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Multi-path navigation method using solar panel-reflected solar oscillations for Earth satellites

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Several autonomous navigation methods have been studied to reduce reliance on the ground stations. Geomagnetic navigation, gravity gradient navigation, and celestial navigation using optical sensors are typical autonomous navigation methods. Geomagnetic and gravity gradient navigation have low navigation accuracy (1301 m [1] and 235 m [2], respectively) due to the poor accuracy of the geomagnetic and gravity gradient maps. Celestial navigation using refracted stars has the highest accuracy (146 m [3]), but it is restricted by atmospheric density errors. In light of the challenges in addressing the drawbacks of the existing methods, it is vital to investigate new methods.

Solar oscillations are vibrations on the surface of the Sun caused by acoustic waves, internal gravity waves, and surface gravity waves [4]. They affect the solar light intensity significantly in a short time, and these changes can be recorded using an atomic frequency discriminator and other sensors. A navigation method using solar oscillations was first discussed in the Mars exploration mission. Simulations show that by using the reflected solar oscillations from Phobos, position errors of 3.55 km for the transfer orbit and 1.76 km for the surrounding orbit can be obtained [5]. However, the accuracy is significantly affected by the distance and geometric relationship between the satellite, reflected body, and Sun.

In this study, a multi-path navigation method using solar panel-reflected solar oscillations for the Earth satellites is investigated, which is a supplement to the existing autonomous navigation methods. In this method, the time delay between two epochs, when the Earth satellite receives direct and reflected solar oscillations is used as a measurement. Considering FY-1 as an example, the performance of the method using solar panel-reflected solar oscillations and that using Moon-reflected solar oscillations are compared, where the solar panels of the BeiDou-3 M1–M24 and GPS satellites are considered reflected surfaces because their orbits are definite which can be approximated as planets or natural bodies and their orbit data can be obtained before Earth satellites are launched. Simulations show that the mean position error of the newly proposed method is only tens of meters. By contrast, the corresponding position error in navigation using Moon-reflected solar oscillations may reach thousands of meters due to long distances and poor geometric conditions.

State model. The position and velocity vector of the satellite in t_1 epoch ($\boldsymbol{r}_{\mathrm{ep}\_t_1}$ and $\boldsymbol{v}_{\mathrm{ep}\_t_1}$) are adopted as state vectors and orbital dynamics in the Earth-centered inertial frame (J2000.0) is selected as the state model [3].

Acquisition of measurement. The proposed method measures the time difference between the epochs when the Earth satellite receives the direct and reflected solar oscillations. Atomic frequency discriminators are installed towards the Sun and reflected satellites to obtain the direct and reflected epochs. The atomic frequency discriminator distinguishes the spectral frequency based on energy level transitions and outputs the intensity of the distinguished spectral line. Because the large variations in the intensity caused by the solar oscillations vary with time, they can be considered features. When the intensities from the direct and reflected paths are measured, data smoothing is used to obtain the detrended variations of the intensity. Once a feature appears in the reflected data series, feature-matching algorithms are used to extract the corresponding epoch from the direct data series. Finally, the time delay measurement is obtained. Due to the small field of view of the discriminator, only one reflected satellite can be observed by one discriminator at a time, and we considered that the solar oscillations are reflected by the satellite that the discriminator is pointing at. In addition, the reflected satellite to be observed can be determined in advance, considering the constraints of the Earth's occlusion and reflected angle (shown in Appendix A). From the calculations, as long as the position error of the Earth satellite is less than 170 km, the reflected satellite can be observed as scheduled where the attitude of the Earth satellite is assumed accurate.

Measurement model. The principle of the reflected solar oscillations is shown in Figure 1. According to the propagation theory of light and the geometric relationship between the Sun, reflected satellite or Moon, and Earth satellite, the measurement $\Delta t = t_2 - t_1$ can be expressed as

$$\Delta t=\frac{|\boldsymbol{r}_{\mathrm{er}\_t_r}-\boldsymbol{r}_{\mathrm{es}\_t_0}|}{c}+\frac{|\boldsymbol{r}_{\mathrm{ep}\_t_2}-\boldsymbol{r}_{\mathrm{er}\_t_r}|}{c}-\frac{|\boldsymbol{r}_{\mathrm{ep}\_t_1}-\boldsymbol{r}_{\mathrm{es}\_t_0}|}{c}, \tag{1}$$

where $|\cdot|$ represents the norm of the vector, t_0 is the epoch solar oscillation occurs, and t_r is the epoch when the solar oscillations are reflected. $\boldsymbol{r}_{\mathrm{er}\_t_r}$ is the position vector of the

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reflected satellite to the Earth in t_r. $\boldsymbol{r}_{\mathrm{es}\_t_0}$ is the position vector of the Sun to the Earth in t_0. $\boldsymbol{r}_{\mathrm{ep}\_t_1}$ and $\boldsymbol{r}_{\mathrm{ep}\_t_2}$ are the position vector of the satellite to the Earth in t_1 and t_2, respectively. c = 299792458 m/s is the velocity of light.

As seen from (1), the measurement model can be established, if we get the expression of $\boldsymbol{r}_{\mathrm{er}\_t_r}$ and $\boldsymbol{r}_{\mathrm{ep}\_t_2}$. Moreover, $\boldsymbol{r}_{\mathrm{ep}\_t_2}$ can be obtained by

$$\boldsymbol{r}_{\mathrm{ep}\_t_2} = f(\boldsymbol{r}_{\mathrm{ep}\_t_1}, \Delta t), \tag{2}$$

where $f(\cdot)$ is the function of orbital propagation.

Because we cannot measure t_r directly, it can only be solved by numerical methods. The motion of the reflected satellite obeys both the propagation theorem of light and orbital dynamics, which can be formulated as

$$\begin{cases} \boldsymbol{r}_{\mathrm{er}\_t_r} = f(\boldsymbol{r}_{\mathrm{er}\_t_1}, t_r - t_1), \\ |\boldsymbol{r}_{\mathrm{sr}\_t_0}| = c(t_r - t_0), \\ t_0 = t_1 - \dfrac{1}{c}|\boldsymbol{r}_{\mathrm{ep}\_t_1} - \boldsymbol{r}_{\mathrm{es}\_t_0}|. \end{cases} \tag{3}$$

Thus, t_0, t_r, and $\boldsymbol{r}_{\mathrm{er}\_t_r}$ can be obtained by resolving (3) using the dichotomy method, assuming $\boldsymbol{r}_{\mathrm{es}\_t_0} = \boldsymbol{r}_{\mathrm{es}\_t_1}$, where the $\boldsymbol{r}_{\mathrm{er}\_t_1}$ is the position vector of the reflected satellite to the Earth in t_1.

Substituting $\boldsymbol{r}_{\mathrm{ep}\_t_2}$ from (2), and $\boldsymbol{r}_{\mathrm{er}\_t_r}$ from (3) into (1), the measurement model can be obtained. As $\boldsymbol{r}_{\mathrm{ep}\_t_2}$ is the function of $\boldsymbol{r}_{\mathrm{ep}\_t_1}$ and Δt, the measurement model, which is an implicit function of Δt, can be rewritten as

$$\begin{aligned} &|\boldsymbol{r}_{\mathrm{er}\_t_r} - \boldsymbol{r}_{\mathrm{es}\_t_0}| + |f(\boldsymbol{r}_{\mathrm{ep}\_t_1}, \Delta t) - \boldsymbol{r}_{\mathrm{er}\_t_r}| \\ &\quad - |\boldsymbol{r}_{\mathrm{ep}\_t_1} - \boldsymbol{r}_{\mathrm{es}\_t_0}| - c\Delta t = 0. \end{aligned} \tag{4}$$

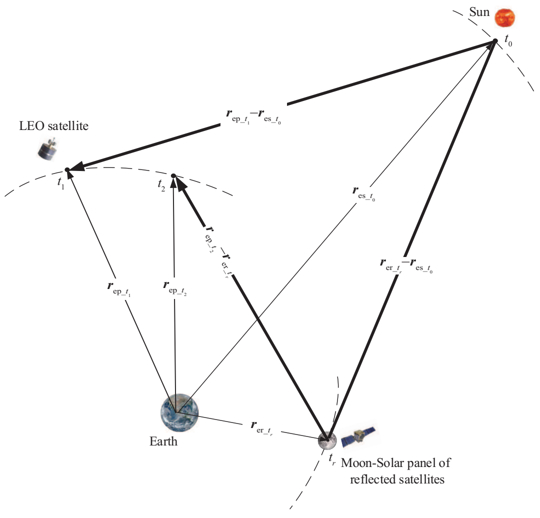

Figure 1 (Color online) Basic principle of reflected solar oscillations.

Simulations. The performance of the navigation method using solar panel-reflected solar oscillations and Moon-reflected solar oscillations is compared in this section. Appendix B provides the simulation conditions, and Appendix C provides the detailed navigation performance. As shown in Figure C1, the overall error trend increases initially and subsequently decreases, and the local error fluctuates periodically. Because the accuracy is significantly affected by the distance and geometric relationship of the Earth satellite, Moon, and Sun, comprising a large period of the Moon's movement and a small period of the Earth satellite's movement around the Earth. Due to these effects, the mean position error is 2215.8 m and the velocity error is 2.3 m/s for the entire simulation period.

Figure C2 shows the navigation performance of FY-1 using solar panel-reflected solar oscillations, where the three measurements initially received are used. Compared with the Moon-reflected solar oscillations, two more measurements are introduced to the system, which improves navigation accuracy. With the correction of the solar panel-reflected solar oscillations, the mean position and velocity errors of the Earth satellite are only 20.61 m and 0.14 m/s, respectively, and the maximum position and velocity errors are 351.44 m and 0.42 m/s, respectively. However, the navigation error of the FY-1 is still not smooth for two main reasons. (a) Measurements are not available all the time and the orbit propagation used in such instances decreases the navigation accuracy (the spikes in Figure C2). (b) The geometric relationship between the Earth satellite, reflected satellite, and Sun changes with time, which influences navigation accuracy (the fluctuations in Figure C2). As simulated, the time resolution of the atomic frequency discriminator should be better than 10^{-6} s. Otherwise, the navigation accuracy decreases sharply with an increase in the measurement error (as shown in Table C1).

Conclusion. This study explores a new navigation method using multi-path solar panel-reflected solar oscillations. Considering the solar panels of BeiDou-3 M1–M24 and GPS satellites as examples, the simulations show that the mean position error of FY-1 using solar panel-reflected solar oscillations is only 20.61 m in 30 days. Compared with the existing autonomous navigation methods for the Earth satellites, the newly proposed method has two advantages. (1) It has the highest navigation accuracy. (2) It does not require any additional accurate geomagnetic map, gravity gradient map, or refraction model. While the proposed method requires at least two atomic frequency discriminators to obtain the measurements and its accuracy is affected by the geometric relationship between the Earth satellite, reflected satellite, and Sun, which are the inherent drawbacks of the method. It is notable that the influence of the relativistic effects on the measurement accuracy needs further research.

Supporting information Appendixes A–C, Figures C1 and C2, and Table C1. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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