ROYAL SOCIETY TERCENTENARY

DURING the last two weeks of this month, Great Britain will celebrate the three-hundredth anniversary of the founding of the Royal Society of London, the world's oldest continuously active scientific organization. The article by Dr. Essen which follows is one of a series written by leading British scientists for publication in the United Kingdom in commemoration of the event.

The Royal Society traces its beginnings to the informal meetings of a small group of seventeenth-century enthusiasts who gathered together frequently in the years following 1645 to discuss the "New Philosophy" dealing with the "improving of natural knowledge by experiments". In the latter part of 1660, a dozen individuals (including Lord Brouncker, Robert Boyle, Sir William Petty, John Wilkins, and Christopher Wren) drafted the framework for a more formal association, an action which gained the quick blessing of the reigning monarch, Charles II. Two years later the organization was incorporated under a royal charter as "The Royal Society of London for Improving Natural Knowledge".

From its earliest years, the Society has been active in the publication of scientific material, in serving in various advisory capacities to the government, and in maintaining scientific relations between Britain and the other nations of the world. *The Philosophical Transactions*, the oldest existing scientific journal, first appeared in 1665 as a periodical of sixteen quarto pages containing selections from contemporary correspondence between members of the Society and natural philosophers in various European countries.

The Royal Society played an instrumental part in the establishment of the National Physical Laboratory late in the nineteenth century, and it appoints most of the members of that Laboratory's governing body. Early in the eighteenth century it was made solely responsible for the work of the Royal Greenwich Observatory, a supervisory function which it now shares with Britain's Royal Astronomical Society. The Society's current responsibilities in international relations are evidenced by its advisory role in Britain's participation in the affairs of UNESCO, by its recent administration of the government grant in support of British scientific activities during the International Geophysical Year, and by its membership in several international scientific unions.

ACCURATE

By ***Louis Essen***

DOMESTIC clocks can be set right to within one second by means of the six "pips" broadcast by the British Broadcasting Corporation, and more accurate clocks used for scientific purposes can be set to about one-hundredth of a second by means of special time signals from the Royal Greenwich Observatory.

The very ease with which clocks can be set in this way may conceal the complex processes involved in establishing the accurate time scale on which the signals are based.

Any process which is repeated in a regular manner can be used to indicate the passage of time, but the regular movements of the bodies of the solar system are so inescapably obvious that they have been adopted for this purpose from the earliest times until the present day. In particular, the rotation of the Earth on its axis gives the solar day, which is divided by means of clocks into hours, minutes, and seconds.

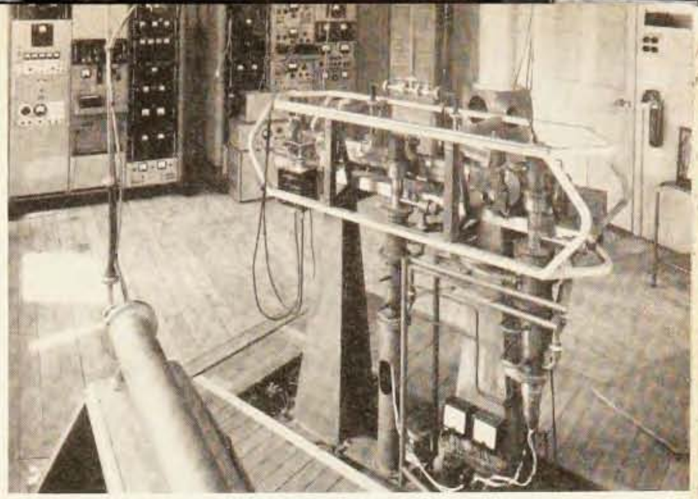
Although the solar day which governs our daily routine is such an obvious choice as the astronomical unit of time, it possesses two marked disadvantages: it is not of equal value throughout the year, and it cannot be measured very precisely.

Anyone who has seen a star moving across the field of a telescope will realize how much more precisely the passing of a star can be timed as it crosses a point vertically overhead; and in practice stellar observations are used to determine the sidereal day which is the time of rotation of the Earth relative to the fixed stars. This is then converted, from a knowledge of the length of the year, into the mean solar day.

A number of other corrections for known irregularities of the Earth's rotation are also made, and the clocks which supply the time signals are adjusted to keep in time with a hypothetical day based on current and past astronomical measurements and corrected to give a unit as nearly as possible uniform throughout the year.

It is important to notice that astronomical time serves two quite different purposes—it gives the time of day, which is required for civil and some scientific purposes, and also furnishes a scale of time on which the duration of events can be measured. It thus supplies the answers to the questions: "What time is it?" and "How long does it take?". Most scientific work is concerned with the second question, and modern developments, par-

MEASUREMENT OF TIME



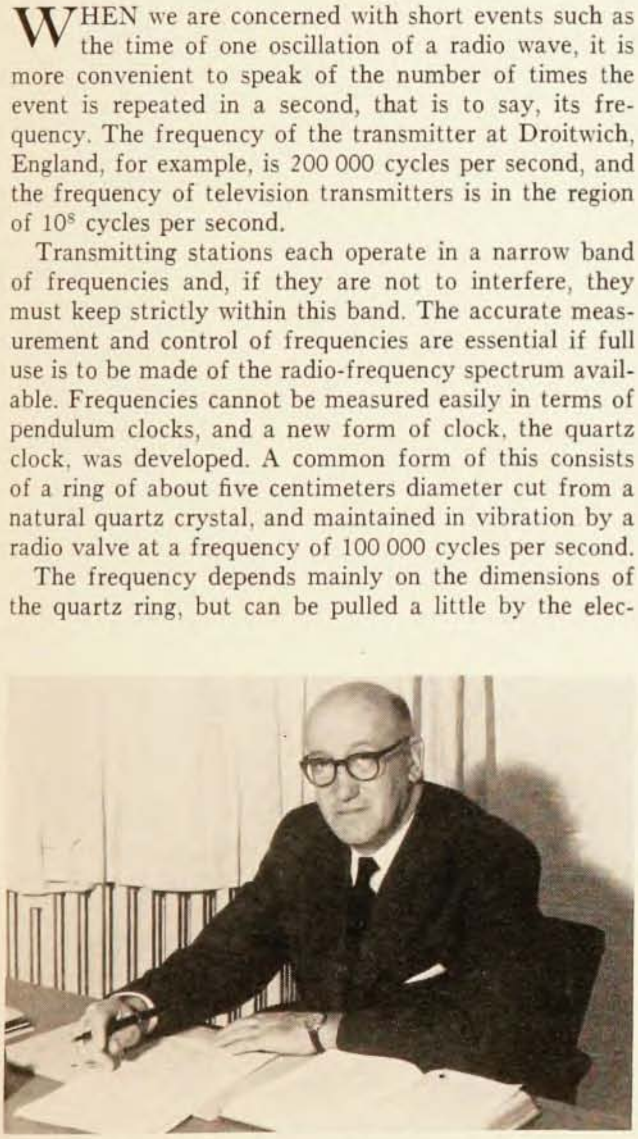
View of atomic clock at the National Physical Laboratory shows (center) cesium beam chamber, in use since 1955, and behind it the new and more accurate cesium standard housed in vertical tube. In left foreground is small self-contained cesium standard.

ticularly in the field of radio, often require a very exact measurement of extremely short events.

WHEN we are concerned with short events such as the time of one oscillation of a radio wave, it is more convenient to speak of the number of times the event is repeated in a second, that is to say, its frequency. The frequency of the transmitter at Droitwich, England, for example, is 200 000 cycles per second, and the frequency of television transmitters is in the region of 10^8 cycles per second.

Transmitting stations each operate in a narrow band of frequencies and, if they are not to interfere, they must keep strictly within this band. The accurate measurement and control of frequencies are essential if full use is to be made of the radio-frequency spectrum available. Frequencies cannot be measured easily in terms of pendulum clocks, and a new form of clock, the quartz clock, was developed. A common form of this consists of a ring of about five centimeters diameter cut from a natural quartz crystal, and maintained in vibration by a radio valve at a frequency of 100 000 cycles per second.

The frequency depends mainly on the dimensions of the quartz ring, but can be pulled a little by the electrical circuit so as to have exactly its nominal value. Radio valves can be used as a reduction gear to give an electrical impulse for every 100 000 vibrations, and these "seconds" impulses can operate an ordinary clock dial. The quartz clock thus gives a time scale which is subdivided into very small fractions of a second and yet can extend for a number of years. This time scale provided by quartz clocks and astronomical observations of the stars enables intervals of time to be measured with an accuracy of 1×10^{-8}.



Louis Essen, a senior scientist at Britain's National Physical Laboratory, Teddington, has worked for thirty years on the measurement of time. Dr. Essen built the first atomic clock using cesium atoms at the Laboratory.

The fine subdivisions of the quartz clock time scale can be displayed on the screen of a cathode-ray oscilloscope, and the duration of a single event can be measured by generating sharp electrical impulses at the beginning and end of the event and applying them to the scale on the oscilloscope. If, however, the event is repetitive, the frequency of repetition can be measured more simply and accurately by making fuller use of the properties of electronic circuits, which can be made to carry out the arithmetical processes of addition, subtraction, multiplication, and division of frequencies.

To take a very simple example, suppose the frequency to be measured is 99 999 c/sec. This frequency is subtracted from the 100 000 c/sec of the standard, leaving a frequency of 1 c/sec, which appears as a variation of the electrical current taken by the valve. This slow variation can be timed by very simple means with an accuracy of one percent. The over-all accuracy of the comparison is thus one hundredth of a cycle in 100 000 cycles, that is, 1×10^{-7}.

Elaborations of this simple technique enable any frequency to be measured in terms of a standard quartz clock with an accuracy of 1×10^{-10}. Such a fantastic accuracy is actually required in scientific work and also in technical applications. The accuracies required in these applications have thus advanced well beyond the accuracy with which the astronomical unit of time can be determined. This is not because astronomers have not made full use of technical improvements, but because of fundamental limitations placed by the solar system itself and of gaps in our knowledge of some of the complexities of its movements.

ALTHOUGH quartz clocks can be used with the required accuracy, it is no longer adequate to calibrate them by means of the rotation of the Earth. This difficulty has been overcome by using as a standard of time another event which is regularly repeated in nature. This is the radio wave generated by an atom when its electron arrangement is changed slightly from one stable condition to another. The frequency of the wave is defined by one of the most fundamentally important relationships in physics and is simply proportional to the difference in the energy of the atom in the two states.

It should be emphasized that we are concerned here only with small changes in the atom, and not with the disruption of the central core, with resulting radioactive radiation. The changes of energy are minute compared with the "atomic energy" liberated when the atom is disrupted. Within this range of minute energy changes the larger differences give rise to radiation at a high frequency which appears as visible light.

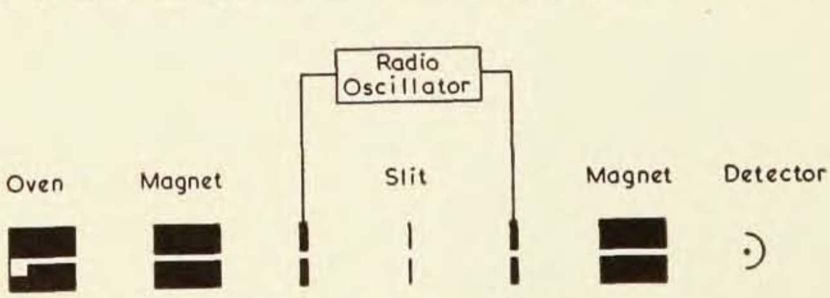
The sodium lamps used for street lighting represent a practical application of visible atomic radiation. There is no technique for comparing the frequency of this radiation with a quartz clock, and it cannot therefore be used as a standard of frequency or time. A smaller difference in energy gives rise to radiation at a lower frequency which falls in the range of radio waves, and this frequency can be measured by a quartz clock by means of the techniques described above. The actual frequency measurement is not difficult, but there are many practical difficulties arising from the weakness of the radiations and from the need to observe them without introducing disturbing effects which cause a slight shift of the natural atomic frequency. To overcome these difficulties, one of the most advanced experimental techniques is used; and of the many atoms or molecules which could be used theoretically the cesium atom has proved to be the most suitable.

Consider the structure of this atom. It consists of a heavy central nucleus surrounded by 55 electrons, 54 of which are arranged in stable groups with a single electron surrounding them. This outer electron and the nucleus itself are spinning, and the spins can be in either the same or in opposite directions. The transition from one condition to another is accompanied by the emission of a radio wave having, according to recent measurements, a frequency of 9 192 631 770 cycles per second. This happens to be in the range of frequencies used for radar during World War II, and corresponds to a wavelength of about three centimeters. It is a very convenient value from the point of view of electronic circuits.

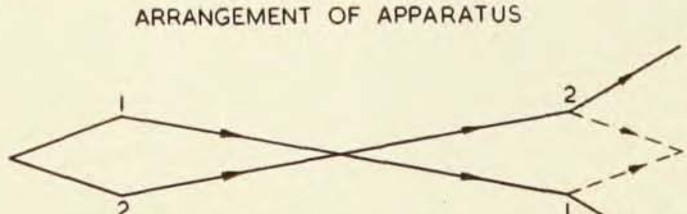
In order to understand how the atomic clock works, it is necessary to consider also the magnetic effects of the spinning electron. A spinning electric charge produces a magnetic field, and the atom therefore behaves as a small magnet the polarity of which is reversed when the spin is reversed. If, therefore, the atoms are passed through a nonuniform magnetic field they will be deflected in opposite directions according to which of the two states they are in.

Atoms in the two states can be separated by the arrangement of apparatus shown in Fig. 1, all the parts being enclosed in a very high vacuum. Atoms leaving the oven travel in straight lines until they are deflected by the magnets. Atoms in opposite states are deflected along paths such as 1 and 2 and are selected by the central slit. Those selected are deflected farther in the same direction, away from the detector.

In the part of the path between the two magnets an alternating field is now applied, and when this has the correct strength and frequency the atoms in the low-energy state absorb energy from the field and jump to the high-energy state. At the same time those in the



ARRANGEMENT OF APPARATUS



PATHS OF ATOMS IN THE BEAM WITH DEFLECTIONS GREATLY MAGNIFIED

Fig. 1.

high-energy state are induced to emit radiation at their natural frequency and jump to the low-energy state. Many of the atoms thus change their state and therefore the direction of their magnetization. They are then deflected in the opposite direction by the second magnet and reach the detector, where they are converted into an electrical current which can be measured by well-known techniques.

The important feature of the atomic standard is the extraordinary sharpness of this effect: it is only when the frequency of the radio oscillator corresponds almost exactly to that of the atoms that transitions from one state to the other occur. In practice, the frequency is varied slowly and set to give a maximum atomic beam current, and this setting can be made with an accuracy of 1×10^{-10}. The sharpness depends only on the length of time which the atoms spend in the field producing the transitions. In the present equipment, which is five feet (1.524 m) long, this is rather less than a thousandth of a second. A new clock which is being built at the National Physical Laboratory is 17 feet (5.182 m) long, and will give a still greater precision.

When the radio oscillator has been set to the atomic frequency it is used to calibrate the quartz clocks, or in sophisticated versions of the equipment it can be made to adjust the clocks automatically so that they keep in step with the atomic radiation.

THUS, instead of making the clocks keep in step with the Earth, which turns on its axis once in 86 400 seconds and revolves once round the sun in roughly 3×10^7 seconds, we now make them keep in step with the atom, which makes roughly 10^{10} vibrations in one second. This change enables the unit of time to be defined much more accurately and conveniently and also much more quickly, in a few minutes instead of a few years.

The problem of time measurement has thus been greatly simplified. When it took at least a year to set the quartz clocks in terms of astronomical time, it was necessary to keep these clocks operating under very stable uniform conditions for periods of years. Elaborate precautions had to be taken to insure this continuity of operation, safeguards being incorporated for such emergencies as the failure of the electrical supplies. It had to be assumed, moreover, that the clock continued to gain or lose by the amount indicated by earlier measurements; and as it is known that even the best quartz clocks are subject to erratic changes, it was customary to employ a number of clocks at each installation. The atomic clock enables the quartz clock to be calibrated or directly controlled in a few minutes, and there is no longer any need for continuity except over the time interval being measured. For most purposes this is relatively short, and it is only long in astronomical work such as the measurement of the time of rotation of the earth in terms of atomic time (Fig. 2).

The standard of time differs from those of length and mass in one important respect: it can, as explained at the beginning of this article, be made available over wide areas by means of radio time signals. In exactly the same way standard frequencies can be made available by controlling the frequency of the transmitter. Thus Droitwich, which has the convenient round number value of 200 kc/sec, is often used for this purpose, and in addition, for more accurate work, a special service of transmissions with the call sign MSF is sent from the Rugby, England, station by the Post Office on behalf of Britain's National Physical Laboratory. These operate on frequencies of 60 kc/sec, 2.5 Mc/sec, 5 Mc/sec, and 10 Mc/sec, and since 1955 they have been measured in terms of the cesium atomic standard.

In this way the great accuracy of this standard has been used for precise time measurements in many different countries. One use of the transmissions has been to compare the frequencies of the atomic standards in the United Kingdom with those in the United States of America, Canada, and Switzerland. The very close agreement between them, in spite of the fact that they have been made quite independently and have many differences in detail, gives strong justification for the use of the cesium resonance as a standard.

The thoughtful person will still ask how we know that the atomic frequency is constant. How do we know that it is the speed of the rotation of the Earth, and not the atomic frequency, which has changed slightly during the last few years? The answer is that there is at present no theoretical reason by which a change in the atomic frequency could be explained, and all experiments that have been made have failed to reveal any change.

On the other hand, there are a number of possible explanations for a small change in the period of rotation of the Earth. As with all standards of measurement, there is no means of knowing positively that the cesium frequency is constant. It is simply the most constant periodic effect of which we have experience, and if anything better is found then that will become the new standard.

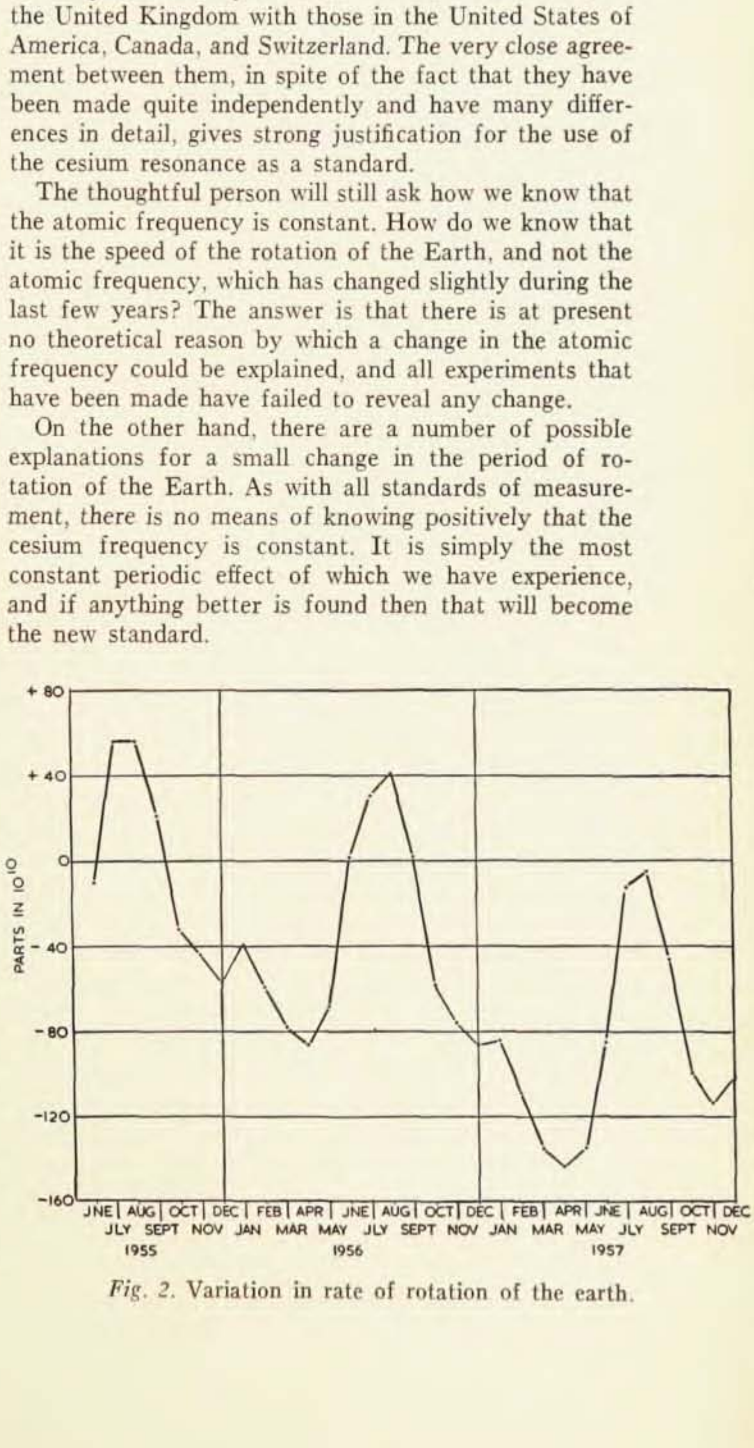


Fig. 2. Variation in rate of rotation of the earth.