1953MNRAS.113...67S

QUARTZ CLOCKS OF THE GREENWICH TIME SERVICE

Humphry M. Smith

(Communicated by the Astronomer Royal)

(Received 1952 November 13)

Summary

A general account is given of the development of the quartz clocks of the Greenwich Time Service, and the present installation is described. The methods by which clock performance may be studied are described and a convenient criterion is proposed. Quantitative results are presented in tabular form. The degree of stability now attained represents a significant advance upon that of some five years ago. Details are given of development work now in progress with a view to improving stability still further.

1. *General description.*—The first quartz clock of the Observatory was installed at Greenwich in 1939, and was of the pattern developed at the National Physical Laboratory (**1**). This employed a ring crystal supported on phosphor-bronze pins and mounted in an evacuated glass vessel held at a constant temperature by means of a mercury thermometer. The crystal was incorporated in a simple Pierce oscillator circuit, and was designed to oscillate at 99·3 kc/s. The divider chain performed successive division by 3, 6 and 11, giving an output of 500 cycles per sidereal second to drive a phonic motor. This clock, Q3, took its place among the standard pendulum clocks of the Time Service, which were also supplemented by data received daily from the National Physical Laboratory regarding two similar quartz clocks Q2 and Q6.

Clocks employing GT-cut plate crystals in a drive circuit based upon the Meacham bridge (**2**) were developed independently at the Post Office Radio Branch Laboratories. The oven and temperature-control arrangements were essentially a simplified version of the thermostat designed by Turner (**3**). The fundamental crystal frequency was 100 kc/s, which was converted by means of regenerative dividers (**4**) into a 1 kc/s output used to drive a phonic motor. A group of three such oscillators, known as "Group 4" (**5**) attained a high standard of performance, and in 1942 arrangements were made for information relating to these clocks to be communicated daily to the Royal Observatory, where it proved of the greatest value. Within a year it became clear that the long-term performance of these clocks was so markedly superior to even the best of the pendulum clocks available to the Time Service that the pendulum clock was rendered virtually obsolete as a long-term standard (**6**).

It was clearly desirable that similar quartz clocks should be installed at the Observatory, so that the Service would not be entirely dependent upon primary standards at an external establishment. There was also an urgent need for secondary standards having good day-to-day stability for the control of the signals, and in this respect also the superiority of the quartz clock had been established. The first three clocks supplied by the Post Office were of the Group 4 pattern, and were brought into use early in 1944 for the control of the GBR radio time signals, thus bringing about a considerable improvement in

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

the day-to-day uniformity of these time signals. Unfortunately, the value of these clocks as long-term standards was seriously impaired by the fact that they were mains operated and that, under war-time conditions, interruptions of the mains electricity supply were of frequent occurrence. It was thus still necessary to base the service on the Post Office Group 4 standards.

During 1945 four groups of three oscillators, similar in general arrangements to the Post Office Group 4, were installed in new clock cellars at the Observatory station at Abinger (**7**). These oscillators, together with their ancillary equipment, were designed for battery operation, and an extensive installation of batteries and control equipment, together with a stand-by diesel generator, was provided. This overcame the main cause of disturbance to the oscillators, and longer uninterrupted clock runs were made possible. The temperature-control circuits, however, were still dependent on a 50 c/s a.c. supply, and in the event of mains failures this was provided automatically by a battery-driven motor alternator. Two similar groups of three oscillators each were subsequently installed at Greenwich, and incorporated some minor improvements. Special types of phonic motors were developed in order that all requirements of the service could be provided directly from the quartz clocks (**8**). Motors incorporating sidereal gearing were used to provide sidereal seconds for the astronomical time observations; and more elaborate timing devices, capable of producing the various forms of time signal distributed by the Department, made the full accuracy of the quartz clocks available for direct practical use. It had thus become possible for the quartz clocks to perform, with greater accuracy, all the functions hitherto carried out by the pendulum clocks: in fact, the manifest inferiority of the pendulum clocks led to their complete elimination.

One result of the widespread employment of quartz clocks was that the clock comparison equipment which had been adequate for use with pendulum clocks was found to be incapable of meeting the new demands for accuracy. In particular, it became necessary to replace the electro-mechanical chronographs by fully electronic decimal counter chronometers (**9**). Moreover, quartz clocks may be conveniently intercompared with great accuracy by methods which are inapplicable to pendulum clocks. Relative rates may be readily obtained by means of a precision beat comparator (**10**) and integrated time differences between standards by means of rotary beat counters (**11**). It thus becomes possible to maintain a constant check on the performance of all oscillators and to connect the dividers and phonic motors to those oscillators giving the best performance at the time.

As initially installed, the three oscillators of each group were mounted on one rack, in accordance with standard Post Office practice. Although oscillators employing GT-cut crystals are not unduly sensitive to mechanical disturbance, it was decided to re-mount the oscillators singly on individual brick and concrete piers, thus making it possible to carry out work on one oscillator without risk of disturbance to the others of the group. In the course of the necessary re-wiring, the power supplies were re-arranged to permit convenient isolation of each oscillator. New crystal ovens were constructed in the Observatory workshop, to an improved Post Office specification which is designed to accommodate either GT or ring crystals. The oven is located in a hollow in a concrete block on top of the pier, where it is protected from accidental disturbance and draughts. The temperature-control unit and maintaining amplifier are mounted independently above the oven. Some minor changes were made in the circuit

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

arrangements: high-stability components were employed, and the layout was modified to facilitate servicing. The step-up ratio of the transformer in the temperature-control circuit was increased to improve the sensitivity, and the constant-temperature arms of the control bridge were re-wound on a solid brass rod. The period of the oven-control cycle was thereby reduced to about five seconds. Duplicate thyratrons were fitted, with separate signal lamps, thus giving warning of impending thyratron failure, and permitting replacement without disturbance of the temperature control. In the new maintaining amplifiers toroidal transformers are employed and precautions have been taken to render the amplifier gain still less sensitive to variations in supply voltages or in the loading of the 100 kc/s output. Some amplifiers have been fitted with prototype long-life valves. During the testing and setting-up of these oscillators it became necessary to devise new techniques for alignment and adjustment.

In view of the excellent results achieved with a bridge drive circuit in association with GT-cut plate crystals, the Post Office Radio Branch Laboratories proceeded to produce a bridge circuit suitable for a ring crystal. Three oscillators, forming the Post Office Group 5, employed ring crystals supported by nickel pins. Later oscillators, forming Group 9, utilized softer metal for the crystal supports, and in the latest type the ring is suspended on silk threads. Very high values of Q (i.e. sharpness of resonance) have been obtained, but perhaps the most significant characteristic of the new ring oscillators is the substantial reduction of the initial frequency drift. An oscillator of this type was installed at the Observatory in 1950 May, and was brought into use almost immediately as the working standard E5. For subsequent employment as a long-term standard, its useful run began only a week or so after installation. A remarkable feature of this particular standard is the small value of the frequency drift, which amounts to only 1 part in 10^8 per year. A second oscillator of the same type, E6, was installed a few months later, and has exhibited a similar degree of stability, but is characterized by a uniformly changing frequency drift. Two further ring-crystal oscillators were installed towards the end of 1951. One of these, C5, is performing satisfactorily, but the other, C6, failed to reach the high standard of the other ring oscillators. It was accordingly removed from service, and the maintaining amplifier was modified in the light of more recent experience. The new run of this oscillator shows a satisfactory improvement in short-term stability, and there is good reason to suppose that the long-term performance will be correspondingly improved.

The ancillary equipment associated with the oscillators has also received attention. The regenerative dividers providing an output at 1 kc/s have been replaced by improved models developed at the Royal Observatory. The earlier pattern employed a large number of metal rectifiers and a total of fourteen transformers. In the new pattern, no metal rectifiers are employed, electronic mixing is used, and the number of transformers has been reduced to four. The valves were previously operated at nearly full rated anode current, and performance was adversely affected by valve ageing. The valves are now operated at low anode current, with consequent saving of power and reduced sensitivity to changes in valve characteristics. In order to meet the need for accurately spaced seconds pulses, new pulse dividers have been designed. A series of identical plug-in units, each giving one output pulse for every ten input pulses, may be connected in cascade to perform frequency division by any required power of ten. The units function with equal reliability at any input frequency

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

from 100 000 pulses per second to one pulse per second. A series consisting of five such units supplied with pulses derived from the 100 kc/s crystal frequency provides seconds pulses of more than adequate accuracy. Full advantage is thus taken of the extremely high stability of the latest crystal oscillators.

2. *Assessment of long-term performance.*—For the operation of a National Time Service of high accuracy the clocks should provide a time scale that is uniform

(*a*) from month to month over a period of two years or so;

(*b*) from day to day over a period of one month or longer.

The clocks which adequately fulfil the first requirement are employed for long-term prediction. Those with a high degree of day-to-day stability are used as working standards in the control of time-signal transmissions. It is therefore necessary to assess the quality of the available clocks from these two different aspects.

The problem of relating the performance of a modern quartz clock to the ultimate standard of time, the rotation of the Earth, has become increasingly difficult on account of the latest developments in quartz clocks. For some years the uniformity of the time scale provided by the clocks has surpassed that defined by the Earth: this disparity has been growing more pronounced since the introduction of improved clocks employing ring-crystal oscillators (**12**). In an attempt to remove the effects of one known cause of irregularity in observed time, it has been the practice for the last five years at the Royal Greenwich Observatory to apply current corrections for the variation in longitude arising from polar motion, or more briefly, "polar variation". These corrections are based on independent data derived from variations of latitude observed at the U.S. Naval Observatory. Another known cause of irregularity is the annual fluctuation in the rate of rotation of the Earth. The mean amplitude of the fluctuation over a number of years was independently determined by several investigators. The degree of agreement between these various results suggested that the effect was sensibly constant from year to year, and that considerable advantage would be gained by the application of a correction based on the average fluctuation observed in preceding years. It has since become apparent that the annual fluctuation is subject to appreciable variation from year to year, and that the use of an average value may be misleading (**13**). This fluctuation can only be determined from the time observations themselves, and current estimations of its magnitude are subject to considerable uncertainty. It has in fact become impracticable to obtain a sufficiently uniform time scale by applying to the astronomical time observations provisional corrections for polar variation and annual fluctuation. A time scale of adequate uniformity may however be established by taking the mean of a number of specially selected quartz clocks of the highest precision. But such a scale is not absolute unless it can be related to the rotation of the Earth. It is therefore necessary to calibrate the scale with reference to the general trend of the astronomical observations over a period of two or three years. The procedure now adopted at the Royal Greenwich Observatory is to use a mean of the best clocks at the various cooperating establishments to define a time scale that is, as nearly as possible, uniform, and to determine the rate of the mean clock by consideration of the astronomical time observations made over an extended period at Greenwich and Abinger.

The application in practice of these principles may be illustrated by reference to the analysis performed for the period 1950 June to 1952 June. Information

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

relating to all available clocks was readily accessible from the current graphs of clock intercomparisons. An examination of the performance of the clocks during the period under review permitted the selection of the five best clocks. These clocks were then referred to the astronomically observed time corrected for polar variation and the provisionally adopted annual fluctuation. An adequate basis was thus provided for the adoption, for each clock, of a preliminary parabolic ephemeris extending over the two-year interval. Where the intercomparisons gave clear evidence of a change of rate or drift in any particular clock, due allowance was made. In the course of the two years, two of the clocks, E5 and 9A, required no such adjustment; the remaining three each had one apparent change of drift: 9C in 1951 April, Q13 in 1951 May, and EA in 1951 November. Each clock was then referred to the monthly means of the observations, corrected for polar variation but not for annual fluctuation. Corresponding monthly points in successive years were differenced to give a series of annual rates. If the fluctuation in the rate of rotation of the Earth were strictly repetitive from one year to the next, it would have no effect upon clock rates determined over these

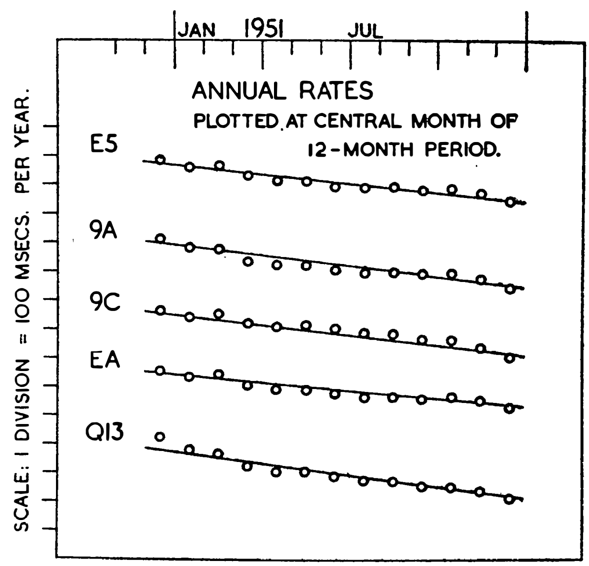

FIG. 1.

twelve-monthly periods. In practice it is found that the fluctuation varies somewhat in amplitude and phase, but that this procedure is effective in removing the major part of the fluctuation in determined rate. Moreover, the use of a long interval considerably reduces the residual effect, and largely eliminates errors arising from observational scatter. The efficacy of the process is demonstrated by the fact that the plotted points adhere closely to straight lines (see Fig. 1), which were used to determine corrections to the parameters of the preliminary parabolic ephemerides.

The five clocks were then combined into a mean clock, which established a provisional uniform time system of which the uniformity and scale value depended upon the drift and rate adopted for the mean clock. Since the drift and rate of each individual clock had been ultimately determined by consideration of annual rates, given by the observations, the time system defined by the mean clock was fundamentally related to the astronomical standard of time, from which the annual fluctuation had been removed. The system was however largely independent of the particular values adopted for the amplitude and phase of

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

the annual fluctuation. This time system is therefore suitable as a basis for the evaluation of the 12-month and 6-month periodicities of the annual fluctuation by a series of simple harmonic analyses, each covering twelve successive monthly means of observations corrected for polar variation. It has been found convenient to start each harmonic analysis at the beginning of a quarter-year so that any given analysis has an overlap of nine months with the previous and following analysis. There were therefore five harmonic analyses in the two-year period under consideration, the first and fifth being independent of each other, and the others overlapping. The five results for the annual fluctuation appeared to be in reasonable agreement, and a convenient set of values was adopted for the whole period. Corrections for annual fluctuation computed from these were then applied to the monthly means of observations, bringing the plotted points to the neighbourhood of a horizontal straight line. The mean ordinate was computed and applied, fixing the zero-point of the uniform time system. The uniformity and scale value having been fixed as previously described, the time system was thus completely determined. The remaining scatter was attributed to observational error, and amounted to a mean deviation of $\pm 6{\cdot}2$ milliseconds for a single monthly point.

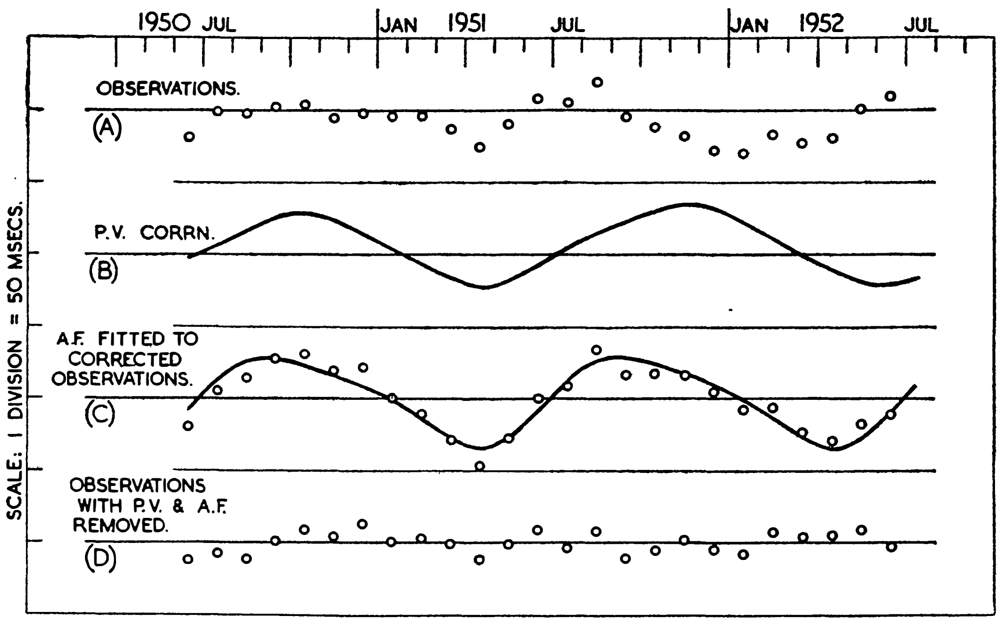

FIG. 2.

In Fig. 2 are shown

(A) the uncorrected observations (monthly means) referred to the mean clock;

(B) the correction for polar variation based on latitude observations made in the U.S.A.;

(C) the observations corrected for polar variation, but still subject to annual fluctuation, together with the curve based upon the mean annual fluctuation adopted for the period; and

(D) the observations corrected for polar variation and annual fluctuation, with the mean ordinate removed.

It will be noticed that the polar variation correction, Fig. 2 (B), shows a preponderance of positive values, arising from an apparent discrepancy in the

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

adopted mean latitude of the U.S. observing station. This is not of serious importance, as it affects only the zero-point of the uniform time system, and thus has no effect whatever upon the determined annual fluctuation, the determined astronomical time (G.M.T.), or the assessment of clock performance. An adjustment of the adopted mean latitude would give rise to a discontinuity in the uniform time system, and is thus better delayed until a revised mean can be adopted from, say, ten years of results. For the same reason, changes in the adopted position of the Earth's mean pole, which are equivalent to adjustments of adopted mean latitude for many stations, are best made as infrequently as possible. It is of interest to note that during the period considered the effect of the polar variation on time observations at Greenwich was nearly equal in amplitude and opposite in phase to the effect of the annual fluctuation. Furthermore, any errors in the adopted corrections for polar variation will be reflected in the determined annual fluctuation. It has been found that the corrections derived from the U.S. latitude observations are substantially confirmed by those based upon the results published subsequently by the International Latitude Bureau.

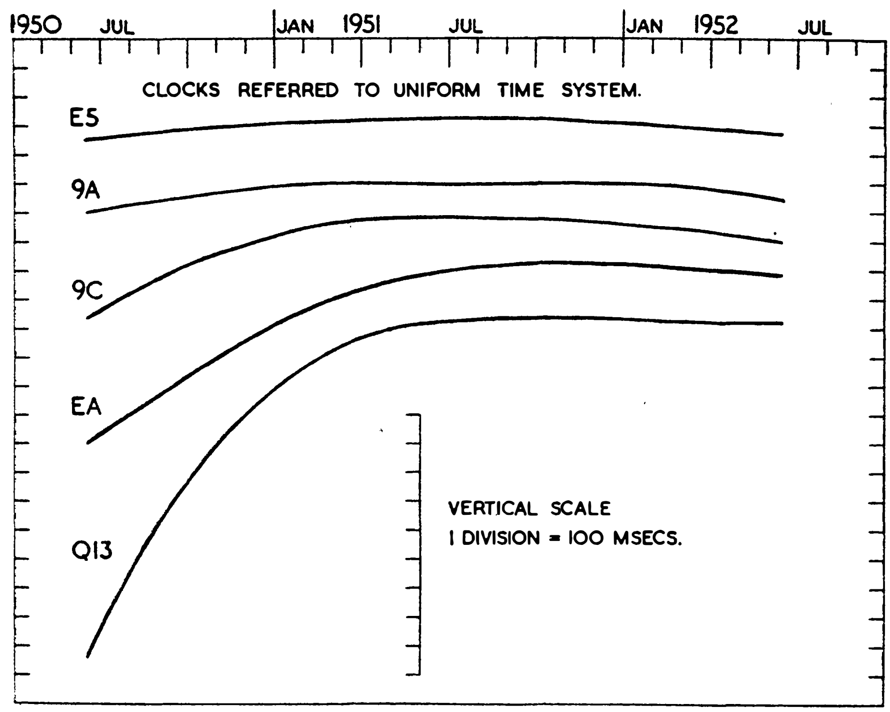

FIG. 3.

The establishment of a uniform time system has been described in some detail, since this is of fundamental importance in the assessment of long-term clock performance (Fig. 3). The mid-monthly values of the daily rates of typical clocks, in terms of this uniform time system, are listed in Table I. The stability in rate from month to month of the two best clocks, E5 and 9A, is indicated in Fig. 4. The clock 9A has been in continuous operation since 1948 January, and has evidently settled to a practically uniform frequency drift. The clock E5, on the other hand, was not installed until 1950 May, and appears to have settled immediately to a frequency drift which was not only practically uniform but also very small.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

The most important requirement in a long-period standard clock is that it should run uniformly with a constant frequency drift for as long a period as possible. Twelve months of uniform run are needed before even one determination of annual rate can be made. A uniform run of two years provides twelve monthly values of annual rate, and represents the shortest period that can give a reliable indication of frequency drift. For any period of approximately uniform run, the first differences of the monthly values of rate will represent the monthly drift in the rate of the clock. For a perfect clock the first differences will be constant, and the second differences zero. The magnitude of the second difference will indicate the departure of the clock from uniformity of run. It was therefore decided to evaluate the mean absolute monthly second difference for each clock as a numerical criterion of clock performance. The appropriate criterion values, in milliseconds per day per month per month, are quoted at the foot of Table I. The requirements of a modern time service are such that a clock should maintain a criterion value not exceeding 0·10 for two years or so.

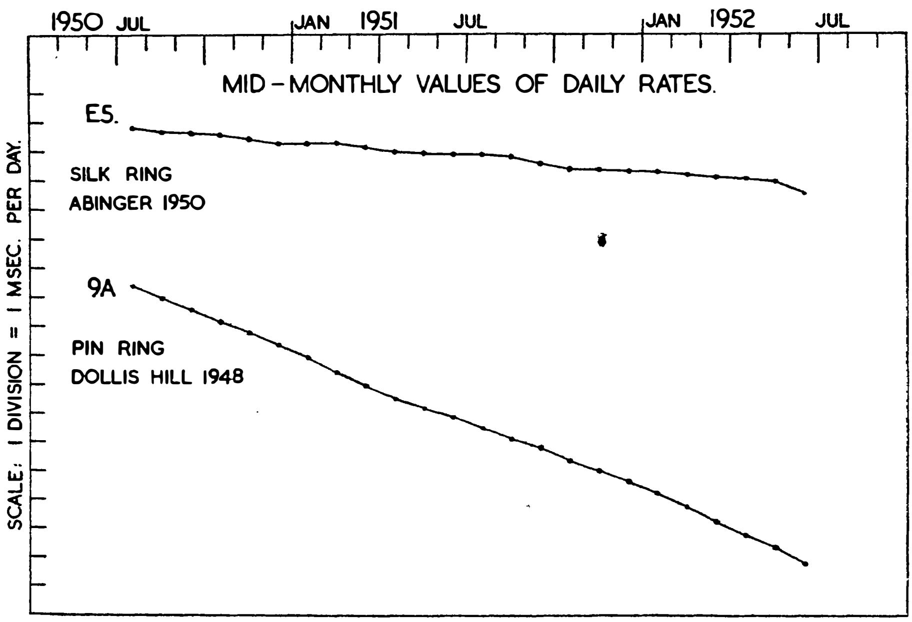

FIG. 4.

It may be noted that the criterion so determined is largely independent of errors in the adopted rate and drift of the reference time system. In fact, over an isolated period of two years, it may be regarded as independent of the astronomical determinations of time, since, for such periods, the mean of several modern quartz clocks gives a more uniform time scale than that defined by the rotation of the Earth. The astronomical observations relating the clocks to the rotation of the Earth are however essential both in current work and in retrospective assessment of performance. Even the best modern clocks are liable to slight changes of rate and drift which cannot be detected by clock intercomparisons until some time has elapsed and an appreciable error has accumulated. The astronomical observations, although subject to considerable scatter, serve to protect the currently adopted time from gross errors which might otherwise arise on this account. In retrospective assessment, the practice of judging the stability of quartz clocks in terms of their relative performance cannot be extended over periods greatly in excess of two years. In order to

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

control long-period changes in rate and drift, it is necessary to refer to an independent fundamental standard. The only practicable fundamental standard at present available for this purpose is the rate of rotation of the Earth, as indicated by observations of stellar transits. A more uniform fundamental standard of time would be provided by the period of revolution of the Earth around the Sun.

TABLE I

Mid-monthly values of daily rates of selected clocks
(milliseconds per day)

	Abinger		Greenwich		Dollis Hill			N.P.L.
Standard	E5	E6	F1	9A	9C	EA	EB	Q13
Ring or Plate	R	R	P	R	R	R	R	R
Silk, Pin or Clamp Support	S	S	C	P	P	S	S	S
1950								
July	+47·83		+84·54	−26·61	−0·32	−56·13	−41·48	+30·47
August	+47·69		+83·83	−27·03	−0·76	−56·54	−41·56	+29·33
September	+47·61		+83·13	−27·47	−1·22	−56·81	−42·01	+28·17
October	+47·58		+82·37	−27·85	−1·83	−57·24	−42·69	+27·12
November	+47·44	−40·39	+81·53	−28·26	−2·35	−57·81	−43·37	+26·22
December	+47·26	−41·98	+80·71	−28·67	−2·69	−58·36	−43·78	+25·30
1951								
January	+47·24	−43·32	+80·04	−29·10	−3·11	−58·89	−44·11	+24·36
February	+47·25	−44·64	+79·42	−29·63	−3·65	−59·46	−44·54	+23·11
March	+47·11	−45·92	+78·85	−30·09	−4·19	−60·09	−44·77	+22·62
April	+46·95	−47·20	+78·47	−30·50	−4·69	−60·69	−44·63	+22·14
May	+46·90	−48·50	+78·20	−30·85	−5·07	−61·14	−44·27	+21·17
June	+46·85	−50·04	+77·89	−31·14	−5·42	−61·66	−44·18	+20·45
July	+46·84	−51·63	+77·69	−31·54	−5·84	−62·26	−44·41	+19·94
August	+46·76	−53·42	+77·61	−31·92	−6·19	−62·77	−44·70	+19·50
September	+46·51	−55·34	+77·31	−32·21	−6·47	−63·17	−45·08	+19·05
October	+46·34	−57·47	+76·74	−32·66	−6·87	−63·72	−45·57	+18·69
November	+46·30	−59·67	+76·25	−33·01	−7·19	−64·15	−45·86	+18·31
December	+46·27	−62·06	+75·54	−33·40	−7·55	−64·60	−46·11	+17·84
1952								
January	+46·23	−64·48	+74·76	−33·81	−7·89	−65·01	−46·21	+17·47
February	+46·16	−67·06	+73·97	−34·28	−8·22	−65·40	−46·25	+17·09
March	+46·05	−69·57	+75·78	−34·78	−8·60	−65·79	−46·11	+16·72
April	+46·00	−72·06	+75·40	−35·23	−8·97	−66·15	−45·90	+16·42
May	+45·92	−74·43	+72·62	−35·67	−9·28	−66·61	−45·70	+16·15
June	+45·50	−76·97	+72·31	−36·21	−9·73	−67·18	−45·62	+15·53
Criterion	**0·08**	**0·10**	**0·53**	**0·06**	**0·07**	**0·08**	**0·17**	**0·15**

Observations made over many years have revealed that the Sun, Moon and planets are departing from their predicted positions by amounts that are proportional to their mean motions (14). This is attributed to an error in the time scale against which the observations have been recorded: the observed secular accelerations of the Sun, Mercury and Venus are thus associated with a progressive retardation in the rate of rotation of the Earth, amounting to an increase of one millisecond per century in the length of the day. It now appears that this may be satisfactorily accounted for by tidal friction. In addition there are fluctuations in the observed motions of the Sun, Moon, Mercury and Venus,

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

arising from variations in the rotation of the Earth. These variations have been interpreted as occasional sudden changes of several milliseconds in the length of the day, but may alternatively be regarded as the cumulative effects of continual random changes.

It is clearly desirable that the motions of the celestial bodies should be referred to a time system unaffected by irregularities in the rate of rotation of the Earth. Such a system is defined by the period of the revolution of the Earth in its orbit round the Sun, making the sidereal year the fundamental unit. At the Conference on the Fundamental Constants of Astronomy (Paris, 1950) it was recommended that the unit adopted should be the sidereal year at 1900·0 (**15**, **16**). The time reckoned in terms of this unit is known as Ephemeris Time and the difference between mean solar time and Ephemeris Time is given by the following expression:—

$$+24^{s}{\cdot}349+72^{s}{\cdot}3165T+29^{s}{\cdot}949T^2+1^{s}{\cdot}821B,$$

where T is measured in Julian centuries from 1900 January 0, Greenwich Mean Noon, and B is the fluctuation in the Moon's longitude, that is, the difference between the observed longitude and the amended tabular longitude (**14**). The previously accepted unit of time, the mean solar second, which is now known to be variable, may be converted to an invariable unit, the second of Ephemeris Time, by use of the same formula.

The second is one of the three fundamental physical units, and thus enters into many scientific measurements besides those of astronomy. In the majority of cases, the errors arising from the use of the variable mean solar second are negligible, but clearly an invariable unit of time should be employed. The second of Ephemeris Time is specifically intended to provide a unit of this kind, but its widespread use is dependent upon the development of satisfactory methods for its current determination. This requires regular accurate observations of the position of the Moon for comparison with the tabular places. Work now in progress at the U.S. Naval Observatory suggests that observations of sufficient accuracy may be secured by the employment of a new photographic technique. These developments may make it possible for a time-keeping observatory to establish a uniform time system, and thus provide a satisfactory basis for the assessment of clock performance and for frequency standardization.

3. *Assessment of short-term performance.*—It will be evident that the day-to-day stability of quartz clocks over periods of a month or so may be satisfactorily assessed from the clock intercomparisons alone without reference to the astronomical observations. As may be expected, the clocks which have been selected in virtue of their high long-term stability also exhibit a high standard of uniformity from day to day. An example is afforded by the relative daily rate of the clocks 9A and 9C, which is plotted in Fig. 5. Throughout the year 1951 the variation in rate was smooth, and the range did not exceed 0·5 millisecond per day. It may be remarked that the drifts of the clocks are sufficiently similar for the relative rate to be plotted direct, without removal of an ephemeris.

The most satisfactory indication of day-to-day performance is provided by an examination of the second differences of the daily values of clock rate. The mean absolute value of the second difference affords a quantitative criterion of the suitability of the clock for day-to-day extrapolation and interpolation. It has recently been pointed out (**17**) that there is some correlation between the second

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

differences on successive days. It should not be assumed, however, that this necessarily impairs their utility as a measure of short-term performance, since it has been shown (**6**) that they may be grouped into three sub-sequences, each of which is entirely free from internal correlation. The re-combination of the sub-sequences does not invalidate the result. In practice, it is unnecessary to separate the sub-sequences and re-combine when forming the mean absolute second difference.

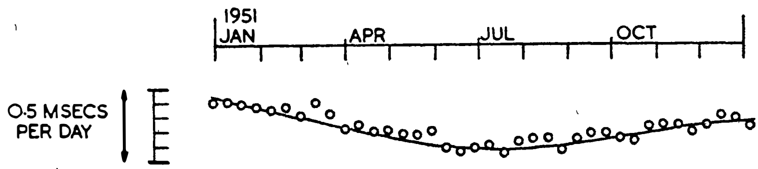

FIG. 5.

Clock intercomparisons of high accuracy are obtainable from the daily readings of the rotary beat counters, which give a continuous indication of the time difference between any two clocks in units of one microsecond. The calculation of the second differences of daily rates is readily performed by means of a National Accounting Machine. These daily values are plotted to give a convenient picture of the day-to-day stability of the clocks. The mean absolute value of the second difference of daily rate provides a useful criterion of short-term performance. The intercomparisons between the two clocks E5 and E6 throughout the year 1951 gave a mean absolute daily second difference of relative rate amounting to 16 microseconds per day. Since the two clocks were of comparable short-term stability, the criterion value was approximately 11 (in the same units) for each clock. The intercomparisons between C5 and C6 for a period of some four or five months after the modification of the C6 maintaining amplifier gave a mean absolute daily second difference of 19 microseconds per day, corresponding to a criterion value of 13 for each clock, if the stabilities were equal. It is clear that a short-period criterion value of 10 to 15 is attained by modern quartz clocks. While this accuracy cannot be fully utilized in Time Service operational work, the precision of the daily intercomparisons provides a valuable indication of any slight deterioration in the stability of the clocks which might, by its cumulative effect, cause a significant deterioration in the long-term performance. It may sometimes be possible to associate an enhancement of these small variations with particular physical causes, such as alterations in the values of certain components, thus providing information of great value in the modification and design of quartz-crystal clocks.

A graph of the direct intercomparisons of E5/E6 and C6/E6 with a parabolic ephemeris removed in each case is given in Fig. 6. It will be noted that the deviations do not exceed 0·1 millisecond in the course of a month.

4. *Present developments.*—The high stability of the performance attained by modern clocks leads naturally to the consideration of the possibility of further progress. It has been suggested that the ultimate limit of accuracy is imposed by the crystal itself, rather than by the ancillary circuits. If this were indeed the case, consideration would have to be given to the development of standards utilizing some control element other than a quartz crystal. Tests on the ancillary

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

circuits have shown, however, that in many cases the crystal is not operating under the best conditions. It has in fact been possible, by improved design of the associated circuits, to obtain a higher standard of stability from crystals of conventional types.

In particular, attention was directed to the reduction of the amplitude of oscillation of the crystal. This cannot be achieved in the conventional bridge-drive circuit, where the amplitude of oscillation is controlled directly by a tungsten filament lamp. As a first step, the tungsten filament lamp was replaced by an indirectly heated thermistor, for which the heating current was derived from a secondary amplifier. This gave some reason to believe that higher short-term stability would result from a lower amplitude of oscillation. In the most recent drive-circuit, the bridge has been replaced by a circuit which is electrically equivalent, and in which the crystal current is less than 30 micro-amperes. The maintaining amplifier uses no transformers, as these were thought to be a source of instability in the circuits previously employed. The achievement of higher precision in the crystal oscillator makes it advantageous to control the temperature of the crystal within closer limits and it is estimated that a new control circuit and oven divide ambient changes by a factor of 50 000.

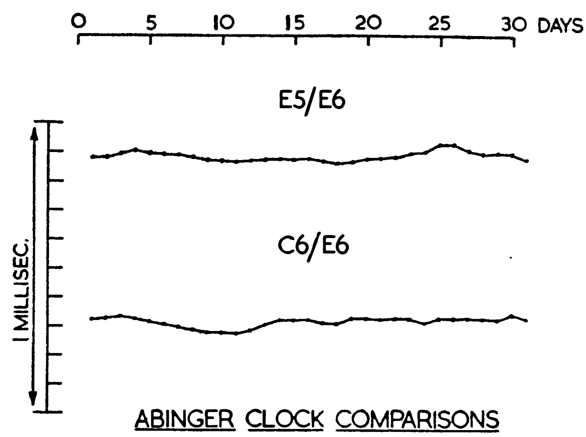

FIG. 6.

Reliability of operation over long periods is of paramount importance, since the clock may often suffer greater disturbance from a failure of temperature control than from a short interruption of oscillation. The previous designs used the 50 c/s mains supply both for the control bridge and for the heater windings. In the new experimental oscillators the current is supplied by a battery-operated 325 c/s oscillator which is amplitude-stabilized. The oscillator valves are in parallel, and removal of either valve has negligible effect on the frequency and amplitude. The controlling amplifier, which employs duplicated hard valves in place of thyratrons, has been designed in such a way that the valves may be replaced without altering the control-temperature by more than half a millidegree. The first oscillator incorporating these refinements employed a GT-cut plate crystal, and was put into operation in 1951 November. A second oscillator, incorporating minor improvements, was installed in 1952 July. Results obtained so far have been encouraging.

5. *Conclusions.*—It is now nearly ten years since the quartz clock, by virtue of its superiority as a long-term standard, displaced the pendulum clock in the fundamental work of the Greenwich Time Service. Almost at once it became

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

apparent that among the advantages of the new type of clock were a considerably higher standard of short-period stability and far better facilities for accurate intercomparisons. The purpose of this account is to show the further advances which have subsequently been made in the quality of the clocks themselves and in the technique of using them in the operation of a national time service.

The past years have afforded an unrivalled opportunity for the gaining of experience and the investigation of the problems concerning quartz clocks. In those observatories which have not yet acquired quartz clocks comparable in stability with those available to the Greenwich Time Service, there is perhaps inadequate realization of the standards now attainable, combined with an instinctive reluctance to forsake the relatively simple pendulum clock in favour of the admittedly more complex quartz-controlled oscillator. The pendulum clock has the valuable property of being capable of prolonged uninterrupted runs, and it has been claimed that this feature is sufficient to justify the retention of pendulum clocks as fundamental standards, and that the long-term performance of the two types of clock is otherwise comparable (**18**).

Considering first the question of length of uninterrupted run, it has been found that modern quartz clocks have attained a high standard of reliability. Given continuity of power supplies, the period of uninterrupted run may easily extend over several years. Among the clocks mentioned in this account, F1 has run continuously since its installation in 1947 July, 9C since 1947 October, and 9A since 1948 January. The clocks at Abinger have not run for such long periods, as the installation has been modified in recent years. It is worthy of note, however, that in the six years since the Abinger clocks were transferred to battery operation there has been only one failure of a crystal oscillator.

As regards performance, the superiority of the quartz clock is firmly established. It is now some years since pendulum clocks were employed as standards in the Greenwich Time Service; but up-to-date information on the performance of high-precision pendulum clocks at Paris is published regularly in the *Bulletin Horaire*. Mean daily rates are quoted for each month, and these may be compared with the corresponding figures for quartz clocks given in Table I. It is also possible to calculate the mean absolute second differences of the monthly rates, thus giving a numerical criterion of performance which may be compared with the values deduced for quartz clocks. During the two years 1950–1951 one of the Paris pendulum clocks, Leroy 1372, attained a standard which can have been only rarely equalled by any other pendulum clock. The mean absolute monthly second difference was found to be 3·4 milliseconds per day. An examination of the other pendulum clocks shows that a value of 10·0 would represent a good average performance, while a criterion of 50·0 or over would be classed as poor. Results are also quoted for the quartz clocks at Paris. The best of these has a criterion of 8·5, whereas the other two have values of about 20·0. It will be evident that, despite recent claims to the contrary (**19**), even the best pendulum clock does not represent a serious challenge to the typical modern quartz clock with a criterion of 0·1 millisecond per day per month per month.

The high short-term stability of a quartz clock has permitted a new standard of accuracy in the control of radio time signals, and the application of frequency measuring technique has made it possible to carry out clock comparisons with a speed and precision hitherto unattainable. But it is perhaps in the realm of

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1953MNRAS.113...67S

long-term performance that the greatest advances have been made. Quartz clocks were first introduced in the Greenwich Time Service as long-term standards, and it is due to the high stability of the present clocks over periods of two or three years that it has become possible to determine the nature of the annual fluctuation in the rotation of the Earth. In current practice the annual fluctuation is determined by referring the astronomical observations to each of a number of selected clocks. The various solutions show a high degree of agreement, and the resulting mean value can be adopted with confidence.

6. *Acknowledgments.*—The various investigations and analyses described were undertaken in the course of normal routine work by the Computing Section of the Time Department, under the direction of Mr R. H. Tucker, who also assisted in the preparation of the paper. Information relating to the quartz clocks at other establishments is regularly supplied to the Royal Observatory and is of great value in the operation of the National Time Service. The author wishes to take this opportunity of expressing his appreciation of the continued cooperation of the Post Office Radio Experimental and Development Branch Laboratories and of the National Physical Laboratory.

Royal Greenwich Observatory,
Abinger Common,
Dorking, Surrey :
1952 *October* 9.

References

(1) L. Essen, *Proc. Phys. Soc.*, **50**, 413, 1938.
(2) L. A. Meacham, *Bell System Technical Journal*, **17**, 574, 1938.
(3) L. B. Turner, *Journal I.E.E.*, **81**, 399, 1937.
(4) R. L. Miller, *Proc. I.R.E.*, **27**, 446, 1939.
(5) C. F. Booth and F. J. M. Laver, *Journal I.E.E.*, **93**, Part III, 223, 1946.
(6) W. M. H. Greaves and L. S. T. Symms, *M.N.*, **103**, 196, 1943.
(7) H. M. Smith, *Annales Françaises de Chronométrie*, 2e Série, **3**, 227, 1949.
(8) H. M. Smith, *British Science News*, **2**, 169, 1949.
(9) H. M. Smith, *British Science News*, **2**, 207, 1949.
(10) H. B. Law, *Journal I.E.E.*, **94**, Part III, 38, 1947.
(11) W. A. Marrison, *Bell System Technical Journal*, **27**, 510, 1948.
(12) H. M. Smith, *Proceedings I.E.E.*, **98**, Part II, 143, 1951.
(13) H. M. Smith, *I.E.E. Monograph*, No. 39.
(14) H. Spencer Jones, *M.N.*, **99**, 541, 1939.
(15) *Bulletin Astronomique*, tome XV, fascicule 4, 291, 1950.
(16) D. H. Sadler, *M.N.*, **111**, 624, 1951.
(17) N. Stoyko, *Annales Françaises de Chronométrie*, 2me Série, **3**, 139, 1949.
(18) R. Forga, *l'Astronomie*, 65e année, 112, 1951.
(19) A. Danjon, *Annales Françaises de Chronométrie*, 2me Série, **3**, 365, 1949.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System