atomic clock

Years ago, the measurement of time was based on the period of the earth's daily rotation. When this proved non-uniform, astronomers adopted the period of revolution of the earth around the sun for the year 1900 as the basis for the measurement of time. This "Ephemeris Time" now forms the basis for many astronomical calculations and forecasts but is not readily available for day to day use.

Similarly, man-made devices for recording and keeping track of time have evolved through sun dials, hourglasses, water clocks, mechanical clocks, pendulum clocks and quartz crystal oscillators. Today, time measurements depend on the cesium atomic clock whose frequency has been measured carefully in terms of Ephemeris Time. Neither atomic nor Ephemeris Time vary with the seasons or the years.

The "atomic" clock is so named not because it is powered by atomic energy but because certain fundamental properties of the atom are used to provide a definition of time.

In a magnetic field, atoms of the element cesium 133 can adopt either of two energy levels corresponding to differences in total angular momentum. Additionally, each level contains a hyperfine structure of closely-spaced sub-levels. In practice, a transition or Rabi resonance can be excited from the lower to the upper level, between two particular hyperfine levels, at a frequency of 9 192 631 770 cycles per second (Hz) in the microwave region. The international (SI) second was thus defined in 1967 by the International Bureau of Weights and Measures as the duration of 9 912 631 770 periods of the radiation corresponding to this transition.

Early experiments on cesium beam standards were conducted in the mid-1950's at the National Bureau of Standards in Washington, D.C., and the National Physical Laboratory in Teddington, England. Activity at NRC began in 1957 with the construction of the cesium beam atomic standard Cs I. In 1963, an improved primary frequency standard, Cs III, was developed and served to calibrate first quartz crystal oscillators and later commercial cesium beam secondary clocks when atomic timekeeping activities started in the following year. NRC also monitored the rates of a group of atomic clocks maintained by the Dominion Observatory, which was then responsible for official time in Canada.

In 1970, the NRC group assumed the entire timekeeping function for the country and thus became responsible not only for research and development of atomic time and frequency standards but also for the generation and dissemination of official time. The staff and equipment from both the Observatory and NRC were combined to form a new section within the Physics Division.

A battery of commercial (secondary) atomic clocks, calibrated and regulated by Cs III, became the basis of the Canadian time scale. Frequent calibrations were necessary since these secondary clocks, with stability and accuracy much poorer than for a primary standard, all tended to run either fast or slow.

There is an important distinction between clocks and frequency standards. Clocks run continuously and generate a time scale indicating total elapsed time from an arbitrary zero. On the other hand, frequency standards such as Cs III are set in operation only at intervals in order to check the rate or frequency of continuously running clocks. In an analogous way, a wristwatch can be adjusted periodically to the time kept by a more accurate electronic timepiece.

To combine in one instrument the accuracy of a primary frequency standard with the capability of continuous operation in a clock generating its own time scale, plans were initiated at NRC in 1970 to construct an improved standard, Cs V.

Dr. Allan Mungall of the Time and Frequency Section was responsible for the overall design and was assisted by Mr. Herman Daams and Mr. Ralph Bailey (now retired).

Since its construction in 1973, Cs V has functioned experimentally as a frequency standard, but the change-over to continuous operation will make it the most accurate and stable clock in the world. By contrast, the primary cesium standards of the other countries are not intended for use as clocks but as frequency standards to measure the mean rate of an ensemble of commercial atomic clocks.

"I feel it is far more important to build a good, stable primary clock than to take an average of a large number of less stable secondary clocks," Dr. Mungall says. "Other countries use elaborate averaging procedures to arrive at a mean time scale but I've always felt that, physically, this is the wrong approach."

Although an ensemble of secondary clocks can provide a fairly stable rate for long periods, the component clocks tend to be of identical design and consequently all eventually drift in the same direction. Inevitably, small frequency shifts arise from aging of electronic components, changes in magnetic shields or a build-up of cesium metal in their cavities. As a result, frequent recalibration by a stable primary reference becomes necessary.

Dr. Mungall concludes: "We think our system will ultimately produce a better time scale, will require fewer people to run it and will cost much less to operate."

The 4 m (13 ft) long Cs V looks nothing like a conventional clock. For its accuracy it depends not on a pendulum or mainspring but on a highly uniform magnetic field in the cesium transition region.

A 5 g (0.2 oz) charge of metallic cesium is initially heated to 80°C (176°F) in a stainless steel oven situated at one end of Cs V. At this temperature, normally solid cesium melts to a dense silvery liquid with sufficient vapor pressure to produce a beam of free cesium atoms which is then shot between the poles of a state selector magnet. Here the atoms are separated into two beams corresponding to different energy levels.

Both beams then pass through a long evacuated space maintained at a uniform low magnetic field (the C field) in which the hyperfine atomic splitting is maintained.

Two different types of atomic transitions can then occur.

In one case, a low frequency transition can be excited in the cesium beam by a series of axially-oriented coils. By monitoring this transition, scientists can determine the magnitude and uniformity of the C field throughout the magnetically shielded region.

In the second case, which corresponds to actual clock operation, the cesium beam is subjected to a source of microwave power (called a Gunn diode oscillator) which excites the atomic transition. The closer the oscillator frequency is to the atomic resonance frequency the more atoms in the beam will undergo transition.

The beam then passes from the microwave and C field region through a second state selector magnet onto a platinum-iridium hot-wire detector. Here, the arriving cesium atoms are ionized, then collected as an electric current.

The amplitude of this current serves to indicate what proportion of the cesium atoms have been excited and, in turn, how close the microwave exciting frequency is to the precise cesium atomic transition frequency. (The microwave frequency is produced from a 5 MHz (5Mc/s) quartz crystal oscillator by a series of electronic multipliers and synthesizers).

Changes in the cesium ion current serve as an indication of error and a feedback signal acts to tune the frequency of the crystal oscillator. Thus the microwave and crystal oscillator frequencies are locked to the cesium atomic frequency which is the basis of the international (SI) second.

"In effect, we are interrogating the atoms to find if our frequency is correct or not," explains Dr. Mungall.

Once the correct frequency has been established and