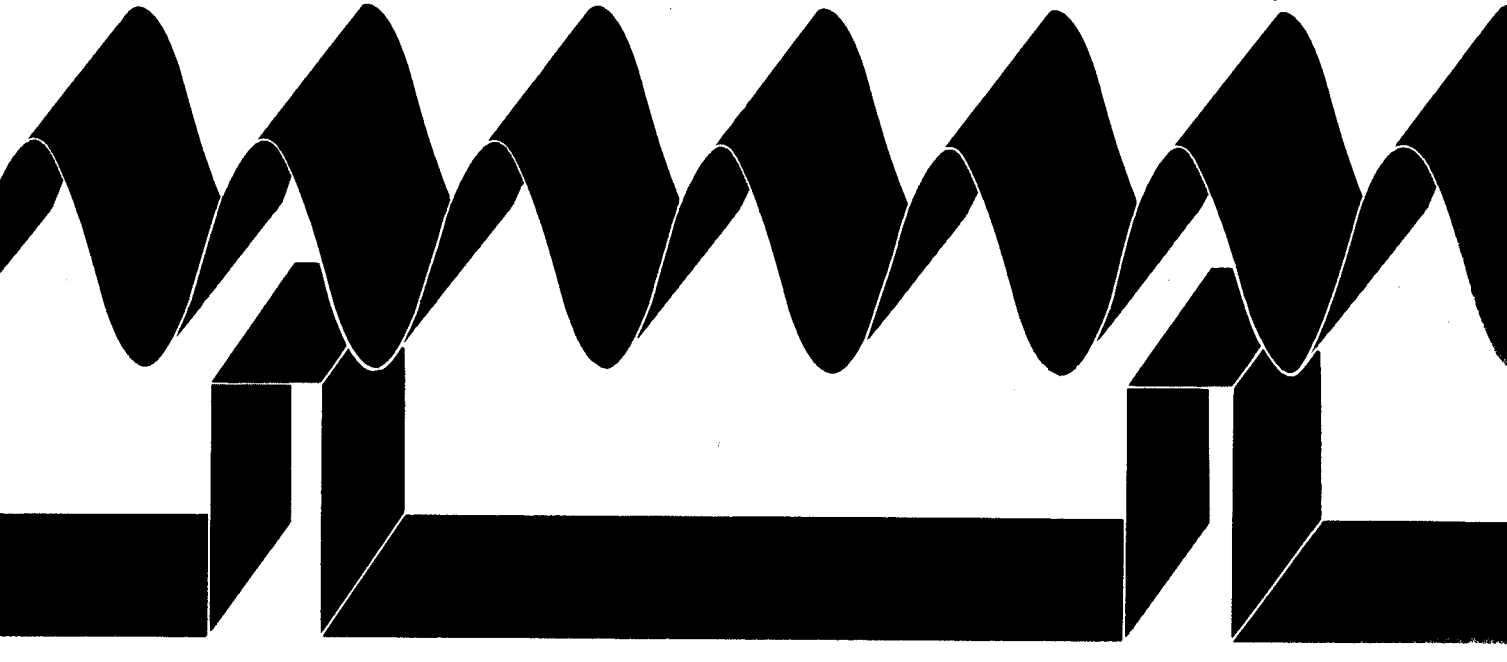
APPLICATION NOTE 52-2

TIMEKEEPING AND FREQUENCY CALIBRATION



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INTRODUCTION

GENERAL

TIME—a very complex subject. Man has been interested since his beginning in the measurement and use of time. Early time measurement systems involved counting the number of days in terms of sunrises, sunsets, or moons. Later, the day was divided into smaller increments by using the sundial, hourglass, candles, lengths of rope, etc. With the discovery of the pendulum, even smaller increments were used and clocks were born. The accuracy of early clocks was around 1 part in 10^3 to 1 part in 10^4.

As more accurate clocks were produced, new uses of time measurement were explored. As new uses were discovered, the need for even more accurate clocks became apparent.

Currently the state-of-the-art in atomic frequency standards has attained an accuracy of 2 parts in 10^{13} in the laboratory. Today the specified accuracy in commercially available atomic clocks has reached ± 7 parts in 10^{12}. This unprecedented commercial accuracy is equivalent to a gain or loss of 1 second in a minimum of 4530 years. Currently, timekeeping consists of maintaining clocks within fractions of microseconds of each other, whereas forty years ago, people were concerned about milliseconds at best. This need to maintain clock systems within fractions of a microsecond is shared by numerous applications spanning international boundaries. Worldwide applications cause strong international pressures to be exerted upon all clock systems to create even more accurate clock synchronization schemes on a global basis. As a result, several techniques of transferring time have been developed which allow accuracies of transfer from milliseconds to 100 nanoseconds.

Before starting the discussion of timekeeping, a review of a few of the basic concepts of time and frequency is in order. First of all, a clock can be defined as a device which counts the number of events that occur from an arbitrary starting point. The events to be counted could be the swings of a pendulum, the oscillations of a quartz crystal, the cycles of a signal in resonance with cesium or some other sequence of events. Accepted units of time are discussed in Application Note 52-1, Fundamentals of Time and Frequency Standards. For the purposes here, the terms of the internationally accepted time scale, Coordinated Universal Time (UTC) whose basic unit is the second will be used. The second was defined by the XIII General Conference of Weights and Measures, in October 1967, as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium atom 133". Therefore, the definition of a clock can be expressed as a device which counts the number of seconds (a well defined measurement of time-interval), occurring from an arbitrary starting time. From this definition it appears that a clock needs three basic parts. First, a source of events to be counted. This source can be labeled a frequency standard, frequency source, or time interval standard. Second, a means of accumulating these events or oscillations, and third a means of displaying the accumulation of time. Figure 1-1 shows a simple clock block diagram, including

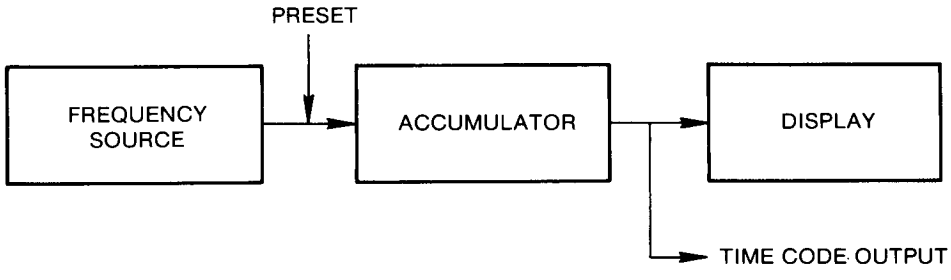

Figure 1-1 Basic Clock

a method of presetting the arbitrary starting time and obtaining an electrical time reading from the clock (time-code-generator).

In a clock there are two major sources of error, the accuracy and stability of the frequency source, and the accuracy of the establishment of initial setting (called epoch). Application Note 52-3 discusses the stability of frequency sources, while this application note discusses the methods of accomplishing accurate time transfer and maintaining frequency accuracy (often called calibration, frequency matching or frequency keeping).

TIMEKEEPING

Timekeeping is the process of maintaining accurate frequency and obtaining accurate time transfer. The timekeeping process involves intercomparing two or more clocks to insure that their time difference is kept within certain limits over a specified time interval. This action requires that the two clocks accumulate time at the same rate (same frequency within limits) but equally important, they must be set to the same starting time (reference time) as accurately as the system requires.

A timekeeping system can be either a relative or an absolute synchronization system. In a relative timekeeping or synchronization system the concern is placed upon keeping the clocks in the system synchronized with each other but not necessarily synchronized with other clocks outside the system. An example of a relative system would be a communications network where all clocks are referenced to the master clock of the system and the major concern is keeping the frequency of the network within appropriate limits for good network operation (e.g., a TV network). An absolute timekeeping system, on the other hand, is concerned not only with maintaining time synchronization of clocks within the system, but also with clocks outside the system. Even more specifically, an absolute timekeeping system is concerned with maintaining time synchronization with the internationally accepted time scale, Coordinated Universal Time (UTC).*

Before turning to the mechanics of frequency calibration and time transfer, some of the design considerations of a timekeeping system will be discussed.

TIMEKEEPING SYSTEM DESIGN CONSIDERATIONS

The purpose of this application note is to assist in the design or establishment of a timekeeping or frequency keeping system. These time or frequency keeping systems may in fact be a subsystem of a communications system, navigation system, or other system requiring time or frequency for its operation.

Prior to selecting specific components, instruments, processes and procedures in a timekeeping system, the system designer must answer several basic questions.

1. Is frequency or time (which implies frequency as well) needed for effective system operation? If frequency only is needed, the system can be much simpler than if time has to be provided as well.
2. Is absolute timekeeping necessary or will relative timekeeping suffice? A relative system may not need the equipment to synchronize with an external reference. This decision may depend on certain regulations (e.g., from the Federal Telecommunications Standards Committee, Fed-Std-1002, April 22, 1974, available from U.S. GSA).
3. What accuracy is required for frequency? for time?
   a. What regulations pertain to this system?
   b. What does system performance require?
   c. Will either regulations or performance requirements change in the future? If so, when?

* For an explanation of UTC and other time scales, refer to AN 52-1, Fundamentals of Time and Frequency Standards, Hewlett-Packard, March 1974.

Each system should be designed to provide at least the minimum accuracy defined by either regulation or performance. Future needs should be anticipated to insure against premature obsolescence of equipment due to increased requirements.

4. What stability is required? Some systems are concerned not only with accuracy but with stability of the frequency source or time jitter of the time-code as well. Application Note 52-3, Stability: Theory and Measurement, is more detailed in this area.

5. What equipment and systems are available for frequency comparison and time transfer? Equipment is generally available on a worldwide basis, but time transfer systems are not. The user's system has to take into account the time transfer or frequency comparison facilities available to him in the location or locations where his system is to be installed.

6. What additional equipment will have to be purchased or designed and built? The user needs to determine what equipment he has available that satisfy his needs and what equipment has to be purchased. Generally speaking most equipment is available as off-the-shelf units, however, occasionally the user may have to design and build some equipment not available in the marketplace. This will normally stretch his time to get the system operating.

7. What funds are available for establishing the system? Generally off-the-shelf equipment will lower the cost of the system. Equipment designed by the user will normally increase the cost of the system. If funds are critical, then a redesign of the system to make more use of readily available commercial hardware may be appropriate.

8. What funds are available for the operation of the system? The operating costs of the system can be very large compared to the initial cost. If funds are limited for operation, then perhaps an increase in funding for initial purchase will allow more accurate and reliable equipment to be purchased, thereby reducing operating costs.

9. What trade-offs can be made? Normally, many trade-offs have to be considered in any design. Trade-offs are generally made in terms of costs: performance vs. costs, operating costs vs. procurement costs, off-the-shelf cost vs. user build cost, etc.

There are numerous sources of assistance available to the system designer in satisfying his requirements. The Hewlett-Packard Company provides application notes discussing various instruments and their applications as well as providing technical assistance through the field sales offices.

The remainder of this application note is divided into three sections. Section II approaches timekeeping from the viewpoint of technical considerations for a timekeeping system. Section III discusses several methods of comparing the frequency of two or more sources. Section IV is concerned with various methods of timekeeping including frequency comparison or matching and time-transfer.