THE GENERAL RADIO
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VLF STANDARD-FREQUENCY CALIBRATION

The initiation of standard-frequency broadcasts in the vlf band has made possible an improvement in the precision of calibration of stable oscillators used as local frequency standards which approaches a factor of 100 over that achievable by other means. With high-frequency transmissions, the best precision is about $\pm 1 \times 10^{-9}$. This precision is generally attainable only by the use of standard-time broadcasts and accurate time-comparison devices. If the high-frequency carrier of the standard-frequency station is used instead of the time pulses, the precision deteriorates slightly, but the accuracy suffers from propagation variations, so that the overall performance of any one calibration can seldom be guaranteed to a figure better than $\pm 1 \times 10^{-7}$, and often this figure is optimistic. Repeated calibrations, and cross-checking of time-tick and carrier-frequency calibration methods, suffice to allow some degree of assurance in local frequency-standard calibration, but that laboratory is indeed fortunate which has never been asked to "guarantee" a frequency calibration obtained from the high-frequency broadcasts to better than $\pm 1 \times 10^{-9}$.

The advent of vlf standard-frequency broadcasts, coinciding approximately with the proving-in of atomic frequency-standard devices, has made available both precision and accuracy of calibration which approach $\pm 1 \times 10^{-11}$ under ideal conditions and $\pm 1 \times 10^{-10}$ most of the time. At present, the vlf standard-frequency broadcast stations are maintained within $\pm 1 \times 10^{-10}$ of their nominal frequencies under normal circumstances, and calibration corrections are available from the operating agencies which include data to $\pm 1 \times 10^{-11}$.

It is difficult to justify any attempt to obtain increased precision of calibration beyond $\pm 1 \times 10^{-11}$ under present conditions. The propagation variations and the difficulty in maintaining perfect stability at the transmitting stations impose a practical limit on the performance of a calibration system based on vlf transmission over long ranges. For increased resolution and precision of frequency comparison, therefore, it is still desirable to have both oscillators being compared in the same location, or at least not widely separated. The $\pm 1 \times 10^{-10}$ guarantee on the accuracy of the signals as broadcast is a further

EXPERIMENTAL RESULTS OF FOUR METHODS OF USING VLF TRANSMISSIONS

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deterrent to any attempts to claim greater accuracy of calibration. The various possible methods of frequency comparison using vlf transmissions have been described by J. A. Pierce.[1] The methods used by the present author were either taken directly from this publication, or derived from it indirectly. Several methods have been tried, with the results indicated below.

In order to use vlf transmissions for frequency-standard calibration, it is necessary to make use of the *phase* of the carrier wave of the standard-frequency signal. The vlf signal supplies a phase, or time, reference which suffers only a slight variation in propagation time compared with that of an hf signal. Hence, the phase difference between the stable oscillator to be calibrated and the received vlf signal is measured, and the frequency difference determined by conversion of the phase change per unit time, $\frac{d\phi}{dt}$, into the appropriate units. For example, there are 86,400 seconds in a day, or, in round numbers, approximately 10^5, corresponding to 10^{11} microseconds per day. Thus, a relative frequency difference of $\pm 1 \times 10^{-11}$ corresponds to a change of phase of only 1 microsecond in 24 hours, while $\pm 1 \times 10^{-10}$ frequency difference corresponds to ± 10 microseconds. In simpler terms, if the local phase changes +10 microseconds the first day, and +10 microseconds the second day also, the oscillator is maintaining a constant frequency which differs from that of the vlf signal by approximately $\pm 1 \times 10^{-10}$. If, however, the frequency of the oscillator is drifting by, say, 1×10^{-11} per day, the phase difference will change by 1 microsecond in each 24 hours, and, for example, will be 10 microseconds the first day, 11 the second. Over a longer period, a uniform frequency drift rate will produce an increase in phase proportional to the square of the elapsed time.

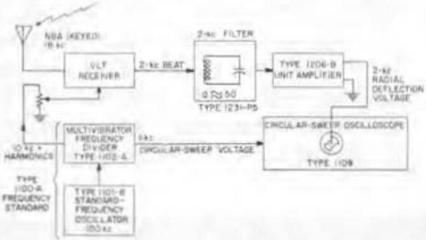

Figure 1. Block diagram of vlf receiving system with oscilloscope display.

The first, and simplest, method tried was an experiment to assess the usefulness of the signal provided by NBA on 18.0 kc. The general arrangement was as shown in Figure 1. In this method, the signal is heterodyned to 2 kc by the injection of 20 kc into the second rf stage of the tunable vlf receiver. The 2-kc beat is then selected by a fixed-tuned filter, amplified, and applied to a circular-sweep oscilloscope driven by the frequency standard being calibrated. In this case, since the frequency of the heterodyning local oscillator is higher than the 18.0 kc signal, an increase in the local-oscillator frequency results in an increase in the beat frequency, resulting in a clockwise rotation of the pattern on the oscilloscope. The time for a one-cycle change in phase gives the frequency difference by simple calculation. The sense of the difference is obtained from the direction of rotation of the pattern. If the local standard is set to reduce the rate of rotation to a very

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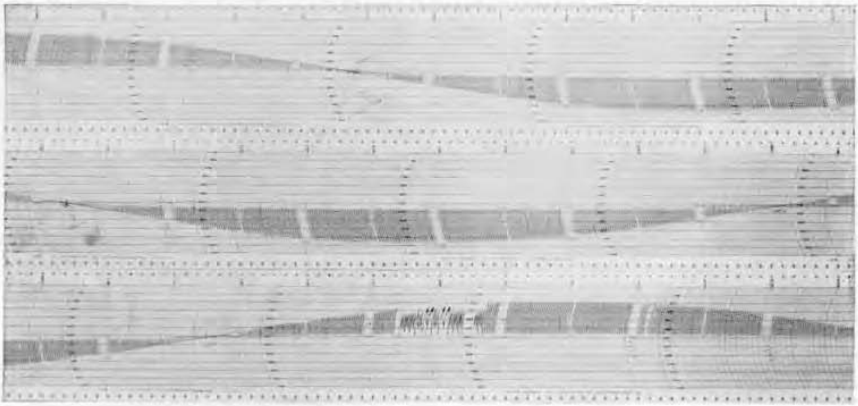
[1] "Intercontinental Frequency Comparison by VLF Radio Transmission," *Proc. IRE*, June, 1957 (pp. 794-803).



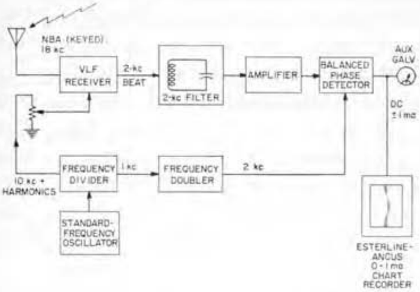


Figure 2. (Right) Block diagram of vlf receiving system using chart recorder on output of phase detector. (Above) A fragment of a recording produced by this system. Frequency difference is measured by the time between the zero crossings on the chart.

slow rate, the phase difference may then be noted and recorded. Unfortunately, for the greatest precision, this method requires rather frequent attention to the phase of the display and is thus somewhat tedious. In addition, it is not practicable to obtain reliable overnight calibrations by this means unless continuous observation of the indicator 'scope is provided, as will be apparent from a study of the typical photographic phase records presented later (Figure 6).

The second method of calibration used experimentally in the GR laboratories is shown in Figure 2. The current from a balanced phase detector was applied to a chart recorder set for zero-center deflection. In view of the small deflection in the vicinity of the zero crossings, the recorder was supplemented with the galvanometer indicator to help estimate the exact moment of zero current in the output circuit of the phase detector. Although somewhat more convenient than the first method described, this still required some manual operations and generated yards of recording tape, which required calibration. The timing pulses radiated by NBA provided an automatic time scale. Alternatively, the frequency of the local standard oscillator could have been set near zero beat with the incoming signal, but the sense of the frequency difference would then not have been immediately apparent; hence a better arrangement was desirable.

The phase-locked oscillator shown in Figure 3 was a logical extension of the

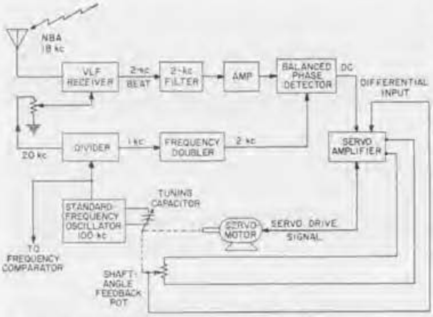


Figure 3. Block diagram of a motor-driven phase-locking system.

arrangement shown in Figure 2. A servo amplifier having a pair of differential input terminals was used to drive a servomotor which changed the frequency of the local standard-frequency oscillator by means of a variable capacitor. For a phase-locked oscillator system, it was necessary to provide one differential input signal to the servo amplifier from the phase-detector output and another from a potentiometer on the capacitor shaft. This system is an electromechanical equivalent of a voltage-variable reactance. The frequency of the local standard oscillator was thus phase-locked to that of NBA. The frequency of this oscillator was then recorded on the frequency comparator used for intercomparison of crystal oscillators in the GR laboratories. In this way, the frequency of NBA was made available as a reference for calibration of other oscillators. The precision attained by this device was approximately $\pm 2 \times 10^{-9}$ at best, and, under conditions of high noise level or sudden ionospheric disturbances (SID), the results were somewhat difficult to interpret. A sample recording is shown in Figure 4. The principal virtues of this system were its completely automatic operation and the direct intercomparison with other locally operated oscillators.

The phase-locking technique illustrated here is not so satisfactory a frequency calibration system as is the servo-driven phase-tracking receiver system originally described by Pierce[1], and now offered in many commercial models. The phase-locked oscillator, however, permitted direct comparison of the frequency of the NBA signal with other local signals without the construction of special phase-tracking equipment. The phase-locked oscillator was put together from already available components.

After several months of experience with the automatic recorder, it became obvious that the daily frequency shifts at dawn and dusk changed in nature, depending on the time of year, and that, even during daylight hours, some large fluctuations seemed to occur. Further investigation seemed indicated if more accuracy was to be obtained from the

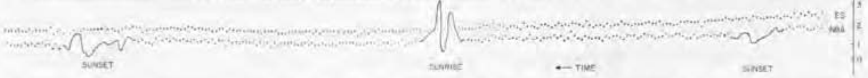


Figure 4. Frequency-comparator records showing relative frequency of two local oscillators with respect to NBA. The record designated WS is that of GR's working standard; ES represents an experimental standard; while NBA is a record of the oscillator phase-locked to NBA. The records show the frequency difference between each of these and a common reference oscillator. The units for the scale at the right are parts in 10^8. The total span of the recorder chart is 5.5 parts in 10^8.

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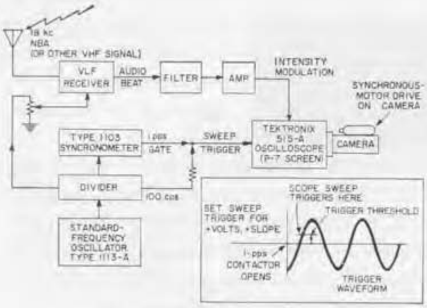
[1] Loc. cit.



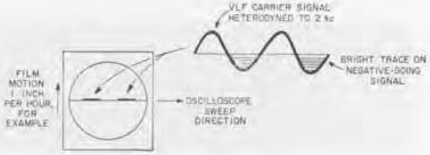


Figure 5. (Left) Block diagram of receiving system using a photographic phase recorder. Inset shows wave form of gated sweep trigger. (Above) Diagram showing mechanism of intensity-modulated oscilloscope display for photographic recording.

vlf transmissions. Accordingly, a photographic technique was devised, after the manner described by Pierce[1].

The photographic recording system is shown in Figure 5. The oscilloscope sweep is triggered either by means of the gated 100-cycle sweep trigger shown or by the ungated 100-cycle signal. The 1-per-second sweep is used with NBA to avoid sweeping when the signal is not present. The 100-sweeps-per-second arrangement is used to record communications-keyed signals.

The use of a modified oscilloscope camera with a synchronous-motor drive on the film holder provides a number of different sweep rates (in inches per hour of film drive) for the recording film, which is exposed one frame at a time in a Polaroid film-back. The vlf signal intensity modulates the trace on the oscilloscope tube, the sweep speed on the oscilloscope being set to show part of two consecutive carrier-frequency cycles. The sweep-time calibration is thus derived from the spacing between the consecutive cycles rather than from a separate oscilloscope calibration. The system can record signals with relatively poor signal-to-noise ratio, since the use of the P-7 screen and photographic recording seems to produce approximately 20-db improvement in apparent signal-to-noise ratio. It is probable that the photographic method alone accounts for most of this improvement, and that almost any phosphor can be used.

Photographic records made by the method of Figure 5 are reproduced in Figure 6a, b, and c. Minor fluctuations in phase apparently occur quite frequently, even almost continuously. It is not immediately apparent, however, that these fluctuations are anything that can be separated from the effects of impulse noise, such as atmospheric static or "sferics." In other words, this recording system records the noise along with the signal phase. One then makes frequency calibrations by calculating the indicated phase change per unit time and converting this figure to a frequency difference or deviation from the received standard frequency. Diurnal phase shifts are readily observed and calibrated, as shown by the record of Figure 6a. Small instabilities in either the received signal phase or the

Figure 6a. Night-time phase record of NBA showing diurnal phase shifts.

local standard oscillator are easily seen and are free from the effects of the complex time constants in the electromechanical systems described above.

One particularly important advantage of the photographic calibration method is illustrated in Figure 6b which is a record of two signals on one frequency, which were of different phase as received, and which were keyed alternately. Both signal phases are easily discerned in the photographic record. When this same set of signals was applied to the servo-driven phase-locked oscillator, it resulted only in continuous hunting of the servo system.

It is of interest to note the characteristics of some of the signals recorded. The signal from NPM over a west-east path shows 5 stable phases during the sunrise shift (Figure 6c). The corresponding sunset shift is smoothed or blurred by the nature of the recombination process in the ionosphere after sunset, which results in a slower change in effective height than that observed at sunrise. As a simplified explanation, the stepwise variation in phase may be thought of as the result of a ray bouncing between ionosphere and earth, with two relatively stable ionospheric effective heights and a transition zone between them. The ray will not change its path length except at certain critical intervals during which one or more of the reflection points is in the transition region as the rotation of the earth causes the transition region to move along the path.

As is readily apparent, the photographic phase-recording method provides the possibility of phase comparison to within a very few microseconds under most conditions. The over-all performance of this system is such that it can provide, in a 24-hour interval, frequency calibration of a precision better than $\pm 1 \times 10^{-10}$, even approaching a few parts in 10^{-11}. More refined photographic techniques should be slightly better but not by so much as an order of magnitude, in view of the propagation fluctuations apparent even on these relatively unsophisticated photographs.

An inspection of these recordings indicates what the possibilities of the photographic method may provide in the way of calibration data, and serves to illustrate the excellence of simple calibration methods which are based on sound basic principles.

A few remarks about the nature of the vlf signals may be of interest to those contemplating exploration of the vlf spectrum. Most of the transmitters whose carrier frequencies are stabilized are used for communication. In the vlf band, this generally means Morse-code-keyed cw, although other types of

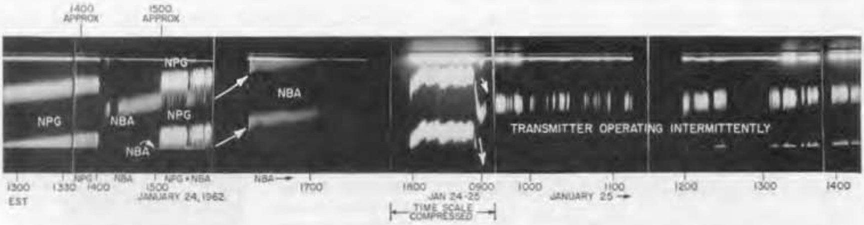


Figure 6b. Photographic record showing phase of signals from NPG and NBA. Note that recording shows phases of both NPG and NBA on January 24, when their transmitters were being keyed alternately. During the nighttime hours the time scale was compressed by slowing the film speed. Note the sudden phase shift at sunrise.

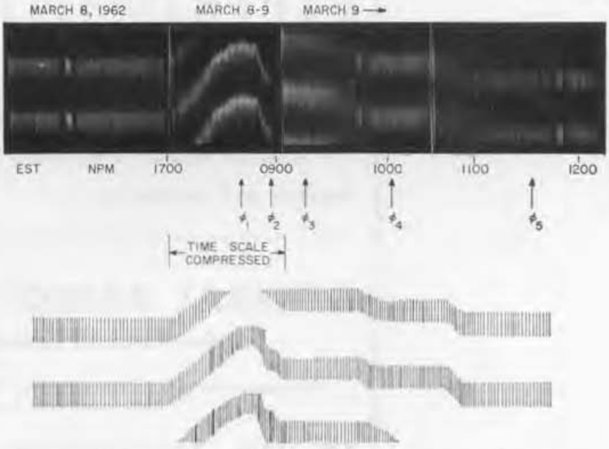


Figure 6c. Record of phase of NPM over a west-to-east transmission path. Note the five relatively stable phases of the signal during the sunrise transition.

modulation are occasionally used. The first vlf standard-frequency station, GBR, Rugby, England, is on 16.0 kc, and occasionally 19.6 kc. All the stations of the United States Naval Radio Service on vlf are used for communications except the NBA transmitter on 18.0 kc (Panama Canal Zone). The other stations are NSS, Annapolis, Maryland, 22.3 kc; NPG/NLK, Jim Creek, Washington, 18.6 kc; NPM, Lualualei, Hawaii, 19.8 kc; and NAA, Cutler, Maine, 14.7 kc. The National Bureau of Standards maintains WWVL on 20 kc and WWVB on 60 kc (Boulder, Colorado) as standard frequency transmitters, transmitting uninterrupted carrier signals with Morse-code-keyed call-letter identification every 20 minutes. The MSF transmitter (England) on 60 kc transmits continuous carrier signals during its scheduled operating times.

The NBA signal has an approximate radiated power of 30 kw, keyed with time signals, also call-letter identification and rated frequency offset from A1* frequency in Morse code. In addition, some silent periods and locked-key periods are observed. The strongest signals are radiated by NAA (approximately 1 megawatt radiated power) and NPG/NLK (250 kw), with NSS (100 kw) close behind, as is NPM (100 kw). The WWVL (20 kc) effective radiated power is estimated at 14 to 15 watts.

Receiving systems that depend on uninterrupted carrier reception for calibration are not generally successful when tried with the keyed-carrier signals. For example, extremely narrow-band filters exhibit keying transients which may obscure the desired phase information. If the signal is not above the noise level, the narrow-band filter has to be very carefully designed to avoid ringing, which may completely mask the desired signal. This is especially true in systems employing voltage-sensitive trigger circuits. In general, the servo-driven phase-tracking receivers and the photographic recording methods have proven more reliable, with the photographic method generally able to handle the widest variety of signals.

— F. D. Lewis

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*A1 time is that time scale in which the transition frequency of cesium is measured as 9,192,631,770 cycles per second.

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