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A Quasi-Kinematic Orbit Determination Method for Deep Space Probes

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This research proposes a novel orbit determination method for deep space probes by the use of simultaneous two-dimensional Delta-DOR measurements and 2-way ranging measurements. Conventionally, Doppler and ranging measurements are mainly used for the orbit determination of deep space probes. Because the angular position in the plane of sky is determined through diurnal variation of Doppler data by the rotation of the earth in the method, at least a few days of the observation arc is required for the orbit determination. Since the imperfectness of non-gravitational acceleration model of probes strongly couples with the diurnal variation of the line of sight velocity component of probes, Doppler-based orbit determination method cannot provide precise solutions for the probes for which contribution of non-gravitational perturbative forces is dominant (e.g., ion propulsion spacecraft or solar sails). Delta Differential One-Way Ranging (Delta-DOR), derived from Very Long Baseline Interferometry (VLBI), is a technique which can change the situation. Since a VLBI measurement determines the geometric time delay between received radio signals at two geographically separated stations, the Delta-DOR data provide a direct measurement of the spacecraft angular position relative to the baseline vector joining the two radio antennas. While measurements from two orthogonal baselines are required to determine both components of angular position (i.e., declination and right ascension) simultaneously, all existing space agencies do not have enough station complexes to provide two orthogonal baselines simultaneously. Now that JAXA's Delta-DOR observation system is operationally available for the joint observations with other agencies, simultaneous two-dimensional Delta-DOR measurements become possible. If two dimensional Delta-DOR and a 2-way ranging measurement are performed during a short period of time, three dimensional position of probes can be almost kinematically determined without assuming any non-gravitational acceleration models and without using Doppler data. We had applied this method to the navigation of the Hayabusa-2 spacecraft during ion-engine thrusting period in February 2017, and successfully got precise OD (orbit determination) solutions without turning off the ion engine. We describe detailed results and conditions of this operation.

Key Words: Delta-DOR, deep space navigation, orbit determination, electric propulsion

1. Introduction

Conventionally, Doppler and ranging measurement data are used as fundamental observables for the orbit determination of deep space probes. Because spacecraft's angular position in the plane of sky (i.e., declination and right ascension) is determined through diurnal variation of Doppler data by the rotation of the earth in the conventional method,[1] at least a few days of the observation arc (i.e., coasting period) is required for the orbit determination as shown in the Figure 1. Since the imperfectness of non-gravitational acceleration model of probes strongly couples with the diurnal variation of the line of sight velocity component of probes, Doppler-based OD method cannot provide precise solutions for the probes for which contribution of non-gravitational perturbative forces is dominant (e.g., ion propulsion spacecraft or solar sails). For the precise orbit determination of the probes which has ion engine like JAXA's Hayabusa-2, it was common to turn off the ion engine to allocate a coasting arc for the orbit determination for at least a few days. This requirement has been a constraint for optimal design of the ion engine cruising plan.

Delta-DOR is a technique which can change the situation because Delta-DOR data provide a direct measurement of the spacecraft angular position relative to the baseline vector joining the two radio antennas. While measurements from two orthogonal baselines are required to determine both components of angular position (i.e., declination and right ascension) simultaneously, all existing space agencies do not have enough station complexes to provide two orthogonal baselines simultaneously. Now that JAXA's Delta-DOR observation system, which had been developed since 2006,[2] is operationally available for the joint observations with other agencies,[3] simultaneous two-dimensional Delta-DOR measurements become possible. If two dimensional Delta-DOR and a 2-way ranging measurement are performed during a short period of time, three dimensional position of probes can be almost kinematically determined without assuming any non-gravitational acceleration models and without using Doppler data, because the variation of velocity due to the un-modeled acceleration during the observation period is small enough and negligible because the observation arc can be very short compared to the Doppler-based conventional method.

This method brings great benefits to the trajectory design of the low-thrust missions because long continuous thrusting arc can be assumed without interruption periods for coasting arcs for orbit determination. While Delta-DOR measurement has been useful tool for low thrust deep space missions, like NASA's Dawn mission, because the duration of coasting arc can be set short enough, such measurements had always been performed during turn-off period of the electric thrusters.

This paper describes some technical topics which should be considered to perform Delta-DOR measurements under poor accuracy of a priori trajectory information due to inaccurate ion engine thrusting modeling, a world's first result of the Delta-DOR based orbit determination without stopping ion-engine thrusting performed for the Hayabusa-2 spacecraft in February 2017, and discuss how this method will contribute to the asteroid approach phase of the Hayabusa-2 in 2018.

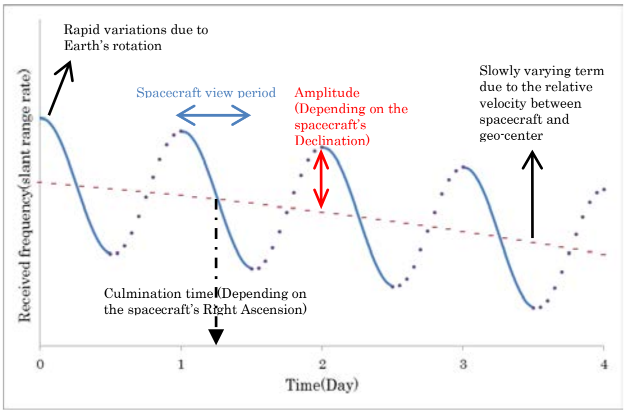


Fig. 1. Schematic illustration which shows the idealized Doppler observable and how to measure the Right Ascension and Declination of the spacecraft from its diurnal variations. This figure is based on the figure in Ref. 1).

2. Conventional navigation scheme during continuous ion thrust phase

As mentioned above, navigation of low thrust spacecraft has been generally performed based on the orbit determination solutions during coasting periods. Because this is a strong constraint for trajectory design of low thrust spacecraft, JAXA had investigated and established an operational OD and navigation scheme during continuous ion thrusting phase.[4,5] In this scheme, three dimensional thrust vector represented in the ion-engine-gimbal-fixed coordinate is calculated from the electrical current and voltage log for each ion thruster and it is averaged over 1024 seconds in the spacecraft's on-board computer. This information is always downlinked to ground station with spacecraft's attitude data and ion engine gimbal angle data during ion thrusting phase. The thrust vector is transformed to the inertial frame and used for orbit determination as initial values of three dimensional acceleration for each 1024-second period. Each 1024-second period is grouped into a few hours to 24 hours of segments

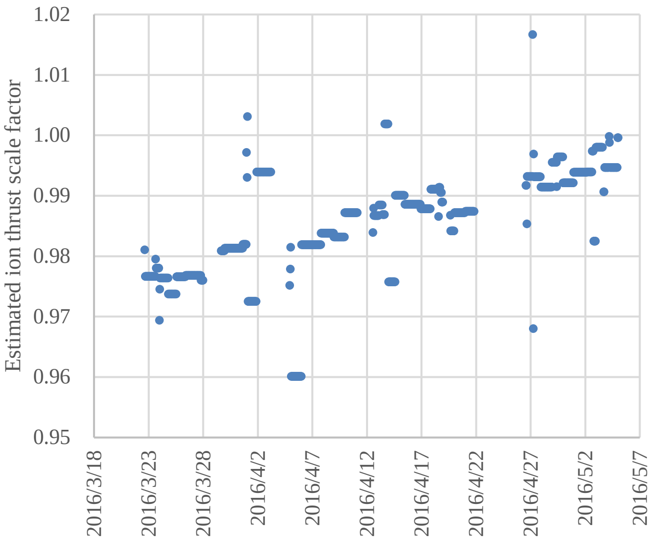


Fig. 2. Time series of the estimated ion thrust scale factor for the Hayabusa-2 during an ion engine operation period between March 22 and May 5, 2016.

(duration of a segment is depending on the operation details), and a scale factor is estimated for each segment in the orbit determination process as shown in the Figure 2. Orbit determination is performed once a week and the spacecraft state at the OD epoch is compared with a reference trajectory. The measured difference from the reference trajectory is fed back to the ion engine thrusting plan for the next one week so that the trajectory difference can be canceled and it can be back to align with the reference trajectory. We evaluate that each component of the thrust vector can be almost correctly estimated but the model error is gradually accumulated as continuous thrusting period becomes longer. Figure 3 shows overlap comparison of position and velocity between two consecutive OD solutions at a common epoch for both solutions. It is clearly shown that inconsistencies between two solutions were gradually accumulated and got bigger after a continuous ion engine operation period started on Nov. 22, 2016.

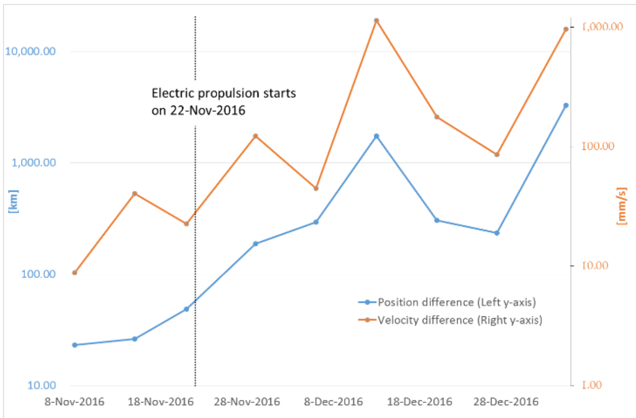


Fig. 3. Overlap comparison of position and velocity between an operational weekly OD solution and the OD solution calculated one week before. Note that no Delta-DOR passes were assigned during this period.

3. Pre-analysis for quasi-kinematic orbit determination method to be performed during a continuous ion thrust phase of the Hayabusa-2

Because the conventional orbit determination scheme during continuous ion thrust phase is exceedingly rely on the telemetry information about ion engine operation, it can be classified as a 'strongly model dependent method'. While it needs at least a few days of observation period because the plane of sky components of the spacecraft position are determined from 2-way Doppler observables, ion engine thrust model error is accumulated and get bigger as observation period becomes longer. In order to solve this drawback of the method, we introduce a quasi-kinematic orbit determination method in which two orthogonal baselines of Delta-DOR measurements and 2-way Ranging measurements are carried out within a short period of time (typically about 1-hour). Because the velocity change of the spacecraft due to the ion thrust is very small in this short period of time, uncertainty of the ion engine thrust model can be ignored in this method. This is quantitatively shown by a covariance analysis in next sub section.

3.1. Covariance analysis simulation for tracking pass assignment

In order to assign tracking passes during a continuous ion thrust phase of the Hayabusa-2 in early 2017 for a demonstration of this new orbit determination method, a covariance analysis simulation was performed based on the assumptions shown in Table 1. The empirical level of uncertainty of the ion thrust acceleration, which is assumed to be 1.5 % of total acceleration, is considered instead of estimating it in this analysis. Several observation scenarios are assumed in Table2 for the types of tracking data and number of passes for an OD solution, and achievable OD accuracy of each scenario is summarized in Table 3. The observation scenario 1 is based on the conventional OD scheme described in the Section 2. Due to an ion thruster model error assumed, achievable position accuracy is only 878km if a 1-week arc of conventional Doppler & ranging based orbit determination is performed. On the other hand, if new method is applied during this period (observation scenario 2), achievable position accuracy is significantly improved to 350m with only 1 hour of ranging measurement and two-dimensional simultaneous Delta-DOR measurements. While a significant improvement can be expected for position accuracy in this scenario, velocity accuracy is not so significant because velocity components are measured from variations of Ranging and Delta-DOR observables in a short period of time in this scenario. While this level of accuracy is generally enough for the ion engine thrust planning for the following weeks, much better velocity accuracy may be needed in certain phases such as in final approaching phase to the target asteroid. In observation scenario 3, the quasi-kinematic method is used in two consecutive days and short periods of 2-way Doppler observables, which are simultaneously acquired with 2-way Ranging observables, are also used in order to improve the accuracy of velocity components. As shown in the Table 3, while positon accuracy is slightly degraded, an improved accuracy can be expected for velocity components in this

Table 1. Covariance analysis assumptions during continuous ion engine operation for the Hayabusa-2

Error source	Estimate / Consider	A priori uncertainty (1σ)	Comments
Range bias at Usuda	Est.	15m	Per pass
Unmodeled solar radiation pressure	Est.	1.5%	Cannonball model
Unmodeled low thrust acceleration	Con.	1.3e-10km/s^2 (per axis)	0.5% of ion thruster acceleration
Spacecraft epoch state	Est.	Position: 1000km Velocity: 5m/s	Per axis

Table 2. Observation scenarios

Data type	Station(s)	Noise level	Sample period	Duration
Observation scenario 1: conventional method				
2-way Doppler	Usuda	1mm/s	60 sec	**7 hour × 1 pass** (1:00 – 8:00 UTC, Feb 28, 2017) **3.5 hours × 4 passes** (1:00 – 4:30 UTC, Mar 1,2,3,& 5, 2017)
2-way Range	Usuda	5m	120 sec	**1 hour × 1 pass** (3:00 – 4:00 UTC, Feb 28, 2017) **0.5 hours × 4 passes** (3:00 – 3:30 UTC, Mar 1,2,3,& 5, 2017)
Observation scenario 2: quasi-kinematic method				
DDOR	Usuda - Goldstone Usuda - Canberra	60ps	15 min	**45 min** (3:30 -4:15 UTC, Mar 2, 2017)
2-way Range	Usuda	5m	120 sec	**15 min** (3:15 - 3:30 UTC, Mar 2, 2017)
Observation scenario 3: extensive quasi-kinematic method				
DDOR	Usuda - Goldstone Usuda - Canberra	60ps	15 min	**45min× 2 passes** (3:30 - 4:15 UTC, Mar 1 & 2, 2017)
2-way Range	Usuda	5m	120 sec	**15min× 2 passes** (3:15 - 3:30 UTC,Mar 1 &2, 2017)
2-way Doppler	Usuda	1mm/s	60 sec	**15min× 2 passes** (3:15 - 3:30 UTC,Mar 1 &2, 2017)

Table 3. Results of the covariance analysis simulations. Solution epoch is 4:00 UTC, Mar 2, 2017 for all scenarios.

Observation scenario	Position error (1σ)	Velocity error (1σ)	Total observation duration
Scenario 1	878.5 km	6.477 m/s	21 hours
Scenario 2	352 m	25.1 cm/s	1 hour
Scenario 3	2.90 km	6.77 cm/s	2 hours

scenario.

4. Observations and results

4.1. Pass assignment

Based on the pre-analysis described in the previous section, totally eight Delta-DOR sessions were requested to JPL for the orbit determination during a continuous ion thrust phase of the Hayabusa-2 in early 2017. Although all of the Delta-DOR sessions were originally intended to have two orthogonal baselines by using Usuda, Goldstone, and Camberra stations simultaneously and also to be performed during turn-on period of the Ion Engines System (IES), these conditions were not satisfied in many sessions due to changes in ion thrusting schedule and several unexpected troubles in either the spacecraft or Usuda station. Observation dates of the performed Delta-DOR passes were summarized in Table 4. All of the Delta-DOR passes in which Usuda was participated were allocated after 15-minutes of 2-way Ranging observations at Usuda.

Table 4. Delta-DOR pass assignments during a continuous ion thrust phase of the Hayabusa-2

Observation time (UTC)	Stations	Comment
3:30 – 4:30 on Jan 25	Usuda, DSS-14, DSS-35	IES on
3:35 – 4:35 on Jan 29	Usuda, DSS-14, DSS-43	IES off
3:35 – 4:35 on Feb 3	DSS-26, DSS-36	IES off, Usuda canceled
3:15 – 4:15 on Feb 5	Usuda, DSS-25, DSS-35	IES off
3:05 – 4:05 on Feb 24	Usuda, DSS-15, DSS-34	IES on
3:05 – 4:05 on Feb 26	DSS-26, DSS-36	IES on, Usuda canceled
3:15 – 4:15 on Feb 28	DSS-14, DSS-34	IES on, Usuda not scheduled
3:35 – 4:35 on Mar 1	Usuda, DSS-15, DSS-35	IES off

4.2. Ambiguity resolution under poor accuracy of a priori trajectory information

In the process of generating Delta-DOR observables from Delta-DOR raw observation data, ambiguities of DOR observables shall be properly resolved at Delta-DOR data correlator center. For the purpose of resolving ambiguity, most of spacecraft transponder has a function to transmit a narrower frequency separation tone pairs in addition to the widest frequency separation tone pairs with which final precision of the observables is determined. As defined in Ref. 6), recommended frequency for the narrower DOR tones which are used for ambiguity resolution, Δf_{min}, is 4 MHz for X-band transponders. This frequency separation is narrow enough for most cases in which accuracy of predict grade trajectory is not so bad. In order to resolve ambiguity of DOR observables in the geometric conditions shown in Fig.4, $\Delta \boldsymbol{r_B}$, that is defined as a priori position accuracy of the spacecraft along with the baseline vector **B** shall be satisfied the following condition:

$$\Delta \boldsymbol{r_B} \ll \frac{\mathrm{cR}}{\Delta f_{min} \mathrm{B}|\sin\theta|} \;, \qquad (1)$$

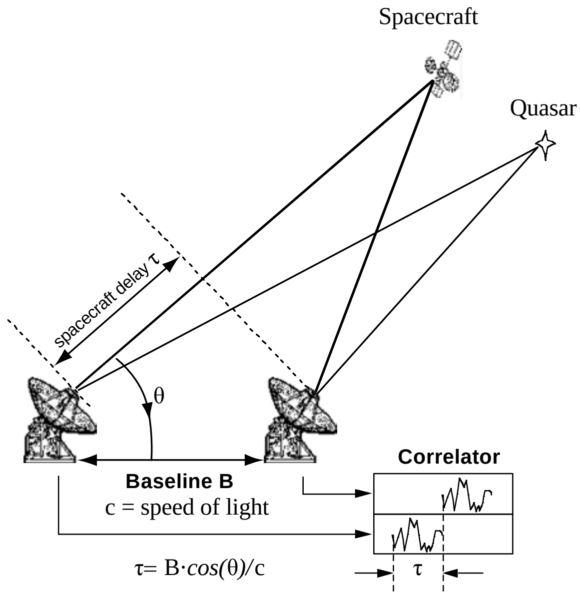


Fig. 4. Delta-DOR Observation Geometry. This figure is from Ref. 7).

where R is distance from a ground station to spacecraft. If the 3.9 MHz of narrower DOR tones of the Hayabusa-2 are used for the ambiguity resolution, it is shown from the equation (1) that less than 1000 km of position accuracy is required for a priori trajectory of the Hayabusa-2 during this period. It is clear from Fig.3 that this requirement is too strict to satisfy during continuous ion thrust phase. Even though accuracy of a priori trajectory can be improved by iteration of OD process in which only Doppler and ranging data are used in the first step if the spacecraft is coasting, the improvement is not enough during continuous ion thrust phase.

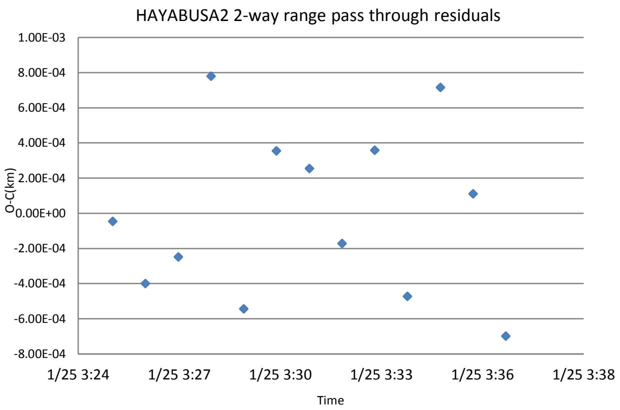
In order to solve this issue short periods of ambiguity resolution scans, in which 2^{nd} harmonics of sub-carrier tones are used instead of DOR tones, were allocated in the beginning and the end of each session in addition to the nominal scans in which DOR tones are used. Subcarrier frequency of the Hayabusa-2 is 262 kHz and a priori position accuracy requirement could be relaxed to 8000 km by the use of 2^{nd} harmonics of sub-carrier tones.

4.3. OD results

As a validation of the observation scenario 2 in Table 2, an OD result with observation data on Jan 25 is evaluated here. Observation data used in the OD is summarized in Table 5 and the pass through O-C residuals are shown in Figure 5. Range bias was not estimated in this OD case but a slightly bigger noise level was set instead. A priori ion thrusting plan was applied to the propagation as constant values and was not estimated in the OD process. Because a few percentage of accuracy can be expected for the ion thrust model, expected variations in position and velocity during this short arc due to uncertainties of the ion thrusting model is well small (e.g., position change is 1.7m & velocity change is 1 mm/s, if assumed model error is 1%) and they can be ignored.

Table 5. Tracking data used for the demonstration of the quasi kinematic orbit determination method (scenario 2).

Data type	Station(s)	Noise level	Duration	Number of data
DDOR	Usuda Goldston Canberra	60ps	3:51-4:17 on Jan 25 (without ambiguity estimation scans)	3 points / baseline
2-way Range	Usuda	30m	3:25-3:36 on Jan 25	13 points



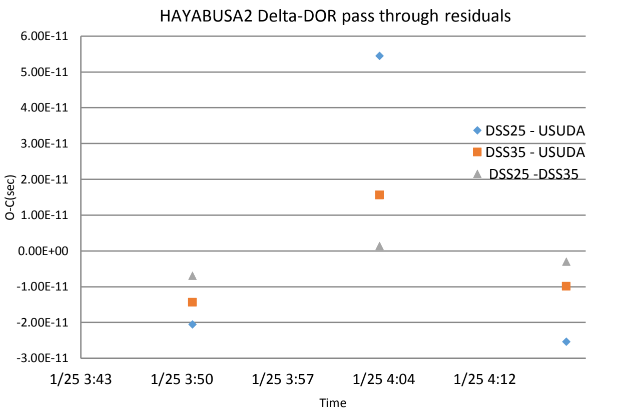


Fig. 5. O-C pass through residuals for the OD solution (quasi-kinematic method).

A posteriori covariance error of this solution is 1.28 km in position and 37.9 cm/s in velocity.

As for the validation of the observation scenario 3 in Table 2, we had expected to use Delta-DOR passes during two consecutive days on Feb 28 and Mar 1, but Usuda couldn't participate in one the sessions and it was impossible to realize the same situation as scenario 3. Instead, we used the Delta-DOR passes on Jan 25 and 29 for the validation of the observation scenario 3. Nominal ion engine thrust plan was used for the initial values and only one scale factor was estimated for the whole ion thrust period between two Delta-DOR passes. No telemetry information regarding the ion thruster log and attitude log was used for this OD solution.

In order to confirm the accuracy of these solutions we generated a reference trajectory with conventional method for which all of tracking data (Ranging, Doppler, DDOR) were used and ion thrust scale factors were estimated as described in section 2. Tracking data used for the reference trajectory was summarized in Table 6. During this period ion engine was unintentionally stopped and relatively long coasting period could be set as shown in the Table 6. Results of the overlap comparison between the reference trajectory and two short arc OD cases are shown in Table 7. The trajectory differences are compatible with a posteriori covariance error of each solutions. This is a remarkable result because almost same OD solutions as reference trajectory were successfully estimated with only 1 hour (scenario 2) or 2 hours (scenario 3) of tracking data without any telemetry information during continuous ion thrust phase by the proposed quasi kinematic OD method. Figure 5 shows overlap comparison of position and velocity between two consecutive weekly OD solutions. Because many

Table 6. Tracking data used for the OD for the reference trajectory.

Periods(UTC)	Observation passes	IES
From: 1:49 on Jan 25 To: 18:04 on Jan 28	Ranging (1 pass, 13 points) Doppler (2 passes, 265 points) DDOR (1pass, 3 points/baseline)	on
From: 18:04 on Jan 28 To: 05:48 on Jan 31	Ranging (2 passes, 43 points) Doppler (2 passes, 324 points) DDOR (1pass, 3 points/baseline)	off
From: 05:48 on Jan 31 To: 08:15 on Feb 1	Doppler (1 pass, 153 points)	on
From: 08:15 on Feb 1 To: 08:16 on Feb 6	Ranging (2 passes, 36 points) Doppler (4 passes, 823 points) DDOR (2passes, 3 points/baseline)	off

Table 7. Overlap comparison between the reference trajectory and quasi-kinematic OD solutions at the epoch 03:00 UTC on Jan 25.

Comparison case	Position difference	Velocity difference
Reference trajectory vs. Scenario 2 case	4.41km	63.5 cm/s
Reference trajectory vs. Scenario 3 case	3.31 km	11..2 cm/s

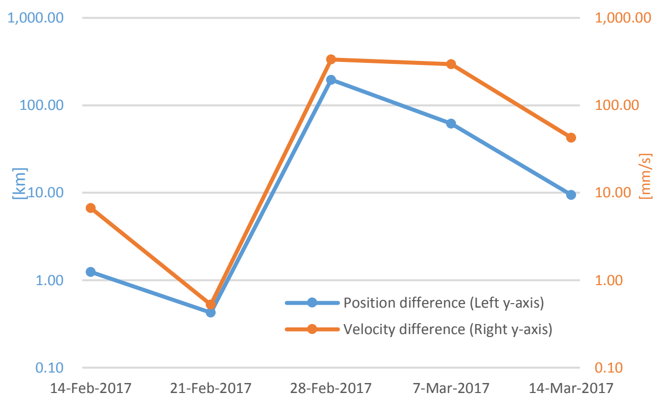


Fig. 5. Overlap comparison of position and velocity between an operational weekly OD solution and the OD solution calculated one week before. Many Delta-DOR passes were assigned during this period.

Delta-DOR passes were assigned during this period, consistencies between two consecutive OD solutions were much better compared to the result in which no Delta-DOR data were used shown in Figure 3.

5. Conclusion

The accuracy and precision of the quasi kinematic orbit determination method were successfully demonstrated through a real navigation operation for the Hayabusa-2 during its ion thrust phase in early 2017. This method will be used for the final approach phase to the target asteroid of the Hayabusa-2 in 2018.

Acknowledgments

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