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The Atomic Clock

A Universal Standard of Frequency and Time

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SINCE the beginning of time, man, in common with other creatures of the earth, has regulated his activities according to the rising and setting of the sun and the advent of the seasons. Thus, it was natural that the interval determined by the rotation of the earth on its axis, known as the solar day, should be used from the very start as the measure of time. Although other methods of counting time—such as the clepsydra or water clock, King Alfred's candles, the hour glass, and pendulum clocks—gradually developed, man has always depended, even to the present, on the rotation of the earth to provide an absolute primary standard with which other secondary time-keepers may be compared.

THE EARTH AND THE ATOM

It was to be expected that the earth, being an enormous, massive sphere spinning in the vacuum of free space, would run at a very constant rate, once it had been set spinning. This was found to be essentially true, but in relatively recent times it was discovered by astronomical measurements that the spin of the earth is not absolutely constant, but undergoes fluctuations on which is superimposed a gradual slowing down. The slowing down is attributed to the dissipation of energy occurring in tidal friction, and perhaps also in friction between the earth's crust and its molten inner core. The fluctuations have not been explained, but they are very large indeed, being of the order of magnitude of one part in 25 million.

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This is so great that a depression of the entire Himalayan mountain range to sea level would not change the moment of inertia of the earth enough to give rise to the observed change in rate of spin. Rather, a world-wide redistribution of the deep inner layers of the earth would be required. It is not hard to believe that such changes could occur, since the earth's crust, in cooling and contracting, must constantly readjust itself. This readjustment is shown by the occurrence of volcanoes and earthquakes; it is even conceivable that accurate measurements of fluctuations in the rate of rotation of the earth could be correlated with observations of very large earthquakes. The observed fluctuations mean that absolute time measurements based on the mean solar day cannot be made with a smaller degree of error than one part in 25 million, or 0.000004 per cent, and similarly all frequencies measured in terms of the mean solar day are likewise limited in absolute accuracy.

One can easily write down the specifications of an ideal new clock to replace the dependable but unsteady rotating earth. A clock which runs at a constant or invariant rate, is reproducible, and has a basic character, is desired. By basic, I mean that the time standard should be determined by the universal constants of nature. (The mean solar day is a completely arbitrary standard, like the meter bar, having no fundamental relation to the structure of the universe.) These specifications immediately rule out all clocks depending on macroscopic entities, such as pendulums and quartz-crystals, because such macroscopic aggregates are always sensitive to external conditions like pressure, temperature and other environmental factors. In addition, no two pendulums or quartz clocks can be made precisely alike, so that if a master or primary standard were destroyed, it would be impossible to reproduce it precisely.

Any periodic phenomenon could be used as a time standard, since the cyclic repetition defines a time unit equal to the period or time interval for one cycle. Similarly, the number of cycles per second is defined as the frequency. If one should not use macroscopic aggregates, the use of microscopic entities, such as atoms or molecules, is immediately suggested. And, in fact, it has long been known that atoms and molecules do have periodic vibrations, or spectrum lines, at sharply defined frequencies, which would make them suitable

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as time standards, since these vibrations are, like all atomic properties, invariant and reproducible. This realization goes back to the beginning of spectroscopy. However, it was not possible to utilize this idea until recently because, although the time from one cycle to the next represents a time standard, one cannot measure time intervals, or in other words make a clock, until it is possible to count up the number of cycles or units of time in the unknown time interval being measured. This situation is analogous to that of using the wave length of light as a length standard, as was first done about fifty years ago, when Michelson measured the meter bar in terms of the wave length of red cadmium light. Michelson counted up the number of times the wave length of cadmium light fitted into the meter bar, which he was able to do by means of an interferometer. Without the interferometer, he had only a length standard; with the interferometer, he had an atomic ruler. It was similarly necessary to be able to count up the vibrations of an atom or molecule in order to make an atomic clock. These vibrations were at such enormous rates (or, in other words, the frequencies of the spectrum lines were so high) that counting was not possible until the discovery of slower vibrations in the microwave range, and the development of microwave techniques. This can be understood since ordinary light waves have frequencies of about a million billion cycles per second—too fast to handle!

As a result of the need for searchlight-sharp radar beams during the war, the development of the microwave region of the radio spectrum received a tremendous impetus. This is the region which extends from approximately a few hundred megacycles up to the infrared, or in terms of wave lengths, from about a meter down to fractions of a millimeter—very tiny indeed compared to broadcast radio waves which are almost half a mile in length. The remarkable advances in technique led to applications of microwaves in many new directions, among the most important of which was the field of microwave spectroscopy, the study of spectrum lines in the microwave region. It had long been known that molecules have spectrum lines at radio frequencies. It was not until recently, however, that techniques were available to make extensive or accurate measurements, although it is true that the absorption of microwaves

by ammonia gas was observed by Cleeton and Williams at the University of Michigan as early as 1934. Spectrum lines result from electromagnetic radiation emitted or absorbed by atoms or molecules at sharply defined frequencies (or for light, colors). These frequencies are invariant and characteristic properties of the substances, as shown by the red light of neon signs, the green of mercury lamps and the yellow of sodium. Popularly speaking, the radiation is emitted or absorbed because of the oscillation or vibration of atoms or molecules.

Having an invariant time standard such as an atom or molecule does not mean that, when this time standard is used in a clock, the accuracy and reproducibility of the clock will be equal to that of the time standard. This situation can be explained by considering two clocks, both of which use pendulums as their time standards. The first clock, an ordinary grandfather's clock, keeps time of a fairly accurate sort. The swings of the pendulum are counted up by the gears and hands of the clock. However, a precision, observatory-type pendulum clock does not make the pendulum do the work of driving the counting mechanism. Rather, a master pendulum swings freely in a partial vacuum and controls a slave clock which does all the work of driving the counting mechanism. This enables the master pendulum to run at a very constant rate, giving accuracy far beyond that of the ordinary pendulum clock. Similarly, when the vibrations of atoms or molecules are used as time standards in an atomic clock, it is still necessary to search for the best clock-design methods in order that the over-all clock will be nearly as invariant and reproducible as the atomic vibration itself. This, however, is an ideal goal which can never be precisely obtained in practice. The counting mechanism inevitably reacts back on the system to affect over-all accuracy. In the case of atomic clocks, everything but the atoms or molecules used as time standards must be considered part of the counting mechanism.

THE FIRST NATIONAL BUREAU OF STANDARDS ATOMIC CLOCK

The strongest absorption or spectrum line which has so far been observed in the centimeter wave length range was also historically the first microwave spectrum to be discovered; it was used in the

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first atomic clock and is a line of the ammonia molecule which occurs at a frequency of 23,870,100,000 cycles per second. The ammonia molecule is shaped like a pyramid; three hydrogen atoms form the triangular base, while a nitrogen atom is at the apex. The spectrum line used in the clock results from the vibration of the nitrogen atom "up and down" through the base of the pyramid. This vibration is the "beat" of the clock. Although high, the vibration rate or frequency was still low enough to enable the counting of the oscillations, yet was high enough to achieve good accuracy—since theory shows that the higher frequencies allow greater accuracy to be obtained. This is partly because the relative sharpness of a spectrum line is greater at higher frequencies; in addition, its intensity is also greater.

Unfortunately, an atom or molecule does not vibrate, or—putting it more accurately—emit or absorb energy at one frequency only, but rather over a range of frequencies. The narrower the range, the more accurate the spectrum line will be as a time standard. The range or width of the spectrum covered by the spectrum line is determined by several factors. Among the most important of these are the violent collisions between the atoms or molecules which disturb the vibration, causing a broadening of the spectrum line. The thermal motion of the gas atoms also gives rise to what is called a Doppler broadening, similar to the change in pitch or frequency of sound heard as a vehicle emitting the sound is moving toward or away from the listener.

If a metal tube is filled with ammonia gas, and radio waves are sent through this tube, the signal will be absorbed when the frequency or vibration rate of the radio wave is exactly equal to the frequency of vibrations corresponding to the spectrum line. One may say the radio wave is tuned to the frequency of the ammonia which then absorbs it much as a broadcast receiver or radio set picks up the one station to the frequency of which it is tuned. Such a tube, filled with absorbing gas, is called an absorption cell. The intensity of absorption of the radio wave will be a maximum at the center frequency of the spectrum line, and weaker on either side, as already explained, because of the finite width of the line. This phenomenon can be made use of in making an atomic clock. If the

yclic or vibrating mechanism giving the beat of the clock is made to generate a radio wave, the absorption of this wave by the gas will be at a maximum when the vibration rate of the wave and the clock is at the right frequency, and weaker if it is off frequency; this is the basic mechanism involved in control, although details of execution may vary.

The National Bureau of Standards clock generates the radio wave which is to be absorbed by the ammonia-filled absorption cell by means of an ordinary quartz-crystal, the most accurate type of oscillator available, plus auxiliary circuits. The quartz-crystal is similar to those used in controlling the frequency of broadcast stations, and oscillates at 100,000 times per second. This frequency or rate of vibration is then divided or reduced by electronic frequency dividers, until it is low enough to furnish driving current for an ordinary electric, synchronous motor clock, similar to 60 cycle, power-line-driven household clocks. The frequency of the power line current controls the rate at which a household electric clock runs. The entire oscillator and divider assembly is called a quartz-crystal clock. Such a quartz clock, although very accurate indeed because of the stable chemical and physical properties of the quartz-crystal, constantly and slowly drifts in rate with age, making it necessary to calibrate it in terms of astronomical time units if it is to keep accurate solar time. However, for periods of several hours to a day, it will run with a constancy of one part in 10 billion or better. To make an atomic clock, it is then necessary only to prevent this slow drift of time-keeping by controlling the quartz clock with the spectrum line. This is done by increasing the 100,000 cycle rate of the signal from the quartz-crystal; that is, frequency-multiplying the signal by means of electronic-frequency multipliers (which may be considered analogous to mechanical speed-increasing gears) until the frequency of the resulting radio wave which is generated is equal to that of the vibration of the ammonia molecule, 23,870,100,000 cycles per second. The multiplied frequency is then compared automatically by electronic circuits to the spectrum line frequency, by sending the generated wave at this frequency through the absorption cell containing ammonia. If it is wrong—that is, if it is not tuned to the right frequency—the

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absorption of the wave will not be a maximum and the circuits will generate an error or control signal, which is applied back to the quartz clock, changing its rate to make it agree with the ammonia molecule. In this way the ammonia locks the quartz clock to the proper frequency. Another and colloquial way of describing this action is to say that, through the control circuits, the beat of the quartz oscillator is tuned to the beat of the nitrogen atom vibrating in the ammonia molecule, as shown by maximum absorption in the ammonia gas of the radio wave generated by the quartz oscillator and multiplier circuits. The synchronous motor or electric clock counts the oscillations of the system since, through the control circuits, it is effectively geared to the molecules by the trains of electronic gears.

This type of atomic clock allows simple and accurate electronic circuits because the stability of the quartz clock is so great that all that is required of the rest of the mechanism is to prevent a long-time drift. Such a regulated clock has been completed at the Bureau of Standards, and run for a period of four days with a constancy of approximately one part in 20 million. The accuracy is already approaching that of the rotating earth. In future models of this type of clock, it is hoped that a theoretically indicated accuracy of one part in 100 million or more will be reached. The Bureau is carrying on development work toward this end, which is to lead to a joint design for the use of the U. S. Naval Observatory, the present keepers of the nation's time.

ATOMIC OSCILLATORS AND ATOMIC BEAMS

It would be desirable to make an atomic clock in full analogy to present quartz-crystal clocks, that is, consisting of an atomic oscillator driving a synchronous motor clock through frequency dividers. Such a clock is under development at the Bureau. It consists of an atomic oscillator in which the spectrum line directly controls the frequency of the microwave oscillator, just as a quartz-crystal determines the frequency of a radio oscillator. No control or regulator circuits of the type used in the first clock are used. The oscillator is of the self-excited, feed-back type in which the output of a microwave amplifier tube is fed back to its own input, ampli-

fyng the signal regeneratively (that is, over and over) until the circuit oscillates; this is much like the howling or oscillation of a telephone circuit when the receiver is placed to the mouthpiece. If the signal can be fed back only at the frequency of the spectrum line, then the oscillator can oscillate only at this frequency. This is done by using an absorption cell to make a spectroscopic filter and placing it in the feed-back path. Since amplifier tubes are not available for operation in the 23,870,000,000 cycle range, spectrum lines at the lower frequencies at which amplifiers are available were needed in order to build a test model. These lower frequency lines were synthesized by slowing down the rate of vibration of ordinary ammonia through the substitution of heavy hydrogen, or deuterium, atoms in the molecule for ordinary hydrogen atoms. Since ammonia consists of three hydrogen atoms and one nitrogen atom, building the molecule with heavy hydrogen atoms resulted in lines which were found in the range from 3,000 to 10,000 megacycles.

The Bureau is also sponsoring development of an amplifier tube, now almost complete, operating at the frequency of ordinary ammonia, where smaller components and more convenient and accurate operation will be possible; considerable development work for this type of clock must still be carried out. Starting with such an atomic oscillator, it is necessary to slow down the rate of oscillation until the oscillation can be counted. If regulator or control circuits are to be avoided, this must be done by means of straight frequency division analogous to using speed reducing gears; no frequency multipliers as used in the first clock are allowable. Such a frequency divider capable of operating at the high rates encountered at microwave frequencies was also successfully built for the first time at the Bureau. It was found by direct measurement that this electronic frequency divider or speed reducer was accurate to at least one part in 10 billion, so that it will not contribute to any errors in the clock beyond those present in the atomic oscillator itself. The atomic oscillator could also be used for general frequency control applications, such as keeping a transmitter on the proper channel in a microwave communication system.

A third type of clock also under development at the Bureau, with the aid of Professor P. Kusch of the Atomic Beam Laboratory of Columbia University, is now in the early stages of construction. In

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this type of clock, one again begins with a quartz-crystal clock which is to be regulated by means of the spectrum line. However, in this case a beam of cesium atoms shot from an oven in a vacuum tank to a target detector is to be used, instead of a tube filled with an absorbing gas. By use of atomic-beam techniques, very much sharper spectrum lines can be obtained, because the broadening of the line due both to collisions and to Doppler effects is eliminated. This is achieved because an atom in the beam, making a collision with another atom, is deflected out of the beam. The target therefore only detects collision-free atoms, obviating collision broadening. In causing the transitions or exciting the vibrations in the atoms, the microwave signal which is to be regulated is applied at right angles to the motion of the beam, thereby eliminating the Doppler broadening. In this way, spectrum lines which are up to 300 times sharper than those obtained with the ammonia molecule will be obtained. After multiplication from the quartz-crystal oscillator, the microwave signal is compared to the spectrum line frequency in the cesium atom, and if it is wrong, a control signal is generated which is fed back to correct the quartz clock. Theory indicates that an accuracy involving a degree of error of one part in 10 billion or more may be possible, because of the extreme sharpness of the spectrum line. This is an accuracy of one second in three hundred years.

ATOMIC TIME

The development of atomic clocks is as yet in its early stages. If the full potential indicated by theory and present results is obtained, it is hoped that a new unit of time, based on a suitable spectrum line of one of the atoms or molecules, can be proposed. This would replace the mean solar day as the present legal, internationally adopted unit of time for all uses in physics, chemistry and engineering. It is doubtful that atomic time would be used for civil purposes, since man's activities will always be controlled by the rising and setting of the sun and by the seasons. Likewise, astronomers will want to know astronomical time in order to point their telescopes properly. Similarly some navigation methods require astronomical time. If atomic time were adopted and initially made equal to astronomical time, the time scales would eventually diverge because of the slow-

ing down of the earth. However, atomic time would be universally applicable throughout space; one is not very much interested in the rotation of the earth for keeping time when living on Mars, for example.

With precision types of atomic clocks, the rotation of the earth could be constantly measured in order to determine just how accurately it runs. At the present time, astronomers find it difficult to tell just when a fluctuation in the rate of rotation occurs; even the year of occurrence is doubtful. It is planned at the Bureau to measure the constancy of rotation without waiting for construction of the necessary clocks by comparing the frequency of rotation of the earth against a spectrum line directly. If it is observed that the spectrum line frequency, measured in terms of mean solar seconds, seems to change, this can be ascribed to a fluctuation in the rate of rotation, since the spectrum line frequency is invariant. It is hoped that the possibility of correlations between the fluctuations and earthquakes or other large-scale terrestrial phenomena can also be determined. It has been proposed by Professor V. P. Starr of M.I.T. and Professor W. H. Munk of the Scripps Institution of Oceanography that atmospheric and oceanographic currents can give rise to small fluctuations in the rate of rotation. Although these effects are very small, it may perhaps be possible some day to look for these also.

If atomic clocks of very much greater accuracy than those presently under development can be built, it will then be possible to make new macroscopic tests of the theory of relativity, since the concept of time is central to the theory, and indeed to investigate whether there is a difference between Newtonian time and atomic time, as some theoreticians predict. Such measurements would of course have consequences of the greatest importance.

It is interesting to note that the atomic clock development has resulted from the application of atomic physics to practical problems. It is another example of the growing importance of atomic physics to engineering developments of universal concern.