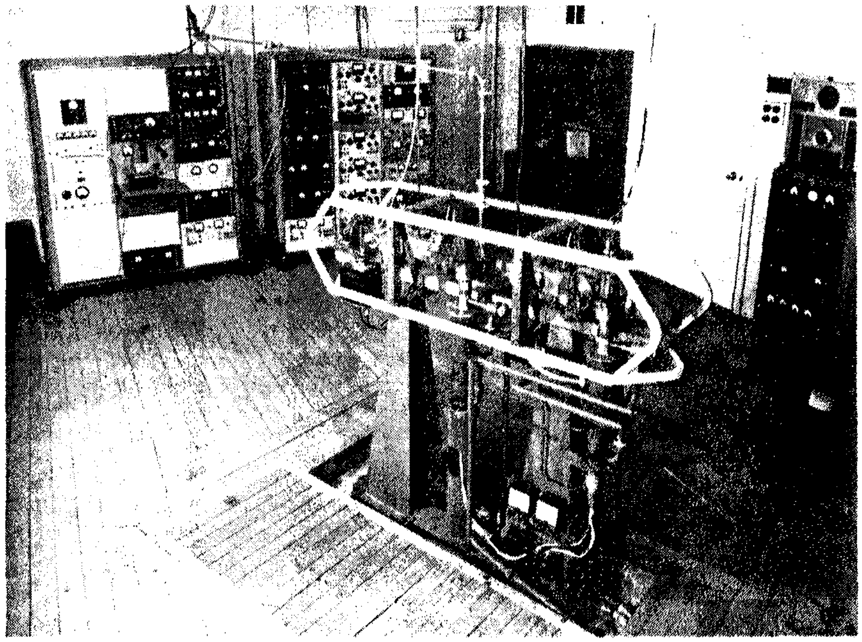
Leap seconds

Story of the transfer from astronomical to atomic time

by L. Essen, D.Sc., F.R.S.

Most people now know that all time measurements and time signals throughout the world are based on atomic clocks but the need to adjust them by one second at the end of the year is not well understood. It follows from the fact that the signals must not only give precise uniform intervals of time but must also give the time of day which is determined by the non-uniform rotation of the earth. The transfer from astronomical to atomic time and the co-ordination of the two systems was an important step in the advance of science and it is surprising that the full story has never been told. The requirements of radio engineers were always prominent in the discussions.



The original caesium resonator, designed at the NPL by the author and J. V. L. Parry, which led to the development of the atomic standard of time.

The time of day is not required very accurately for civil purposes – it is changed by an hour, twice a year – but for navigation at sea it should be fairly close to the time scale based on the position of the stars, known as UT1. Time intervals, on the other hand, are required to be as precise and uniform as possible, particularly for air navigation and the control of the frequencies of radio transmitters. For these applications the actual time or epoch of the signals is irrelevent.

These two requirements are so different that it might be asked why two separate sets of signals are not used, giving astronomical time for sea navigation and civil purposes and atomic time for everything else. This was indeed suggested by Dr G.M.Clemence of the US Naval Observatory who proposed that two units of time should be defined, adding, probably not very seriously, that the atomic unit should be called the Essen. The fundamental objection to this is that it would constitute a duplication of one of the basic units of measurement; and a practical objection is that the use of two time scales would undoubtedly lead to confusion, as our experience with standard frequency transmissions had shown. It was therefore worth while to make an effort to construct a single time scale, which would give the full accuracy of the atomic clock and the time of day as accurately as needed. This principle was accepted but it took 16 years to get international agreement on the details.

The first caesium atomic clock was put into operation at the National Physical Laboratory, Teddington, in June 1955; and it was immediately obvious to us that the necessary checks on its performance under different conditions could not be made in terms of astronomical time. A provisional atomic unit was defined and an atomic scale maintained by quartz clocks checked by the atomic clock, under standard conditions, as often as necessary.

It happened that the International Astronomical Union was meeting in Dublin that summer and through the courtesy of the Astronomer Royal, Sir H. Spencer Jones, I was able to attend this meeting to describe the clock and the initial results. One of the main topics of discussion at the meeting was a proposal to redefine the unit of time, making it in effect a fraction of the time of revolution of the earth round the sun instead of a fraction of the time of rotation on its axis. It was believed that this unit, the second of ephemeris time (ET) would be more constant than the second of universal time (UT1). It is difficult to measure it and the value being recommended was in effect the average value of the second of UT1 over a period of 200 years. Such a unit might be useful for astronomical work but it is not of the slightest use to the physicist and radio engineer. I suggested that it might be wise to delay a decision until agreement was obtained on the definition of an atomic unit which would certainly be required in the future.

However, the proposal to change to ET was adopted and was confirmed at the General Conference of Weights and Measures in 1956. It was a strange decision and it meant that from 1956 until 1967, when an atomic unit was defined, the definitive unit of time existed only on paper. The unit used in practice was the second of UT1; and at the NPL this was defined in terms of the provisional atomic unit, which was made available throughout the world by our standard frequency transmissions and their 1s timing pulses derived from the standard. These were used at the International Bureau de l'Heure to smooth out the irregularities of the astronomical signals.

Although the atomic clock had a lukewarm reception at the Dublin meeting an important resolution was passed with the advocacy of Dr W. Markowitz. It was agreed that when the relationship between the atomic frequency and the second of ET had been established the atomic clock

> The next leap second will be on 30th June 1981 in the last minute of the day. The minute before midnight will contain 61 seconds instead of 60 seconds.

would be used to make ET available. We planned together a programme of measurements to obtain this relationship: the time interval between certain agreed signals about a month apart was to be measured at the NPL in terms of the atomic clock and at the USNO in terms of ET. Markowitz had developed a method of obtaining ET more quickly than by direct observations of the sun; but even so the measurements were continued for three years before it was decided that further averaging was not likely to improve the accuracy of the result which was therefore announced. The result expressed as the frequency of the caesium atomic transition in terms of the second of ET was:

9192631770±20 cycles

The second of atomic time was therefore the time occupied by 9192631770 cycles of the caesium line, the limits of error being omitted since they were due almost entirely to the astronomical measurements. This value was used at the NPL in place of the provisional value, from 1958, in accordance with the Dublin resolution.

There was still strong opposition from astronomers to the formal adoption of the atomic unit. They regarded the atomic clock as a kind of superior quartz clock which could be used to smooth astronomical time, and ignored the fundamental difference between them. The quartz clock is simply a stable oscillator which can be adjusted to have any frequency by altering its dimensions, whereas the atomic clock has a frequency determined with great precision by natural constants. It is reproducible anywhere in the world and provides a unit of time which is immediately and readily available. It is ideally suited to be a definitive standard of measurement. It must be admitted, as was often pointed out, that unlike the earth, it does sometimes stop, but this is an academic point of no practical significance. When one clock stops it can be reset by reference to one that has not, with a precision enormously greater than any astronomical measurement. And even if they all stop they can be reset by reference to the stars so that one is no worse off.

It must be remembered too that the major observatories, including the Royal Greenwich Observatory, were founded with the specific object of providing the navy and merchant ships with time. Their responsibility was later extended to providing a uniform time scale for scientific purposes. The determination of astronomical time became a complex operation, the measurement made at many observatories being correlated at the Bureau de l'Heure which published the definitive corrections to time signals about 12 months in arrears. There was a considerable vested interest in retaining astronomical time as the definitive system. As several of those concerned jokingly said, there was no doubt that we must change to atomic time, but not before we retire, please.

Another question to be settled was the type of atomic clock to choose. In spite of the known performance of the caesium standard at the NPL and then at laboratories in Canada, the USA, and Switzerland, clocks based on the same spectral line of hydrogen and thallium were possible contenders. A lot of attention was also devoted to the study of a spectral line of ammonia; and although this was never a serious contender as a time standard it led to the development of the maser and the laser. The advantages of the caesium clock prevailed and in 1967 it was accepted for defining the unit of time, with the value given above.

The co-ordination of the 1s pulses carried on standard frequency transmissions with astronomical time signals presented some awkward problems. The first step was taken when they were made to coincide on 1st January 1958. It was realised that they would diverge because of the variations in the rate of rotation of the earth, and the question to be resolved was the amount of divergence that could be tolerated. The first figure suggested was 0.1s and to keep within this tolerance the actual frequency of the transmissions was offset from its nominal value by a stated amount each year, and in addition occasional step adjustments of 0.1s had to be made to the timing pulses. A further move towards co-ordination was made in 1960 when it was agreed with the RGO that all time signals transmitted from the UK would have the same epoch.

It was of course rather illogical to offset the constant unit in order to accommodate the variations of the astronomical unit and strong efforts were made to end this situation particularly through the International Scientific Radio Union. A satisfactory solution became possible when astronomers agreed that the signals could diverge by as much as 0.7s from astronomical time UT1. The frequency offset was eliminated, standard frequency transmissions operated on their true nominal values and the timing pulses on them gave true atomic time intervals. The divergence of the pulses from UT1 was compensated by a step adjustment of precisely 1s, when necessary on 30th June or 31st December. This enabled the pulses to continue undisturbed but the marker distinguishing the 1 minute pulse was moved along by 1s. The use of these leap seconds enables the time signals to be maintained within 0.7s of UT1, and for those who need it, the difference from UT1 is given more accurately by a code or Morse announcement. The only inconvenience caused to those measuring time interval is the need to check whether there have been any leap seconds if the interval extends through June or December. The astronomer no longer had to struggle to derive a uniform time scale from the complex and non-uniform periodicities of the solar system, but could measure these periodicities in terms of the atomic clock.

If I may finish on a personal note, I often think how lucky I was to work in a branch of science which was advancing rapidly, which exploited many different techniques and in which there was full international co-operation. The problem being tackled at the NPL when I joined in 1929 was the measurement of radio frequencies. The first solution was to measure them in terms of a tuning fork maintained in continuous oscillation. The accuracy achieved was 1 part in 10^7 which was considered by the Radio Research Board to be adequate for the foreseeable future, making further financial support unnecessary. The next advance was the quartz clock, which proved to be much more stable than the observatory pendulum clocks and gradually replaced them. They revealed an annual periodic change of 1 part in 10^8 in the rate of rotation of the earth. It was clear that any further improvement was prevented by the uncertainty in the value of the astronomical second. In 1945 I.I.Rabi, at Columbia University, suggested that the atomic beam magnetic technique might be adapted to form the basis of an atomic unit of time. The atomic clock has not only made the measurement of time and frequency far easier but has increased its accuracy by about one million times.

Louis Essen was born in 1908 and educated at High Pavement School in Nottingham and Nottingham University College, gaining a London external degree. Joining the NPL in 1929, he worked with D. W. Dye on tuning-fork and quartz oscillators and has continued to investigate frequency standards throughout his career. Working with A. C. Gordon-Smith from 1946 to 1950, he was able to establish, using a cavity resonator, a new value for the velocity of light, which is still accepted.

Taking up a proposal by I. I. Rabi in the United States, Dr Essen collaborated with J. V. L. Parry at the NPL to produce, in 1955, the first atomic caesium frequency standard: a later design now serves as the British national standard. Work in this field brought an involvement with relativity, which led to a belief that Einstein was wrong in one important respect and to a different interpretation of the Michelson-Morley experiment.

Dr Essen gained a Ph.D in 1941, a

D.Sc. in 1948 and was elected FRS in 1960. He was awarded the Popov Gold Medal of the USSR Academy of Sciences in 1959 and, in the same year, the OBE.