New possibilities in time-frequencey standards

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By invitation of Edoardo Proverbio, the President of Commission 31 (Time), this report attempts to summarize "new possibilities in time-frequency standards". Especially because recent work in this highly specialized field is so diverse and so complex, I appreciate the support of our colleague, Dr. G. Busca, who will survey the extensive progress being made east of the Atlantic. I confine this paper to work that has appeared in the open literature from the United States and Canada.

(I) INTRODUCTION:

Since much of this work is proprietary, and since it is difficult to assign credit fairly, I will not attempt to give either a comprehensive or selected bibliography of references in this paper. There are three primary symposia where such work is published: (1) the annual IEEE International Frequency Control Symposia; (2) the more recently organized annual European Frequency and Time Forums; and (3) the (United States) Annual Precise Time and Time Interval (PTTI) Applications and Planning Meetings, organized jointly by the Department of Defense and NASA. The best general review of recent work on frequency standards, which appeared just before our last IAU General Assembly and is not yet outdated, is the special issue of the Proceedings of the IEEE, volume 79, no 7 (July 1991), and especially the papers "An Introduction to Frequency Standards" by Lindon L. Lewis, "Atomic Ion Frequency Standards" by Wayne M. Itano, and "Laser- Cooled Neutral Atom Frequency Standards" by Steven L. Rolston and William D. Phillips.

What constitutes progress? From a technical point of view, the three primary properties of frequency standards that were itemized by Norman Ramsey are the most important: accuracy, stability, and reproducibility. Accuracy is the measure of how well a frequency standard reproduces (or can be used to reproduce) the SI second. Stability is how nearly constant the frequency output remains over time. Reproducibility is a measure of our confidence that properly built clocks of the same design will give the same results. Notice that accuracy and stability are scientific standards, and their definition belongs to the realm of applied mathematics; but reproducibility is an engineering standard, involving design, prototyping, and manufacture.

To these three technical criteria, one may add four engineering criteria which apply to any hardware system or subsystem: (i) economy; (ii) standardization; (iii) maintainability; and (iv) reliability. These four engineering criteria extend the concept of reproducibility; and the degree to which they are satisfied determines whether a theoretical design is likely to be implemented at all, and if implemented, whether in one experimental laboratory or many, or even outside the laboratory among a wide field of users. When we try to foresee the future of the development of frequency standards, we must not only consider the feasibility of a technique from the standpoint of the experimentalist, but the practicality of securing financial support and a wide circle of user interest, from the standpoint of the laboratory director. For example, the pace of development of hydrogen maser frequency standards has been dominated by the vagaries of the government and commercial marketplace far more than by the technical concerns of accuracy and stability, and that market is driven by the four engineering concerns just listed, and by competition between techniques.

These engineering criteria for time- frequency standards are broadly the same as for any advanced type of equipment, and the concerns of the laboratory director are much the same as those of a commercial user. Economy means that the design should minimize the total costs of development, use, and maintenance, as estimated over the total lifetime of the equipment. The use of Commercial Off The Shelf (COTS) hardware and software can be helpful in meeting the goals of economy and reliability, but there are many pitfalls -- for example, the risk of a vendor on which one depends withdrawing his product or going out of business altogether. The cost of use is the total expense of the training of personnel, of normal operations, of extraordinary operations entailed by equipment failure or other emergencies, and the analysis of anomalies. Logically, the criterion of economy includes the remaining goals of standardization, maintainability, and reliability. Standardization may seem a strange goal for laboratory research, and yet the need for a single systems design applied to all subsystems components and replacements is essential. Maintainability means that the system design, choice of computer languages, and choice of vendors shall be such as to reduce the need for extensively trained maintenance personnel, and minimize the time required for necessary software modifications and upgrades. Reliability applies not only to the hardware components, but requires robust software and firmware and good systems integration. All these engineering criteria are included in what Ramsey called reproducibility, once we move from the scientific description of a basic technique to its implementation.

Obviously, the timing community is too small and too limited in funding to drive basic developments in science. Historically, new frequency control techniques have been byproducts of methods in applied physics that had wider application -- for example, the cesium clock from atomic/ molecular beam technology. The most promising of the new clock designs reported in recent years rest on a broad base of laboratory hardware: the trapped ion standard, on radio frequency Paul traps; and the cesium fountain, on "optical molasses" -- that is, on applications of laser technology. To these wider applications, the four engineering criteria are directly relevant. So the most important advantage of the "cesium fountain" technique, for example, is one that does not directly appear in scientific papers: it exploits the methods of laser cooling and trapping of neutral particles, methods which are equally powerful and important in physics, chemistry, and biology. All the goals of good engineering practice -- flexibility, maintainability, interoperability, and the rest -- will be developed and applied in wide markets, and the concepts and components so evolved will move into the timing laboratory. Can we see, at least in dim outline, the road events will take?

(II) NEW TIMING STANDARDS: THE BASIC PHYSICS:

The stability of an atomic standard depends on three elements: (1) the Q-factor, the resonance frequency divided by the atomic linewidth; (2) the square root of the signal to noise ratio; and (3) the averaging time of the measurement, raised to one power or another. The Q-factor describes what the optical spectroscopist calls natural line broadening. In classical physics, one gets maximum amplitude of an oscillator at the natural or resonant frequency, but it will oscillate to some degree at frequencies higher or lower than the resonant frequency, and the measure of how much higher or lower is the Q-factor. In quantum physics, by the Heisenberg uncertaintyprinciple, if an atom remains in a certain level for time dT and then decays, the uncertainty of the quantity of energy it emits must be dE, such that dE * dT = h, Planck's constant. So the longer the atom remains in an excited state before decaying, the narrower the natural line width -- in classical terms, the higher the Q- factor. The second element of precision, the signal to noise ratio, is proportional to the square root of the number of atoms emitting per unit time -- that is, the signal is directly proportional to the number, and the noise to the square root. So the second element of precision fights the first, in the sense that extending dT reduces the number of atoms emitting per unit time; but, since S/N enters by the square root, there is some benefit to increasing dT. All other factors being equal, the more atoms, the better. Finally, until reaching the so-called "flicker floor", the stability of a measurement using an atomic standard increases with the square root of the averaging time; but the stability of a macroscopic oscillator (e.g. a quartz crystal) may be limited only by the uncertainty in the phase divided by the number of cycles in the measurement interval, until reaching the limit imposed by environmental factors. In fact, the oven- controlled quartz crystal oscillator (OXCO) has been the flywheel of atomic clocks, controlling the output of the passive H- maser for averaging times less than ten seconds, and high performance cesiums and rubidiums for less than one hundred seconds. One pressing need is for a better flywheel, since the best OXCO's are limited to a few parts in 1E13.

Ideally, then, we are searching for an atomic device that uses a gas of atoms/ ions in a state with long decay times, at high density, allowing long averaging times before being limited by macroscopic effects (e.g., cavity shifts). But these factors tend to defeat each other. At high density, atoms collide, de-excite each other, and perturb one another's energy levels. To achieve long decay times, atoms/ ions must be brought nearly to rest by electromagnetic or laser traps, and then they are perturbed by (for example) fluctuations in the applied electric/ magnetic fields, or collisions with the cavity wall, or energy exchange with the photons used to slow them down. As the literature shows, recent progress has been steady but slow; there is no magic. To be sure, the "magneto-optic" trap first proposed by Jean

Dalibard (first implemented in 1987) has revolutionized the design of optical traps used to cool neutral atoms, and we dare not assert that major discoveries will not be made in other areas that affect clock designs. Nevertheless, the improvements over the past five years or so have not come by dramatic breakthroughs in physical principles, but by patient engineering.

(III) RECENT PROGRESS: A SURVEY OF CURRENT LITERATURE:

The advantages of the optically pumped cesium beam standard were summarized by Lindon Lewis: "no state selection magnets are used, larger numbers of atoms contribute to the signal, and the spatial symmetry of the optical pumping reduces certain frequency shifts". These advantages are realized in NIST-7, the new US primary frequency standard which replaces NBS-6. The short-term stability of the device, relative to an active hydrogen maser, was reported to be 8E-13 / sqr(tau), where tau is the averaging time. In this device, diode lasers can be used to put the cesium atoms in the proper excited state, in the same way that the rubidium standards are pumped by an absorption cell using the Kastler technique; but the cesium standard is free of the buffer gases that cause frequency shifts in the rubidium device.

Altho the accuracy of rubidium devices remains limited, potential has been demonstrated for improving the stability, by increasing the difference in the number of atoms between the two ground state sublevels and so increasing the signal. First, a diode laser is used to pump the rubidium vapor with circularly polarized light at 7947 A; this excites most of the atoms in one of two high angular momentum states. Then the vapor is further excited by two sequential radio frequency pulses. The experimenters claim a fractional population difference of 70% to 90%, compared to 1% using a conventional discharge lamp.

Commercial active hydrogen masers of standard design have been in operation for about ten years, and provide good statistics on long term stability and reliability. One supplier has reported differences between an old and new active maser of less than one part in 1E14, indicating no degradiation in the Teflon wall coating, and no problems with ion pump rates or other evidence of saturation.

In the laboratory, the cryogenic hydrogen maser now exists in prototype, operating in the vicinity of 0.5 Kelvin. Altho frequency stability should be increased by the improved signal to noise ratio due to lower thermal noise and reduced H-H spin- exchange rate, it may in fact be limited by previous spin- exchange effects reported in the recent literature.

The trapped ion device illustrates the problem mentioned above, that the low density of trapped ions results in low signal levels, partly offsetting the advantage conferred by the small natural line width and high Q. A partial solution is to improve the trap design. The two most commonly used charged particle traps are the Penning trap, which

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uses a static electric field to confine particles in the axial direction and a strong magnetic field to damp out radial motion, and the Paul trap, which has the same electrode configuration, but uses a high frequency electric field instead of a magnetic field to produce the same effect. The drawback in using such traps in a time/ frequency standard is that the volume in which ions are trapped is very small, and therefore the signal is weak. One group has exploited a linear RF trap for which the electrical fields are zeroed out along a line rather than a point, which therefore confines ions along the whole volume of the central axis. Nevertheless, the signal is still weak, and to be useful, requires a "flywheel" oscillator to generate a waveform which is controlled by the trapped ion standard in the same way that a quartz crystal is controlled in a conventional atomic clock. At present, a quartz crystal oscillator is still being used as the "flywheel". However, a superconducting maser oscillator, still in the experimental stage, is planned as the replacement for quartz crystal in the final working frequency system.

The cesium fountain technique promises to overcome the problems of low particle density inherent to an ion device. Neutral atoms can be slowed by a laser tuned to a frequency just above their absorption level; if they move toward the laser, they are doppler shifted into the laser frequency, absorb light and are slowed by the recoil. Six laser beams can reduce atomic motion in all directions and produce a cold gas. But this is not sufficient to prepare atoms for a frequency standard application, since the trap perturbs the internal energy levels of the atoms by an amount of the order of the trap depth, thus broadening the natural line width and ruining Q. To be useful, atoms must be released from the trap, or the trap turned off. By the Zacharias technique, atoms are first cooled by a set of laser beams (by "optical molasses"), gently launched upward by one of the beams, and then the beams turned off; the atoms pass thru an interaction region twice, once on the way up and once on the way down. The two interactions correspond precisely to the two separated fields of a Ramsey cavity in a conventional cesium beam clock. The principal advantage of the fountain over the beam is that the transit time is much longer -- about one second instead of a few milliseconds -- and so the Heisenberg uncertainty between energy levels is reduced and the Q-factor improved by about two orders of magnitude. Perhaps the second most important advantage is that the oscillatory (Ramsey) fields are not separated spatially, so that (at least, in principle) only the temporal variations in environment require control. Furthermore, since neutral atoms do not repel one another, the densities produced by laser traps can be much higher than in trapped ion devices -- typically 1E8 in a volume of one cubic centimeter -- and the signal to noise ratio much better.

Of course, as with any technique, there are complications. High atomic densities perturb the energy states; they produce "pulling". Furthermore, the density of atoms (at least in current designs) is lower on the way down than on the way up, and the power absorbed during the two phases of the Ramsey interrogation will be different. Nevertheless, all the problems seem tractable. The ratio

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of densities can be measured by a magnetic probe. Since the atoms (after release from the trap) spend most of their time at the top of the trajectory, the critical volume that needs most to be shielded and controlled is small.

IV) NEW POSSIBILITIES: SOME TENTATIVE CONCLUSIONS:

We may expect that frequency standard development over the next ten years will be driven by engineering concerns, and not primarily by the quest for higher stability and/or accuracy. The few centers that do have a charter for either pure research or applied research toward very demanding goals -- e.g., NIST, JPL -- will pursue the trapped ion and cesium fountain techniques, toward stabilities of 1E-17 and an accuracy yet to be determined. For the rest, a leader in commercial research projects the following developments of the more conventional techniques.

Quartz: There will be no extensive change, but increased emphasis on environmental control and packaging. In the far future, quartz will be replaced by ceramics in some devices to give very high frequency output with quartz stability and accuracy.

Rubidium: Reduction of size will continue, driven primarily by space applications, and reduction in cost. Eventually, we may expect inroads into the cesium market by GPS steered miniature rubidium standards. Especially for space applications, development is expected to be toward smaller size (down to seven cubic inches) and lower price (less than $1000 US). An anonymous commercial developer anticipates "some kind of solid- state physics approach, by which a block or junction of non-vaporized material would yield performance at present rubidium levels", but this only after a development period of at least ten years.

Cesium: The HP 5071 is well established as the industry standard for accuracy, and points the way to digital environmental control and calibration in smaller, more inexpensive units. Optical pumping will be applied to commercial cesium devices for special applications in rack mounted units. Both cesium and rubidium commercial units may anticipate stiff price competition from GPS regulated quartz crystal devices (in the near future) and GPS regulated rubidium (over the next ten years).

H- Maser: Rack mounted passive masers to compete with high performance cesiums, for which a US made prototype already exists. Eventually, especially if new coatings (e.g., cold Teflon) can reduce drift, there will be rack mounted active masers at the 1E-16 stability level to compete with cesium. Primary laboratory improvements may be in cryogenic masers, and the use of frozen hydrogen or superfluid helium as wall coatings.