An Orbit Plan toward AKATSUKI Venus Reencounter

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Abstract

In December, 2010, we failed to inject "AKATSUKI" (Japanese Venus Explorer) into a Venus orbit. In this talk, we present an orbit plan toward AKATSUKI Venus Reencounter.

「あかつき」の金星再会合軌道計画

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摘要

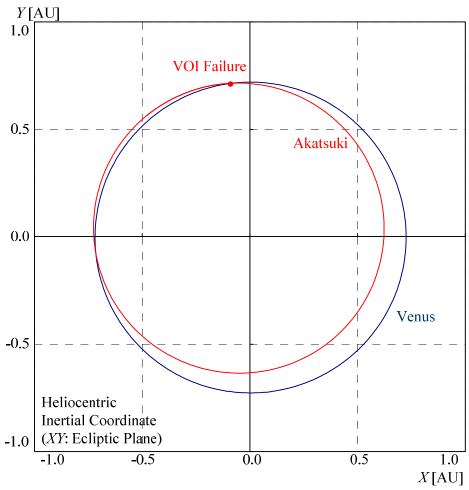
2010 年 12 月、金星周回軌道投入に失敗した「あかつき」について、その金星再会合までの軌道計画の検討結果を報告する。

1. Introduction

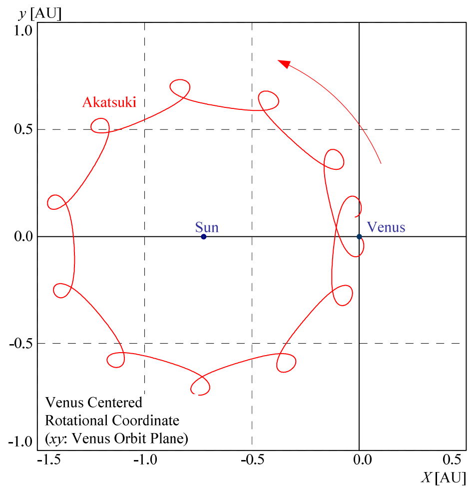
AKATSUKI, the Japanese Venus explorer, was successfully launched in May, 2010 to investigate the climate and the atmospheric phenomena of Venus. After favorable 200-day interplanetary journey, AKATSUKI arrived at Venus on December 7, 2010. At the arrival, a deceleration maneuver was performed to inject AKATSUKI into the Venus orbit. However, due to a malfunc-tion of the propulsion system, the maneuver was interrupted and AKATSUKI again escaped out from Venus into an interplanetary orbit.

As is shown in Fig. 1(a), AKATSUKI orbits around the Sun slightly inside the orbit of Venus. The perihelion radius is approximately 0.62, which imposes on AKATSUKI 40% stronger solar intensity than that expected on the Venus orbit. The mean motion of AKATSUKI is slightly faster than that of Venus, and AKATSUKI go away from Venus to the leading side. When it is viewed on the Sun – Venus line fixed rotational frame, AKATSUKI revolves around the Sun in counterclockwise direction, and finally catch up with Venus some time later (Fig. 1 (b)). The orbit period of AKATSUKI was 203 days, which is in the ratio of 10:11 with that of Venus. If any orbit maneuver is not performed, AKATSUKI will re-approach the Venus in the end of 2016 (Fig. 1 (c)).

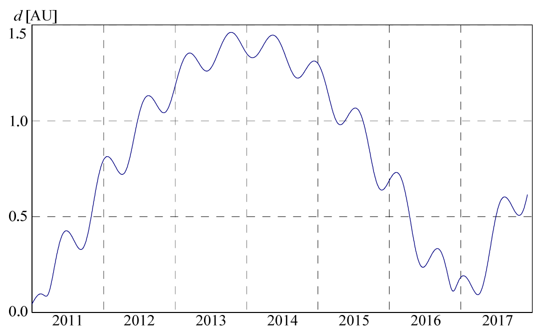
The telemetry data from AKATSUKI around and after



(a) Heliocentric Inertial Frame.



(b) Venus Centered Rotational Frame.



(c) Profile of the distance from Venus.

Fig. 1. Orbit of AKATSUKI after the Venus Orbit Injection Failure.

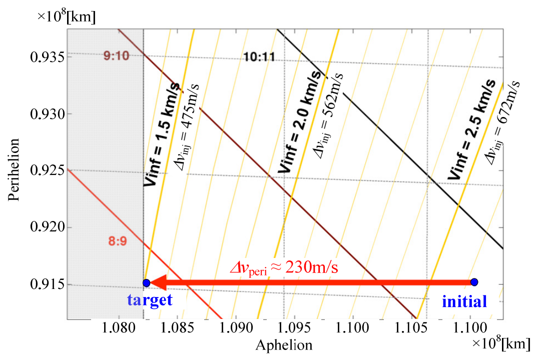


Fig. 2. Preliminary Analysis on Reencounter Strategy.

the injection failure suggested the possibility to perform orbit maneuvers to reencounter Venus and retry the Venus orbit injection (VOI). The bipropellant orbit maneuver engine (OME) showed the thrust 75% of its full performance at the end of the injection maneuver. The monopropellant reaction control system (RCS) is healthy and it can be used for the attitude control during the OME firing as well as limited orbit maneuvers. The propellant spent so far was less than 20% of initial amount on board, and most of it still remained. Under this situation, an orbit plan was investigated for AKATSUKI's Venus reencounter (VRE) and VOI, which is the main theme of this paper.

The following sections are composed in the way that the actual investigation and operation progressed. First, an orbit to reencounter Venus was planned under the assumption that OME is available. An orbit maneuver plan was mapped out to achieve the injection into the originally planned Venus orbit. According to the plan, orbit maneuvers were performed in autumn 2011 around the second perihelion passage after the VOI failure.

2. An Orbit Plan toward Venus Reencounter

Though the attempt of VOI was failed, the state of AKATSUKI seems well except for its OME. Besides, OME showed the thrust 75% of its full performance at the end of the injection maneuver, and 80% of propellant remained on board. These facts suggested the possibility to perform orbit maneuvers to reencounter Venus and retry VOI.

Under this situation, the study was started on orbit plans toward VRE and VOI. The study was conducted step by step, which is introduced in this section. First, the chart so called "pericenter – apocenter graph" is used to establish basic strategy toward VRE. The use of 8:9 Venus resonant orbit was resolved, which moved forward the date of VRE (T_{VRE}) to November, 2015 without any increase of necessary velocity increment (Δv). The new T_{VRE} is about one year earlier than that expected from free orbit propagation. Then, concrete orbit maneuver sequence was studied using two body model. A number of orbit transfer types and sets of parameters were investigated, and evaluated from the point of necessary Δv and other practical factors. As a result, a perihelion maneuver (PHM) is scheduled in autumn 2011, around the second perihelion passage after the VOI failure, to reencounter the Venus. Finally, the sequence is brushed up using full model. The result obtained in the two body model worked well as an initial estimate, however, slight shift of the schedule and slight reduction of necessary Δv was resulted from the detailed study. Details of these topics are introduced in the following sub-sections.

2.1 Preliminary analysis on reencounter strategy

Preliminary analysis is performed using the chart so called "pericenter – apocenter graph" (Fig. 2). The initial orbit of AKATSUKI (a set of aphelion/perihelion radiuses) after the VOI failure is shown as the mark labeled "initial" at the right-bottom corner of the chart. The contours of excessive velocity (v_∞) at VRE indicate that v_∞ (or injection Δv (Δv_{inj})) decreases as the aphelion radius of the transfer orbit decreases. It means that, even if a deceleration maneuver at perihelion costs 230m/s to decrease the aphelion radius to be tangent to the orbit of Venus (to the mark labeled "target" at the left-bottom corner), it is paid back by the decrease of Δv_{inj} of the same amount. Though the total amount of Δv (Δv_{tot}) required for the "target" orbit is almost the same as that of the "initial" orbit, there are two obvious merits in the target orbit. First, Δv required for VOI, which is the most critical operation, is smaller than that of the initial orbit. To clarify the second merit, we have to remark that the target orbit has 8:9 resonance with Venus. That is, if AKATSUKI is injected into the target orbit immediately, it will reencounter Venus eight Venus years after the VOI failure. T_{VRE} in this case is November, 2015, which is about one year earlier than that expected from free orbit propagation. As a result, the use of 8:9 VSO was decided, which moved forward the VRE to November, 2015 without any increase of necessary velocity increment (Δv).

2.2 Sequence design under two body model

The analysis in the previous sub-section provides useful insight to the characteristics of the problem. However, in order to construct a concrete orbit maneuver sequence, a sort of orbit design is necessary. Then, a two impulse transfer in a two body model, that is, a Lambert problem is used as the first step of the sequence design. Though it is a simple ballistic orbit design problem, the transfer assumes multiple revolutions around the Sun, and the problem has a number of local minimums. It is important to understand the structure of the solution space, and find a good initial guess of the solution prior to seeking accurate solutions by numerical methods. To this objective, theoretically established two body model is more advantageous than full model introduced in the next sub-section.

The result of the analysis in the previous sub-section defines a couple of orbit design conditions. First, as a result of adopting 8:9 VSO, T_{VRE} is set around November, 2015. Second, the transition from the initial orbit to the

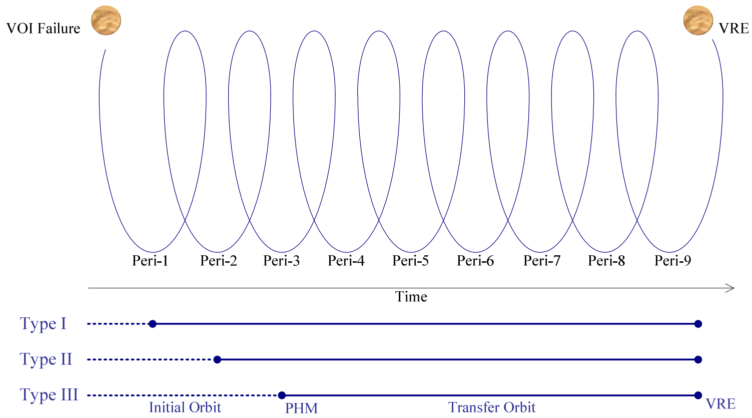


Fig. 3. Schematics of Transfer Types.

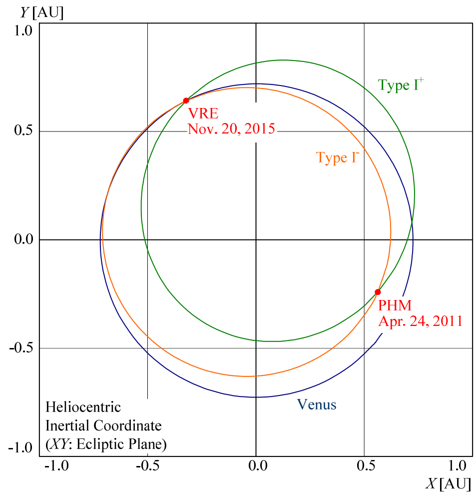


Fig. 4. Two Solutions of Lambert Problem.

transfer orbit is achieved by PHM in order to lower the aphelion of the orbit. Accordingly, the chance of the first maneuver is limited to the date around perihelion passages. Additionally, an immediate transition to transfer orbit is necessary to achieve 8:9 VSO with small Δv. It requires the first maneuver to be performed in the early phase of the transfer. Based on these conditions, three types of transfer sequence, Type I to III, are defined in this study (Fig. 3). They are typified by the range of PHM date (T_{PHM}), the range of T_{VRE}, and the number of revolutions from PHM to VRE (n_{rev}). For example, a transfer sequence in Type I has T_{PHM} around the first perihelion passage (i.e. April, 2011), T_{VRE} around November, 2012, and n_{rev} of eight.

Even if the three design parameters (T_{PHM}, T_{VRE}, n_{rev}) are assigned, a multi revolution Lambert problem still has two solutions.1 Both solutions comply with the three parameters, however, they have different semi-major axes (a). Fig. 4 shows an example of the two solutions for the same parameters. The parameters are chosen from the range of the Type I (T_{PHM} = April 24, 2011, T_{VRE} = Nov. 20, 2015, n_{rev} = 8). Though the two orbits (orange and green) have the same T_{PHM}, T_{VRE}, and n_{rev}, the shape of the orbits are quite different. Hereafter, these two sub-types of the orbit are distinguished by superscripts '+' (for larger a) and '-' (for smaller a) such as Type I$^+$ and Type I$^-$.

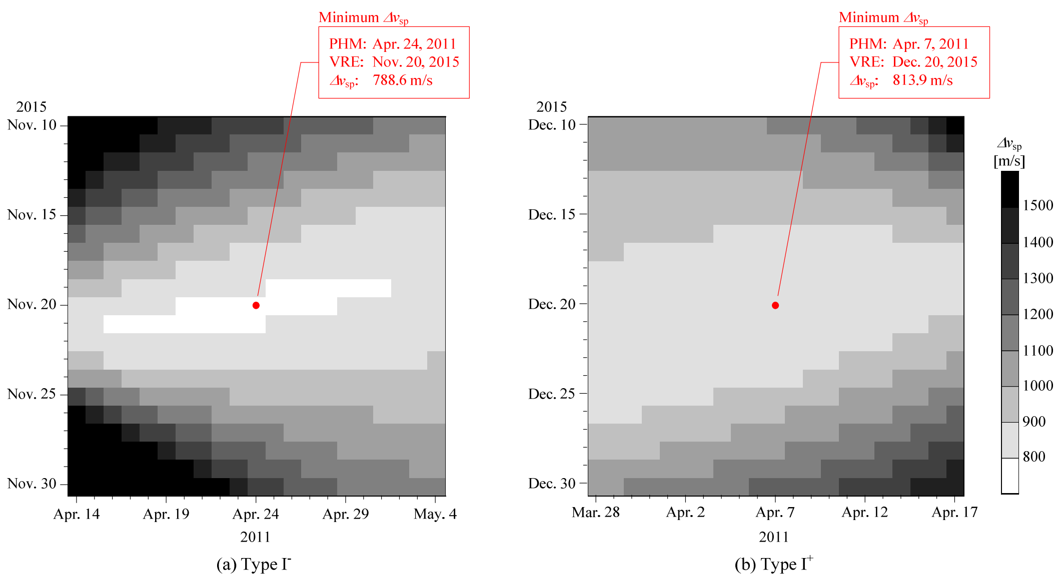


Fig. 5. Δv Level Sets of Two Lambert Solution Types.

Table 1. Minimum Δv Solutions under Two Body Model.

Type	PHM		VRE		Δv_{sp}
	date	Δv_{peri}	date	Δv_{inj} (*)	
I^-	Apr. 24, 2011	230.7m/s	Nov. 20, 2015	557.9m/s	788.6m/s
I^+	Apr. 7, 2011	262.0m/s	Dec. 20, 2015	551.9m/s	813.9m/s
II^-	Nov. 12, 2011	269.1m/s	Nov. 24, 2015	523.1m/s	792.2m/s
II^+	Oct. 27, 2011	290.4m/s	Dec. 17, 2015	522.9m/s	813.3m/s
III^-	Jun. 10, 2012	320.7m/s	Nov. 30, 2015	489.3m/s	810.0m/s
III^+	May 15, 2012	322.8m/s	Dec. 12, 2015	492.7m/s	815.5m/s

(*) Venus Reencounter Δv assumes injection into 30h orbit.

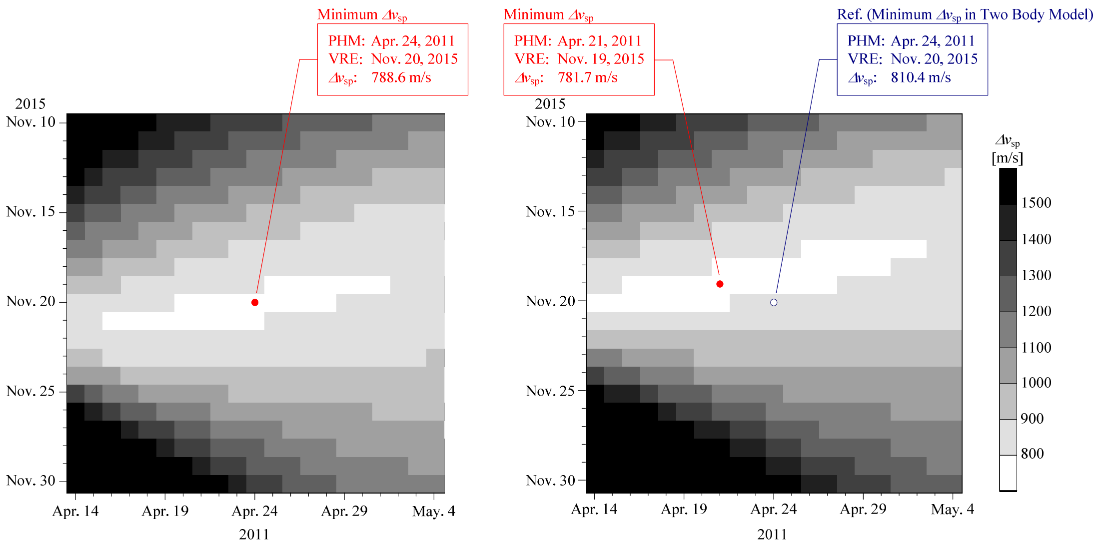
Fig. 5 shows Δv_{tot} level sets with respect to T_{PHM} and T_{VRE} of Type I^+ and Type I^-. They are produced independently (since the formulation of Lambert's problem is different), and the ranges around their respective local minimum are focused. Though the both types have their local minimum in the range of Type I (i.e. T_{PHM} around April, 2011, and T_{VRE} around November 2015), they are apparently independent. Considering that they have close value of Δv_{tot} (788.6m/s and 813.9m/s respectively), the two minimums have to be found out and evaluated in the detailed design as well.

Two impulse transfer orbits are constructed for all the combination of T_{PHM} and T_{VRE} in each type. Δv_{tot} is evaluated for each case and the local minimum of Δv_{tot} is specified for each type. The list of local minimums is shown in Table 1. First observation is that, for all types (Type I to III), the minimum of sub-type '-' provides smaller Δv_{tot} compared with sub-type '+'. Hence, within a type in this range, the adoption of sub-type '-' looks better (The superiority of sub-type '-' is reconfirmed in the following detailed analysis). Then, in the comparison between Type I^- to III^-, the type with earlier T_{PHM} (Type I^-) provides smaller Δv_{tot} compared with later T_{PHM} (Type III^-). This tendency complies with our prospect that the earlier transition to transfer orbit will save Δv to achieve 8:9 VSO. However, we paid attention to the fact that the difference of Δv_{tot} between Type I^- and II^- is so small that we can take other aspects into account to decide the baseline sequence. In actual, the schedule of OME ground tests (to find out the operation condition under malfunction) is so tight to perform the first maneuver at the first perihelion passage (April, 2011). As a result, a perihelion maneuver (PHM) is scheduled in autumn 2011, around the second perihelion passage after the VOI failure, to reencounter the Venus.

2.3 Trajectory design under multi body model

Finally, the sequence is brushed up using full model. In contrast with the two body model, there is no difference between types or sub-types in the formulation of full model analysis. From this point, to provide a good initial guess is necessary to obtain the solution in mind. The result obtained by two body model is used for this objective. That is, for each set of T_{PHM} and T_{VRE}, Δv_{PHM} obtained in the two body model is used as the initial guess to find out the solution of the type in intention. This procedure works well, and all the local minimums are successfully found in the full model as well.

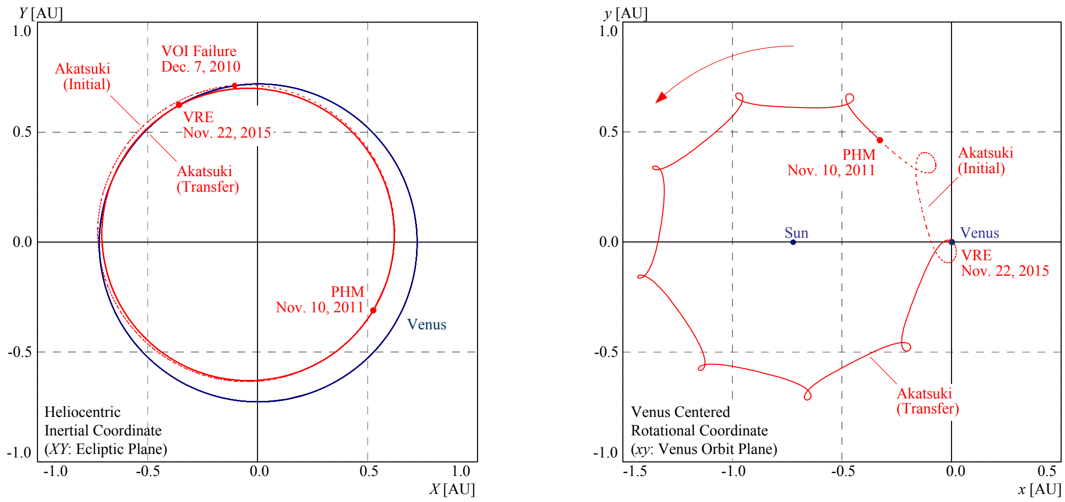
Fig. 6 shows Δv_{tot} level sets with respect to T_{PHM} and T_{VRE} of Type I^-, constructed by two body model and full model respectively. Obviously, the solution space holds its basic structure which means that the Type I^- solutions are successfully found in the full model as well. The local minimum in the full model is provided by the set of T_{PHM} and T_{VRE} in the neighbor of the set provides the minimum in the two body model. This fact suggests that even if we use the convergence process to find the local minimum in the full model, the results obtained in the two body model provide good initial guess of the set of T_{PHM} and T_{VRE}. On the other hand, Δv_{tot} for the same set of T_{PHM} and T_{VRE} differs seriously between the two body model and the full model. For example, Δv_{tot} for T_{PHM} = Apr. 24, 2011, T_{VRE} = Nov. 20, 2015 are 788.6m/s and



(a) Two Body Model

(b) Multi Body Model+

Fig. 6. Δv Level Sets under Two Body / Multi Body Model (Type I^-)



(a) Heliocentric Inertial Frame.

(b) Venus Centered Rotational Frame.

Fig. 7. An Orbit Plan of AKATSUKI towardVenus Reencounter

810.4m/s in the two models respectively. This fact suggests that the set of T_{PHM} and T_{VRE} which provides the minimum Δv_{tot} in the two body model cannot be used directly as the set to provide the minimum Δv_{tot} in the full model.

Two impulse transfer orbits are constructed under full model for all the combination of T_{PHM} and T_{VRE} in each type. Δv_{tot} is evaluated for each case and the local minimum of Δv_{tot} is specified for each type. The list of local minimums is shown in Table 2. When the list is compared by type by type with that made under two body model (Table 1), slight shift of the schedule and slight change of Δv_{tot} are observed. However, the basic characteristics derived under the two body model still holds in the results obtained in the full model. That is, the minimum of sub-type '-' provides smaller Δv_{tot} compared with sub-type '+', and Type I^- and II^- provides smaller Δv_{tot} compared with Type III^-. Considering the practical aspects mentioned in the previous sub-section, the local minimum of Type II^- transfer sequence is selected as the baseline trajectory sequence.

The orbit profile of the baseline sequence is shown in Fig. 7. The initial orbit is drawn in dashed line whereas transfer orbit after PHM is drawn in solid line. The orbit profile drawn on the inertial frame (Fig. 7 (a)) shows that PHM lowers the aphelion of the orbit so that the transfer orbit tangent with the Venus orbit nearby its aphelion. Hence VRE occurs around the aphelion of the orbit. In the orbit profile drawn on the rotational frame (Fig. 7 (b)), there are a number of small circles along the path. They comply with the aphelion passages of AKATSUKI. If the figure is carefully compared with Fig. 1 (b), it is found that the number of aphelion passage by VRE reduced to nine (from eleven), and the stroke between the circles slightly gets longer due to the increase of relative orbit velocity of AKATSUKI.

Table 2. Minimum Δv Solutions under Multi Body Model.

Type	PHM		VRE		Δv_{sp}
	date	Δv_{peri}	date	Δv_{inj} (*)	
I^-	Apr. 21, 2011	226.5m/s	Nov. 19, 2015	555.2m/s	781.7m/s
I^+	Apr. 6, 2011	251.3m/s	Dec. 19, 2015	554.1m/s	805.4m/s
II^-	Nov. 10, 2011	261.4m/s	Nov. 22, 2015	522.0m/s	783.4m/s
II^+	Oct. 21, 2011	283.4m/s	Dec. 17, 2015	529.9m/s	813.3m/s
III^-	Jun. 6, 2012	314.1m/s	Nov. 28, 2015	481.0m/s	795.0m/s
III^+	May 17, 2012	319.2m/s	Dec. 9, 2015	484.5m/s	803.6m/s

(*) Venus Reencounter Δv assumes injection into 30h orbit.

5. Conclusion

Discussed in this paper is an orbit plan toward AKATSUKI's Venus reencounter and orbit injection. The construction process of the baseline sequence toward the Venus reencounter is introduced in detail.