CESIUM ATOMIC BEAM FREQUENCY STANDARDS:

A SURVEY OF LABORATORY STANDARDS DEVELOPMENT FROM 1949-1971 *

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Summary

A general review is presented of progress achieved by the more active standards laboratories in developing laboratory cesium beam standards during the 1949-1971 period. For each significant time period during this 22-year interval an attempt is made to point out the basic approaches employed, principal characteristics of some of the more important devices developed, main problems encountered, some solutions attempted in meeting these problems, and the main accomplishments. For background purposes a brief discussion of the differences in approach between commercial and laboratory cesium standards and a general review of cesium beam operating principles are also included.

Key Words: Atomic frequency standards, Cesium beam frequency standards, Laboratory cesium standards.

Comparison of Laboratory and Commercial Cesium Standards Approaches

The purpose of this paper is to review progress achieved during the past 22 years in the development of cesium atomic beam frequency standards. The emphasis will be primarily on developments in the national standards laboratories, as contrasted with those achieved by commercial firms. For more information regarding some of the latest developments in commercial cesium standards, the reader is referred to the paper in this volume by R. Hyatt, et al. [1]

Figure 1 illustrates some of the differences between the approaches followed by commercial firms and the national standards laboratories in designing, building, and using cesium beam frequency standards. Clearly, developers of both commercial and laboratory standards strive for high accuracy and high stability; these characteristics, obviously needed by national standards labs, also make good commercial sense. However, the commercial developer must operate within constraints imposed by the necessity to produce a standard of reasonable size, weight, and reliability which will provide good performance over the rather wide range of environmental conditions found in typical field applications. Because most time and frequency applications, such as the proposed time and frequency collision avoidance system, for example, require stable sources rather than accurate ones, commercial compromises are more often made with respect to accuracy than stability. In the case of laboratory standards, on the other hand, accuracy is of paramount importance and such factors as size, weight, electrical power consumption, and so forth, are not permitted to compromise the accuracy achieved. Most laboratory standards are designed not only to provide a high accuracy capability but also to allow for thoroughly evaluating and documenting this accuracy as often as is required.

A further difference between the commercial standards laboratory approaches shows up when one examines the respective design features for achieving good frequency stability performance. One way to express this quality of stability is the widely used concept of figure of merit, which for cesium beam tubes is proportional to the signal-to-noise ratio of the cesium beam tube output signal divided by the resonance linewidth. In commercial developments a high figure of merit--and hence a good stability performance--is achieved primarily by designing for a very high beam signal-to-noise ratio. In the laboratory standards case--at least until rather recently--the designer usually tried to achieve a high figure of merit by means of a very narrow resonance linewidth--a technique that resulted in some very long beam tubes as we shall see later.

These differences in approach between commercial and laboratory standards appear to be decreasing, however, in recent years. Careful design and attention to detail are resulting in commercial tubes with stability performance comparable to that of recent laboratory standards. At the same time, factors which affect accuracy in commercial cesium standards are receiving closer scrutiny. Conversely, present-day designs of laboratory beam tubes are making increasing use of design techniques and technologies--for example, gettering materials to improve the vacuum--developed or used first by the commercial designers. One laboratory device, now being designed in Canada, is actually intended for essentially continuous use in a time scale application--much like its commercial counterparts. [2] At NBS, we have tried to obtain the best of both the commercial and standards laboratory "worlds" by contracting with Hewlett-Packard to jointly design and construct a refined beam tube, known as NBS-X4. This increasing cross-fertilization of ideas between commercial and standards laboratories is most encouraging; it seems quite clear already that accelerated improvement of both commercial and laboratory standards is taking place as one direct result.

In the remaining part of this paper the discussion will mainly concern laboratory standards developed during the past 20 years or so at five of the more active laboratories in Europe and North America as shown in figure 2. This is not to imply, however, that other labs have not in the past or are not now also contributing to the general progress being made in this field.

Review of Cesium Beam Operating Principles

To provide a brief refresher on how a cesium beam standard, commercial or laboratory, operates, figure 3 shows one common form of the basic technique. Cesium atoms effuse from a source, shown on the left; travel down an evacuated tube at thermal velocities through a series of magnetic fields; and depending on their exact path through the tube they either strike the detector on the right side of the slide or are lost from further consideration. Atoms following either of the trajectories shown have their magnetic moments aligned by the first deflecting magnet, called the A magnet, in such a direction that forces are exerted forcing the atoms back toward the axis of the tube. As the atoms next pass through the excitation cavity region, a resonance condition exists if the microwave field in the cavity has precisely the same frequency as that corresponding to the separation of two possible energy states of the cesium atom. If the frequencies match, and if certain other conditions regarding the microwave power level and directions of the fields are satisfied, the atom will change from one of its energy levels to another, effectively causing a 180° change in the orientation of its magnetic moment as compared to its previous direction in the A magnet field. When the atom now enters the B deflecting magnet, which is identical to A, it is deflected in the opposite direction as in the A field, since its magnetic moment has been reversed in the process of making a transition between energy states. As the trajectories indicate, these atoms then strike the detector where they are ionized, producing an electrical current proportional to the number of atoms per second hitting the detector. As we have seen, this number is also proportional to the number of atoms per second making a transition and is thus a measure of whether the oscillator frequency providing the microwave field in the cavity matches the resonance frequency characteristic of the cesium atom. The detected signal, if combined with suitable servo electronics, can then be used to automatically and continuously correct the slave oscillator frequency to a constant value, related in a known way to the cesium frequency. A small, uniform DC magnetic field terms the C field, is also provided in the center region between the A and B deflecting magnets in order to keep the magnetic moments of the atoms oriented properly and to make it possible to utilize only one particular microwave energy state transition from among the group of 21 that are theoretically possible with the cesium atom.

Influences on Stability and Accuracy Performance

As background for the upcoming discussion of stability and accuracy achievements and limitations, it may be worth noting some of the aspects of this magnetic resonance technique that influence these performance measures. The stability, as we have already seen, depends on the resonance linewidth and the beam signal-to-noise ratio. It is characteristic of the technique that the resonance linewidth becomes narrower as the time of flight of the atoms between the two arms of the U-shaped excitation cavity becomes longer. The signal-to-noise ratio of the beam depends mainly on how many atoms per second make transitions and are processed by the detector, and this, of course, depends in turn on the detailed design of the beam optics system. The signal-to-noise ratio is also degraded by any background level of cesium seen by the detector, since such atoms contribute shot noise to the detection process without adding signal component. Finally excessive noise levels in the various electronic systems involved can also degrade the output stability.

The accuracy performance of a cesium standard, on the other hand, is generally degraded by any effect which causes the actual working cesium frequency as provided by the atomic beam machine to be shifted away from the ideal frequency associated with a completely unperturbed, isolated cesium atom. It is important to realize, however, that often it is only the uncertainties in the exact amount of these frequency shifts that contribute to inaccuracy. In principle, a frequency shift whose magnitude and direction are perfectly known can be compensated for by applying a correction to all measurements.

One source of error in this magnetic resonance technique involves frequency shifts produced by unwanted and unknown phase differences between the microwave fields in the two ends of the excitation cavity. A second possible problem area is uncertainties in our knowledge of the C field--that is, its magnitude, direction, and uniformity over the length and cross-section of the atomic beam. Further errors may result from uncertainties in first and second order Doppler shifts which involve knowledge of the velocity distribution of the atoms in the beam. The electronics systems can contribute a variety of errors from sources such as second harmonic distortion of the modulation signal, an asymmetrical RF spectrum used to excite the cesium resonance, and miscellaneous effects related to the servo system electronics. As implied earlier, the detailed evaluation of such accuracy-limiting effects as these for each particular cesium standard built is one of the principal activities in standards labs working with state-of-the-art devices.

Early History of Laboratory Cesium Standards

This magnetic resonance technique being reviewed is neither very new nor restricted in usefulness to atomic frequency standards. In fact, the method, without some of today's refinements, was actually perfected by Dr. Isidor Rabi at Columbia University back in the 1930's as a tool for studying atomic and molecular physics.[3] It apparently wasn't until 1945 that Dr. Rabi first suggested that this technique should be useful in building an atomic frequency standard.[4] About four years later, NBS--with the help of Professor Kusch, also from Columbia--started work on the first direct application of Rabi's technique to frequency standards. In 1952 the standard shown in figure 4, NBS-I, was successfully operated in the sense of producing the 4, 0 ⟷ 3, 0 resonance curve of cesium-133, using only a single excitation region[5] rather than the separated field method developed by Professor Ramsey two or three years earlier.[6] Within a few months NBS-I had been modified to use the new Ramsey technique and a narrow cesium resonance only 300 Hz wide was observed.[7] At this point, Dr. Harold Lyons of NBS predicted that accuracies of 1×10^{-10} appeared possible with this type of device. NBS-I was not used during this very early period as a routine frequency standard for regular calibration work, but rather was considered a research system for making further studies and improvements of this new type of standard. By 1955 other cesium standards were also coming on the scene. At MIT, Zacharias, Yates, and Haun were the first to develop servo systems for electronically locking a crystal oscillator to the cesium resonance.[8] Their work later led to the first commercial cesium beam standard--National's Atomichron. At NPL, Dr. Essen and his colleagues became the first group to build and place into routine operation a cesium standard for periodic calibration of secondary oscillators.[9] Figure 5 is a picture of Essen's original standard, NPL-1. It was this machine which generated the cesium-referenced measurements during the 1955-1958 period in cooperation with the U. S. Naval Observatory that led to the famous 770 number referring the cesium frequency to Ephemeris time.[10] That number has, of course, now staked out its claim to further immortality since the redefinition of the second in 1967.*

Development of Laboratory Cesium Standards: 1955-1971

In order to discuss the development of laboratory cesium standards after 1955 the next 16-year period will be divided into three separate time periods, each one of which covers a significant phase of development in getting to where we are now. The first period covers the original group of standards from four of the major labs, including the early NBS and NPL work already mentioned. The second period covers a group of second-generation standards from the same labs. Finally, the third significant period starts about 1967 when some newer approaches began to be explored and continues up to the present--and perhaps even a year or so beyond.

In the remaining portion of this paper each of these three periods will be examined in more detail--certainly not on a standard-by-standard basis, but rather from the point of view of looking for the general approaches, accomplishments, and problems coming out of each period spanning several years.

Early Development Period: 1955-1958

Beginning with the 1955-1958 period, the general approach, in simplest terms, was to build an atomic frequency standard, using the magnetic resonance technique, that would work! Little thought was given to refinement; the important thing was to develop an operating model so that studies could be made of its basic advantages and limitations. In other words, it was a necessary period in which laboratories gained valuable experience in the application of this new technique.

Since all of the labs were starting from nearly the same base level of experience, it's perhaps not too surprising that one can fairly easily identify some features which were common to all or at least most of these earliest devices. First, they all used the Ramsey technique to obtain narrower linewidths. Probably due to a general lack of experience, the beam optics systems were kept quite simple and very closely related to what had been used successfully in earlier work with the magnetic resonance technique. Since relatively small beams were used with some fairly inefficient beam optics, the resulting beam signal-to-noise ratio was rather low. Phase shift errors, if they were seriously evaluated at all, were measured by physically reversing the microwave cavity and observing a resulting change in direction of any phase shift error present. Resonance linewidths were typically a few hundred hertz wide. With the exception of the standard at LSRH these early standards did not include servo electronics, but rather required an operator to manually plot out resonance curve after resonance curve in order to calibrate an oscillator.

In spite of many problems there were some very significant accomplishments. For one thing, independent standards were constructed in at least four different laboratories which operated successfully and proved the value of the basic technique for standards applications.[9, 11-13] The accuracies achieved within a range of a few parts in 10^{11} to one part in 10^{10} may sound a little crude to laboratory standards people today, but in 1958 these results were little short of remarkable. And, as already noted, the cesium frequency was carefully related to the best known astronomical time unit.[10]

An important outgrowth of this early period was well-documented information regarding the main limitations which had to be overcome for improved performance. Some of these are listed in figure 6. The first three primarily limited the short and medium-term stability of the standards and indirectly also their accuracy, while the latter two problems affected more the very long-term stability and the accuracy evaluation of the devices. As one further example of a product of this early development period, CsI, developed at NRC in Canada, is shown in figure 7.

Second-Generation Laboratory Standards: 1959-1966

The second major time period identified--from 1959 to 1966--might be termed the "age of refinement." The general approach to building better laboratory cesium frequency standards was to refine the techniques and hardware that worked in the earliest models just discussed. Better frequency references--in the form of more stable crystal oscillators and the early atomic standards--became available and greatly aided in the evaluation of the second-generation standards. For example, at NBS, NBS-I was used as a stable reference for evaluative measurements on NBS-II, and NBS-II later proved most helpful in the evaluation of NBS-III. As understanding of the basic strengths and weaknesses of the various devices increased during this 1959-1966 period, so did the appreciation of the need for more refined evaluation techniques and measurements in order to fully document the improved accuracy and stability being observed.[14]

In terms of stability improvements during this period the trend was mainly toward designing for narrower resonance linewidths, thereby improving the figure of merit and thus the stability performance. The narrower linewidths were achieved by increasing the time for atoms to interact with the excitation field by building standards of greater length.[15-18] This trend toward longer lengths finally stopped at about 6 meters overall length and 3.7 meters interaction length for NBS-III, although a proposal was actually submitted to NBS at one

* In 1967 the 13th General Conference on Weights and Measures defined the "second" as: "the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom."

point for a vertical standard 17 meters long! Some efforts were also made during this period to increase the stability via improved beam signal-to-noise ratio--mainly, by employing larger beams with larger dipole deflecting magnets. The higher-quality crystal oscillators already mentioned helped to provide more stable excitation sources, while the more widespread use of electronic servo systems for controlling the excitation frequency finally eliminated the need for tedious and inefficient manual measurement techniques.

Significant improvements were made in these second-generation standards in reducing error sources identified from experience with the earlier models.[14-18] The frequency errors caused by cavity phase shifts were attacked on at least three different fronts. First, the basic cavity construction techniques were refined so that phase differences between the ends of the cavity were not as likely to occur. Careful measurements of electrical asymmetries during construction proved most helpful. Second, more laboratories began to make better evaluations of cavity phase shifts by physical reversal of the cavity. In one case at least, NBS-III, the cavity was left undisturbed but the beam was reversed by physically interchanging the oven and detector with some improvement in the reproducibility of the phase shift data. Third, a new technique was tried at MIT which employed square-wave phase modulation instead of the more common sinewave frequency modulation.[19] This technique makes use of the transient response of the atomic beam to provide an electrical signal related to any existing cavity phase difference, but so far none of the standards labs have adopted the method.

C-field errors were reduced somewhat by providing better magnetic shielding through additional separated layers and materials with superior magnetic properties. The uniformity of the C-field was improved in several labs by adopting a 4-wire field-producing structure.

Frequency shifts caused by RF spectrum asymmetries received much closer attention during this period. Various systems and techniques were developed for looking at spectrum problems, such as analysis of the beat note between two X-band excitation systems, use of an ammonia maser in a narrow band spectrum analyzer system, and measurements of the microwave power dependence of the cesium frequency, which turns out to be sensitive to RF asymmetries. Theoretical studies, particularly regarding the power dependence, have been helpful in pointing the way to better evaluation techniques for spectrum effects.[20] The sensitivity of the cesium frequency to RF spectrum effects added impetus to the development of lower-noise electronics components during this period and to a generally increased activity in designing and building multiplier chains, modulation systems, and servo components that were compatible with the increased performance beam tubes appearing on the scene. The possible accuracy-limiting errors caused by the presence of second harmonic distortion of the modulating signal are a specific example of an electronic problem that received much attention. In addition to the successful, straightforward reduction of second harmonic distortion levels through better circuit designs and construction procedures by most of the labs, a more novel approach was taken at NRC by developing a new, square-wave frequency modulation system that employed 10-second-interval switching between two appropriate microwave frequencies to successfully reduce systematic errors from the electronics.[21]

Summarizing the main accomplishments during this 1959-1966 period, a number of second-generation laboratory standards were built, most of which are still used today--though perhaps with added improvements. The accuracy performance was improved by a factor of ten to levels varying from 3×10^{-12} (1 σ) to 1×10^{-11} (1 σ). Stability improvements, largely due to the narrow 40-100 Hz linewidths achieved, resulted in performance of 1×10^{-11} (1 σ) for 1-second averaging times improving as $\tau^{-\frac{1}{2}}$ to a level of 1×10^{-13} or better. Typical tabulations of bias uncertainties showed that in spite of significant progress phase shift errors, electronics effects, and C-field uncertainties continued to be the most serious accuracy limitations.

Figures 8, 9, and 10 show three of these second-generation standards: NPL-2, NBS-III, and CsIII (NRC), respectively.

More Recent Laboratory Standards: 1967-1971

The last of the three time periods covers the period from 1967 to the present and is characterized by a continuing attempt to refine existing techniques but also by a more active development of some new techniques. It might also be considered as a period of greater sophistication where previous tendencies to design longer standards to achieve greater stability have been replaced by concentrated attempts to increase the signal-to-noise ratio of the beam. For example, the present PTB standard with an excitation region only 79 cm long has produced 1-second stabilities as low as 3×10^{-12} or a figure of merit of nearly 30 as compared to about 10 for present long-beam standards.[22] An even smaller tube being developed as LSRH has shown promise of even better stability based on signal-to-noise measurements.[23] In the case of the NBS-X4[24] and NBS-5[25] designs, a large increase in signal-to-noise ratio is made possible by using a large digital computer to optimize the parameters of the beam optics systems. NBS-X4, with a total length of about 1.3 meters, should provide a figure of merit of nearly 100, corresponding to a stability of 1×10^{-12} in 1 second. NBS-5, which is a major rebuilding of NBS-III, is designed for a figure of merit of at least 500, corresponding to a 1-second stability of about 2×10^{-13}.

Other laboratories, particularly NRC,[25] PTB,[27] and LSRH,[23] have been working with beam tubes employing hexapole or combinations of hexapole and dipole deflecting magnets to increase the useful beam intensity significantly. The primary advantage in using hexapole magnets, of course, lies in their ability to focus a cylindrical beam of atoms. In addition to the direct increase in useful beam intensity that results, a further advantage is gained indirectly by being able to operate a higher cesium oven temperatures without running into collision problems in the simpler beam collimator permitted by the hexapole design.[28]

Figure 11 shows some of the possible variations on the multipole beam optics designs. For comparison, the upper scheme is just the usual flop-in technique with dipole deflecting magnets. In the second situation--the hexapole flop-in case--atoms which make transitions are focused on an annular detector. Two difficulties with this scheme are that the relatively large surface area of the annular detector tends to increase noise levels in the detection system and the annular detector is harder to construct. The hexapole flop-out system shown next, which is that used in the present PTB standard,[27] permits a small, spot detector, but suffers somewhat from the relatively high background of atoms which strike the detector without first making a transition. These atoms contribute to the shot noise without adding useful signal. Lastly, the bottom scheme shows the hybrid system being constructed and tested now at LSRH, featuring a hexapole A magnet and a double-gap dipole B magnet.[23] In this design the previously-mentioned disadvantages of large detector surface area and difficult construction problems in one case and a large background of unflopped atoms in the second case are all eliminated. A small price is paid, however, in terms of an intensity reduction due to the dipole B magnet's inability to process some of the atoms supplied by the hexapole A magnet. Figure 12 shows a view of this rather unique double-gap dipole B magnet used at LSRH--the center structure serves both as one of the magnet poles and a beam stop to eliminate unwanted atoms.

Good progress is also being made on the reduction of systematic errors which affect the accuracy of these newer laboratory standards. The cavity phase shift problem is being approached mainly along three lines. First, more of the standards are now being built with facilities for reversing the beam direction through the undisturbed cavity as a means of precisely and accurately evaluating this error source. Second, in the case of the existing NBS-X4 and CsI (PTB) beam tubes, the single oven and detector can be physically interchanged--in the case of the PTB standard, without breaking the vacuum. Third, the modified long-beam machine at NPL,[29] the new CsV(NRC) standard now being designed in Canada,[26] a proposed new standard at PTB,[22] and the nearly-completed NBS-5[25] are all designed with a movable oven and detector at each end to operate with a beam in either direction for phase shift evaluation quickly, easily, and under more optimum conditions. Errors from this source should then be reduced to 1×10^{-13} or below. Another more novel approach is employed in the present PTB standard where the dependence of the phase shift error on the average beam velocity is used to detect phase shift error.[27] The beam velocity can be varied in this machine over a ratio of 2:1 by interchanging two different sets of focusing magnets designed to focus widely different velocities--the interchange requires only about one second to complete.

C-field errors are still being improved in the newer standards both by better shielding designs and materials and by generating more uniform fields. As an impressive example, the present CsI standard at PTB employs a longitudinal C-field rather than the usual perpendicular-to-the-beam orientation, allowing the use of a very uniform solenoid coil structure to produce fields sufficiently uniform over the transition region to reduce associated errors to less than 3×10^{-14}.[(33)] Figure 13 shows a picture of this machine.

Electronics improvements seem to be generally keeping pace with beam tube progress. Some impressive results have been obtained by NBS and some commercial labs in terms of building signal processing equipment and even oscillators with greatly-improved phase noise characteristics.[25, 30] Also in the area of electronics, NRC has developed an improved version of their square-wave frequency modulation system.[31] The new system uses a faster switching rate of 8 1/3 Hz, and NRC feels that the total error contributed by the complete electronics system, including multipliers, modulation system, and servo components, is now less than 1×10^{-13}. PTB has adopted the same general type of square-wave system, featuring a 3 Hz switching rate and appropriate suppression of transient effects. The PTB group has also attempted to provide more stable excitation sources by designing their system for locking the excitation oscillator to either a rubidium cell, a hydrogen maser, or a very good crystal oscillator.

Finally, the second order Doppler shift uncertainty, which becomes very important at accuracy levels of 5×10^{-13} or better, has been studied extensively at NRC[26] and NBS.[32] The major effort is directed toward developing methods of inferring the actual velocity distribution in the atomic beam from an analysis of the observed Ramsey resonance curves. Results thus far look very promising for reducing this uncertainty to less than 1×10^{-13}.

Conclusion

Figure 14 summarizes the accuracies achieved by the various national standards labs, beginning in 1956 and including some projected values for standards now in the process of construction. The plotted values are generally equivalent to 1 σ estimates and are based on published results from the various labs discussed. The exact placement of some of the points is somewhat uncertain, since it is not always possible to determine exactly when a given accuracy was first achieved. However, it is clear that accuracies of 4×10^{-13} have already been achieved[22, 33] and that improved values of near 1×10^{-13} are expected within the next year or so.[22, 25, 26]

In terms of stability performance the best reported value so far[22, 33] is $\sigma(2, \tau) = 2.8 \times 10^{-12} \tau^{-\frac{1}{2}}$. Within the next year this value should be improved by more than a factor of ten[25] to near 2×10^{-13}.

The generally high level of performance being achieved by today's laboratory cesium standards is confirmed by analyses of long-term comparison data among the various standards by means of Loran-C and portable clock trips. The peak-to-peak spread of frequencies of the lab standards appears to be about 1×10^{-12}.[34]

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General approaches to Cs standards

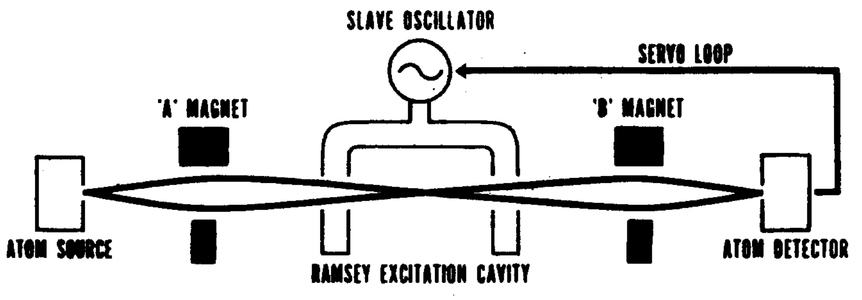
COMMERCIAL
- SIZE, WEIGHT, POWER CONSUMPTION, RELIABILITY
- GOOD PERFORMANCE OVER WIDE ENVIRONMENTAL RANGE
- ECONOMIC CONSIDERATIONS
- STABILITY EMPHASIZED OVER ACCURACY
- GOOD FIGURE-OF-MERIT VIA HIGH BEAM S/N RATIO
- CONTINUOUS OPERATION

LABORATORY
- ACCURACY, EVALUATION & STABILITY
- WIDE ENVIRONMENTAL RANGE NOT IMPORTANT
- GOOD FIGURE-OF-MERIT VIA NARROW LINEWIDTH & HIGH S/N RATIO
- INTERMITTENT OPERATION

Important laboratories in development of Cs standards

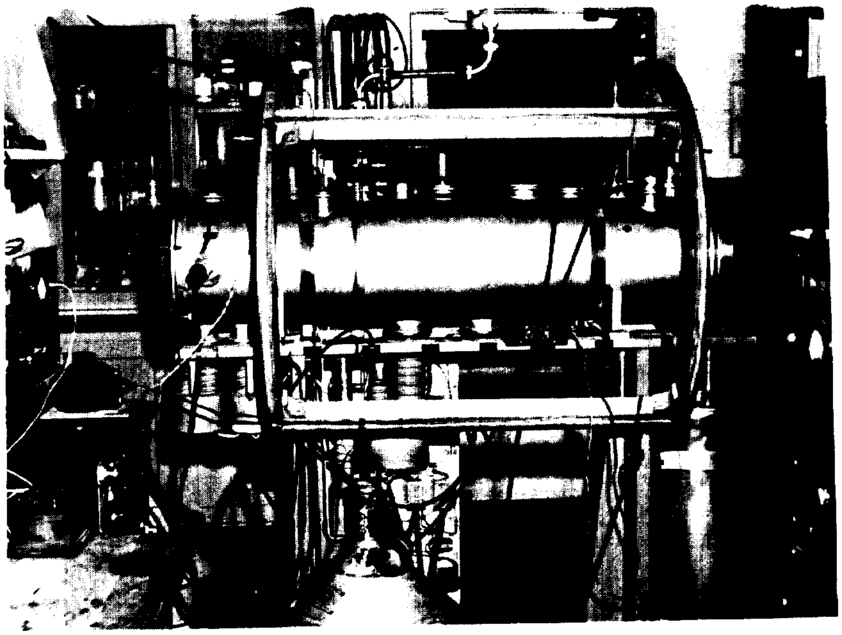
LSRH	LABORATOIRE SUISSE DE RECHERCHES HORLOGERES NEUCHATEL, SWITZERLAND
NBS	NATIONAL BUREAU OF STANDARDS BOULDER, COLORADO
NPL	NATIONAL PHYSICAL LABORATORY TEDDINGTON, ENGLAND
NRC	NATIONAL RESEARCH COUNCIL OTTAWA, CANADA
PTB	PHYSIKALISCH–TECHNISCHE BUNDESANSTALT BRAUNSCHWEIG, W. GERMANY

FLOP-IN ATOMIC BEAM

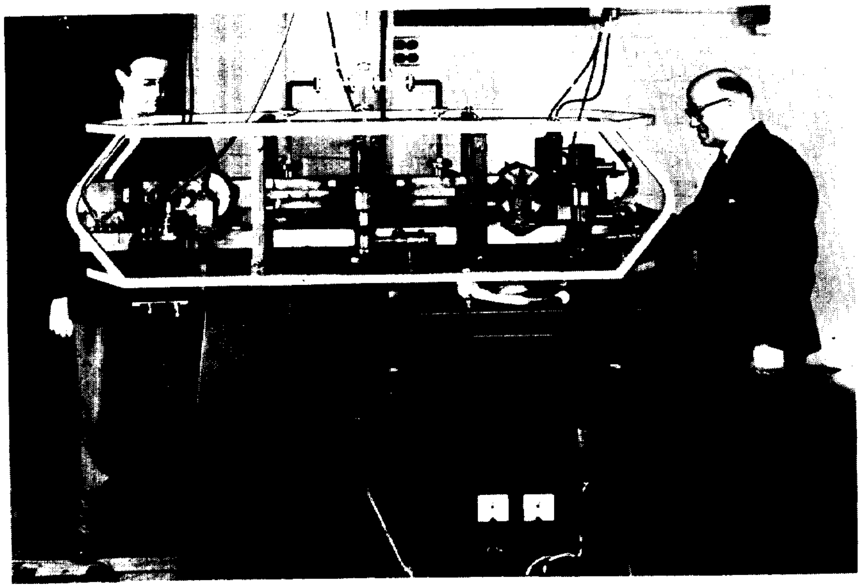


CESIUM 9 GHz

Operating principles for flop-in atomic beam technique



NBS-I cesium beam standard.



NPL-I cesium beam standard (courtesy of Dr. L. Essen, NPL, Crown Copyright Reserved).

Early models

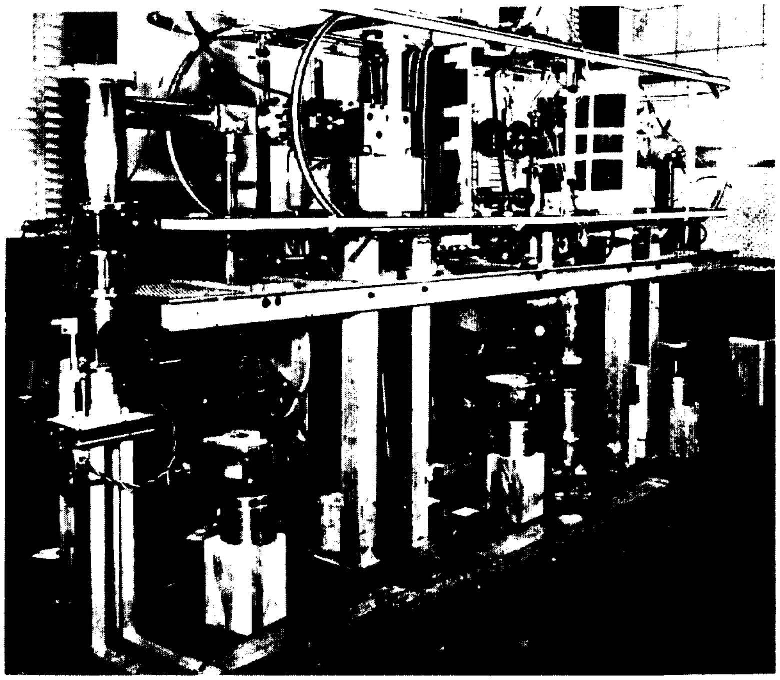
BASIC ACCOMPLISHMENTS

- APPLICATION OF MAGNETIC RESONANCE TECHNIQUE
- HIGH ACCURACY & STABILITY POTENTIAL
- ACCURACIES: A FEW $\times 10^{-11}$ TO 1×10^{-10}
- MEASUREMENT OF Cs FREQUENCY IN TERMS OF EPHEMERIS TIME

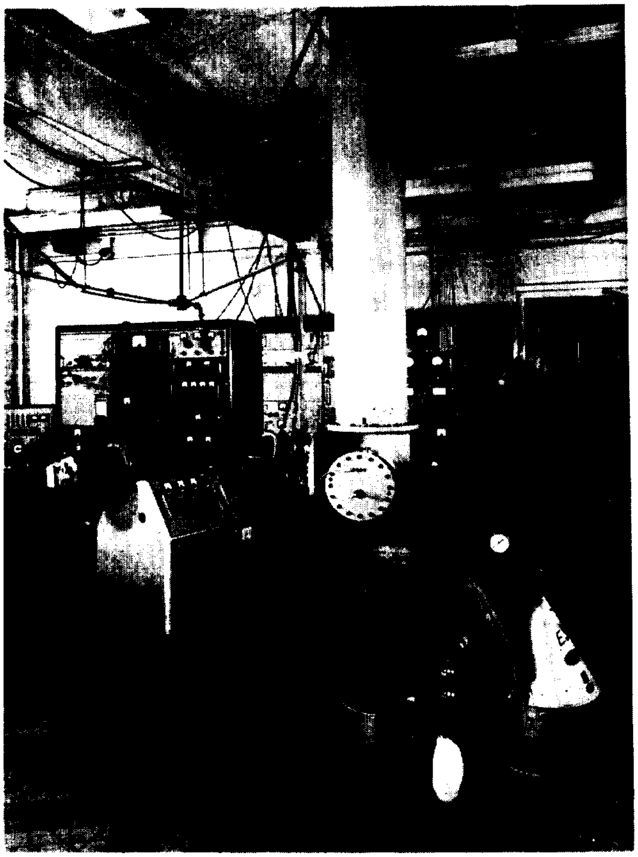
MAIN LIMITATIONS

- STABILITY OF EXCITATION SOURCES
- MANUAL MEASUREMENTS
- LOW BEAM S/N RATIO
- LARGE, UNSTABLE CAVITY PHASE SHIFTS
- MAGNETIC FIELD UNCERTAINTIES & NON-UNIFORMITIES

305 Basic Accomplishments and limitations of early cesium beam standards



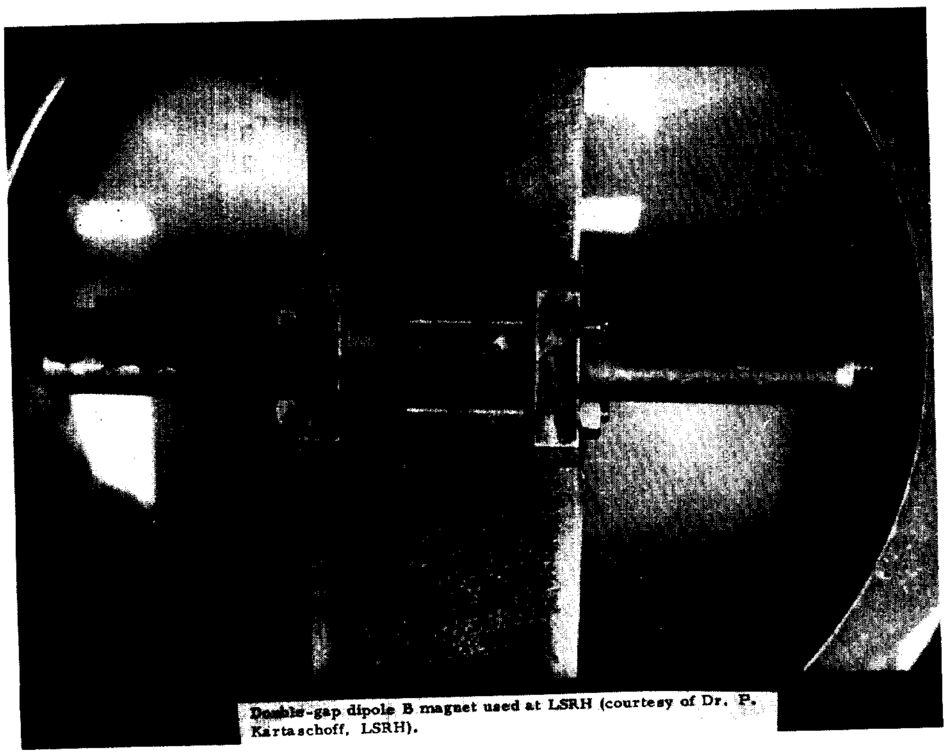
CsI (NRC) cesium beam standard (courtesy of Dr. A. Mungall, NRC).



NPL-2 cesium beam standard (courtesy of Dr. L. Essen, NPL, Crown Copyright Reserved).

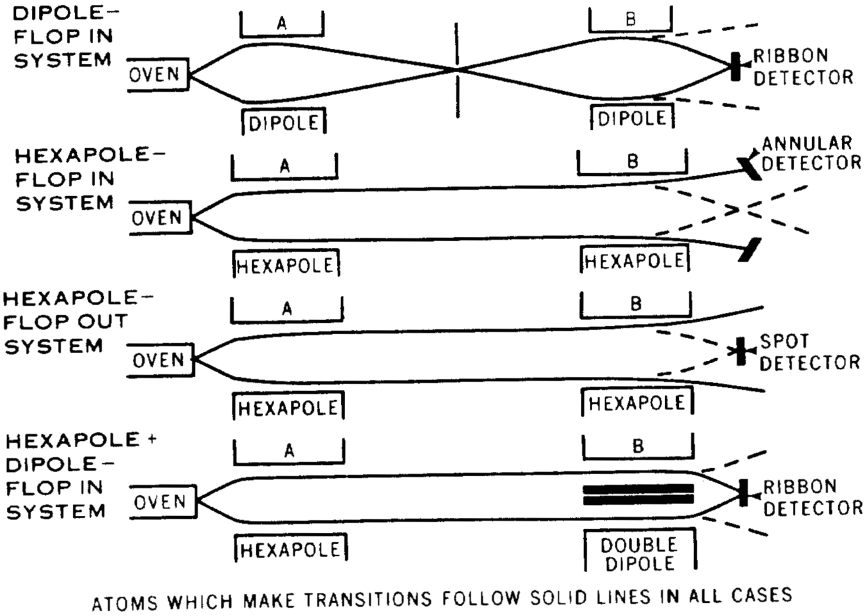
NBS-III cesium beam standard.

Cs III (NRC) cesium beam standard (courtesy of Dr. A. Mungall, NRC).



Double-gap dipole B magnet used at LSRH (courtesy of Dr. P. Kartaschoff, LSRH).

Dipole and multipole beam optics systems



Cs I (PTB) cesium beam standard (courtesy of B. Fischer, PTB).

Accuracy trends in lab Cs standards