NBS TECHNICAL NOTE

379

Standard Time and Frequency: Its Generation, Control, and Dissemination from the National Bureau of Standards Time and Frequency Division

JOHN B. MILTON

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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STANDARD TIME AND FREQUENCY: ITS GENERATION, CONTROL, AND DISSEMINATION FROM THE NATIONAL BUREAU OF STANDARDS TIME AND FREQUENCY DIVISION

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STANDARD TIME AND FREQUENCY: ITS GENERATION, CONTROL, AND DISSEMINATION FROM THE NATIONAL BUREAU OF STANDARDS TIME AND FREQUENCY DIVISION

John B. Milton

The Time and Frequency Division of the National Bureau of Standards produces the NBS time scales, AT(NBS), SAT(NBS), and UTC(NBS). These time scales are developed by utilizing the properties of the NBS frequency standard, NBS-III. The main byproduct of these time scales is the operational clock systems. These operational clock systems are used, among other things, to calibrate the clocks and secondary standards necessary for the operation of the NBS radio stations, WWV, WWVB, WWVL, and WWVH. These stations transmit SAT(NBS), UTC(NBS), and various tones, alerts, and corrections for time-of-day information.

Key Words: clock synchronization; frequency and time dissemination; primary frequency standard; standard frequency broadcasts; time interval; time scales

1. INTRODUCTION

Since its inception in 1901, the National Bureau of Standards has been involved in the design, construction, maintenance, and improvement of standards of frequency and time interval. During the first two decades of the Twentieth Century, the work on these standards was done by quite diverse groups.

The people maintaining the standard of time interval were concerned primarily with problems of navigation, while the standard of frequency was maintained by a group concerned chiefly with radio interference between adjacent channels in the radio spectrum.

The operational time-interval standard has progressed from a pendulum clock with electrical pulse output through crystal clocks to the present-day "atomic clock." During the same period, the operational standard of frequency has evolved from a tuning fork to a quartz crystal oscillator to an atomic beam device. While there may be only a superficial connection between a pendulum clock and a tuning fork, the present-day standards of time interval and frequency are, by their very nature, inseparable.

Along with the maintenance and improvement of these standards came the need to disseminate these standards. In 1923 the National Bureau of Standards radio station WWV was established to disseminate the standard of frequency via experimental broadcasts. Time pulses were added to these broadcasts in 1935. Voice announcements of the time-of-day were added to these broadcasts in 1945.

In 1948, NBS radio station WWVH was placed in operation. In the 1950's, very good commercial standards were controlling both of these high frequency radio stations. At that time, nothing was done at the stations beyond providing good crystal oscillators. Utilizing the ultra-high precision oscillators located at the NBS Boulder Laboratories, the time and frequency of these stations were measured daily. Any deviations from the NBS standard were noted and corrective instructions were relayed to the radio stations.

In 1956, the Boulder Laboratories of the NBS began experimental transmissions on 60 kHz from radio station WWVB. The 60 kHz driving frequency for this station was derived directly from the NBS standard of frequency located at the Boulder Laboratories. There was no control of the transmissions beyond providing this standard driving frequency.

In 1960, utilizing an antenna borrowed from the Central Radio Propagation Laboratory of NBS, radio station WWVL was placed in experimental operation on 20 kHz. This station was located some ten miles west of the Laboratories in a high mountain valley. Direct generation of the transmission frequency by the Boulder Laboratories was not feasible, but a method of phase control using servo systems was employed. Since January 1, 1960, when NBS began using a cesium beam device as its official standard, all broadcast frequencies have been referenced to the cesium resonance frequency.

WWVB and WWVL were moved to Fort Collins, Colorado, and began operation there in July 1963. The original time and frequency control for these stations was accomplished by continuously operating servo systems that compared the phase of these stations as received in Boulder against a phase reference derived from the NBS Frequency Standard. Phase corrective information was then sent to Fort Collins via a radio link.

Primarily in order for NBS to increase the precision and accuracy of the transmissions from station WWV, through more uniform U. S. coverage and the replacement of obsolete transmitting and control equipment, a new facility for that station was installed at Fort Collins, Colorado, in 1966.

Stations WWV, WWVB, and WWVL are, in essence, a composite facility disseminating standards of time and frequency from 19.9 kHz to 25 MHz. At the present time, these stations provide information at both atomic frequency and an internationally agreed upon offset frequency. The offset frequency is used to generate a Universal Time scale, called UTC, which closely approximates the UT2 scale based on the rotation of the Earth.

Even though the time and frequency control of these stations was provided by a highly precise ensemble of clocks and standards, the problem remained of finding a simple, reliable, and inexpensive method of providing a daily calibration of the Fort Collins standards with respect to the NBS reference standards in Boulder.

This paper describes some of the current efforts of the Time and Frequency Division of the NBS. These include the generation of the computed NBS time scales, their translation into real working clocks, and the use of these clocks in coordination efforts with other standards laboratories. The coordination of the Fort Collins site clocks and frequency standards, the measurement and control of LF and VLF radiated phase, and the method of coordination of the Fort Collins master clock with that of NBS/Boulder are also described.

2. STANDARD FREQUENCY AND TIME GENERATION

2.1 Atomic Frequency and Time Standards Section

With the advent of the first working atomic clock system in 1948, developed by Harold Lyons at NBS/Washington, the era of the highly accurate atomic standards was born. The first work at NBS/Boulder was under the project direction of Dr. R. C. Mockler. This early work included, among other things, the refinement of the original NBS cesium-beam device, NBS-I.

In late 1959, the Atomic Frequency Standards Project, including the cesium beam and ammonia maser development work, was combined with the project concerned with theoretical and practical aspects of atomic time scales to form the Atomic Frequency and Time Standards Section.

2.1.1 The NBS Frequency Standard

The operations of the Atomic Frequency and Time Standards Section are presently centered on a device known as NBS-III, which serves as the NBS Frequency Standard. This machine, which is a long-beam cesium resonance standard, is probably the most thoroughly evaluated standard of its kind. The most important requirement for a primary frequency standard is high accuracy, where the term "accuracy" refers to an estimate of how far the output frequency of the standard may deviate from the ideal frequency defined with respect to an isolated cesium atom. In order to determine the limits of accuracy of such a standard, the possible causes, the cures in some cases, and the estimated magnitude of any and all small frequency shifts must be known: hence the continuing study of NBS-III by the Section personnel. NBS-III does not operate continuously; its main function is the frequency measurement of the frequencies of the working ensemble of clocks. These data, as described in the next section, are used in producing the AT(NBS) time scale. The accuracy of NBS-III is $\pm 5 \times 10^{-12}$, based on 3σ estimates of all uncertainties.

2.1.2 Computed or "paper" time scales

The Section maintains six oscillator-clock combinations that are used in producing three computed time scales. One might ask not only what is a "paper" time scale, but also how is it produced, and then how is it used.

The paper time scales, AT(NBS),* SAT(NBS),* and UTC(NBS),* are in fact computer printouts which relate the indicated time of each of the six clocks in the ensemble to the computed scales that are

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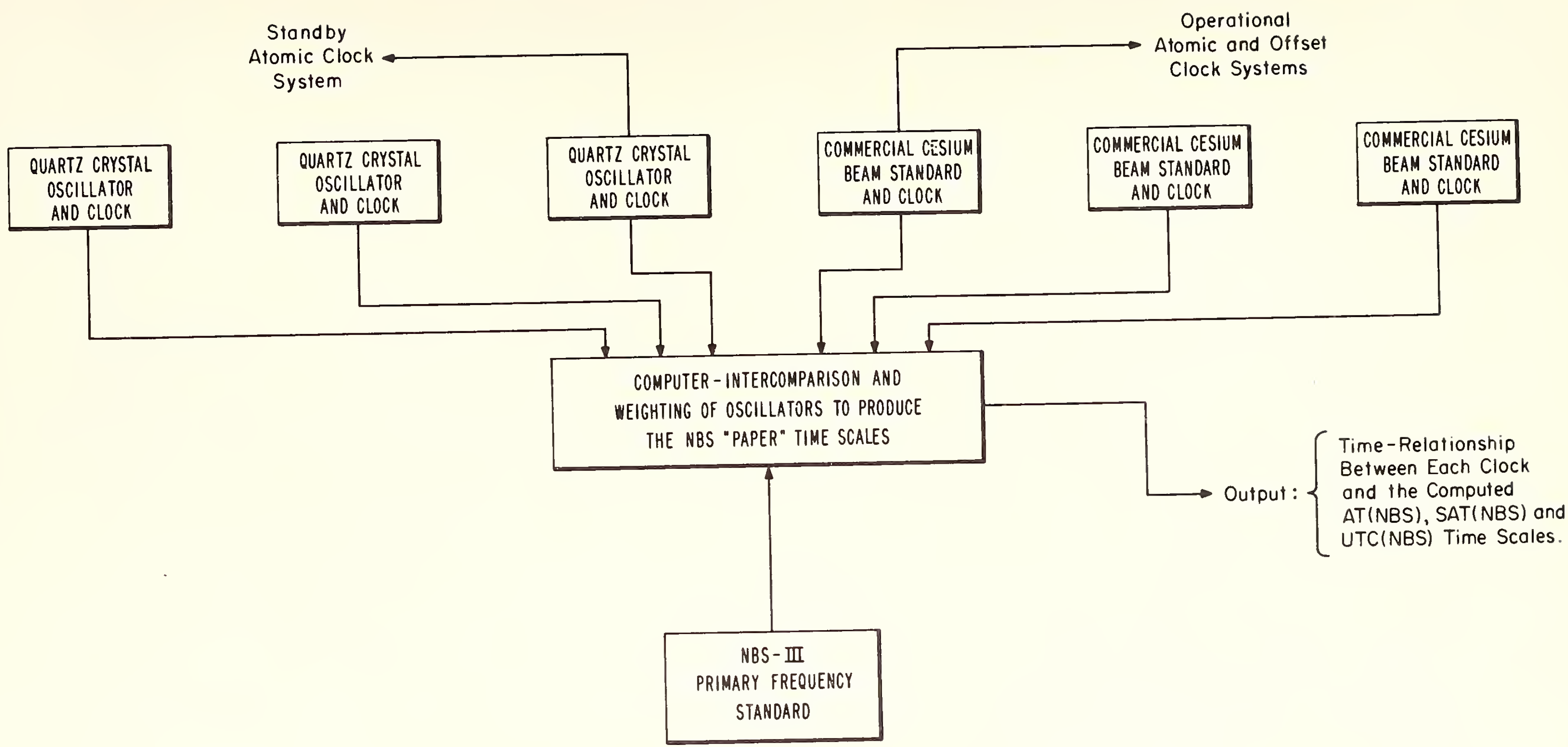
*See Appendix.

produced by the computer. The computer utilizes the current measured frequency of each oscillator with respect to NBS-III along with the past history of each of the six oscillators to apply a weighting factor to each oscillator based on its performance. The computed scales produced are more uniform than a scale produced by the best unit of the ensemble. The computer output is a set of numbers that are the time differences between each clock output and the computed scales. With this information, one has a mechanism for comparing clocks nationally or internationally and also for comparing the timekeeping performance of individual clocks comprising the time scale system. Figure 1 is a simplified diagram of the system that produces the NBS time scales. More comprehensive versions of all drawings in this document are available from the Frequency-Time Broadcast Services Section of the Time and Frequency Division.

2.1.3 Operational clock systems

The Section maintains three operational clock systems. The outputs of these systems are electrical seconds pulses as well as visual displays of epoch. The time scale based on the primary NBS clock, designated as Clock #7, closely approximates the AT(NBS) time scale. Corrections for Clock #7 relative to the AT(NBS) time scale are computed at regular intervals. Probably the most useful clock in a practical sense is the unit designated Clock #8. This clock's output closely approximates the UTC(NBS) time scale. The daily deviations of Clock #8 from the UTC(NBS) time scale are published monthly in the NBS Time and Frequency Services Bulletin. The deviation of this clock from the UTC(NBS) time scale is constrained to always be less than 1 microsecond and seldom exceeds ± 0.2 microsecond. The third system, operating from an independent quartz crystal oscillator, is a backup atomic rate clock designated Clock #0. A time comparator and 24-hour alarm system



SYSTEM FOR GENERATION OF COMPUTED TIME SCALES
AT(NBS), SAT(NBS), AND UTC(NBS)

Figure 1

are associated with Clock #0 and Clock #7. This alarm is actuated if Clock #7 diverges from Clock #0 by more than 5 microseconds. All of the frequency standards in the operational system operate on the "atomic" frequency. To produce an operational clock whose rate more nearly approximates that of the UTC clock based on the earth's rotation, a fixed frequency offset generator is placed between the atomic standard and the operational clock, such as Clock #8. This offset rate for 1969 is -300×10^{-10}. An adjunct to the operational clock systems is the clock comparison link to Fort Collins that utilizes television synchronizing pulses. Figure 2 is a simplified diagram of these operational clock systems.

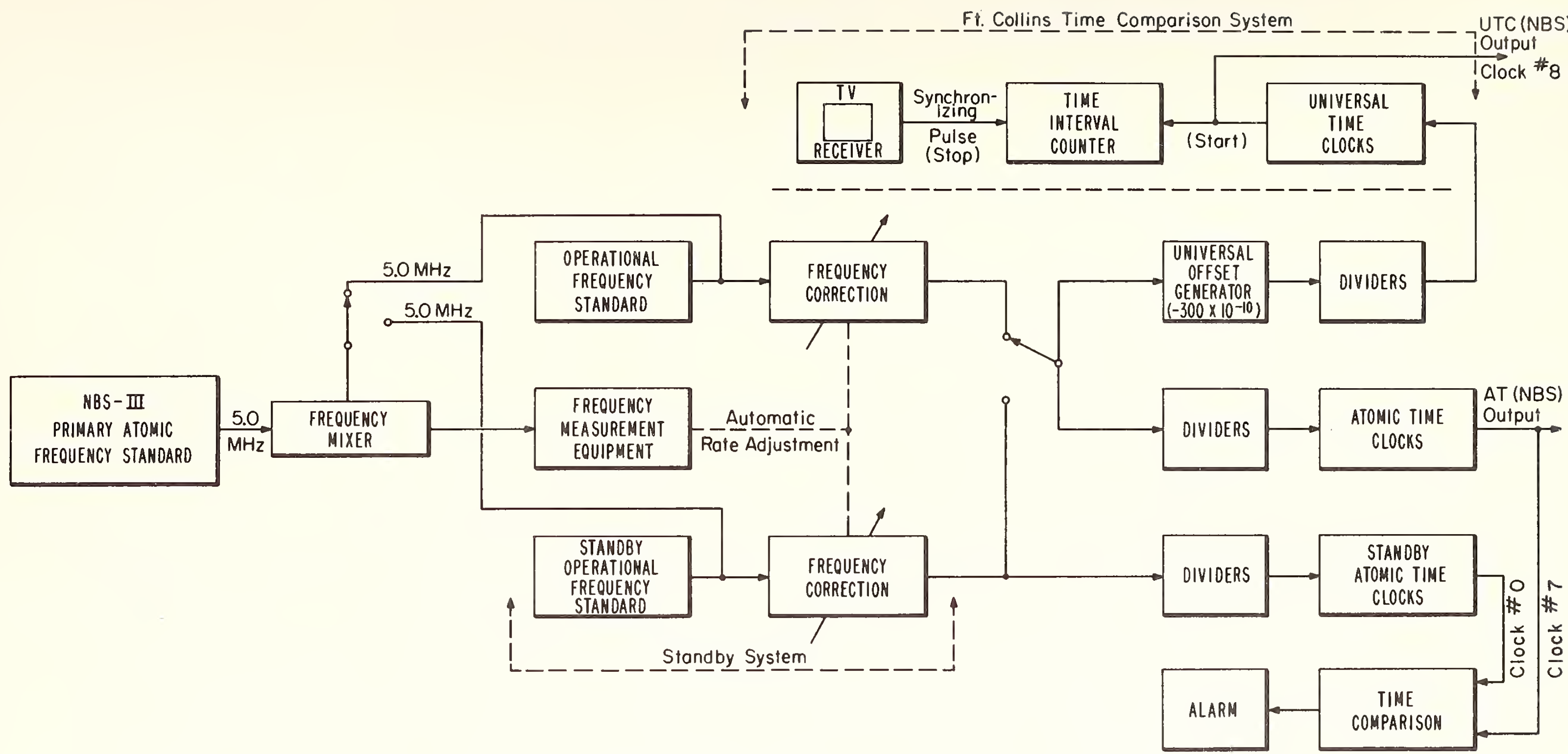
2.2 Radio Station WWV, Fort Collins, Colorado

The heart of the time and frequency generation system at WWV is a set of three commercial cesium-beam frequency standards. These standards are the basis for three identical generating units which provide to the transmitters a composite rf signal containing the complete WWV format.

The Cs standards, through a series of dividers and distribution amplifiers, drive the three master clocks or, more specifically, the three WWV time-code generators. These time-code generators provide the standard 600 Hz, 440 Hz, 1 kHz, and all the gates, codes, etc., necessary to produce this rather complex format. Figure 3 shows a simplified drawing of the WWV time and frequency generating system at Fort Collins.

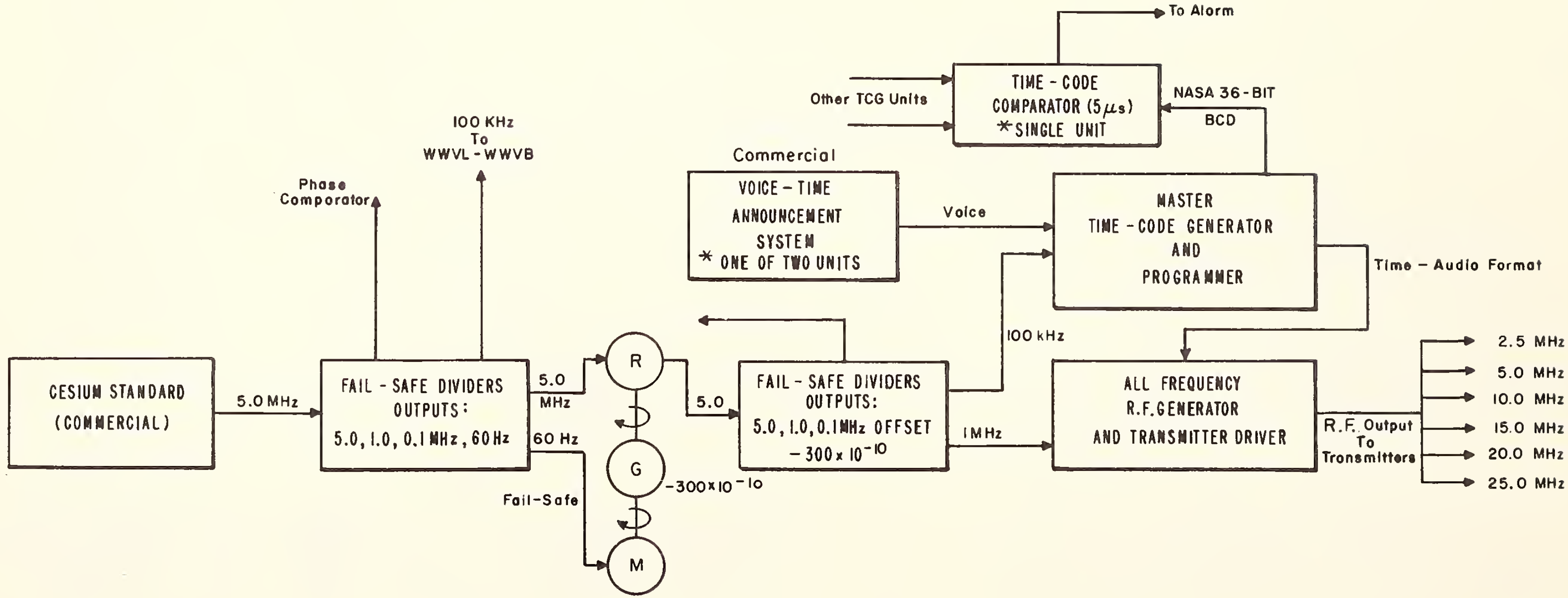
2.3 Radio Station WWVB, Fort Collins, Colorado

The WWVB time and frequency generating system is somewhat similar to that of WWV, although not as elaborate. WWVB uses a highly



STANDARD FREQUENCY AND TIME INTERVAL GENERATING SYSTEM
TIME AND FREQUENCY DIVISION
SECTION 273.04

Figure 2



WWV TIME AND FREQUENCY GENERATION
ONE * OF THREE IDENTICAL SYSTEMS SHOWING INTERCOMPARISONS
FT. COLLINS, COLORADO

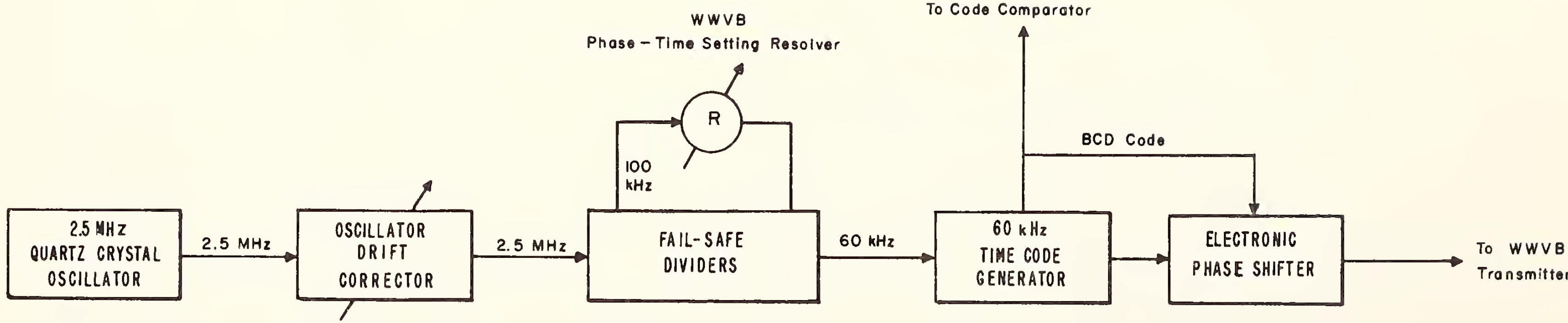
Figure 3

stable quartz crystal oscillator as the standard frequency generator. This crystal oscillator is referenced against NBS-III as noted later. Following this quartz crystal oscillator is a device known as a frequency drift corrector, which compensates for both frequency offset and rate change of the quartz crystal oscillator. The format for the time code and the 60 kHz driving frequency are produced by a special time-code generator, while two other generators are driven by a second quartz oscillator. These generators, along with the oscillators and other equipment, provide three semi-independent generating systems. Figure 4 shows the arrangement of this equipment.

2.4 Radio Station WWVL, Fort Collins, Colorado

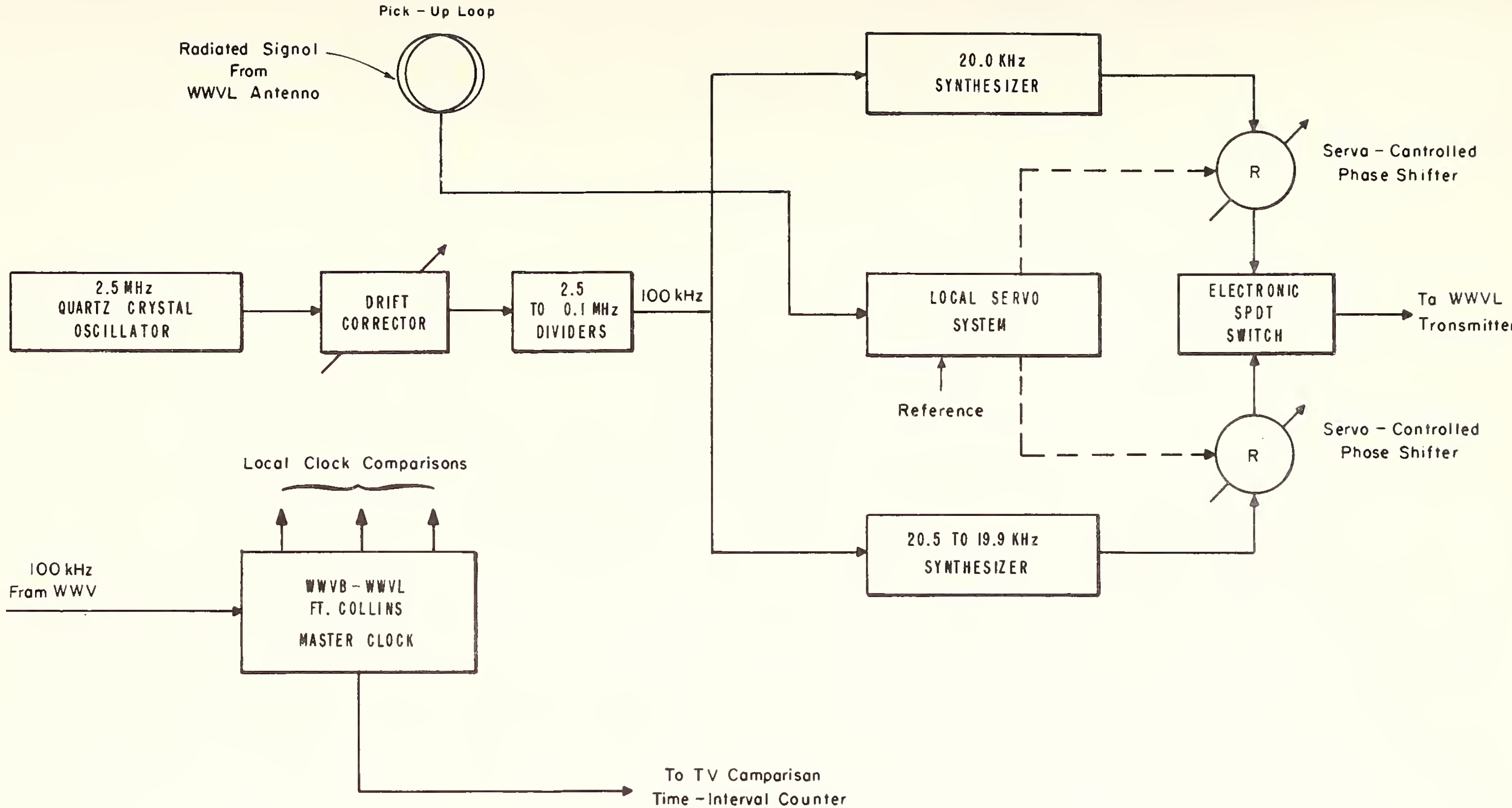
The frequency generation for WWVL is like that of WWVB in that quartz crystal oscillators and drift correctors are used as the primary frequency generators. Since there is no complex time format in this case, the one or two operating frequencies are programmed to the transmitter by NBS-built equipment. The synthesizers are units from commercial VLF phase-tracking receivers. At present, two frequencies are transmitted alternately every ten seconds. The transmitter is shut off for about 0.1 second out of each ten-second period to allow the frequency changeover. The carrier shutoff is "on time" with respect to the UTC(NBS) time scale. See fig. 5 for a simplified diagram of this system.

A second complete generating and programming system for WWVL is nearing completion. The new system will allow the transmission format to encompass from one to three operating frequencies. The order of frequency transmission and the time length of each can be controlled. The local servo system for the new generation and control equipment is discussed in section 3. Figure 5a shows this new system.



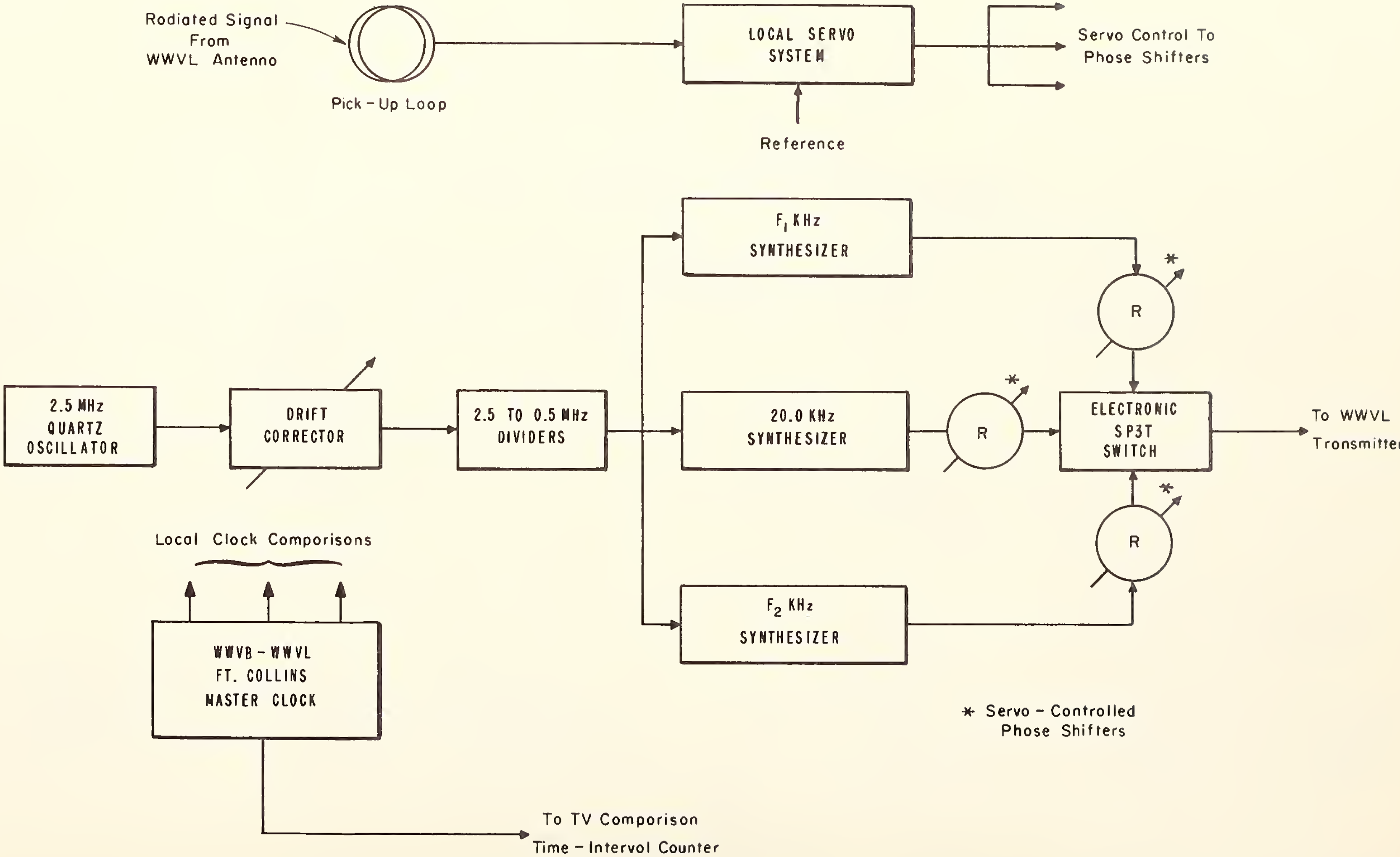
WWVB TIME AND FREQUENCY GENERATION AND CONTROL – ONE OF THREE SEMI – INDEPENDENT SYSTEMS FT. COLLINS, COLORADO

Figure 4



WWVL FREQUENCY CONTROL AND GENERATION
SYSTEM 1967 - 1969

Figure 5



REVISED WWVL FREQUENCY AND TIME GENERATION AND CONTROL SYSTEM

Figure 5a

2.5 Radio Station WWVH, Maui, Hawaii

Station WWVH began operation in 1948 and is now the oldest existing facility operated by the NBS Time and Frequency Division. Because the generation and control systems and equipment have been little modified since 1948, they remain rather primitive. A good quality quartz crystal oscillator provides the driving frequency at 2.5 MHz. This oscillator is referenced indirectly against NBS-III via the NBS VLF broadcasts. The 440 Hz, 600 Hz, and 1200 Hz tones for the format are generated by NBS-constructed equipment. WWVH has one standby clock system.

WWVH is soon going to be completely rebuilt on a new site at Kauai, Hawaii, with operation at the new facility commencing about January 1, 1971. The generation and control equipment for the new WWVH will mirror the system now in operation at WWV. Figure 3 shows the WWV system.

3. TRANSMISSION OF TIME AND FREQUENCY

3.1 Transmission from WWV

The multiple outputs from the rf driver units in the shielded control room are supplied directly to the transmitters. The WWV transmitters are simply high-power linear amplifiers and therefore do not contain audio circuits or modulators. The delay from the time-code generator to the antenna is much less than the transmitted accuracy specified for WWV and is therefore neglected.

The specifications as published in the Time and Frequency Services Bulletin are: frequency within $\pm 5 \times 10^{-12}$ of the NBS Frequency Standard; time within ± 5 microseconds of the UTC(NBS) and UTC(USNO) time scales (these two time scales have been coordinated since October 1968 and are identical to within state-of-the-art comparison techniques).

3.2 Transmission from WWVB

WWVB's transmitter and radiating system have an overall "Q" factor of somewhat less than 100. This "Q" factor is sufficiently low to allow operation without any phase control on the antenna. Future plans call for a "local" servo system to continuously adjust the transmitted phase at the antenna to be in agreement with the local station reference. The local servo system compensates for the phase perturbations due to wind shifting the antenna. These excursions seldom exceed 0.5 microsecond peak-to-peak. To correct for discrete phase shifts that occur whenever the antenna is tuned, a manual phase compensation is made based on a continuously-operating phase monitor.

The relationship between a time pulse or carrier cycle and the epoch of a time scale becomes important when one operates a standard time and frequency station in the LF range. The time at which a particular carrier crossover occurs for WWVB is published on a daily basis in the monthly issues of the Time and Frequency Services Bulletin. This first carrier crossover at the antenna occurs about 6 microseconds after the marker pulse of SAT(NBS).

The following points should be noted: (1) The radiated phase is late relative to the epoch of SAT(NBS) because of the delays through the WWVB transmission system. The master time-code generator at WWVB is maintained in close agreement with SAT(NBS) and any time difference between SAT(NBS) and the WWVB time-code generator is known at all times. (2) When a phase or time error between the epoch of SAT(NBS) and the WWVB time-code generator, and hence the WWVB radiated phase, occurs, the error is corrected by changing the frequency of the WWVB quartz crystal oscillator. The maximum rate of correction is limited to 0.1 microsecond per four-hour period. In other words, during times of phase correction, the frequency of WWVB can be in error with respect to the NBS reference frequency by as much as 6×10^{-12}.

3.3 Transmission from WWVL (Experimental)

The transmitted phase of WWVL is controlled more precisely than that of any other NBS transmission. There are two reasons for this: (1) The realizable stability of the transmission through the medium in the 20 kHz region is quite high, and (2) the susceptibility of the transmission system to phase perturbations is also quite high. The "Q" of the antenna system is of the order of 1000. With a tuning reactance of greater than 500 ohms, a change in this reactance of 0.2% causes a phase shift of 45^{o} or more than six microseconds. Every effort is made to hold the transmitted phase to within ± 0.1 microsecond of its nominal value. This calls for a highly sensitive "local" servo system.

This local servo begins with a pickup loop located in the building containing the antenna loading coil. The voltage from this coil is supplied through a buried coaxial cable to the shielded control room in the transmitter building. This signal, through an AGC amplifier, is compared with the output of the WWVL rf synthesizers. Any phase shifts detected at the loading coil building are quickly compensated for by the local servo-driven phase shifter. There is one of these phase shifters for each transmitted frequency. In addition, the input phase to the transmitter is adjusted so that the zero voltage crossover of the radiated field as measured at the antenna occurs at the epoch of the UTC(NBS) time scale. This is done for all transmitted frequencies.

Mentioned briefly in section 2.4 was the new WWVL generation and control system, which has been tested but is not yet in use. This new system is much improved over the existing control servo. For instance, the "dead-band" of the original system was about 0.2 microsecond. The new system "dead-band" is of the order of 20 nanoseconds. The new system has a single servo motor-amplifier driving the three phase shifters. Since each phase shifter is continuously driven, any error is "precorrected" by the phase shifter that will be controlling the transmitter in the next transmitting 10-second period. This tends to reduce the phase-noise of the transmission. This noise can be as high as 2 microseconds peak-to-peak in the current system.

Again, as in the case of WWVB, any errors between the radiated phase and the epoch of UTC(NBS) are known at all times, and corrected by the same procedure and at the same maximum rate of $\approx 6 \times 10^{-12}$.

3.4 Transmission from WWVH

Unlike the high-frequency transmitters at WWV, the units at Maui are high-level modulated standard AM transmitters. The 2.5 MHz from the controlling crystal oscillator is fed to each transmitter. Amplification or multiplication of this frequency is carried out by each transmitter as necessary. The various time-ticks, tones, voice announcements, and Morse Code information groups are fed to the modulators of the transmitters. Even though the WWVH master clock is nominally maintained in close agreement with UTC(NBS), the transmitter's modulation circuits degrade this performance somewhat. Station specifications are: frequency within $\pm 5 \times 10^{-11}$ of the NBS Frequency Standard, and time nominally within ± 20 microseconds of UTC(NBS) and UTC(USNO).

4. TIME AND FREQUENCY INTERCOMPARISONS

4.1 Among the Fort Collins Standards

4.1.1 WWV self comparisons

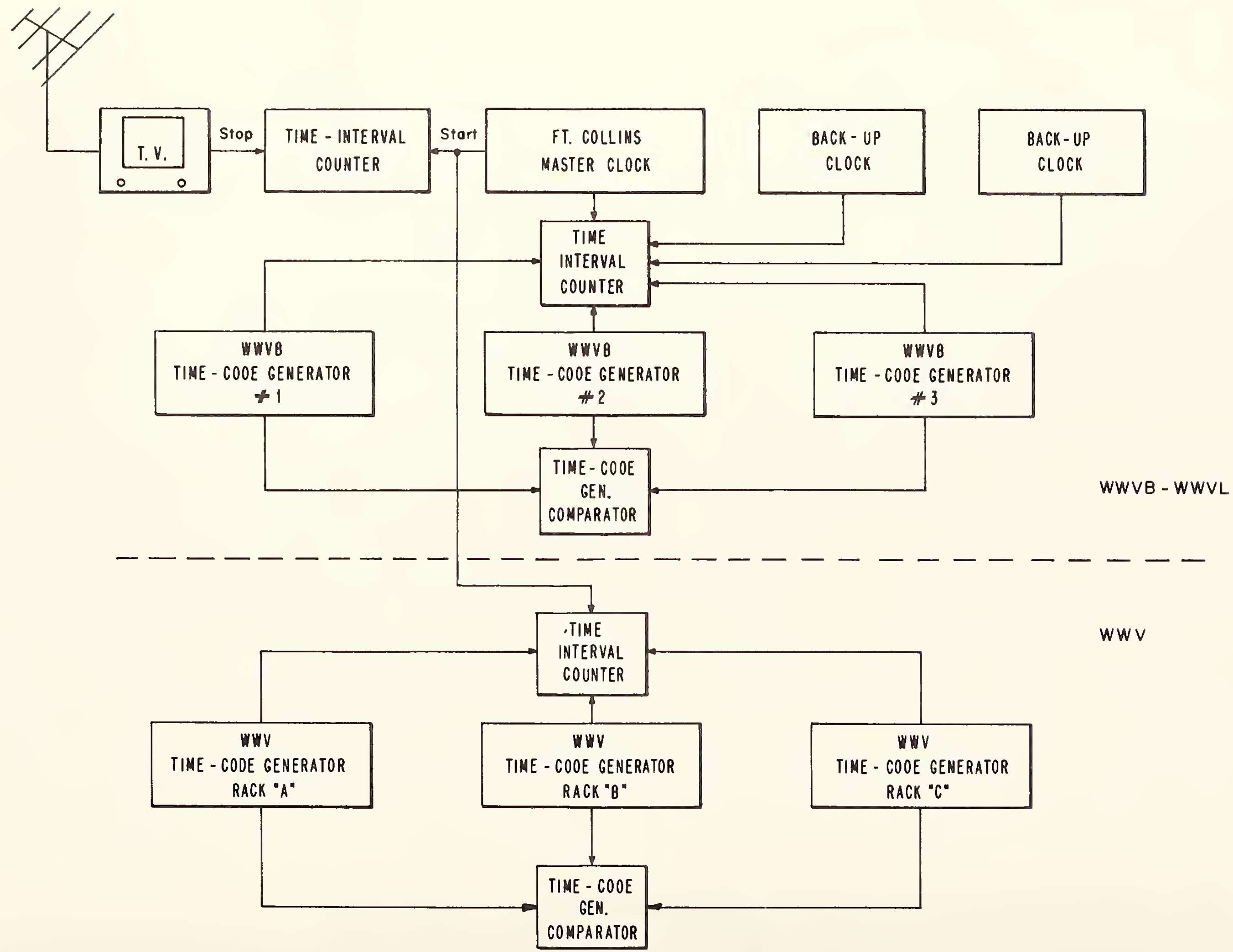
As was mentioned earlier, WWV has three independent time and frequency generating systems. These units are intercompared at three different locations in the systems: First, the phases of the "atomic" 1 MHz outputs from the dividers following the cesium standards are intercompared. The outputs of the phase detectors used are applied through meter relays to a multi-channel chart recorder with a 1-microsecond full scale. Second, following the motor-driven offset generator, the phases of the 1 MHz outputs from the UTC dividers are intercompared. The phase comparison record is arranged to be on the same multi-channel recorder. The meter relays are so adjusted that a 1-microsecond change in the phase difference between any two standards results in an alarm sounding. The third intercomparison is accomplished at the time-code generators. The 36-bit NASA time code from each generator is monitored by a code comparator. The alarm is sounded if the output from any unit diverges from any other by 5 microseconds, or if a clock jumps phase such that its code is misaligned with respect to that of any other unit. With these three comparison systems any standard, offset generator, divider chain, or time-code generator that fails can be immediately detected. See fig. 3 for a simplified block diagram showing the comparison systems.

4.1.2 WWV to WWVB and WWVL

The standard 100 kHz output from the WWV time and frequency generating system designated "Rack A" is sent by coaxial cable to the WWVB/VL control room. This standard frequency drives a digital clock designated as the "Fort Collins Master Clock." All measurements of the WWVL and WWVB local clocks, which are driven by the quartz crystal oscillators, are in terms of this Master Clock. This Master Clock pulse is also returned by coaxial cable to the WWV control room.

This system of clock intercomparisons effectively prevents undetected clock or time-code generator failures.

In addition to the clock comparisons, the quartz crystal oscillators that form part of the LF and VLF generating systems are continuously compared with the standard 100 kHz signal from WWV (see fig. 6).



CLOCK INTERCOMPARISON WWV - WWVB - WWVL
FT. COLLINS, COLORADO

Figure 6

4.2 Between the Fort Collins Standards and the WWVH Standard

Station WWVH uses all available information to maintain close ties with the Fort Collins standards. This includes continuous monitoring of stations WWVB and WWVL and frequent comparisons, via portable clock, with a phase stabilized Naval communications station on the island of Oahu. Via portable clocks and other means the relationship between the master clock at this Naval radio station and the clocks at Fort Collins and Boulder is known at all times to within a few microseconds.

4.3 Between the Fort Collins Standards and the NBS Standards

4.3.1 Portable clocks

The most reliable high-precision method of comparing the Fort Collins Master Clock with the NBS/Boulder Clock #8 is to physically carry a cesium-standard-driven clock between the two locations. A highly accurate clock of this sort normally loses or gains less than 0.1 microsecond during the four-hour round trip. To perform this task on a daily basis is expensive and unnecessary. Nevertheless, a portable clock is occasionally carried to Fort Collins when circumstances dictate.

4.3.2 TV synchronizing pulse method

a. Theory

Because the portable clock method for clock synchronization is expensive and time consuming, and the Boulder-Fort Collins continuous phase loop had been eliminated because it added short-term phase errors due to sky-wave interference, a new method had to be found. In 1967, Tolman, et al[1] described a method for comparing remote clocks using television synchronizing pulses for time transfer. Since May 1968,

[1] Tolman, et al, "Microsecond clock comparison by means of TV synchronizing pulses," IEEE Trans. on Instr. and Meas., vol. IM-16, No. 3, September, 1967.

this method has been used to compare the Master UTC Clock at Fort Collins with the NBS Clock #8 at Boulder.

Figure 7 is a space-time diagram of how the method is developed. Assume fig. 7 is a map of the geographical area in question at one instant in time. Located on the map are five TV synchronizing pulses as they might be at this instant.

From the diagram, if the Boulder clock and the Fort Collins clock agree, the delay time over the distance $D_1 - D_2$ is

$$D = \frac{4\lambda}{c} + B - A \text{ microseconds,} \tag{1}$$

where $\frac{\lambda}{c}$ = one synchronizing pulse period, or 63.55 microseconds. The values B and A are found by using the local clock tick as the start pulse of a time-interval measurement and a synchronizing pulse from a local TV set as the stop pulse. In the case of fig. 7, pulse #1 stops the Boulder time interval measurement at the value "A" and pulse #5 stops the Fort Collins time interval measurement at the value "B". If now the Fort Collins clock is early relative to the Boulder clock, the value B will increase because the interval will be longer. From the diagram, this longer interval B' will be

$$B' = B + \Delta t_e \tag{2}$$

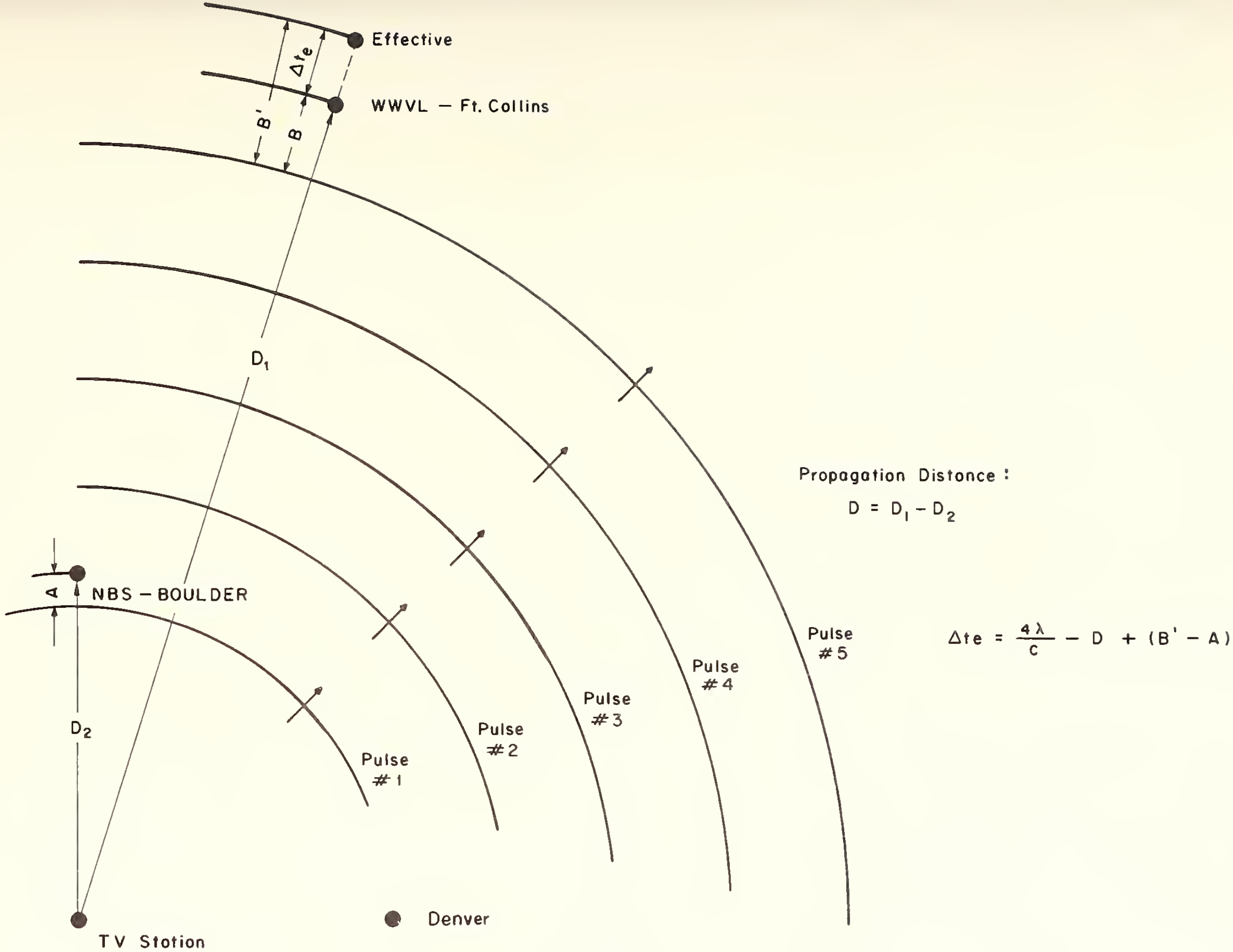
where Δt_e is the amount early.

Computing the delay time D using great circle distance calculations and substituting eq. (2) into eq. (1),

$$\Delta t_e = \frac{4\lambda}{c} - D + (B' - A) \text{ microseconds.} \tag{3}$$

b. Results

The TV synchronizing pulse method of clock intercomparisons was put in service in May 1968. The measurements have been made on a daily basis since then. During the actual measurement, some ten to



SPACE — TIME DIAGRAM
OF BOULDER TO FT. COLLINS
CLOCK SYNCHRONIZING.
DIAGRAM AT ONE INSTANT OF TIME

Figure 7

twenty readings are taken. The spread over this number of readings has seldom exceeded ± 0.5 microsecond. The average of this group is recorded. When the Fort Collins Master Clock has diverged from NBS Clock #8 by about one-half microsecond, the Fort Collins clocks are all reset to the correct time. These "correct" times will vary from clock to clock. For instance, the master clock at WWVL is maintained at a nominal and arbitrary 18 microseconds early with respect to Clock #8, to allow for easier clock intercomparisons at Fort Collins. The WWV clocks are maintained "on time."

The following table shows the results of the comparisons between the TV synchronizing pulse method and eight portable clock trips from Boulder to Fort Collins, starting in May 1968 and ending in December 1968.

Table 1

Date	Portable Clock Reading Fort Collins Master Clock - #8	TV Reading Fort Collins Master Clock - #8
May 14	17.63 μs	17.92 μs
May 20	17.99 μs	18.64 μs
July 5	17.34 μs	17.74 μs
July 8	17.10 μs	17.20 μs
Oct. 23	17.65 μs	17.57 μs
Nov. 1	17.89 μs	17.79 μs
Nov. 15	18.20 μs	18.24 μs
Dec.	17.33 μs	17.26 μs

It seems probable from the data that as the staff became more familiar with the measurement scheme, the accuracy with respect to the portable clock readings improved.

The method was proved to be satisfactory--the precision and accuracy are of a high order. The drawbacks to the current system are mainly in the measurement technique. The amplified synchronizing pulses themselves are not used; the actual measurement is made with the set's internal oscillator that is phase locked to the incoming pulses. It will be obvious to servo-systems people that this method is fraught with problems (the free-running frequency of the internal oscillator must be preset, for example).

A new system under development at the NBS utilizes the amplified pulses from a more stable color TV system. The new system has promise of improving the accuracy of the measurements by an order of magnitude.

APPENDIX

EXPLANATION OF NBS TIME SCALES

AT(NBS)

AT(NBS) is an Atomic Time Scale, previously called NBS-A, whose rate is determined by the primary frequency standard of the National Bureau of Standards (NBSFS). This standard (NBS-III cesium beam) realizes the second as defined in the International System of Units (SI). The epoch of the scale was in agreement with UTC(NBS) at 0000 UT 1 January 1958.

SAT(NBS)

Stepped Atomic Time is a coordinated time scale; i.e., the International Time Bureau (BIH) determines when steps in epoch of 0.2 second should occur to keep this scale in approximate agreement with UT2. The rate for this scale was the same as for AT(NBS) prior to 1 October 1968. The NBS and the U. S. Naval Observatory (USNO) agreed upon a coordinate rate starting 0000 UT 1 October 1968 for SAT(NBS), and this rate may be written as:

$$f_{coordinate} = (f_{NBSFS})\ (1 + 4 \times 10^{-13}) \text{ from } 10/1/68 \text{ to } 5/1/69$$

$$f_{coordinate} = (f_{NBSFS})\ (1 + 5 \times 10^{-13}) \text{ from } 5/1/69 \text{ to present}$$

In other words, SAT(NBS) presently runs at a rate higher in fractional frequency than AT(NBS) by 5 parts in 10^{13}. SAT(NBS) is the time scale broadcast by Radio Station WWVB. Note: The difference in rate between these scales is relevant only to international and national standards laboratories and observatories such as the BIH and NBS, and this in no way affects all other users of this transmitted signal.

UTC(NBS)

UTC(NBS) is a coordinated time scale; i.e., the BIH determines when steps in epoch of 0.1 second and changes in rate should occur to keep this Universal Time Scale in approximate agreement with UT2. Near 1 October 1968, the time difference, UTC(USNO) - UTC(NBS), was zero. The NBS and the USNO agreed on a coordinate rate for these two time scales starting 0000 UT 1 October 1968. The coordinate rate was chosen as an average of the two rates, as determined by portable clocks, prior to 1 October 1968. The USNO and NBS intend to maintain synchronization of the UTC scales to within about 5 microseconds by using an appropriate coordinate rate. The present coordinate rate of UTC(NBS) is:

$$f_{UTC(NBS)} = (f_{coordinate}) (1 - 300 \times 10^{-10})$$

or

$$f_{UTC(NBS)} = (f_{NBSFS}) (1 - 299.995 \times 10^{-10}).$$

This last equation is, again, useful only to other standards laboratories.

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