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X-ray pulsar/Doppler difference integrated navigation for deep space exploration with unstable solar spectrum

Jin Liu [a,b], Jian-cheng Fang [a], Zhao-hua Yang [a,*], Zhi-wei Kang [c], Jin Wu [b]

[a] School of Instrumentation Science & Opto-electronics Engineering, Beihang University (BUAA), Beijing 100191, People's Republic of China
[b] College of Information Science and Engineering, Wuhan University of Science and Technology, Wuhan 430081, People's Republic of China
[c] College of Information Science and Engineering, Hunan University, Changsha 410082, People's Republic of China

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ABSTRACT

To eliminate the effects of unstable solar spectrum on the Doppler velocity measurement, a solar light Doppler difference measurement method is developed. In this method, two Doppler velocities with respect to the Sun and the Mars are measured. And their difference, which does not include the Doppler velocity bias caused by the unstable solar spectrum, is utilized as the navigation measurement. As the novel Doppler difference navigation method cannot work alone due to its accumulative position error, we combine it with the X-ray pulsar navigation method, and propose the X-ray pulsar/Doppler difference integrated navigation for deep space exploration. The simulation results demonstrate that the proposed integrated navigation method is robust to the Doppler velocity measurement bias caused by the instability of the solar spectrum effectively, and keeps the high accuracy of the pulsar/Doppler-integrated navigation system.

1. Introduction

In the area of the deep space exploration, the navigation information is crucial to the missions. The reason is that only according to the navigation information, can guidance determine what the spacecraft must do to reach its target celestial body [22]. The celestial autonomous navigation, which can provide high-accuracy and real-time navigation information, is highly attractive [17,18,28]. The celestial navigation system obtains the navigation information via measuring the information of celestial bodies. The celestial navigation measurements include the angle measurement, the distance measurement and the velocity measurement.

The angle measurement is the angle which is the subtended at the spacecraft between the line of sight to the star and that of the near celestial body [15,16]. The positioning accuracy of the angle measurement-based method is high when the spacecraft is close to a celestial body. However, in the Earth–Mars transfer orbit, its positioning accuracy is very low and cannot fulfill the requirement of the deep space exploration due to the long-distance between the near celestial body and the spacecraft [9].

The distance measurement-based method is the X-ray pulsar navigation method [3,24,26]. X-ray pulsar navigation system utilizes an X-ray sensor to collect the X-ray radiation signals from the pulsar, and deals with these signals to obtain the pulse TOA (time-of-arrival) [10,20,25]. According to the TOAs of multi-pulsars, we can get the position vectors with respect to the SSB (solar system barycenter) [16,21]. As the radiation signals from X-ray pulsar can be received in the whole space, this navigation method is suitable for the whole space. But its positioning accuracy, whose mathematical model can be found in Ref. [21], is dependent on the collecting area of the X-ray sensor and the collecting time. Thus, it cannot provide the real-time and high-accuracy positioning information due to the long collecting time and the small area of the X-ray sensor.

The velocity measurement-based method adopts the spectrometer to measure the frequency shift of the solar spectrum since the Sun is the sole light source in the solar system. The Doppler velocity with respect to the Sun can be extracted accurately according to the frequency shift. Obviously, this navigation method is suitable for the solar system. We can get the position information by integrating the velocity information. Unfortunately, the velocity error unavoidably exists, which results in the growth of position error. Thus, the velocity measurement-based method cannot work alone because of the accumulation of position error [12,14]. Therefore, this method can be only used as an aided navigation method. What is worse, in fact, due to the existence of the sunspots, the

* Corresponding author at: School of Instrumentation Science & Opto-electronics Engineering, Beihang University (BUAA), Beijing 100191, People's Republic of China. Tel.: +86 13718282241; fax: +86 010 82316813.
E-mail address: yangzh@buaa.edu.cn (Z.-H. Yang).

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solar flare and the solar prominence, the solar spectrum is unstable, which results in great decline of the velocity measurement accuracy.

Many integrated navigation methods based on three measurements [12,19] have been proposed. In 2011, considering that both the pulsar navigation and the Doppler navigation are suitable for the deep space exploration, Liu has proposed the pulsar/Doppler integrated navigation method [14] under the condition of stable solar spectrum. Compared with the pulsar navigation, the integrated navigation can provide higher accurate and real-time navigation information. In 2012, Yang has developed the integrated navigation based on pulsars and Sun observation [27], which includes angle, velocity and distance measurements. However, when the solar spectrum is unstable, there is a large bias in the Doppler velocity measurement unavoidably. On this condition, the positioning accuracy of these two integrated navigation declines greatly, and is even worse than that of the X-ray pulsar navigation.

To resist the velocity bias caused by the instability of the solar spectrum, we develop a novel solar light Doppler velocity difference measurement method, where two Doppler velocities with respect to the Sun and the Mars respectively are measured, and their difference is adopted as the navigation measurement. As the novel Doppler difference navigation method can also not work alone due to its accumulative position error, we utilize it to aid the X-ray pulsar navigation method which can work individually, and propose the X-ray pulsar/Doppler difference integrated navigation for the deep space exploration with unstable solar spectrum.

This paper is organized into seven sections. After the introduction, the solar light Doppler difference measuring method with unstable solar spectrum is developed in Section 2. The X-ray pulsar navigation is described in Section 3. The transfer orbit dynamic model for Mars explorer is outlined in Section 4. The integrated navigation scheme is described in Section 5. The simulation results in Section 6 demonstrate the robustness and accuracy of this presented method and conclusions are drawn in Section 7.

2. Doppler difference measurement method with unstable solar spectrum

In the traditional Doppler navigation method, the spacecraft utilizes the spectrometer to observe the solar light which comes from the Sun directly, and get the Doppler velocity with respect to the Sun according to the frequency shift of the solar spectrum. Unfortunately, when the solar prominence, the sunspots or the solar flare happens, the distortion of the solar spectrum happens. What is worse, these disturbing interferences usually last several minutes. As a result, there is a large and long-time bias in the Doppler velocity measurement.

To address this problem, we develop a Doppler difference measuring method. In this paper, we take the Mars exploration as instance since the Mars exploration is a research hotspot in the area of deep space exploration. As we know, the observed light from Mars is the solar light reflected by the Mars, whose frequency shift can also be utilized to estimate the velocity of a spacecraft with respect to the Mars [29]. Namely, not only the solar light spectrum but also the light spectrum of Mars is interfered by the interference factors, such as the solar prominence, the sunspots or solar flare. For instance, the solar flares cause the asymmetric redshift or blueshift of the solar spectrum [6,8,13]. As the Doppler velocity is obtained by comparing the measured solar spectrum with the standard one, the asymmetric redshift or blueshift caused by the solar flares is certain to affect the measured Doppler velocity. In the outburst process of the solar flares which usually lasts for several minutes, it causes the bias in the Doppler velocities with respect to both the Mars and the Sun. Therefore, the difference of these two Doppler velocities does not contain the Doppler velocity bias. Namely, the Doppler difference is immune to these interference factors.

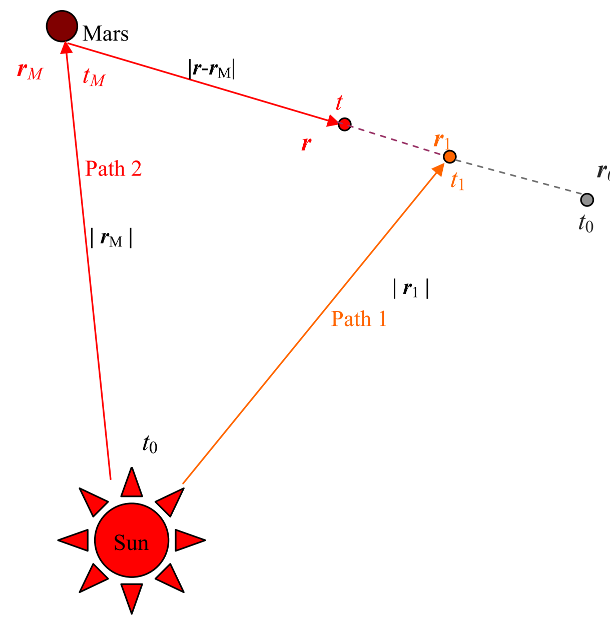

Fig. 1. The basic principle of Doppler difference measurement method. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

In this paper, we utilize the spectrometer 1 to observe the solar light that comes from the Sun directly, and adopt the spectrometer 2 to collect the solar light reflected by the Mars. And then, we get the Doppler velocities at two directions from the obtained light spectrum. Finally, the difference of two Doppler velocities is utilized as the navigation measurement instead of the traditional Doppler velocity with respect to the Sun.

The basic principle of the Doppler difference measurement method is presented in Fig. 1. We adopt the Sun coordinate frame in this paper. Its origin is at the Sun center. The X-axis points to the vernal equinox, the Z-axis points to the celestial North Pole, while the Y-axis completes a right-handed system. Suppose that two solar photons leave the Sun at time t_0. One solar photon flies along the path 1 (orange), and is captured by the spectrometer at position $\boldsymbol{r}_1$ at time t_1 ($t_1 > t_0$). The other solar photon flies along the path 2 (red). It is reflected by Mars at position $\boldsymbol{r}_M$ at time t_M ($t_M > t_0$), and then is collected at position $\boldsymbol{r}$ at time t ($t > t_1$). Assume that the position and velocity vector of spacecraft are $\boldsymbol{r}_0$ and $\boldsymbol{v}_0$ respectively at time t_0, and the velocity of the Mars is $\boldsymbol{v}_M$ at time t_M. Therefore, if the solar spectrum observed by the spectrometer 1 at time t_1 is interfered, the Mars light spectrum observed by the spectrometer 2 at time t is also interfered. If t_1 and t are obtained, we can get the Doppler velocity difference without the bias caused by unstable solar spectrum.

Next, we calculate t_1 and t, and design the Doppler difference measurement model.

In the transfer orbit, the approximate relationship equation between $\boldsymbol{r}_0$ and $\boldsymbol{r}_1$ can be expressed as follows:

$$\boldsymbol{r}_1 = \boldsymbol{r}_0 + \boldsymbol{v}_0(t_1 - t_0) + \frac{1}{2}\boldsymbol{a}(t_1 - t_0)^2 \tag{1}$$

where $\boldsymbol{a}$ is the acceleration vector of spacecraft.

In the time interval ($t_0 \sim t_1$), the flying distance of the solar photon can be expressed as:

$$c(t_1 - t_0) = |\boldsymbol{r}_1| = \left|\boldsymbol{r}_0 + \boldsymbol{v}_0(t_1 - t_0) + \frac{1}{2}\boldsymbol{a}(t_1 - t_0)^2\right| \tag{2}$$

where c is the speed of light.