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4. TIME/FREQUENCY

1. Plenary Invited Paper

THE PAST AND FUTURE OF ATOMIC TIME AND FREQUENCY

Norman F. Ramsey
(Harvard University, Cambridge, MA 02138, USA)

ABSTRACT

The early history of time and frequency standards is reviewed. The most accurate and stable present standards are described. Prospective future improvements, particularly with trapped ions and atoms are discussed.

THE PAST

The first successful magnetic resonance experiments were those of Rabi and his associates[1,2] with molecular beams in 1938. The initial experiments measured the interactions of nuclear magnetic moments with external magnetic fields, but radiofrequency spectra were soon observed that depended on internal interactions within molecules[2] or atoms[3,4]. Some of the radiofrequency spectra lines were almost independent of external conditions[5] and could therefore be used as the highly stable periodic component of an atomic clock[6,7].

In 1949 Ramsey[8,9] invented the separated oscillatory field method which provided narrower resonances, eliminated first order Doppler shifts and was useable at much higher frequencies. In 1962 Kusch, Lyons Sherwood and others[10] did some initial work on a separated oscillatory field atomic cesium clock, but the work was soon discontinued. In 1954 Zacharias[11] stimulated renewed interest in an atomic cesium clock and began[12] the development of a commercial atomic cesium clock. The first atomic beam apparatus extensively used as an actual frequency standard was constructed in 1955 by Essen and Parry[13]. From 1956 on atomic frequency standards developed rapidly with major contributions coming from a number of laboratories in many different countries[7,14]. Stabilities and accuracies of about 10^{-13} have been achieved with atomic cesium clocks[14] and the second, by international agreement, has been defined as the duration of 9,192,631,770 cesium periods.

Concurrent with the advances in atomic beam clocks, a number other atomic and molecular clocks were developed[7]. Microwave absorption devices using molecular resonances, such such as the NH_3 inversion transition, were developed by Townes and others[7]. Later Townes[15] discovered the maser principle and developed the ammonia maser which operated well but lacked the stability to be competitive.

The combination of Kastler's optical pumping technique[16] with Dicke's use of buffer gases[17] provided strong oscillations free from first order Doppler effects, so optically pumped rubidium can be used as a frequency standard. Although other atomic clocks have greater accuracy and stability, rubidium clocks are frequently used since they are much lighter and less expensive.

The atomic hydrogen maser was invented by Kleppner and Ramsey[18] and a number of scientists[7] contributed to its improvement. In the hydrogen maser, atoms in the higher hyperfine state of atomic hydrogen are stored in a teflon coated bottle inside a tuned microwave cavity where by stimulated emission they emit coherent highly stable microwave radiation. The stability of a hydrogen maser can be better than 10^{-15} over several hours.

Townes and Schawlow[19] first pointed out the possibility of applying the maser principles at infrared and light frequencies and the first successful laser was made by Maiman[20]. Since then laser developments have occurred at a rapid pace with dramatic improvements in frequency range, power and stability. Major advances came from the suppression of first order Doppler shifts by such techniques as two photon absorption spectroscopy[7] and from the development of successive chains of laser frequencies so that the laser frequencies could be calibrated in terms of cesium.

At present different atomic clocks can be chosen to fit the need. When high stability is not required, optically pumped rubidium cells can be chosen for their low cost, small size and light weight. When greater accuracy and stability is required, cesium beam tubes are usually used. For the highest stability requirements, as in long baseline radio astronomy, hydrogen masers are often required. When optical frequencies need to be measured lasers must be used even though they are not yet absolute standards.

THE FUTURE

Many improvements are being developed for the clocks that are currently widely used. Optically pumped atomic oscillators are being improved by the use of different atoms, by suitable wall coatings which permit the omission of buffer gases[7] and by combining optical pumping techniques with those of atom trapping and cooling. Possible improvements for the hydrogen maser include operation at low temperature, electronic cavity tuning, operation in a passive mode and new confinement surfaces, such as superfluid ^4He or other liquids. Improvements for atomic beam clocks include the use of different atoms or molecules, operation at higher frequencies, the use of two beams going in opposite directions to compensate for phase shifts, the use of lasers to select states and detect beams and better velocity definition to reduce uncertainties in second order Doppler corrections. Optical frequency standards can be improved by the use of narrower lines, by the adaptation to optical frequencies of the separated oscillatory field method[8], by improved frequency chains to compare different frequency standards and by the various ion and atom trapping and cooling techniques discussed below.

Dehmelt[21,22] first used electromagnetic ion traps in radiofrequency resonance studies. Penning traps overcome the limitations of the Earnshaw theorem by confining the ions in one direction with an inhomogeneous electric field and in the two other orthogonal directions with a uniform magnetic field. Alternatively, suitable inhomogeneous electric fields can provide focussing in all three directions in Paul or radiofrequency traps which alternately provide focussing and defocussing in each direction but with an average focussing in all directions. Ion traps have the advantage that the observed transition frequencies are approximately independent of the trapping fields. Originally the trapped ions had high kinetic energy (approximately 1 eV) and excessively high second order Doppler shifts. However, Cutler[29] and others[29] have cooled the ions by collisions with helium gas. Lasr cooling, as proposed by Wineland and Dehmelt[22,23] and by Hansch and Schawlow[24], can go even to much lower temperatures by shining intense laser light at the frequency of an allowed optical transition onto a trapped atom or ion slightly below the resonance frequency so the light pressure is greatest on the ion when it is approaching the light. Dehmelt and Wineland and others[7] have used this technique to cool trapped ions to temperatures of a few micro Kelvin where the second order Doppler shifts are negligible. This is a very promising technique for a stable clock with the principal limitation being the low ion density required to avoid space charge effects and the low density in turn reduces the signal to noise ratio.

In 1985, Phillips[25] and his associates used laser cooling of a focussed atomic beam to slow the atoms and even reverse their velocity. Since the Doppler shift changes as the atom slows down, either the atomic optical frequency or the laser frequency must change for the slowing to continue. Phillips did so by having the atoms pass through a region where the magnetic field gradually changed as the atom moved along its path. Alternatively, Hall[7], Wieman[7] and others[7] have changed or "chirped" the laser frequency as the atom has slowed down. The success of atom cooling permits atoms to be stored in weak traps so there has been a virtual explosion of new ideas and developments in laser trapping of atoms during recent years. Laser trapping forces on neutral atoms can arise either from the gradients of the laser electric field interacting with the induced electric dipole moment of the atom (gradient or dipole force traps) or by the transfer of momentum in the absorption and emission of radiation (spontaneous radiation or scattering force traps), with the gradient traps being intrinsically weaker. When slow atoms are introduced into a region with oppositely directed laser beams along three orthogonal directions at frequencies slightly below the resonance frequency, the atoms will be laser cooled in whatever direction they move. Although such "optical molasses" does not provide a stable trap Chu[26], Pritchard[27], Wieman[27], Cohen-Tannoudji[28] and others[29] have combined optical molasses with either gradient or radiation trapping to obtain useful atom traps. Atoms stored in such traps have been cooled to temperatures of a few micro-K. The principal disadvantage of an atom trap is that the strong laser fields that provide the trapping also distort the energy levels and resonance frequencies of the atoms. Usually this makes it necessary to turn the trapping lasers off while the resonance is being with a consequent reduction in storage time. One possibility for increasing the effective storage time is to allow the atoms to have a small vertical component of velocity so that they rise up and then fall under gravity, in some cases passing through two coherent laser Ramsey fields on the way up and down.

Some atomic clocks, such as cesium beam tubes, have much better long term accuracy than short term stability in which case the shorter term stability of the clock can be greatly improved by suitably coupling it to a fly wheel oscillator of high short term stability. Very high Q cavities appear are good for this purpose and superconducting cavities are particularly promising since they are highly stable. Circuits with either optical or electrical feedback from