Application of ANFIS for Frequency Syntonization Using GPS Carrier-Phase Measurements

Kun-Yuan Tu
Dept. of Computer Science and Information Engineering
Vanung University
Chung-Li, Tao-Yuan, Taiwan, R.O.C.
kytu@msa.vnu.edu.tw

Chia-Shu Liao
National Standard Time & Frequency Lab., TL
Chunghwa Telecom Co., Ltd.
Yang-Mei, Taoyuan, Tawan, R.O.C
csliao@cht.com.tw

***Abstract*—A new scheme of frequency syntonization based on the GPS carrier-phase measurements using an adaptive neural-fuzzy inference system (ANFIS) is proposed in this paper. A GPS carrier-phase disciplined oscillator (GPSCDO), which uses pure carrier-phase measurements to steer an oven-controlled crystal oscillator (OCXO) has been designed. High short-term frequency stability of the GPSCDO is obtained. However, like traditional GPSDO, the long-term performance of the GPSCDO is limited due to the atmospheric effect. Therefore, an ANFIS is employed in an attempt to improve the long-term frequency stability of the GPSCDO. By applying the off-line data, which are predicted by the ANFIS, the remote GPSCDO can correct its estimations of the frequency offsets, which is used as input of a fuzzy controller. Experimental results show that for averaging times of one day, the frequency stability of the GPSCDO can be improved from a few parts in 10^{12} to 10^{14} .**

I. Introduction

Precise frequency sources play important roles in high-speed communications, navigations, power systems, instrumentation and in numerous other applications [2][10]. The technique of GPS disciplined oscillators (GPSDOs) is one of the principal methods of maintaining worldwide high accuracy time and frequency dissemination. The GPSDOs are usually based on C/A code observations nowadays. Therefore, the short-term frequency stability of the GPSDOs is limited due to the lower resolution of the C/A code. From experiences of positioning, it is well known that the signal quality of GPS carrier phases is much better than that of GPS codes. Hence, higher performance of time and frequency techniques is expected if the GPS carrier phases are considered. The possibility of using the pure carrier phase measurements to steer the OCXO is investigated in this paper. In addition, a new scheme of frequency syntonization by using an adaptive neural-fuzzy inference system (ANFIS) is proposed. The frequency variations mainly caused by the atmospheric effect are predicted by the ANFIS. The predicted data is then applied to the GPSCDO in order to improve its long-term performance. Experimental results show that the performance of the GPSCDO is higher than the conventional ones about two orders.

This paper is organized as follows:

1) Section II presents models of GPS carrier phase observables and the ANFIS architecture.
2) Section III describes the system architecture.
3) The experimental results are illustrated in Section IV.
4) Finally, the concluding remarks are given in Section V.

II. Methord

A. GPS carrier phase observables

The typical model of GPS carrier phase observables is [1][5][7]

$$\Phi_A^j = \rho_A^j + c(dt^j - dT_A) + \lambda N_A^j - d_{ion}^j + d_{trop}^j + \varepsilon_A^j , \quad (1)$$

where

- Φ_A^j carrier phase measurement of the receiver from the *j*th GPS satellite in meter;
- ρ_A^j true distance between the receiver and the *j*th GPS satellite;
- c speed of light;
- dt^j clock bias of the *j*th satellite;
- dT_A the clock difference between the GPS time and receiver clock;
- λ GPS carrier wavelength;
- N_A^j initial phase integer ambiguity;
- d_{ion}^j the ionospheric delay;
- d_{trop}^j the tropospheric delay;
- ε_A^j unmodeled error primarily due to multipath, temperature variation, physical factors, etc.

This work was supported by the National Science Council of the Republic of China under contract number NSC 95-2218-E-238 -001.

To achieve the frequency syntonization using GPS carrier phase, this paper first examines the behavior of the oscillator. Hence, the GPS receiver clock is synchronized to an external reference. Under this arrangement, the term dT_A in (1) represents the time difference between the external clock and the GPS clock. In addition, if the satellite signal is continuously tracked and there is no cycle slip occurring, the difference of cycle ambiguities remains a constant. Accordingly, this study takes the difference on (1) with respect to different times to obtain the time-difference model

$$\delta\Phi_A^j = \delta\rho_A^j + c(\delta dt^j - \delta dT_A) - \delta d_{ion}^j + \delta d_{trop}^j + \delta\varepsilon_A^j , \quad (2)$$

where $\delta(\cdot)$ denotes the operator for differences between two epochs.

B. ANFIS architecture

The ANFIS architecture used in this study is shown in Fig. 2. All data processing and scheme generation was done using MATLAB and the Fuzzy Logic Toolbox. The number of membership functions (mf_i) assigned to each input of the ANFIS was arbitrarily set to 2, so the rule number is 16. The ANFIS used here contains a total 104 fitting parameters, of which 24 are premise parameters and 80 are consequent parameters [8].

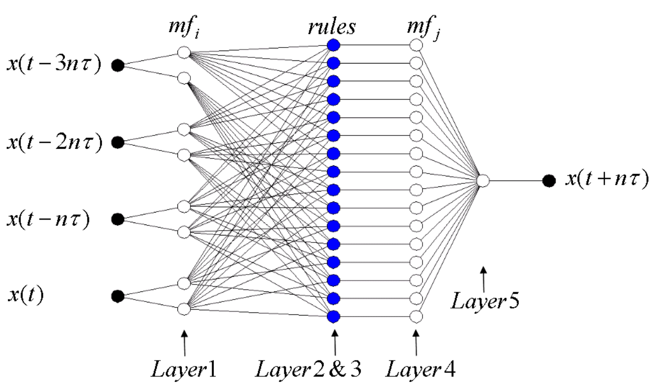

Figure 1. The ANFIS architecture employed in this study.

In this study, a Type-3 ANFIS, as defined by Jang, was employed [8]. By definition, a Type-3 ANFIS employs a first-order Sugeno fuzzy model [4][8], dictated by the following rule base structure:

$$\textit{if } \boldsymbol{x} \textit{ is } \boldsymbol{A} \textit{ and } \boldsymbol{y} \textit{ is } \boldsymbol{B}, \textit{ then } z = px + qy + r , \quad (3)$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ are fuzzy sets for the input and p, q, and r are constants. The inputs to the ANFIS are the phase differences between the external cesium cock and the GPS. The output of the ANFIS is a predicted phase data.

For the ANFIS employed in the study, the node functions in Layer 1 are all bell-shaped with maximum equal to 1 and minimum equal to 0, such as

$$\mu_{A_i}(x) = \frac{1}{1 + [\left(\frac{x - c_i}{a_i}\right)^2]^{b_i}} , \quad (4)$$

where $\{a_i, b_i, c_i\}$ is the parameter set.

Every node in Layer 2 multiplies the incoming signals and sends the product out. The output of this layer (w_i) is given by

$$w_i = \mu_{A_i}(x(t-3n\tau)) \times \mu_{B_i}(x(t-2n\tau)) \times \mu_{C_i}(x(t-n\tau)) \times \mu_{D_i}(x(t)) \quad (5)$$

In Layer 2, each node output is then fed to Layer 3 to determine the individual rule's firing strengths as a ratio of all the rules firing strengths. For the nth node in this layer, the output of this layer (normalized firing strength) is given by

$$w_n = \frac{w_n}{w_1 + w_2 + \ldots w_i} \quad (6)$$

Every node in Layer 4 multiple the normalized firing strengths by the consequent parameters

$$\text{output} = w_i f_i \text{ , where } f_i = p_i x + q_i y + r_i , \quad (7)$$

where $\{p_i, q_i, r_i\}$ is the parameter set. The output of this layer is passed to the final layer (Layer 5), which computes the weighted average of all the outputs to generate a summarized output signal

$$\text{Over all output} = \frac{\sum w_i f_i}{w_i} \quad (8)$$

III. System Architecture

Fig. 2 shows the functional block diagram of our system. It consists of the reference station and the remote station. The reference station contains a cesium atomic clock, L1 GPS receiver, and PC. The GPSCDO is placed at the remote station, which includes the low-cost oven-controlled crystal oscillator (OCXO), L1 GPS receiver, D/A converter and PC. Through the data links, the off-line data, which are predicted by an ANFIS, are then sent to the remote stations.

The external clocks at both stations are connected to GPS receivers in order to estimate the frequency offsets with respect to the GPS. Therefore, the frequency offsets can be estimated by performing the time-difference [i.e., (2)]. In the process, the integer cycle ambiguities in (1) can be eliminated and the biases and errors from satellites and receivers can be reduced. (2) can be further expressed as follows:

$$\delta\Phi_A^j - \delta\rho_A^j = c(\delta dt^j - \delta dT_A) - \delta d_{ion}^j + \delta d_{trop}^j + \delta\varepsilon_A^j , \quad (9)$$

in which the left-hand side of the equation is the difference of measured data and known values. This term $\delta dT_A(t_i)$ (= $dT_A(t_i) - dT_A(t_{i-1})$, where $t_i = t_{i-1} + \tau$) can be obtained by averaging (2) for all-in-view GPS observations. Since dT_A is the phase differences between primary clock and the GPS, the associated frequency offset is [6][9]

$$y_\tau(t_i) = \frac{\delta dT_A(t_i)}{\tau}, \qquad (10)$$

where τ is the observation interval.

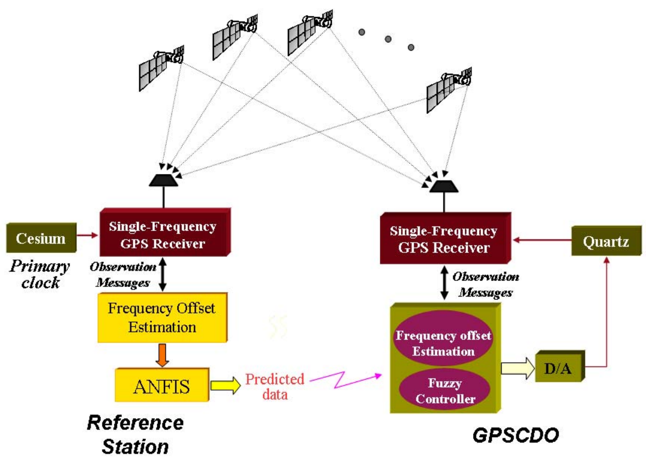

Figure 2. Functional block diagram of our system.

In general, the fine frequency tuning can be performed on the inexpensive oscillator through voltage control. Because of environmental effects such as vibration, temperature, pressure, and humidity, the desired frequency output is not always under a constant voltage. In our system, the frequency offset $y_\tau(t_i)$ and its change $\Delta y_\tau(t_i)$ $(= y_\tau(t_i) - y_\tau(t_{i-1}))$ are chosen as the input variables of fuzzy controller.

A. Fuzzy Controller

The block diagram of the fuzzy controller applied in our system is shown in Fig. 3. The inference engine part in Fig. 3 contains the knowledge-base of a fuzzy controller, which is composed of two components, the data base and the fuzzy control rule base.

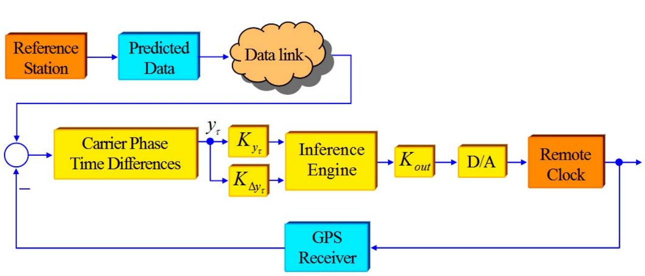

Figure 3. Fuzzy control block diagram.

The input space is divided into five sets:

1) negative big (NB);
2) negative small (NS);
3) zero (ZE);
4) positive small (PS);
5) positive big (PB) for a frequency offset or its change.

In this study, triangular-shaped membership functions (MFs) are chosen for the control input variables due to their simple structure and computation. The sets were designed to be closer to the desired value of zero in order to provide precise control. The control output is determined from the center-average method formulated as follows:

$$u^0 = K_{out} \frac{\sum_{i=1}^{n} w_i u_i}{\sum_{i=1}^{n} u_i}, \qquad (11)$$

where

K_{out} output control gain;
w_i grad of the ith output MF;
u_i output label for the value contributed by the ith MF;
n number of contributions from the rules.

The rules in the fuzzy controller are based on the process frequency offset y_τ and its change Δy_τ. These rules are expressed as

$$\textit{If}\ \{ y_\tau\ \textit{is}\ \textbf{\textit{ZE}}\ \textit{and}\ \Delta y_\tau\ \textit{is}\ \textbf{\textit{ZE}} \},\ \textit{then}\{ \boldsymbol{u}\ \textit{is}\ \textbf{\textit{ZE}} \} \qquad (12)$$

The rule table is shown in Fig. 4.

Δy_τ \ y_τ	LN	SN	ZE	SP	LP
LN	LP	LP	LP	LP	LP
SN	LP	SP	SP	ZE	ZE
ZE	SP	SP	ZE	SN	LN
SP	ZE	ZE	SN	SN	LN
LP	LN	LN	LN	LN	LN

Figure 4. Fuzzy rule table.

IV. Experimental Results

The experimental structure for tests is shown in Fig. 2 in Section III. In the reference station, the 10 MHz of the cesium clock (HP5071A) used as primary clock was connected to a GPS receiver. The predicted phase data were passed to the remote station via the Internet. An OCXO (Datum™ FTS1130) was used as remote clock. In our experiment, the software, including the fuzzy controller, communication interfaces such as the Internet, and data collection, were designed in C.

In the reference station, the phase differences between the cesium clock and the GPS were obtained by accumulating the frequency offsets y_τ. This study chose about six-day input-output phase data pairs of the following format:

$$[x(t-3\tau), x(t-2\tau), x(t-1\tau), x(t); x(t+1\tau)] \quad (13)$$

The first one-day pairs were used for training the ANFIS while the remaining about five-day pairs were used for validating the identified model. After 200 epochs, we had $RMSE_{chk} = 9.437\times10^{-11}$ s. Fig. 5 illustrates the test for the ANFIS where the desired values in Fig. 5(a) and predicted values in Fig. 5(b) for both training data and checking data are essentially the same; their differences can only be seen on a finer scale.

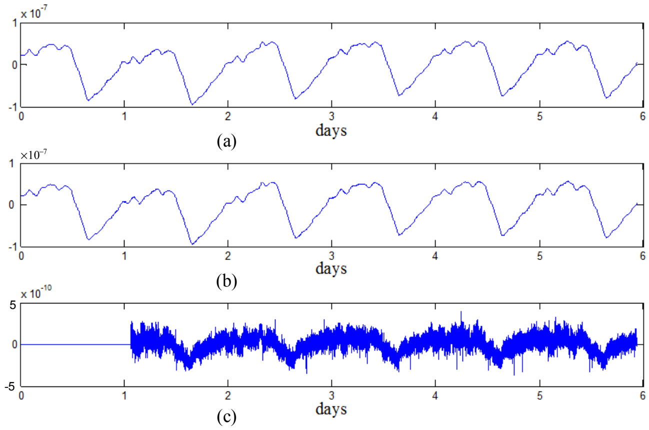

Figure 5. (a) Phase differences between the cesium clock and the GPS. (b) Predicted data of the NFIS. (c) Prediction errors.

We examined the performance of the free running OCXO used in our system, OCXO under carrier-phase discipline (GPSCDO) and the GPSCDO applied the predicted data. These frequency analyses are shown in Fig. 6. The OCXO line in Fig. 6 shows the frequency instability. The GPSCDO line shows high short-term frequency stability. However, its performance is degraded over averaging times between 1000 s and one day due to the satellite clock bias, the atmosphere effects, etc. The ANFIS line reveals the high frequency stability of the remote clock not only over the short term, but also over the long term. The frequency stability of the GPSCDO could be improved from a few parts in 10^{12} to 10^{14} for average times of one day.

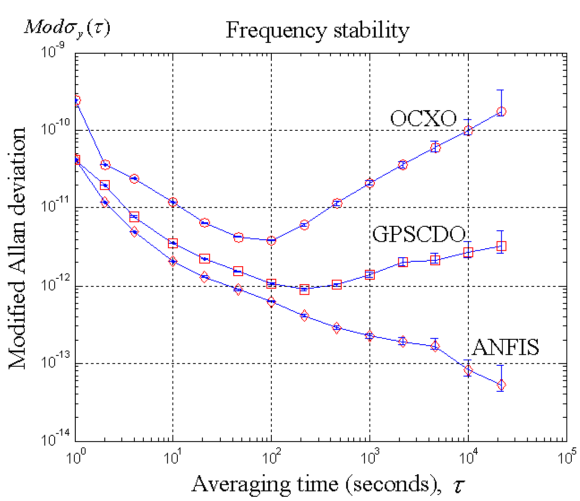

Figure 6. Frequency stability analyses of the free running OCXO (OCXO line), GPSCDO (GPSCDO line) and the GPSCDO assisted by the ANFIS.

V. Conclusions

The present results demonstrate the feasibility of predicting phase differences between the external clock and the GPS using an ANFIS. By applying the off-line predicted data, the remote GPSCDO can improve its long-term performance. Experimental results show that our system is sound and cost effective. A further study will be done on the investigation of other frequency control system by applying the proposed method.

Acknowledgment

This work was supported by the National Science Council of the Republic of China under contract number NSC 95-2218-E-238 -001.

References

[1] B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, Global Positioning System: Theory and Practice, Springer-Verlag Wien New York, 1994.

[2] B. J. Cory, P. F. Gale, “Satellites for power system applications,” Power Engineering Journal, vol. 7, no. 5, Oct. 1993, pp. 201 – 207.

[3] D. B. Sullivan, D. W. Allan, D. A. Howe, F. L. Walls, Characterization of Clocks and Oscillators, Boulder, Colorado, March 1990.

[4] D. Drianko, H. Hellendoorn, and M. Reinfrank, An Introduction to Fuzzy Control, New York: Springer-Verlag, 1992.

[5] D. Wells, Gude to GPS Positioning: Canadian GPS Associates, 1996.

[6] Definitions and Terminology for synchronization, Int. Telecommun. Union, Telecommun. Stand. Sector (ITU-T), G. 810, Ag. 1996.

[7] E. D. Kaplan, Understanding GPS: Principles and Application, Artech House, London, 1996.

[8] J. S. Jang, “ANFIS: Adaptive-network-based fuzzy inference system,” IEEE Trans. Syst., Man, Cybern., vol. 23, no. 3, pp. 665-685, May-Jun. 1993.

[9] Timing characteristics of primary reference clocks, Int. Telecommun. Union, Telecommun. Stand. Sector (ITU-T), G. 811, Sept. 1997.

[10] W. Lewandowski, J. Azoubib, W.J. Klepczynski, “GPS: Primary Tool for Time Transfer,” Proceedings of the IEEE, vol. 87 Issue: 1, Jan. 1999, pp. 163 –172.