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MODERN METHODS OF TIMEKEEPING.

A GEOPHYSICAL Discussion on the above subject was held by the Royal Astronomical Society at their rooms at Burlington House on 1947 March 21 at $16^h\ 30^m$. A small exhibition of quartz crystal oscillators was held immediately before the meeting.

The British Post Office showed an apparatus demonstrating the modes of vibration of a quartz plate and also its extremely low decrement. Samples of quartz and a compact crystal-controlled clock were also on view. *Messrs. Standard Telephones and Cables Ltd.* exhibited a quartz plate mounted in an evacuated glass bulb, and photographs of the processes used in the manufacture of such resonators. *The Department of Geodesy and Geophysics*, Cambridge University, showed two portable frequency standards, made by Standard Telephones and Cables Ltd. These were connected to amplifiers and used to drive phonic clocks. Beats between the two crystals were used to operate a counter, so that, within a period of 50 seconds, the relative rate could be determined with an accuracy of 2 parts in 10^7.

The Chair was taken by Sir Robert Watson Watt and the discussion was opened by the Astronomer Royal, Sir Harold Spencer Jones.

The Astronomer Royal. The ultimate standard of time is the rotation of the Earth, but to provide a generally useful time service, it is necessary to use some sort of clock not only to sub-divide the intervals between astronomical observations but also to extrapolate when weather conditions make direct observation impossible. In the past, pendulum clocks were almost exclusively used, but they are now superseded by quartz crystal oscillators, which have proved greatly superior for short-term prediction. Using these it is possible to provide a frequency standard accurate to about two parts in 10^8, and it is hoped that this figure will be improved in the near future. Owing to the integrated effect of small frequency changes, it is much more difficult to provide accurate time. For this purpose, accurate control of the long-period performance of the clocks is necessary. Several factors complicate the assessment of the long-period performance.

In the first place, instrumental and personal errors limit the accuracy with which the time can be determined. The instrumental errors are continually varying. Even when the greatest care is taken to control and to eliminate them, there are still unexplained differences between observations made at different observatories. As an example, measurements made at Abinger and Edinburgh may be compared. These show differences up to as much as 25 milliseconds, the maximum rate of change being one-fiftieth of a millisecond per day.

Using a small transit instrument, the probable error of a single determination is at least ± 20 milliseconds, but using a zenith telescope and photographic recording, it is possible to reduce this error to ± 2 milliseconds.

Uncertainties in the position of the stars also introduce errors. For time-keeping purposes it has been decided, by international agreement, that the FK3 star system shall be used. Periodic errors in the star systems may be misinterpreted as fluctuations in the clocks. The right ascensions

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given in these tables can in course of time be controlled by using a zenith telescope and an accurate clock, and making observations as soon as possible after sunset and as late as possible before sunrise. It is hoped that in time it may be possible to correct the star system so that these errors are negligible.

The motion of the pole introduces another source of uncertainty, since its movements are not entirely predictable. It includes a term with a period of one year and another with a period of about 432 days. At Greenwich the total fluctuations due to this cause may be as much as $\pm$ 26 milliseconds, the maximum rate error being $\frac{1}{4}$ millisecond a day. The component of the polar motion along the meridian can be derived from observations of the variation of latitude, but the component in the perpendicular direction can only be known from observations of latitude variation at an observatory differing in longitude by about 90°.

Finally, the changes in rate of rotation of the Earth, which show up as a variation in the mean longitude of the Moon and other bodies in the solar system, give rise to changes in the length of the day. The effect is not very large, usually not amounting to more than 2 milliseconds per day. However, larger changes occur from time to time. Around the year 1900 the length of the day altered by 5 milliseconds in less than 5 years. It is not known with certainty whether these changes occur rather suddenly or are spread over a few weeks, or over several months. Small changes in the rate of rotation of approximately annual period have been suspected.

Dr. Essen. Besides quartz crystal oscillators, several other types of timekeeper have been used at the National Physical Laboratory. The pendulum clock, though not so accurate as the best modern instruments, has the great advantage of being very reliable: it will run for years without interruption. An elinvar bar, vibrating longitudinally, has been tested and found to give results comparable with those obtained from a quartz crystal, but it is somewhat less stable and its large size makes it inconvenient for general use. Tuning forks, if properly designed and mounted, can be most useful when observations of moderate accuracy are required over short periods of time.

However, undoubtedly the most successful frequency standard at present known is the quartz crystal oscillator. One of the chief problems is to design a suitable type of mounting which will not only hold the crystal securely but also impose as little damping as possible and at the same time insulate the crystal from external mechanical shocks.

Frequency drift is another source of trouble. There is some evidence to show that this is at least partly a surface effect, as ring and bar crystals with a large volume-to-area ratio appear to be rather more stable than the flat plate type.

Mr. Bigg. Tests carried out at the N.P.L., comparing the rates of two quartz crystal oscillators, two vibrating elinvar bars and a Shortt clock, had to be given up, after only three weeks, at the outbreak of war in September 1939. The results over this short period showed little difference between the various types.

During the period May 1943 to July 1945 the Essen type quartz-ring oscillator showed no error exceeding $\pm$ 1 part in 400 million of this period, after eliminating a uniform rate and bridging various discontinuities due

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to stoppage of the phonic motor. The absence of frequency drift is particularly noteworthy. During the same period the rate of the N.P.L. Shortt clock changed 2 milliseconds per week per week, but gave a completely uninterrupted performance whose residual error was also within $\pm$ 1 part in 400 million of the 26-month period.

Capt. Booth. Radio engineers are generally more concerned with standards of frequency than with those of time, but in the course of their work have developed the crystal-controlled oscillator which is the best standard of frequency yet devised and which is likely to prove itself as a timekeeper in the form of the quartz clock. However, much work remains to be done in perfecting these instruments.

A typical quartz clock comprises four units:—

(1) The crystal-controlled oscillator and its maintaining circuit oscillating at 100 kc/s.

(2) Electronic frequency-divider circuits to reduce the frequency to 1 kc/s.

(3) An amplifier to provide the necessary power at 1 kc/s to operate a phonic motor.

(4) A phonic motor to operate a clock mechanism including "second" contacts.

An example of such an instrument can be seen in the Science Museum at South Kensington.

One of the most unreliable components at present is the phonic motor, and there is a tendency in modern design to substitute purely electronic methods of producing pulses of current at the required time intervals.

The effects of temperature changes can be largely overcome by using special types of crystal vibrator, and with some of these, temperature coefficients of frequency that are as low as 1 part in 10^7 per 1°C. can be obtained over a range of some 20°C. By careful design the rate of the oscillator can be made almost independent of mechanical vibration and changes such as variation in H.T. and L.T. voltage, and replacement of valves. Future designs will aim not only at greater frequency stability but also at increased reliability: in this connection continuous operation for periods of at least ten years should eventually become possible. Attempts are also being made to construct high-grade crystals operating directly on 1 kc/s rather than on 100 kc/s and so to reduce the complexity of the equipment and correspondingly to improve its reliability.

The present frequency standard used by the Post Office contains three quartz oscillators whose frequencies are continuously intercompared to an accuracy of 1 in 10^{10}. During 1946, between the beginning and end of the year, frequency drift produced a change in the daily rate of the best clock of 8 milliseconds per day.

Mr. H. M. Smith. The standard clocks used at the Royal Observatory are of the type developed as frequency standards by the Post Office Radio Branch. These are compared with the clocks at the National Physical Laboratory and at the Post Office by means of the 10^h Rugby radio time signals. The performance of each clock may thus be determined in relation to the astronomical observations, and charts are kept showing the variations in clock error. Information from the three stations is used in forming the final estimate of time.

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If it is assumed that the rate of change of the rate of each clock is constant, the clock error E_t at time t may be represented approximately by $E_t = a + bt + ct^2$, where t is the time interval in days reckoned from a chosen epoch, and a, b and c are constants. The values of a, b and c are determined and charts are kept, the plotted points being in the form of residuals from the predicted curve. At present the inaccuracies of the observations are such that, even supposing the run of the clock to conform strictly to the given formula, a normal series of observations extending over some 100 days would be required before the current rate could be deduced with a probable error of ± 1 ms/day. But before rates can be predicted with a certainty of 1 ms/day over, say, one or two weeks, the above conditions would have to prevail over a period approaching one year.

The obstacles to obtaining sufficiently accurate values of the coefficients make prediction over long periods a matter of considerable difficulty. [This was convincingly illustrated by a series of slides. The predicted and observed clock errors were plotted against dates for a number of standard clocks over a given period and the audience was asked to predict how the clock rate would vary during the next interval. The next slide showed what happened during the following few days and subsequent diagrams continued to build up the chart over a period of several weeks, continually falsifying all reasonable predictions.] It is clear that disturbances in the electrical circuits of the clocks, especially those which affect the oven temperature, make accurate prediction impossible. Reliability is the most urgent requirement and it is in this direction as much as in increased accuracy of star observations that development is needed in order to reduce the errors in timekeeping.

In the discussion which followed, it was pointed out that the quartz clock in the Science Museum is not at present on view, but it is hoped that it will be working again in a few months.

Mr. Hope-Jones. Although in the past the free pendulum clock has proved the best timekeeper, there is no doubt that the quartz crystal has now superseded it as a standard instrument. The greatest need is for increased reliability. Once this is achieved, its steady rate and ability to measure very small time intervals will render the crystal clock not only the best timekeeper but also the most reliable frequency standard. Its complications, however, make it unlikely that it will supersede the pendulum clock where simplicity and reliability are of primary importance.

[In a communicated contribution to the discussion, *Mr. Hope-Jones* writes: I expected to hear rather more of W. A. Marrison, whom I have always looked upon as a pioneer, and of his paper "The Crystal Clock" of July 1930.

The famous trial carried out with Mr. A. L. Loomis from March 1927 to December 1928, Quartz versus Pendulum, revealing the lunar period, is sometimes assumed to be in the nature of a competition between the two to see which was the best timekeeper, but that is a misconception of the experiment, which demanded an equally constant rate of both. Only thus could the fasting and slowing of the pendulum, resulting from Earth *plus* Moon and Earth *minus* Moon, be revealed. The periodic gain and loss in indicated time was about 0.0002 second per lunar day. In 1935, and again in 1938, Marrison interested me in his trials of quartz clocks as

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chronometers on submarines for the U.S. Navy, and he showed me how the clock was being used in the Washington Observatory for the transmission of wireless time signals.]

Lt.-Col. Thompson. The chief difficulty in predicting time appears to be the determination of the coefficient c. Would it not be better to dispense with the term in t^2, since this is always bound to predominate after long time intervals?

Mr. H. M. Smith. Inclusion of a term depending on the square of the time is essential, since the rate of crystal clocks is, in general, not constant. In practice it is simplest to assume that the rate of change of rate is constant to a first approximation and to correct the coefficients from time to time when it is found that the values adopted are not sufficiently accurate, or have changed.

Lt.-Col. Thompson. The development of portable crystal clocks may prove of considerable value for survey purposes, as a means of bridging the gap between time signals. They have already been used with considerable success in connection with observations of gravity.

Capt. Booth. A portable crystal clock could certainly be produced, which would give an accuracy of a few parts in 10^8.

Mr. Browne. The portable frequency standards exhibited by the Department of Geodesy and Geophysics before this discussion are examples of this type of instrument. They have given excellent results during the submarine gravity survey carried out in H.M.S. *Tudor* during August 1946: their rates remained steady to within one or two parts in 10^7. The question of power supplies is, however, of importance and in considering the portability of such instruments, this must not be overlooked.

The question of the broadcasting of time signals and standard frequencies was then discussed.

Dr. Atkinson pointed out the advantages of the standard frequency transmissions of the United States Bureau of Standards and suggested that the carrier wave might be employed to drive a clock.

It was also mentioned that the B.B.C. broadcasting station at Droitwich operates on a frequency of 200 kc/s which is normally constant to within 1 part in 10^7. Four short-wave stations are also available, of which the frequencies are controlled to the same accuracy.

Capt. Booth stated that the effective signal-to-noise ratio of the interrupted WWV signal at a distance from the transmitter would be such that it would not be practicable to use the received carrier-wave signal to drive a local clock. However, it was practicable to intercompare very accurately the frequency of the radio frequency oscillation generated by the local quartz clock with that of the WWV transmission.

The Chairman then called for a vote of thanks to the speakers and also to those who had contributed to the exhibition of crystal oscillators.

The meeting adjourned at $18^h\ 40^m$.