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Carrier-Doppler-based real-time two way satellite frequency transfer and its application in BeiDou system

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Abstract

Two-way satellite time and frequency transfer (TWSTFT) method is valuable for precise time and frequency transfer. The frequency could be directly transferred by utilizing two-way carrier Doppler measurement. This method requires each station observing both its own and associated station's transponder signals transferred by satellite. In BeiDou system (BDS), the reference station and the field station construct a two-way link via a GEO satellite, and the field station sends pseudorange and carrier phase information to the reference station by transmission signal, in order to achieve real time TWSTFT. This paper analyzes the theory of carrier Doppler based TWSTFT (called CD-TWSTFT), and validates it by using on line data of BDS. The results demonstrated that the performance of CD TWSTFT is much better than code based TWSTFT in short-term frequency transfer and almost same at long-term frequency transfer.

Keywords: BDS; TWSTFT; Carrier Doppler; Real-time; Frequency stability

1. Introduction

Global Navigation Satellite Systems (GNSS) have been widely used in positioning, navigation, timing (e.g., Jin et al., 2010, 2011, 2014), such as time and frequency transfer using GNSS Common View (CV) and GNSS carrier phase (GNSS CP). GNSS CV method using single frequency or multi-frequency GNSS measurement could get the accuracy of several ns, which is currently the most widely used method, while GNSS CP uses carrier phase to obtain precise positioning and clock difference for frequency transfer (Liang and Zhang, 2009). In addition, the two-way satellite time and frequency transfer (TWSTFT) is valuable at precise time and frequency transfer. With the improvement of the frequency stability of atomic clocks, the accuracy of TWSTFT also needs to be increased accordingly.

The clock difference accuracy of TWSTFT is hundreds of ps, but needs complex equipment and communication satellite, so TWSTFT has a limited application. Besides, the international TWSTFT link is less, and it is difficult to achieve real-time work due to the short transfer period every day. However, BDS has a mixed constellation of the system, which includes MEO, IGSO and GEO satellites. Each station makes double two-way transfer links via two GEO satellites. The field station sends the signal modeled with pseudorange and carrier phase information to the reference station, in order to achieve real time TWSTFT. The traditional TWSTFT utilizes two-way code pseudorange to calculate relative clock difference. The pseudorange, with measurement noise of 10 cm, affected by multipath effect although the parabolic antenna is employed (as shown in Fig. 1). So code pseudorange cannot meet the frequency stability estimation requirement of ground station clocks, such as hydrogen atomic clock (Allan, 1987).

Carrier phase measurement is more precise. There are two ways to use carrier phase to perform frequency transfer: (1) calculating relative clock difference, then

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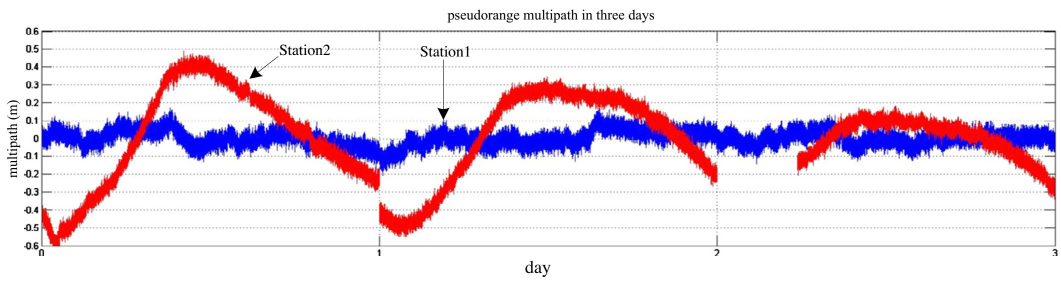

Fig. 1. Multipath in code based TWSTFT.

make differential at relative clock difference to obtain relative frequency difference (Fujieda et al., 2012); (2) using the carrier Doppler measurement to calculate relative frequency directly, which was presented by Fonville et al. in 2002 (Fonville et al., 2004; Kanj et al., 2012). In this paper, considering the characteristics of real-time and double two-way link in BDS, we prefer the second approach. Two tests are carried out: one test is using the collocated stations in laboratory and the other test is using two remote stations in BDS. It is different from traditional TWSTFT that the carrier is in C-band and transferred by GEO satellite of BDS, and the modems and antennas are special for BDS.

2. Theory and equations

In CD-TWSTFT system, as shown in Fig. 2, two stations simultaneously measure its own and the other station's signal transferred by a GEO satellite, and the relative frequency difference is calculated by the Doppler measurement. Because the relative movement of the satellite with respect to the two stations, an offset will be added to carrier frequency received by station. The magnitude of the offset is mainly concerned with the four variables of the system shown in Fig. 2: δ_f, f_S, δ_f is the relative frequency difference which is to be estimated, q_1 and q_2 are associated with satellite velocity, f_S is the local oscillation frequency of satellite which is known.

In Fig. 2, station 1's frequency is the known frequency f_{sys}, and station 2's frequency is offset from f_{sys} by a value δ_f ($f_{clk2} = f_{sys} + \delta_f$), F_{xy} is the frequency measured by station y and transmitted by station x. The signal, which is reflected to station 2 by a satellite, has a Doppler effects due to the movement of satellite. The first-order Doppler coefficient can be described by the following two equations:

$$q_1 = \frac{\overline{V}_1}{c} \tag{1}$$

$$q_2 = \frac{\overline{V}_2}{c} \tag{2}$$

where $\overline{V}_n$ is the velocity vector of the satellite in the direction of station n and c is the speed of light through the vacuum. Two stations could get four observations, so four equations are got. Linearizing the four equations at an initial estimation vector $\tilde{\overline{x}} = [\tilde{f}_S, \tilde{q}_1, \tilde{q}_2, \tilde{\delta f}]$, and the estimation $\tilde{q}_1 = \tilde{q}_2 = \tilde{\delta f} = 0$ is made, the δ_f could be calculated by:

$$\delta_f = \frac{f_{sys}}{6}\left(\frac{f_S(F_{ab} - F_{bb}) + 2f_S(F_{aa} - F_{ba}) - 3f_{tr}(F_{ab} - F_{ba})}{2f_{tr}(f_{tr} - f_S)}\right) \tag{3}$$

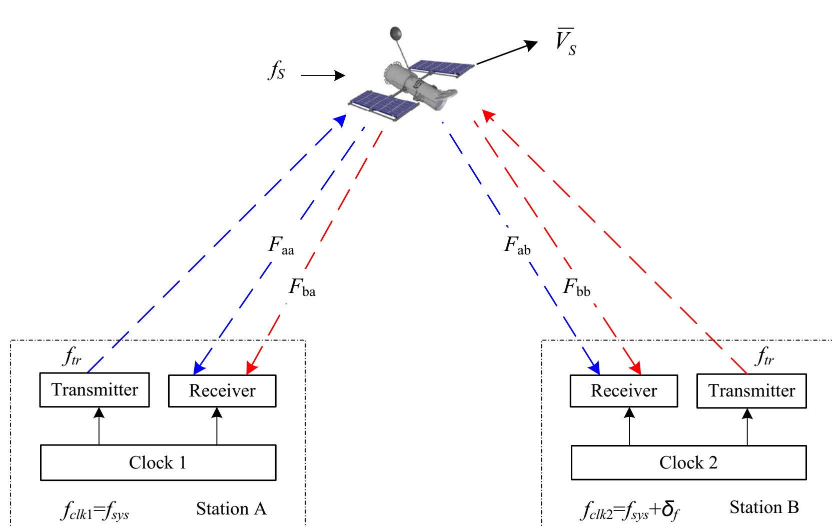

Fig. 2. Carrier phase two-way system.