LF-VLF Frequency and Time Services of the National Bureau of Standards

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Abstract—**The United States Frequency Standard and National Bureau of Standards Time Scale are described, and the techniques by which they are used to control the broadcasts from WWVB and WWVL, Fort Collins, Colo., are presented. A practical method for control of frequency and time broadcasts from WWV, Greenbelt, Md., is described and actual results shown.**

Introduction

RECENT ADVANCES in space technology have imposed upon timing systems a greater need for precise time synchronization between ground stations separated by thousands of miles. The National Bureau of Standards is meeting this challenging requirement with improved standards and improved techniques for disseminating them by means of radio broadcasts at LF and VLF.

Frequency Standard

The National Bureau of Standards maintains the United States Frequency Standard at its laboratories in Boulder, Colo. The USFS has a defined frequency of 9 192 631 770.00 Hz for the $(F=4,\ m_F=0)\leftrightarrow(F=3,\ m_F=0)$ transition in the ground electronic state of cesium^{133}.

This frequency standard is physically realized in atomic beam devices designated NBS-II and NBS-III. NBS-II and its forerunner, NBS-I, are fully described elsewhere[1] by Mockler and others of his staff. NBS-III has a separation of 366 cm for its perturbing oscillating field as against 164 cm for NBS-II, which results in the narrower line width of 50 Hz compared with the 120 Hz line width of NBS-II.

These devices realize the USFS with an uncertainty of $\sim 1\times10^{-11}$ and have precisions approaching 2×10^{-12}.

Upon this standard all of the frequency and Time Services of the National Bureau of Standards are based.

NBS-A Time Scale

The frequency of a continuously running device is measured daily in terms of the United States Frequency Standard (the devices designated NBS-I, NBS-II, and NBS-III are high-quality laboratory machines, unsuited by nature and complexity to continuous operation), and it is possible to generate a time scale with the same uncertainty and stability as that of the USFS. This derives partly from the fact that frequency and time interval are inversely related.

The National Bureau of Standards Atomic (NBS-A) time scale, described by Barnes, Andrews, and Allan,[2] approaches the USFS uncertainty very closely. Actually five continuously running frequency generators are compared with the USFS each working day. These generators are well aged and are assumed to have a linear frequency drift between measurements. At intervals of about two weeks the daily frequency measurements are examined with the aid of a computer to obtain the deviation of each one from a straight line. Time is computed then on the basis of the group of generators weighted inversely as the square of the deviation of the frequency of each generator from the straight line.

This system produces an extremely good time scale which, however, has the same disadvantage, from an operating point of view, as the devices used to realize the USFS. It presently is incapable of producing a continuously available time reference incorporating the full accuracy of the USFS.

NBS-UA Time Scale

Time signals presently broadcast from the NBS radio stations are an approximation to UT (Universal Time) based on a fixed annual offset from the atomically determined frequency and with step time adjustments of 100 ms as needed to keep the time as broadcast within about 150 ms of actual UT2. During the calendar year 1964 the frequency used to approximate UT2 is 150 parts in 10^{10} lower than the atomically determined frequency.

The National Bureau of Standards derives the NBS-UA time scale by applying the appropriate offset frequencies and time jumps as required to the NBS-A time scale.

This still lacks the continuity necessary to operate radio stations.

A further approximation, having the desired continuity, is made by applying drift-rate correction to the output of one of the frequency generators. Since the generator used for this purpose has very good stability and very nearly linear drift rate, it is quite practical to "program out" the drift. At Boulder a system for ac-

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[1] R. C. Mockler, R. E. Beehler, and C. S. Snider, "Atomic beam-frequency standards," *IRE Trans. on Instrumentation*, vol. I-9, pp. 120–132, September 1960.

[2] J. A. Barnes, D. H. Andrews, and D. W. Allan, "The NBS-A time scale—its generation and dissemination," this issue, page 228.

complishing this mechanically is used. The system was developed concurrently, but independently, with a commercial system, and was in use at Boulder prior to the availability of a commercial unit. This drift-rate corrector consists [2] of a phase shifter driven by two ball-disk integrators in cascade with appropriate gear reduction units and synchronous motors.

The time derived from the drift-corrected oscillator is compared frequently with time computed on the NBS-UA time scale. Corrections are made to the drift-rate settings as necessary to keep the drift-corrected time in close agreement with the NBS-UA time scale. In practice it has been possible to do this within a few microseconds tolerance, at the same time holding the frequency within 1 or 2×10^{11} of the USFS.

The previously described system provides the broadcasting services with a continuous source of standard frequency which is time-locked to the NBS-UA time scale for all practical purposes.

Phase-Lock Link

Since the high field strengths associated with transmitters make it highly undesirable to have them in close proximity to precision laboratories, the LF and VLF transmitters are located about fifty miles away from the Boulder laboratories at Fort Collins, Colo. This adds to the problem of precise control of the transmitted frequencies. Also phase fluctuations normally occur due to temperature variations at the transmitters and shifting of the antenna system due to winds, ice, and thermal expansion.

All these fluctuations and the relating of the frequency to the drift-corrected oscillator are taken care of in the phase-lock system in use between Boulder and Fort Collins.

The phases of the signals transmitted at 20 kHz and 60 kHz are monitored at the Boulder laboratories and compared with the phases of signals generated by the drift-corrected oscillator.

When the phase of the received signal varies from the phase of the reference signal, an error vcltage is produced. Then this error signal is made to produce appropriate FM signals feeding a transmitter operating at 50 MHz. This transmission is beamed by a directional antenna array to Fort Collins.

Signals as received at Fort Collins operate servo systems to control the transmitted phases at each frequency. The transmission system actually broadcasts both the reference signal and the error signal for each correction servo system. By this technique it has been possible to eliminate most of the propagation fluctuations due to the control link in the phase of the transmitted signals at 20 kHz and 60 kHz.

Figure 1 shows in block diagram form the steps involved in making possible the accurate transmissions from WWVB and WWVL at Fort Collins. Later the significant part these transmissions play in the control of WWV will be described.

Figure 2 illustrates in block diagram form the Boulder end of the phase-lock system. From left to right this diagram shows the LF and VLF receivers, phase detectors, oscillators, modulator amplifiers, and the mixer necessary to provide the reference and error signals to the 50 MHz FM transmitter.

Figure 3 continues the phase-lock system at the Fort Collins end of the link. The 50 MHz receiver at the upper right of the diagram picks up the signals beamed from Boulder. The received signal is split then into its three component signals whose frequencies are 400 Hz, 5.4 kHz, and 10.5 kHz. The three frequencies carry, respectively, the reference phase information, the 20 kHz error phase information, and the 60 kHz

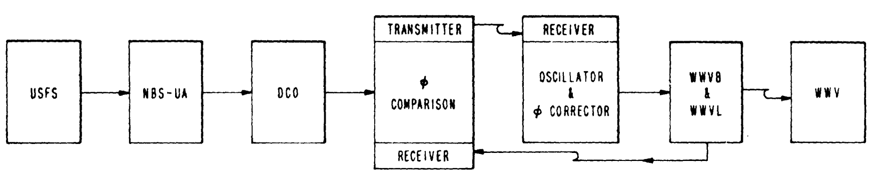

Fig. 1. Frequency-time control of WWV.

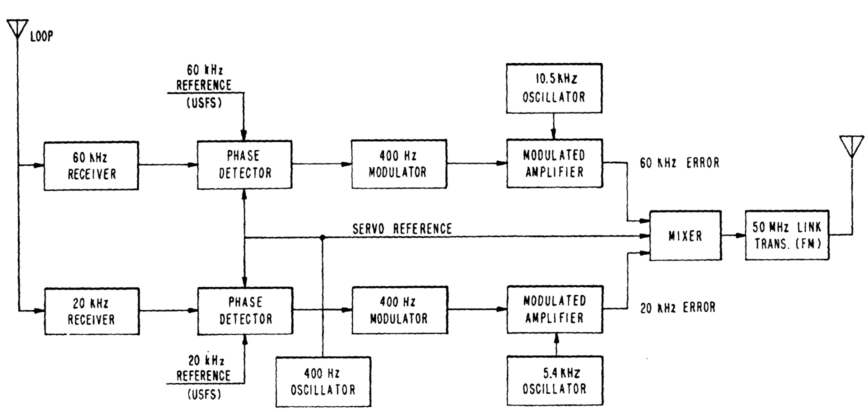

Fig. 2. Phase-lock system, Boulder section.

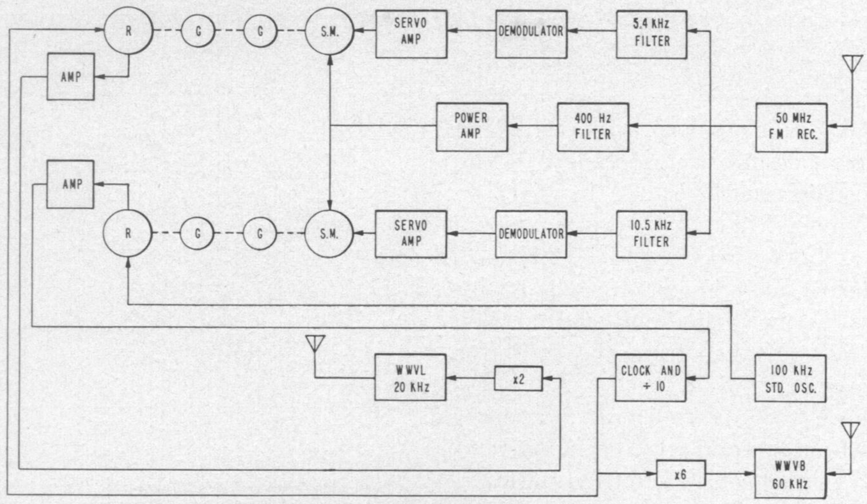

Fig. 3. Phase-lock system, Fort Collins section.

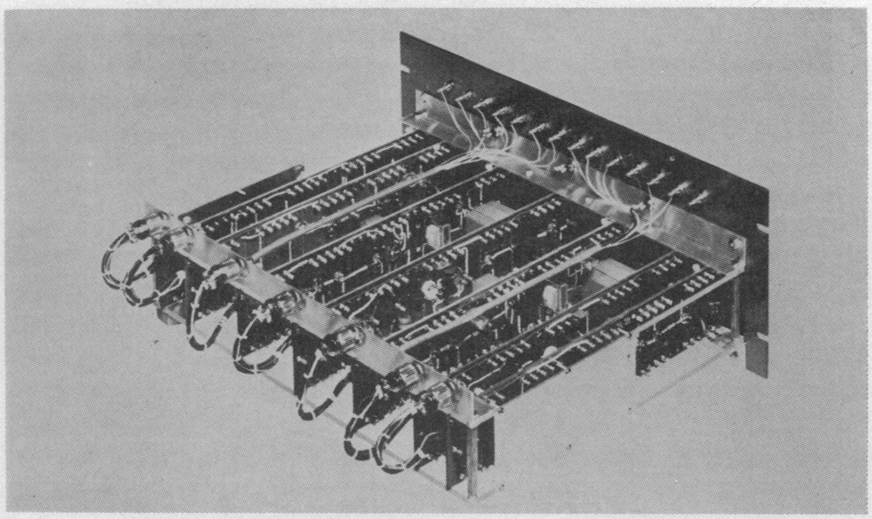

Fig. 4. Boulder phase correction equipment.

error phase information. As will be noted the 60 kHz system bears the brunt of the oscillator drift correction, and the 20 kHz system compensates mainly for variations in the phase of the VLF antenna system. This serves to share the load on the servo systems when both transmitters are working. It can also be seen that the system will function quite well with either frequency alone.

The system is basically a simple servo system with an FM link coupling the phase detectors to the servo motors and phase correcting devices.

The performance of this system has been remarkably excellent. Very few malfunctions have been observed in more than a year's operation. The circuitry is almost entirely transistorized.

Figure 4 shows the Boulder part of the phase correction equipment. The unit at Fort Collins is constructed along similar lines. The 50 MHz transmitter and receiver are not included in this photograph. They are commercial items which have been modified for this purpose by the National Bureau of Standards.

The system maintains the transmitted phase of each signal within about 0.1 μs of the reference phase at Boulder. Short term variations of a few microseconds occurring with a period of several seconds, may occur when heavy winds are blowing at Fort Collins causing the antenna to sway and detune.

LF-VLF Antenna Properties

At this point it may be well to describe briefly the LF and VLF antenna properties at Fort Collins.

Two large diamond shaped antennas each supported by four 400-foot masts are used for radiating the power from two 50 kW transmitters operating at 20 kHz and 60 kHz. The radiated power from these antenna systems is presently about 500 watts at 20 kHz and 4 kW at 60 KHz. It is expected that improvements that will be made in 1965 will raise the transmitted power to 1 kW at 20 kHz and 10 kW at 60 kHz.

The radiation pattern is believed to be substantially omnidirectional. Field studies are planned which will determine what effect the mast configuration and nearby mountains have on the concentricity of the radiation pattern.

Monitoring at WWV

Having described briefly the frequency standards maintained by the Boulder laboratories and shown how the signals from WWVB and WWVL are related to these signals, it is now possible to proceed with the methods and techniques presently in use by NBS to control WWV at Greenbelt, Md.

The transmissions at both 20 kHz and 60 kHz are received at WWV using techniques referred to by Morgan and Andrews[3] in an earlier publication. The reference signal at WWV is taken from the oscillator controlling the broadcasts.

Each week the phase records taken at both frequencies are mailed to Boulder, and have been analyzed for time drift of WWV's signals relative to the stabilized phase transmissions from Fort Collins.

It has been possible to maintain good records, even during the time when WWVB and WWVL were on the air for only six hours a day. This is quite practical when the oscillator at the receiving site is of such stability that the daily drift never exceeds a half cycle of the frequency being monitored.

The monitoring records are most favorable when readings are taken at the time when noon occurs at the midpoint of the path between the transmitter and the receiver. For this path the best observation time is 1 P.M. EST or 11 A.M. MST. Converted to Universal Time, this is 1800.

For the purpose of this study readings were taken each day at 1800, 1900, 2000, and 2100 UT and averaged. The phase records were taken with a 50 μs full scale at 20 kHz and with a $16\frac{2}{3}$ μs full scale at 60 kHz. These scale widths equal a full cycle at each frequency and conveniently avoid phase ambiguities occurring due to diurnal effects.

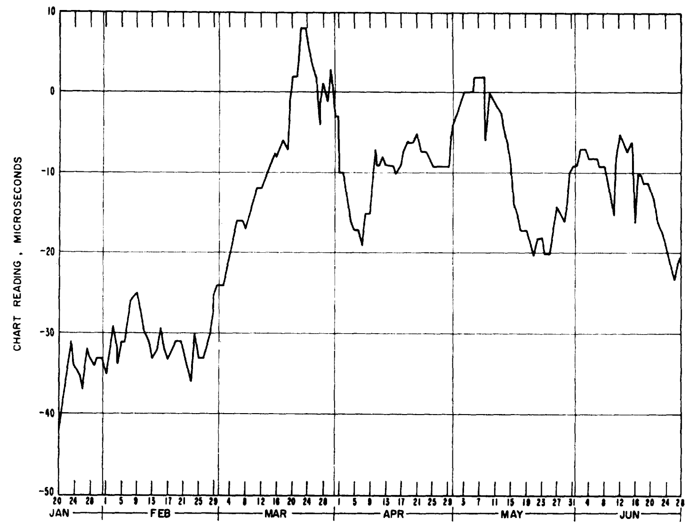

Fig. 5. Monitor chart readings of WWVL at WWV.

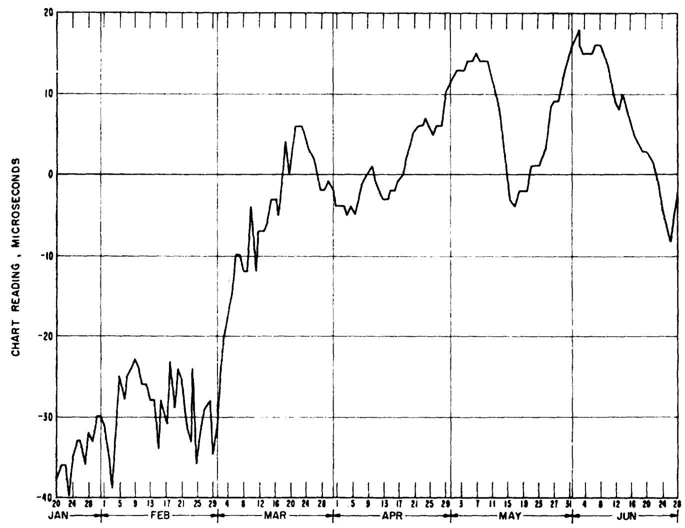

Fig. 6. Monitor chart readings of WWVB at WWV.

Experimental Results

The experimental results obtained in time control of WWV during five months in the first half of 1964 are presented in four charts that will be described in detail.

On January 18, 1964, the drift corrected oscillator, referred to previously, was put in control of WWVB and WWVL by means of the phase-lock link between Boulder and Fort Collins. At that time, the operator at WWV was instructed to maintain phase between the WWV master oscillator and the transmissions of WWVB and WWVL as closely as possible by simple step adjustments of the controlling oscillator in increments not exceeding 1×10^{-11}. Pending the availability of more sophisticated equipment to do this task this technique has been in effect for all of 1964 except the first half of January.

Results of this experiment are shown in Figs. 5–8. The abscissa of each of these figures is time of the year blocked off by months. The ordinate scale of Fig. 5 is blocked off in 10 μs increments. The values plotted are actual chart readings in microseconds with an arbitrary zero point. The curve consists of daily values plotted point by point. This shows the raw data as observed on the monitor at WWV recording WWVL. Even though this curve is quite jagged, it is immediately evident that WWV time has been maintained within ± 25 μs of WWVL phase throughout this period.

The jaggedness of the raw data plot is thought to be attributable, at least partly, to propagation variations. Experience with the controlling oscillator at WWV indicates that the variations from day to day are in excess of any that can be attributed to the oscillator.

Figure 6 shows a very similar curve, this time being a plot of WWVB as monitored at WWV. Again the ordinate is the monitoring chart reading plotted in microseconds with an arbitrary zero.

Perhaps the most significant point to note in this plot is the jaggedness of the curve during January and February. During these months the curve fluctuated much more severely when monitoring WWVB than when monitoring WWVL. While not so pronounced, there seems to be the reverse effect during May and

[3] A. H. Morgan and D. H. Andrews, "Frequency calibration receiving systems and techniques using standard LF and VLF signals," April 2, 1962, private communication.

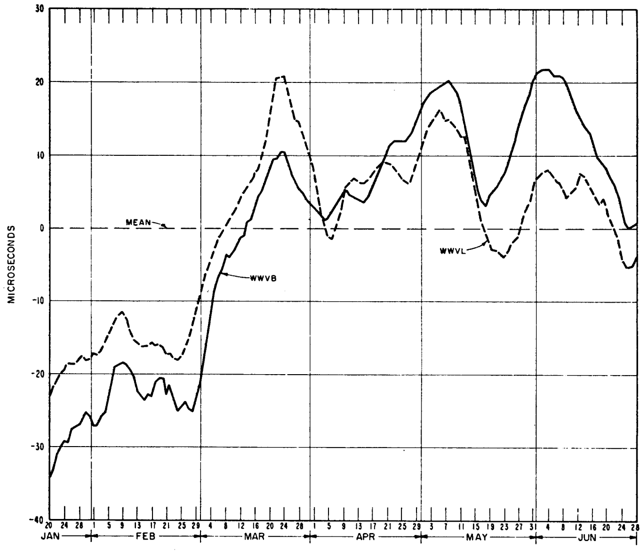

Fig. 7. Five-day-average deviations of WWVB and WWVL as monitored at WWV.

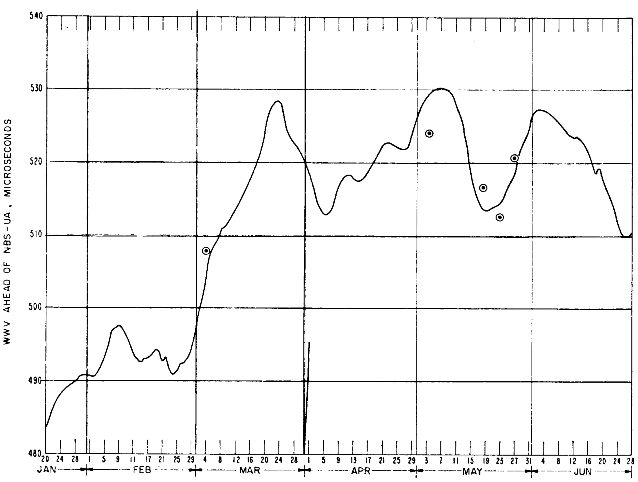

Fig. 8. Daily values of WWV clock time vs. standard clock at Boulder.

June, in that the monitoring records of WWVL show greater fluctuations than those of WWVB.

To obtain the curves presented in Fig. 7 several operations were performed on the raw data previously shown. Firstly, somewhat smoother curves were obtained by using five day averages of the raw data instead of daily values. This is justifiable upon the premise that propagation variations, such as might be caused by the effective height of the ionosphere changing from day to day, would be random in nature and thus average out in several days.

In addition to smoothing of the data by using five-day running averages, the mean value for the period of time shown was obtained for the data taken for WWVB and WWVL. Secondly, the curves were related to each other by making the mean value of each curve equal to zero microseconds on an arbitrary ordinate scale.

Thirdly, an average was taken of the curves shown in Fig. 7 and is plotted in Fig. 8. Notice now, however, that the ordinates are on a new scale which is the time relationship of the clock pulse at WWV with respect to the NBS-UA time scale. To establish this scale a number of trips were made with a portable clock between the NBS-UA clock at Boulder and the station clock at WWV. The relative time differences between the clocks obtained by these measurements are plotted as encircled points in Fig. 8. To fit the curve to the points the average values were obtained for the curve on the clock-point days and matched to the average value of the time differences obtained from the portable clock measurements. The scatter of the points relative to the monitoring time curve shows a standard deviation of less than 1.5 μs.

It should be noted that the portable clock measurements are made customarily on a round-trip basis so that the time loop can be closed and thus avoid gross errors in the measurements. In general, it has been possible to make a clock trip to WWV with a closure time of from 1 to 3 μs, which is consistent with the scatter of the points on the monitoring time curve.

Conclusions

Using a combination of LF and VLF monitoring of WWVB and WWVL at WWV, Greenbelt, Md., it has been possible to establish a gain-or-loss time curve for the WWV clock relative to NBS-UA which controls WWVB and WWVL by phase-lock techniques described earlier.

Further, it has been possible to establish within a very few microseconds the actual time relationship between the gain-or-loss time curve at WWV and the NBS-UA time scale by means of portable clocks.

The techniques described here can be refined. Improvements can be made in LF-VLF station control, in monitoring techniques, in techniques for minimizing the effects of scatter in monitoring data due to propagation effects, in smoother control of the remote clock oscillator, and in the portable clocks.

It is concluded that the combination of 1) LF and VLF monitoring, 2) portable clock synchronization, 3) a high quality local clock, and 4) simple manual adjustments of the oscillator in the local clock can maintain the time synchronization between widely separated clocks within ± 10 μs.

Acknowledgment

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The aid of V. Heaton in reducing the mass of monitoring data to the curves presented herein is also appreciated sincerely.

References

[1] J. A. Barnes and R. L. Fey, "Synchronization of two remote atomic time scales," *Proc. IEEE* (*Correspondence*), vol. 51, p. 1665, November 1963.
[2] R. L. Fey, J. B. Milton, and A. H. Morgan, "Remote phase control of radio station WWVL," *Nature*, vol. 193, pp. 1063–1064, March 17, 1962.