The APL Time and Frequency Standards Laboratory has the function of providing standards of time and frequency accurately referenced to national and world standards. Precise frequency comparison over intercontinental ranges is accomplished by monitoring the transmissions from frequency-stabilized VLF transmitters located throughout the world. Instrumentation to provide a versatile VLF propagation research capability is also included in the facility.

B. W. Shaw
and
C. R. Haave

Frequency Monitoring of
VLF Transmissions

The Navy Navigational Satellite System now under development at APL is only one of many recent technological developments that require precise knowledge of time and frequency as well as improved methods of monitoring these basic parameters. A major function of the Time and Frequency Standards Laboratory, established at APL in connection with the satellite program, is to maintain time and frequency standards accurately referenced to national and world standards. Monitoring of the very-low-frequency (VLF) range (3-30 kc) of the radio spectrum occupies an important place among the techniques developed for this purpose. The special value of this monitoring, and the problems inherent in it, are most easily grasped in relation to the chain of monitoring operations of which it is a part.

The major portion of our laboratory installation is shown in Fig. 1. It includes two Atomi-

ATOMICHRON   WWV RECEIVERS   DIGITAL CLOCK   COUNTER   CLOCK DIVIDER   VLF RECEIVER

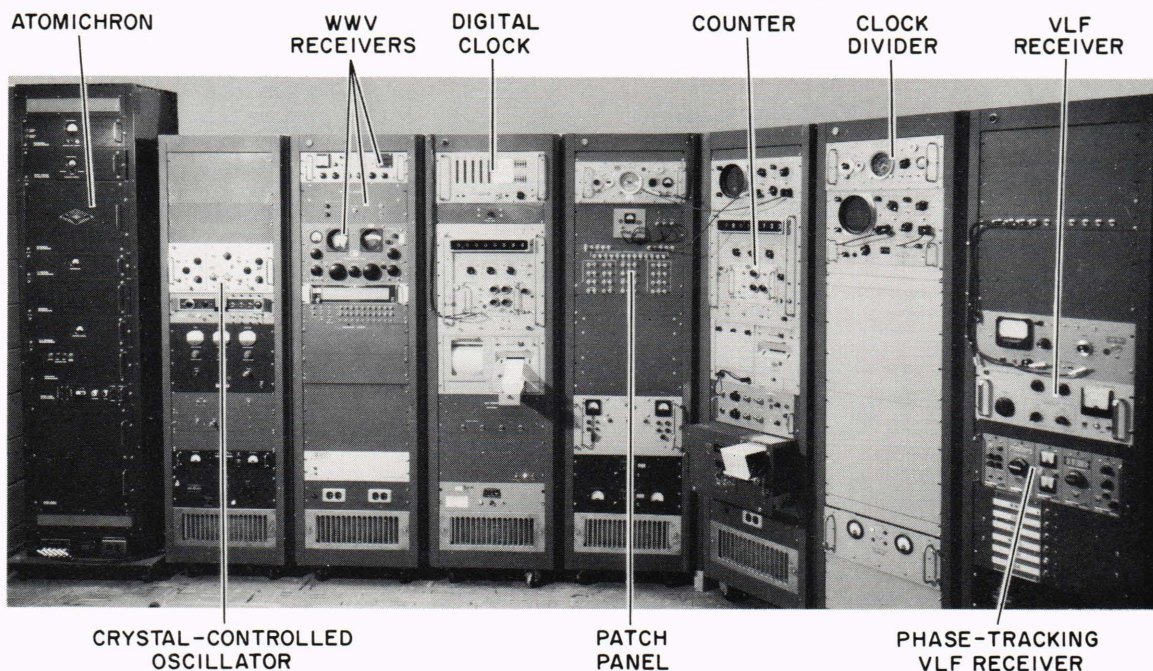CRYSTAL-CONTROLLED OSCILLATOR   PATCH PANEL   PHASE-TRACKING VLF RECEIVER

Fig. 1—Time and Frequency Standards Laboratory at APL. One of the two Atomichrons in use is shown.

chrons, one of which is seen at the extreme left of the photograph, several precision, crystal-controlled reference oscillators, HF and VLF receivers, and the requisite associated circuitry, counters, and printers. The primary, crystal-controlled reference oscillators, together with a stand-by battery power supply, are located in the more stable temperature environment of a basement room.

Routine operations of this laboratory involve making approximately 400 frequency comparisons monthly, many with a precision of 1 part in 10^{11} or better. The precision required in the comparisons demands not only extremely accurate standards of frequency, but also continuous monitoring of these standards with respect to others throughout the world. Thus, the frequencies of the laboratory reference oscillators are compared daily with stabilized VLF transmissions from NBA (Panama), GBR (Rugby, England) and WWVL (NBS, Boulder, Colorado) and with transmissions from WWV. Timing of laboratory reference time-ticks is compared with timing signals received from WWV. These measurements thus constitute a running record of the APL reference oscillator frequencies relative to others in the world. They enable us to disseminate to other APL activities standard frequencies and timing pulses having known, stable timing relative to the world-wide timing network of coordinated stations. These measurements are made with three basic systems of instrumentation.

Internal Frequency Standards System

The first of these (Fig. 2) measures frequencies of the several crystal-controlled reference oscillators relative to either or both Atomi-
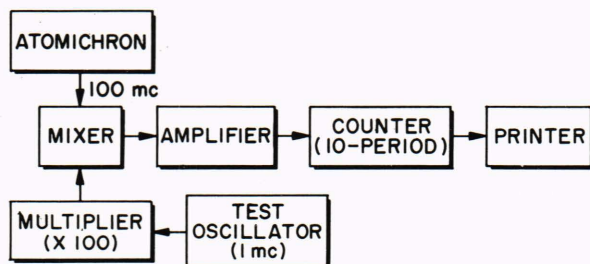

Fig. 2—Oscillator frequency-comparison system for measurement of frequencies of crystal-controlled reference oscillators relative to the Atomichrons.

chrons. The resolution capability of this system in making frequency comparisons between os-

cillators is better than 1 part in 10^{15} in less than 1 sec. In routine operation, each oscillator is checked daily to maintain a running record of its frequency compared to APL atomic standards.

In a typical case, the beat frequency output of the mixer is of the order of 1 cps. The counter, operating in the 10-period mode, can indicate a period of about 1 sec to an accuracy of 10^{-8} sec; ten such 10-period measurements are normally printed out for each oscillator test. The mean of these ten measurements gives the mean period of the beat frequency $\overline{T}$. The relative frequency difference between the test oscillator and the Atomichron is then calculated.

Received VLF Signal System

The second system (Fig. 3) compares the frequency of a local reference oscillator with that of a remote VLF transmitter. (Since the same basic measuring technique is used to compare timing marks on the 2.5-mc WWV transmission with reference ticks from the laboratory, this function is also in the diagram.) In recent years, the low attenuation (typically of the order of 2-4 db/1000 km) and good phase stability of VLF propagation have led to wide use of stabilized VLF transmissions for making long-range frequency comparisons.[1] A number of VLF stations whose carriers are stable to 1 part in 10^{10} are now operating throughout the world. However, in these comparisons the state of oscillator development is now such that propagation factors associated with the VLF transmission link are usually more important than the oscillator stabilities. Therefore, the vagaries of VLF propagation must be taken into account if precise frequency comparisons are to be made.

According to the well-developed VLF mode theory,[2] propagation is considered to take place in the spherical waveguide formed by the earth's surface and the lower ionosphere. Effective D-layer ionosphere heights, at VLF frequencies, are about 70 km during daylight hours and 90 km at night. The effective dimension of the waveguide thus changes significantly from darkness to daylight, and this effects a diurnal change in propagation time between transmitter and receiver. The magnitude and nature of this change are

[1] A. D. Watt, R. W. Plush, W. W. Brown and A. H. Morgan, "Worldwide VLF Standard Frequency and Time Signal Broadcasting," *J. Research Nat. Bur. Standards*, **65D**, 6, Nov.-Dec. 1961, 617-627.
[2] J. R. Wait, "A New Approach to the Mode Theory of VLF Propagation," *J. Research Nat. Bur. Standards*, **65D**, 1, Jan.-Feb. 1961, 37-46.
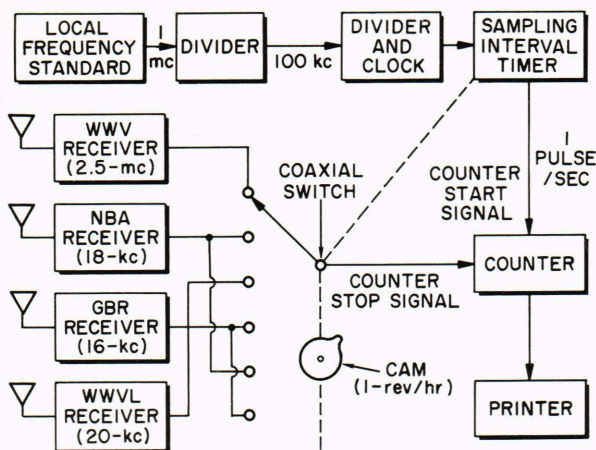
Fig. 3—The VLF frequency- and WWV timing-measurement system, one of two systems for comparison of a remote signal with a local oscillator.

functions of the path length between transmitter and receiver, the geometry and nature of the path on the earth's surface, the time of year, and various perturbing factors which can change the electrical properties of the ionosphere. Ionosphere irregularities associated with magnetic disturbances, meteor showers, abnormal ionization in the D-layer due to cosmic-ray flux enhancements, and solar flares are known sources of perturbations superimposed on the regular diurnal change.

Another interesting propagation factor derives from the nature of the VLF waveguide itself, which differs from the conventional waveguide in that its significant dimension is of the order of several wavelengths. This means that several modes can be propagated. Attenuation is greater for the higher-order modes, so that at some range from the transmitter the higher-order modes become negligible with respect to the dominant mode. The range at which the higher-order modes become negligibly small is usually considered to be about 2000 km; beyond this range, the total diurnal change should be closely proportional to range. However, this does not seem to be true for all paths at ranges considerably greater than 2000 km, but we need more experimental data for a variety of paths before we can accurately define this transition region. Some paths also show consistently a large "over-shoot" attributable to mode interference during the diurnal phase change. These times of rapid phase change are not suitable for precision frequency comparisons. In general, a north-south path is preferable to an east-west path because the sunrise and sunset transitions over the entire path occupy a smaller portion of the 24-hr period.

Comparison of the frequency of a local oscillator with that of a distant VLF station, therefore, involves the following important propagation factors: variations in propagation time due to the diurnal darkness-daylight transition,

and apparent "roughness" of the lower iono sphere caused by sporadic natural phenomena giving rise to ionosphere irregularities. The time derivatives of phase deviations resulting from propagation irregularities represent frequency deviations which degrade the precision that is possible in a given observation time. As an example of the diurnal variation, Fig. 4 shows the mean diurnal variation in propagation time, for the month of June 1961, for two signals: the 18-kc standard-frequency transmission from NBA, about 3400 km almost due south of APL; and for the 16-kc signal from GBR, Rugby, England, about 5800 km distant. Some indication of the predictability of the diurnal change from day to day under normal conditions is given by the 1σ limits associated with these two VLF paths, as shown on the figure for several times of day; 1σ values are of the order of 1-2 μsec for the daylight hours and two to three times this during darkness. However, maximum deviations up to 10μsec from the mean curve are not uncommon, particularly during darkness or during ionosphere disturbances.

A striking example of the D-layer perturbation caused by a class 2 solar flare[3] was observed on March 1, 1962. At 11:38 A.M. EST, the phase records for NBA, GBR, and WWVL deviated rapidly from their norm, reaching maximum deviations at 11:40 A.M. EST, followed by a slow recovery to normal in about 2 hr. Peak deviations recorded were about 7.5 μsec for WWVL, 13 μsec for NBA, and 20 μsec for GBR. In each case, the maximum deviation was of the order of one-third the total diurnal shift normally observed. Deviations of this magnitude could, of course, seriously compromise the accuracy of a frequency comparison if not recognized and taken into account.

The basic relationship between frequency, phase, and observation time in these VLF measurements is $\overline{\Delta f} = \Delta t / T$, where $\overline{\Delta f}$ is the mean relative frequency difference between the two oscillators during the period of comparison, Δt is the change in relative phase measured in seconds, and T is the duration of the measurement, in seconds.

The minimum time required to get any desired frequency resolution may be calculated by substituting the desired frequency resolution for $\overline{\Delta f}$, the resolution of the clock used in making the phase comparison for Δt, and calculating T.

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[3] The class of a solar flare refers to its duration and extent, and to the Hα radiation associated with it.
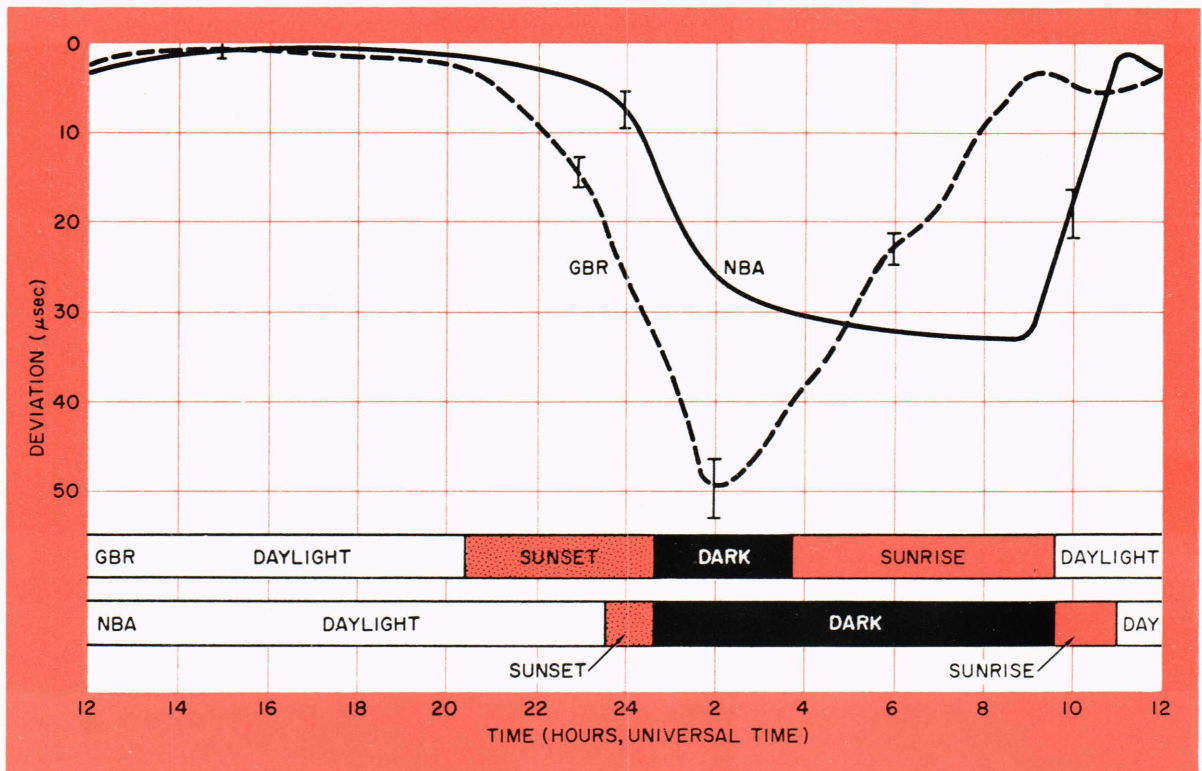
Fig. 4—Mean diurnal variation in propagation time for June 1961 for two remote signals compared with the frequency of a local oscillator.

With a clock resolution of 0.1 μsec, for example, a frequency resolution of 1 part in 10^{10} can, in theory, be obtained in 1000 sec. The actual time will depend on the signal-to-noise ratio of the received VLF signal and on the character of the diurnal and random variations in propagation time between the VLF transmitter and the monitoring point. If only propagation phase shifts are considered, 0.36 μsec/hr is the maximum shift consistent with a comparison to 1 part in 10^{10}, with the clock resolution specified above.

Analysis of the accumulated data on VLF phase stability has proved that highly reliable frequency comparisons to at least 1 part in 10^{10} can be made via VLF, with an averaging time of 24 hr. Comparisons to 1 part in 10^{10} can be made with much shorter averaging times during selected parts of the day, but precision and reliability will both be somewhat degraded. Preferably, the 24-hr measurement should begin and end during the period of all-daylight propagation. The allowable phase error compatible with comparison to 1 part in 10^{10} for the 24-hr measurement is given by $\Delta t = \overline{\Delta f} T = 8.64 \times 10^{-6}$ sec. Since the root-mean-square deviation from the mean propagation time during daylight is about 1 μsec, well below the allowable 8.64 μsec, a 24-hr comparison would be expected to be somewhat better than 1 part in 10^{10}.

As shown in Fig. 3, the measurement technique consists of starting the counter interval timer with a pulse from the local reference oscillator, and stopping the counter with a subsequent positive-going zero crossing of the VLF wave. Data are recorded by printing out the time and the relative delay time, in seconds and tenth-μsec, respectively, at preselected intervals. The WWV timing measurement is similar except that the interval count is stopped by the detected tick from WWV rather than by a VLF zero-crossing.

Our system uses a timer-motor-driven cam to advance a six-position coaxial switch sequentially from one monitoring function to another. Four signals — NBA -18kc, GBR-16kc, WWVL-20 kc, and WWV-2.5 mc—are thus monitored with one counter and one printer. In the routine-monitoring duty cycle, NBA and GBR signals are monitored for two 1-min periods in each hour, at the rate of one data point

per second during the sampling period, and WWVL and WWV for one minute in each hour.

Another method of comparing the phases of a received VLF signal and a local reference oscillator makes use of a commercially-available phase-tracking VLF receiver. This type of receiver synthesizes the nominal frequency of the VLF signal from a 100-kc signal derived from the reference oscillator and compares the phase of the synthesized signal with that of the received signal. The phase-comparator output controls a phase shifter in the 100-kc reference channel so as to maintain phase lock between the two signals. The mechanical servo that drives the phase shifter also drives a potentiometer whose output may be recorded as a continuous analog record of the relative phase of the VLF signal.

The servo also drives a counter that indicates the relative phase of the received VLF signal in μsec. In a 24-hr comparison, for example, the mean frequency difference between the VLF signal and the reference oscillator is simply determined by subtracting the reading of the counter dial from the reading recorded 24 hr earlier and dividing the difference by the number of seconds in a day. This type of instrumentation, because of its operational simplicity as compared with the digital system described above, has been recommended for satellite ground station use. Also, since the phase-shifted, 100-kc reference signal is phase-locked with the received VLF signal, a clock driven from the 100-kc signal is synchronized with the distant VLF transmitter. The clock will, of course, exhibit the diurnal propagation delay variation characteristic of the path from the transmitter to the receiver.

Received HF Signal System

The third system (Fig. 5) provides a method of comparing the average frequency of the 5-mc WWV transmission with the Atomichrons, with a resolution of better than 1 part in 10^{11} in the mean difference frequency over the 1-hr duration of the comparison. Basically, this measurement is made in the same way as the VLF phase measurement, with the distinction that propagation effects are negligible since the WWV transmitter is only about 13 miles distant. Also, the WWV phase measurement is made on the 455-kc IF frequency output of a superheterodyne receiver rather than on the carrier frequency itself.
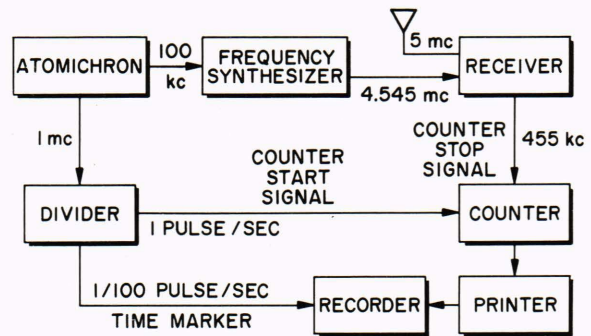

Fig. 5—The WWV frequency-measuring system for comparing a remote HF signal with one of the Atomichrons.

To eliminate the effect of local oscillator variations on the accuracy of the frequency comparison, the normal, internal, local-oscillator signal is replaced by a signal synthesized from the output of one of the Atomichrons. The reduction of data is facilitated by recording the phase shifts on a recorder. In this form, the phase shift exhibits a sawtooth variation with a period of about 36 sec. The mean frequency difference between the local frequency standard and the received WWV signal is then calculated from the mean period of the sawtooth variation determined from the records. The results of this measurement are transmitted daily to WWV to assist in evaluating the WWV transmission.

Other instrumentation has been developed to improve the accuracy of the frequency comparisons, to decrease the time required to obtain a given accuracy, and to reduce the manual effort now involved in data reduction. One of these, soon to be added to the installation, will make time-interval phase measurements at a rate of up to 1000/sec, sum a pre-set number of these intervals, and, after a number of such summations, print out that sum which shows the least variance between individual phase intervals. Since the number of pre-set summations is some integral power of 10, the printed sum, with an appropriate shift of the decimal point, is the mean phase interval for the measurement.

To conclude, we should note also that the practical merit of VLF as a stable link, useful in making intercontinental frequency comparisons, is not its only application. The sensitivity of VLF phase-monitoring to lower ionosphere conditions makes it a research tool of proven value for studying this region of the ionosphere; this is not easily done by conventional sounding methods.