THE ATOMIC CLOCK

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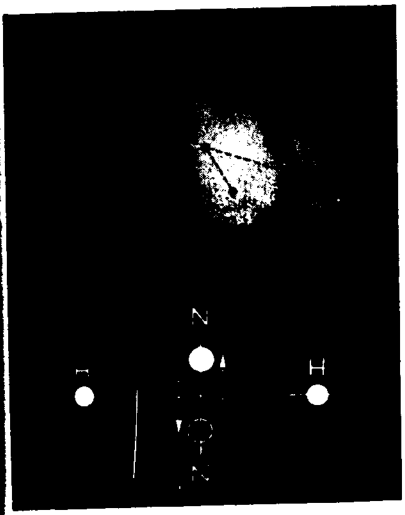
A BASICALLY NEW primary standard of frequency and time, invariant with age, has been developed at the National Bureau of Standards. The new standard takes the form of an atomic clock based on a constant natural frequency associated with the vibration of the atoms in the ammonia molecule. This, the first atomic clock ever built, promises to surpass by one or two orders of magnitude the accuracy of the present primary standard, the rotating earth. It is controlled by a constant frequency derived from a microwave absorption line of ammonia gas, providing a time constancy of one part in ten million. Theoretical considerations indicate a potential accuracy of one part in a billion or even ten billion, depending on the type of atomic system and spectrum line used.

The present crowding of the radiofrequency spectrum has imposed severe limitations, both nationally and internationally, on the expanding use of radio for industry and communications. The atomic clock may be expected to benefit greatly the communications industries and the military services, for it will, in effect, provide additional room in the radiofrequency range for more communication stations of all types. The present "radio space" allows for a drifting of each station's frequency, so that a broad "radio space" is required to avoid interference with other stations. Utilization of available "space" thus depends on the accuracy with which individual station frequencies can be controlled, especially at the higher frequencies used by radar, television relays, and microwave equipment in general. These frequencies, where quartz crystals cannot be used as frequency-controlling elements, could be controlled by atomic elements. Such control would also make possible the permanent establishment of radio channels on such an exact basis that tuning could be made as automatic as the dialing of a telephone number.



The quantum transition by which the ammonia molecule (top), absorbing energy at one sharply-defined frequency, can turn itself inside out is illustrated in classical terms by the schematic diagram (bottom). An absorption line produced by such a transition serves as the frequency control for the NBS Atomic Clock. The ammonia molecule is in the form of a pyramid with a nitrogen nucleus at the apex and three hydrogen nuclei at the base; each nucleus is surrounded by its characteristic electron charge. The average distance between the nitrogen nucleus and each hydrogen nucleus is 1.01 Angstroms; that between the hydrogen nuclei is 1.63 Angstroms. The pyramid is about 0.38 Angstroms high, and the H-N-H apex angle is 107 degrees.

The improvements in frequency and time measurement offered by the atomic clock are also of fundamental importance in many fields of science. An absolute time standard will be of special importance in astronomy, where present time standards leave much to be desired.

FRONT-COVER PHOTOGRAPH

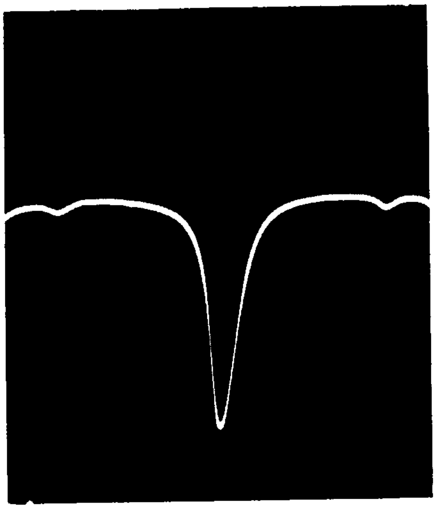
Dr. E. U. Condon (left), Director of the National Bureau of Standards and Dr. Harold Lyons, inventor of the NBS Atomic Clock, stand before the control panel of the clock. Dr. Condon is holding a model of the ammonia molecule whose microwave absorption line (shown on the oscilloscope screen at right) provides the invariant frequency which controls the timekeeping of the clock. The ammonia gas is maintained at low pressure in the 30-foot absorption cell wound around the synchronous clock (directly above the scientists).

The atomic clock and the new invariant method represent important tools of research and development in every technical field where precise measurements of time and frequency are crucial—for example, in long-range radio navigation systems, in the upper range of the microwave region where atomic systems can serve as electronic components, in microwave spectroscopy, and in research in molecular structure.

The present time and frequency standards are based on astronomical determinations of the period of rotation of the earth. However, the earth is being gradually slowed down by the forces of tidal friction in shallow seas. In addition, there are irregular variations—some of them rather sudden—in the period of rotation, the reasons for which are unknown. These two causes are responsible for changes in mean solar time and therefore in the frequency of any periodic or vibrating systems measured in terms of such time standards.

In recent years, vibrations of atoms in molecules—or, more specifically, spectrum lines originating in transitions between energy levels of these atomic systems—have been found in the microwave region of the radio spectrum. It has been possible to make extremely precise measurements of these lines by radio methods using equipment of unprecedented sensitivity and resolution. When it became evident that such spectrum lines might eventually provide new primary frequency standards, we scientists at the NBS began seeking a means of utilizing one of these lines to control an oscillator which in turn could be used to drive a clock. Because the resulting equipment, the atomic clock, is controlled by the invariable molecular system of ammonia gas, it is independent of astronomical determinations of time.

The NBS atomic clock consists essentially of a crystal oscillator, a frequency multiplier, a frequency discriminator, and a frequency divider, all housed in two vertical-type cabinet racks, on top of which are mounted a special 50-cycle clock and a waveguide absorption cell. Ammonia gas under a



While the NBS Atomic Clock is in operation, the monitoring oscilloscope continuously displays a trace of the 3,3 absorption line of ammonia. The symmetric output pulse is produced by absorption of the FM control signal as it sweeps across the natural absorption-line frequency of the ammonia gas. The sharpness of this line on the 'scope screen is an indication of the timekeeping accuracy of the atomic clock. A frequency scale may be inferred from the known frequency interval (1.74 Mc.) between the main 3,3 pulse and the first satellite pulse on either side. This shows that the 3,3 absorption line width at the half-power points is about 0.335 Mc.; dividing the center frequency (23,870 Mc.) by this value yields a Q of 71,200.

pressure of 10 or 15 microns is maintained in this cell, a rectangular 0.50 in. by 0.25 in. copper tube wound in a compact 30-ft. spiral about the clock.

The new instrument uses an absorption frequency of ammonia to hold a microwave signal fixed. If the microwave signal output of a generator differs in frequency from the ammonia absorption line, then the control circuits generate an error signal which brings the microwave signal back to the frequency of the spectrum line. The oscillator generating the microwave signal is thus controlled, and the setting of the clock which it drives can be compared with an astronomical clock.

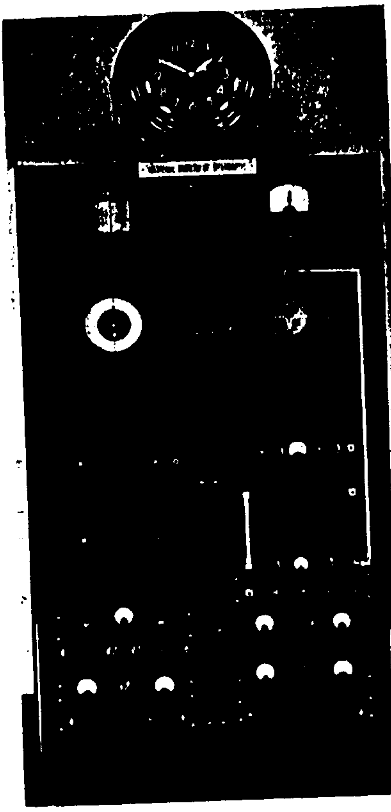
The microwave signal is initiated by a 100-kc. quartz-crystal oscillator or any other oscillator which, for purposes of convenience and accuracy, is designed for a high degree of stability. By means of vacuum-tube circuits and silicon-crystal diodes, this frequency is multiplied to provide output signals throughout the microwave range. These signals are compared with the frequency of a microwave spectrum line, in this case of ammonia gas, by suitable frequency-discriminator or servo control circuits. If the quartz-crystal oscillator drifts after the microwave signal at the upper end of the multiplier chain has been exactly tuned to the frequency of the spectrum line, the discriminator circuit generates an output signal which, through the proper control circuits, can be applied to the oscillator at the bottom of the multiplier chain to bring it back to the proper frequency. By means of a frequency divider, the 100 kc. may be reduced to any desired frequency for driving a clock; e.g. one thousand cyles or 50 cycles.

PRINCIPLES AND OPERATION

The control circuit in the present atomic clock is one successful form of several frequency-discriminator or servomechanism control circuits being developed by the NBS. It is now being refined to give even greater time-keeping accuracy.

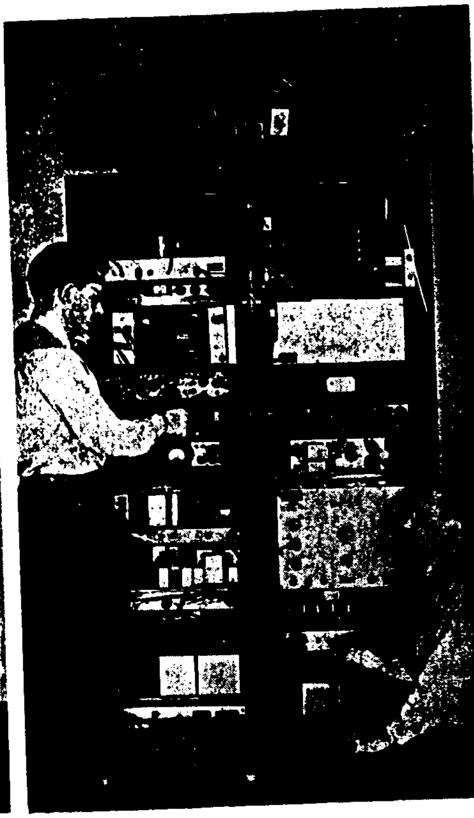
The fundamental frequency signal generated by the 10-kc. oscillator is first multiplied up to 270 Mc. by a frequency-multiplying chain using standard low-frequency tubes. In the next step, the multiplying chain is continued up to 2970 Mc. by means of a frequency-multiplying klystron, which is also modulated by an FM oscillator generating a signal at 13.8 plus-or-minus 0.12 Mc. This makes the frequency-modulated output of the klystron 2983.8 plus-or-minus 0.12 Mc. After further amplification, the frequency-modulated signal is multiplied in a silicon crystal rectifier to 23,870.4 plus-or-minus 0.96 Mc., and fed to the ammonia absorption cell. As the frequency of this modulated control signal sweeps across the absorption line frequency of the ammonia vapor, the signal reaching the silicon crystal detector at the end of the absorption cell dips because of the absorption, thus giving a negative output pulse.

A second pulse is generated when the output of the frequency-modulated oscillator at 13.8 Mc. is fed to a mixer (or radio receiver) into which is also fed a 12.5-Mc. signal from the quartz-crystal multiplying chain. When the signal sweeps across the proper frequency to be tuned in (12.5 Mc. plus the 1.39-Mc. intermediate frequency of the receiver, or 13.89 Mc), an output pulse is generated. The time interval between the two pulses—that from the absorption cell, caused by the absorption line, and that from the receiver or mixer—is a measure of the degree to which the frequency-multiplying chain is tuned to the absorption line. The two pulses can therefore be made to control a discriminator circuit which will give zero output when the time interval is right (that is, when the circuit is tuned to the absorption line) and will generate a control signal when the time interval is wrong. If the quartz-crystal oscillator drifts in frequency to higher values, the time interval between the two pulses increases; for frequencies which are too low, the interval decreases. The control signals thus generated are fed to a reactance tube, which then forces the quartz-crystal circuit to oscillate at the correct frequency to tune to the absorption line. The quartz-crystal oscillator is thus locked to the ammonia line.



(Left)

The NBS atomic clock is completely contained in this unit with the wave-guide absorption cell wound in a spiral around a 50-cycle synchronous clock on top of the cabinet. From top of the cabinet. From top to bottom, on left panels: frequency deviation recorder; 1000-cycle synchronous clock (24-hour dial); electronic frequency meter (drives deviation recorder); 100-kc. quartz-crystal oscillator; frequency dividers (divide 100 kc. down to 50 and 1000 cycles); regulated power supply for klystron tubes; regulated plate and filament power supply. On right panels: frequency comparator and deviation indicator; monitoring oscilloscope; pulse amplifiers and shapers, and pulse discriminator; d-c. control voltage indicator; sweep generator, FM modulator, and klystron frequency multiplier (270 Mc. to 2984 Mc.); frequency multiplier (100 kc. to 270 Mc.); vacuum gage; regulated plate and filament power supply.

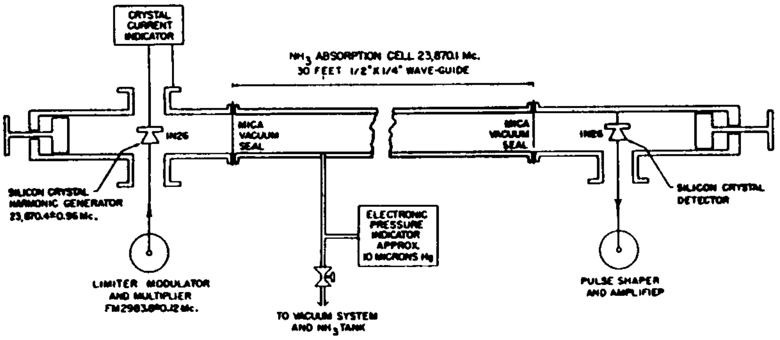


(Right)

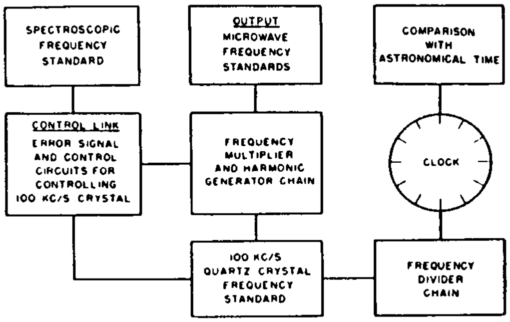
General view of back of the equipment. E. F. Huston (left) and E. D. Heberling (right) are shown making adjustments on the clock's amplifier and power supply circuits. The amount of equipment shown is larger than needed for the clock alone since some of the instruments are for measurements and tests of performance. Actually, the circuits essential to the operation of the atomic clock could be condensed into one of the two cabinet racks.

Frequency dividers then divide th precise 100-kc. signal down to 50 cycles to drive an ordinary synchronou motor clock, and also down to 100 cycles to drive a special synchronous-motor clock, which is designed for exac adjustment and comparison with astronomical time to within five milliseconds.

Control of the quartz-crystal circu depends on the relative duration of th positive and negative portions of square-wave signal generated by th discriminator. In the discriminator, th two pulses between which the time i terval is to be measured turn a trigg circuit or square-wave generator on a off. When the time interval is corre the on-off cycle generates no outp signal from the positive and negative peak detectors driven by the squarewave signal. The detectors or rectifiers draw current on the positive and negative peaks of the squarewave, but when the positive and negative portions of the square wave are of equal duration, they balance and give no d-c. output. However, if the time interval between the two input driving pulses gets longer or shorter, the relative durations of the positive and negative parts of the squarewave change, so that a resultant d-c. output is generated. This output is positive or negative, depending on the change in the time interval. Thus, no control voltage is generated when the quartz-crystal oscillator is on the proper frequency to agree, through the frequency-multiplying chain, with the ammonia line; but a positive or negative control voltage is produced for correcting the oscillator circuit when it drifts one way or the other from its proper value.



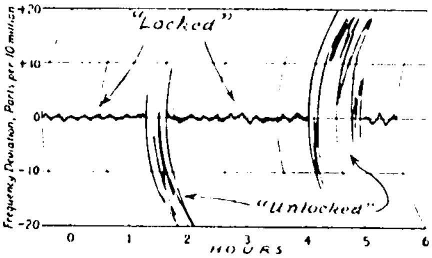
The wave-guide absorption cell used in the NBS Atomic Clock is a rectangular copper tube wound in a compact spiral and provided with mica windows to seal in the ammonia gas at reduced pressure. A 2983.8-Mc. signal is fed through a coaxial cable to a type-1N26 silicon-crystal rectifier inside the wave-guide. This crystal rectifies the input current and generates strong harmonics which radiate down the wave-guide. Tuning plungers are shown at the input and output of the cells for impedance matching so that all of the signal is used and none reflected. The present 30-foot cell gives a two-to-one total reduction in signal amplitude. After passing through the absorption cell, the signal is received by another type-1N26 silicon-crystal rectifier. This rectifier, acting like a receiving antenna, generates an output current which dips by reason of absorption as the input frequency sweeps across the absorption-line frequency.



Simplified block diagram. The fundamental driving signal originates in the 100-kc. oscillator. The frequency-multiplier and harmonic-generator chain then multiplies this signal up to microwave frequencies. Frequency-discriminator circuits in the control link then compare the frequency of these signals with the ammonia frequency standard. Any tendency of the oscillator to drift will cause of discriminator circuits to send an error signal back to the oscillator, maintaining it at the proper frequency. The crystal oscillator is thus locked to the invariant frequency of the ammonia line. A frequency divider chain then drives a synchronous-motor clock.

One great advantage of this particular clock circuit lies in the inherent short-time stability of the quartz-crystal oscillator, which makes it unnecessary for the discriminator circuits to apply correcting control signals to the oscillator at a rapid rate. The crystal and multiplier circuits bridge the gap between the frequency of the clock and that of the absorption line.

Recording equipment and a frequency meter are used in checking the accuracy of the clock. For this purpose, the frequency of the clock's crystal oscillator is compared to the frequency of the Bureau's primary frequency standards, a group of precision 100-kc. quartz-crystal oscillators calibrated in terms of the U. S. Naval Observatory time signals. These oscillators maintain constant frequency with respect to each other to an accuracy of one part in a billion for intervals up to ten hours, and better than one part in 100 million per day. They can therefore be used to measure the constancy of the atomic clock to this accuracy. This is done by beating the signals from the two sources together at a frequency of 12.5 Mc. to obtain greater measurement sensitivity. A change of one cycle per second in the frequency of the beat note, as recorded on the frequency meter or on an autographic recorder, indicates a frequency variation of one part in 12.5 million. In recent tests the clock maintained a constancy of one part in ten million for several hours. These tests show that the clock will lock accurately to the ammonia line even when a perturbng signal is applied to the reactance tube in a deliberate attempt to force the clock to change its rate.



Frequency-deviation record for a six-hour test run. Narrow portions, recorded while the clock was locked to the ammonia absorption line, indicate a constancy of one part in ten million.

ULTIMATE ACCURACY

The ultimate accuracy of an atomic clock depends on many factors, of which the most important are those governing the width of the spectrum line. Spectrum lines have a finite width because atoms or molecules do not emit or absorb radiation at only one frequency but rather over a narrow band of frequencies. The ratio of a line frequency to its width at the half-power points—its "sharpness"—is called the Q of the line, in analogy to the Q (quality) factor of resonant circuits used in standard radio technique. In the case of ammonia, the natural line width determined by the uncertainty principle of quantum mechanics gives a Q of about 10^{18}. If a line width were determined only by the natural time of an excited state in the ammonia molecule, given a Q of 10^{18}, frequency and time could be determined to better than one part in a billion billion. However, the line is broadened by other factors which lower the Q to a value of 50,000 to 500,000, depending on the temperature and pressure of the gas. The ammonia spectrum line thus has a Q approximating that of the best quartz crystals, though much more constant and stable.

The ammonia molecules in the absorption cell are moving rapidly in random thermal motion at an average speed of almost 2000 fp.s at room temperature. When a gas molecule in an absorption cell is approaching or receding from the source of an electromagnetic wave because of its heat motion, its absorption frequency is different from that which it would have if it were standing still. This gives rise to a Doppler broadening of the absorption line, analogous to the change in pitch of sound as its source approaches, passes, and leaves an observer. Thus, the line width can be reduced slightly by lowering the temperature of the gas (or by using a heavier molecule). Doppler broadening lowers the Q of the ammonia line to about 330,000 at room temperatures.

Molecular collisions also broaden the absorption line. This broadening occurs because the collisions abruptly terminate the absorption process, causing the molecules to absorb wave-trains whose lengths vary in a random way determined by the distribution of time intervals between collisions. A frequency analysis of these wave-trains shows a corresponding random distribution of absorbed frequencies, all centering about a mean value determined by the number of collisions per second. In ammonia gas at a pressure of 10 microns,

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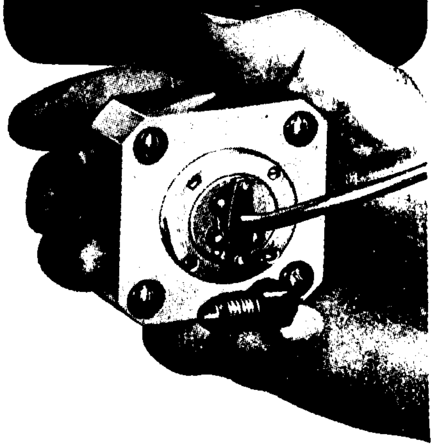

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there are about 120,000 collisions per second, giving an experimentally-measured Q of 45,000 for the absorption line used. (This is the 3,3 line, for which the quantum numbers J and K are each equal to 3).

Actually, there are more collisions effectively interrupting the absorption process in ammonia than the kinetic theory of gases would indicate. Further broadening of the line results from collisions of the molecules with the walls, and even near-misses between molecules cause interaction strong enough to interrupt absorption. The number of collisions per second, and thus the collision broadening, can be reduced by lowering the gas pressure. This process, if not carried too far, does not reduce absorption in the gas, because the decrease in number of molecules absorbing energy is offset by the increase in absorption per molecule resulting from the increase in Q. However, when the pressure is reduced too much a phenomenon known as saturation of the line sets in, caused by an excess of radiation. Too few molecules are then left in the proper energy states to absorb the microwave radiation coming into the cell. Many molecules, which normally would be in the proper energy state to absorb the incoming radiation, are in an excited state as a result of previous absorption. Eventually these molecules will emit the quanta which they have absorbed, returning to the normal level where absorption is again possible. However, as this process is slow, the molecule usually returns to the ground level in a collision with another molecule, converting the absorbed radiation into heat. As the gas pressure is lowered, the number of collisions is greatly reduced, and not enough molecules return to ground level. The excessive incoming radiation then weakens and broadens the absorption line through saturation.

Saturation can be eliminated by reducing the strength of the incoming radiation. However, as the gas pressure and radiation intensity are both lowered, a condition will finally be met for which the signal strength will be down in the natural electrical level of the circuits used to detect the signal. Circuit noise then sets the ultimate limitation on the reduction of collision and saturation broadening. It is estimated that a Q of 300,000 to 400,000 can be attained at pressures of about one micron—still a long way from the Q of the natural line width. Assuming that effective Q values of 400,000 can be obtained with ammonia, an accuracy of one part in 100 million or better should be possible since a measurement of the center of the absorption line to within 0.004 of the width of the line could be made.

The author wishes to express his appreciation to B. F. Husten, E. D. Heberling, and other members of his staff for assistance in the design and construction of the atomic clock.