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Technological Workhorses: Metrology's Atomic Standards

It is essential to our technology-oriented nation to have a complete and consistent system of physical measurements. The system is important not only for domestic industry and commerce but also for our trade with other nations. Our system is based on atomic standards of length, time, and temperature and on the prototype standard (nonatomic) of mass.

The standards that are the basis of our measurements have been improved enormously in recent years. Today, our practical measurements involving distance, frequency, and time are linked to standards that have been created by atomic physics. These atomic standards allow far greater precision and accuracy than the prototype standards of the past. They also allow this precision and accuracy to be attained with far less effort and cost than were characteristic of the earlier, far less precise standardization methods. The commercial production of these atomic standards has made them widely available to the technological community, thus greatly enhancing their usefulness. This chapter describes the resulting economic impact of atomic standards.

Of the four basic standards, only the standard of mass is still a prototype standard—a particular "hunk" of bulk metal. Hopefully, an atomic standard of mass eventually will be used. The advent of an

accurate atomic standard for mass would eliminate the fear that the size of the standard might be altered by an accident. Concerning the U.S. prototype kilogram, Allen V. Astin[10] of the National Bureau of Standards (NBS) wrote:

> The U.S. copy of the international standard of mass, known as Prototype Kilogram No. 20, is housed in a vault at the Gaithersburg laboratory of the National Bureau of Standards. It is removed no oftener than once a year for checking the values of lesser standards. Since 1889, Prototype No. 20 has been taken to France twice for comparison with the master kilogram. The national standard is never touched by hands. When it is removed from the vault, two people are always present, one to carry the kilogram in a pair of forceps, the second to catch the first if he should fall.

Although we face problems in the use of atomic standards, we do not have to worry about damaging or losing atoms. As far as we know, they do not rust, bend, shrink, or age.

The Metric Convention in Paris in 1875 was the beginning of our international agreements for standardized units of measurement. In 1960, the meter bar that was used for length standardization was finally replaced by the krypton-86 atomic wavelength standard (the meter, if defined as 1650 763.73 wavelengths of its orange-red line). Atomic wavelength measurements of fairly high precision were made before 1900, but the widespread use of atomic length standards has just begun. The methane-saturated, absorption-frequency standard of R. L. Barger and J. L. Hall (1968)[11] is a further step in the direction of highly accurate length standards. We can expect that, in turn, it will be surpassed by other even more accurate atomic standards. Probably by 1975, 100 years after the Treaty of the Meter, our best standards of length will routinely and reliably afford an accuracy one million times greater than that of the famous prototype meter bar (on those rare occasions when lesser standards are checked against it).

Hardly 15 years ago, accurate timekeeping required a combination of careful astronomical observations and fastidious maintenance of a bank of oscillators (typically quartz) over long periods of time. Today, with the hundreds of commercially produced cesium atomic beam frequency standards as well as the more elaborate but one-of-a-kind

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[10] A. V. Astin, "Standards of Measurement," *Scientific American*, *218* (6), 50–62 (1968).

[11] R. L. Barger and J. L. Hall, "Pressure Shift and Broadening of Methane Line at 3.39 μ Studied by Laser-Saturated Molecular Absorption," *Phys. Rev. Lett.* *22* (1), 4–8 (1969).

laboratory cesium standards, timekeeping is easier, more accurate, and more precise by at least a factor of 10,000. The economy and performance of these atomic resonance devices continue to improve, and, as this occurs, the number of customers for these devices increases.

A scale for assigning dates is called a time scale. A scale of International Atomic Time probably will be implemented in January 1972, less than five years after the international definition of the unit of time, the second, was changed from astronomical to atomic (the second is defined as the duration of 9192 631 770 cycles of the radiation resonant, with a specified hyperfine transition of the cesium-133 atom). Most of the world's time and frequency broadcast stations will then either broadcast a stepped version (with occasional leap-seconds) of the International Atomic Time or will indicate the relevant corrections to their time as broadcast. The commonly used time scale (UTC, Universal Time Coordinated) that it will replace has been tightly tied to the errant earth. The new internationally accepted scale, with its uniform atomic rate, will allow a greater simplicity of routine operation in thousands of factories, ships, and laboratories that must do timekeeping.

Looking ahead, we see that one primary atomic standard (the choice of atom or molecule is not yet clear) soon may serve simultaneously as the most accurate standard for frequency, time, and length. And eventually the development of atomic physics may enable us to refer mass measurements also to the single, unified atomic standard—The Standard, as it would be called.

Better standards allow better measurements. But, are better measurements worthwhile? Let us consider some generalities about poor measurements.

All systems must be overdesigned (often at appreciable expense) to compensate for inadequate accuracy and precision of measurements. Not only is the expense greater, but the design time will tend to be longer, since one has to estimate the degree of overdesigning that will be adequate. W. A. Wildhack[12] of the NBS has said:

> . . . [I] naccurate measurement . . . can negate the values of extensive research . . . can spell failure for costly missiles or satellites . . . can lead to over-design, overweight, and over-cost. Always, the result is waste. . . .

The use of atomic frequency standards, though already large, is accelerating. Due in part to the unrivaled accuracy and precision of

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[12] W. A. Wildhack, "Averting the Measurement Pinch," *Instrum. Soc. Am. J.*, 9 (5), 31 (1962).

frequency–time measurements that atomic frequency standards allow, there is currently a tendency to use frequency–time techniques to solve complex measurement problems. In many cases the complex problem does not involve frequency–time, but some of the proposed solutions rely on frequency–time metrology for their success.

Already more than 500 cesium-beam frequency standards have been produced in the United States, where currently three companies are marketing them. Their price is about $15,000 each. In addition, more than 1000 rubidium gas cell frequency standards have been sold; these currently are made by three companies in the United States. A complete rubidium standard sells for about $7500.

A. BROADCASTING

More than 50 atomic clocks are in use by television stations in the United States. Among other benefits, this precise control of the carrier frequencies and video timing reduces channel interference and allows accurate synchronization of frames from separated locations (no picture "roll" when switching the point of origin; also, "split-screen" operation is possible).

B. COMMUNICATIONS

Atomic standards, with their accuracy and stability, allow improvements in high-bit-rate data communications, ultranarrow-band communications, secure communications, coding techniques (for example, bipolar phase modulation), and spectrum conservation. The coherent optical radiation created by lasers, with its high carrier frequency and associated (potential) large modulation bandwidth, may give us a system having a capacity of greater than 10^{12} bits per second. To be economically justified, such a system would have to have a capacity of greater than 6×10^{10} bits per second (estimated).

A classified military system, ICNI (Integrated Communications, Navigation, Identification), with an estimated cost of greater than $1 billion, is planned. It would rely on state-of-the-art time and frequency metrology.

C. POWER DISTRIBUTION

Large parts of the U.S. electrical power system rely on standard frequency and time signals broadcast from the 60-kHz NBS station, WWVB (controlled by atomic standards), for assistance in controlling power flow among various sections of the country.

D. LASERS

Reliable and inexpensive laser systems are produced and sold for routine length metrology (for example, one commercial unit has a usable resolution of 1 μin. together with an accuracy of better than one part in a million, for distances up to 200 ft).

At least one company is producing He–Ne lasers to sell for $48 each in lots of one thousand. Part of the mass market for this He–Ne laser is expected to be home video cartridge players.

E. NAVIGATION

The United States spends hundreds of millions of dollars on navigation each year, and the rate of expenditure is increasing. Navigation satellites probably will be an important navigation aid within the next ten years. Atomic standards will assist in the dating and synchronization of present and future navigation systems.

The two large-scale radio navigation systems, Omega and Loran C, probably will serve also as worldwide atomic time dissemination systems for a large number of users. The cost of these navigation systems will exceed $1 billion. The Omega system has only recently been approved for full worldwide implementation (eight stations) by 1972 at an estimated cost of $100 million. Equipment manufacturers believe sales of Omega user equipment will reach $4 billion once the complete system is fully operational. In addition to being a potential supplier of precise time, the entire Omega system depends heavily on the availability of state-of-the-art timing at each transmitter. All stations will be controlled by a group of atomic standards.

Similar comments apply to the Loran C navigation system. For Loran C, many more stations are involved at a cost estimated to total $250 million (ten chains). User costs will range from $100,000 downward to a few thousand dollars per receiver, depending on whether navigation or timing information is desired from the system and the degree of automation needed.

A classified military system, NAVSAT (Navigation Satellite), with an estimated cost of $2 billion, is planned. It would use state-of-the-art time-and-frequency technology.

The Air Transport Association has proposed and tested (but not yet adopted) an Aircraft Collision Avoidance System (ACAS), which also is based on advanced timing equipment and techniques. This ACAS represents a very large potential economic impact. There would be perhaps 50 precisely controlled master ground stations, and each aircraft—possibly eventually on a worldwide basis—would have on it a precise atomic clock as part of its complex timing equipment.

Aircraft congestion is creating an urgent need for improved methods of collision avoidance. The commercially available atomic frequency standards barely achieved sufficient accuracy and stability to allow the Air Transport Association to consider seriously a time–frequency type of ACAS. If the atomic standard state of the art had not reached that critical level, a time–frequency ACAS would not have been regarded as feasible. The unit cost of the atomic standard still presents a problem in this ACAS application, but future increased mass production may solve it.

F. SPACE

The National Aeronautics and Space Administration's (NASA) immense satellite tracking networks depend heavily on precise timekeeping (atomic) at all ground stations for a great variety of space missions, including the Apollo landings on the moon. About 1200 WWVB receivers are installed at NASA tracking stations, but timing at these types of sites is so critical for both NASA and the Department of Defense that they also must use a combination of millions of dollars worth of satellites for this timing information plus expensive periodic portable clock trips to achieve and maintain adequate timing at more than 100 sites around the world. The Air Force alone spends more than $1 million each year on portable clock operations. The clocks themselves, portable and otherwise, represent a capital investment of about $1 million.

G. ASTRONOMY

Atomic standards allow highly precise and revealing astronomical measurements. As the late French astronomer, A. Danjon, suggested, atomic clocks create a vicious circle: Heretofore the motions of the stars could not be studied except by time that was itself defined by motions of the stars.[13]

Atomic devices are used in several methods of measuring the fluc-

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[13] This statement is credited to Danjon by John M. Richardson. See J. M. Richardson and J. F. Brockman, "Atomic Standards of Frequency and Time," *The Phys. Teacher*, *4* (6), 247–256 (1966).

tuations in the rate of rotation of the earth. These fluctuations are still a mystery, but they might have a close connection to environmental factors such as earthquakes, shape of the earth, tides, sea level, slow movement of land masses, air circulation, heat balance of the earth and its atmosphere, and magnetic fields. One of the methods, the on-going Lunar Ranging Experiment, uses a burst of intense laser light as the measurement probe. The absolute accuracy obtained with this ranging system depends on the clocks used in the timing system. Four clocks are continuously compared against each other. These are the quartz crystal oscillator and an atomic clock on site in Texas, a tie-in to the low-frequency WWVB signal (controlled by atomic clocks), and the Loran C navigational timing signal (also controlled by atomic clocks).