ORBIT DETERMINATION DEMONSTRATION FOR AKATSUKI (PLANET-C) MISSION

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Abstract: *Venus Climate Orbiter, Planet-C known as "Akatsuki", has been launched on May 21, 2010 on H-IIA booster from Tanegashima Space Center (TSC), Kagoshima, Japan. And arrived at Venus in December 6, 2010 without trouble after the cruising interplanetary approximately seven months. The main engine (OME: Orbit Maneuver Engine) failed to complete the Venus orbit insertion (VOI: Venus Orbit Insertion) maneuver required to insertion Venus orbiter. Currently, a spacecraft cruising heliocentric orbit and has been communicated at ground station with telemetry, command, and observation of Earth-based radiometric data.*

It is carried out three times of trajectory control using RCS in a perihelion November, 2011. As a result, this spacecraft cruising interplanetary for Venus re-encounter without trouble. By these trajectory controls, the orbital period was reduced from 203 days to 199 days. And this mission design, which now plane to rotate about the Sun, will approach to Venus again in 2015.

From view point of navigation, we describe OD (Orbit determination) demonstration interplanetary cruising phase and orbital maneuver phase.

Keywords: *Venus missionn, Navigation, Earth-based radiometric data. Kalman Filter.*

1. Introduction

AKATSUKI aims at elucidating the mechanism behind the mysterious atmospheric circulation of Venus, with secondary objectives of exploring the ground surface and observing zodiacal light during its cruise to Venus. The exploration of the Venusian meteorology has been given a high priority not only for understanding the climate of Venus but also for the general understanding of planetary fluid dynamics. Meteorological information will be obtained by globally mapping clouds and minor constituents successively with four cameras at ultraviolet and infrared wavelengths, detecting lightning with a high-speed imager, and observing the vertical structure of the atmosphere with radio science technique. The equatorial elongated orbit with westward revolution fits the observations of the movement and temporal variation of the Venusian atmosphere which rotates westward.

AKATSUKI has been launched on May 21 2158:22 (UTC), 2010 on H-IIA booster from Tanegashima Space Center (TSC), Kagoshima, Japan. And arrived at Venus in December 6, 2010 without trouble after the cruising interplanetary approximately seven months. The main engine (OME: Orbit Maneuver Engine) failed to complete the Venus orbit insertion (VOI) maneuver required to insertion Venus orbiter. Currently, a spacecraft cruising heliocentric orbit and has been communicated at ground station with telemetry, command, and observation of Earth-based radiometric data and additional Delta-DOR data.

2. Overview of the spacecraft

The main body is comprised of an aluminum structure box. Its width, depth and height are 1040[mm], 1450[mm] and 1400[mm], its nominal mass is 500 kg including maximum fuel, and the science payload weights 35 [kg]. Based on the mechanical environments of the H-IIA structural analysis has confirmed that the structure has enough stiffness and strength. A spacecraft has a maximum power of 700 [W], including all the mission and bus instruments. The solar array panel (SAP) has one degree of freedom about the Y-axis of the spacecraft body, and its orientation is directed toward the Sun independent of the attitude of the main body. The communication system will be used for radio science as required. The X-band High Gain Antenna (HGA) will be oriented toward the Earth by attitude control for communication with the ground station. The telemetry rate will be higher than 8 [kbps] at 1.5 [AU], 16 [kbps] at 1.1 [AU] and 32 [kbps] at 0.7 [AU]. Akatsuki's system configuration is shown in Figure 1.

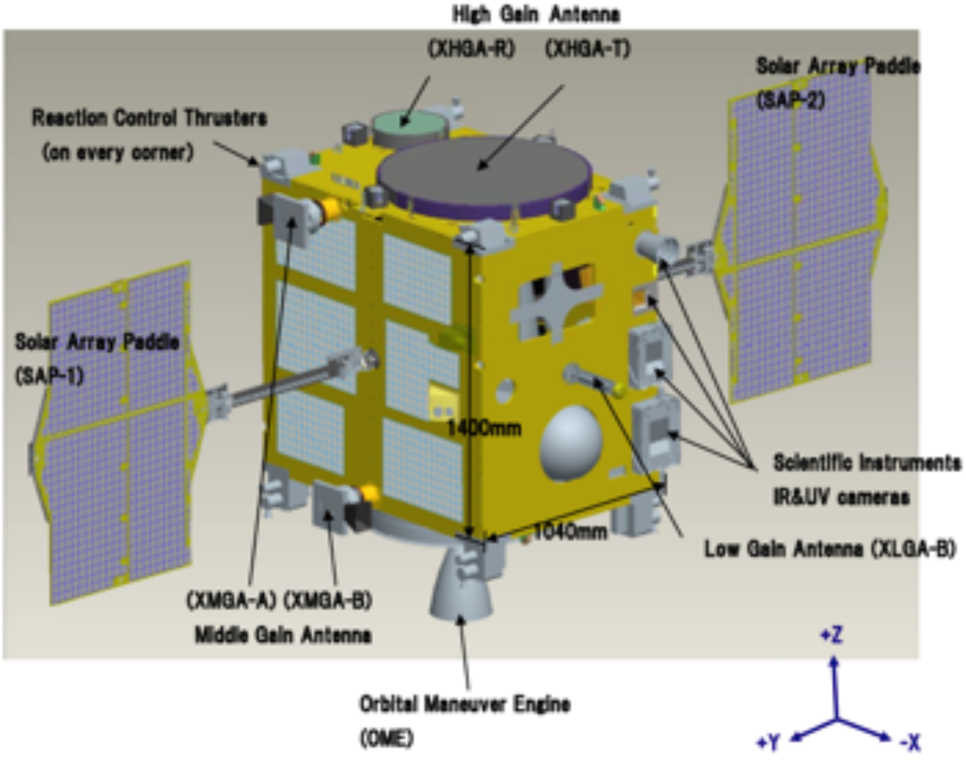


Figure 1. Akatsuki System Configuration

Viewpoint from the spacecraft telecommunication subsystem is as follows.

The new onboard instruments to be flight qualified are digital transponder (TRP), high-gain antenna (HGA), low-gain antenna (LGA), and traveling wave tube amplifier (TWTA). It is composed of redundant TRPs and 10W solid-state power amplifiers (SSPAs). The TWTA is provided for the increase of scientific data acquisition. The TWTA output power is twice as high as the SSPA. The available output power is strictly limited by the thermal requirements imposed to the spacecraft on the Venus orbit. They are connected with antennas via switches. The switch matrix should keep redundant routes among them. The antennas are a HGA composed of HGA-T (for transmission) and HGA-R (for reception), medium gain antennas (MGAs), and LGAs. The safety measures to keep uplink and downlink of the spacecraft are the MGAs and the LGAs. In general, the LGAs are selected in the spacecraft safe mode (spin mode along the Sun pointing +X-axis). It is also true even in other situations when the secured links are necessary. Each LGA covers hemisphere being combined with each TRP. No interruptions due to spin occurs because the LGAs are installed so that their pattern symmetric axis matches with that of spin (See Fig.1). The spacecraft can receive commands in any attitudes in this configuration. After the recovery from the safe mode, the spacecraft re-establishes downlink with the appropriate MGA in the three-axis stabilized mode.

The RCS propulsion system is composed of monopropellant thrusters adopted for the attitude control and the OME for injection into Venus orbit. These ceramic thrusters are excellent for combustion in high temperatures and oxidation-proof. Therefore, thrust with higher specific impulse can be expected by the reduction of fuel to film cooling.

Attitude and Orbit Control Subsystem (AOCS) is characterized by its precision: the attitude stability (±0.05 [deg]/100 [sec]) and the on-board attitude determination accuracy (±0.15 [deg]). In addition to these nominal attitude control requirements, there are new observation requests for adapting with the equatorial elongated Venus orbit. AOCS is comprised by three types in function, Sensors, Actuators and Processors. Sensor components are (1) Star Tracker (STT), (2) Two types of Sun Acquisition Sensor (SAS), (3) Inertial Reference Unit (IRU), (4) Acceleration Meter (ACM), (5) Sun Presence Sensor (SPS).

Actuator components are (6) Reaction Wheel (RW) and (7) Driving Unit (DRV). All sensors and actuators are connected (8) Attitude and Orbit Control Unit (AOCU).

2. Navigation overview

The operation sequence specifies four phases for different parts of the mission, (1) Launch, separation and initial health check, (2) Cruise trajectory to Venus after midcourse navigation and final course adjustment, (3)VOI (Venus Orbit Insertion) by burning on OME, (4) Nominal Venus Observation by mission instruments. But the stage (3) and (4) failed.

Continuing a long-standing tradition of co-operation, 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.

2.1. Navigation models

Orbit determination models can divided into two broad categories : dynamic and observable. Dynamic models are those which affect the translational motion the spacecraft. The dynamics models include the Venus gravity field, spacecraft attitude and solar radiation pressure, and thruster activity. The observable model are those which change the path length of the tracking signal, such as two-way range and Doppler data. The observables comprise the signal path environment and station transmitter and spacecraft transponder biases and delays. For the cruising phase, we have modeled the spacecraft's attitude in spacecraft coordinates. To account solar radiation pressure (SRP), the spacecraft is modeled using collection of the several plates. These components can be oriented with respect to the Sun independently. The area, specular reflectivity and diffuse reflectivity of each component have been calculated.

2.2. Navigation strategy

The orbit determination filter configuration for cruising operation using single batch, weighted least squares, square-root information algorithm. The tracking data used for each orbit solution consists of X-band Doppler data collected at 10 second samples over several orbits

Plans for during initial launch phase to VOI phase operation originally called for USUDA and UCHINOURA back up stations of JAXA and add to NASA/DSN tracking data.

3. Orbit determination

Navigation sequence specifies four phases for different parts of the mission, (1) Launch, separation and initial health check, (2) Cruise trajectory to Venus after midcourse navigation and final course adjustment.

3.1. Overview fundamental estimator

There are shown the results by used conventional estimator. This estimator is a weighted least-squares filter

The observation set **z** contains 2-way range and Doppler measurements.

$$H_x = \begin{bmatrix} \partial z_1 / \partial \mathbf{x} \\ \partial z_2 / \partial \mathbf{x} \\ \cdots \\ \partial z_N / \partial \mathbf{x} \end{bmatrix} \tag{1}$$

For a weighted least-squares estimator, the statistics associated with the estimation error can be readily computed by using the partial derivative matrix, H_x. A weighted least-squares estimate is one that minimizes the weighted sum of squares of the deviations between the actual and predicted measurements expressed by the scalar, quadratic cost function Q, written as

$$Q = \frac{1}{2}\left[\mathbf{z} - H_x \hat{\mathbf{x}}\right]^T W \left[\mathbf{z} - H_x \hat{\mathbf{x}}\right] \tag{2}$$

in which $\hat{\mathbf{x}}$ is the optimal estimate of the unknown parameter vector $\mathbf{x}$ and W is taken to be a symmetric, positive definite weighting matrix. The case in which $W = \Gamma_n^{-1}$, where Γ_n is the covariance matrix associated with data noise vector n, the estimate $\hat{\mathbf{x}}$ that minimizes Q is the unbiased, minimum-variance estimate of $\mathbf{x}$, and is given by

$$\hat{\mathbf{x}} = \left[H_x^T \Gamma_n^{-1} H_x\right]^{-1} H_x^T \Gamma_n^{-1} \mathbf{z} \tag{3}$$

A priori statistics and regression equation can be combined to derive a modified form of the weighted least-squares estimator, expressed as

$$\hat{\mathbf{x}} = \left[\tilde{J}_x + H_x^T \Gamma_n^{-1} H_x \right]^{-1} H_x^T \Gamma_n^{-1} \mathbf{z} \tag{4}$$

The term $\tilde{J}_x$ denotes the a priori information array and is usually taken to be equal to inverse of $\hat{\Gamma}_x$, the initial covariance matrix for $\mathbf{x}$.

4. Orbit phase

4.1 Initial Launch phase

This launch phase, the orbit determination operation had been carried out by NASA/JPL navigation team. JAXA orbit determination group received five sets of orbit solutions called ICV (Inter 1 through ICV5 from JPL as scheduled, and made antenna predications, Akatsuki mission ephemeris as well as several information files required for its operation based on those received orbital elements.

Tab. 1 shows an accuracy of JPL orbit determination during its launch phase. ICV1 and ICV2 which contain the state vectors were calculated using only one pass (Goldstone tracking data). Although we planned to use ICV2 for the trim maneuver, a trim maneuver was cancelled because of a great success on the spacecraft orbit insertion by H-IIA rocket.

We have also evaluated an accuracy of the spacecraft orbit solutions after its launch operation. In all cases, data weight of Doppler is 0.5 mm/s, DSN range data is 1m, and Uchinoura (USC) range data is 10m. Estimation parameters include orbital elements, coefficient of solar radiation pressure and USC range bias. Modeling errors of small forces are considered as 5e-12km/s^2 in each direction of XYZ

ID	Time	Used data	Accuracy		Difference from ICV5	
			Position (km)	Velocity (km/s)	Position (km)	Velocity (km/s)
ICV1	L+5.5h	5/21 GDS	63.3	1.4e-3	36.6	9.7e-5
ICV2	L+6.5h	5/21 GDS	29.8	6.0e-4	18.5	9.2e-5
ICV3	L+8.5h	5/21 GDS,CAN	0.07	4.4e-6	1.7	9.7e-6
ICV4	L+1day	5/22	0.11	1.2e-6	1.5	8.2e-6
ICV5	L+3day	5/22	0.15	7.5e-7	-	-

Table 1. Accuracy of JPL orbit solution

4.2 Midcourse cruising phase

From the interplanetary cruising phase until Venus closest approach phase, we carried out the orbit determination to supported by NASA/JPL navigation team from NASA/DSN tracking data. And we start to the orbit determination based on USUDA tracking data and DSN tracking data May 27, 2010. After this time, it was provided the orbit solution to Akatsuki mission side and the antenna prediction data was provided to USUDA and USC stations of JAXA.

Fig. 2. and 3 are shown the difference position and velocity comparison JPL's orbit solution with JAXA's solution each other .

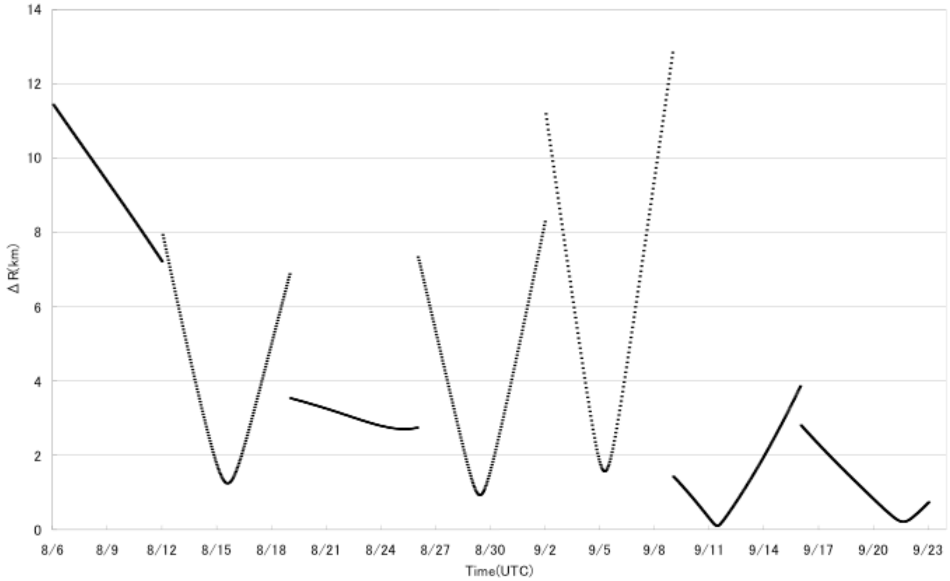


Figure 2. The difference in position at midcourse navigation

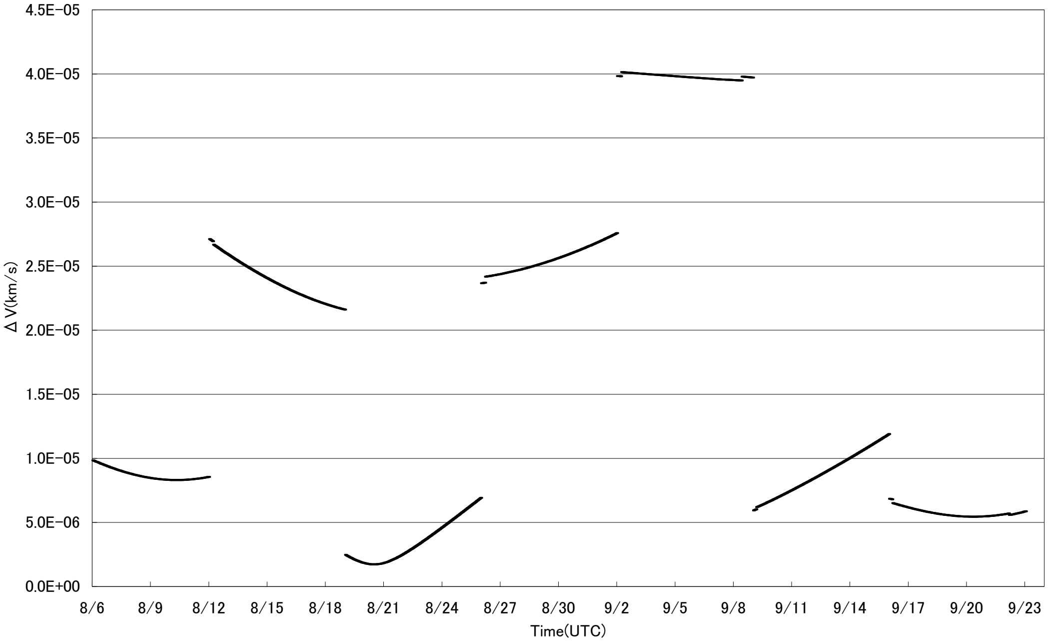


Figure 2. The difference in velocity at midcourse navigation

The results of the difference is within a few ten km in position and a few cm/s in velocity.

4.3 VOI phase

Navigation and guidance control was operated by using three times targeting maneuvers: TRM-1 (Trajectory correction maneuver-1) , TRM-2, and TRM-3. It is described the result of B-plane error ellipse after TRM-3:final maneuver.

B-plane definition

The purpose of developing an error budget is to determine the contribution of individual error sources, or groups of error sources, to the total navigational uncertainty. In general, an error budget is a catalog of the contributions of the error sources which contribute to errors in the Weighted least square filter estimate at a particular point in time, whether explicitly modeled in the filter or not. For the first analysis, it is assumed that filter is optimal, that estimator model is an accurate representation of the physical world.

In order to establish an error budget, it is necessary to compute a time history of the filter gain matrix for the complete filter and to subsequently use these gains in the sensitivity calculations during repeated filter evaluation mode runs, in which only selected error sources or groups of error sources are ‘turned on’ in each particular run. In this way, the individual contributions of each error sources or group of error sources to the total statistics uncertainty obtained for all of the filter parameters for given radiometric data set can be established.

Using the tracking data schedule and the filter model derived for Venus mission scenario, orbit estimation error statistics were computed for the range and Doppler data. The orbit estimation were propagated to the nominal time of Venus encounter and expressed as dispersions in a Venus centered aiming plane, or B-plane, coordinate system; specifically, the one-sigma magnitude uncertainty of the miss vector, resolved into respective miss components B・T (parallel to planetary equatorial plane) and B・R (normal to planetary equatorial plane.

The orbit solution provided before VOI dated December 4,2010 (ID: 48I2) by JAXA orbit determination team. And the reconstruction orbit result receive from JPL navigation team dated December 5, 2010 (ID:48J3). These results is shown Fig. 4.

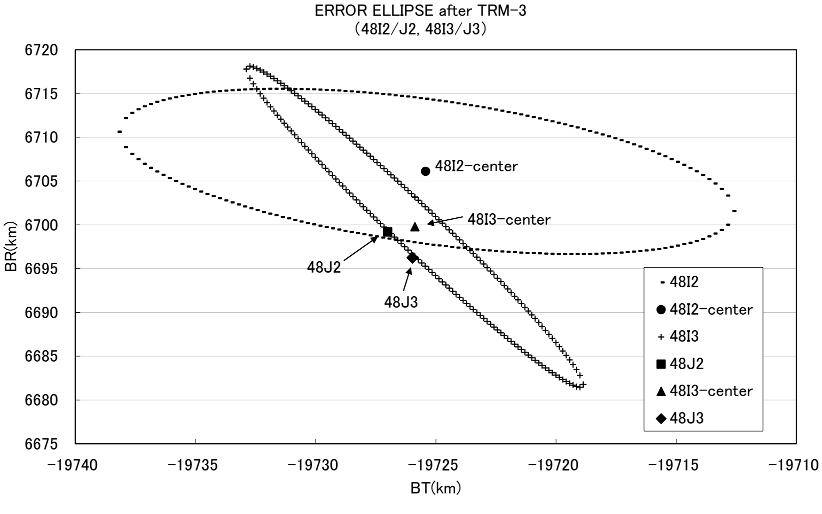


Figure 4. The error ellipse on B-plane

Figure 4. is shown after TRM-3 which means the final maneuver before VOI time.

It was evaluated that there is JPL's solution within JAXA's error budget. And Figure 5. is shown the height from Venus at closest approach time.

Figure 11. The error ellipse on B-plane

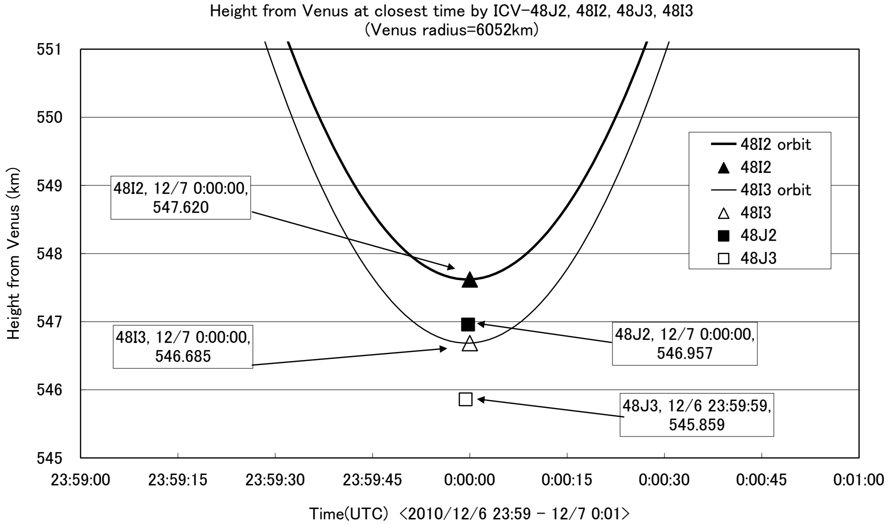


Figure 5. The error ellipse on B-plane

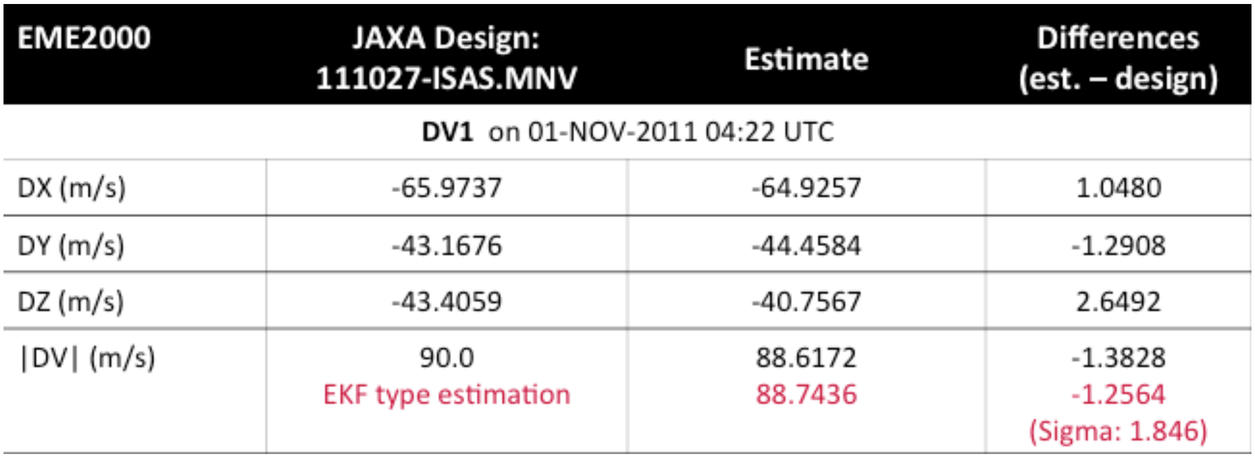
5. Results of orbital maneuver after Venus fly-by

Table 2. and 3. is shown the first time to three times of the orbital maneuver. So, call "DV#1" The difference values compare with JPL's result described in Tab.2

Table 2. Difference between JPL's and JAXA's solutions

Sun Centered EME2000	JAXA 111104-ISAS.ICV	JPL	Differences
Epoch: 03-NOV-2011 08:00 UTC			
X (km)	6.464934e+07	6.464936e+07	-1.99e+01
Y (km)	-5.738848e+07	-5.7388482e+07	2.17e+00
Z (km)	-3.004531e+07	-3.0045324e+07	1.07e+01
DX (km/s)	2.770850e+01	2.7708497e+01	1.68e-06
DY (km/s)	2.665304e+01	2.6653212e+01	-1.67e-04
DZ (km/s)	1.013544e+01	1.0135099e+01	3.41e-04
Position (km)			2.27e+01
Velocity (km/s)			3.80e-04

Table 3. The maneuver estimation



EME2000	JAXA Design: 111027-ISAS.MNV	Estimate	Differences (est. – design)
	DV1 on 01-NOV-2011 04:22 UTC		
DX (m/s)	-65.9737	-64.9257	1.0480
DY (m/s)	-43.1676	-44.4584	-1.2908
DZ (m/s)	-43.4059	-40.7567	2.6492
|DV| (m/s)	90.0 EKF type estimation	88.6172 88.7436	-1.3828 -1.2564 (Sigma: 1.846)

The maneuver estimation presented in Tab.3. This estimation result is calculated by two type method. One is shown by the difference of a priori minus posteriori and another is the result of estimation based on the method of Extended Kalman Filter type.

These results are very well in agreement.

5. Summary and Remarks.

This paper will describe a discussion of the orbit determination results at each orbit phase. And also, it is described the maneuver estimation evaluation. These solutions and estimation results are consistent. We are plan to try experiment additional Delta-DOR (Differenced One-way Range) observation data to Orbit estimation from Japanese and DSN tracking station in the near future. Furthermore, we study the highly precise estimator based on recursive type filter.

6. References

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