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# Method of Clock Noise Generation Corresponding to Clock Specification

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## ABSTRACT

Clocks for time synchronization using radio signals such as global navigation satellite system (GNSS) may lose reference signals by intentional or unintentional jamming. This is called as holdover. When holdover occurs, a clock goes into free run in which synchronization performance is degraded considerably. In order to maintain the required precise time synchronization during holdover, accurate estimation on main parameters such as frequency offset and frequency drift is needed. It is necessary to implement an optimum filter through various simulation tests by creating clock noise in accordance with given specifications in order to estimate the main parameters accurately. In this paper, a method that creates clock noise in accordance with given specifications is described.

**Keywords:** clock noise, GNSS, holdover, Allan deviation, stability

## 1. INTRODUCTION

Current digital information technologies, mobile communication systems, power networks and military applications require high-precision time synchronization. For time synchronization, signals from the global navigation satellite system (GNSS) have been widely employed (Allan et al. 1997). However, since the GNSS signal has a relatively very low signal level when it is received in the ground, it has a weakness that is vulnerable to unintentional or intentional jamming (Poisel 2004). Once the GNSS signal is disrupted due to jamming, a receiver loses reference timing signals that maintain a clock so that a local oscillator embedded in the receiver results in free run. As a time of free run becomes longer, a timing error is increased so that the required synchronization accuracy may not be satisfied after a certain period of time. In order to prevent this, it is necessary to have a means to maintain timing accuracy required in synchronization system by adding a holdover function to GNSS receivers (Lee et al. 2015, Wikipedia 2016).

To perform the holdover function, it is required to predict a timing maintaining performance at the time when a local oscillator loses GNSS signals and gets into the free run state. To do this, it is necessary to predict characteristics of main parameters of oscillators such as frequency offset and aging (or frequency drift). In order to predict such main parameters accurately, it is required to create noise according to the oscillator specifications. Noises can be different according to an oscillator type and are generally obtained as a sum of various types of colored noise rather than white Gaussian noise. There have been many proposed methods to create colored noises individually (Kasdin & Walter 1992, Greenhall 2002, Park et al. 2003). However, no studies that proposed a method of creating noises in accordance with given oscillator specifications have been yet found. In order to simulate noise characteristics of real oscillators, it is necessary to sum each of the noises that are created individually by placing a

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different weight on each of the noises in accordance with the oscillator characteristics. In this paper, a method that creates colored noises according to various oscillator specifications is presented. In order to verify the validation of the proposed method, comparison of frequency stability for the measured noises of commercial clocks is performed and the results are presented. Among the methods of performance analysis, time deviation or maximum time interval error can be effectively utilized to estimate overall synchronization performance of clock synchronization network such as synchronization of mobile communication base stations. However, this paper is focused on the method of how to create clock noise appropriately so performance analysis was conducted only with respect to the most suitable comparison method called Allan deviation.

The rest of this paper is organized as follows: In Section 2, characteristics of clock error and clock noise are described. In Section 3, comparison results between clock noise created using the proposed method according to a single commercial clock specification and noise obtained via real measurements using the Allan deviation are presented. Finally, in Section 4, conclusions are presented.

## 2. TIME ERROR MODEL AND NOISE GENERATION

### 2.1 Timing Error Model

A basic time error of a free run clock can be expressed as follows (Riley 2008).

$$T_{err} = a_0 + a_1 t + \frac{1}{2} a_2 t^2 + n(t) \tag{1}$$

where $a_0$ refers to the initial synchronization error (or phase offset), $a_1$ refers to a frequency offset (or clock drift), $a_2$ refers to aging (or frequency drift), and $n(t)$ refers to a random noise of the clock. As shown in Eq. (1), the time error includes a variety of factors, conditions, and assumptions so that it is difficult to predict a clock error accurately, which is why error budget creation is needed. Each of the error terms is explained briefly as follows:

- Initial synchronization error

The initial time synchronization error is a constant time offset due to reference time error, finite measurement resolution, and measurement noise. The measurement resolution and noise can be different according to an average time.

- Initial frequency synchronization

The initial frequency error is a linear error varying in proportion to a time. Thus, since it can be a cause of the largest time error without periodical frequency re-synchronization, it is important to provide a method of synchronizing clock frequency periodically. In this regard, the frequency synchronizing error is generated due to factors such as reference frequency, measurement and adjustment resolution, and noise.

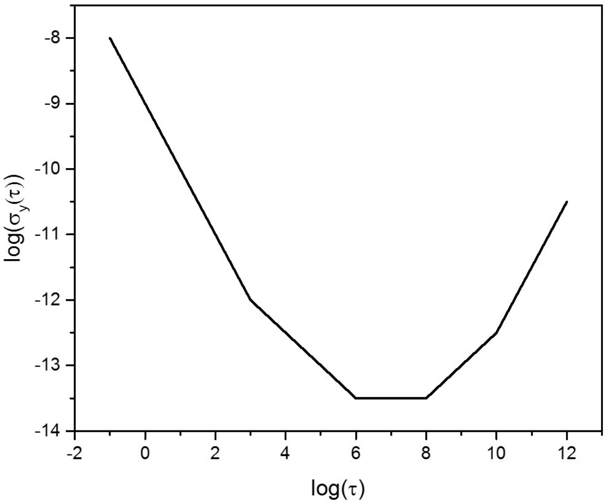

**Fig. 1.** Example of a sigma-tau diagram.

- Measurement environment

The largest factor that generates a time error after the initial frequency synchronization is sensitivity to the environment. The environmental frequency sensitivity varies depending on equipment and their operating conditions. Therefore, it is important to separate the deterministic elements generated according to environmental factors from the random noise when frequency stability is analyzed.

A clock noise is largely divided into white phase modulation (WPM), flicker PM (FPM), white frequency modulation (WFM), flicker frequency modulation (FFM) and random-walk FM (RWFM). One of the most general methods that observe the frequency stability characteristics at the time domain with regard to noise is sigma-tau plot. A log sigma plot with respect to log $\tau$ shows a trend of stability with regard to average time as well as stability value and noise types. One of the examples is shown in Fig. 1. As shown in the figure, clock noise can be divided into three types. The first type is that as a mean interval ($\tau$) is increased, Allan deviation ($\sigma_y(\tau)$) is decreased. These types of noises are WPM, FPM, and WFM. The second type is that a noise has a constant value regardless of the average interval. The FFM noise belongs to this type. Finally, as the average interval is increased, Allan deviation is increased. The RWFM noise belongs to this type.

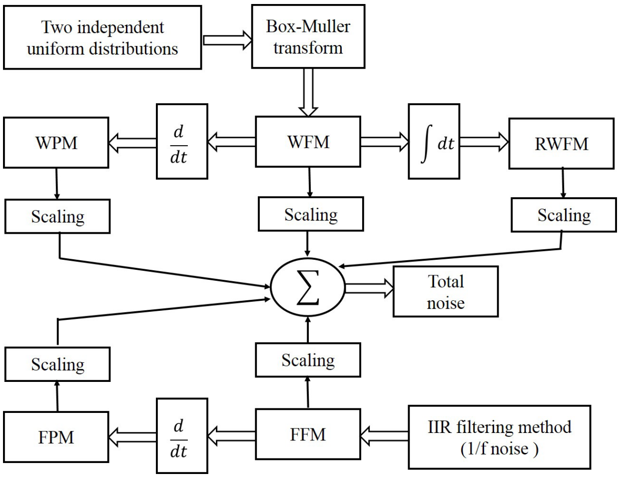

**Fig. 2.** Example of generating clock noises.

### 2.2 Clock Noise Generation

The frequency stability of most frequency sources can be modeled by combinations of power-law noises. The power law noises have power density with regard to fractional frequency ($y$) which has a type of $S_y(f) \propto f^{\alpha}$·$\alpha$ is an exponent having a range of -2 to 2 normally. At $\alpha = 2$, it is WPM; at $\alpha = 1$, FPM; at $\alpha = 0$, WFM; at $\alpha = -1$, FFM; and at $\alpha = -2$, it is RWFM. Fig. 2 shows one of the methods that create an overall clock noise by generating the above noises individually and summing the all kinds of noises. One of the methods that generate a white noise is to generate a random sequence that has two independent uniform distributions and to sum them using the Box-Muller transformation as shown in the figure. If white noise is integrated, RWFM of $f^{-2}$ is generated. In contrast, if white noise is differentiated, WPM of $f^{2}$ is generated. One of the methods that are generally used to generate a flicker noise is to use fast Fourier transform, by which all noises that have integer exponent can be generated.

As shown in Fig. 2, it is necessary to generate each of the noises individually followed by scaling. Here, similar noises with real clock can be generated if scaling is done in accordance with the clock specification. For clock specifications used commercially, Allan deviation is mainly used with regard to time domain and phase power density is used with regard to frequency domain. The Allan dispersion according to exponent noise type can be expressed as follows:

$$o_y^2(\tau) = h_{-2}\frac{2\pi^2}{3}\tau + h_{-1}2\log_e 2 + h_0\frac{1}{2\tau}$$
$$h_1\frac{1.038 + 3\,log_e(2\pi f_h\tau)}{2\pi^2\tau^2} + h_2\frac{3f_h}{(2\pi\tau)^2} \qquad (2)$$

where $h_\alpha$($\alpha$=-2, -1, ..., 1, 2) refers to intensity factor and $f_h$ refers to the cutoff frequency of the measurement system. A relationship between phase power density and noise type is

$$L_\phi(f) = \sum_{\alpha=-2}^{2} C_\alpha f^{\alpha-2} \qquad (3)$$

and here, $C_\alpha = h_\alpha f_0^2$ and $f_0$ refers to an output frequency of the oscillator. In the specification, it is represented as a type of $\mathcal{L}_\phi(f) = 10log(L_\phi(f))$ dBc/Hz, which is a log value of $L_\phi(f)$ mainly.

## 3. PROPOSED NOISE GENERATION METHOD AND RESULTS

### 3.1 Noise Generation Corresponding to the Provided Specification

As mentioned in the above, it is necessary to compensate frequency offset and aging through estimation in order to maintain a time error, which is generated during holdover, within the synchronization performance required by the system. To do this, it is important to generate a random noise of clock in accordance with the specification. In this section, this method is described.

In the commercial clock, mainly Allan deviation for the average time $\tau$ within 1,000 seconds is provided as the specification on the frequency short-term stability in the time domain. For 10 MHz output signal with regard to signal side band (SSB) phase noise, offset frequency up to 100 kHz is provided in more detail with regard to the frequency domain. Thus, one of the valid methods is to select a noise type using the characteristic of phase noise and using the Allan deviation for scaling according to the noise types.

In Fig. 3, a flow chart to generate a noise according to the clock specification is shown and the explanation is as follows:

a. Main noise types are selected among the five noise types using the Allan dispersion value given in the specification. In most cases, a short-term Allan deviation values whose $\tau$ values are within 1,000 sec are given.
b. Linearized sections in which phase noise types have integer values are calculated and the values and frequency offsets are acquired. Here, main noise types acquired at *a* shall be included.
c. A main noise is scaled using the Allan deviation given in the specification at $\tau$ = 1 second. If RWFM is included in the main noises, a scaling value for this is calculated after estimating the noise floor value.
d. The Allan deviation value that corresponds to the noise floor is calculated. If a floor value is given in the specification, this value is used. Otherwise, a general

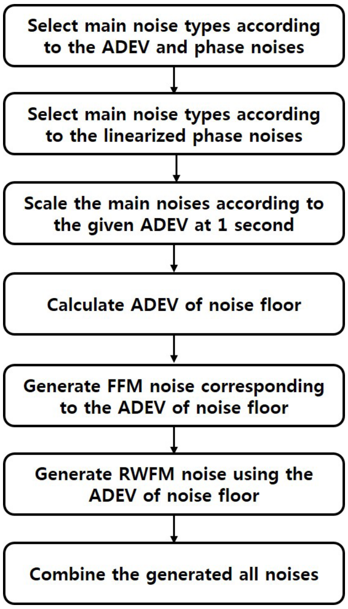

**Fig. 3.** Flow chart for generating colored noises corresponding to the clock specification.

**Table 1.** Noise types corresponding to oscillators.

| Noise type | | XO | Rubidium | Cesium |
|---|---|---|---|---|
| *a* | Type | | | |
| 2 | WPM | $\tau \leq 10^{-3} s$ | | |
| 1 | FPM | $\tau \leq 1 s$ | | |
| 0 | WFM | | $\tau \geq 1 s$ | $\tau \geq 10 s$ |
| -1 | FFM | $\tau \geq 1 s$ | $\tau \geq 10^{3} s$ | $\tau \geq 10^{5} s$ |
| -2 | RWFM | $\tau \geq 10^{3} s$ | $\tau \geq 10^{5} s$ | $\tau \geq 10^{7} s$ |

value according to the used oscillator type is used. In Table 1, noise types according to oscillator types are presented. Since a noise type where noise floor is started with FFM and noise floor is finished by RWFM in Table 1, a range of noise floor can be set up based on such values. For example, for crystal oscillators such as TCXO and OCXO, a value from 1 to 1,000 seconds is employed and for rubidium oscillator, a value from 1,000 to 10,000 seconds is employed.

e. The FFM noise that corresponds to the Allan deviation of noise floor is generated.

f. The RWFM noise at the largest $\tau$ that corresponds to noise floor is generated using the Allan deviation value of noise floor.

g. Each of the noises calculated according to the above procedure is summed and the Allan deviation is calculated to verify the generated noise.

### 3.2 Measurement Results

A commercial CSAC clock was used for simulation experiments. The CSAC clock specification is summarized in Table 2 and noises are generated as follows according to the procedure described in Subsection 3.1. First, since the frequency stability has a tilting of $\tau^{-1/2}$, the noise will have the WFM type. Second, the result of linearized type with regard to the phase noise is shown in Table 3. A type of noise that CSAC has can be three types mainly: WFM, RWFM, and FPM or FFM. Since the oscillator used in CSAC is rubidium and it has a type of FFM noise in general, FFM noise type is selected among FPM and FFM. Third, a value of $L(f)$ that is close to the Allan deviation $2.5 \times 10^{-10}$ at one second with regard to the WFM noise is –52 dBc/Hz and the Allan deviation value here is $2.51 \times 10^{-10}$. Fourth, the Allan deviation value at $\tau = 10^4$ is approximately $2.51 \times 10^{-12}$ utilizing the reduction in the WFM noise in proportion to $\tau^{-1/2}$ to select a noise floor value. Fifth, the FFM noise whose Allan deviation is $2.51 \times 10^{-12}$ is generated. Sixth, a value of the RWFM noise is set to $2.51 \times 10^{-12}$ whose Allan deviation at $\tau = 10^5$ is the noise floor. Finally, noises generated using the above procedure are summed and the Allan deviation with regard to total noise is calculated. Then, the Allan deviation is compared with the value given in the specification thereby verifying whether noises are generated appropriately as preferred.

**Table 2.** Specification of the CSAC clock about ADEV and SSB noises.

| Stability (ADEV) | | Phase noise (SSB) | |
|---|---|---|---|
| Tau (s) | | *(Hz)* | *(dBc/Hz)* |
| 1 | $2.5 \times 10^{-10}$ | 1 | < -50 |
| 10 | $8.0 \times 10^{-11}$ | 10 | < -70 |
| 100 | $2.5 \times 10^{-11}$ | 100 | < -113 |
| 1,000 | $8.0 \times 10^{-12}$ | 1,000 | < -128 |
| | | 10,000 | < -135 |
| | | 100,000 | < -140 |

**Table 3.** Linearized phase noises.

| Phase noise (SSB) | | |
|---|---|---|
| *(Hz)* | *(dBc/Hz)* | Noise type |
| 1 | < -50 | WFM |
| 10 | < -70 | RWFM |
| 100 | < -110 | WFM |
| 1,000 | < -130 | FPM or FFM |
| 10,000 | < -135 | FPM or FFM |
| 100,000 | < -140 | |

Fig. 4 shows each of three noises (WFM, FFM, and RWFM) generated according to the above-mentioned procedure. The validation of whether such noises are generated appropriately can be done by comparing the ADEV values of the summed noises with values given in the specification and measured values. Prior to this, characteristics of each of the noises are explained as follows. As shown in the figure, the WFM behaved like random noise whose mean value is 0 at the time domain and the FFM had no significant change approximately at

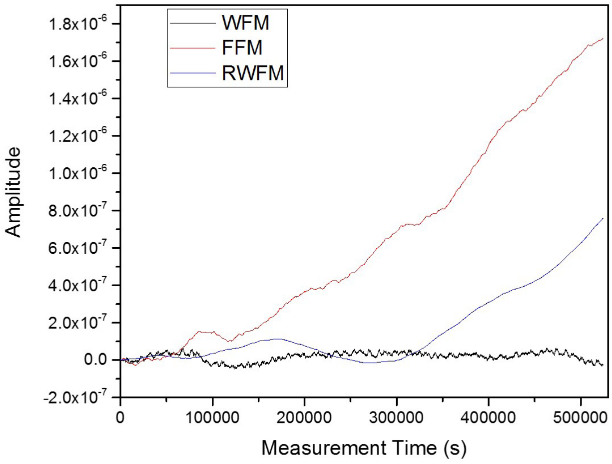

**Fig. 4.** Generated WFM, FFM and RWFM noises through proposed procedure.

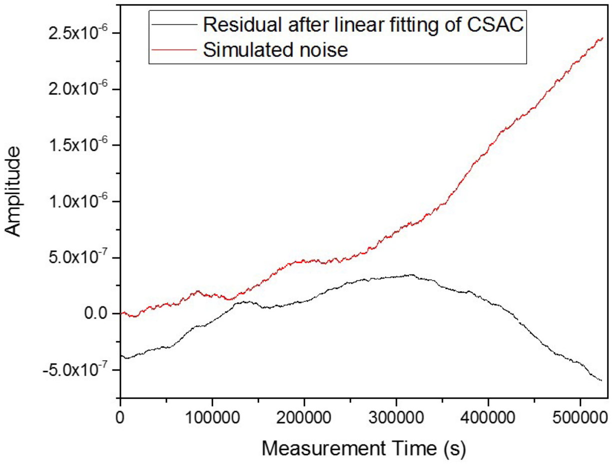

**Fig. 5.** Comparison between simulated noise and measured residual CSAC noise after linear fitting.

measurement time of 5000 seconds or earlier but since then, a large frequency offset is occurred. The RWFM is changed to a sinusoidal type which has a single period prior to 3,200 seconds approximately but since then, a frequency offset is occurred. Fig. 5 shows the result of summation of three types of generated noises and the residual CSAC noise after linear fitting. As shown in the figure, the residual of the real clock calculated after linear fitting revealed a Gaussian type around approximately $2.5 \times 10^5$ seconds whereas the generated noise revealed a small frequency offset up to $2.5 \times 10^5$ seconds followed by having a large frequency offset. This figure shows that estimation method of frequency offset shall be different depending on measurement time interval when frequency offset of real measured clock is estimated.

Fig. 6 shows the Allan deviation with regard to generated noise and real measured data. From the figure, the followings are observed. First, the comparison result of the generated noise with the noise given in the specification showed that the two ADEVs are matched very well in each other at a range of 10% or smaller within 1,000 seconds of $\tau$. Next, the real measured data showed 20% better performance approximately than that given in the specifications. The comparison of two graphs showed that a trend that was proportional to $\tau^{-1/2}$ was matched until noise floor was generated and performance of real measured data was 20% better with regard to overall average time. The reason for the better performance of real measured data than values given in the specification was because manufacturer provided a kind of upper-bound that was better than real performance when specifications were given. Therefore, if clock noise is generated using the proposed method, considerably accurate noise that is in accordance with the specification can be generated.

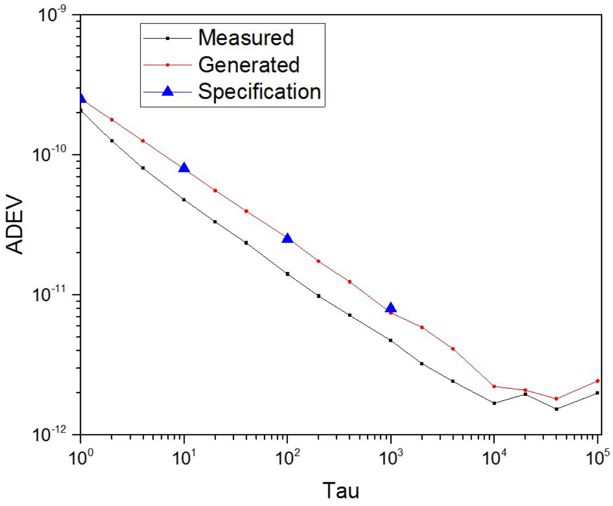

**Fig. 6.** ADEV of the generated and the measured noises.

## 4. CONCLUSIONS

In this paper, a method of generating clock noises according to the commercial clock specification was discussed. The generation of accurate clock noise according to the specification is one of the main elements that estimate frequency offset and drift basically required to enhance performance of time synchronization of clocks. A clock noise is a format in which many noises are summed and basic noise is first generated and then scaling is required in order to generate noise according to the specification. For appropriate scaling, main noises are scaled first according to the Allan deviation given in the specification when the average time interval is one second. After this, the estimated noise floor based on the above result is used to generate the FFM and RWFM noises. The generated noises are summed and the Allan deviation is calculated, which is then compared with the Allan deviation values given in the specifications to verify the result.

The verification on the generated noises was conducted by comparing with Allan deviation of clock data provided commercially in practice. The frequency stability was compared and the comparison result showed that the estimated results were well matched with the Allan deviation values of real measured data with regard to overall average time by using the procedure proposed in the present study. Thus, if clock noises are generated using the method proposed in the present paper, it can be utilized effectively in designing optimum filters via various methods in order to estimate main parameters such as frequency offset or drift. Furthermore, it is necessary to verify the validation of the proposed measure in the present paper through diverse commercial clocks for the future research.

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