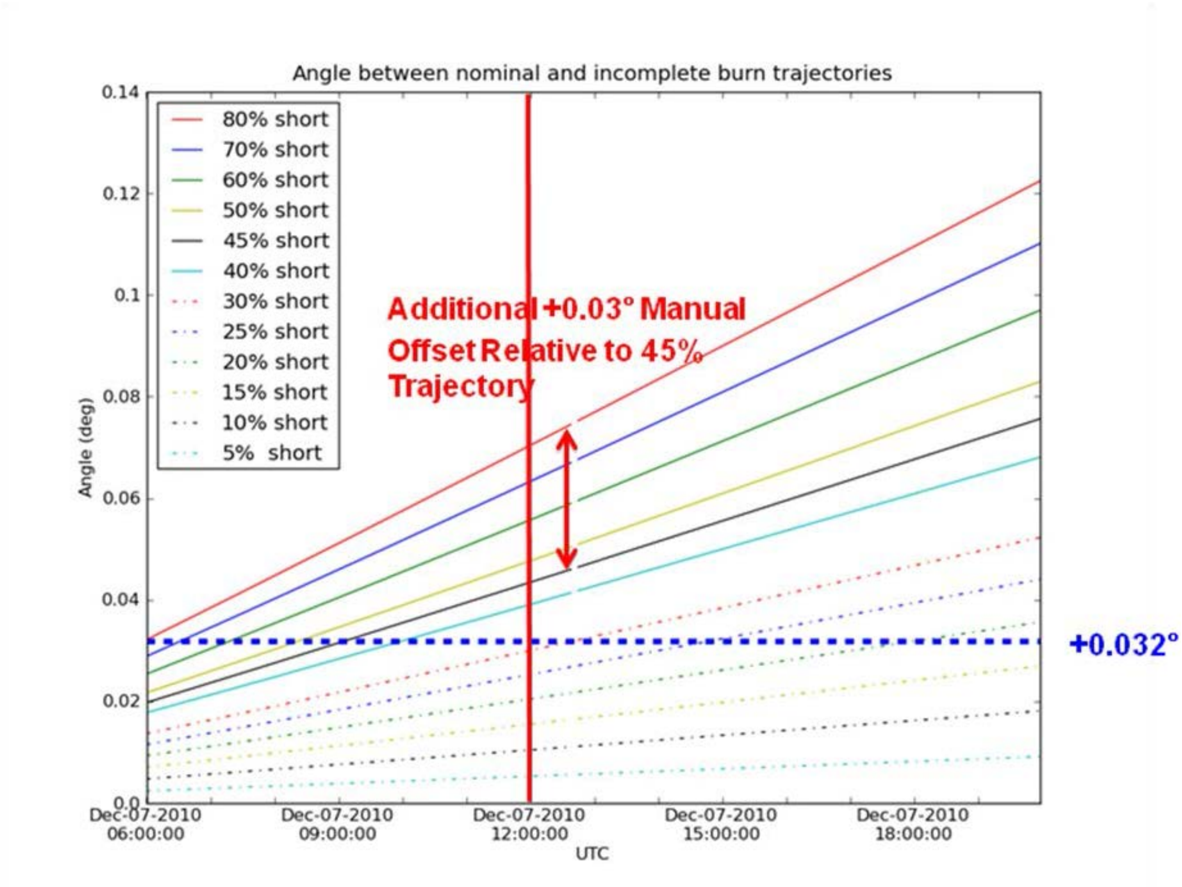

Figure 7. Angle Between Nominal and Akatsuki OME Incomplete Burn Trajectories. The 0.032º threshold corresponds roughly to the expected loss of contact for a 34m DSN tracking station

JPL navigation developed a new solution based on this improved analysis of the maneuver performance; the solution incorporated an estimate of 80% underburn maneuver performance, somewhat less than the initial 55% estimate. This solution improved the link margin with the spacecraft through the Goldstone 34m DSS-25 station.

It is important to note that no two-way Doppler was available any time during this interval. Later on the JPL liaison in Japan the need to acquire some two-way tracking data in order to accurately establish the post VOI trajectory and improve predicts. As a result, about 3 hours of two-way Doppler were obtained from Goldstone. A new orbit solution was created at JPL using the post-VOI tracking data by ~17:35 UTC on 07-Dec-2010. Antenna predicts based on this solution provided reliable contact with no degradation over the remainder of the track. Attitude control of the spacecraft was established during the subsequent Japanese tracking pass and communications via the high gain antenna allowed significant data playback. Shortly after, the JAXA team determined that the orbit insertion could no longer be achieved by commanding another maneuver.

Ultimately, analysis of telemetry determined that the maneuver anomaly was caused by safe mode entry triggered by excessive attitude excursions at approximately 156 seconds into the planned 718 second burn. This safe mode entry caused the OME to shut down. The spacecraft is currently in heliocentric orbit and in good communications with the ground.

Lessons Learned

A number of important lessons-learned can be garnered from this unsuccessful experience.

- A contour plot showing pointing dispersions as a function of burn performance should be prepared prior to critical maneuvers. This would allow an expeditious rough assessment of maneuver performance based on signal strength when telemetry or Doppler tracking is unavailable.
- Acquisition of two-way Doppler early after a critical maneuver should be an essential part of the plan – especially given that anomalies can occur. No problem can be diagnosed or corrected while the team is struggling to establish contact with the spacecraft.
- The presence of a navigation liaison onsite at the partner agency was essential. JAXA's receptivity and responsiveness to JPL navigation's on-site suggestions were ultimately responsible for JPL and NASA's successful support of this critical event.
- Low bit-rate telemetry (8-16 bps) is of little value when contact times with the spacecraft are brief, infrequent or unstable.

THE FUTURE OF AKATSUKI

Currently, the Akatsuki spacecraft is in communication with the ground from a 203-day heliocentric orbit while plans for a return to Venus are being considered (estimated approximately 6 year return trajectory). Assessment of the health of the spacecraft main engine is in progress. Ground testing supports the conclusion that a valve in the propellant sub-system became clogged which resulted in an insufficient flow of oxidizer to the engine. An on-orbit test of the OME is scheduled for September 2011.

After the unsuccessful VOI attempt, staff from JPL's Mission Design and Navigation section took a preliminary informal look at the possibility of visiting Near Earth Asteroids (NEAs) that might pass through the vicinity of Akatsuki's 2016 return trajectory. A flyby of one (or more) of the asteroids NASA may consider for a human mission or any that are classified as Potentially Hazardous Objects (PHOs) would be an interesting way to utilize the spacecraft in a "mission of opportunity" mode. Initial studies indicate that there is a potential opportunity for Akatsuki to flyby candidate asteroids identified in NASA's recent NEA target accessibility study for potential human missions to an asteroid. Several objects were found that would require only tens of meters/second of propellant to visit along the way. In particular, asteroid "2003 LN6" is an attractive candidate with a human mission launch date around 2026, though it would require some modest changes to the JAXA Venus return trajectory. Such a flyby would provide an opportunity to assess the spacecraft health and the operability of the onboard instrumentation. Specific benefits to NASA of an Akatsuki encounter with asteroid "2003 LN6" or other NEA of interest include:

- Improvement in the asteroid ephemeris quality for a future human encounter
- Assessment of the physical characteristics of the asteroid such as pole, spin, brightness, composition, density, etc.
- Continued space exploration collaboration between Japan and the United States

As JAXA continues to assess Akatsuki's capabilities, new spacecraft constraints specifically related to the propulsion system could affect this flyby prospect, or the suite of science instruments may not be suitable for NEAs. For now, at least from a trajectory standpoint, there appear to be viable opportunities. Typically, performing the targeting with the maximum lead time prior to an encounter minimizes the required fuel. A very preliminary estimate is an additional tens of meters/second to flyby at a close distance then retarget Venus and complete the VOI and science orbit operations.

CONCLUSION

Although the Akatsuki VOI maneuver was not successful, the delivery to the target was very accurate. The mission was a good example of international teaming at a significant level. In its role of providing joint navigation support for Akatsuki, JPL provided critical support in maintaining orbital knowledge for ground tracking following the off-nominal VOI maneuver. JPL Navigation hopes to continue to be a part of the Akatsuki mission in the future, perhaps participating in a second attempt to put the spacecraft into orbit around Venus. JPL navigation admires the perseverance of the JAXA team, which has indicated that they "share the never-give-up spirit with the 'Hayabusa' team that finally made a successful sample return from an asteroid."[7] We are confident that JAXA's Akatsuki team will be successful in eventually guiding Akatsuki to its ultimate destination.

ACKNOWLEDGMENTS

Akatsuki's delivery to Venus is a direct result of the contributions of many people. The authors would like to express their appreciation and deep respect for the members of the JAXA navigation team. Their technical open communication, cooperation and heroic efforts were directly responsible for the success of the navigation task. Thanks also go to the JPL DDOR team, led by Jim Border, for implementing the telemetry-based DDOR capability, operational interfaces and cogent advice.

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