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FOREWORD

These Proceedings contain the papers presented at the Twenty Secoond Annual Precision Time and Time Interval Applications and Planning Meeting. The meeting was held at the Sheraton Premiere in Tysons Corner, Virginia this year. A good attendance at the meetings and the banquet was an indication of the continuing interest in the field. We had a number of invited papers, some of which are included in this proceedings. A few papers are missing because they were not received in time for publication or were withdrawn from publication by sponsors. The question and answer periods following each talk are included as usual.

This is the second year that we have had a Poster Session. Acceptance of this session was uniformly positive, both by attendees and by presenters. The advantage of this session is the one–on–one interaction between the presenter and the attendee.

The Hydrogen Maser Workshop, organized by Jacques Vanier, and the Environmental Effects Session, organized by Helmut Hellwig, were outstanding successes due to the efforts of these two gentlemen and to the interest in these aspects of the field.

There were 251 registered attendees, very high for an East Coast meeting.

The objective of these meetings is to provide an opportunity for program planners to meet those who are engaged in research and development and to keep abreast of the state–of–the–art and latest technological developments. At the same time, they provide an opportunity for engineers to meet program planners.

The success of these meetings depends on the efforts of the Program Chairman and the individual Session Chairmen and the organization of the entire meeting by the Chairman of the Executive Committee. Without their unstinting labor, such meetings could not be held.

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THE PAST, PRESENT AND FUTURE OF ATOMIC TIME

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Abstract

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

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]. Rabi, Zacharias and Ramsey at Columbia discussed the possibility of atomic clocks at Columbia as early as 1939 and Rabi discussed these ideas publicly in his 1945 Richtmeyer lecture to the American Physical Society; the first published description of atomic clocks was the New York Times article based on this lecture.

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 1952 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.

In recent years a number of major new techniques for trapping and cooling ions have been developed including cooling by collisions with inert gases such as He, laser cooling and sympathetic cooling. Likewise techniques for trapping and cooling neutral atoms have developed at a rapid pace including slowing of atoms with a laser beam, laser trapping of atoms, laser cooling and optical molasses. Since most of these developments hold great promise for the future but are not yet incorporated into current clocks, they will be discussed later in the section on the future.

THE PRESENT

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; such cells are stable to 10^{-11} over a one month period and more stable for shorter periods. When greater accuracy and stability is required, cesium beam tubes are usually used; they are accurate to better than 10^{-13} over extended time periods. For the highest stability requirements, as in long baseline radio astronomy and navigation in outer space, hydrogen masers are often required; they are stable to better than 10^{-15} over several hours. When optical frequencies need to be measured lasers must be used even though they are not yet absolute standards.

THE FUTURE

Niels Bohr once said, "It is always difficult to make predictions, especially predictions about the future". Long range predictions in a rapidly developing field like that of accurate timing are particularly unreliable because unanticipated new ideas usually occur and greatly change the future. Short term predictions are usually much better because they depend mostly on developments that have already partially occurred. I shall devote most of this section to describing current plans and recent research developments which have particularly promising implications for the future and which are the essential ingredients to rational predictions of both the near and distant futures.

Many improvements are being developed or are in prospect for the atomic clocks currently used. For example, the simple and low cost 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.

A number of improvements can be made on the next generation of accurate atomic beam frequency standards[21→24]. Instead of state selection by deflection with inhomogeneous magnetic fields, the atoms may be optically pumped to the desired state. The ends of the separated oscillatory fields cavities can be designed to minimize distributed cavity phase shift[23] and an axial magnetic field may be chosen to minimize Rabi and Ramsey pulling[23]. Beam reversal can be used to evaluate any remaining phase shift between the two oscillatory fields and the excitation can be with counter–propagating waves[21→24]. Although cesium is the atom currently most frequently used in atomic beam frequency standards, other atoms such as Mg are being investigated. Higher excited states may also be used to obtain atomic beam frequency standards at higher frequencies. The atoms in an atomic beam may be laser cooled to reduce the second order Doppler shift. Many of the laser cooling and trapping experiments discussed below are combined laser and atomic beam experiments. Uncertainties in the second order Doppler shift can also be reduced by velocity selection of the beam, but at the cost of a serious reduction in beam intensity.

Many 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 with high short term stability. Crystal oscillators, for example, can be used for the fly wheel oscillator. Very high Q cavities are good for this purpose and superconducting cavities are particularly promising since they are highly stable. Circuits with either optical or electrical feedback from a high Q cavity markedly diminish the noise and increase the short term stability. Consideration is even given to the possibility of using a hydrogen maser as a fly wheel oscillator.

Possible improvements for the hydrogen maser[25] include more stable tuned cavities, electronic cavity tuning, operation at low temperatures, operation in a passive mode and new confinement surfaces, such as superfluid ^4He or Fomblin oil. Superfluid helium surfaces have the advantage that they are reproducible since the superfluid helium covers all impurities and does not change its character with time.

Infra–red and optical frequency standards can be improved by the use of narrower lines, by the adaptation to optical frequencies of the separated oscillatory field methods, by improved frequency chains to compare different frequency standards and by the various ion and atom trapping and cooling techniques discussed below.

Dehmelt[26,27] 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, Prestage, Dick and Maleki[28] have used a hybrid rf/dc linear ion trap which permits storage of large numbers of ions with reduced susceptibility to the second order Doppler effect caused by the rf confining fields. Alternatively, Cutler[29], Dehmelt[30] and others[30,31] have obtained promising frequency standards by cooling trapped ^{191}Hg ions to 300K by collisions with low pressure helium gas.

Laser cooling, as proposed by Wineland and Dehmelt[27,32] and by Hansch and Schawlow[33], can go to even 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 by the first order Doppler shift is greatest on the ion when it is approaching the light. Dehmelt[34] and Wineland[27,35] 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. Laser cooling of ions has been effective with both Penning and electric quadrupole rf traps. If the cooling laser beams act directly on the stored ions being used for time keeping, they must be turned off when the clock frequency is being measured, However, this can be avoided by the process of "sympathetic cooling" in which two different ions are trapped with one being the clock atom while the other is laser cooled; the two kinds of atoms interact sufficiently in the trap for the clock ions to be "sympathetically" cooled by the other ions[36]. Trapped ions have been cooled to the lowest vibrational state of the trap. Laser cooling of trapped ions is a very promising technique for stable clocks 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.

The extreme limit for low density of ion traps are those with only a single ion[34]. In such such experiments the expected low signal to noise ratio can be improved by the technique of "shelving". In shelving, say with say $^{138}Ba^+$, the ion is excited from the $6^2S_{1/2}$ ground state to the $5^2D_{5/2}$ state with two intense laser beams and the transitions between the $5^2D_{5/2}$ state and the $5^2D_{3/2}$ state are induced at the clock frequency. When the ion is "shelved" in the $5^2D_{3/2}$ state the laser induced transitions stop until the ion leaves that state. In this fashion each clock induced transition can affect 10^6 observable fluorescent photons which greatly improves the signal to noise ratio.

In 1985, Phillips[38] and his associates used laser cooling of a focussed atomic beam to slow electrically uncharged 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 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[39], Pritchard[40], Wieman[40], Cohen-Tannoudji[41] and others[42] have combined optical molasses with either gradient or radiation trapping to trap atoms at about 100 K.

Phillips and his associates[43] in 1988 made the startling experimental discovery that Na atoms could be cooled to lower velocities than had previously been considered to be the theoretical cooling limit. It was thought that there was a theoretical limit, often called the Doppler limit, below which the atoms could not be cooled by laser cooling. This theoretical limit quite reasonably occurs when $k_BT/2 = h\Gamma/4$ where Γ is the spontaneous emission rate from the excited atomic state and k_B is the Boltzmann constant. For Na, this theoretical temperature limit $T = 240\ \mu K$. In contrast. Phillips and associates[43] found experimentally a cooling to 40 μK. Another theoretical limit to cooling was thought to be the recoil limit which occurs when the recoil energy $(hk)^2/2M$ of the atom of mass M emits a photon of momentum hk. Cooling below the Doppler limit has been explained[42→45] by Cohen-Tannoudji, Dalibard, Solomon, Chu and others as due to polarization gradient cooling in a multilevel system and the Sisyphus effect according to which a moving atom is mostly climbing a potential hill of a light shifted doublet ground state sublevel before being optically pumped to the other sublevel. With polarization gradient cooling Cs atoms have been cooled to 2.5 μK. Aspect, Cohen–Tannoudji and their associates[44,45] have also used a velocity selective process based on coherent trapping of atomic populations into a nonabsorbing coherent superposition of states to achieve transverse cooling of ^{4}He atoms in the triplet metastable state to well below the usual 23 μK one dimensional Doppler cooling limit and the 4 μK recoil limit down to about 2K.

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 studied with a consequent reduction in storage time. One possibility for increasing the effective storage time is to give the atoms a small vertical component of velocity so that they rise up and then fall under gravity, in some cases passing through two coherent oscillatory fields[8] on the way up and down, as recently done successfully by Chu[46] and his associates with microwaves and as planned by others at laser frequencies. In the first succesful fountain experiments the atoms were somewhat heated by giving them the small vertical velocity, but in the future the heating can probably be avoided by slightly shifting the frequency of the vertical cooling lasers so that the optical molasses will move vertically[42,45,46]. Chu[46] also plans to increase the beam intensity for his experiments with an atom funnel based on dissipative optics. As an alternative to the fountain, Wieman[42] has suggested that the atoms can now be cooled to such low temperatures that they can be stored in a magnetic trap so weak that it does not significantly affect the spectrum.

With the impressive recent developments just discussed it is apparent that there are many possibilities both for future improvements of the currently used time and frequency standards and for totally new standards based on trapped ions or atoms. The possibilities are so numerous that it is impossible to predict which ones will be best. But with such promising new techniques already available and with the prospect for further new ideas, the next few years in the field of atomic time should be exciting and productive.

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