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Phase tracking approach for TDOA measurements in critical lunar spaceflights

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Dear editor,

In the coming years, China will make a series of profound breakthroughs in the field of lunar and deep space explorations, such as the Chang'E-4 landing on the far-side of the moon, the Chang'E-5 sample return, and the ambitious Mars mission. These missions include a spacecraft powered descending flight, which is the most critical and challenging mission phase of orbit determination and space operations. Delta-differential one-way ranging (Delta-DOR), an application of time difference of arrival (TDOA) measurement in deep space navigation, is a powerful and effective radiometric tracking technique that is used globally for the orbit and trajectory determination of lunar and deep space missions [1, 2]. The key signal-processing step in Delta-DOR is correlating the spacecraft signals that are received by different stations. In the current approach, which is originated from quasar signal correlation, an FX-type signal correlator [3] or a second-order phase-locked loop (PLL) [4], has been implemented to process downlink spacecraft signals, in which a priori time-delay model is critically needed to compensate for the effects of spacecraft's flight dynamics. For instance, in the case of Chang'E-3 mission, inaccuracy in priori time-delay model arising from the descending trajectory design and an improper processing approach, led to the unsuccessful acquisition of differential Doppler and phase estimation approximately three minutes after the onset of the power descending flight in Chang'E-3 mission [5]. Here, we review certain signal models of TDOA measurements and propose more appropriate phase-tracking approach for the correlation of deterministic spacecraft signals. The raw data of Chang'E-3 powered descending flight have been processed, proving the capability of this approach.

Basics of spacecraft DOR measurement. In Delta-DOR measurements, TDOA (or equivalently, the range difference) observable is determined from the signals received at different stations, as shown in Figure 1(a). For instance, for the DOR signal in Chang'E-3 mission, the spacecraft emitted a downlink carrier phased-modulated by two DOR tones with angular frequencies of ω_1 and ω_2. The spacecraft time-delay observable could be generated by

$$\tau_g^{\mathrm{SC}} = \frac{\varphi_{\mathrm{dif}}(\omega_2) - \varphi_{\mathrm{dif}}(\omega_1)}{\omega_2 - \omega_1}, \tag{1}$$

where τ_g^{SC} is the time delay, and $\varphi_{\mathrm{dif}}(\omega_2)$ and $\varphi_{\mathrm{dif}}(\omega_1)$ are the differential phases between two stations for the DOR tones with the angular frequencies of ω_2 and ω_1, respectively. In the Chang'E-3 mission, the carrier power was 12 dB higher than each DOR tone component, which is typical in lunar missions.

Signal models for TDOA measurement. The TDOA technique was first employed for locating underwater acoustic targets [6], where the signal model was treated as a wide-sense, stationary ran-

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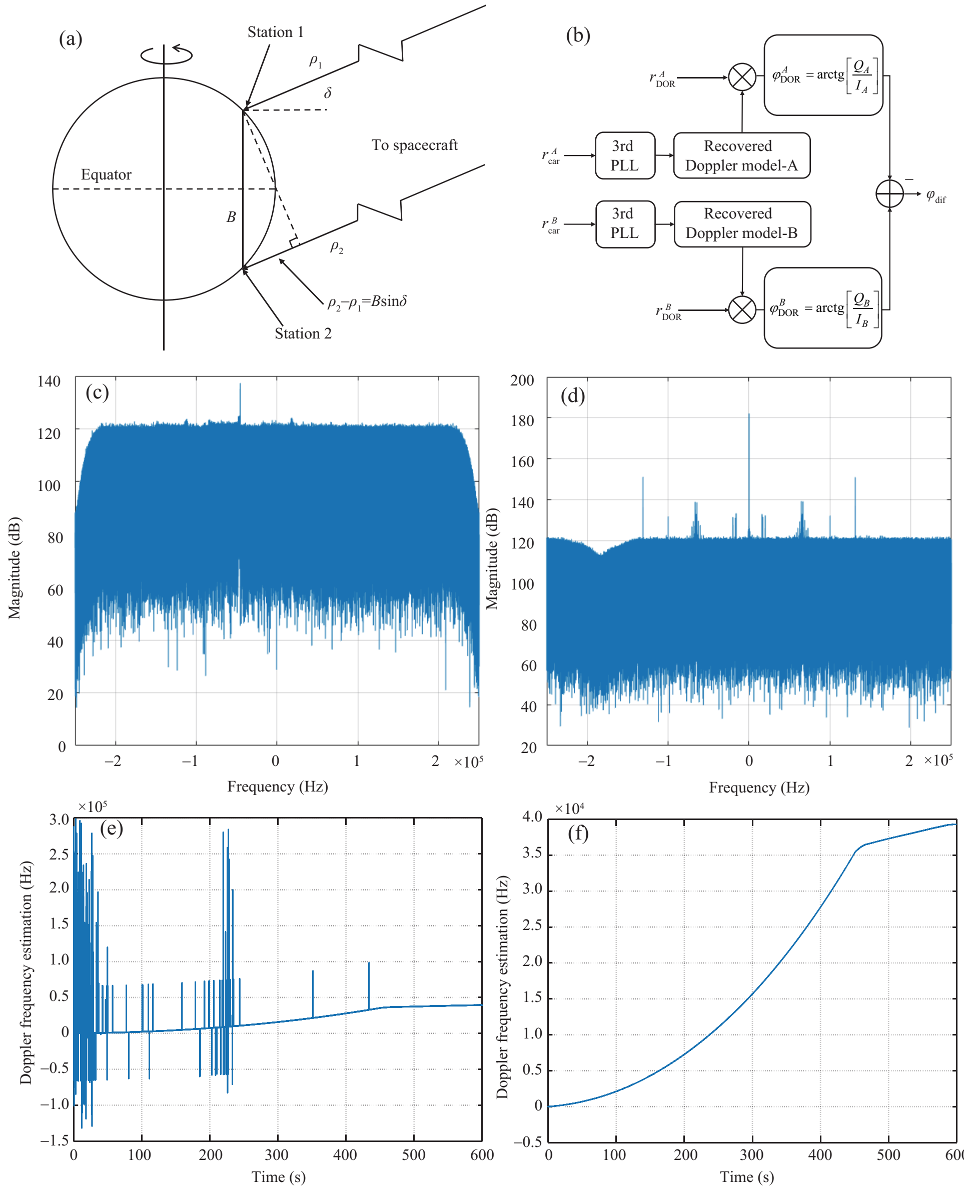

Figure 1 (Color online) (a) Principle of spacecraft DOR; (b) algorithm of DOR tone phasor stopping; (c) spectrum of Chang'E-3 raw data; (d) spectrum of Chang'E-3 data after phasor stopping; (e) frequency estimation without phasor stopping; (f) frequency estimation with phasor stopping.

dom process with the probability density function (PDF) of which appears in (2), and the maximum likelihood estimation (MLE) of the corresponding time delay is represented by the cross ambiguity function (CAF) in (3) [7].

$$p_{\rm ac}(\boldsymbol{r};\tau) = \frac{1}{\det(\pi \boldsymbol{C}_\tau)} \exp\{-\boldsymbol{r}^{\rm H}\boldsymbol{C}_\tau^{-1}\boldsymbol{r}\}, \qquad (2)$$

$$\widehat{\tau}_{\rm ML,ac} = \arg\max_{\tau}\{\boldsymbol{r}^{\rm H}\boldsymbol{C}_\tau^{-1}\boldsymbol{r}\}. \qquad (3)$$

For electromagnetic sources, Stein (1993) showed that a deterministic signal model, the PDF of which is given by (4), is more appropriate [8], while Fowler et al. [9] pointed out that initially, the MLE of time delay for a target with deterministic signal should be (5).

$$p_{\rm em}(\boldsymbol{r};\tau) = \frac{1}{\det(\pi \boldsymbol{C})} \exp\left\{-(\boldsymbol{r}-\boldsymbol{s}_\tau)^{\rm H}\boldsymbol{C}^{-1}(\boldsymbol{r}-\boldsymbol{s}_\tau)\right\}, \qquad (4)$$

$$\widehat{\tau}_{\rm ML,em} = \arg\max_{\tau}\left\{(\boldsymbol{r}-\boldsymbol{s}_\tau)^{\rm H}\boldsymbol{C}^{-1}(\boldsymbol{r}-\boldsymbol{s}_\tau)\right\}. \qquad (5)$$

Based on this theoretical review on signal models and MLE for TDOA measurements, it is clear that the spacecraft signal should be recovered before the estimation of time delay is performed, which is different from the time delay estimation by CAF in the quasar signal correlation approach. According to the statistical signal processing theory, the superiority of the model in (4) compared with the model in (2) comes from the noise covariance reduction, which improves the performance of parameter estimation.

Phase tracking approach for signal correlation. As the carrier and the DOR tone signal received at the same station undergo the same propagation process, the dynamic effects on each signal component are definitely the same, which could be seen in (6) and (7):

$$\varphi_{\text{car}}^{\text{rec}}(t) = \omega_c t - \omega_c \frac{\rho(t)}{c} + \varphi_0^{\text{car}}, \tag{6}$$

$$\varphi_{\text{DOR}}^{\text{rec}}(t) = \omega_{\text{DOR}} t - \omega_{\text{DOR}} \frac{\rho(t)}{c} + \varphi_0^{\text{DOR}}, \tag{7}$$

where $\varphi_{\text{car}}^{\text{rec}}$ and $\varphi_{\text{DOR}}^{\text{rec}}$ are the received carrier and DOR tone phases at sky frequencies that need to be recovered, respectively, $\rho(t)$ is the topocentric range of the spacecraft with respect to the receiving station, and the middle term in both equations accounts for the same Doppler effect. The MLE of the DOR tone phase requires that the phasor of the DOR tone should be stopped first, which could be realized by

$$\varphi_{\text{DOR}}^{\text{Dop}}(t) = \frac{\omega_{\text{DOR}}}{\omega_{\text{car}}} \varphi_{\text{car}}^{\text{Dop}}(t), \tag{8}$$

where $\varphi_{\text{car}}^{\text{Dop}}$ and $\varphi_{\text{DOR}}^{\text{Dop}}$ are the Doppler phase contributed from $\rho(t)$. So, recovering the carrier Doppler phase is the first key step in the adaptive phase recovery approach, and the corresponding differential phase estimation approach could be simply illustrated in the diagram of the full algorithm, shown in Figure 1(b), where r_{car}^{A} and r_{car}^{B} are the received carriers and r_{DOR}^{A} and r_{DOR}^{B} are the received DOR tone signals in stations A and B, respectively. After carrier phase tracking and phasor stopping of each DOR tone at each station, the spacecraft time delay observable could be computed by

$$\tau_g^{\text{SC}} = \frac{(\varphi_{\omega 2}^{B} - \varphi_{\omega 2}^{A}) - (\varphi_{\omega 1}^{B} - \varphi_{\omega 1}^{A})}{\omega_2 - \omega_1}, \tag{9}$$

where $\varphi_{\omega 2}^{B}$ and $\varphi_{\omega 1}^{B}$ are the estimated phases for DOR signals at station B, and $\varphi_{\omega 2}^{A}$ and $\varphi_{\omega 1}^{A}$ are the estimated phases at station A.

Validation on Chang'E-3 power descending. A designed third-order PLL was used to recover signal dynamics information from the carrier raw data received at each Chang'E-3 station, with which the DOR tone phasors with relatively weaker signal powers could be stopped to extend the integration time for precise time delay measurement by (8). As a processing example, one of the spacecraft's DOR tone signals had its raw data signal and 600 s integration frequency spectrum after phasor stopping shown in Figure 1(c) and (d), respectively; these figures describe that after having been beaten to exactly zero frequency (middle of the spectrum), the weak DOR tones had the frequency and phase precisely estimated after phasor stopping. Figures 1(e) and (f) illustrate the frequency estimation results without (there a lot of outliers) and with phasor stopping.

Conclusion. We proposed an adaptive phase tracking approach to correlate the spacecraft DOR tone signal in critical spacecraft powered flight phase, other than the direct cross ambiguity function computation originated from the classical quasar signal correlation. This could be used for the future lunar and deep exploration missions.

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