FREQUENCY SYNTHESIS AND METROLOGY AT 10^{-17} AND BEYOND[1]

F. L. Walls*, F. Ascarrunz+, C. W. Nelson+, and L. M. Nelson*
*Time and Frequency Division, National Institute of Standards and Technology, Boulder CO, USA
+Spectradynamics Inc., Boulder, CO, USA

Abstract

A number of new types of atomic frequency standards have been proposed that show a potential for short-term frequency stability of approximately $3 \times 10^{-15} \tau^{-1/2}$ and a long-term frequency stability of order 10^{-17} or better. This paper investigates the systematic timing errors due to variations in temperature and signal amplitude in distribution amplifiers, cables, mixers, frequency dividers and multipliers. The effect of harmonic distortion in the reference signals on timing errors in phase detectors is also considered. We outline the basic configurations necessary to synthesize and distribute the reference frequencies and measure the performance of potential new clocks having a frequency stability of approximately $3 \times 10^{-15} \tau^{-1/2}$ and 10^{-17} in the long term.

Timing Errors

The timing errors in signal transmission are caused by variations in transit time delay and the phase of standing waves on the transmission line. (See [1] for details.) The timing delay due to signal transmission is

$$t = \frac{L}{\beta c} + \frac{\rho_l \rho_s}{4\eta\upsilon_0}\sin\phi, \qquad (1)$$

where L is the equivalent free-space transmission line length, β is the propagation constant, c is the speed of light, υ_0 is carrier frequency, η is attenuation of twice the signal path, ρ_l is the voltage reflection coefficient from the load, ρ_s is the voltage reflection coefficient from the source, and ϕ is the angle of the twice reflected wave at the load relative to the primary signal. The largest contributor to changes in the first term originates from the temperature coefficient of the dielectric material. The second term takes into account reflections from the load and source. Changes in the reflection coefficients depend on temperature, drive and supply voltages and scale as $1/\upsilon_0$. (See [1] for a discussion.)

To reach a frequency stability of 1×10^{-17} in 10^4 s, timing errors must be kept under 0.1 ps. Amplifiers used in building blocks or for distribution must maintain ultra-low sensitivity to environmental effects such as temperature. To achieve the timing error of 0.1 ps it is necessary to control the ambient temperature to better than 0.1 K for a state-of-the-art 5 MHz amplifier and 0.2 K for a 100 MHz amplifier [2,3].

 This paper is a summary of work published in the papers cited in the reference section.

In mixers used as phase detectors, the phase error $\delta\phi$ is given by

$$\delta\phi = \frac{\delta V}{K_d}, \tag{2}$$

where δV is the dc output voltage error and K_d is the phase detection slope in volts/radian. The timing error δt is given by

$$\delta t = \frac{\delta V}{2\pi \upsilon_0 K_d}. \tag{3}$$

The dc voltage error δV is caused by the imbalance in the detector transformers, diode I-V curves and asymmetric stray impedances. These imbalances, which are functions of temperature and drive level, lead to changes in apparent time or phase. The timing error in mixers can be reduced by going to higher frequencies [1].

Harmonic distortion changes the zero crossing of a signal by an amount dependent on the amplitude and phase of each harmonic. The environmental sensitivity of the zero crossing gives rise to a change in the timing error. To first order, the worst case timing error for a true zero crossing detector is given by

$$\delta t_{max} = \frac{\sum_{n=2}^{\infty} V_n}{V_1 2\pi \upsilon_0}, \tag{4}$$

where V_n is the amplitude of the nth harmonic. These errors are also reduced by using higher frequencies. A double-balanced mixer used as a phase detector offers significant improvements over a true zero-crossing detector because even-order harmonics are suppressed. (See [4] for discussion and experimental data.)

White phase modulation (PM) noise limits the stability of a system in the short term and flicker and environmentally driven noise limit stability in the medium-term. Amplifiers and mixers have white PM and flicker PM noise. In recent state-of-the-art mixers and distribution amplifiers, stability is not limited by phase noise [1]. The limiting factors to stability of these components are the environmental sensitivities of gain, phase, standing wave ratio, and delay [1-3].

Conclusion

PM noise processes should not be a limiting factor in reaching stabilities of 10^{-17}. The environmental sensitivities of operating parameters such as gain, phase, standing wave ratio, harmonic distortion, and DC bias are the limiting factors on long-term stability. With current technology, it is much easier to achieve the desired time-domain performance using carrier frequencies of 100 MHz than 5 MHz. Even at 100 MHz it is necessary to stabilize the system temperature to less than 1K.

References

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