

NAT'L INST. OF STAND & TECH



A11107 231880

A UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION



NBS TECHNICAL NOTE 379-1

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100
U5753
no. 379-1
1972
c.2

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

U. S.
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TECHNICAL NOTE 379-1

ISSUED JUNE 1972

Nat. Bur. Stand. (U.S.), Tech. Note 379-1, 26 pages (June 1972)
CODEN: NBTNAE

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

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NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

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Bulletin 100

May 1, 1972

BULLETIN

NBS Radio Station WWVL

Notice is hereby given that effective 0000 UTC 17 May 1972, the WWVL broadcast format will be changed from 19.9 kHz and 20.0 kHz to 20.0 kHz and 20.9 kHz with each frequency transmitted on a 50% duty cycle.

Effective 1 July 1972, regularly scheduled transmissions from WWVL will be discontinued. Contingent upon the need and the availability of funds, the station will broadcast experimental programs thereafter on an intermittent basis only.

Transmissions may be made available on a subscription basis to organizations or agencies of the Federal government. Arrangements for use of WWVL to broadcast experimental programs should be made through the Frequency-Time Broadcast Services Section 273.02, National Bureau of Standards, Boulder, CO 80302.

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) and UTC(NBS). These time scales are developed by utilizing the properties of the NBS frequency standard, NBSFS. 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 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 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 with the ability to disseminate standards of time and frequency from 19.9 kHz to 25 MHz. These stations provide standard atomic frequency and a Universal Time scale, called UTC, which approximates the UT1 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

Since about 1959 the NBS Frequency Standard (NBSFS) has been based on a series of thoroughly-evaluated laboratory cesium beam standards, designated NBS-I, NBS-II, and NBS-III. During this period the specified one-sigma accuracy of the NBSFS - i. e., an estimate of how far the output frequency of the standard may deviate from the "ideal" frequency of the isolated cesium atom, has improved from several parts in 10^{11} to 5×10^{-13} . The accuracy estimates are determined from an extensive set of evaluative measurements to assess

the magnitude of any possible frequency errors that might be introduced by various components, subsystems, and environmental conditions of the overall NBSFS system. Currently, the Atomic Frequency and Time Standards Section is developing a new, refined cesium standard, designated NBS-5. This device, which will be in operation during 1972, should produce a documented accuracy near 1×10^{-13} , once the complete system is fully evaluated. Present plans call for operation of this new NBSFS only on an intermittent basis in order to periodically calibrate the frequencies of the working ensemble of clocks in the NBS time scale system. These data, as described next, are used in producing the AT(NBS) and other related time scales.

2.1.2 Computed or "paper" time scales

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

The paper time scales, AT(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 produced by the computer. The computer utilizes the current measured or estimated frequency of each oscillator with respect to the NBSFS, 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

*See Appendix

this information, one has a mechanism 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.*

2.1.3 Operational Clock Systems

The Section maintains a number of operational clock systems. The outputs of these systems are electrical seconds pulses as well as visual displays of time of day. 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 used to compute data found in the NBS Time and Frequency Services Bulletin, published monthly. The deviation of this clock from the UTC(NBS) time scale is constrained always to be less than 1 microsecond and seldom exceeds ± 0.2 microsecond. Another system, operating from an independent cesium beam standard, is a backup atomic rate clock designated Clock #0. A time comparator and twenty-four hour alarm system are associated with Clock #0 and Clock #7. This alarm is actuated if Clock #7 diverges from Clock #0 by more than 5 microseconds. 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.

*It should be noted that three of the six atomic clocks in the ensemble are physically located at Fort Collins, Colorado.

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 cesium 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 audio tones, time-ticks, 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 stable quartz crystal oscillator as the standard frequency generator. This crystal oscillator is referenced against NBSFS 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 (Intermittent Experimental)

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, two, or three operating frequencies are programmed to the transmitter by NBS-built equipment. The synthesizers are units from commercial VLF phase-tracking receivers. If multiple frequencies are being transmitted, the transmitter is shut off for about 0.1 second out of each period to allow the frequency changeover. The carrier shutoff is "on time" with respect to the UTC(NBS) time scale. See Figure 5 for a simplified diagram of this system. The transmission period of each frequency is usually ten seconds.

The local servo system for the generation and control equipment is discussed in Section 3. Figure 5 shows this system.

2.5 Radio Station WWVH, Kauai, Hawaii

Station WWVH began operation at an old Navy site on the island of Maui in 1948. After long and distinguished service, this station was relocated near the town of Kekaha on the island of Kauai.* The standards at WWVH are referenced indirectly against NBSFS via the NBS broadcasts and by way of portable clocks that are referenced to the U. S. Naval Observatory time scale, which is, in turn, referenced to the NBS time scale.

The generation system for WWVH, Kauai, Hawaii, is essentially the same as the system at WWV. Figure 3 shows this system.

* This transfer taking place at 0 hours UT, July 1, 1971.

3. TRANSMISSION OF TIME AND FREQUENCY

3.1 Transmission from WWV and WWVH

The multiple outputs from the rf driver units in the shielded control room are supplied directly to the transmitters. The WWV and WWVH 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 either station and is therefore neglected.

The specifications for WWV are: frequency within $\pm 1 \times 10^{-12}$ of the NBS Frequency Standard; time within ± 5 microsecond of the UTC(NBS) time scale. The time and frequency specifications for WWVH are somewhat degraded due to the difficulty in making comparisons over such long geographical distances.

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 marker 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. The first carrier crossover at the antenna occurs about six microseconds after the marker pulse of UTC(NBS).

The following points should be noted: (1) The radiated phase is late relative to the time marker of UTC(NBS) because of the delays through the WWVB transmission system. The master time-code generator at WWVB is maintained in close agreement with UTC(NBS), and any time difference between UTC(NBS) and the WWVB time-code generator is known at all times. (2) When a phase or time error between the marker of UTC(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. These 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 percent causes a phase shift of 45° or more than 6 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 coil, 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. In the control equipment, this signal is compared with the rf output of the WWVL synthesizer. Any phase shifts detected at the loading coil building are quickly compensated for by the servo-driven phase shifter. Each transmitted frequency has its own phase shifter, but the system contains a single servo motor geared to all the phase shifters. Since each phase shifter is continuously driven, any phase error is "precorrected" to the phase shifter that will be controlling the transmitter during the upcoming transmitting period. This pre-correction reduces the phase noise of the transmission considerably. 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 in coincidence with the time marker of the UTC(NBS) time scale.

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

4. TIME AND FREQUENCY INTERCOMPARISONS

4.1 WWV and WWVH Self-Comparisons

As we mentioned earlier, WWV and WWVH have three independent time and frequency generating systems: First, the phases of the 1 MHz outputs from the dividers following the cesium standards are intercompared. The outputs of the phase detectors used are applied to a multi-channel chart recorder with a 1-microsecond full scale. Second, following the manual phase shifter, the phases of the 1 MHz outputs from the next set of dividers are intercompared. The phase

comparison record is arranged to be on the same multichannel recorder. The third intercomparison is accomplished at the time-code generators. The IRIG-H 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, divider chain, or time-code generator that fails can be immediately detected. See Figure 3 and Figure 6 for simplified block diagrams showing the comparison systems.

4.2 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 Figure 6).

4.3 Between the Fort Collins Standards and the WWVH Standards

Station WWVH uses all available information to maintain close ties with the Fort Collins standards. This includes monitoring of

stations WWVB and WWVL and frequency comparisons, via portable clock, with a phase-stabilized Naval communications station on the island of Oahu. Via portable clock and other means the relationship between the master clocks at this Naval radio station and the clocks at Fort Collins and Boulder is known at all times to within a few tenths of microseconds.

4.4 Between the Fort Collins Standards and the NBS Standards

4.4.1 Portable Clocks

A 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.

4.4.2 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 had short-term phase errors due to sky-wave interference, a new method had to be found. In 1967, Tolman, et al¹ described a method for comparing remote clocks using television synchronizing pulses for time transfer. Since

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

May, 1968, 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 Figure 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

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

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 Figure 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

$$B' = B + \Delta t_e \quad (2)$$

where Δt_e is the amount early.

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

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

b. Practice

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 readings are taken. The spread over this number of readings seldom exceeds ± 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, it is reset to the correct time.

5. APPENDIX

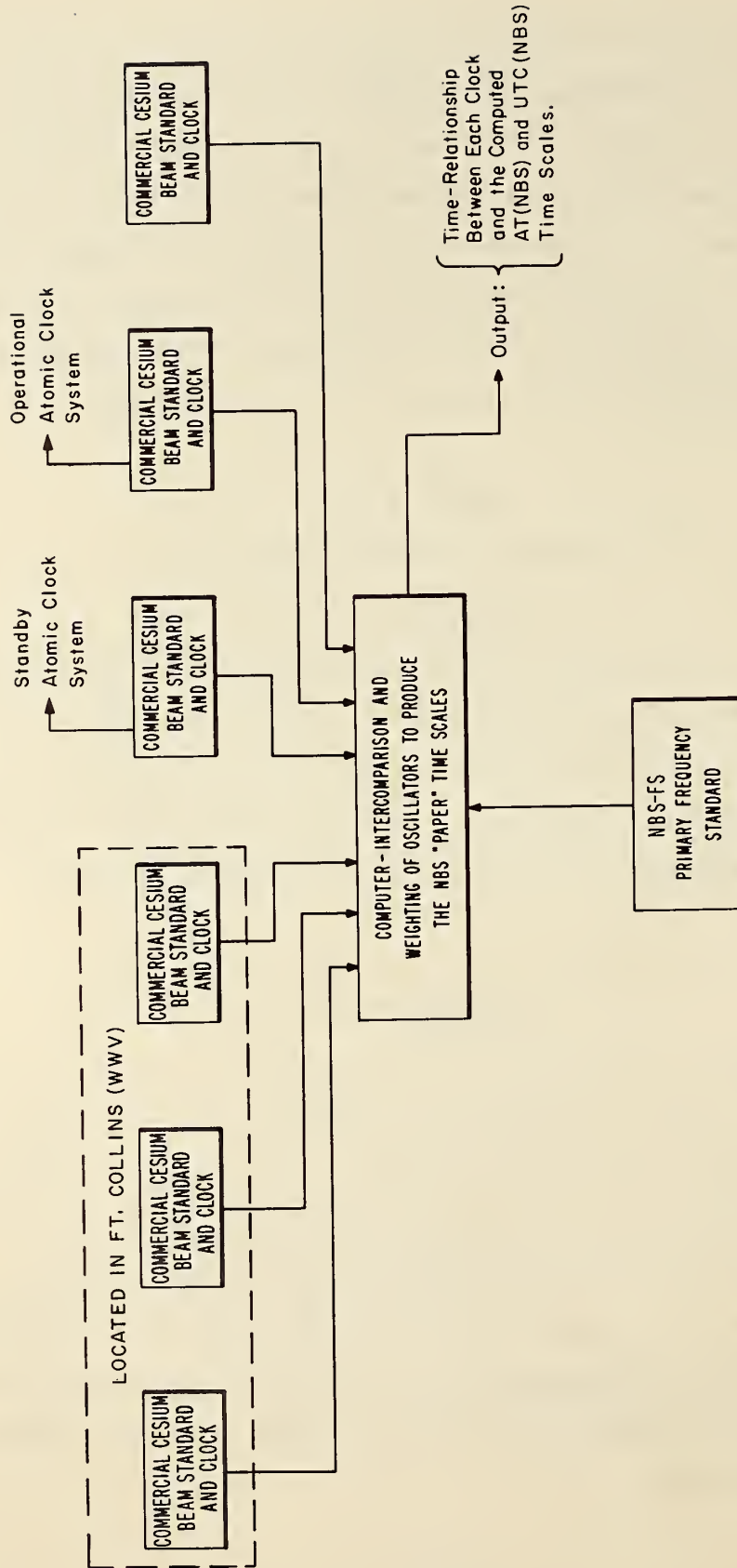
5.1 Explanation of NBS Time Scales

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 realizes the second as defined in the International System of Units (SI). The origin marker of the scale was in agreement with UTC(NBS) at 0000 UT 1 January 1958.

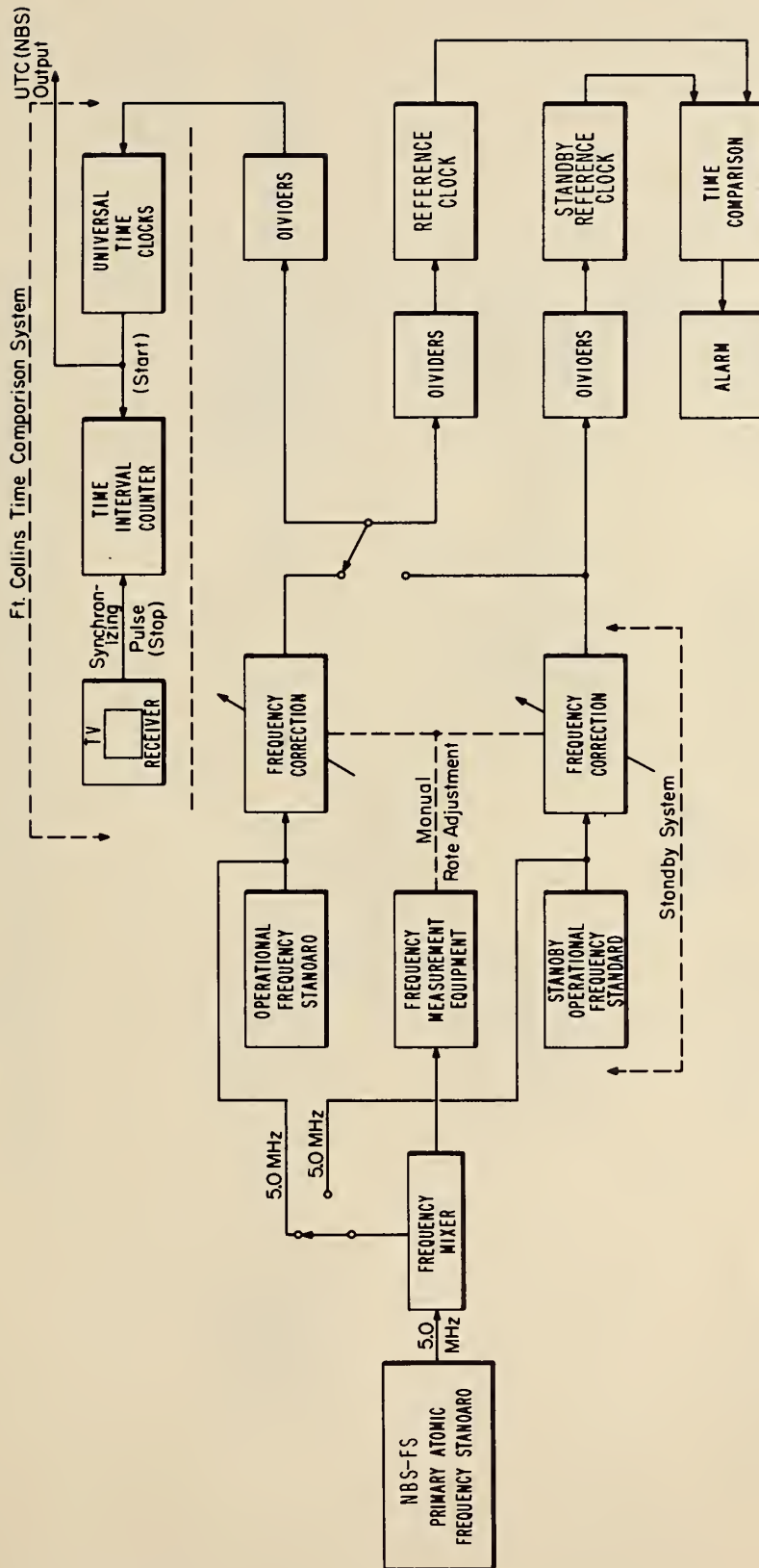
UTC(NBS)

UTC(NBS) is a coordinated time scale; i.e., the BIH determines when steps of 1.0 second should occur to keep this Universal Time Scale in approximate agreement with UT1. The NBS and the USNO agreed on a coordinate rate for these two time scales starting 0000 UT1, 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.



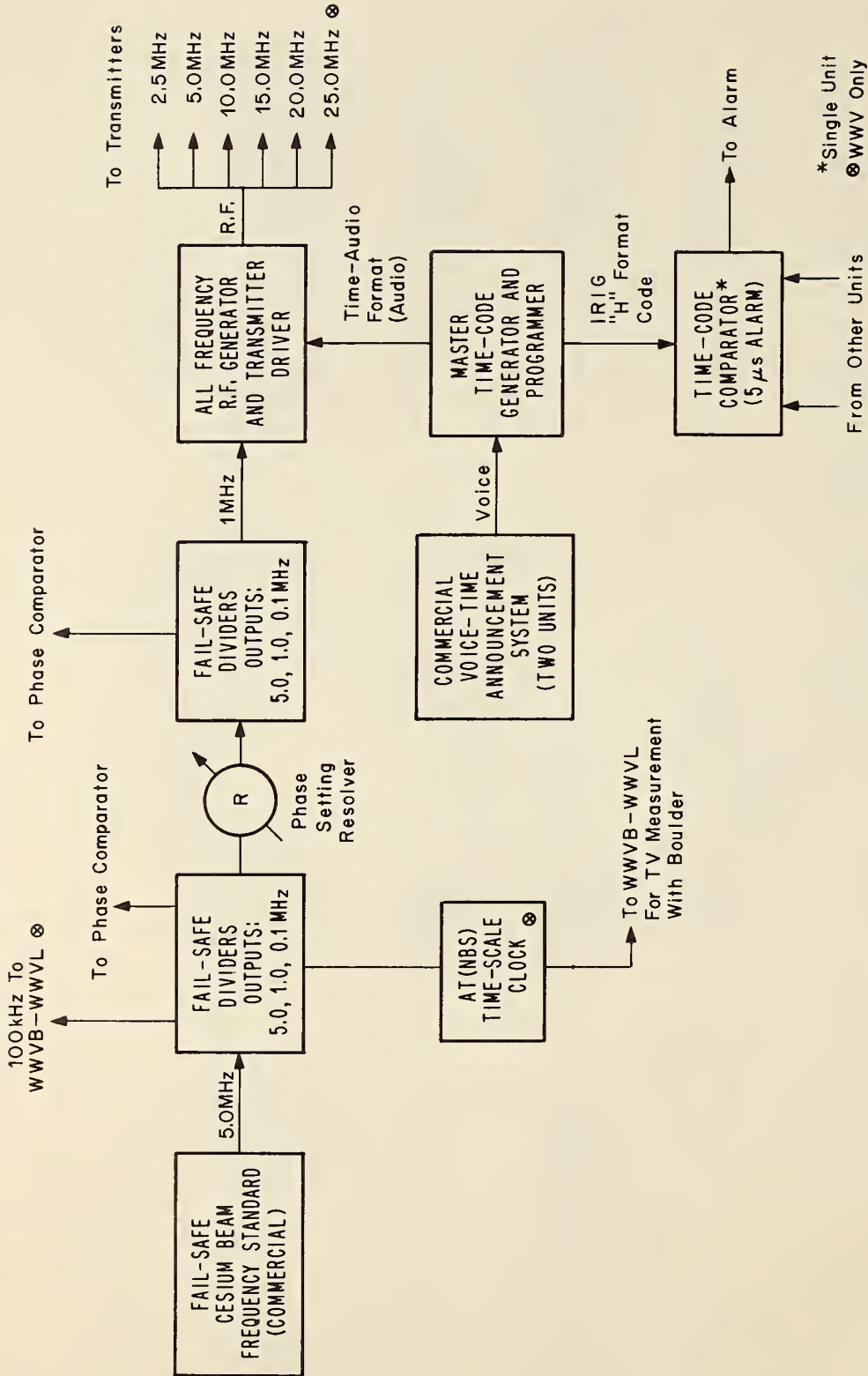
SYSTEM FOR GENERATION OF COMPUTED TIME SCALES
AT(NBS) AND UTC(NBS)

Figure 1



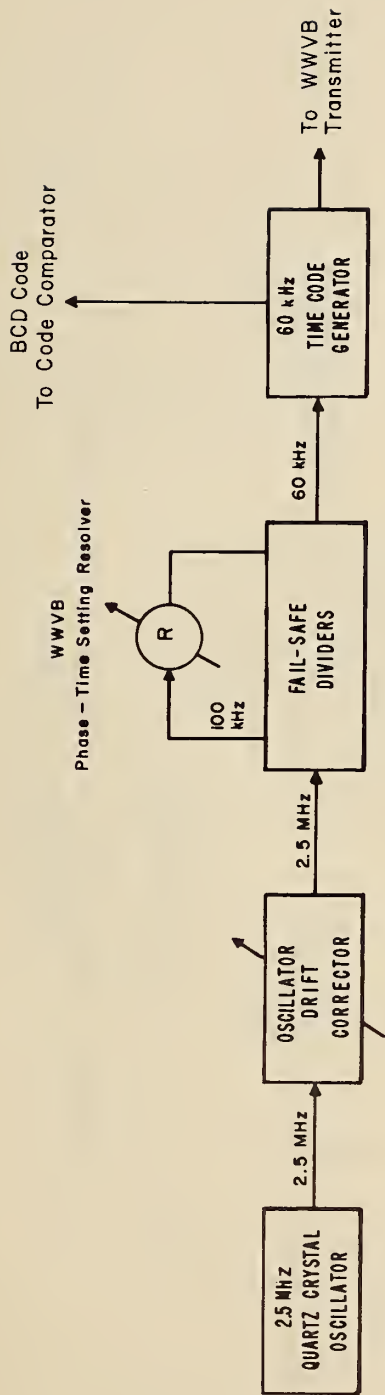
STANDARD FREQUENCY AND TIME INTERVAL GENERATING SYSTEM
 TIME AND FREQUENCY DIVISION
 SECTION 273.04

Figure 2



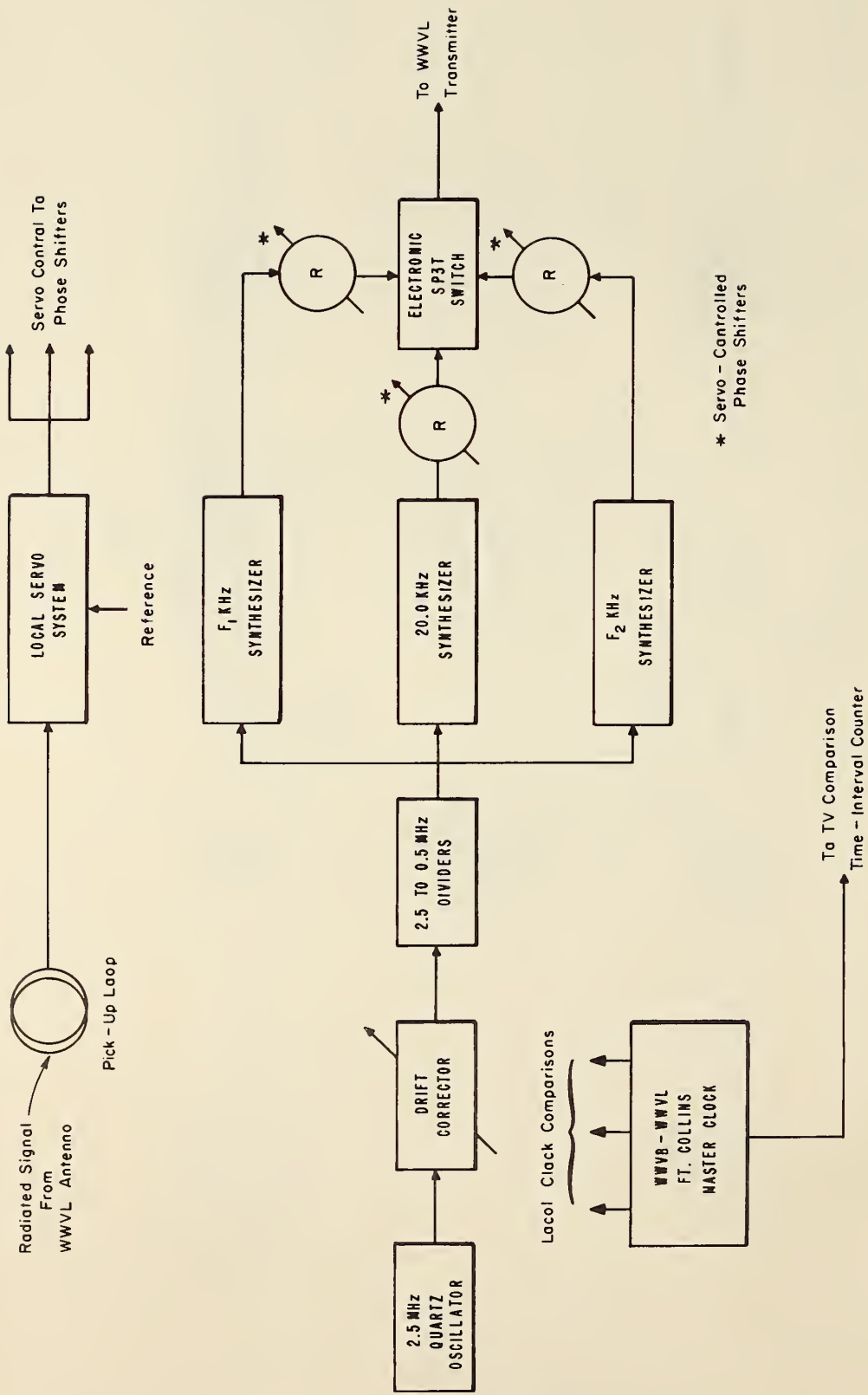
WWV AND WWVH TIME AND FREQUENCY GENERATION -
 ONE OF THREE IDENTICAL SYSTEMS

Figure 3



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

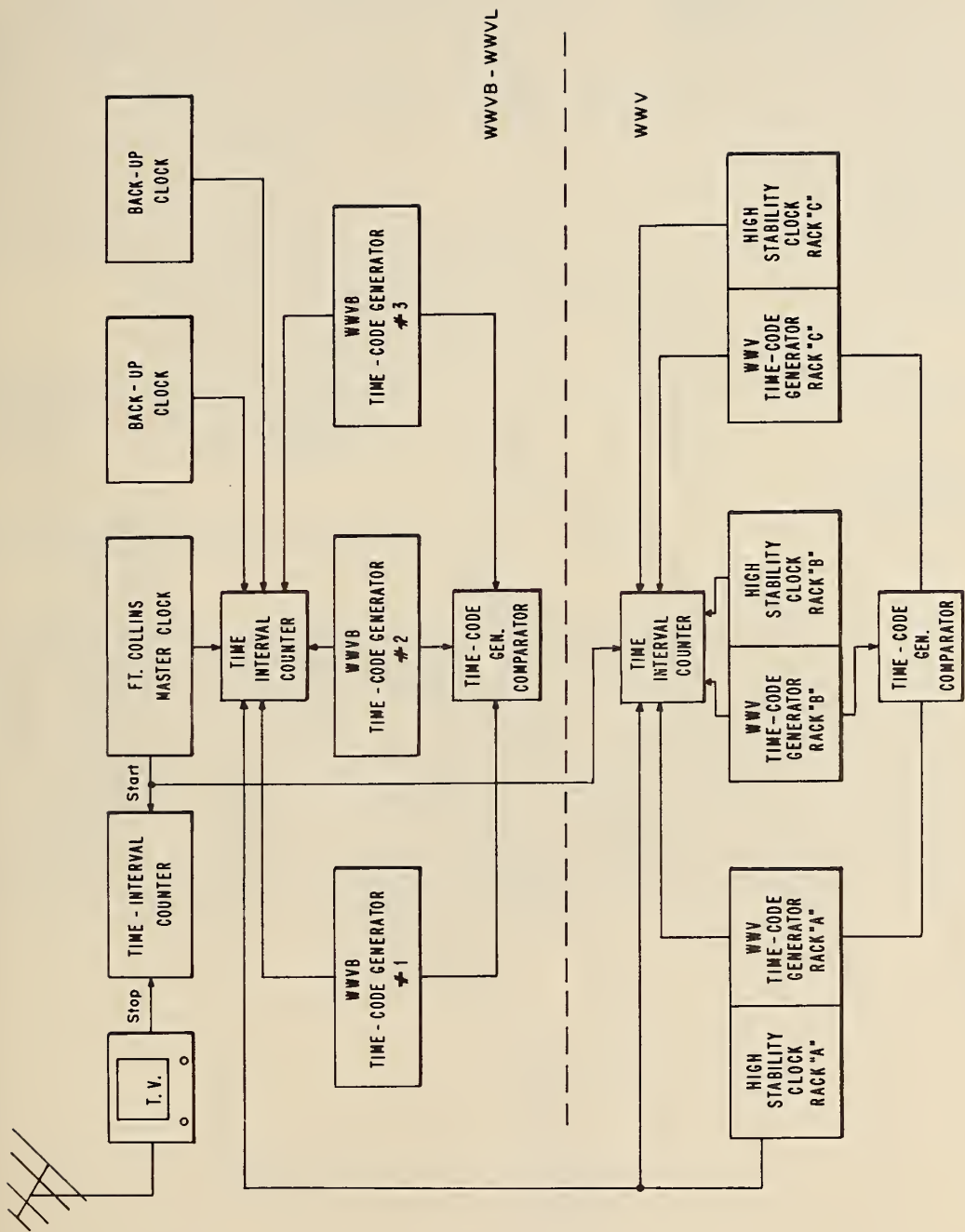
Figure 4



REVISED WWVL FREQUENCY AND TIME GENERATION AND CONTROL SYSTEM

1969-1972

Figure 5



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

Figure 6

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4. TITLE AND SUBTITLE Standard Time and Frequency: Its Generation, Control, and Dissemination From the National Bureau of Standards Time and Frequency Division		5. Publication Date June 1972	6. Performing Organization Code
7. AUTHOR(S) John B. Milton		8. Performing Organization	
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS, Boulder Labs. DEPARTMENT OF COMMERCE Boulder, Colorado 80302		10. Project/Task/Work Unit No. 2730128	11. Contract/Grant No.
12. Sponsoring Organization Name and Address National Bureau of Standards Boulder, Colorado 80302		13. Type of Report & Period Covered	14. Sponsoring Agency Code
15. SUPPLEMENTARY NOTES			
<p>16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)</p> <p>The Time and Frequency Division of the National Bureau of Standards produces the NBS time scales, AT(NBS) and UTC(NBS). These time scales are developed by utilizing the properties of the NBS frequency standard, NBSFS. 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 UTC(NBS), and various tones, alerts, and corrections for time-of-day information.</p>			
17. KEY WORDS (Alphabetical order, separated by semicolons) clock synchronization; frequency and time dissemination; primary frequency standard; standard frequency broadcasts; time interval; time scales			
18. AVAILABILITY STATEMENT <input checked="" type="checkbox"/> UNLIMITED. <input type="checkbox"/> FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NTIS.		19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 26
		20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price .35

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