atomic
stan

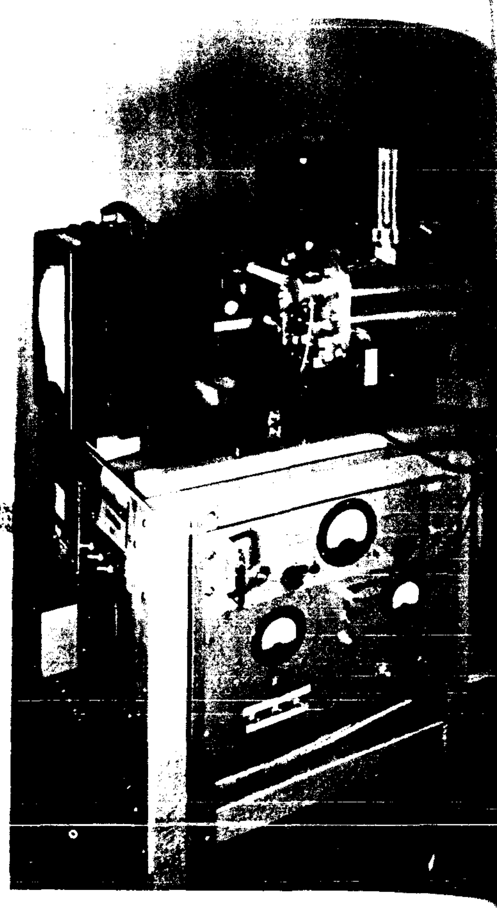
IN RECENT YEARS, the Bureau has been conducting developmental research on the precise measurement of frequency. For radio communications, the tracking of satellites, the control of long-range rockets, and astronomical observations, timing accuracies of one part in a billion or better will be required in the future. Many scientific activities rely on regular radio transmissions of standard frequencies from Bureau stations WWV, WWVB, and WWVH and from the Navy's NBA to provide high accuracies. These broadcasts are based on astronomical observations related to the earth's rotation as made by the U.S. Naval Observatory. However, to meet the ever-increasing need for even greater accuracy, the Bureau has been investigating atomic frequency standards, [1,2,3] which are potentially three orders of magnitude more precise for time-interval determinations than the rotation of the earth.

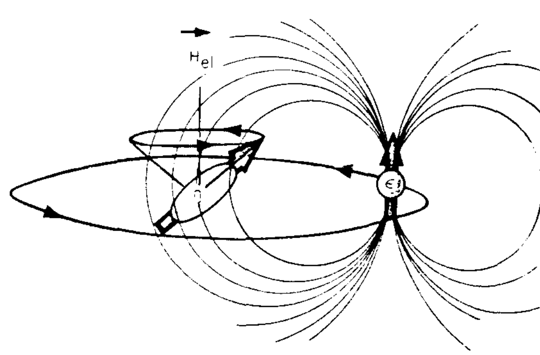
Over the past several months comparisons have been made between two dissimilar cesium-beam atomic frequency standards constructed at the NBS Boulder Laboratories. The devices were tested independently, the pertinent parameters measured, and frequency comparisons subsequently made. The results of the experiments, carried out by R. C. Mockler, R. E. Beehler, and C. S. Snider, demonstrate that beam devices of rather modest length (55 cm between the oscillating fields for the shorter machine) can have precisions of ± 2 parts in 10^{12} for measurement periods of one to a few hours. The frequency difference between these two machines is 1.0×10^{-11}. This frequency difference has remained within $\pm 2 \times 10^{-12}$ over the last 9 months. Greater accuracy, by at least an order of magnitude, should be attainable with some improvements in the apparatus.

At the present time, radio transmissions controlled by the Bureau's master quartz-oscillators are being monitored with the cesium beam frequency standards. Corrections for the 60-kc/s standard frequency broadcasts from NBS radio station WWVB (formerly KK2XEI) at Boulder, Colo., are being made each week and are available on request from the Broadcast Services Section at the Bureau's Boulder Laboratories. Corrections for the 20-kc/s transmission from NBS station WWVL will be available shortly.

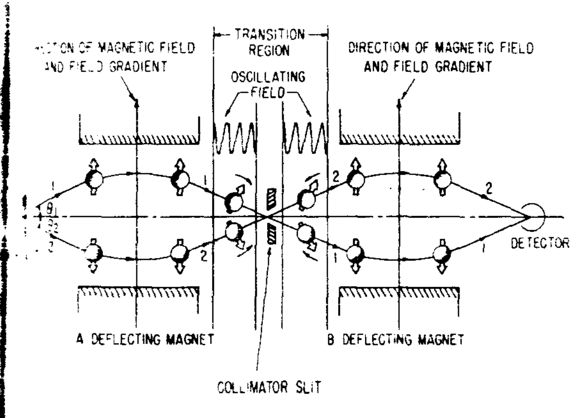
Until the development of atomic frequency standards, the most uniform time-intervals available were those derived from astronomical observations of the rotation of the earth relative to the fixed stars corrected to the orbital motion of the earth about the sun. This orbital motion of the earth is the basis of Ephemeris Time. It has been measured with a probable error of 2 parts in 10^9 in a period of 3 years. Higher precision is expected for longer measurement times. In 1956, the second of Ephemeris Time was adopted as the fundamental unit of time by the International Committee of Weights and Measures and this action was confirmed by the General Conference on Weights and Measures in 1960. Steps were taken by the Conference toward the adoption of an atomic standard for time-interval.

A time scale approximating Ephemeris Time can be made immediately available by the use of atomic stand-





quency
rds



ards, quartz oscillators, and counters. In terms of the Ephemeris second, the frequency of the cesium transition is experimentally found to be 9,192,631,770±20 c/s.[4] The probable error, ±20 c/s (or 2 parts in 10^9), results from the limitations on the precision of the astronomical measurements. The frequency of the transition is assumed to be exactly 9,192,631,770 c/s for the purpose of maintaining constancy of broadcast frequencies.

Measurement of a frequency or a time interval in terms of the cesium transition can be made with a precision of ±0.2 c/s and is not limited by the instrumental difficulties involved in astronomical observations. However, it does not supplant the present definition of a scale for time based on the uniform apparent motion of the sun.

It seems natural to base the standard of time-interval on the physical process or experimental technique that provides the most uniform and most accessible interval. The precision of measurement for the atomic standards is two orders of magnitude better over a 2-min period than astronomical measurements made over a period of 3 years.

Also under investigation as a standard of frequency is the thallium atom, which has certain significant advantages over the cesium atom in this application. However, thallium may have some disadvantages in practical use. A thallium beam is now being placed in operation at the Boulder Laboratories to determine which of the two atomic techniques is the more suitable.

The cesium beam frequency standard is essentially an atomic beam spectrometer excited by a crystal oscillator driving a frequency multiplier chain. The spectrometer puts out a signal only when the excited atoms go through a quantum transition. The exciting signal from the frequency multiplier chain is designed to have a frequency very nearly equal to this transition frequency. Therefore, if there is an output from the spectrometer when it is excited by this signal generator, the frequency of the generator must be the same as the transition frequency of the cesium atom.

In practice, the signal generator is manually or automatically varied over a narrow band to find the "center" frequency, and when the spectrometer output is at a peak, the signal generator frequency is known within ±0.2 c/s or two parts in 10^{11}. Suitable automatic equipment could be used to control the signal generator so that the spectrometer output would stay at the maximum, thus providing a signal of known and nearly constant frequency for as long as the device can be kept running. As the separations of the quantum states of an isolated atom are constant with time, they

Top: NBS-II Atomic Beam Frequency Standard. The separation between the oscillating fields inducing the atomic transition is 164 cm. The spectral line width is 90 to 140 cps. Below, left: Precessional motion of the cesium nucleus in the strong magnetic field produced by the valence electron. Below, right: Schematic of an atomic beam spectrometer. The trajectories are drawn for those atoms whose magnetic moments are "flipped" in the transition region.

can be expected to provide a stable, reproducible standard of frequency and time interval when the atomic beam resonance technique is used.

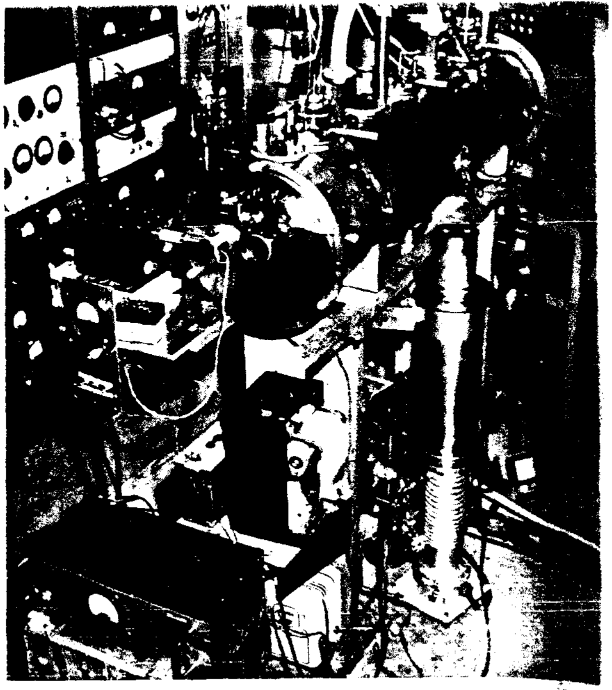
The atomic beam magnetic resonance technique introduces the smallest perturbation on the atomic system of the presently known techniques. This small perturbation is important because the presence of the measuring apparatus introduces an uncertainty in the measurement. Although the state separations are time invariant for an isolated atom, the atoms are no longer completely isolated when observations are being made.

The most precise measurements of quantum state separations can be made for those energy levels in the ground electronic state of atoms and molecules. For a standard of frequency, it is important to choose a quantum transition of high frequency, within the scope of existing coherent radiators, and of high intensity, for the sake of precision in measurement. Reducing line breadth due to collisions between the atoms and line broadening due to the Doppler effect is important. The transition in cesium between two hyperfine structure levels in the ground state satisfies these requirements.

This hyperfine splitting of the ground state is due to the interaction between the magnetic moment of the nucleus and the magnetic field produced by the valence electron at the position of the nucleus. The nuclear dipole moment may be pictured as precessing rapidly in the relatively large field supplied by the electron as shown (see drawing, preceeding page). One group of the hyperfine structure levels is associated with one direction of the electron dipole moment (or spin) and the other group of levels is associated with the opposite direction of spin orientation. If the atom makes a transition from the upper of the two levels to the lower, a quantum of energy is released. In the reverse process, a quantum of energy is absorbed.

An atomic beam spectrometer is shown in the photograph on the preceeding page. Neutral atoms effuse from the oven and pass through the non-uniform magnetic field of the deflecting magnet. As the atoms have a magnetic dipole moment, a transverse force will act upon them in this non-uniform field. The magnitude and direction of this force depend upon which of the states the particular atom is in. Of all the atoms effusing from the oven at angle θ_1 and speed v, suppose those in the upper group of hyperfine levels (electron spin up)* have their trajectories bent toward the axis and follow the path 1. All atoms in the lower group of states (spin down) effusing at angle $\theta_2 = -\theta_1$ and speed v will have their trajectories bent toward the axis also and follow a trajectory along path 2. Note that atoms with upward spins and those with downward spins experience forces in opposite directions. The upward-spin atoms traversing trajectory 1 and the downward-spin atoms traversing trajectory 2 will cross the axis at the collimator slit, pass through the slit, and enter the region of the B deflecting magnet.

As the B magnetic field is exactly like that of the A magnet, it exerts the same transverse force on the atoms as does the A magnet field. The upward-spin atoms will experience a downward force as before and the downward-spin atoms will be acted on by an upward force, as before. As the two sets of atoms are now on opposite sides of the center line of the machine, these forces will tend to make their trajectories more divergent from the center line. However, if a radiation field is applied at just the proper frequency ν_0 (where $h\nu_0$ is the energy separation of 2 of the quantum states) to induce transitions between 2 of the states in the region between the A and B magnets, the spins will be reversed for those 2 states, and a quantum of energy ($h\nu_0$) will be either emitted or absorbed. Since the sign of the magnetic moment has changed in moving from the A magnet to the B magnet, the force on these atoms will reverse its direction and the atoms will be refocused onto the axis at the detector. Thus, as the exciting radiation is swept in frequency, the detected signal will increase and reach a maximum at ν_0 and then decrease as the radiation frequency is varied beyond ν_0.



NBS-I Atomic Beam Frequency Standard. The separation between the oscillating field inducing the atomic transitions is 55 cm. The spectral line width is 250 to 300 cps.

[1] The cesium resonator as a standard of frequency and time, *by L. Essen and J. V. L. Parry, Phil. Trans. Roy. Soc., London,* **A250**, *45 (1957).*

[2] Comparison and evaluation of cesium atomic beam frequency standards, *by J. Holloway, W. Mainberger, F. H. Reder, G. M. R. Winkler, L. Essen, and J. V. L. Parry, Proc. IRE* **47**, *1732 (1959).*

[3] A comparison of atomic beam frequency standards, *by R. E. Beehler, R. C. Mockler, and C. S. Snider, Nature* **187**, *681 (August 20, 1960).*

[4] Frequency of cesium in terms of Ephemeris Time, *by W. Markowitz, R. G. Hall, L. Essen, and J. V. L. Parry, Phys. Rev. Letters* **1**, *106 (1958).*

*It is assumed that the deflecting fields are strong fields for the purpose of qualitative discussion.