# 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 have been considered to be major observation methods 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 conventional 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 has a weakness for the missions in 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), 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 [1], is operationally available for the joint observations with other agencies [2], 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. Example cases for the orbit determination during an ion engine operation phase of the Hayabusa-2 probe in March 2017 are show in Table 1 and Table 2. Due to a large ion thruster model error assumed, achievable position accuracy is only 764km if a 4-day arc of conventional Doppler & ranging based orbit determination is performed. On the other hand, if new method is applied during this period, achievable position accuracy is significantly improved to 200m with only 1 hour of consecutive ranging measurement and two-dimensional simultaneous Delta-DOR measurements. We are planning to demonstrate it in a real operation of the Hayabusa-2 in March 2017.

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

| Error source | Estimate or Consider | A priori uncertainty (1σ) | Comments |
|---|---|---|---|
| Range bias Usuda | Est. | 15m | per pass |
| Unmodeled Solar Radiation Pressure | Est. | 1.5% | Cannonball model |
| Non-gravitational accelerations | Con. | 1.3e-10km/s$^2$ (per axis) | 0.5% of ion thruster acceleration(per axis) |
| Spacecraft epoch state | Est. | Position:1000km Velocity: 5m/s | per axis |

Table 2. Measurement assumptions and achieved accuracies (Upper: conventional method, Lower: proposed new method)

| Data type | Ground station | Noise level | Duration |
|---|---|---|---|
| 2-way Doppler | Usuda | 1mm/s | 7 hour × 1 pass<br>3.5 hour × 4 pass |
| 2-way Ranging | Usuda | 5m | 1hour × 1 pass<br>0.5 hour × 4 pass |
| Achieved accuracy | Position error(1σ): 764.4[km]<br>Velosity error(1σ): 6.795[m/s] | | 21 hours (Total durations) |

| Data type | Ground station | Noise level | Duration |
|---|---|---|---|
| DDOR | Usuda-Goldstone | 40ps | 45min |
| | Usuda-Canberra | 40ps | 45min |
| 2-way Ranging | Usuda | 5m | 15min |
| Achieved accuracy | Position error(1σ): 203[m]<br>Velosity error(1σ): 16.8[cm/s] | | 1 hour(Total durations) |

## References

[1] H. Takeuchi *et al*., "Delta-DOR Observations for the IKAROS Spacecraft", Proceedings of the 28th ISTS, Japan, 2011-o-4-14v (2011).
[2] M. Mercolino, J.S.Border, H. Takeuchi, "A worldwide Delta-DOR Interoperable Network", Proceedings of the 7th ESA international workshop on Tracking, Telemetry and Command Systems for Space applications, 2016.