A New Modem for Two Way Satellite Time and Frequency Transfer

Shengkang Zhang*+, Xueyun Wang *, Haifeng Wang*, Hongbo Wang*, Yuan Yuan*, Keming Feng*
*Metrology and Calibration Laboratory, Beijing Institute of Radio Metrology& Measurement, Beijing, China
+Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, U.S.A.
E-mail: Zhangsk@126.com

Abstract— **A new time transfer modem for two-way satellite time and frequency transfer (TWSTFT) has been developed recently at Beijing Institute of Radio Metrology and Measurement (BIRMM). The DSSS and BPSK modulation techniques are used to generate a PRN signal. A FFT fast parallel algorithm is applied to achieve fast acquisition of the PRN modulated receiving signal. A 2nd order FLL assisted 3rd order PLL is designed to keep both of the performance of loop dynamic stress and carrier phase tracking accuracy, and a 2nd order DLL is used to track and measure the code phase. A short baseline TWSTFT experiment was done with two 1.2 m VSAT earth stations and a commercial geosynchronous orbit communication satellite to evaluate the modem's performance. The result shows very low noise with the standard deviation (1 σ) equal to 0.13 ns at a 2.5 MChip/s code rate.**

Keywords—two-way satellite time and frequency transfer (TWSTFT); modem; acquisition; phase lock loop; delay lock loop

I. INTRODUCTION

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is a precise time and frequency comparison technique, which is widely used in time metrology [1-2], time synchronization in the applications of satellite navigation, radio ranging and measurement [3], etc. Its performance is better than that of GPS common-view [4-5]. The TWSTFT result has no data boundary discontinuity and we can obtain the results more directly and quickly compared to GPS carrier-phase time transfer [6-7]. Nowadays, many time metrology laboratories in Europe, United States and Asia established TWSTFT links. Time transfer modem is the most crucial instrument in TWSTFT system. The modem's transmitter unit (Tx) modulates a timing signal (in some case, the one pulse per second (1 PPS) signal) from a reference clock onto the pseudorandom noise (PRN) codes and outputs the Tx signal at intermediate frequency (IF) The IF signal is then up-converted to the radio frequency (RF), amplified, and transmitted to the satellite. The received RF signal is again amplified, down-converted to IF, and demodulated by the modem's receiver unit (Rx). The time interval between the Tx 1 PPS and Rx 1 PPS is measured on each site. Based on the reciprocity of the TWSTFT signals' bidirectional paths, the time offset of the two clocks are obtained by exchanging and differencing the time interval measurements at the two sites [8].

Due to the limit of Rx channels in a modem, most TWSTFT operations have to switch between links. That is, a station can only do TWSTFT with up to three stations simultaneously, and the station has to change the Tx and Rx settings for doing TWSTFT with another group of stations. It usually takes from about 40 s to 1 min to change the settings and to lock on a set of new Rx signals. This link switch scheme makes TWSTFT operations less efficient. The time spent on the link switch can be used to extend the measurement period and that may improve the link performance.

To increase the efficiency of TWSTFT operation, a new time transfer modem for TWSTFT has been developed recently at Beijing Institute of Radio Metrology and Measurement (BIRMM). In this instrument, we generate the Tx IF signal by direct sequence spread spectrum (DSSS) and binary phase-shift keying (BPSK) modulation. In order to retain the performance of loop dynamic stress and carrier phase tracking accuracy, a 2nd order frequency lock loop (FLL) assisted 3rd order phase lock loop (PLL) are designed, and a 2nd order delay lock loop (DLL) is used to track and measure the code phase. The Rx of modem is accomplished by a field-programmable gate array (FPGA) and digital signal processing (DSP) based all-digital structure. Using this structure, we can increase the processing ability of the Rx PRN signals. Thus, the Rx channel can be extended easily to about eight or even more without any extensions on the hardware. A fast Fourier transform (FFT) algorithm is achieved for signal acquisition which significantly decreases the time needed for Rx signal search and lock.

In the first phase to evaluate the performance of the modem, a short baseline experiment was done. Two rubidium (Rb) clocks are used as the time and frequency references for two BIRMM modems. A TWSTFT link is established by two 1.2 m dish earth stations using the ChinaSat N10 satellite. The modems measured the time difference of Tx 1 PPS – Rx 1 PPS, where the Tx 1 PPS is derived from the local Rb clock and the Rx 1 PPS is derived from the remote Rb clock plus the delay of the signal path. Meanwhile, a commercial time interval counter (TIC) is used to directly measure the two Tx 1 PPS signals. Then we difference the TWSTFT and TIC measurements, which show quite small instability with standard deviation (1 σ) equal to 0.13 ns at a 2.5 MChip/s code rate.

II. DESIGN OF THE MODEM

A. Structure of the Modem

This paper is partly financed by China Scholarship Council (CSC).

The modem is mainly composed of a modulator unit, an demodulator unit, an embedded Rb clock unit, a TIC unit, a frequency distribution amplifier (FDA) unit, a frequency synthesizer unit, a pulse distribution amplifier (PDA) unit, a 12 times frequency multiplier unit, a Global Positioning System (GPS) receiver and its antenna, etc. Fig. 1 shows the block diagram of the modem structure and its inner connections. The Rb clock is the frequency reference of all the units in the modem, which is distributed by a FDA. The modulator unit generates the PRN codes and data to be transmitted, and then modulates them on a 70 MHz carrier. In case of demodulating, the 70 MHz Rx signal is initially preprocessed by an automatic gain controller (AGC) to make the signal voltage level stable. Then the stabilized signal is digitalized by an analog to digital (AD) converter in the demodulator unit. After that the code in the digital signal is acquired, which will be used for the next tracking process. Signal tracking is the most critical part for the modem. It's divided into two loops called the carrier loop and code loop. The carrier loop tracks the carrier phase and frequency. The code loop follows the code phase variation.

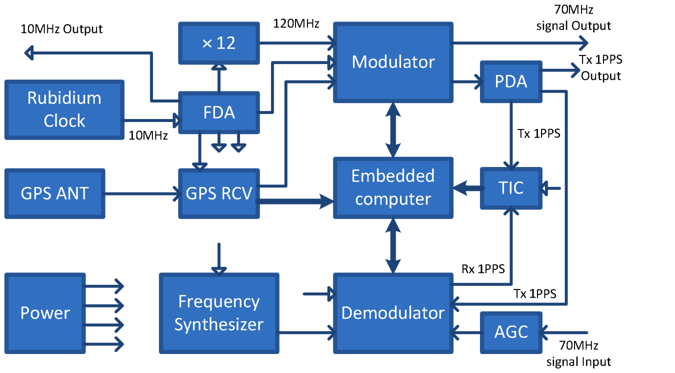


Fig. 1. Block diagram of BIRMM modem (The hollow arrows in the diagram indicates 10MHz references from the FDA to different functional unit.).

B. Signal Modulation

Signal modulation is used to generate the PRN direct sequence spread spectrum signal and to modulate the Tx 1 PPS and the Tx – Rx data measured by the modem using BPSK. The logic block is shown in Fig. 2. The embedded computer sends the data and commands through a serial communication (COM) port. Then data are decoded and buffed before they are formed to a whole frame and coded with cyclic redundancy check (CRC). Each time a 1 PPS signal arrives, a frame is generated. The frame consists of a header, timestamp, delay measured by demodulator unit and CRC segment. Each frame is comprised of 500 bits. After that, the frame is modulated to a sequence of PRN codes and a transient digital carrier at 15 MHz. Fig. 3 provides the spectrum graph measured by a spectrum analyzer. Then, it is up-converted and transformed to a 70 MHz analog signal.

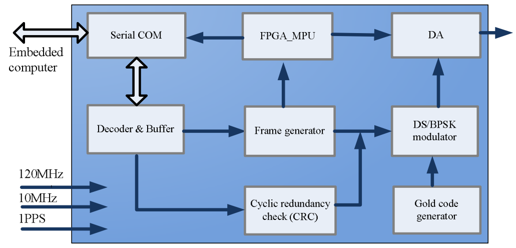


Fig. 2. Signal modulation functional diagram.

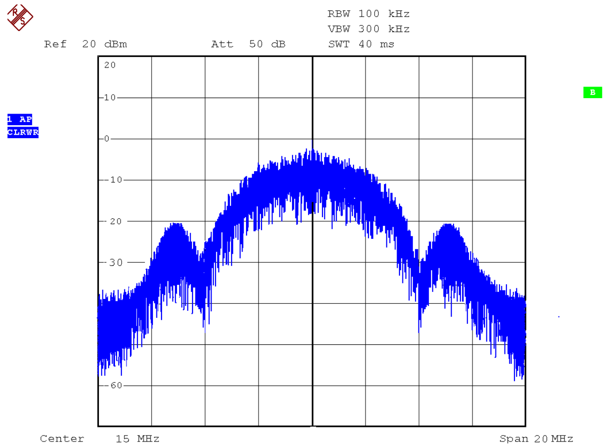


Fig. 3. Signal spectrum measured at transient intermediate frequency.

C. FFT Fast Acquisition

Signal acquisition is the first step to start the measurement. A commonly used method called moving correlator is utilized to slide the local code phase and to correlate them with the received code. It will take some time to find the correlation by this serial search method, especially when the PRN code is quite long. FFT based acquisition is an all-digital fast algorithm to acquire the coded signal. Fig. 4 illustrates the flow chart of the algorithm. The local codes are calculated, transformed to the frequency domain by FFT, conjugation processed, and then stored in memory for use in the correlation process. Each time the acquisition function starts, the Rx digital signal sequence collected flows to a data buffer and is multiplied by an estimated local digital carrier to remove the carrier. After carrier removal, the data sequence is filtered by an interpolation and decimation filter. Then it is transformed to the frequency domain by FFT processing. The spectrum data sequence of Rx signal is then multiplied by the local sequence, and transformed to the time domain by inverse FFT (IFFT) process. From the amplitude of the IFFT output, it can be identified if the correlation is found. If there is no peak large enough to be identified, the estimated carrier frequency will be adjusted until a peak appears. In the BIRMM modem, the frequency adjustment step is 500Hz, and the carrier searching range is ±10 kHz. This allows the signal to be acquired quickly even if there is a quite large frequency offset, which is a common case in many TWSTFT links.

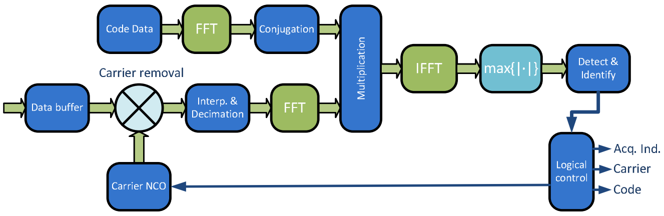


Fig. 4. Flow chart of FFT acquisition algorithm.

Fig. 5 shows a simulation plot of the FFT acquisition. When the code is matching and the estimated carrier frequency is close enough to the received intermediate frequency, a large peak will come out. If the peak is larger than a predetermined threshold, it means that the correlation of Rx signal is found. The corresponding value of the peak on the carrier frequency axis and code phase axis indicates the estimated carrier frequency and code phase, respectively.

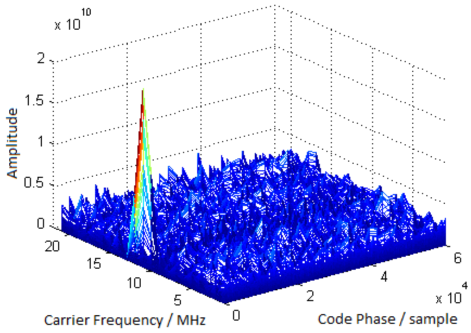


Fig. 5. Simulation of FFT acquisition.

D. *Carrier and Code Tracking*

A carrier tracking loop steers the local reference frequency to follow the phase and frequency of the carrier. A code tracking loop measures the code phase. They are the most delicate parts which affect the modem performance directly. A narrow band 3rd order PLL is designed to track and measure the carrier phase or frequency precisely. However, sometimes, it may lose lock due to interference, an oscillator transient jump, or other dynamic stress. Therefore a 2nd order FLL is also included to assist tracking the carrier. If a large frequency jump occurs, the FLL will soon find the frequency offset and pull the PLL to a new balance.

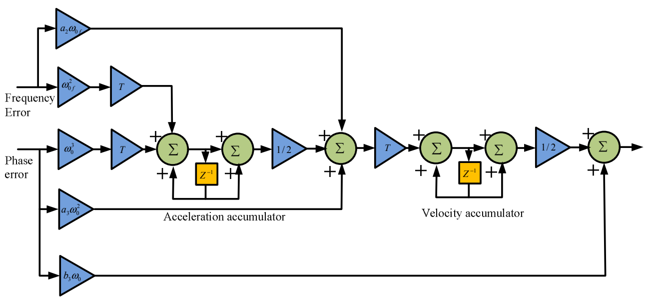


Fig. 6. Diagram of the 2nd FLL assisted 3rd PLL designed in the BIRMM modem.

A code tracking loop aligns the local code with the restored code signal and measures the phase. Code tracking is fulfilled by a 2nd order DLL in the modem. The code phase discriminator is achieved by a normalized non-coherent early minus late envelope algorithm which is not sensitive to amplitude variation. Figure 7 shows the loop filter structure of the DLL. It is a first order filter with a differential equation as in eq. (1), where $e_c(k)$ is the digital sample of code phase error, $y(k)$ is the output of the filter, and ω_n is the natural radian frequency of the DLL that directly affects the loop's bandwidth.

$$y(k) = y(k-1) + \frac{(\sqrt{2}\omega_n + \omega_n^2 T)}{K} e_c(k) - \frac{\sqrt{2}\omega_n}{K} e_c(k-1) \cdots\cdots\cdots (1)$$

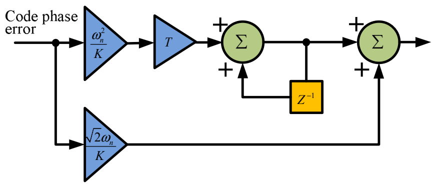


Fig. 7. Diagram of the 2nd DLL filter structure used in the modem.

III. EXPERIMENTS AND DISCUSSIONS

In order to evaluate the performance of the BIRMM modem, a short baseline experiment was done. The devices used and the cable connections of the experimental system are illustrated as shown in Fig. 8. In the system, two 1.2 m diameter dishes and two Aancom transceivers are used as the earth station (ES). Two BIRMM modems with Rb clocks as references in their interior are connected to the earth stations. Then, the short baseline TWSTFT link was established using the Chinasat N10 commercial communication satellite. The modem makes the Tx – Rx measurements every second. The interval of the two Tx 1 PPS derived by the two internal Rb clocks is obtained from the difference of the two TWSTFT measurements. At the same time, a TIC is used to measure the same interval. The nominal resolution of the TIC measurements is 50 ps. Fig. 9 shows the experimental system on a building roof separated about only several meters. Thus, the difference of time of arrival (TOA), ionosphere delay, Sagnac effect, and some other nonsymmetrical effects in TWSTFT are eliminated.

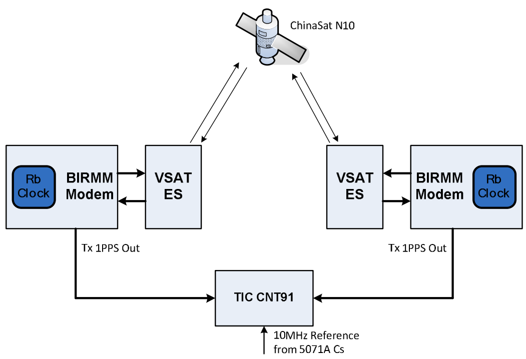
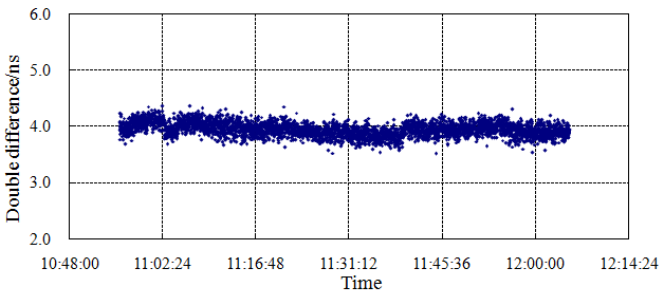


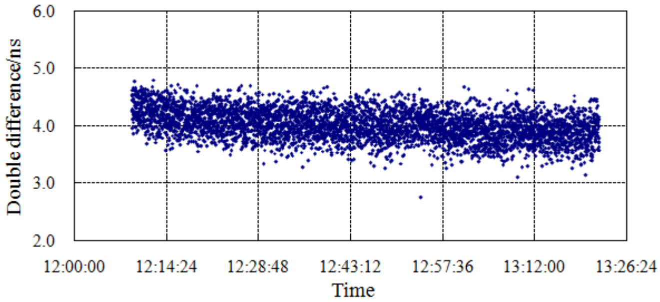
Fig. 8. Short baseline experimental system diagram.

Fig. 9. Experimental system image with two 1.2 m dishes and two transceivers (The device in red frame is the BIRMM modem developed.).

Theoretical, the results from the TWSTFT and the TIC measurements should be absolutely the same because they are measuring the same physical signals. In practice, the device delay and cable delay make the measurements quite different. The variation of the double differences between the TWSTFT and TIC measurements indicates the performance of the BIRMM modem, because the TIC measurement is simple and should be more stable. Fig. 10 shows the results of the double differences. Two different code rates are tested in the experiments. In case of the 2.5 MChip/s code rate, the double differences have an average value of 4 ns, and have instability with standard deviation (1 σ) equal to 0.13 ns. When code rate changed to 1 MChip/s, the mean value is almost the same. But the jitter becomes larger with the standard deviation (1 σ) equal to 0.26 ns.



(a) With chip rate at 2.5 MChips/s, standard deviation (1σ) equals 0.13 ns



(b) With chip rate at 1 MChips/s, standard deviation (1σ) equals 0.26 ns

Fig. 10. Double difference of the two Tx 1 PPS between modem and TIC.

Currently, the modem collects data at a rate of one point per second, and there isn't any smoothing process. In fact, those data can be smoothed such as with N seconds. In this circumstance, the data instability will decrease with a factor of $1/\sqrt{N}$. For example, if the data is smoothed with a average time of 100 s, the data jitter of 2.5 MChip/s code will be about 13 ps.

Besides, the FFT acquisition algorithm decreases the link initializing time greatly. Basically, the total time required for acquisition and lock together is far less than 1 s. But because a data exchange is needed in the TWSTFT link, it takes about 5 s to get the first TWSTFT time difference value in the actual test.

ACKNOWLEDGMENT

Special thanks are given to Victor Zhang, Tom Parker and Mike Lombardi at the Time and Frequency Division of NIST for their reviews of this manuscript.

REFERENCES

[1] V. Zhang and M. A. Lombardi, "Time and Frequency Transfer Activities at NIST," Proc. 40th Precise Time and Time Interval (PTTI) Meeting, pp. 623-639, 2008.

[2] M. Imae, M. Hosokawa and K. Imamura, "Two-way satellite time and frequency transfer networks in Pacific Rim region," IEEE Trans. on Instrumentation and Measurement, vol. 50, no. 2, pp. 559-562, 2001.

[3] S. Zhang, L. Zhang and Y. Yang, "Ultra-Short Term Clock Offset Prediction for Two-Way Satellite Time Synchronization," 2013 Joint UFFC, EFTF and PFM Symposium, pp. 335-338, 2013.

[4] W. H. Tseng, S. Y. Lin, H. M. Peng, H. T. Lin and C. S. Liao, "The comparsion between TWSTFT and GPS time transfers on inter-continental baseline links," Proceedings of 20th Eruopean Frequency and Time Forum, pp. 557-561, 2006.

[5] W. Lewandowski, J. Azoubib, W. J. Klepczynski GPS: Primary Tool for Time Transfer. Proceedings of the IEEE. Vol. 87, no.1, pp. 163-172, 1999.

[6] J. Yao, and J. Levine, "GPS measurements anomaly and continuous GPS carrier-phase time transfer," Proc. 46th ION Precise Time and Time Interval (PTTI) Meeting, pp. 164–169, 2014.

[7] J. Yao, and J. Levine, "A new algorithm to eliminate GPS carrier-phase time transfer boundary discontinuity," Proc. 45th Precise Time and Time Interval (PTTI) Meeting, pp. 292–303, 2013.

[8] D. Kirchner, "Two-way time transfer via communication satellites," Proceedings of the IEEE, vol.79, no.7, pp. 983 -990, 1991.