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A Design of LORAN Disciplined Oscillator

Sang-wook Hwang[1], Yun Sub Choi[1], Sang-Rae Yeo[1], Chansik Park[2], Sung-Hoon Yang[3], Sang Jeong Lee[1†]
[1]Department of Electronics Engineering, Chungnam National University, Daejeon 305-764, Korea
[2]Department of Electronics Engineering, Chungbuk National University, Cheongju 361-763, Korea
[3]Division of Physical Metrology, Korea Research Institute of Standards and Science 305-340, Korea

ABSTRACT

This article presents the design of long range navigation (LORAN)-disciplined oscillator (LDO), employing the timing information of the LORAN system, which was developed as a backup system that corrects the vulnerability of the global positioning system (GPS)-based timing information utilization. The LDO designed on the basis of hardware generates a timing source synchronized with reference to the timing information of the LORAN-C receiver. As for the LDO-based timing information measurement, the Kalman filter was applied to estimate the measurement of which variance was minimized so that the stability performance could be improved. The oven-controlled crystal oscillator (OCXO) was employed as the local oscillator of the LDO. The controller was operated by digital proportional-integral-derivative (PID) controlling method. The LDO performance evaluation environment that takes into account the additional secondary factor (ASF) of the LORAN signals allows for the relative ASF observation and data collection using the coordinated universal time (UTC). The collected observation data are used to analyze the effect of ASF on propagation delay. The LDO stability performance was presented by the results of the LDO frequency measurements from which the ASF was excluded.

Keywords: LORAN-C, eLoran, ASF, OCXO, disciplined oscillator, timing stability

1. INTRODUCTION

The conventional precise timing information is national basic infrastructural information that is necessary to the extensive applications in the military and industrial technologies. As the GPS began to be widely operated and commonly applied in the late 1980's, timing information is also greatly dependent on it, and timing information with the precision of tens of nanoseconds can be provided by it (Lombardi 2008). The vulnerability of GPS to jammer, however, is pointed out as a problem in various aspects, which leads to the need for the consideration of a backup system in order to prepare for the possibility of confusion that may be caused by malfunctioning as well as the following ripple effect. The long range navigation (LORAN) system is suitable for the GPS backup system because it has high stability and repeat accuracy due to the low-frequency and high-power signal characteristics in 90~110 kHz band, being different from GPS having high-frequency and low-power signal characteristics, and is robust to interference signals,. At present, the US and UK has adopted the enhanced LORAN (eLORAN), which has a higher performance than that of the conventional LORAN-C, as the GPS backup system (FAA 2004, U. S. DoT & DoD 2001, John & Volpe Center 2011).

LDO is the system that generates the timing information synchronized with the LORAN system. Since the LORAN signal utilizes the ground wave, it produces ASF which is defined as the propagation delay caused by the altitude and conductivity change that exists on the radio wave propagation path in addition to the propagation delay caused by the distance between the transmitter and the receiver. Conductivity is time-varying according to the weather and the climate. Therefore, as for the short-term and long-term stability performance of the LDO, there is the

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†**Corresponding Author**
E-mail: eesjl@cnu.ac.kr
Tel: +82-42-821-6582 Fax: +82-42-823-4494

need to consider not only the LDO local oscillator control performance but also the effect of the ASF that can reach the maximum of hundreds of microseconds. In general, the ASF correction is carried out by the method to correct the spatial and the temporal ASF. The spatial ASF is the mean of the ASF values generated at the individual reception locations and measured for a long period of time, usually more than one year. The spatial ASF is generated by the geographical features of the propagation path. When measuring the spatial ASF, we use ASF-map to which the ASF values of the unit grids are reflected on the basis of the ASF model or the actual ASF measurement values. The temporal ASF is the ASF that is time-varying by the weather and the climate that are related to the earth surface conductivity. The temporal ASF is corrected by transferring the ASF correction values in real-time to the neighboring locations through the differential LORAN reference bases (Pelgrum 2006).

In this article, we present the design of the OCXO-based LDO hardware platform to utilize the timing information for the GPS backup. As for the LDO-based timing information measurement, the Kalman filter was applied to estimate the measurement of which variance was minimized so that the stability performance could be improved. The OCXO was employed as the local oscillator of the LDO, and the controller was operated by digital PID controlling method. The LDO performance evaluation environment allows for the relative ASF observation and data collection, considering the ASF characteristics of the LORAN that requires a long period of observation. The collected observation data are used to analyze the effect of ASF on propagation delay. The LDO stability performance was presented by the results of the LDO frequency measurements from which the ASF was excluded.

2. DESIGN OF LDO

2.1 Hardware platform for LDO

Fig. 1 shows the LDO structure. The LDO uses the 1 PPS output of the LORAN-C receiver as the reference signal. The local oscillator synchronization of the LDO is carried out by tracking the reference signal. The LDO time interval counter (TIC) measures the phase difference between the OCXO output signal and the reference signal as the tracking error. For this, the OCXO 10 MHz output signal is demultiplied as 10^7 and applied to the TIC for the comparison with the reference signal. The signal processer and controlling are carried out by the Kalman filter that has been applied to minimize the variance of the TIC phase difference measurement noise and by the PID controller for the OCXO control. The OCXO control value is determined by the results of the signal processing. The OCXO control value passes through the DAC and the signal conditioning circuit and then varies the OCXO frequency in the form of an analogue signal (Cui et al. 2009, Cui & Zhou 2010, Dewey 1989).

Table 1. Hardware Components for the LDO.

Components	Product Name
LORAN-C Receiver	LOCUS Cs Sync 1030
OCXO	OSCILLOQUARZ OCXO 8789
TIC	Agilent 53132A Universal Counter
Frequency Divider	SDI PPS-2
DAC	NI USB-6289
Controller	NI LabView

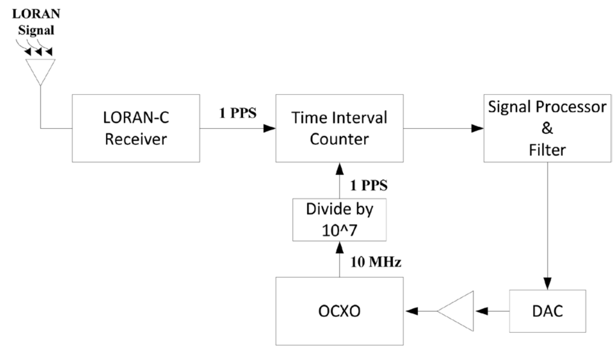

Fig. 1. Structure of the LDO.

Table 1 shows the composition of the LDO hardware designed in this study. The Cs Sync 1030 receives the transmission signals of a specific LORAN-C transmission station and generates 1 PPS signal synchronized with the transmission station signal. The time interval resolution of the TIC is 150 ps. The OCXO 8789 has the short-term stability characteristic of 5×10^{-10}/day and the long-term stability characteristic of 2×10^{-10}/day. The 10 MHz frequency is output at the control voltage of 5 V. The output frequency is varied by ±0.8 ppm in the range of 0~10 V. The frequency divider has the temperature-signal time delay coefficient of 3 ps/℃. The USB-6289 is the digital-to-analog convertor (DAC) that converts the digital control value to an analogue voltage value. Its analogue output voltage range is ±10 V, and the resolution is 18 bit. The DAC generates the control signal of the OCXO 8789, interconnected with the signal processer and controller implemented on the LabView, NI.

2.2 Signal conditioning filter

Noise is included in the measured phase difference between the LORAN-C 1 PPS reference signal measured by the TIC and the OCXO 1 PPS output signal. Eq. (1) shows the phase difference model that assumes w_{LO} as the phase jitter having zero mean Gaussian noise (AWGN) characteristic:

$$x_{LO}(t) = x_{LO}(0) + \{y_{LO}(0) - u_{LO}(t)\}t + \frac{1}{2}D_{LO}t^2 + w_{LO}(t) \quad (1)$$

where x_{LO} denotes the phase difference of the OCXO output signal at time t, $x_{LO}(0)$ the initial phase synchronization error of the OCXO output signal, $y_{LO}(0)$the initial frequency offset of the OCXO output signal, $u_{LO}(0)$ the OCXO output frequency by the control input at time t, D_{LO} the frequency drift, and $w_{LO}(0)$ the OCXO noise. By considering the LORAN-C 1 PPS reference signal performance and the update period of the controller, the second-order frequency term in Eq. (1), which is the drift, can be approximated as in Eq. (2), making the OCXO phase model a first-order function:

$$x_{LO}(t) = x_{LO}(0) + \{y_{LO}(0) - u_{LO}(t)\}t + w_{LO}(t) \quad (2)$$

The measured phase difference between the LORAN 1 PPS and OCXO output signals is presented as a discretized model as shown in Eq. (3) where k denotes the discretized sample number, and the $\triangle T$ the update period:

$$x(k+1) = x(k) + \{y(0) - u(k)\}\Delta T + w(k) \quad (3)$$

To apply the Kalman filter, the system model and the measurement model for the phase difference measurement values in the linearized Eq. (3) are defined as in the Eq. (4) where $\Phi(k)=1$, $\Gamma(k)=y(0)-u(k)$, and $H(k)=1$:

$$\begin{aligned} x(k+1) &= x(k) + \{y(0) - u(k)\}\Delta T + W(k) \\ z(k) &= x(k) + v(k) \end{aligned} \quad (4)$$

In the system model defined in Eq. (4), the frequency drift can be obtained by calculating the gradient that minimizes the variance by linearizing the phase difference measurements, as shown in Eq. (5):

$$a = \frac{N[\sum(t_i x_i) + \sum x_i t_i] - \sum t_i \sum x_i - \sum t_i \sum x_i}{N\sum t_i^2 - (\sum t_i)^2} \quad (5)$$

Substitution of the frequency drift obtained from Eq. (5) to the system model of Eq. (4) gives Eq. (6):

$$\begin{aligned} x(k+1) &= x(k) + a\Delta T + W(k) \\ z(k) &= x(k) + v(k) \end{aligned} \quad (6)$$

By applying the Kalman filter, the estimated phase difference of the OCXO can be obtained through Eq. (7) where $\hat{X}$ denotes the estimated phase difference, z_m the measured phase difference, and K the Kalman gain. The Kalman gain is obtained from Eq. (8) where Q and R denote the process noise and the observation noise, respectively (Hardin & Yankowski 1992):

$$\hat{X}(k+1|k+1) = \hat{X}(k|k) + K(k+1)[z_m(k+1) - \hat{X}(k|k)] \quad (7)$$

$$\begin{aligned} P(k+1|k) &= P(k|k) + Q(k) \\ K(k+1) &= P(k+1|k)[P(k+1|k) + R(k+1)]^{-1} \\ P(k+1|k+1) &= [1 - K(k+1)]P(k+1|k) \end{aligned} \quad (8)$$

2.3 PID controller for oscillator

The PID control theory was applied for the frequency control of the OCXO output signals. The PID controller calculates the control value by adding the proportional, integral and differential terms of the error, as shown in Eq. (9):

$$MV(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de}{dt} \quad (9)$$

where K_p denotes the proportional gain, K_i the integral gain, and K_d the differential gain. For the design of the PID controller of the LDO, the propotional gain, differential gain and integral gain were chosen in the order. Firstly, the proportional gain was adjusted to the value that showed the oscillation of the phase difference measurement in the feedback structure, and chosen as the value that did not exceed the OCXO input voltage range. Then, the differential gain was chosen in order that the steady-state error of the phase difference measurement could be within 10% by applying the previously determined proportional gain simultaneously. In particular, the differential gain was selectively applied depending on the situations to make the convergence rate faster in the initial operation of the LDO and to make the steady-state error smaller after the measured phase difference was converged. The integral gain was not separately chosen because a sufficiently small steady-state error could be obtained through the PD controller using the proportional gain and the differential gain that were chosen in the previously described manner (Astrom & Hagglund 2004).

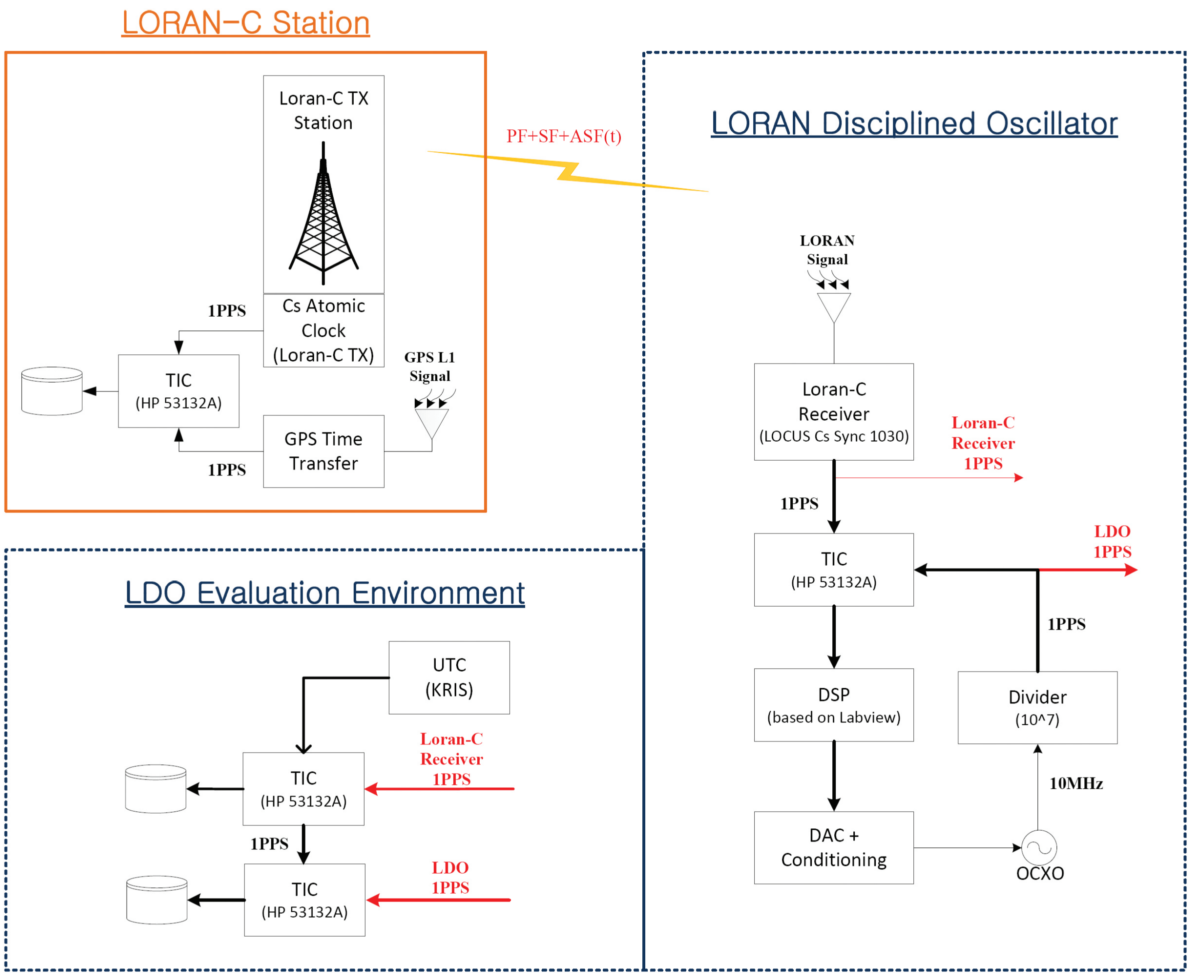

Fig. 2. Evaluation Environment for LDO.

3. PERFORMANCE EVALUATION

3.1 Evaluation environment

In the LORAN-C signal, propagation delay factors on the wave propagation path such as PF, SF and ASF affect the 1 PPS reference signal of the receiver. Among them, ASF needs to be corrected by applying the ASF correction method, since it is a time-varying factor (Pelgrum 2006). As the second best method, the ASF is derived by comparing the 1 PPS output signal of the LORAN-C receiver with the UTC (KRIS) in order to separate the effect of the ASF from the LDO experimental environment shown in Fig. 2. Therefore, the LDO performance evaluation can be carried out by calculating the difference between the measured phase difference obtained from the comparison of the 1 PPS output signal of the LORAN-C receiver with the UTC (KRIS) and the previously derived ASF, thus excluding the time-varying ASF.

3.2 Evaluation results

Fig. 3 shows the evaluation of the LDO feedback loop stability performance using the LDO performance evaluation environment. Fig. 4 shows that phase convergence performance of the OCXO output signal with reference to the UTC (KRIS). It was found that the phase difference converged into 0 as time passed, which indicated that the designed PID controller was successfully synchronized according to the input reference signal.

Fig. 4 shows the stability of the feedback loop synchronized with reference to the UTC (KRIS). The one-second Allan variance was 1.5×10^{-2}, which indicated a higher level of stability performance than that of the UTC (KRIS) measured with the same equipment, 7.5×10^{-11}. The result was because the effect of the measurement noise was attenuated by the designed noise attenuation filter. The Allan variance increased in the mean range up to 100 seconds due to the effect of the time constant of the designed filter and

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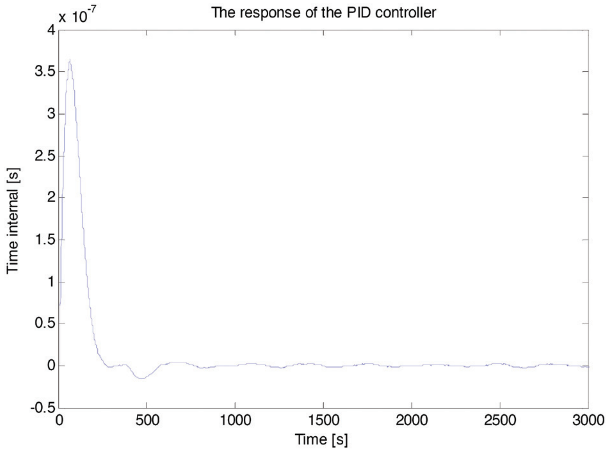

Fig. 3. Response of the PID controller.

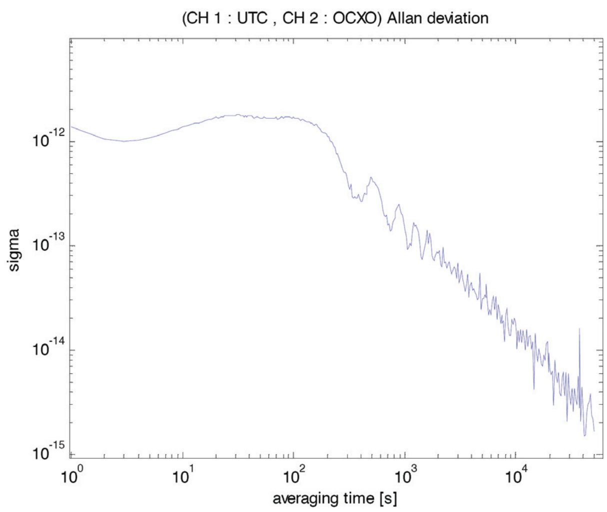

Fig. 4. Stability of the LDO feedback loop with UTC (KRIS).

controller, while it decreased gradually after the mean range of 100 seconds.

Fig. 5 shows the results of the LDO stability performance evaluation carried out by excluding ASF, the time-varying propagation delay factor. The Allan variance of the UTC (KRIS) was also included in Fig. 5 as an absolute performance index. The one-second Allan variance of the UTC (KRIS) showed the ability level of 10^{-12}, approximately, while the stability performance evaluation of the feedback loop and LORAN-C receiver with reference to the UTC (KRIS) showed a lower stability level with the one-second Allan variance higher than 10^{2}. This might be because of the effect of noise such as the satellite noise on the output signal of the LORAN-C receiver. The effect of the error factors included in the output signal of the LORAN-C receiver was verified by $1PPS_{UTC}$-$1PPS_{LOR}$ in Fig. 5. Although $1PPS_{UTC}$-$1PPS_{LOR}$ incorporated the error of the designed PID as well as the error

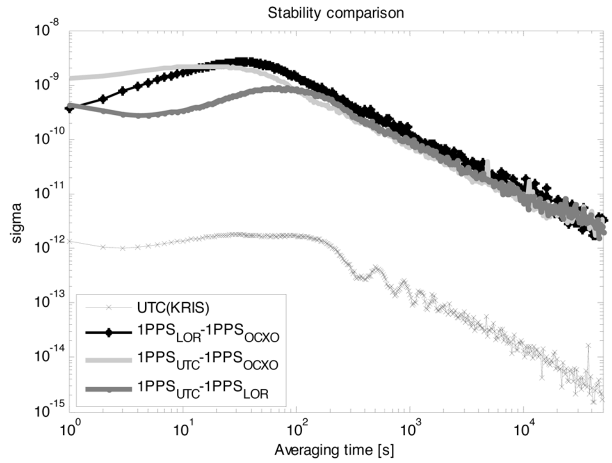

Fig. 5. Stability comparison results.

included in the output signal of the LORAN-C receiver, the stability performance was better in the time range between 100 seconds and 300 seconds than that of the $1PPS_{UTC}$-$1PPS_{LOR}$, pointing out that the designed PID controller and the noise attenuation filter worked out successfully.

4. CONCLUSIONS

In this study, we designed the PID controller and the noise attenuation filter of the LDO, realized them as hardware, and evaluated the performance. The UTC (KRIS) was used in the LDP performance evaluation environment to exclude the effect of ASF. We also applied the UTC (KRIS) to check out the controller operation and evaluated the LDO stability and presented the evaluation result. The LDO stability evaluation showed the result of the operation of the Kalman filter for the noise attenuation and the PID controller, indicating that the effect of noise on the LORAN-C receiver output signal. Additionally, it is presumed that the LDO can be synchronized within tens of nanoseconds if the effect of time-varying ASF is properly corrected. Therefore, the LDO can be utilized as a backup timing source of the GPS timing information in various industrial areas.

The future studies will be carried out on the ASF model-based ASF correction method and the LDO applications to correct the time-varying propagation delay in order to improve the LORAN signal processing performance.

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Sang-wook Hwang received the Master's degree in Electronics from Chungnam National University in 2010. His research interests include anti-jamming techniques and GNSS SDR.

Yun Sub Choi received the Bachelor of degree in Electronics from Chungnam National University in 2010. His research interests include GNSS receivers and anti-jamming techniques.

Sang-Rae Yeo received the Bachelor of degree in Electronics from Chungnam National University in 2012. His research interests include GNSS SDR and precise time, Anti-jamming.

Chansik Park received the Doctor's degree in Control and Measurement in Seoul National University in 1997. His research interests include GNSS, SDR, AJ, ITS and WSN.

Sung-Hoon Yang received the Doctor's degree in Control in Chungnam National University in 2012. His research interests include time synchronization and time transfer.

Sang Jeong Lee received the Doctor's degree in Control and Measurement in Seoul National University in 1987. His research interests include GNSS and Robust Control.