

# High Resolution Time Interval Counter

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## Abstract

*In recent years, we have developed two types of high resolution, multi-channel time interval counters. In the NIST two-way time transfer MODEM application, the counter is designed for operating primarily in the interrupt-driven mode, with 3 start channels and 3 stop channels. The intended start and stop signals are 1 PPS, although other frequencies can also be applied to start and stop the count. The time interval counters used in the NIST Frequency Measurement and Analysis System are implemented with 7 start channels and 7 stop channels. Four of the 7 start channels are devoted to the frequencies of 1 MHz, 5 MHz or 10 MHz, while triggering signals to all other start and stop channels can range from 1 PPS to 100 kHz. Time interval interpolation plays a key role in achieving the high resolution time interval measurements for both counters. With a 10 MHz time base, both counters demonstrate a single-shot resolution of better than 40 ps, and a stability of better than  $5 \times 10^{-12}$  ( $\sigma_x(\tau)$  after self test of 1000 seconds). The maximum rate of time interval measurements (with no dead time) is 1.0 kHz for the counter used in the MODEM application and is 2.0 kHz for the counter used in the Frequency Measurement and Analysis System. The counters are implemented as plug-in units for an AT-compatible personal computer. This configuration provides an efficient way of using a computer not only to control and operate the counters, but also to store and process measured data.*

## Introduction

Time interval measurements are essential not only to the analysis of a time scale or a frequency standard, but also to the synchronization of time scales at remote locations. Many of these measurements require a time interval counter with better than 100 ps resolution. The technology advancement in electronics and in personal computers makes it possible to have such high resolution time interval counters at fairly low costs.

Two types of high resolution, multi-channel time interval counters have been developed at NIST in recent years. One of them is used in the NIST spread spectrum two-way time transfer MODEM<sup>[1]</sup> (MODEM counter); the other one operates in the NIST Frequency Measurement and Analysis System<sup>[2]</sup> (FMAS counter). Both counters are designed to make time interval measurements on more than one pair of start/stop signals input from different channels. The measurements are taken at rates ranging from 1 Hz to a maximum of 100 kHz. Instead of having a microprocessor for each counter, the counters are implemented as plug-in units for an

AT-compatible personal computer. The counters are controlled by software. This configuration provides an efficient way of using a computer not only to control and operate the counters, but also to process and store data. Although the two counters are designed for a specific application, the software can be easily re-programmed so that the counters can perform as a universal time interval counter, or for customized applications. To obtain accurate and stable measurements, a stable reference frequency of either 1 MHz, 5 MHz or 10 MHz is required for both counters. The estimated cost of parts for either a MODEM counter or a FMAS counter is around \$500.

The MODEM counter and the FMAS counter are different in some respects; the FMAS counter offers more capability in terms of simultaneous time interval measurements. However, they have one thing in common. Both use time interval interpolation to achieve the high resolution time interval measurements. This paper presents a discussion of the time interval interpolation technique, and a description of each counter's operation and performance.

## Time Interval Interpolation

Every digital time interval counter uses an oscillator (counter clock) to provide a time base for the time interval measurement. The time interval between start-count and stop-count signals  $\Delta t$  is measured by the counter as an integer multiple of the time base period; that is,

$$\Delta t = NT, \quad (1)$$

where  $N$  is the number of clock periods recorded by the digital counter in the interval and  $T$  is the period of the counter clock or the time base of the time interval measurement. In general,  $NT$  is only an approximation (the main portion) of  $\Delta t$ , because the start-count and stop-count signals are not in phase with the counter clock, as illustrated in Figure 1. Because both  $\delta t_1$ ,  $\delta t_2$  are less than  $T$ , they can not be measured directly by the digital counter. Therefore, the resolution of the digital counter measurement is dictated by the frequency of the time base. The resolution can be improved by increasing the frequency  $f = 1/T$  of the counter clock. However, this approach puts greater demands on the electronic devices and makes implementation more difficult.

Both the MODEM counter and the FMAS counter estimate the time intervals  $\delta t_1$ ,  $\delta t_2$  to achieve the high resolution time interval measurement. The estimations of  $\delta t_1$ ,  $\delta t_2$  are accomplished by two interpolators. The interpolator scales  $\delta t_1$  or  $\delta t_2$  into a magnified time interval and then estimates the interval with the time base  $T$ .

A block diagram of a simplified start-count interpolator is depicted in Figure 2. The interpolator consists of two integrators, a delay cell, a voltage comparator, and a digital counter. Both integrators are charged with a constant current  $I_{REF}$ . The delay cell introduces a delay  $\delta t_1 + T$ , where  $T = 100$  ns and  $\delta t_1 < 100$  ns for the 10 MHz time base used in the counters. The function of the integrators and the delay cell is to scale  $\delta t_1$  into a larger time interval. The digital counter, together with the 10 MHz time base, is used to estimate the scaled  $\delta t_1$ . The arrival of the start-count signal turns on the charging current  $I_{REF}$  to Integrator A. At this

time, the digital counter begins to count the periods of the 10 MHz time base. Integrator A is charged in the period of  $\delta t_1 + T$  and the charging current  $I_{REF}$  is then switched to Integrator B. The voltage  $U_R$  developed on Integrator A is held as a reference voltage for the comparator during the course of Integrator B being charged. When  $V_B > U_R$ , the comparator blocks the connection between the 10 MHz clock and the digital counter. Figure 3 shows a timing diagram of the start-count interpolator, where  $C_A$  and  $C_B$  ( $C_A < C_B$ ) are the ramping capacitances used in Integrator A and Integrator B, and  $K = (C_A/C_B)$  is the scaling factor of the interpolator.

Because the 10 MHz time base is connected to the digital counter during the magnified time interval

$$K \cdot (\delta t_1 + T) = K \cdot T + K \cdot \delta t_1 , \quad (2)$$

the number of 10 MHz pulses recorded by the digital counter during that interval,  $N_{st}$ , is linearly proportional to the time interval of  $\delta t_1$ . The relationship between  $\delta t_1$  and  $N_{st}$  can be expressed by the linear equation

$$\delta t_1 = A \cdot N_{st} + B , \quad (3)$$

where the slope A and the intercept B are determined through the interpolator calibration. During the calibration, the minimum  $N_{st}$  and the maximum  $N_{st}$  are obtained by slewing the phase of a test signal with respect to the 10 MHz time base to simulate the different values of  $\delta t_1$ . Because the minimum  $N_{st}$  corresponds to  $\delta t_1 = 0$  and the maximum  $N_{st}$  corresponds to  $\delta t_1 = T$ , the slope and intercept of the interpolation are

$$A = \frac{T}{\max[N_{st}] - \min[N_{st}]}, \quad B = \frac{\min[N_{st}] \cdot T}{\max[N_{st}] - \min[N_{st}]} . \quad (4)$$

Therefore,

$$\delta t_1 = A \cdot N_{st} + B = \frac{N_{st} - \min[N_{st}]}{\max[N_{st}] - \min[N_{st}]} \cdot T . \quad (5)$$

This result is illustrated in Figure 4. Because

$$K = \left( \frac{C_B}{C_A} + 1 \right) = \max[N_{st}] - \min[N_{st}] , \quad (6)$$

the resolution of the interpolation is given by  $T/K$ . With  $T = 100$  ns,  $C_A = 150$  pF,  $C_B = 0.47$   $\mu$ F the resolution is

$$\frac{T}{\frac{C_B}{C_A} + 1} = \frac{100 \times 10^{-9}}{3134} = 32 \times 10^{-12} . \quad (7)$$

The function of the stop-count interpolator is the same as that of the start-count interpolator. It is applied to estimate the interval of  $T - \delta t_2$ . Because of this, the main digital counter takes one more 10 MHz pulse after the arrival of stop-count signal. By combining the main digital counter measurement  $NT$  and measurements of the two interpolators together, the time interval counter presents the measurement as

$$\Delta t = NT + \frac{N_{st}T}{\max[N_{st}] - \min[N_{st}]} - \frac{N_{sp}T}{\max[N_{sp}] - \min[N_{sp}]}, \quad (8)$$

where  $N_{sp}$  is the digital counter measurement of the stop-count interpolator.

The time interval interpolation has a side-effect of reducing the maximum sample rate of the time interval measurements. Assume that both start-count and stop-count interpolators have the same scaling factor so that  $\max[N_s] = \max[N_{st}] = \max[N_{sp}]$ . Because it takes  $\max[N_s] \cdot T$  to complete an interpolation, the time interval measurements can be made only at a rate  $< 1/(\max[N_s] \cdot T)$  in order to avoid dead time.

## The MODEM time interval counter

The NIST spread spectrum two-way time transfer MODEM is developed for synchronizing remote time scales through geostationary satellites. The accuracy of the two-way time transfer is expected to achieve sub-nanoseconds. This requires a high resolution time interval counter for the measurements. The MODEM counter is designed with two functions, and it is installed in an AT-compatible personal computer. The interface of the MODEM counter is used to link the transmit (TX) and receive (RX) of the MODEM to the computer which controls the operation of the MODEM and the counter. The time interval counter portion of the MODEM counter is configured to measure the 1 PPS from TX, RX, and local time scale. The characteristics of the MODEM counter are similar to that of the FMAS counter in terms of the time interval measurement, except that the MODEM counter has only three input channels and a maximum sample rate of 1.0 kHz.

## The FMAS time interval counter

The Frequency Measurement and Analysis System (FMAS) is a new frequency calibration and characterization tool developed at NIST in the past year. It is designed to be used at calibration laboratories or other institutions to perform on-site high-level frequency calibrations traceable to NIST. All the frequency measurements are made by the FMAS counter in terms of the phase differences between the oscillators being calibrated and their corresponding reference frequency source<sup>[3]</sup>. Table 1 lists the FMAS specifications which

Table 1.	
Number of measurement channels	5
Input frequencies accepted by system: Start-count channel (with Frequency Divider) Other Start-count channel and Stop-count channel	1, 5, and 10 MHz $\leq 100$ kHz
Primary Oscillator Frequency	1, 5, 10 MHz
Single Shot Measurement Resolution	$< 40$ ps

are relevant to the FMAS counter. A block diagram of the simplified FMAS counter in a typical FMAS application is given in Figure 5.

The FMAS counter offers 7 start-count channels and 7 stop-count channels for connection to the secondary oscillators. Four of the 7 start-count channels are designed for oscillators with 1, 5, or 10 MHz output frequencies. A frequency divider is used on each of these 4 channels to divide the 1, 5, 10 MHz input down to 1, 5, or 10 kHz. The time interval measurement can be started with any of the start-count channels and stopped with any of the stop-count channels by the control of start-count channel select and stop-count channel select. The time interval between the start-count and stop-count signals is measured by the main counter and the two interpolators with a 10 MHz time base. The 10 MHz time base VCXO is locked to a primary oscillator of 1, 5, 10 MHz. Because it takes approximately 0.4 ms for the FMAS counter's interpolators to complete a time interval interpolation, the FMAS counter is able to make the time interval measurements of a single pair of start-count and stop-count signals at the rate of 2.0 kHz with no dead time. The maximum time interval of the main counter is about 429 s. Besides resolution, stability is another important characteristic of the counter. Figure 6 and Figure 7 show a typical result of the FMAS counter stability through self test measurements. Resolution of the time interval measurement should not be confused with the absolute accuracy of the time interval measurement. The accuracy of a time interval counter is influenced by many factors including the resolution. Our test results have shown both the MODEM counter and the FMAS counter have an accuracy estimated to be in the range of 200 ps to 300 ps, when used with a high quality primary oscillator.

According to the FMAS specification, the counter is configured to provide up to 5 of the 7 start-count channels for the secondary oscillators. The phase of a 1, 5, 10 MHz input signal can be shifted by integer multiples of 10  $\mu$ s with respect to the time base. The phases of all the secondary oscillators can also be shifted with respect to the phase of the time base by multiples of 100 ns. The phase shift is necessary in order to avoid the underflow or overflow measurements caused by the fast drift of the secondary oscillator. One of the direct (without the divider) start-count channels and one of the stop-count channels are connected to the 500 kHz output of the 10 MHz time base for the diagnostic purposes. Because all the secondary oscillators are calibrated with respect to the primary oscillator, and because the 10 MHz time base is locked on the primary oscillator, all the time interval measurements are stopped by the 10 kHz signal derived from the 10 MHz time base. The counter's operation and measurements are fully controlled by the FMAS software. Up to 5 secondary oscillators can be calibrated simultaneously.

## Summary

Time interval measurement is critical in the field of time and frequency standards. By combining today's technologies in electronics and personal computers, we have developed two types of high resolution time interval counter at low cost. Both counters have demonstrated a sufficiently high stability performance. Although the counters are designed for their specific applications, they can be readily to be modified for other applications.

## References

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- [3] D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls, editors, **Characterization of Clocks and Oscillators**, NIST Technical Note 1337, 1990.

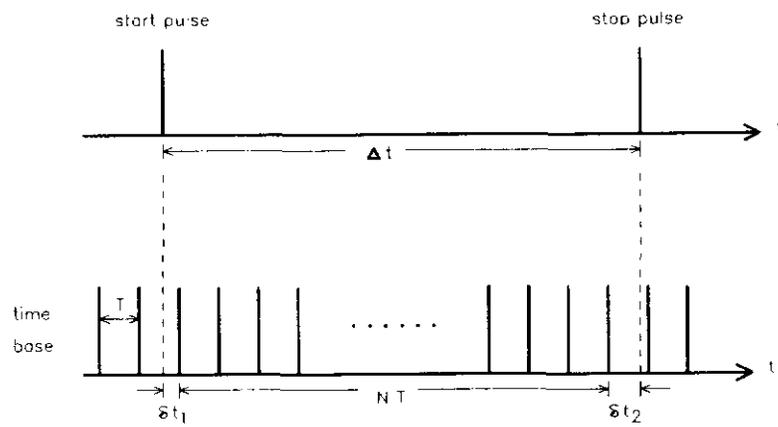


Figure 1. Time interval measurement by digital counter

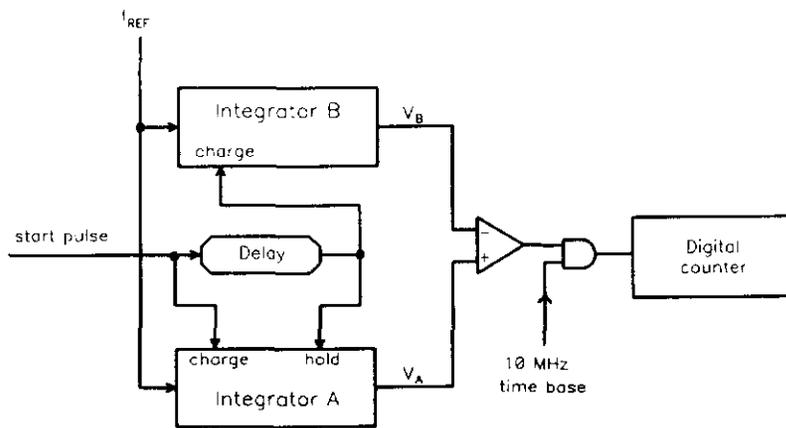


Figure 2. Block diagram of start-count interpolator

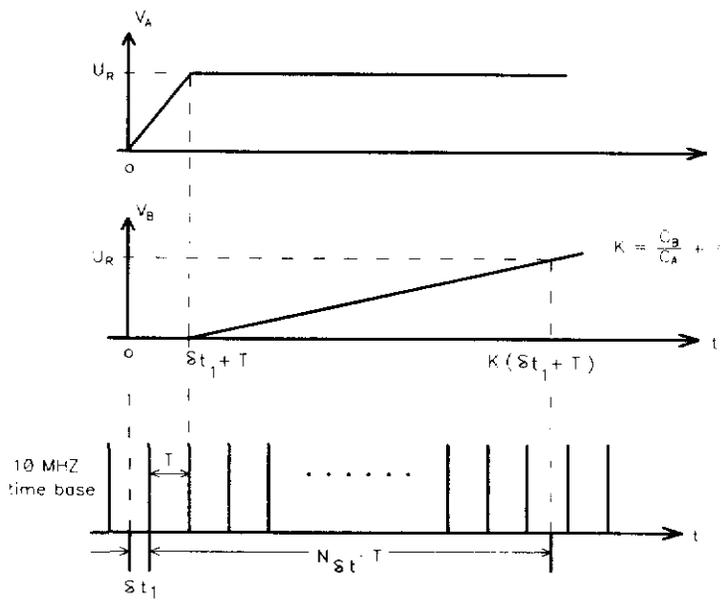


Figure 3. Timing diagram of start-count interpolator

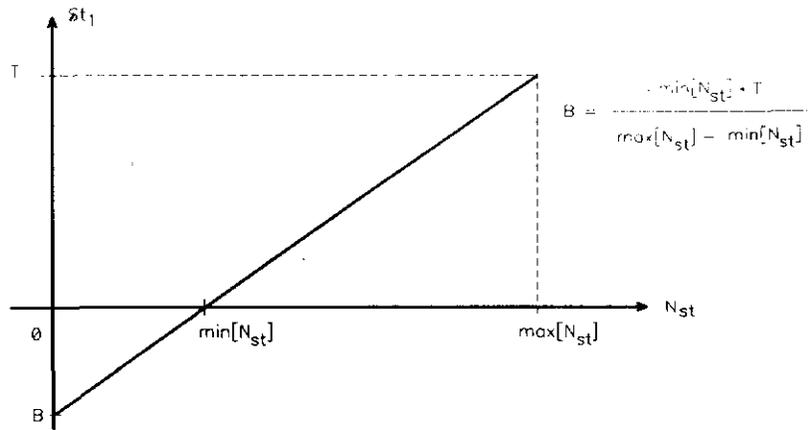


Figure 4. Time interval interpolation

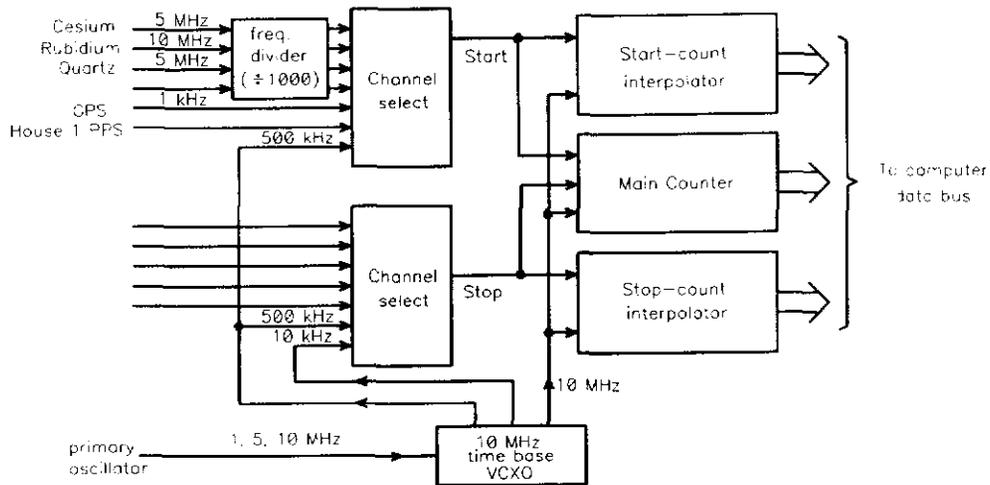


Figure 5. Block diagram of FMAS counter

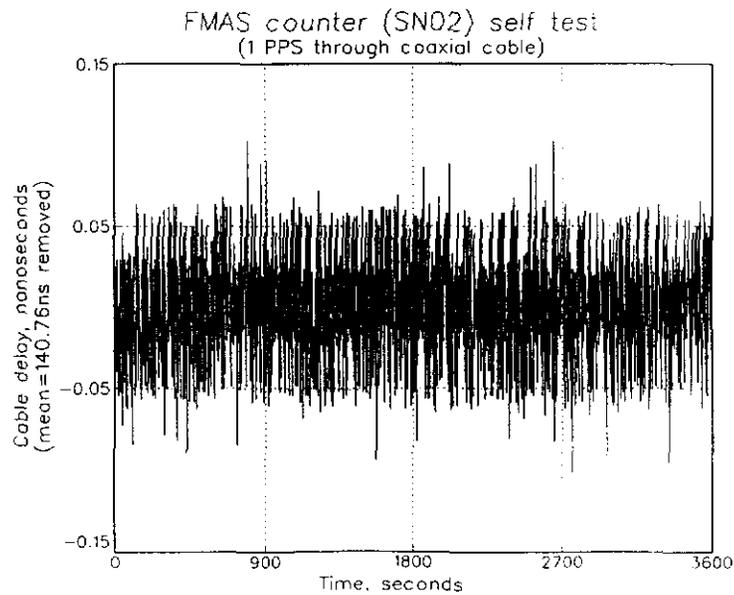


Figure 6. FMAS counter self test measurements

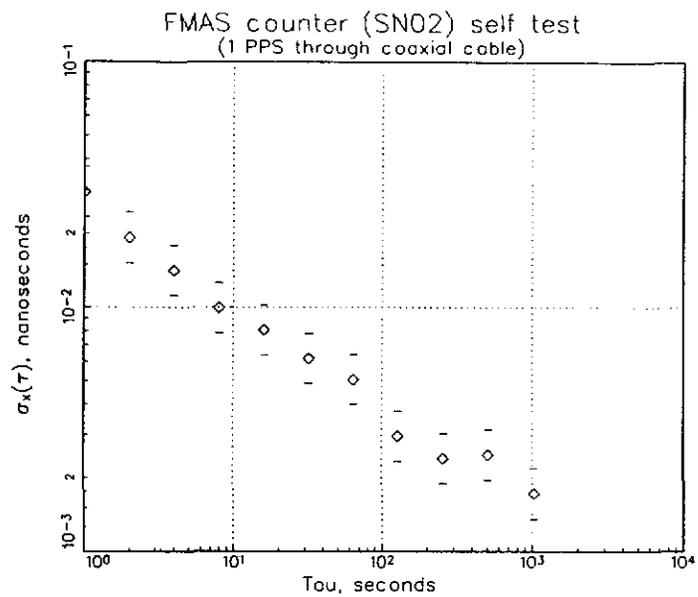


Figure 7.  $\sigma_x(\tau)$  of FMAS counter self test