【助成 39－27】

# 非太陽周回小天体ミッションにおける天体暦エラーの影響の定量化と軽減

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〔研究の概要〕

Many small celestial bodies (i.e., comets, asteroids, and small planetary moons) preserve pristine relics of the early solar system. Small-body missions Hayabusa-1, -2, Rosetta, and Osiris-REx have returned notable samples and data. The confirmed MMX (JAXA) and HERA-Juventas (ESA) missions will explore Martian moons (i.e., Phobos and Deimos) and the binary asteroid Dimorphos, respectively, which are small bodies orbiting a primary body. In such missions, not only the complex gravity of the primary body, but also the position of the secondary relative to the primary, the ephemeris, perturbs the orbiting operations as well as the science return. The ephemeris error had not been experienced in previous missions. However, it can greatly perturb the GNC and geodesy in the near-term non-heliocentric small body missions. The impact of ephemeris error had not been identified nor tackled before, which was addressed in this project.

〔研究経過および成果〕

**Problem statement**

Previous work generally constraints the number of estimated variables or set the *a-priori* uncertainties to 5%, and only assumes a few hundred meters of ephemeris error. The error of estimated $C_{22}$ goes to 30%, libation amplitude cannot be estimated, errors of orbits are 200 m and 5 cm/s large, libration amplitude cannot be observed, as ephemeris error goes from 0 to just a few hundreds of meters. The realistic ephemeris error can be a few kilometers. This accuracy of degree-2 gravity terms and libration amplitude is useful in reflecting the internal structure of the target. Ephemeris error has at least three influencing position components. It is tricky to identify all variables, namely, spacecraft's six orbit states, geodetic parameters, and the ephemeris error, as the overall uncertainties are too large, and the estimation problem has too many local optima.

Approach 1: **Consider ephemeris time shift in estimation**

The ephemeris error can by approximated by the error in the transvers direction and represented by a mean anomaly or time shift $\Delta$et. As the fly tracking information barely exhibits signature of the ephemeris error, it is still tricky to recover this single variable. The applicant treated $\Delta$et as a “consider parameter” in estimation. That means, it is not estimated, but its noise on the estimation of other parameters is considered (Pub. [1]). As a result, even under an ephemeris error of 2 km, orbit determination error becomes 10 times smaller, and the libration amplitude ($\theta$) identification of geodetic parameters of the target is significantly improved. The degree-2 terms can be estimated to an accuracy of 0.5%, and libration amplitude 8%. which is excellent for distinguishing the interior families (Fig.1).

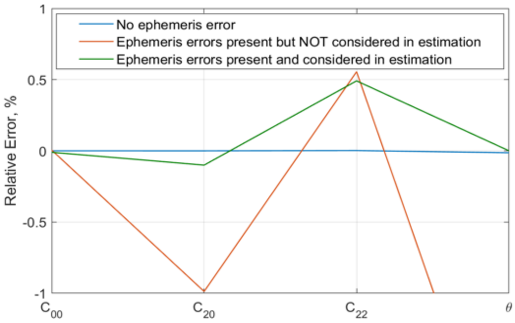


**Fig. 1 Errors of gravity coefficients estimated in the three situations**

Approach 2: **Parallel high-fidelity orbit propagator-based estimation**

The applicant developed the full dynamics orbit propagator that can take dynamical variables, such as ephemerides and non-spherical gravity fields of celestial bodies. The tool is coded in C to enjoy fast integration and can be called by Matab (using the C-MEX interface) to enjoy fast and handy matrix operations. In the problem of interest with many variables to estimate, many local minima exist and can cause the linearization-based estimation (e.g., extended Kalman filter) to fail. The estimation based on the more accurate modeling unscented transform (e.g., unscented Kalman filter) works much better for such a non-convex problem. While there are the sigma points, which are 2 times the number of estimated variables, to propagate, the propagations can be performed in parallel. Therefore, the parallel propagator comes to play a role (Fig.2). The estimation takes into account almost all variables (30 of them) and reasonable a-priori uncertainties, and still return good estimation performance. The OD accuracy reaches 20 m and 0.4 cm/s in just one day (Fig.2), much more advanced than the presumed performance of MMX, namely 86 m and 0.5 cm/s in one week. Thus, <u>this mission manner is promising to support quick and autonomous navigation in the highly perturbed small-body environment</u>.

〔発表論文〕

1. Chen, H.; Rambaux, N.; Lainey, V.; Hestroffer, D. Mothership-Cubesat Radioscience for Phobos Geodesy and Autonomous Navigation. *Remote Sens.* 2022, 14, 1619.
2. Chen, H., Rambaux, N., Lainey, V., and Hestroffer, D., "Mothership-CubeSat Radioscience for Phobos Geodesy and Autonomous Navigation", in *44th COSPAR Scientific Assembly. Held 16-24 July*, 2022, vol. 44, p. 228.

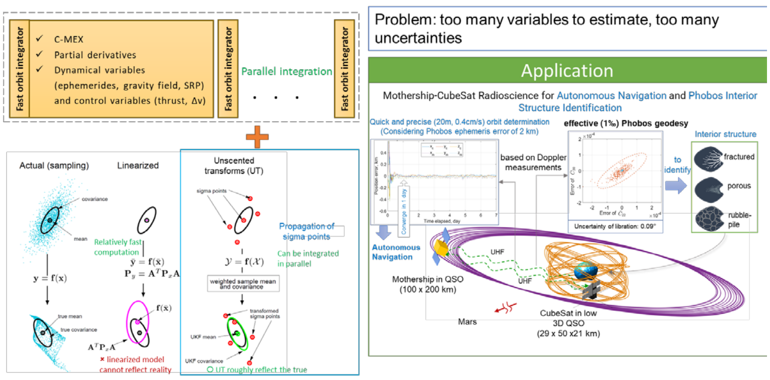


**Fig. 2 Parallel high-fidelity propagator-based estimation result.**