Modern Developments in Precision Clocks

BY ALFRED L. LOOMIS*
Non-member
and
W. A. MARRISON†
Associate, A.I.E.E.

AT THE beginning of the present century it was believed by many that the limit of accuracy attainable by mechanical clocks had been reached. This presumption was based on the performance of specific mechanisms which had indeed been brought to a high state of perfection, but this presumption did not allow for the possibility of other *types* of mechanism for measuring time nor for certain refinements that have since then more than doubled the accuracy and reliability of the best clocks then available.

In 1911 Lord Grimthorpe wrote[1] "It seems to follow that the extent to which astronomical clocks can be made accurate, *viz.*, 1/30 of a second average variation from their mean daily rate . . . is a degree of accuracy sufficient for present purposes, and it seems rather doubtful whether mechanical science will, in the case of clocks, be likely to reach a much higher figure."

As the words clock, chronometer, etc., have come to have definite technical meanings in the art, we shall use the more general term "Timekeeper." In the broadest sense a timekeeper may be defined as any physical means that can be used for the subdivision of time into intervals known in terms of a standard time interval. Thus any periodic phenomenon can be adopted in a timekeeper, provided its period can be recorded in terms of another. In this sense the earth and the moon are timekeepers, as well as vibrating pendulums, tuning forks, and other sustained oscillators. As all man-made timekeepers are essentially "oscillators" we will consider first the equation of motion of a simple oscillator which can be expressed as

$$M\ddot{x} + R\dot{x} + Sx = A \sin (\omega t + \phi)$$

where M corresponds to the mass, R to the resistance or damping and S to restoring force proportional to displacement x. The right hand term represents the sustaining force required on account of the dissipation of energy in the oscillator.

For an oscillator to be a perfect timekeeper, all of the quantities, M, R, S, A and ϕ must remain invariable. While M and S are the chief rate governing quantities, the others are, from a design point of view, the most difficult to control.

The ultra precise practical timekeepers of today can all be contained within two classes, depending on whether S (the restoring force) is

(a) Gravity (as in pendulum clocks)
(b) Elasticity (as in quartz crystal oscillators)

*Loomis Laboratories, Tuxedo Park, N. Y.

†Bell Telephone Laboratories.

1. For references see Bibliography.

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The second class is a development of the last decade and was made possible by the development of the vacuum tube and associated electrical circuits. Intercomparisons between timekeepers of the two classes provide a most valuable means for the study of changes in gravity and related phenomena. These two classes are discussed separately.

Gravity Timekeepers (Pendulum Clocks)

Unfortunately the motion of a pendulum is not quite simple harmonic motion since the restoring force varies as the sine of the angular displacement (instead of directly as the displacement) and therefore the period is not truly independent of the amplitude. This can be seen from the equation of motion of the pendulum which in its simplest form, neglecting damping and sustaining forces, is

$$Ml\theta + Mg \sin \theta = 0$$

the free period T for any given angular displacement can be expressed by the series:

$$T = 2\pi \sqrt{\frac{l}{g}} \, (1 + 0.0625\, \alpha^2 + 0.00358\, \alpha^4 + \ldots)$$

Where α is the maximum deflection from mid swing expressed in radians. The corresponding change in rate expressed in seconds per day is shown in the curve Fig. 1.

Various attempts have been made to construct pendulums having a period independent of arc. Huygens[2] demonstrated that a pendulum constrained to move in the arc of a cycloid under the influence of gravity would have a rate independent of arc, but mechanisms to accomplish this result have always introduced larger irregularities than those which they attempted to cure. Suggestions have also been made that an elastic restoring force could be used to supplement gravity in such a way that the sum of the two would make the restoring force directly proportional to the displacement. Loseby first made this suggestion in 1851.[3] But such an additional control robs the gravity pendulum of one of its greatest advantages, as the rate is markedly affected by changes in the elastic restoring force.

Practical design has been confined to keeping the amplitude small and to providing a governing action so that any slight increase in amplitude causes an opposing tendency to decrease the amplitude, and *vice versa.*

The old anchor recoil escapement[4] accomplished this by increasing the friction on the pendulum with increase of amplitude. The inertia escapement[5] in the Shortt clock attains a similar result without the serious disadvantage of introducing friction. This inertia escapement is based on the principle that a weight rolling down an inclined plane applies a greater horizontal force to a slowly moving plane than to a faster moving one. A suitable inclined plane attached to a pendulum receives an amount of energy roughly inversely proportional to the amplitude, or to the velocity at midswing. As the amplitude increases, the energy delivered into the system becomes less. But in spite of these controls the amplitude does vary in fact, which at the present time probably accounts for more irregularities than any other factor. Dr. Jackson has shown[6] that if the daily amplitude is regularly recorded and the clock rate corrected accordingly, a number of the irregularities in the Shortt clocks at Greenwich can be explained.

If a direct amplitude control could be applied to a clock such corrections ought not to be necessary. Such a method is now being tried on a Shortt clock in the Loomis Laboratory. When the amplitude of the pendulum exceeds a predetermined amount by even 0.0001 inch, a signal is sent, via a pointed electrode which hangs in the evacuated pendulum casing, to a vacuum tube which operates a relay so that the next 30-second driving impulse is omitted. The electrode is so adjusted that about every fifth impulse is omitted in this way. It is found in practise that the device operates without the bob ever coming in contact with the electrode, so that no energy is taken from the pendulum by physical contact. The difference in amplitude between the operating and non-operating conditions is only about 10^{-6} cm. which corresponds to about 0.3 second of arc. Thus the mean amplitude can be controlled to within approximately 0.1 second of arc. In order to insure that changes in level of the whole clock mechanism will not be the direct cause of changes in amplitude through this control mechanism, the mounting for the control electrode is suspended so as to be free to swing in the same plane as the pendulum, though of course having a different period and being highly damped in order to avoid sympathetic oscillations. With this control the constancy of rate appears to be improved, but at least a year's record is needed for conclusive proof, as the variations which this device seeks to control usually only occur at intervals of several months.

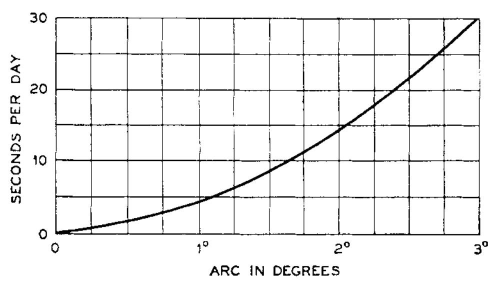


FIG. 1—CHANGE OF RATE OF PENDULUM WITH SEMI-ARC EXPRESSED IN SECONDS LOST PER DAY

The complete solution for the period of a pendulum swinging in a resisting medium, such as air, involves a factor $\sqrt{1 + kR^2}$ where R is the resistance to motion and k is a constant depending on the structure of the pendulum and the nature of the drive. Although it would appear from this that all pendulums should be operated in a high vacuum, practically it has been found[7] that the most satisfactory pressure for the Shortt clock, from the standpoint of stability of period with pressure variation, is about 15 to 20 mm. of mercury. When the pressure is very low or zero the arc, when not definitely controlled, is very unstable and causes large changes in rate, but in the neighborhood of 15 mm. of pressure there is a stabilizing action due to the air friction, and a neutralization of the following four effects of pressure variation:

1. Change in the restoring force due to buoyancy of pendulum in air.
2. Change of center of gravity due to buoyancy when pendulum is made of dissimilar materials.
3. Change of effective mass due to air carried along by the pendulum.
4. Change of friction and consequent change in arc.

The first and fourth are probably of greatest importance. With decrease in pressure the first decreases the period and the fourth increases it. At the critical pressure the two effects are about equal and opposite. In the determination of gravity,[8] where very precise pendulums are used, all of these factors must be considered very carefully.

When the amplitude control device described above is used, the pressure can be reduced to a small fraction of a millimeter, which thereby reduces the effect of friction to a minimum. The term $\sqrt{1 + kR^2}$ then becomes practically unity and the required sustaining energy can be very much reduced.

So far we have considered variations in the restoring force. Variations in the inertia term are now considered.

The expansion of the pendulum with temperature must either be reduced or compensated for. At the present time practically all clocks of high precision employ invar pendulum rods with bobs of type metal or invar. The bob rests on an expansion collar, the dimensions of which are calculated to compensate for the lengthening of the rod. Some recent studies[9] in Japan have produced a "super-invar," to use the expression given, which may have a zero or even a slightly negative coefficient of expansion. If these new alloys are as stable as invar, they may have an important use in precision clock making, as the entire pendulum could be made from a single piece of material.

With the new technique recently developed in the laboratories of the General Electric Company it is now possible to produce pieces of clear fused quartz large enough to construct the entire pendulum for a clock. Some experiments are now being conducted with such clocks in the Loomis Laboratory. Fused quartz has a temperature coefficient of expansion of about 0.5 parts in 10^6 per deg. cent. A temperature variation of one degree would therefore cause a change in rate of only 0.02 second a day due to this effect alone. In a constant temperature vault with a fused quartz pendulum a variation of 0.01 degree would only affect the rate 0.0002 second a day. Means have been developed whereby temperature can be controlled to within 0.01 degree over long periods.

There are two other major effects that should be considered in connection with pendulum length. These are (1) variations in the position of the point of oscillation, and (2) the instability of materials with time, in other words, aging. The effect of knife edge wear on the period of an ordinary pendulum is appreciable. A wearing of one thousandth of a millimeter will change the rate of a seconds pendulum nearly a tenth of a second a day. Largely for this reason, a flexible spring suspension of elinvar[10] is used in most precision clocks. But even the spring is suspected of changes in length and, what is just as bad, also of variation in stiffness which would change the point of flexure and the restoring force. Aging effects in the pendulum rod can be reduced only by finding better materials. It may be that fused quartz, or possibly some large single crystal, will be found finally to be the most suitable material to use.

The effect of knife edge wear on the period of a pendulum can in theory be almost entirely avoided by suspending the pendulum at a distance from its center of mass equal to the radius of gyration about that point. This simple principle of mechanics, has of course long been recognized,[11] and experiments are being conducted in Germany[12] and elsewhere to determine its value in a precision timekeeper. In the case of a uniform straight rod this distance should be $\frac{1}{2\sqrt{3}}$ of the total length from the center. With this condition fulfilled a change in this length due to knife edge wear of one part in a thousand would affect the period less than one part in a million.

Returning to the fundamental equation at the beginning of the paper

$$M\ddot{x} + R\dot{x} + Sx = A \sin (t + \phi)$$

we have considered briefly the terms on the left-hand side.

We will now consider the right-hand term—the driving force—and especially the quantity ϕ the phase angle, which presents perhaps the most difficult problem in the design of all timekeepers.

The impulse should be delivered to the pendulum at the time when the velocity is a maximum, that is, at the center of the swing, in order to reduce to the minimum the effect of variations in the driving force on the rate. If the impulse is applied *before* the instant of maximum velocity, the rate is momentarily increased. If the impulse is applied *after* the instant of maximum velocity the reverse is true. Of course the impulse actually is of finite duration and the desired effect is approximated by supplying the pulse symmetrically with respect to the instant of maximum velocity thereby tending to neutralize the above mentioned acceleration and retardation effects.

The necessity for this method of applying sustaining power pulses to a pendulum has been realized almost from the beginning of precision clock history but cannot be over-emphasized.

In the Shortt clock[13] the impulse to the master pendulum is controlled by means of an auxiliary or "slave" pendulum which in turn is automatically synchronized with the master pendulum to within ± 0.003 second at all times. The means by which this is accomplished can be seen from the schematic drawing Fig. 2 which shows the master and slave pendulums with all of the essential control elements, and the counting or time indicating dials. Although the master pendulum determines the rate of the system, the slave pendulum and associated mechanism does the work of releasing the driving pulses at the proper time. The slave pendulum, through a jeweled ratchet and pawl-operated count wheel, releases mechanically a weight arm once each 30 seconds at just

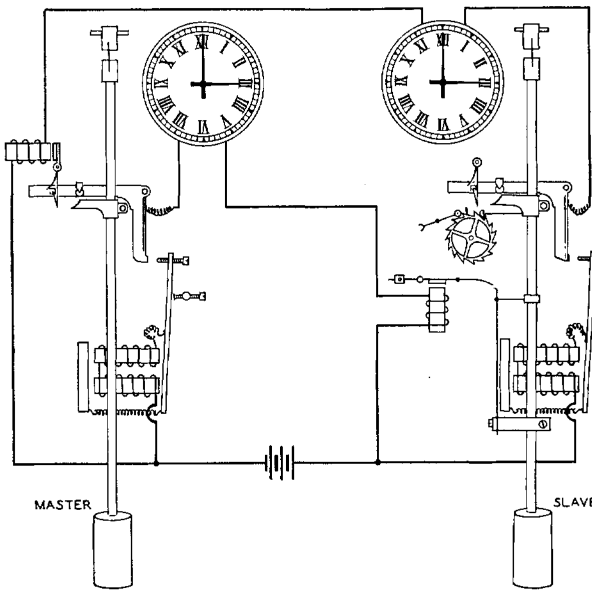


Fig. 2—Schematic Drawing of Shortt Clock Mechanism and Circuit

the right time so that a small wheel on the gravity lever, rolling down a curved inclined track associated with the slave pendulum rod, imparts the sustaining impulse to it. As soon as the mechanical impulse is delivered, this arm closes an electrical contact which resets the weight arm, before the return swing of the pendulum, in readiness for the next 30 second impulse. The current which resets the slave clock drive also releases the impulse mechanism for the master clock thereby avoiding the use of *any* mechanical connection with the master pendulum other than that of the impulse wheel. As in the case of the slave drive mechanism, the impulse lever makes an electrical contact after delivering its impulse to the master pendulum, which resets the gravity arm and in addition operates the "hit and miss" synchronizer on the slave clock. The slave pendulum normally runs a little slower than the master and is speeded up when necessary by means of a spring attached to the pendulum rod which is engaged by the synchronizer whenever the slave lags by more than 0.002 second behind a definite phase relation to the master.

There are reasons to believe, however, that small changes in phase do occur especially with variations in amplitude. Probably future improvements in gravity timekeepers will include improved methods for keeping the phase of the driving force more nearly constant.

It would be impossible even to survey adequately the developments leading up to the final design of any given type of clock in the limited space for this paper. It must not be assumed that the excellent performance of any timekeeping device is due entirely to any one person or company or period, but represents the combined efforts of a large number of people over an extensive period.[14,15,16] The three clocks most often recognized as precision timekeepers are the Leroy,[17] Riefler[18] and Shortt[13]. One or more of these is to be found in most of the important time laboratories and astronomical observatories throughout the world.

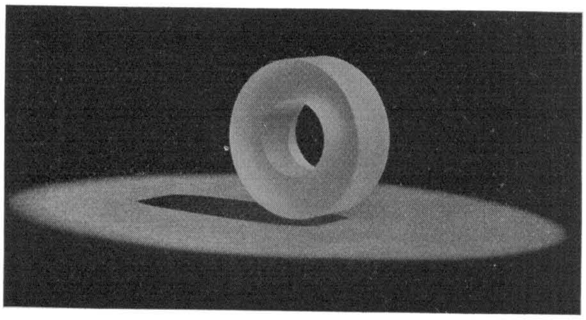


Fig. 3—Quartz Crystal with Zero Temperature Coefficient Used in Crystal Clock

Crystal Oscillators as Timekeepers

Within recent years developments have so far progressed that the constancy of rate of certain mechanical resonators, maintained in vibration by vacuum tubes, may be comparable with that of the best pendulum clocks. Such oscillators have the chief attributes of a good clock and can be used to operate or control a wide variety of time mechanisms with even greater versatility than the conventional pendulum.

The most accurate oscillators of this type known to the authors are controlled by plates of quartz crystal vibrating at a high frequency, that is, high in comparison with the frequency of a pendulum. Probably the most accurate of these at the present time are a set of four 100,000-cycle oscillators[19] that have been built by Bell Telephone Laboratories primarily for use as a primary frequency standard. These laboratories have also supplied a similar set of oscillators to the U. S. Bureau of Standards for the same purpose.

In this type of oscillator the frequency is controlled by a ring of quartz crystal about three inches in outside diameter as shown in Fig. 3. The frequency of the oscillator is the same as that of the crystal, that is, 100,000 cycles per second. One complete oscillator, including temperature and pressure controlled crystal, and shielded vacuum tube circuit, is shown in Fig. 4.

In order to operate clock mechanisms in the most direct way it is necessary to control from this high frequency another which is low enough to operate a synchronous motor. This is done by an electrical circuit known as a sub-multiple generator which controls one frequency at a definite fraction of another in absolute synchronism. Several types of circuit have been used for this, all of which are as positive in action as a set of gears. Usually the low frequency used to operate the motor is 1,000 cycles. Each pole on the motor in motion therefore corresponds to one milli-second in

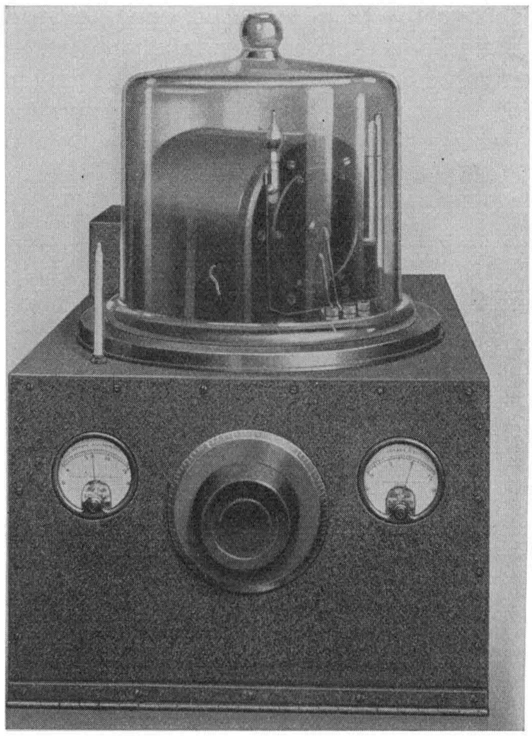


Fig. 4—Complete 100,000 Cycle Quartz Oscillator

Including temperature and pressure controlled crystal and shielded vacuum tube circuit

time and hence any variation in the motor mechanism or operation can amount at most to a fraction of a milli-second. Such a motor can be used to operate time indicating or measuring apparatus in a wide variety of forms.

As a rate controlling element a crystal of quartz used in this way has a number of outstanding useful properties. As previously discussed, the rate of vibration is controlled chiefly by the effective mass and stiffness of the resonator. On account of the chemical stability of the substance Si O_2 and the physical stability of the crystal structure of quartz these may be expected to be constant in very high degree. At the present time, variations introduced by the vacuum tube circuit and the crystal mounting are such that no conclusive evidence of aging in the quartz has been obtained.

Since the elasticity is a constant for such displacements as are required (amounting to less than one part in 100,000 change of dimensions) the rate is substantially independent of amplitude. The amplitude can be controlled at nearly a constant value, however, by proper adjustment of the vacuum tube circuit.

The temperature coefficient of frequency can be made as near to zero as required at any given operating temperature by properly adjusting the shape of the resonator. Crystals that have been in continuous operation for three years have not shown any appreciable change in this adjustment.

Crystals are not affected by gravity or magnetic fields and can be shielded readily from electrostatic fields. They can be mounted so as to be relatively immune to vibrations which always seem to be present in the earth, especially near traveled roads and manufacturing centers.

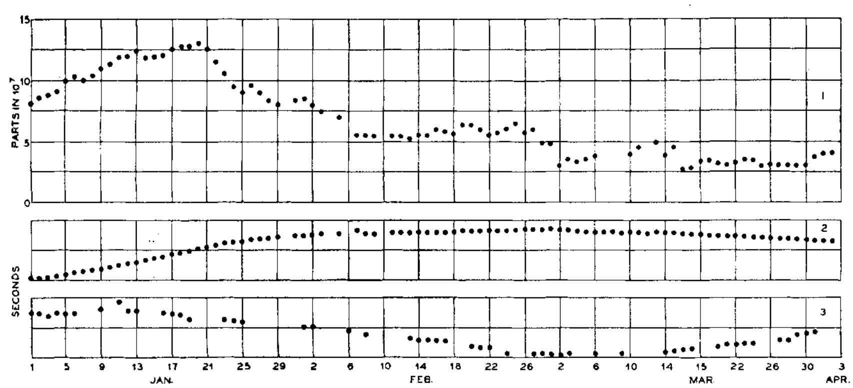


Fig. 5—Performance Data for Crystal Clocks

Curve 1. Rate comparison between crystals 1 and 2 expressed as parts in ten million

Curve 2. Integral of curve 1, showing running comparison between crystals expressed in seconds

Curve 3. Indicated time of one crystal clock vs. corrected time signals from U. S. Naval Observatory

This may be found to be an important factor in the location of accurate clocks in cities or near earthquake zones. The crystals referred to above are mounted on the seventh floor near a much traveled thoroughfare in New York City.

The electro mechanical coupling to a crystal for imparting the sustaining energy to it makes use of its piezo activity. As far as has been determined there is no increase in decrement directly due to this means of coupling, although, of course, properties of the electrical circuit, such as damping, may be manifested in the crystal through this coupling. The logarithmic decrement of a 100,000-cycle low coefficient crystal mounted in air at atmospheric pressure and coupled into the electrical driving circuit is about 0.00012.

Probably the largest rate disturbing factors in the crystal clock at the present time are due to effects of the phase ϕ of the applied driving force. This factor varies slightly with circuit variables, aging of vacuum tubes and power voltage variations. Developments now in progress indicate, however, that the effects of these variables can be greatly reduced, which should make a marked improvement in performance.

The performance, as clocks, of a pair of crystals is shown for a three-month period in the graph Fig. 5. The comparison rate curve shows the variations in relative rates between the crystals while the time comparison curve shows the variation in indicated time (integrated rates). The third curve gives the rating of one of the crystals against corrected Naval Observatory time signals for the same three-month period.

While the crystal clock assembly is more costly than a pendulum clock and requires more elaborate associated electrical equipment, we believe that for many purposes it is decidedly superior because of its great versatility. For example, its rate can be adjusted at will over a sufficient range to allow for such aging effects as occur. Also, the phase, or indicated time, can be adjusted with extreme accuracy. This can be done most advantageously in the electrical circuit by means of a phase shifter which operates continuously through 360 elec. deg., or any fraction or multiple thereof. If used in the 100,000-cycle circuit, one complete turn of the dial corresponds to a final adjustment of one hundred thousandth of a second, which obviously is greater accuracy than needed in any ordinary time mechanism.

The accuracy of inter-comparison of crystal clocks may be very high. An absolute comparison accurate to better than one-hundred thousandth of a second can be maintained continuously, while under special conditions, short time comparisons accurate to one part in 10^{10} can be made.[19] This high accuracy of comparison is due chiefly to the large number of vibrations per second, 200,000 times greater than with a "seconds" pendulum. Even greater accuracy of comparison could be obtained by the use of higher frequency crystals, but for reasons of convenience and greater freedom from the effect of external circuits and the mounting, the lower frequency is preferred.

One application of considerable interest is that two clock mechanisms can be operated from the same crystal control in this way so that one keeps true mean solar time when the other keeps true sidereal time.[20] It can be shown readily that any ratio of rates can be obtained for such a purpose accurate to at least one part in 10^{10} without the use of an unduly complicated mechanism. Lord Grimthorpe has shown why a pendulum cannot be used for this purpose,[21] but his reasons do not apply to the crystal control method.

By means of a shutter of the type shown in Fig. 6, and a photoelectric cell, signals of extreme accuracy can be controlled which could be used for radio transmission of time signals or for any purpose requiring great accuracy. When this disk is rotated at ten revolutions per second by a crystal controlled motor the current from the photo cell is 1,000 cycles modulated, in the manner indicated in oscillogram No. 1, at 100 cycles per second. By marking one 0.01 second element, as for example by partially blocking one sector, a positive 0.1 second indication is obtained. The oscillograms shown in Fig. 7 were made with the disk shown and indicate how, with the use of a suitable oscillograph, a continuous time signal can be recorded that can be read to a fraction of a milli-second. This resolution would be very useful for accurate time measurement work, for studies in radio propagation times, and for measurements of gravity. Observers requiring less resolution than this could obtain 0.01 second accuracy by the use of a rectifier and a recorder accurate to only 0.01 second. The same is true for 0.1 and 1.0 second accuracy by a suitable choice of transmitting disk and receiving equipment.

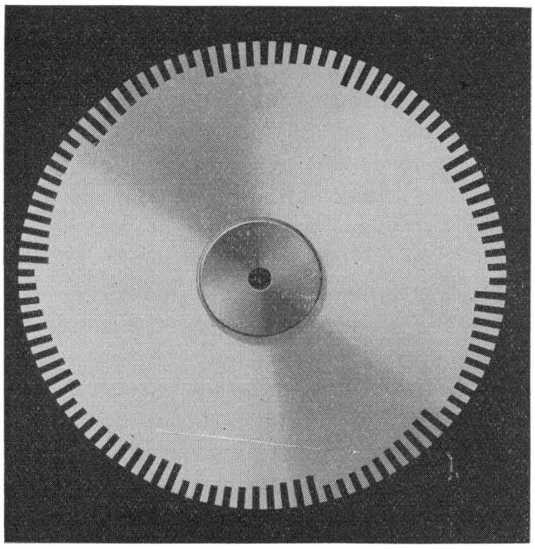
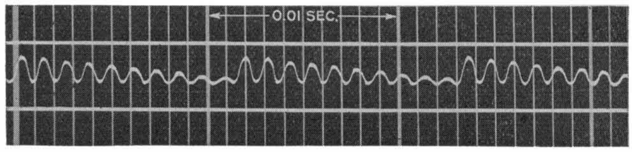


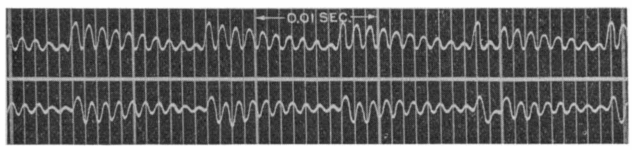
FIG. 6—SPECIAL LIGHT INTERRUPTER FOR THE PRODUCTION OF ACCURATE TIMING SIGNALS BY PHOTOELECTRIC CELL

The second oscillogram shows the signal directly from the disk and after it had gone through a complete radio transmitter and receiver consisting of a total of eleven tandem vacuum tube stages and the associated equipment. As indicated, the total delay encountered was about 0.1 milli-second, and the distortion is not appreciable. Of course any combination of make and break signals can be controlled in this way using either a continuous or a modulated tone. If desired a series of half second dashes could be controlled, interspaced by a dot-dash code to designate each dash.

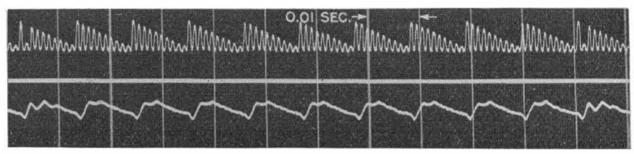
A complete time signal control mechanism based on this idea is shown diagrammatically in Fig. 8. In the method shown, light from a straight filament lamp is imaged on the slotted edge of a disk driven at 10 revolutions per second by a 1,000-cycle motor. The light entering the photo cell is modulated as indicated, at 1,000 times and 500 times per second alternately, and controls a corresponding electrical signal. The slow speed shutter, rotating at one revolution per second, causes the effective light path to alternate between the two disks once each second, and gives a corresponding variation of electrical signal. This signal can be used for any resolution from one second down to one milli-second and can be received through static and fading. It can be reduced to the dash-space type by the use of a



No. 1. Direct signal obtained from photo-cell



No. 2. Direct signal (above), and the same signal transmitted and received by radio (below). A method is indicated for marking every tenth of a second



No. 3. Direct signal as in No. 2 (above) and same signal rectified (below) for recording with only 0.01 second resolution

FIG. 7—OSCILLOGRAM OF TIME SIGNALS PRODUCED BY PHOTO-CELL METHOD

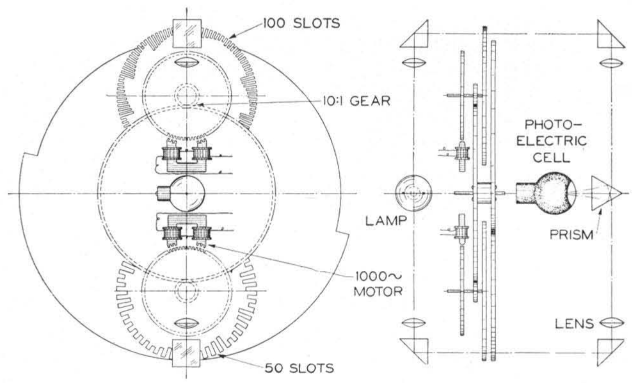


FIG. 8—PROPOSED METHOD FOR PRODUCTION OF ACCURATE TIME SIGNALS BY PHOTOELECTRIC CELL

simple voice-frequency filter to suppress the undesired half signal, or used as a continuous signal for oscillograph recording.

Among the advantages of the crystal clock it should be mentioned that in order to control any number of clock mechanisms with the same precision it is only necessary to distribute the constant frequency current derived from the crystal to the separate mechanisms. This can be done on any scale economically feasible.

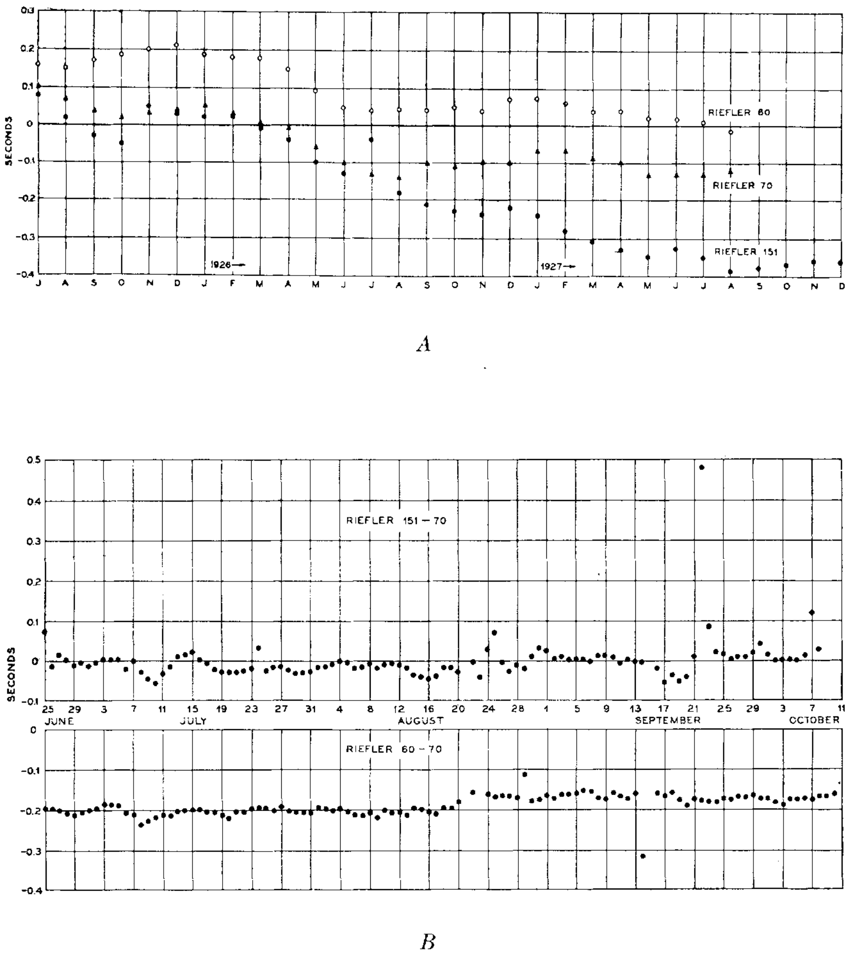


FIG. 9—U. S. NAVAL OBSERVATORY, WASHINGTON, D. C.

A. Observed mean daily rates of Riefler Clocks No. 60, No. 70 and No. 151
B. Relative rates of Riefler 151 *vs.* 70 and Riefler 60 *vs.* 70. (Data supplied by U. S. Naval Observatory)

PERFORMANCE OF CLOCK INSTALLATIONS

In order to indicate the performance that may be expected of precision clocks, data have been obtained from several actual clock installations and presented herewith in the form of curves. These do not show in every case, perhaps, the performance that could be obtained under ideal conditions but they do indicate the type of performance to be expected under present normal working conditions. In studying these curves, care should be taken to examine the coordinates because it was impossible to present all the data plotted to the same scale on account of the different times and the different errors involved. Also some of the data are plotted as daily rates and others as indicated time. The effect of this is that over a short period a rate curve shows greater apparent variations than a time curve and *vice versa*. In some cases the mean gaining or losing rate was removed from the data, as this has no bearing on the *constancy* of rate which alone determines the value of a clock as a timekeeper.

The essential descriptive information concerning the clocks represented accompanies each figure. Some data relative to the performance of Shortt Clocks 20, 21 and 22 in the Loomis Laboratory and the Crystal Clocks in Bell Telephone Laboratories are discussed in the following section.

EXPERIMENTS IN TIME AT LOOMIS LABORATORY

The clock installation at Tuxedo Park and some of the experimental results obtained there have been described elsewhere.[7] In brief it consists of three Shortt clocks mounted in an especially favorable location practically free from traffic and electrical disturbances, and carefully temperature controlled. The excellence of the location is enhanced by the fact that the clock vault is excavated in the solid rock of the mountain on which the laboratory stands, and the three massive masonry piers for mounting the clocks are effectively a part of this rock. One of the three Shortt master pendulums in its casing is shown in Fig. 14 mounted on its pier within the temperature controlled vault.

By means of the Loomis Chronograph[7]

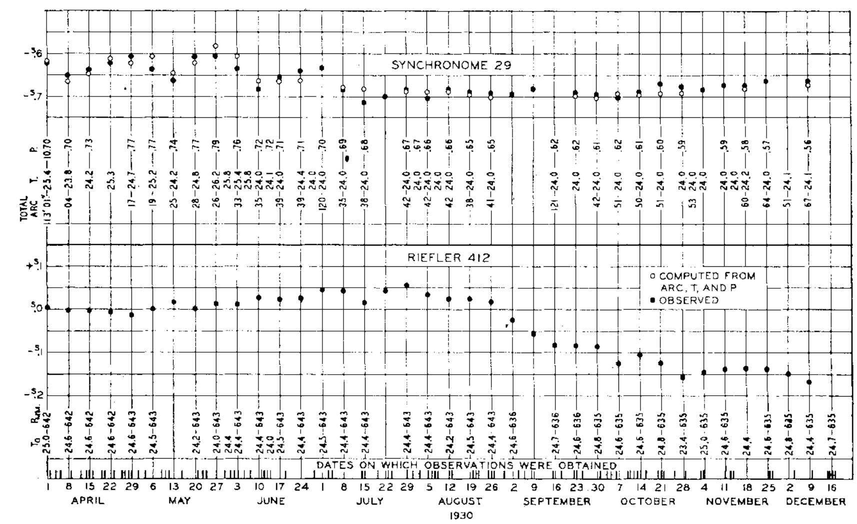


FIG. 10—DOMINION OBSERVATORY, OTTAWA, CANADA

Observed daily rates of Riefler 412 and Shortt 29. (Data supplied by Dominion Observatory) it has been possible for the first time to obtain a running phase comparison of a number of clocks with great precision. Prof. E. W. Brown and Dr. Brouwer have shown[22] that the probable error of the mean hourly rates as measured by this chronograph is less than 0.0001 sec. With a resolution of this order, it is possible to study some effects that would be forever unsuspected with the use of any comparison equipment used heretofore.

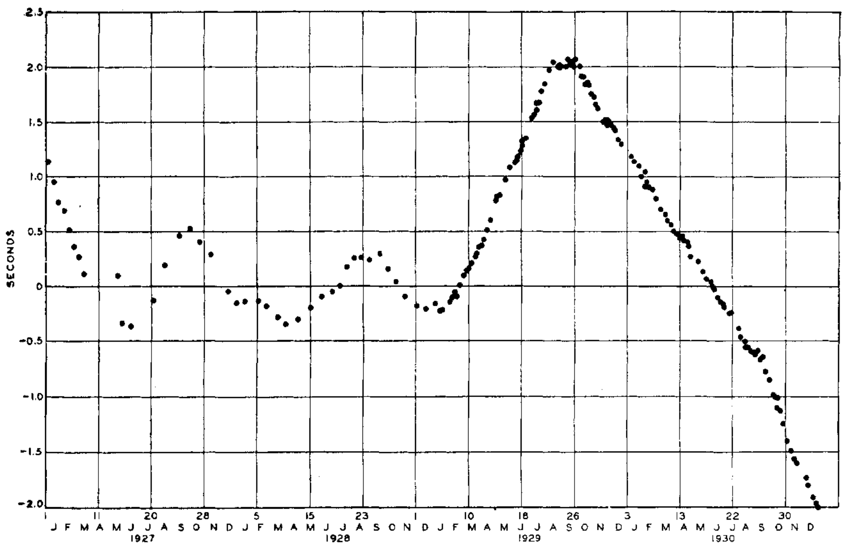


FIG. 11—ROYAL OBSERVATORY, GREENWICH, ENGLAND

Comparison of observed correction for Shortt clock No. 11 with those computed from the following formula which was based on observations from March 1927 to December 1928. Formula: $98^{s}\,905 + 28^{s}\,2002t + 1^{s}7542t^{2} + 0^{s}\,2524 \int (T\text{-}62^{o}8)\,dt$ + Nutation (Information from Monthly Notices of R.A.S. 1928-1931 inc.)

The rate curves on Fig. 15 will illustrate a case in point. These three curves show the differences in rates between the three Shortt clocks taken in cyclic order, plotted on a very open scale over a period of about three months. Although the *mean* rates over this and much longer periods are constant to one part in ten million, there are fluctuations in rate having for the most part perfectly definite periods. These fluctuations are real and a study[22] of the data by Professor Brown showed that the periods correspond to the differences in periods of the pendulums taken in pairs. This implies that there is coupling between the pendulums and that the rate of one is *modulated* by that of the others even though the pendulums swing practically in vacuum and are mounted on separate massive piers, and that they swing in planes 120 degrees apart. This would seem to show that, massive as the piers have been made, they are not infinite in comparison with the 14-lb. pendulums, and that strains are set up by each pendulum that are felt in some degree by the others through the piers and solid bed rock.

In order to indicate the comparison of these three Shortt clocks on the same basis as the Observatory clocks previously discussed, the data of the rate curves in Fig. 15 are replotted on the same graph on the basis of indicated time. This shows that although the rate variations are quite appreciable as measured by the Loomis Chronograph, the relative performance, as clocks, is all that could be desired, and indicates that factors having small but real effects on the rate can be detected by a chronograph with this high resolving power when they would not be observed at all by ordinary methods. The three rate curves and the three time curves are plotted to the same scale as the corresponding crystal data in Fig. 5.

The Loomis Chronograph consists of the following essential parts:

1. A strip of paper about 10 inches wide moving at a uniform rate between a long grounded electrode and a comb consisting of one hundred separate equally spaced pointed electrodes.

2. A distributor having one hundred segments separately connected to the one hundred elements of the comb, operated at exactly ten revolutions per second by a synchronous motor from a source of 1,000-cycle current.

3. A source of high potential consisting of an induction coil through the primary of which a large condenser is discharged when a record is to be made.

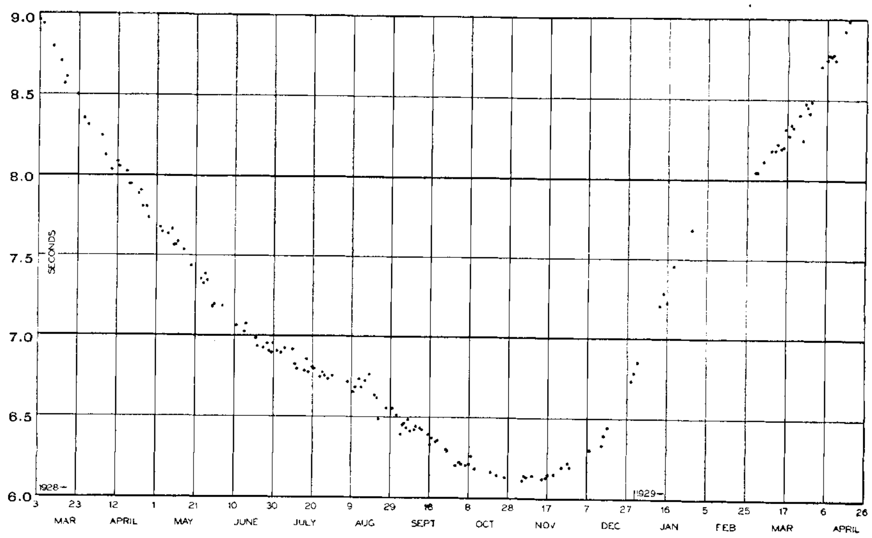


FIG. 12—PARIS OBSERVATORY, PARIS, FRANCE

Observed correction of Leroy clock No. 1185 (Information from Bulletin Horaire 1928-1930)

A small condenser on the induction coil secondary stores sufficient energy to produce an intense spark of very short duration; and

4. A single relay in the common circuit of all the time devices to be recorded on the moving paper strip.

Fig. 16 shows this chronograph in operation.

If the relay is operated every time the distributor makes some exact whole number of revolutions a series of perforations will be made in a line parallel with the edge of the paper. If in the time between sparks, the motor revolves a whole number of times plus or minus one hundredth, successive perforations will be displaced an amount corresponding to one milli-second in time. One second in time is represented by ten complete transits of the chart, so that, in effect, the chart is 100 inches wide and the effective recording element moves at the rate of 500 ft. a minute. Thus from the slope of the line of perforations with respect to the edge of the paper the difference between the rate of the distributor and the rate of the sparks can be determined with high precision. Similarly any number of separate sets of sparks can be recorded simultaneously on the same chart, using the same actuating relay and distributor. The relative rates may be determined by measuring the difference of slopes of the rows of perforations.

This is the method used for intercomparing the three Shortt clocks and for comparing them with the crystal oscillators in New York. To accomplish this, 1,000-cycle current controlled by the Bell Laboratories' crystal is sent over a private wire to Tuxedo and there used to drive the distributor as outlined above. The resulting records are continuous comparisons of the three Shortt clocks and the crystal accurate to better than one milli-second in time.

Since the crystal does not respond to variations in gravity while the pendulum does, the difference in rates contains a term having the period of the lunar day, corresponding to the direct gravitation effect of the moon on the pendulums. Several months' record of the Loomis Chronograph have been analyzed,[22] by Professor Brown and Dr. Brouwer and a lunar term observed having the proper period and magnitude. A graph of the lunar effect derived in this way is reproduced from

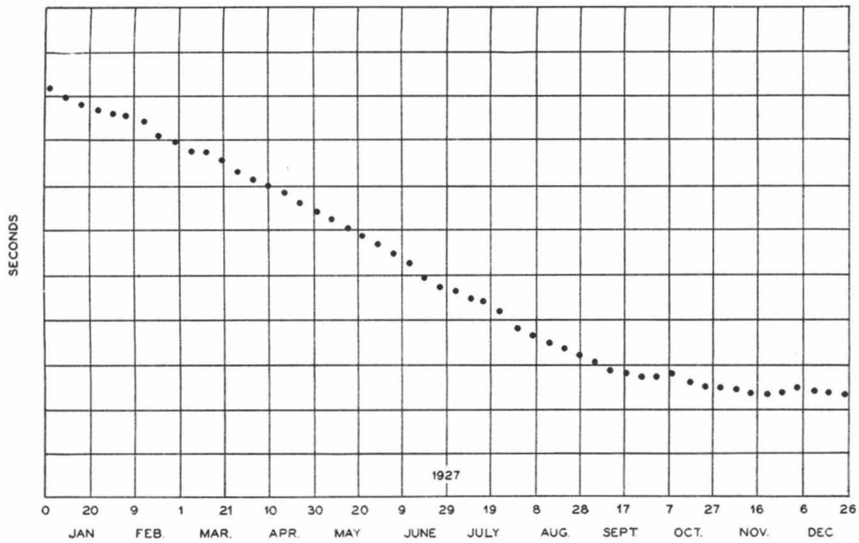


FIG. 13—ROYAL OBSERVATORY OF EDINBURGH, SCOTLAND

Observed correction of Shortt clock No. O. (Information from Proc. Royal Soc. Edinburgh Vol. XLVIII, page 161)

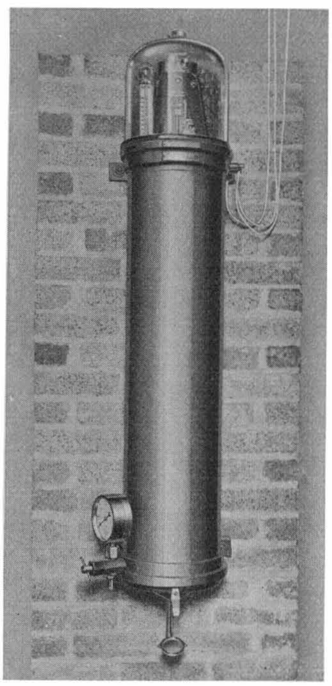


FIG. 14—MASTER PENDULUM (IN CASING) FOR ONE OF THREE SHORTT CLOCKS IN THE LOOMIS LABORATORY, TUXEDO PARK N. Y.

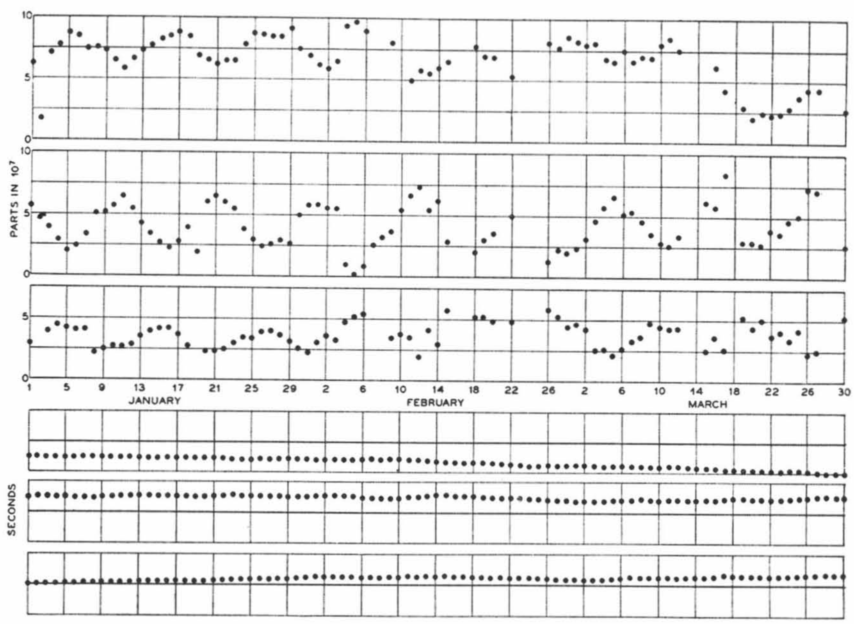


FIG. 15—INTERCOMPARISON OF THREE SHORTT CLOCKS IN LOOMIS LABORATORY

A. Rates, expressed in parts in ten million
B. Integrated rates expressed in seconds

their paper in Fig. 17. The periodic gain and loss in indicated time is about 0.0002 second per lunar day.

The results of time studies obtained at the Loomis Laboratory have been very encouraging and it is planned to continue the researches in clocks and time measurement methods. Some aspects of this work were discussed by Professor C. V. Boys in *Nature* for October 17, 1931.

Possible Future Investigations

No doubt there is a practical limit to the accuracy attainable in a timekeeper but as long as random changes in rate are observed which cannot be explained by uncontrollable properties of matter (such as Brownian movement) that limit has not been reached, even with the types of mechanism at present in use.

The suggestion has been made of utilizing the constant velocity of light between fixed points as a measure of period. At present the velocity of light is known to less than one part in a million.[23] Even if it were known with greater accuracy, the practical difficulties of establishing such a standard, except in a very rough way, would be insuperable. In the first place the distance between the measuring points would have to be known to one part in a million, that is, better than 0.06 inch in a mile, assuming no other error, to define a standard good to only 0.1 second a day. Considering the difficulties in measurement, an accuracy of a little better than a part in a million is about all that could be expected of such a method by any means now known.

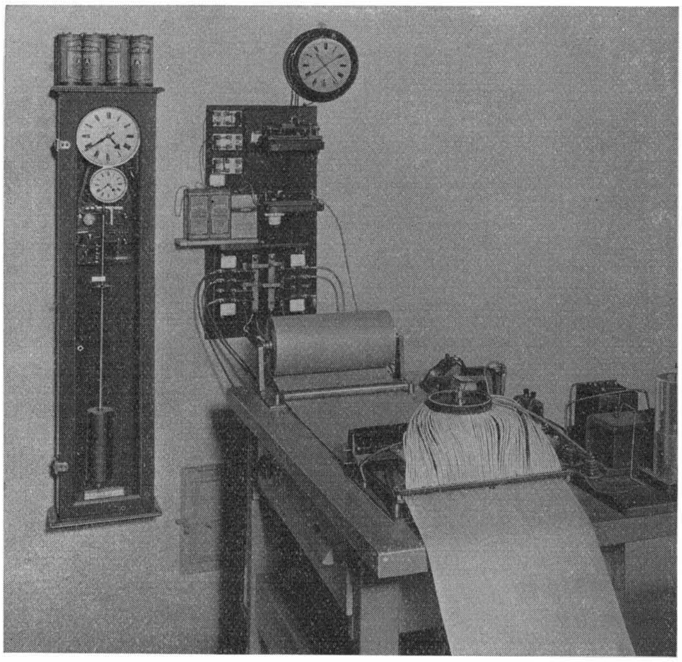


Fig. 16—Loomis Chronograph and One of Three Shortt Slave Clocks in the Loomis Laboratory

The extreme definition of some spectral lines indicates a very slightly damped oscillation of some sort in the atom, and some thought has been directed to means of making a frequency comparison between these vibrations and others of lower frequency that could be used to measure time as previously outlined. The effective logarithmic decrement of the "oscillator" behind the red line of cadmium can be estimated as about one tenth of that of a quartz resonator. The difficulties of utilizing this sort of thing as a time (or frequency) standard are: First, it is not known at present whether the "frequency" of an atomic disturbance has the same physical significance as vibrations-per-second and, second, even

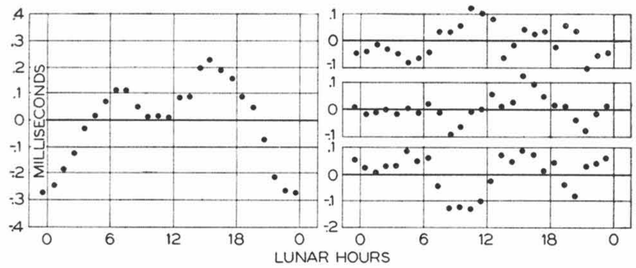


Fig. 17—Analysis of Comparison Data Between Crystal Clock and Three Pendulum Clocks Revealed the Periodic Lunar Day Variation Shown in the Left Hand Curve

Similar analyses of the comparison between the three pendulum clocks taken in pairs showed no corresponding effect

if the significance were the same, the orders of the two frequency ranges are so far separated that no means known at present could be used to effect the comparison. Besides, the energy of a spectrum line is no doubt made up of a large number of damped wave trains superposed in some fortuitous fashion as would cover the identity of separate cycles.

Probably the real final limit in the accuracy of timekeepers is concerned with the measure of our time standards. Some observations indicate that the rate of the earth's rotation is not constant, but that there are both systematic and apparently random changes in rate as compared with the motion of other astronomical bodies believed to be more stable.[24] For example; about 1918 a rather abrupt change in rate was observed which amounts to about one part in thirty million. This is small to be sure, but points to the improbability that the rate of any phenomenon is absolutely constant. After all, time is relative and the most nearly accurate measure of time must always be in terms of the most nearly constant motion that can be observed.

At the present time in the official observatories of the various countries the usual procedure is to plot the star observations in terms of their master clock and then to draw a smooth curve, which curve is adopted as the official clock correction. To some extent the drawing of this curve is a matter of judgment, based partly on the number and certainty of the star observations and partly on the estimated performance of the master clock in terms of their other clocks. These observatories at the present time also transmit and record radio time signals and publish periodically corrections to these signals in terms of their "standard clock error." From these data alone it is not possible for any one observatory to compare its clocks directly with the clocks in another observatory. If the observatories would publish one additional number for each of their important clocks, namely, the comparison of each clock with their official time, it would be possible to compare the rates of the clocks in such observatory directly with clocks anywhere else in the world where the radio time signals can be received. This would involve only a very small amount of additional work as the numerical data have to be obtained in any case. It is well to note in this connection that the United States Naval Observatory has adopted a procedure which is very similar to this, the only difference being that instead of publishing the corrections to each of its principal clocks, it publishes a single number which represents the correction of the weighted mean of several clocks. This is an excellent beginning and it is hoped in the interest of future clock developments and of studies in gravity and related phenomena, that others will follow.

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Discussion

For discussion of this paper see page 550.