



NBS TECHNICAL NOTE 691

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Clock Synchronization and Comparison: Problems, Techniques and Hardware

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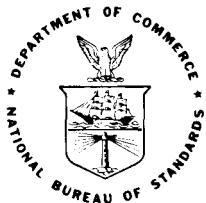
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CLOCK SYNCHRONIZATION AND COMPARISON:
PROBLEMS, TECHNIQUES AND HARDWARE

James E. Gray

This report summarizes a lecture-discussion of practical problems in measurement electronics as experienced in a laboratory for precise timekeeping. It includes environmental problems, instrumentation problems, procedural problems and ends with a description of a convenient automatic measuring instrument, the chronograph.

KEY WORDS: Chronograph; frequency-stability measurement; instrumentation; laboratory technique; time measurement.

INTRODUCTION

Experiments are planned, using idealized models of the hardware to be used, and one of the surprises of laboratory work is the occasional discovery that the behavior of some instrument is neither so simple nor so ideal as it was supposed to be. I shall be discussing this class of problems - problems which could have been foreseen and avoided, but which sometimes are not. The assortment of instruments used in a precise time laboratory presents an assortment of problems. I have grouped the ones I shall discuss in three categories: environmental problems, instrumentation problems and procedural problems. Finally, I shall describe a convenient automatic measuring instrument, the chronograph.

I. Environmental Problems

- A. Time is often kept by digitally counting the cycles of an oscillator to produce a tick once per second. Occasionally the digital divider will count some cycles which did not occur in the oscillator - the clock jumps. In this laboratory, I have most often found this to be due to electrical noise potentials existing between the "grounds" in different relay racks. Most of our signals are communicated over RG-55 cables, grounded at both ends. Although this system is convenient when using commercial instruments with grounded BNC jacks on their panels, it does have the disadvantage that ground noise potentials and their associated currents are in the signal circuits. Several remedies might be considered. For example, a bifilar choke, a length of coaxial cable wound on a transformer core, can be placed at the input of the divider. Depending upon the location of the noise source, this may cause the noise current to take some alternative route. In practice, I have found this method rather ineffective if used alone. In my experience, a heavy copper braid connected between racks has been most effective. Passing the oscillator signal through an isolation transformer should also help, though I have not yet tried it, because ground straps have been adequate.
- B. In a laboratory that uses the short-term stability of a cesium frequency standard, a surprising amount of isolation may be needed. Suppose that a 5 MHz sine wave signal is stable to a part in 10^{11} at one second. 10^{-11} seconds of phase shift is 314 micro-radians of phase shift. Thus an admixture of 8 parts in 10^6 of some other 5 MHz signal, will cause phase shifts in the desired signal which are comparable to the stability being utilized. That requires an isolation

between 5 MHz signals of 70 dB or better. Many laboratory devices do not meet that specification. Isolation amplifiers, dividers, and even cables laid parallel in cable races may provide more cross coupling than can be tolerated in some high-precision measurements.

- C. Temperature changes may alter the phase delay of a divider. We have some old dividers with slow rise-time circuits and ripple-carry design which move 20 nanoseconds from day to day. Some of our newer dividers have a temperature coefficient of about 0.05 nanosecond per degree, estimated from the circuit. There seems to be a variety of circuits on the market; look at the specifications before choosing one.

II. Instrumentation Problems

- A. Generation of Ticks. The commercial dividers that I have recently seen for generating precise one-second ticks generally use "window" or re-clocked circuits to avoid propagation delay through the dividers, but I still find one-shot multivibrators used to provide an adjustable delay. Such convenience is purchased at the cost of added jitter and temperature sensitivity. One popular clock is specified at 5 nanoseconds jitter. An alternative to using ticks, is to measure the time of zero crossing of the sine wave coming from the oscillator. A divider is still needed to identify the correct zero crossing, but measurements can be made on the sine wave directly. Typical errors in setting the trigger levels of the counter used to measure the time of zero crossing can introduce errors of the order of 1 nanosecond at 5 MHz, 7 nanoseconds at 1 MHz and 66 nanoseconds at 100 kHz. These estimates assume 1.5 volt peak sine wave amplitude and trigger level set using a $\pm 2.5\%$ meter on its 2.5 volt scale.
- B. Impedance Problems. The sine wave from an oscillator is often carried to the site of measurement by RG 55 cable. In addition to cross talk mentioned above, consider impedance matching of these cables. Any mismatch along such a cable will cause a reflection. The reflected sine wave adds to the original one to produce a resultant with altered phase. Although it is not necessary to maintain a perfect match along such cables, it is necessary to remember that any impedance change is capable of shifting the phase being measured. In addition to the effects of reflected waves on the cables, load impedance changes affect the phase of the output from some oscillators. This load sensitivity is large enough to be important in many applications. For example, I observed the following phase shifts when I connected an additional load in parallel with a 50 Ω resistive load on the 5 MHz output of a commercial cesium frequency standard:

<u>Additional Load</u>	<u>Phase Shift (nanoseconds)</u>
100 Ω	+ 2.6
47 Ω	+ 4.8
24 Ω	+ 7.8
330pf	-13.3
680pf	-21.2
1000pf	-27.6

Phase shift with load is not one of the specified characteristics of these frequency standards, so that the effect is probably different for other instruments, but these observations suggest the approximate magnitude of the problem. 47 Ω might represent an additional 50 Ω cable paralleled on the output of the oscillator; 680 pf might represent about 5 meters of 50 Ω cable terminating in a high impedance device.

Similar considerations apply to cables carrying pulses. For example, we observed erratic results when the arrival times of pulses were measured with a time-interval counter after they had travelled between buildings via underground cable. There appeared to be a discrete error. Sometimes the pulses were late; when they were, the delay was always the same. An oscilloscope paralleled with the counter showed the rising edge of the pulse as in figure 1. Slight errors in setting the trigger level of the counter resulted in some measurements being taken above the step, an error. Investigation showed that someone had run a few meters of cable from the source of each tick to an open jack on a nearby patch panel for trouble shooting use. This was in addition to the long, underground cable. The two cables presented an initial load of 25 Ω to the source which expected 50 Ω . Thus the pulse only rose part way. Later, when the pulse returned to its source after reflection from the open jack, the voltage at the source rose to its full height. The resulting stepped rise was causing an intermittent error equal to the round-trip transit time for the pulse on that few meters of open-ended cable to the patch panel (about 10 nanoseconds per meter of cable).

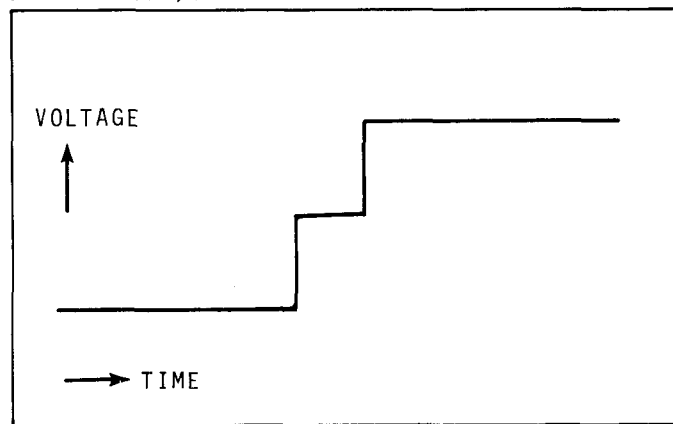


FIG. 1 Stepped rise due to cable reflections.

- C. Internal Errors of Instruments. The errors of time interval counters appear to be rather well described in the counter specifications. Resolution and trigger errors of the order of a nanosecond are available. Other errors that depend upon the length of the interval being measured, can also be of the order of a nanosecond for intervals of about one second. These errors include time-base accuracy and interpolator accuracy. In using such counters for precision measurements, one usually needs to use a matched load at the end of the cable to avoid ringing which can trouble the trigger circuits of the counter.

The chronograph is a less well-known method of time keeping which deserves to be mentioned because of its ability to measure the relative phases of the oscillators in an ensemble with high precision. The chronograph is an instrument which mixes the sine-wave signals from pairs of radio frequency oscillators and records the times of zero crossing of the resulting low-frequency beat. Although the chronograph was developed for other purposes, it can be used to take the data needed to construct a time scale with an ensemble of oscillators. For example, the following procedure might be used.

All the five-megahertz oscillators, except number one, are set low in frequency by one part in 10^8 so that each will have a 20 second beat period when mixed with number one. Oscillator number one is used to drive a 1/20 pps divider. The ticks of that divider are used to start a time interval counter. The zero crossing of the beat between oscillator one and oscillator i is used to stop the counter. Call the measured time interval B_i .

If all the oscillators started in phase with one another and were noiseless and on frequency, then all the zero crossings would coincide with the ticks of the 1/20 pps divider. In fact, they occur at other times as measured by B_i . Thus B_i represents the accumulated phase error between oscillator one and oscillator i . From another point of view, B_i represents the phase error of oscillator one as measured by oscillator i . From this data (the B_i 's), a time scale computation can be made which will give a value for the error of oscillator one as measured by the ensemble of oscillators. Oscillator one can also be used to drive conventional hours, minutes, seconds displays and put out 1 pps ticks if desired.

The random noise and frequency offsets of commercial cesium beam frequency standards in such an ensemble are small enough so that there would generally be a period of several days before the phase of an oscillator has changed by one cycle. Thus, daily measurement would be sufficient to keep track of all the oscillators even if only number one had a divider.

Suppose that the time-interval counter had a resolution of 0.1 microsecond so that the phase comparisons were made with a resolution of 0.1 microsecond out of 20 seconds or five parts in 10^9 . This is a resolution of one femto second in the phase at 5 MHz. Using commercial double-balanced mixers and operational amplifiers, the zero crossings are probably not detectable with this precision, but a resolution of one picosecond seems reasonable.

III. Procedural Problems

A. Redundancy. Useful protection can be achieved against the effects of human errors and equipment failures by redundant measurements. In a time-keeping laboratory it is useful to have the relative phase of each signal recorded at several different reference planes, each under fully specified conditions of measurement. At times of equipment failure and repair, the phase history of an oscillator after the equipment repair can be related to that before, because not all of the reference planes will be affected by the failure and repair work. For example, on a portable clock trip, if the divider fails or jumps, the data can still be obtained by measurement of the times of zero crossing of the sine-wave outputs of the clock, providing that tick-to-phase time intervals are known for that portable clock. The time of zero crossing of the 5 MHz output can be measured with a precision of about one nanosecond and the zero crossings of the 100 kHz output are far enough apart to make it reasonably easy to identify the correct cycle.

A second example: when we placed in service a new pulse cable from one laboratory to another, we calibrated its delay by carrying a portable quartz clock from one end to the other. But we made a redundant measurement by observing the return of the pulse, reflected from the open-circuited end of the cable. I paralleled an oscilloscope across the sending end of the cable and saw something like figure 2a, a completely unexpected result.

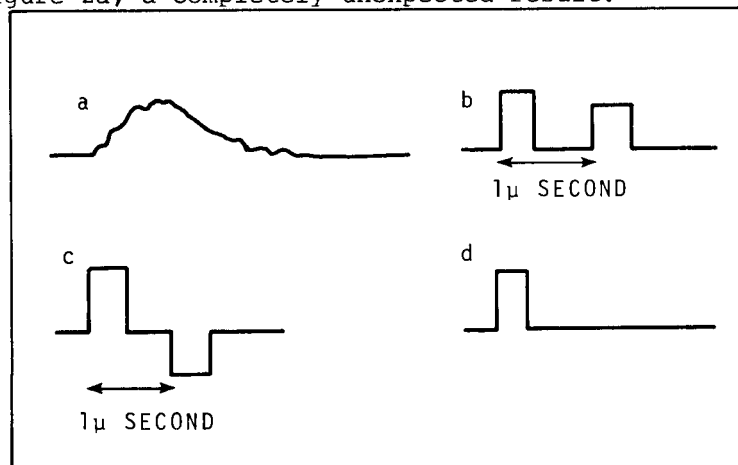


FIG. 2 Voltage at sending end of a pulse cable
a) faulty connector
b) open-circuit load
c) short-circuit load
d) matched load

Investigating the find the cause, we found a badly installed connector at the sending end, which did not contact the outer conductor. When we replaced the connector, the oscilloscope trace looked like figure 2b. A short circuit at the far end gave figure 2c, and a matched load gave figure 2d. 2b, 2c, and 2d are just what I would expect to observe. The redundant measurement not only gave us an independent measurement of the cable delay, but also permitted us to correct a fault before it caused trouble.

- B. Rate Effect. A time-interval counter is often thought of as a device that measures the instantaneous phase relationship between two oscillators. Actually it compares the phase of one oscillator at the instant it starts counting with the phase of the other oscillator at the instant it stops. Thus the measured value includes any phase change between the two oscillators during the measurement interval. That phase change is often negligible but in some circumstances it can cause trouble if overlooked. If the oscillators are offset 300 parts in 10^{10} , and the measurement interval is one second, the error will be 30 nanoseconds.
- C. Remeasurement error. In constructing our time scale, we measure the time of each clock daily, using a time-interval counter with a resolution of one nanosecond. If the counter makes an error of one-half nanosecond every day, by the end of the year, a few tenths of a microsecond error will have accumulated. This is an acceptable error in our application, but if we were to measure once every hour rather than once a day the remeasurement error would be 24 times as great and no longer acceptable.
- D. Portable clock trip. A portable clock is also a non-ideal device. Many of the imperfections of portable clocks are unpredictable and merely set limits to the precision of the time transfer. An interesting exception is a rubidium clock developed at NBS. Its frequency is a known function of barometric pressure. Even an approximate record of barometric pressure during the trip will permit adequate corrections to the time of such a clock. For example, this clock was recently taken from NBS Boulder to the United States Naval Observatory and gave a result within 0.1 microsecond of that obtained a few days later with a cesium clock. The approximate barometric record is shown in figure 3. At Boulder pressure and aircraft cabin pressure which happened to be the same, the clock went late 0.78 microseconds and at sea level pressure, it went late another 0.27 microseconds as calculated from the data shown in figure 3. This total correction of 1.05 microseconds was applied as a clock correction. Assuming a time of descent of pressure of one-half hour, the error due to the uncertainty in the shape of the curve during that period is of the order of one hundredth of a microsecond and can be neglected.

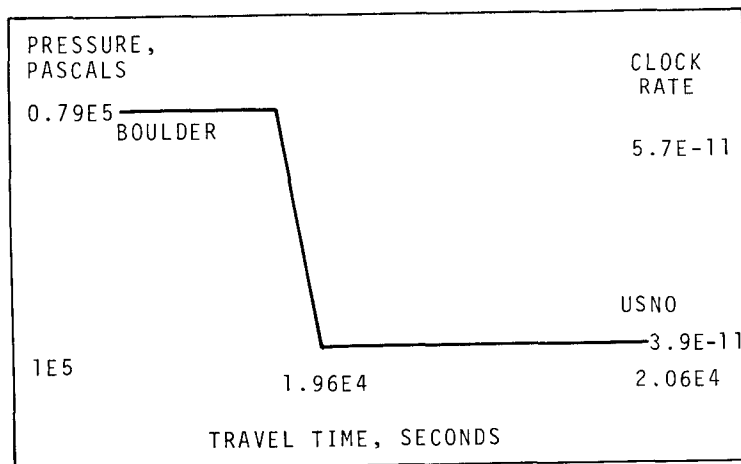


FIG. 3 Barometric record of portable clock trip.

IV. The Chronograph

A. Specifications

The chronograph is a versatile measuring instrument designed for time and frequency measurements. It mixes the sine-wave signals from pairs of radio frequency oscillators and records the times of zero crossing of the resulting low frequency beat. From the recorded data, relative frequencies and stabilities of oscillators can be computed for various sample times, τ , without dead time. I am building a new chronograph to the following performance estimates:

- 1) Ten channels to permit simultaneous measurements on ten pairs of oscillators.
- 2) Input 1 volt nominal, broadband from 1 MHz through 60 MHz.
- 3) Averaging times $\tau \geq$ one millisecond.
- 4) Scale factors $N = 1, 16, 256, 8192$.
(The chronograph will record every Nth zero crossing)
- 5) Measurement bandwidths 2 Hz, 20 Hz, 200 Hz, 1800 Hz.
- 6) Noise floor $\sigma_y(1 \text{ second}) \approx 1 \times 10^{-14}$.

B. General Configuration

Figure 4 shows the overall structure of the chronograph.

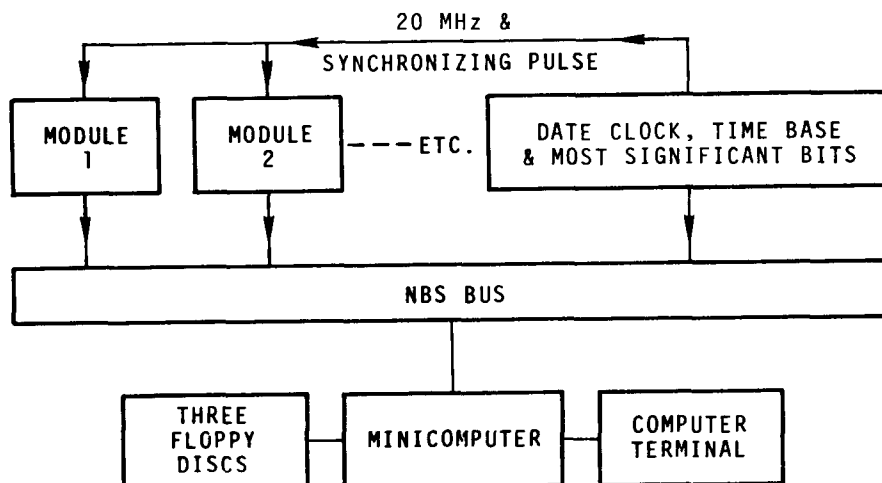


FIGURE 4. Chronograph Configuration

A group of independent modules plug into a computer-access bus. Each module accepts the signals from one pair of oscillators and feeds the time of phase-crossing to the computer. Completely independent modules facilitate maintenance and permit the use of special purpose modules for unusual experiments. The data is stored on three floppy discs, one to receive incoming data, one to permit examination of data taken in the past (without interrupting current measurements) and a third disc for overflow. The NBS bus is a computer interface for which many instrument interfaces are available. Consequently, temperature sensors, etc., can be connected to the bus to permit the measurement of the environmental sensitivity of oscillators.

The minicomputer supervises data acquisition and in its spare time, reduces the data to yield convenient measures such as Allan variances. It controls the modules, setting their bandwidth, scale factors, etc. This permits the experimenter to adjust his measurement parameters directly from the keyboard or indirectly under programmed control.

C. Module Operation

Figure 5 is a block diagram of a typical module.

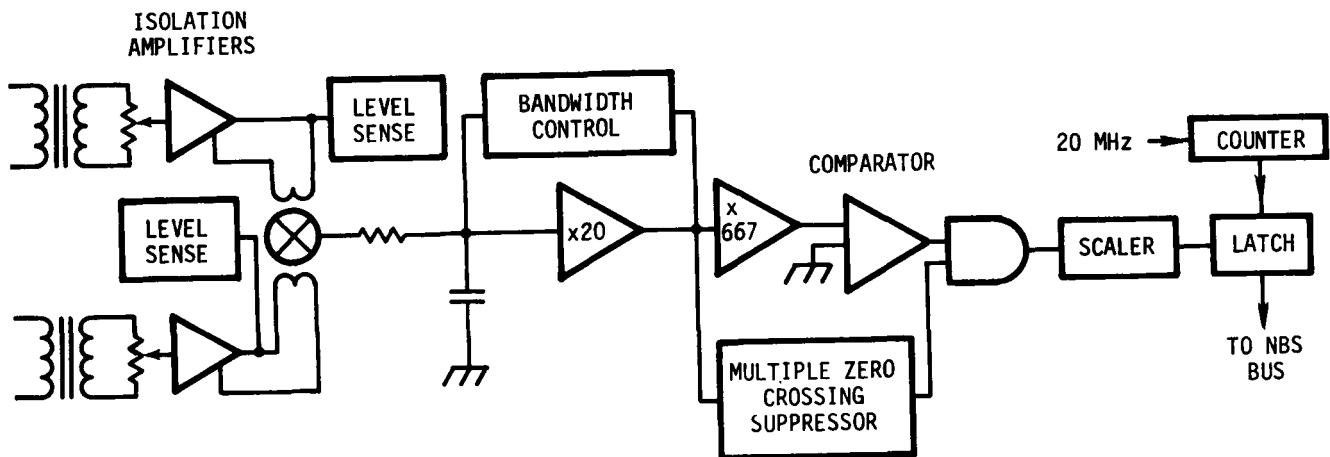


FIGURE 5. Chronograph Module

The two incoming signals are suitably isolated to protect them from contaminating each other by cross-modulation or ground loops and are mixed to produce the low-frequency beat. Zero-crossings of this beat are detected and counted by the scaler. On the Nth zero crossing, the reading of the time-base counter is strobed into the latch for transfer to the computer.

In addition to the standard mode of operation described above, there are two special modes. In the slave mode, the chronograph does not record every zero crossing but rather it records the time of the next zero crossing after it is armed by a command from the computer. It also records how many zero crossings have occurred since the last one that was recorded. This effectively compares the relative phases of the oscillators at a time chosen by the experimenter. In the double mixer mode, each of the two oscillators to be compared is fed to a different chronograph module, and the remaining two input ports are driven by a common oscillator. The computer then takes the difference between the times of phase-crossing in the two modules. This subtraction eliminates most of the noise introduced by the common oscillator. In this mode, oscillators can be compared even though they are on the same frequency and therefore cannot beat with one another directly.

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