Progress on Two-way Satellite Time Transfer using DPN Signals

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Abstract—The use of dual pseudo-random noise (DPN) signals for two-way satellite time and frequency transfer (TWSTFT) improves the time transfer precision such that it is approximately one order of magnitude better than that of conventional TWSTFT. The interference between the transmission signals must be considered to further improve the time transfer precision because the DPN signal uses very narrow-band pseudo-random noise (PRN) codes. We investigated the interference noise between the transmission signals, and propose an alternative signal scheme to reduce the interference noise.

Key words:* *two-way satellite time and frequency transfer, dual pseudo random noise code

I. INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) [1] can easily achieve more precise time synchronization between remote clocks than can techniques such as the common-view method using Global Navigation Satellite System (GNSS) satellites [2], which requires a complicated analysis strategy, because the propagation path delays between the stations can be canceled in the two-way method. On the other hand, the operational cost of TWSTFT is more expensive than that of GNSS time transfer, for which the only equipment requirements are an antenna and a receiver, because TWSTFT uses a commercial communication satellite in a geostationary orbit. To reduce the operational costs, we devised the use of a dual pseudo-random noise (DPN) signal as a timing signal. The DPN signal consists of a pair of pseudo-random noise (PRN) codes which are separated in the frequency domain. Because the observation error of the DPN signal is equivalent to that of the simple wide-band PRN code, it is possible to perform precise time transfer with a decrease in the occupied bandwidth on the satellite transponder. We also developed a new time transfer modem using the DPN signal based on software defined radio technology. The modem consists of an arbitrary wave form generator, a versatile analog-to-digital sampler, and a graphics processing unit (GPU) equipped PC. By performing two-way time transfer experiments between Japan and Taiwan, we demonstrated that the DPN signals improve the time transfer precision to be about one order of magnitude better than that of conventional TWSTFT [3, 4].

The interference noise between transmission signals is a source of observation errors in TWSTFT. In GNSS time transfer, the overlap of many PRN codes does not degrade the time transfer precision too greatly because GNSS uses non-geostationary satellites and the Doppler frequencies of each satellite are quite different. However, in the case of TWSTFT using geostationary satellites, the Doppler frequencies of the earth stations are almost the same, and the interference noise would be shown as a periodic component of the time transfer results. Because the self- and cross-correlation factors of PRN codes are degraded when the chip rate is smaller, the interference noise becomes higher with decreasing transmission signal bandwidth.

The interference noise is one of the most important factors in the use of DPN signals because each PRN code of the DPN signal is about one-tenth of that of the conventional TWSTFT. In this paper, we describe the results of our investigation of DPN interference noise, and propose an alternative signal to prevent this noise.

II. DUAL PSEUDO-RANDOM NOISE SIGNAL

A. Principles of the DPN Signal

The measurement precision of TWSTFT is equivalent to the group delay estimation precision of a simple PRN code, and it is determined by three factors: the bandwidth of PRN code, the cross-correlation integration time, and the signal-to-noise ratio [5]. If we consider the fact that the estimation of the group delay is equivalent to the determination of the phase slope across the cross-correlation spectrum, then a pair of coherent PRN codes that are separated in the frequency domain as shown in Figure 1 can also use the acquisition of the group delay. The measurement precision is equivalent to that of the simple PRN code when the bandwidth of the simple PRN code is nearly equal to the separation frequency of the DPN signal [6]. Consequently, we can perform a precise time transfer, through a decrease in the transponder's occupied bandwidth on the commercial communication satellite.

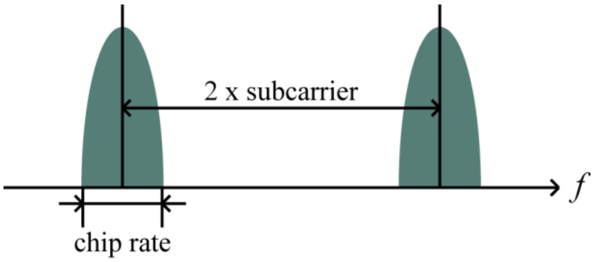

Figure 1. Dual pseudo-random noise signal.

B. Interference Between Transmission Signals

We used a pair of PRN codes where the center frequencies are separated by 31.7 MHz and the individual bandwidth is 200 kHz for our time transfer experiments. Although a long code period is preferable to reduce the interference noise, the maximum code period used is only up to 5 ms because of the limitations of the experimental equipment. We used a Global Positioning System (GPS) L2 civil code with the first 800 bits for each PRN code of the DPN signal. The chip frequency is 200 kHz, and the code period is 4 ms.

We can estimate group delays from each PRN code of the DPN signal, although the bandwidth of individual code is at most 200 kHz. Henceforth, LSB indicates the lower frequency band and USB indicates the upper frequency band of each DPN side-band signal. Although the Doppler frequencies of the LSB and USB are slightly different, the two group delays estimated by using the LSB and USB are identical observations, and the differences between these observations should have a Gaussian distribution.

Figure 2 shows the differences in the round trip signals. The earth stations used are Koganei, Tokyo and Kashima, Ibaraki, with a baseline length between the two stations of about 110 km. Figure 2 (a) shows the case where there is only one transmission signal from the Koganei station, and (b) shows the case where there are two transmission signals from the two stations. The vertical axis shows the time differences in nanoseconds, and the horizontal axis shows the observation time in hours. The absolute bias was removed for greater visibility. When the two stations transmit the DPN signals simultaneously, we see a small periodical variation in the LSB and USB differences.

Figure 3 (a) and (b) show similar observations when using a PRN code with a 9 bit maximum length sequence code and a chip frequency of 127.75 kHz. Also, Figure 4 shows the instabilities of each LSB and USB difference computed from the Koganei round trip signal.

Because we estimate the group delays of the DPN signal on the assumption that the LSB and USB are coherent signals, the collapse of the LSB and USB uniformity leads to the degradation of the DPN time transfer precision. Figure 5 (a) shows the time transfer results between the Koganei and Kashima stations.

Each point of the plot shows the one second average of the 127.75 kHz chip frequency. The bias and drift were removed from the plot for greater visibility. Figure 5 (b) is the same plot but with a chip frequency of 200 kHz. Both plots show the undesirable variations which arise from the interference noise between the two transmission signals.

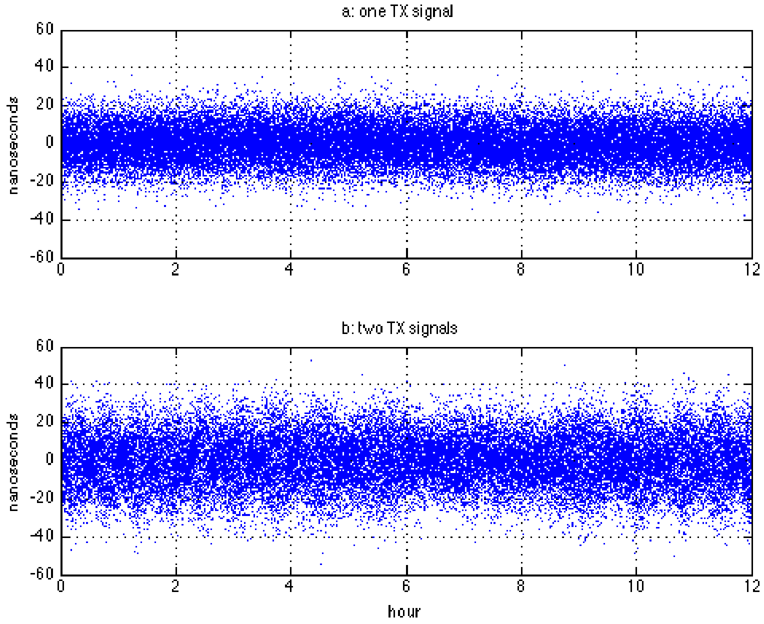

Figure 2. LSB and USB differences of a 200 kHz PRN code.

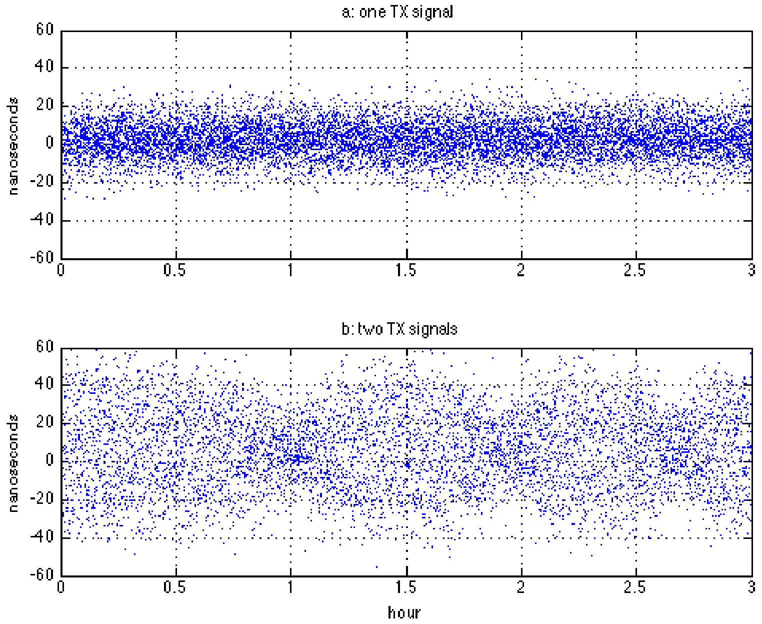

Figure 3. LSB and USB differences of a 127.75 kHz PRN code.

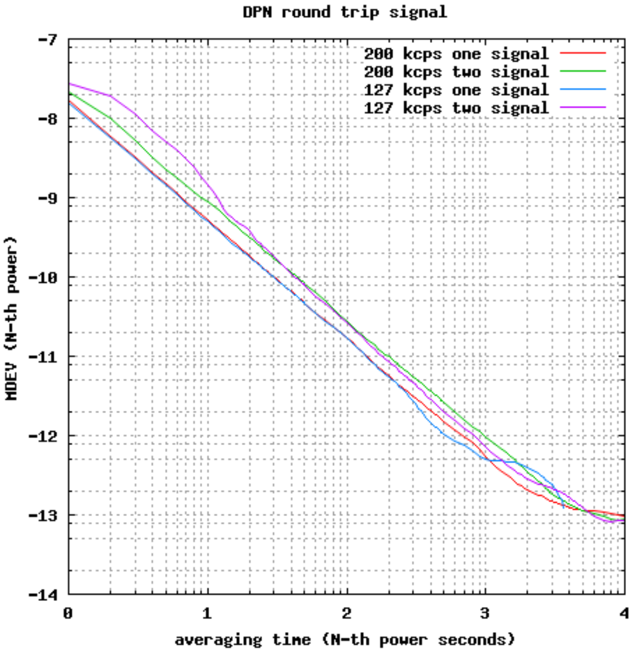

Figure 4. Instabilities of each LSB USB difference.

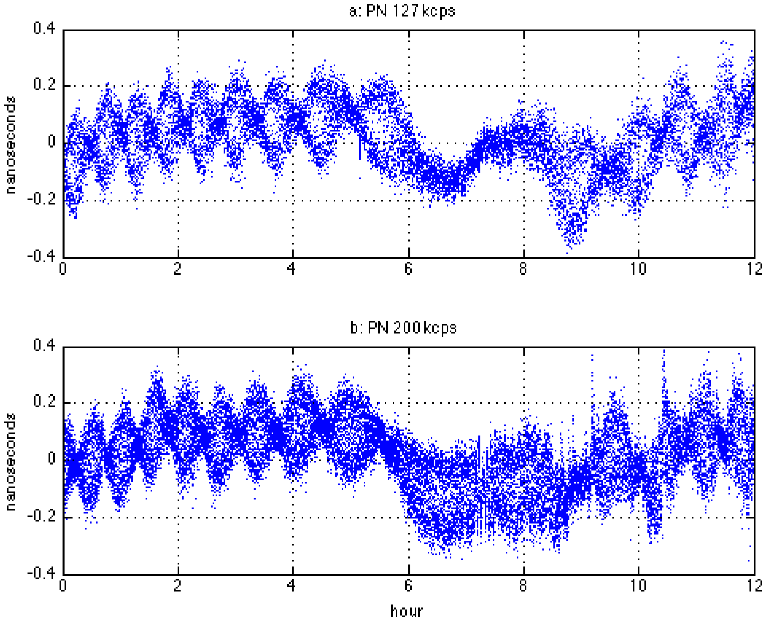

Figure 5. DPN time transfer results.

C. Combination of PRN Code and Tone Signal

Because we estimate the group delay by using the slopes of the LSB and USB phases, a tone signal is also available as a transmission signal when it provides feasible phase information. Therefore, we were considered an alternative signal scheme where one station transmits the signal with the PRN code as the LSB and the tone signal as the USB, while the other station transmits the tone signal as the LSB and the signal with the PRN code as the USB. These half and half signals do not arise from interference between the PRN codes. The drawbacks of this signal are that the pair of stations only compares clocks, and the tone signal is weaker because of noise than the PRN code.

Figure 6 (a) to (c) show the group delays of the round trip signals. Figure 6 (a) and (b) show the result for one and two DPN transmission signals with a 200 kHz chip rate, respectively, and (c) shows the half and half signal. Each point in these plots shows the quadratic fit residuals with a coherent integration time of 20 ms. When we transmit the PRN code and tone signal simultaneously, the group delays obtained from the PRN codes have undesirable periodical variations.

Figure 7 (a) to (c) show similar observations when the chip rate is 127.75 kHz. In this case, the degradation of the round trip measurements is not seen when transmitting the PRN code and the tone signal simultaneously.

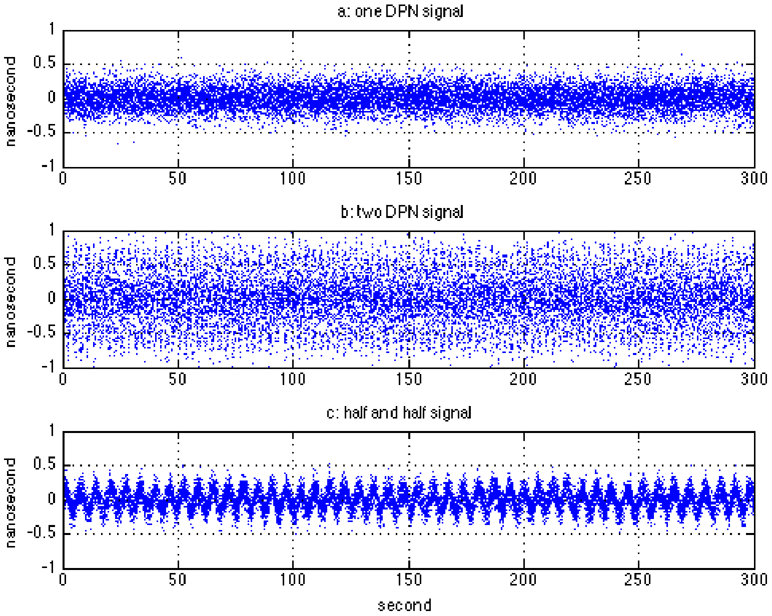

Figure 6. Quadratic fit residuals of 200 kHz chip frequency.

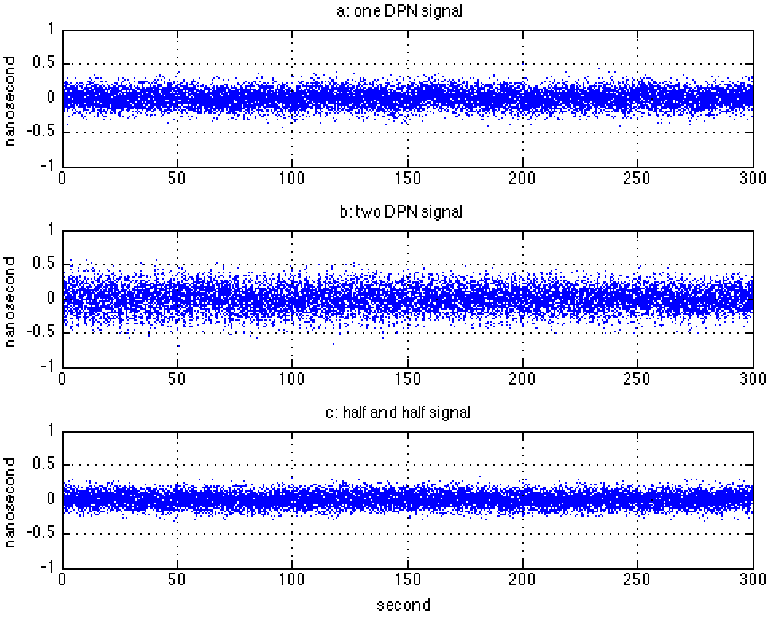

Figure 7. Quadratic fit residuals of 127 kHz chip frequency.

III. SIGNAL COMPARISON EXPERIMENTS

To observe the difference between the DPN signal and the half and half signal, we performed time transfer experiments between the Koganei and Kashima stations using a geostationary communication satellite. Real-time processing with the DPN signal was possible; however, post processing was necessary for the half and half signal. We therefore stored sampling signals every 20 seconds with time intervals of 10 minutes to the hard disk on the PC, and estimated the group delays through a post correlation process. The DPN signal used the PRN code with a chip frequency of 200 kHz, and the half and half signal used the chip frequency of 127.75 kHz.

Figure 8 (a) shows the time transfer results of the DPN signal, and (b) shows the results of the half and half signal. The bias and drift components were removed from both results. No apparent periodical variations are seen in the half and half signal, but they are clearly seen in the DPN signal. However, diurnal variations of about 1 ns peak-to-peak are seen in both plots.

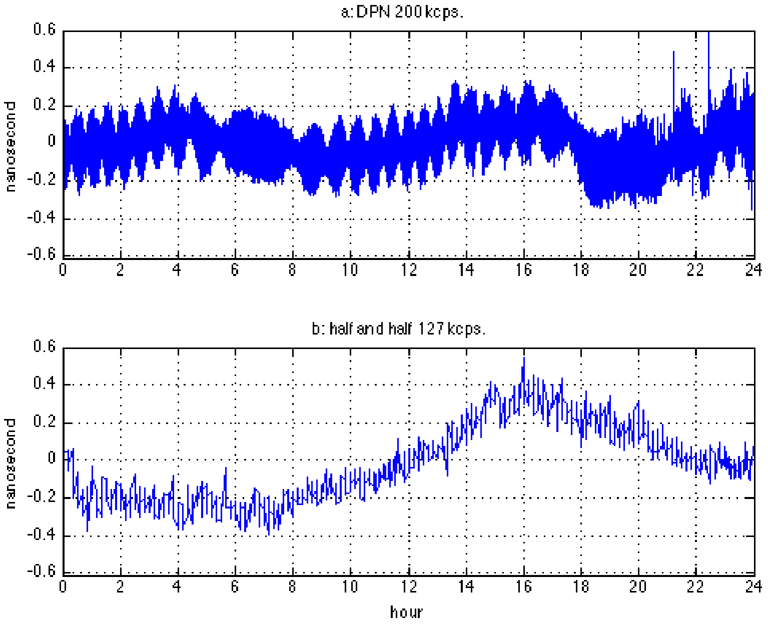

Figure 8. Time transfer results using the DPN and half and half signals.

IV. CONCLUSION

We investigated the interference noise of the DPN signal, and proposed an alternative signal scheme to reduce this noise. The short-term observation errors can be reduced by using a combination of the PRN code and the tone signal. Because diurnal variations remained when using the half and half signal, we will continue to investigate the reason for these variations using environment data such as the temperature variation of the low-noise amplifier (LNA).

We also demonstrated the flexibility of software-based correlation in this paper. Software correlation can easily change the transmission signals, e.g. from the PRN code to the tone signal.

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