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THE CAESIUM RESONATOR AS A STANDARD OF FREQUENCY AND TIME

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CONTENTS

The construction, operation, and testing of the standard are described.

The resonance employed is that due to the hyperfine splitting of caesium, having a frequency of approximately 9192 Mc/s. The transitions between the two atomic states F, m_F (4, 0) and F, m_F (3, 0) are detected in an atomic-beam chamber, in which the length of the transition region is 47 cm, giving a width of resonance, at half deflexion, of 350 cycles, and a standard deviation of setting to the peak of the resonance of ± 1 c/s. It is shown that the geometrical parameters of the beam chamber such as slit widths, alinement of the beam, and shape of the pole-pieces of the deflecting magnets are relatively unimportant, and that other parameters, including the pressure in the beam chamber, the temperature of the oven, from which the caesium atoms are evaporated, and the radio-frequency power exciting the transitions can be varied throughout wide limits without causing changes in resonant frequency exceeding 1 part in 10^{10}.

A unidirectional magnetic field is applied over the transition region to remove the field-dependent resonant lines of the Zeeman pattern from the central line which depends on the field to only a second-order extent. It has been found that a satisfactory resonance is obtained with a field as low as 0·05 Oe at which the total effect of the field on the frequency is only 1 c/s. The dependence of the frequency on the phase conditions in the two-cavity resonators carrying the exciting field is studied, and it is concluded that the phases can be made sufficiently close to enable the frequency to be defined with a precision of ± 1 part in 10^{10}.

The resonator is used as a passive instrument to calibrate the quartz clocks, usually at intervals of a few days; and it is estimated that the clocks calibrated in this way provide at all times the atomic unit of frequency and time interval with a standard deviation of ± 2 parts in 10^{10}. The quartz clocks are also calibrated in terms of astronomical time and the results are compared for the period from June 1955 to June 1956.

For operational purposes the frequency of the resonance was taken as 9 192 631 830 c/s which was the value obtained in terms of the unit of uniform astronomical time made available by the Royal Greenwich Observatory in June 1955. The value is being determined in terms of the second of ephemeris time, which has now been adopted by the International Committee of Weights and Measures as the unit of time, but to obtain the accuracy required the comparison must be extended over a long interval in view of the difficulties associated with the astronomical measurements.

1. Introduction

Rabi (1945) first suggested that the atomic-beam magnetic-resonance technique could be used to establish a unit of frequency and time, and he indicated that it might be possible to achieve an accuracy sufficient for measuring directly the change of rate of a clock with gravitational potential, which is predicted by the general theory of relativity. A practical apparatus outlined by Kusch (1949) was constructed at the National Bureau of Standards (Sherwood, Lyons, McCracken & Kusch 1952), and it gave an improved value for the caesium resonance although it did not give the accuracy required for a standard. Zacharias, Yates & Haun (1954, 1955) obtained a caesium resonance 200 c/s wide, indicating its potential precision as a standard although its frequency was not measured. An operational caesium frequency standard was designed and constructed at the National Physical Laboratory (Essen & Parry 1955), largely on the basis of Kusch's proposals, but using some recent technical advances. It has been operated since June 1955 and used to calibrate the quartz clocks and to correlate atomic and astronomical time (Essen & Parry 1956; Essen 1956). A standard of frequency based on the inversion spectrum of ammonia and called the Maser (microwave amplification by stimulated emission of radiation) has been described by Gordon, Zeiger & Townes (1955). The frequency has not been related accurately with the quartz working standards or with astronomical time,* but a comparison between two similar standards revealed a high stability of operation over short periods. The resonance was, however, relatively ten times wider than that of the caesium standard and the frequency was more dependent on external influences. In its present state therefore it is less suitable as a definitive standard.

Theoretical considerations indicate that the frequency of the caesium resonance should be almost independent of the parameters of the apparatus except for small effects due respectively to the external magnetic field and the phase conditions of the exciting oscillations. But conditions in practice inevitably depart from those stipulated by theory, and there are a number of factors which might cause a distortion of the resonance and a shift of the peak. The N.P.L. apparatus was therefore designed to allow the effect of varying all the parameters to be checked experimentally.

In this paper the resonator is described in detail, and the results are given of an experimental investigation of its performance as a definitive standard of frequency and time. Results are also given of the comparison between the atomic and astronomical units of time during the period of the investigation; finally, the design of an improved resonator is briefly outlined.

* But see reference [Bonanomi & Herrmann 1956] added in proof.

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2. The nature of the resonance

It is well known that atoms can exist in energy states which are so closely spaced that the radiation emitted or absorbed during transitions between them falls in the radio-frequency part of the spectrum. The radiation frequency f is given by the usual Bohr relationship

$$W_1 - W_2 = \Delta W = hf, \tag{1}$$

where W_1 and W_2 are the energies of two such states, and h is Planck's constant.

The ground state of caesium, for example, consists of two components spaced by an amount corresponding to a frequency of approximately 9192 Mc/s. It is this splitting of the ground state which gives rise to the hyperfine structure of lines in the optical spectrum of caesium, and it is therefore known as the hyperfine structure separation. This frequency f_0 (usually called $\Delta\nu_0$ in the literature) is a fundamental constant of the atom, and forms the basis of the standard to be described.

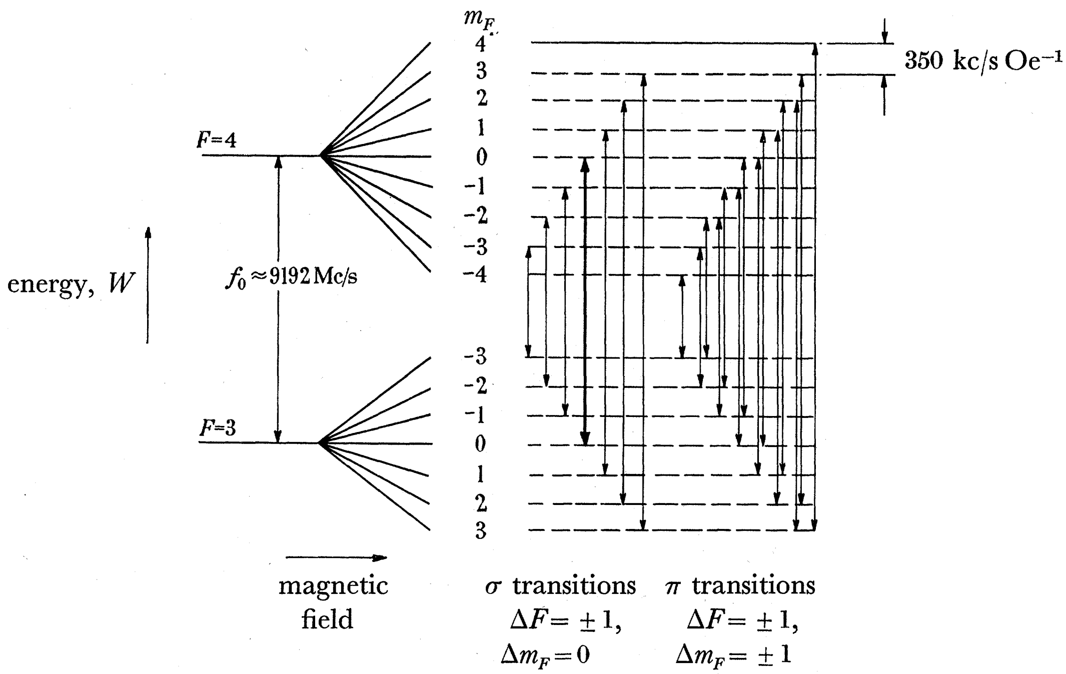

Figure 1. Magnetic energy levels of caesium atoms.

The hyperfine splitting is a consequence of the interaction between the spin of the valency electron of the atom and that of the nucleus. The spin of the electron (J) is $\pm\frac{1}{2}$, indicating that the angular momentum associated with it is $\pm\frac{1}{2}$ $(h/2\pi)$; and that of the nucleus (I) is $\frac{7}{2}$. According to the direction of the electronic spin therefore, there are two states designated by the quantum number F, where $F = I \pm J$. These levels are represented diagrammatically in figure 1. In the presence of a magnetic field they are subject to the usual Zeeman splitting represented by an additional quantum number m_F which can have any integral value between $\pm F$. In a weak magnetic field transitions can occur in accordance with the selection rules

$$\Delta F = 0, \pm 1; \quad \Delta m_F = 0, \pm 1.$$

The transitions for which $\Delta F = \pm 1$ correspond to frequencies in the region of 9192 Mc/s and are shown in figure 1. The complete system of lines must be taken into account since, for practical reasons, the standard is operated in the presence of a small magnetic field. The theory of the transitions and details of the Rabi magnetic resonance technique have been fully described (Ramsey 1956; Smith 1956), and it is proposed to reproduce here only the general features required for an appreciation of the investigation.

It can be shown that for caesium the energy associated with the magnetic energy states is

$$W(F, m_F) = -\frac{hf_0}{16} - \frac{2\mu_I H m_F}{7} \pm \frac{hf_0}{2}\left(1 + \frac{m_F x}{2} + x^2\right)^{\frac{1}{2}}, \tag{2}$$

in which f_0 is the hyperfine splitting at zero field, H is the magnetic field and

$$x = (-2\mu_J + \tfrac{2}{7}\mu_I)\, H/hf_0, \tag{3}$$

where μ_I is the nuclear magnetic moment and μ_J is the electronic magnetic moment. In this expression the nuclear moment is relatively small and can be neglected while the electronic moment can be taken as equal to the Bohr magneton μ_0. Inserting these values we find

$$x = 3{\cdot}045 \times 10^{-4}\, H.$$

The energies and the transition frequencies will vary with the field, but for the case when $m_F = 0$ we have

$$\frac{\Delta W}{h} = \frac{W(4, 0) - W(3, 0)}{h} = f_0\,(1 + \tfrac{1}{2}x^2),$$

i.e.

$$f = f_0 + 426\, H^2. \tag{4}$$

The frequency of this line, the central line of the pattern, is thus nearly independent of field, the total effect of a field of 0·1 Oe, for example, being only 4 c/s. The frequencies of the other lines deviate from this central line by successive amounts of $0{\cdot}35H$ Mc/s, if second-order terms are neglected.

The spins impart magnetic properties to the atom, which, in the presence of an external magnetic field, behaves as a magnetic dipole, the moment being positive for one state and negative for the other. In consequence of this moment the atom is deflected in a non-uniform magnetic field and the deflexions are in opposite directions for atoms in the two states. This gives a means of recognizing when transitions from one state to the other occur.

The effective moment of the atom is given by

$$\mu_{\text{eff.}} = -\partial W/\partial H, \tag{5}$$

and can be determined from equations (2) and (3). For atoms in the (4, 0), (3, 0) levels it is approximately $\pm 0{\cdot}6\mu_0$ at a field of 3300 Oe. To obtain a good deflexion of the atoms both a large gradient and a large field are therefore required. The deflexion depends on the velocity of the atom as it travels between the pole-pieces of the deflecting magnet. For atoms having the most probable thermal velocity at a temperature T the angular deflexion

$$\theta = \mu_{\text{eff.}} \frac{\partial H}{\partial z} \frac{d}{4kT}, \tag{6}$$

where d is the length of the magnet and k is Boltzmann's constant. The spreading of the beam due to the velocity distribution is overcome in Rabi's double-deflexion method illustrated in figure 2. The second deflecting magnet is identical with the first and the paths 1 are typical of atoms in the levels (4, 0) and (3, 0). If the transitions are induced in the region between the deflecting magnets, the magnetic moments and hence the deflexions are reversed and these atoms are deflected along paths 2 to the detector. The atoms will follow different paths of this nature according to their initial directions, velocities and moments, the slit selecting those having an appropriate combination of values, but all the selected atoms which undergo a transition are brought to a sharp focus at the detector. As there are sixteen energy levels equally populated, one-eighth of the atoms in the collimated beam should suffer transitions and reach the detector.

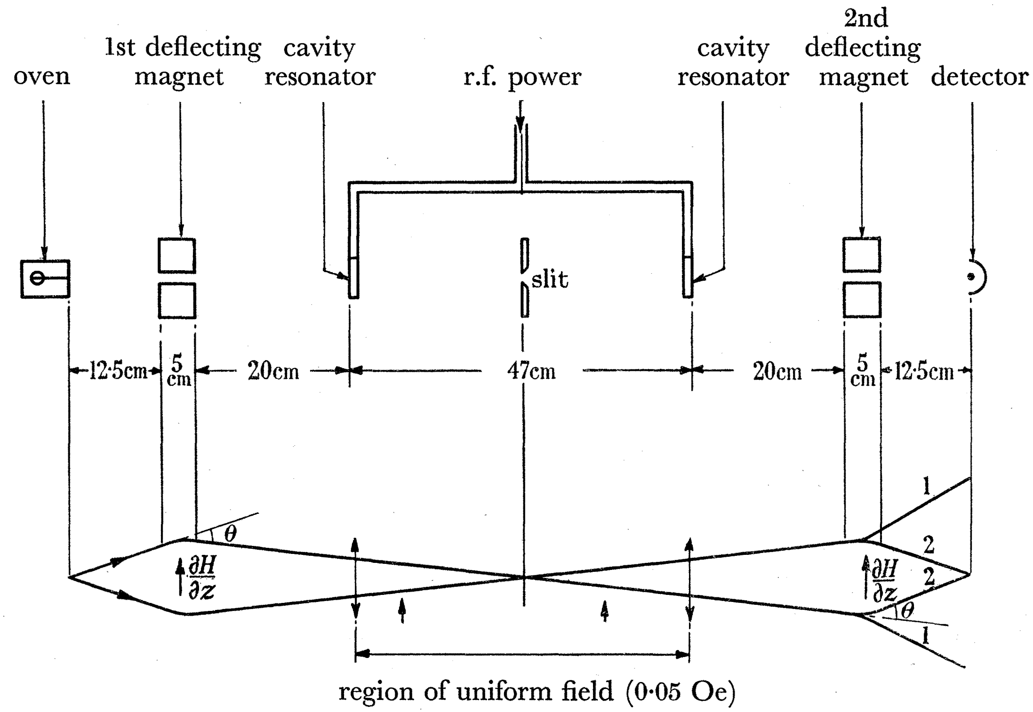

FIGURE 2. Arrangement of components in the beam chamber.

The magnetic field in the region between the deflecting magnets can be quite small, and it is this small uniform field which determines the separation of the lines in the Zeeman pattern. In the classical experiments a high-frequency magnetic field was applied along the major part of this region, the width of the resonance curve being determined by the length of the transition region, in accordance with the simple 'uncertainty' formula $\Delta f \Delta t = 1$. For the most probable velocity of about $2{\cdot}5 \times 10^4$ cm/s and for a length of 50 cm the width Δf is 500 c/s. It would be very difficult to obtain an r.f. field of uniform phase and amplitude over such a length, but Ramsey (1956) has shown that it is preferable to excite the atoms over two short regions, and this scheme lends itself very well to the use of the wave-guide cavity resonators as shown in figure 2. The width of the curve is then reduced, the exact formula, taking account of the velocity distribution, being

$$\Delta f = 0{\cdot}65\ \alpha/L,$$

α being the most probable velocity and L the distance between the exciting regions. The first exciting field acting alone gives a resonance about 25 kc/s wide at the half-amplitude points, and the second field introduces a somewhat complicated effect depending on the relative phases of the two fields. If the fields are in phase, which is the normal operating condition, and the frequency is exactly equal to the line frequency f appropriate to the uniform field, then a maximum transition probability is obtained. If the applied frequency is $f \pm \alpha/L$, maximum probabilities are again obtained because in the transit time the applied frequency has changed in phase by 2π with respect to f and the two exciting pulses are thus again in phase. These secondary maxima clearly depend on the velocity of the atoms, and if they all travelled with the same velocity a series of maxima and minima would be obtained; but as in practice there is a wide velocity distribution the secondary maxima are quickly smoothed out and curves are obtained such as that shown in figure 3. The curve previously published (Essen & Parry 1955) shows a minimum instead of a maximum because at that time the gradient of the second deflecting magnet was reversed, relative to that of the first magnet. All atoms were initially focused on to the detector and when transitions occurred a resonance dip was obtained.

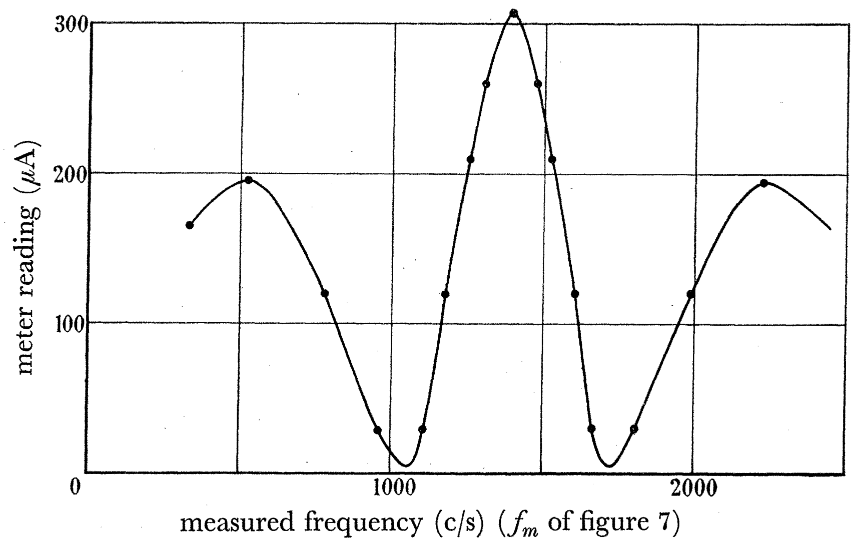

FIGURE 3. Experimental plot of the caesium resonance $(3, 0) \rightleftharpoons (4, 0)$ at a field of 0·05 Oe.

3. DESCRIPTION OF THE APPARATUS

(a) *Beam chamber*

The beam chamber (figure 4) consists of a length of copper wave guide of section $8{\cdot}9 \times 4{\cdot}45$ cm, which was chosen because it was readily available and is known to have smooth, clean surfaces, suitable for vacuum work. The vacuum is produced by three oil-diffusion pumps constructed from a non-magnetic alloy. The pumps, only two of which are shown for the sake of clarity, are followed by refrigerated baffles and liquid-nitrogen traps. The refrigerator, which maintains the temperature of the baffles at $-30°$ C is housed in an adjacent room together with the backing pumps. Three diffusion pumps are used because in atomic beam work it had often been found necessary to have a separately pumped baffle chamber between the oven and the main chamber in order to secure a sufficiently low pressure. It was found, however, that this is not needed with the type of oven used, and all three pumps are operating on the single chamber.

The chamber was mounted on a heavy bronze beam supported on two bronze castings in a magnetic east-west direction. There was, therefore, no component of the earth's magnetic field along the direction of the beam, and two sets of coils were used to compensate for the vertical and horizontal components and to produce, when required, a small uniform field in a horizontal plane at right angles to the direction of the beam.

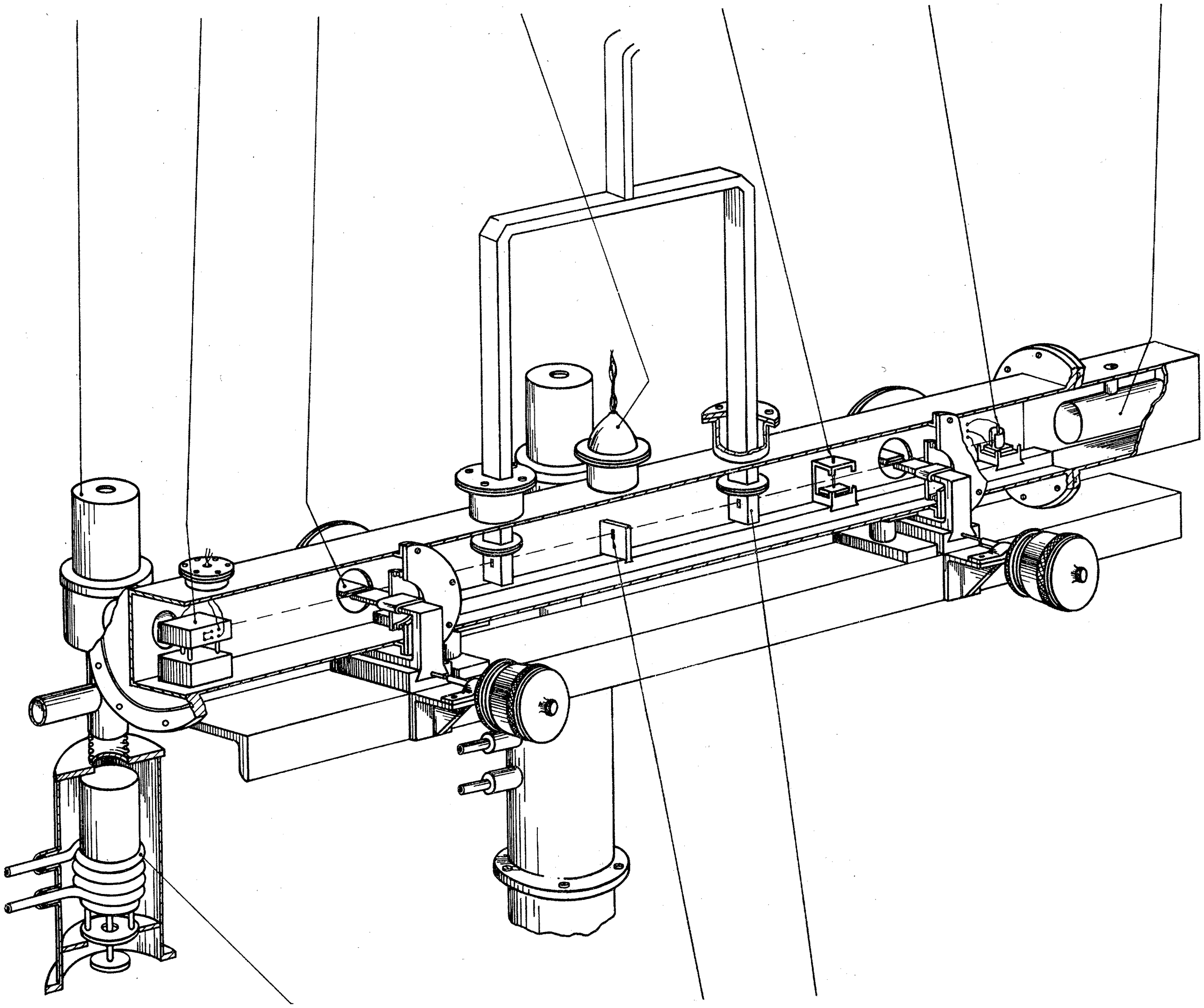

FIGURE 4. Atomic beam chamber for caesium frequency standard.

(b) *The oven*

The oven is of the general form described by Davis, Nagle & Zacharias (1949), but the slit, of overall dimensions $3 \times 0{\cdot}2$ mm, is split into ten channels ground in the face of one of the blocks from which the oven is constructed. All faces making contact are optically polished, but even so it was found that there was some loss of caesium through the interfaces, which could probably be eliminated by using copper seals. The oven, which is maintained at a temperature of 200° C, is charged with about 0·25 g of caesium chloride and 0·25 g of metallic sodium, a process which can be carried out easily in the open. One charge usually lasts about six weeks, and although this life could certainly be improved, it is adequate for a laboratory model. This relatively long life proved of great help in the initial efforts to make the equipment work. Recharging the oven takes very little time, and the standard can be put back in operation after several hours of pumping. The oven is mounted on a kinematic support and can be moved across the beam chamber and also tilted by means of external micrometers operating through bellows. Access to the oven is through the flanged end of the beam chamber.

(c) *The deflecting magnets*

The beam leaves the oven in the form of a thin strip about 3 mm high and 0·2 mm wide, and the magnets are designed to impart a uniform deflexion to a beam of this section as described in Ramsey's book (1956). Details of the design can be seen in figure 5. A novel feature is that although the yoke is outside the vacuum chamber the use of bellows enables the magnet to be moved across the chamber for the alinement of the beam. This arrangement also enables the field coils to be made of 900 turns of insulated wire carrying a low

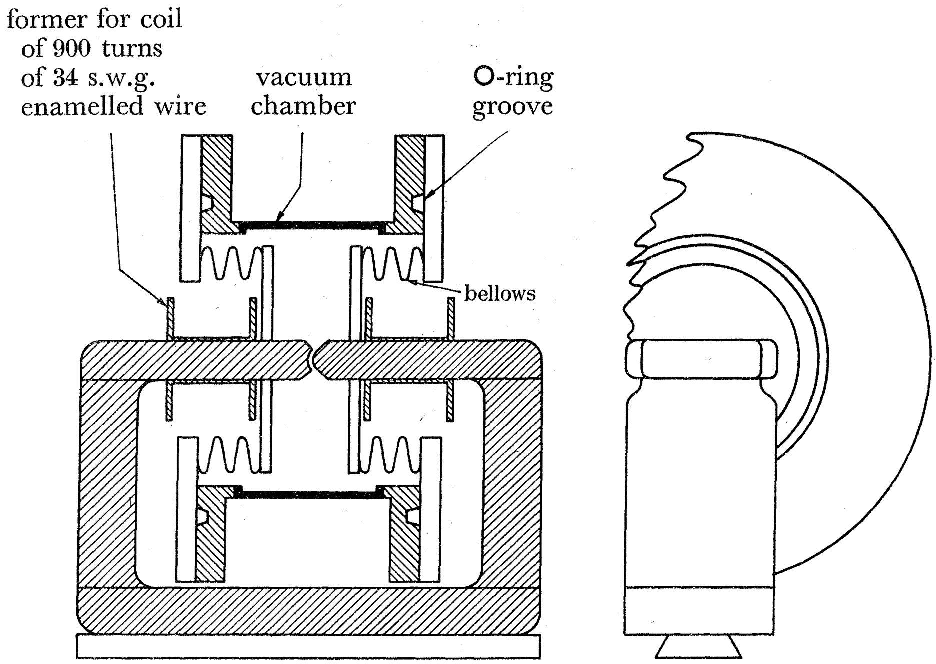

FIGURE 5. Magnet assembly.

current of 300 mA instead of the usual few turns of bare copper wire carrying hundreds of amperes. The field in the gap is 3300 Oe with a gradient of approximately 3000 Oe/cm. The gap was originally 1 mm, but since evidence was found that the pole-pieces were obstructing a part of the beam it was later increased to 2 mm without producing any noticeably adverse effect. It is thus clear that the shape of the pole-pieces is not critical.

The coils are wound as closely as possible to the pole-pieces and can be seen inside the bellows in figure 5. The micrometers for driving the magnet assemblies are mounted on the bronze beam.

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(*d*) *The collimating slit, stopping wire and detector*

The collimating slit, stopping wire and detector are mounted on a bronze beam of section $1{\cdot}9 \times 1{\cdot}9$ cm which runs most of the length of the beam chamber and can be withdrawn after the liquid-air trap at the end of the chamber has been removed. The components slide in grooves cut in the beam and are moved through bellows by micrometer heads mounted outside the chamber (not shown in figure 4).

The slit is made from two Monel metal knife edges, the width being adjustable by an external micrometer, made of phosphor bronze, in order to avoid the use of magnetic material near the transition region. The width normally used is 0·2 mm.

The stopping wire, also about 0·2 mm in diameter, was included to stop the very fast atoms which suffer little deflexion and increase the background level of the signal. It was, however, found to be unnecessary, and was not used in most of the experimental work.

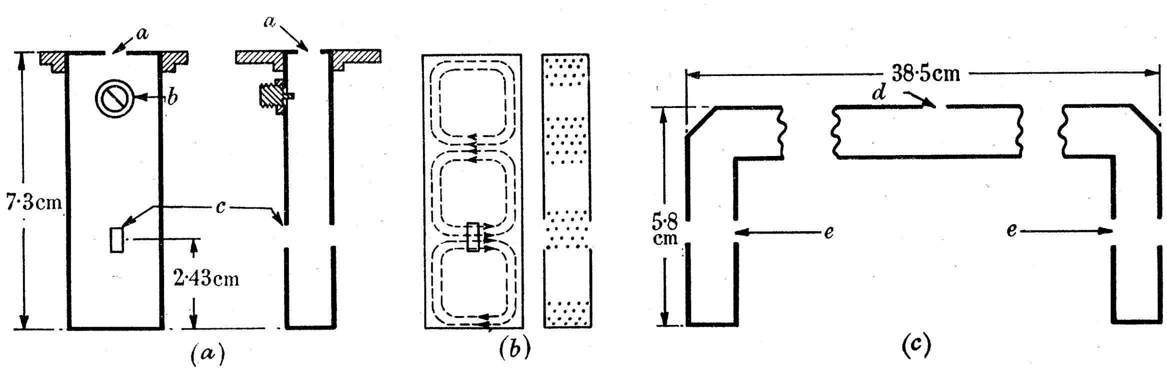

FIGURE 6. Cavity resonators. (*a*) H_{013} cavity: *a*, coupling hole; *b*, tuning plunger; *c*, beam aperture. (*b*) Magnetic field distribution in H_{013} cavity. (*c*) Single H_{01} cavity: *d*, coupling hole; *e*, beam apertures.

The detector consists of a tungsten strip heated to about 1000° C, at which temperature the caesium atoms striking it are emitted again as positive ions and are collected by a curved plate maintained at a potential of −20 V relative to the wire. The strip 1 mm wide was used in place of a wire for its extra robustness, and the effective detector width was reduced to 0·2 mm by a slit in front of it. The collector plate is connected through a sealed lead to a vibrating reed electrometer, in which the voltage developed across a $10^{10}\ \Omega$ resistor is converted to an a.c. voltage and amplified. The amplified signal is rectified and a final reading proportional to the beam intensity is obtained on a microammeter.

For detection by a hot tungsten wire in this way the ionization potential of the atom must be less than the work function of tungsten. This is one of the reasons for choosing caesium, although the convenient frequency is another important consideration.

(*e*) *The cavity resonators*

The r.f. exciting field is applied as the beam passes through two cavity resonators, or alternatively a single U-shaped resonator, of the dimensions shown in figure 6. They are made from standard copper wave guide of internal dimensions $2{\cdot}39 \times 1{\cdot}02$ cm and are excited in the H_{01} mode of resonance. The field shape for this resonance is illustrated in figure 6*b*, and it will be seen that the field is at right angles to the path of the beam, is of constant phase and amplitude in the direction of the path, and is of constant phase, and nearly constant amplitude over the height of the beam.

Two separate cavities (figure 6*a*) are coupled together through holes of approximately 7 mm diameter which were adjusted so that the resonances of the cavities locked together. Glass vacuum windows are fitted where the wave guide passes through the walls of the beam chamber, and a common wave guide leads to the oscillator. Single cavities (figure 6*c*) were made for experimental purposes of lengths such that the end portions through which the beam passes were either in phase or 180° out of phase.

(*f*) *Radio-frequency oscillators and frequency measurement*

The oscillator first used to provide the r.f. magnetic field was a velocity-modulated valve (CV 129) controlled in frequency by a cavity having a very low decrement, in the manner described by Pound (1947). It has been shown (Essen 1953) that this oscillator has a band width of 1 c/s under suitable conditions and a frequency drift as low as 1 part in 10^8 per hour. It seemed well suited therefore to the present purpose, especially as the power requirements were not known and it was useful to have available the maximum that could readily be obtained. The wide frequency range was also an advantage for exploring the whole Zeeman pattern of resonances.

The oscillator was used until June 1956, but the manipulation of its controls which had to be carried out in order to obtain the necessary frequency stability was an empirical and sometimes tedious operation. As soon therefore as the r.f. power required to produce the transitions was determined a multiplier and amplifier were built to operate from a quartz oscillator (Marconi's Wireless Telegraph Co. type RD 6170) which had been manufactured with a frequency of 5·0069 Mc/s and a range of frequency adjustment of $\pm 3\times 10^{-5}$. The multiplying factors used are $2\times 17\times 3\times 3\times 2\times 3$. The fine control giving a range of 5×10^{-8} is mounted on the front panel of the instrument and is the only one that need be used for setting to the peak of the caesium resonance.

The quartz oscillator, like the Pound controlled oscillator, is used simply as the exciting source, and its frequency is measured in terms of the primary quartz standard immediately the setting to resonance has been made.

The method of relating the caesium resonance frequency with the quartz clocks and astronomical time is shown schematically in figure 7. The choice of method was to some extent influenced by the apparatus and experience already available, and although it may not be the simplest that could be devised it satisfies the following conditions which are regarded as essential:

(*a*) The exciting source and the various signals derived from the quartz standard for its measurement all have a band width not exceeding 1 c/s.

(*b*) There are no oscillations of other frequencies, such as 'side-bands', which are of sufficient amplitude to affect the atomic resonance or the frequency measurement.

(*c*) The frequency measurement is made within a time of about 1 s of the setting to resonance in order to eliminate the effect of frequency drift of the exciting source.

When the r.f. oscillator has been set to the caesium resonance its frequency f is subtracted from a frequency $n_2 f_2$ (approximately $9{\cdot}2\times 10^9$ c/s) derived from a 5 Mc/s quartz oscillator.

The latter frequency could be derived by direct multiplication from the 100 kc/s primary standard but experience at the N.P.L. has shown that it is not easy to avoid troubles due to phase modulation at the lower frequencies, which result in an increased band width at the high-frequency end of the multiplying chain. A high-quality 5 Mc/s quartz oscillator which was available is therefore used as an intermediate stage. Its frequency f_2 is determined in terms of the 100 kc/s standard throughout the measurement and its use does not add any significant error.

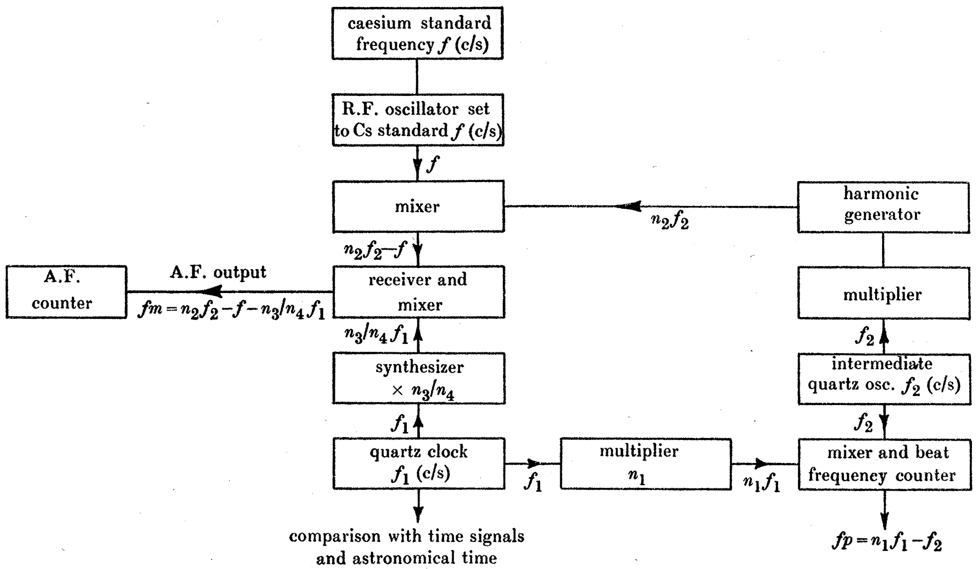

FIGURE 7. The factors n_2, n_3 and n_4 are chosen so that the output frequency f_m is approximately 1000 c/s. The frequency f_1 can then be calculated from the atomic frequency f, and the measured frequencies f_m and f_p as follows:

$$f_m = n_2 f_2 - f - \frac{n_3}{n_4} f_1, \quad f_p = n_1 f_1 - f_2,$$

then

$$f_1 = \frac{f + f_m + n_2 f_p}{n_1 n_2 - n_3/n_4}.$$

In the experiment described the following values were used: $f = 9\ 192\ 631\ 831$ c/s ($= f_0 + 1$; field $= 0{\cdot}05$ Oe). $f_1 =$ nominal 10^5 c/s standard quartz clock. $f_2 =$ nominal 5×10^6 c/s quartz oscillator. $n_1 = 50$; $n_2 = 1840$; $n_3 = 7367$; $n_4 = 100$.

All results are given in the form:

$$\frac{\Delta f_1}{f_1\ (\text{nom.})} = \frac{f_1 - 10^5}{10^5} = \frac{f_m + 1840 f_p - 1169}{0{\cdot}9193} \times 10^{-10}.$$

The resulting difference frequency $(n_2 f_2 - f)$, which is in the region of 7·4 Mc/s, is amplified and mixed with a similar frequency synthesized from the 100 kc/s standard. The synthesis is carried out only far enough to give frequencies in steps of 1 kc/s and is technically straightforward. The final difference frequency is in the region of 1 kc/s and is measured either by means of a counter or by reference to a calibrated audio-frequency oscillator, with a precision of 1 c/s corresponding to a precision of approximately 1 part in 10^{10} in the frequency comparison.

For experiments of short duration the quartz frequency f_1 is assumed to be constant, and variations in the caesium frequency f can be measured. If f_1 is calibrated in terms of astronomical time the comparison gives the caesium frequency in the astronomical unit, but if some value is assumed for the caesium frequency then the quartz frequency and the astronomical unit are determined in terms of the caesium standard.

(g) *Other electronic circuits*

The electronic circuits occupy altogether six 6 ft. racks, but apart from those concerned with the frequency measurement they are of a standard form and do not call for special description. They provide constant low-current supplies for the various magnetic field coils, high-current supplies for the oven and detector wire, supplies for operating the vacuum gauges, and also include the main amplifier of the vibrating reed detector.

4. Experimental results

The object of the investigation was to determine the accuracy with which a quartz oscillator can be calibrated in terms of the caesium resonance. For this purpose there are advantages in using the resonance as a passive system, and no attempt has been made to control the frequency of the quartz oscillator, at a value having some fixed relationship with that of the resonance, by means of a servo loop.

It is already well established (Essen 1955; Smith 1953) that the N.P.L. quartz standards operate with a day-to-day stability of ± 1 part in 10^{10}, and that their drift rates of about $+3$ parts in 10^9 per month are in general constant to several parts in 10^{10} per month. If, therefore, they can be calibrated in terms of a definitive standard at intervals of say a few days and with a precision of ± 1 part in 10^{10} they can be used to distribute frequencies and time intervals with this accuracy. This represents an improvement of about 100 times over what can be achieved when the quartz standards are calibrated by astronomical means. Any further increase in accuracy could not be readily exploited with the existing means of distributing standard frequencies and time intervals by means of quartz clocks and standard frequency transmissions. The accuracy of ± 1 part in 10^{10} seemed therefore to represent a reasonable target.

(a) *Initial operation of the equipment*

The beam of atoms emerging from the oven is expected to diverge over several degrees, so that if the collimator slit is fixed in position a part of the beam should be received by the detector at some position of its traverse across the beam chamber. The gaps between the pole-pieces of the deflecting magnets are comparatively wide, and with reasonable alinement the magnets should not restrict the beam. It did not appear, therefore, that there would be much difficulty in finding and alining the beam, and no facilities for precise alinement by optical means were provided.

However, as the authors lacked previous experience of beam techniques the detector was initially placed near to the oven in the position of the first deflecting magnet. A strong beam having been found, the detector was moved to its normal position at the end of the beam chamber. The direct, undeflected beam was again found without difficulty, and the positions of the magnets and detector were set to give a maximum beam current. The deflecting magnets were then energized and the deflexions produced were noted. The first magnet reduced the beam strength by 50 %, and the second magnet which was initially connected with the gradient in the opposite direction restored the beam to 80 % of its initial value. These seemed reasonable figures and r.f. power was applied to a single cavity resonator, a uniform field of about 0·5 Oe being applied over the transition region. The search for the broad resonance corresponding to a single cavity was not at first successful, no more than a slight indication of resonance being observed. It was concluded that the beam, or at least the atoms in the required levels, were being obstructed by the magnets owing to some lack of alinement. As an easy way of testing this, the gaps were increased to 2 mm, the current being increased to restore the field to its earlier value. After some adjustment of the r.f. power the resonance was then found. The next step was to add the second cavity, and to search for the sharp Ramsey resonance. This called for a very slow, smooth adjustment of the frequency of the oscillator through the whole extent of the broad resonance and also a rather more critical adjustment of the r.f. power. After some hours of searching the resonance was found, and its precise frequency having been determined it was subsequently found at will.

Although the magnet gap had been doubled the gradient was not significantly changed and an adequate deflexion was obtained. For some time the equipment was operated in the condition described in which a decrease of current was obtained at resonance; but later the pole-pieces of one magnet were reversed so as to give 'flop-in' instead of 'flop-out' resonances. Most of the subsequent tests were made using 'flop-in' resonances.

(*b*) *Precision of setting*

The resonant frequency is measured by varying the frequency of the r.f. source manually and setting it to give the maximum current reading on the microammeter, or alternatively to give equal readings on either side of the peak, in which case the mean of the two frequencies obtained is taken as the resonant value. The mean of twenty such settings is normally regarded as one determination of resonant frequency, and the precision obtained is illustrated by the results of twelve successive determinations given in table 1. These results are not selected, as this particular test was carried out only on the one occasion,

TABLE 1. PRECISION OF MEASUREMENT

1 set no.	2 f_m (c/s) mean of 20 observations	3 standard deviation of single observation in set $10^{-10}\times$	4 standard error of mean of 20 observations $10^{-10}\times$	5 f_p (c/s)	6 $\Delta f_1/f_1$ $10^{-10}\times$
1	1457·4	1·8	0·6	0·5296	1373·8
2	1458·0	2·0	0·7	0·5303	1375·9
3	1461·0	1·5	0·5	0·5288	1376·1
4	1458·4	2·5	0·8	0·5294	1374·4
5	1459·4	1·5	0·5	0·5298	1376·4
6	1456·0	2·7	0·9	0·5301	1373·2
7	1458·0	0·8	0·3	0·5301	1375·4
8	1458·5	2·1	0·7	0·5292	1374·3
9	1456·5	1·2	0·4	0·5306	1374·7
10	1458·7	2·5	0·8	0·5292	1374·4
11	1457·8	2·0	0·7	0·5297	1374·5
12	1456·4	1·6	0·5	0·5299	1373·7

Mean $\Delta f_1/f_1$	1374·7
Standard deviation	1×10^{-10}
Standard error	$0·3\times10^{-10}$

under normal operating conditions, with an oven temperature of 200° C, an amplitude of resonance curve of 300μA, a pressure of 5×10^{-7} mm Hg, and with a uniform magnetic field of 0·05 Oe. The significance of the various columns will be clear from figure 7. The last column gives the deviation of the 100 kc/s clock designated Q_{26} in terms of the caesium resonance. For this purpose the value of the resonant frequency is taken as that first measured (Essen & Parry 1955), 9 192 631 830 c/s at zero field, with 1 c/s added to allow for the field of 0·05 Oe, in accordance with equation (4).

It is seen from column 6 that the standard deviation of the values of the 100 kc/s standard, which includes the error in the measurement of f_p, is ±1 part in 10^{10}. If the errors of measurement are random the standard error of the whole set is $\pm0·3$ part in 10^{10}, but as in practice only one determination is usually made the standard deviation of the calibration of the quartz standard in terms of the caesium resonance will be taken as ±1 part in 10^{10}.

Another set of results extending through a 24 h period was taken to check that there was no significant periodic variation of the quartz standard during the day. There was already strong evidence of the absence of such a variation, from the inter-comparison between the various quartz standards, but there was the possibility that all of them could have a similar diurnal variation which would remain undetected. The results given in table 2 for quartz clock Q_{13} reveal no variations exceeding 1 part in 10^{10} from the known average drift of Q_{13} which was approximately $+1$ part in 10^{10} per day. Different clocks are used for the results of tables 1 and 2 because these experiments were actually made at different times, and the operational standard had been changed.

TABLE 2. DIURNAL VARIATION

time (G.M.T.)	mean of 20 readings of f_m (c/s)	f_p (c/s)	$\Delta f_1/f_1$ $10^{-10}\times$
0945	1392	−0·296	−350
1030	1389	−0·295	−350
1115	1389	−0·295	−350
1330	1390	−0·295	−349
1440	1389	−0·293	−347
1540	1389	−0·293	−347
1615	1387	−0·293	−348
2100	1388	−0·294	−348
0730	1385	−0·292	−349
0840	1390	−0·294	−347
0930	1390	−0·295	−349

The symmetry of the resonance curve is an important indication that the experimental conditions are satisfactory, as will be explained in more detail later, and complete curves are therefore plotted whenever any important change to the equipment is made. A typical set of results given in table 3 shows that even at the flatter part of the curve well removed from the resonance peak the symmetry can be checked to a few parts in 10^{10}. The curve obtained from these values, reproduced in figure 3, illustrates the shape obtained with the Ramsey double excitation method.

Some of the experiments carried out to check the effect of varying the parameters of the equipment occupied several days. The quartz clocks could be relied on to maintain their steady drift rates to ±1 part in 10^{10} over such periods, and if the setting accuracy is taken as ± 1 part in 10^{10} an overall accuracy of ± 2 parts in 10^{10} is obtained. For some of the tests the conditions necessarily departed from those giving the optimum precision and the accuracy was reduced to about ± 5 parts in 10^{10}.

Table 3. Symmetry of resonance curve

($1\ \text{c/s} \approx 1 \times 10^{-10}$)

deflexion (μA)	means of ten settings of f_m (c/s)		mid points (c/s)
185			1388
160	1301	1471	1386
120	1256	1518	1387
60	1170	1600	1385
0	1107	1667	1387
0	971	1813	1387
60	779	1991	1385
110	522	2218	1370
90	320	2444	1382

Note. The readings for 110 μA correspond to the rather flat side peaks in the resonance curve; the accuracy of setting is therefore inferior to that at other points.

(*c*) *Variation of frequency with magnetic field*

The complete Zeeman pattern is formed from transitions for which $\Delta F = 1$, $\Delta m_F = 0, \pm 1$, and on each side of the central $(4, 0) \rightleftharpoons (3, 0)$ line there are three other σ lines ($\Delta m_F = 0$) at frequencies of $f_0 \pm 0{\cdot}7H$ Mc/s, $f_0 \pm 1{\cdot}4H$ Mc/s and $f_0 \pm 2{\cdot}1H$ Mc/s, H being the uniform field in oersteds. These are all excited with the r.f. magnetic field parallel to the uniform field. There are also on each side of the central line four π lines ($\Delta m_F = \pm 1$) at frequencies $f_0 \pm 0{\cdot}35H$ Mc/s, $f_0 \pm 1{\cdot}05H$ Mc/s, $f_0 \pm 1{\cdot}75H$ Mc/s and $f_0 \pm 2{\cdot}45H$ Mc/s excited by a field at right angles to the uniform field. In practice, if the field is at some intermediate angle all the lines can be excited by the same field, the actual separation being determined by the total amplitude, and not the component, of the field. The frequencies of the lines were measured at a number of field strengths, and the separations were found to agree with the theoretical values within the accuracy of the field measurements.

The Ramsey pattern for the central line was found without difficulty, but only after fairly careful adjustment of the field for the other lines; and in the above measurements only the broad resonances corresponding to the path length of the individual cavities were observed. Tests with a small magnetometer made from the description of Palmer (1953) revealed that the 'uniform' field varied along the beam path as shown in figure 8. This was clearly due to the stray fields of the deflecting magnets and was not unexpected. Care had been taken in the design of the equipment to avoid the use of magnetic materials in the vicinity of the beam, which could cause small local irregularities in the field distribution. Large masses of iron in the room construction made broad variations inevitable, but it was planned to compensate for these by suitable coils if necessary. The field actually obtained was very symmetrical, and the non-uniformity in the space between the cavities was largely removed by supplementary coils taking a current of about 15 mA situated near the cavities. The Ramsey pattern could be found for the central line, which is independent of field to a first order under almost any conditions even with a field deliberately distorted as in figure 8*c*.

In order to check relationship (4) for the central line the vertical and horizontal components of the earth's field were compensated by suitable currents in the field coils which were then used to give horizontal fields in the range 0 to 1 Oe, the stray fields of the

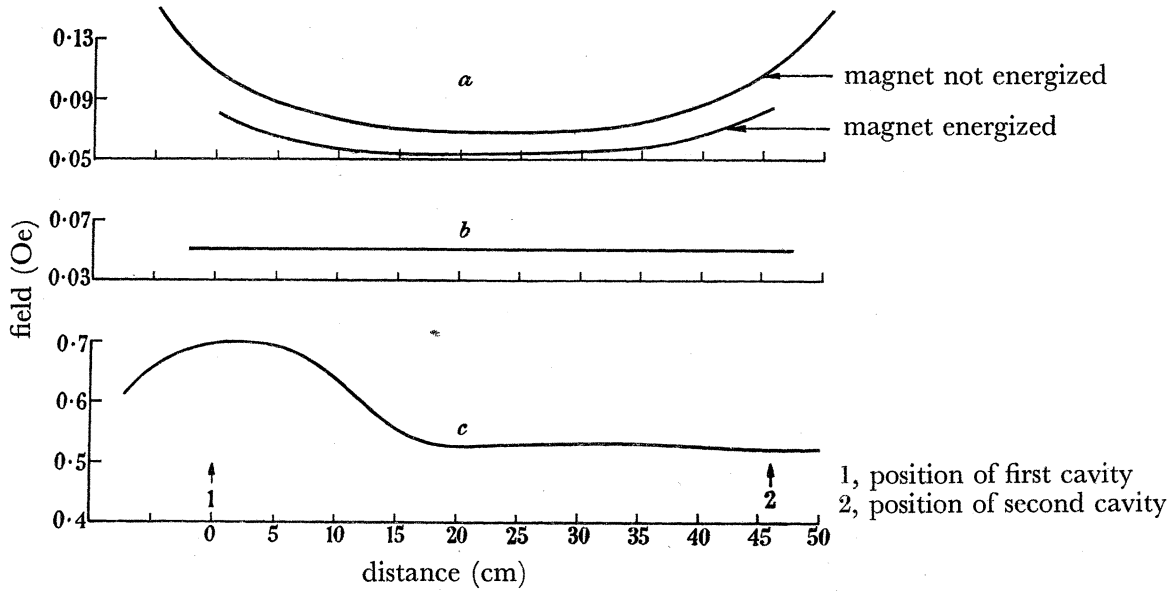

FIGURE 8. Field distribution (deflecting field in opposition to earth's field). (*a*) Without small compensating coils. (*b*) With small compensating coils. (*c*) Distorted field.

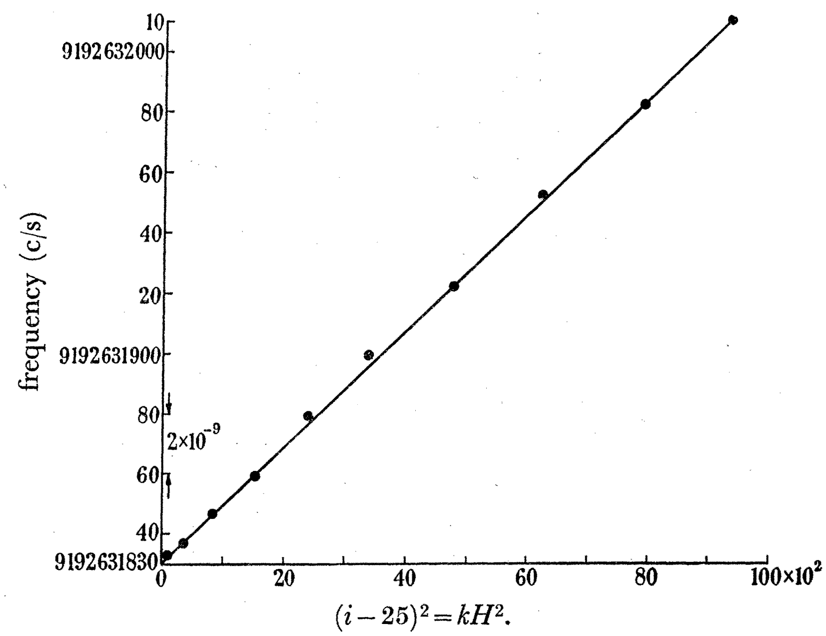

FIGURE 9. Variation of the caesium resonance frequency with field squared. From the slope of the line, $\Delta f/H^2 = 422$ c/s.

deflecting magnets also being compensated. The current required to give zero field was 25 mA and the quantity (current $-25)^2$ is therefore taken as being proportional to H^2 in the graphical representation of the results in figure 9. To determine the proportionality constant an independent calibration of the field coils was obtained by measuring the frequency displacement of the field-dependent lines for a known coil current. Such a calibration gave a constant of 422, compared with the theoretical value of 426. The agreement is very good considering the smallness of the correction term; and with the field of 0·05 Oe now normally used the difference between the frequencies obtained using the theoretical and measured values of the correction term is only 1 part in 10^{12}.

The amplitude of the resonance became smaller at very low values of uniform field, and no usable resonance was obtained at fields below 0·02 Oe.

It was first decided (Essen & Parry 1955) to make routine measurements of the frequency of the central line at the field which made the neighbouring field-dependent σ line exactly 500 kc/s away from the central line; and the frequency-measuring equipment of figure 7 was provided with an alternative channel for setting on this line. The frequency was set and the field varied to give the Ramsey resonance. The equipment was then switched for normal operation and the central line was measured at the same field. This process was reasonably satisfactory, but the field had to be set for each measurement because of local variations of the field in the building from day to day. Moreover, the sharp resonance of the field-dependent line was not always easy to observe. The standard field was therefore changed to 0·05 Oe which still gave a very good resonance and was large enough to separate the peaks of the other lines. The nearest σ lines are 35 kc/s away, and although the broad single-cavity resonances overlap, any effect of these on the sharp central resonance, which is only 330 c/s wide, is negligible for the present accuracy. With such a small field it is sufficient to maintain the current in the field coils at the appropriate value (31 mA), and any variations of field due to external causes have no significant effect on the resonant frequency. Increasing the field by 40 %, for example, would change the frequency by only 1 part in 10^{10}.

(*d*) *The relative phase of the fields in the two exciting regions*

The transition probabilities for different phase conditions in the two exciting regions have been calculated by Ramsey (1956), and table 4 gives the displacement of the resonance peak and the asymmetry introduced by phase differences of 5, 10 and 15°. A measurement of the symmetry of the curve provides an experimental criterion of equality.

In two overcoupled cavities or in a single cavity, the regions through which the beam passes will be in phase or antiphase, as a property of the circuits, apart from small effects which may arise from unequal losses in different parts of the resonator.

The system normally used consisting of two overcoupled cavities was carefully constructed in the workshop, but several single U-shaped cavities, shown in figure 6, were roughly made in the laboratory for experimental purposes. Initial results gave evidence of a difference of about 10 parts in 10^{10} between the resonant frequencies obtained with different cavities. These experiments were extended over a period of 14 days, and it was decided to repeat them in such a way that the change from the normal two-cavity system to the other was made in a few minutes. Both systems were mounted in the beam chamber at the same time, and the only change that had to be made was a reassembly of the waveguide feed from the oscillator to the cavities. There is in table 5 definite evidence of different frequencies according to the method of excitation, and in this connexion it should be mentioned that the 39 cm cavity was obtained from the 25 cm cavity by adding a length of guide in the middle section, the same end-pieces being used. The cavities were inspected, and it was noticed that the short circuits closing the ends were badly soldered. Resoldering effected some improvement, and it is noteworthy that the frequency deviation was

Table 4. Errors due to a phase difference between the exciting fields in the separated oscillating field method

phase difference (δ)	$\Delta\omega L/2\pi\alpha$	maximum and minimum values of P	error in centre peak (parts in 10^{10})	asymmetry: difference in separation of side maxima from centre maximum (parts in 10^{10})	asymmetry: difference in height of side maxima (%)	asymmetry: difference in minima (%)
5°	−1·31	0·4736	5	10	1·5	10
	−0·60	0·1099				
	+0·01	0·7655				
	+0·63	0·1199				
	+1·35	0·4669				
10°	−1·28	0·4771	13	17	2·5	20
	−0·58	0·1053				
	+0·03	0·7649				
	+0·64	0·1251				
	+1·38	0·4637				
15°	−1·26	0·4807	17	26	4	30
	−0·57	0·1010				
	+0·04	0·7637				
	+0·66	0·1306				
	+1·40	0·4606				

where
δ is the phase difference between the exciting fields,
L is the length of transition region (47 cm),
α is the most probable velocity,
$\Delta\omega = 2\pi\,(fa - f)$,
f is the resonance frequency,
fa is the applied frequency,
P is the transition probability.

Table 5. Results with different cavities

date (1956)	cavity	asymmetry % difference between amplitude of subsidiary peaks	frequency deviation (parts in 10^{10})
(1) 30 June	single cavity 25 cm between beam paths	20	$+15 \pm 2$
(2) 30 June	separate cavities spaced 47 cm	<0·5	0 ± 2
(3) 9 July	single cavity 39·3 cm between beam paths	40	$+18 \pm 2$
(4) 9 July	separate cavities as in (2)	0	0 ± 2
(5) 12 July	single cavity as in (3) but ends of cavity resoldered	3	-6 ± 2
(6) 12 July	separate cavities as in (2)	0	0 ± 2
(7) 19 July	separate cavities as in (2)	0	0 ± 2
(8) 19 July	single cavity as in (5) but reversed	10	$+9 \pm 2$

reversed with reversal of the cavity, and that the mean value agreed within the limits of error with that obtained under normal conditions.

The asymmetry of the experimental curves, one of which is reproduced in figure 10, gave an immediate warning of incorrect conditions with the single cavities. It is estimated that the experimental symmetry check serves to establish that there are no errors exceeding ± 2 parts in 10^{10} due to phase difference, and that with a carefully made cavity the error will be very much less than this. It should be pointed out that there was no direct evidence that the effects observed were due to phase differences.

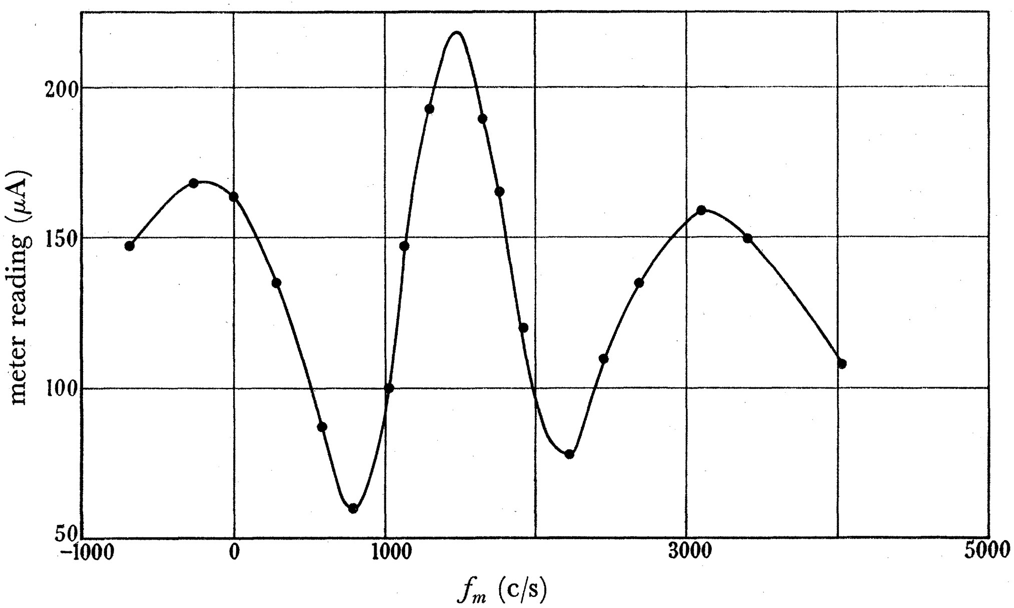

FIGURE 10. Experimental curve showing asymmetry due to a phase difference between the exciting fields in the separated oscillating field method. Single cavity $L = 25$ cm.

(*e*) *Radio-frequency power requirements*

The power absorbed in the wave-guide feed and the exciting cavity or cavities was measured, at a point near the oscillator, throughout the range of power giving the normal Ramsey resonance. The powers and the associated amplitudes, widths and frequencies of resonances are given in table 6. There is no significant change of frequency with power, so that in operation the power need not be monitored. The width decreases a little with decrease of power but by a smaller extent than is indicated by theory. When the power was increased beyond 600 μW, distorted curves were obtained, and it appears that the most suitable power is somewhat less than that giving the maximum amplitude of resonance. The measurements were made with a uniform field of 0·05 Oe, and similar measurements at a field of 0·7 Oe gave results which were not very different.

TABLE 6. RADIO-FREQUENCY POWER MEASUREMENTS

microwave power (μW)	resonance amplitude (μA)	deviation of resonant frequency (parts in 10^{10})	width of resonance curve at half height (c/s)
4·5	110	−2	330
14	175	+1	330
36	270	−1	330
60	340	+1	370
95	300	0	400
148	250	0	400
322	100	−1	390
600	80	0	390

(*f*) *Exciting fields of more than one frequency*

Ramsey (1956) has discussed the effect on the resonant frequency of an exciting field having components at more than one frequency. Since in these transitions the effective field is circularly polarized the linear field used in practice can be regarded as the combination of two frequencies f and $-f$, but the effect of a component differing by $2f$ is quite negligible in our case. In the two methods of generating the r.f. oscillations which have been used in the investigation care was taken to keep any spurious signal at very low intensity, but this would have been less easy to achieve if the exciting source had been derived by frequency synthesis from a 100 kc/s quartz standard. In order to simulate the worst conditions likely to arise the source obtained by multiplication from a quartz oscillator was mixed with the Pound stabilized oscillator, offset in frequency by various amounts. The powers of the two components were comparable and were in both cases adequate to excite the Ramsey resonance. The results given in table 7 show that the effect could be significant in these circumstances. If the source offset in frequency was attenuated by 10 db the effect was reduced to a negligible amount. The last column shows that two equally spaced sidebands will not have any significant effect on the frequency of the resonance.

TABLE 7. EFFECT OF R.F. FIELD HAVING COMPONENTS OF MORE THAN ONE FREQUENCY

deviation of added frequency from resonance (kc/s)	deviation of resonant frequency (parts in 10^{10})	average magnitude of effect (parts in 10^{10})	error of mean (parts in 10^{10})
+ 5	+ 6	± 7	−1·5
− 5	− 9		
+ 10	+12	±11	+1
− 10	−10		
+ 20	+19	±15	+4
− 20	−10		
+ 30	+18	±15	+3
− 30	−12		
+ 50	+10	±11	−1
− 50	−12		
+100	+ 5	± 4·5	+0·5
−100	− 4		
+150	+ 2	± 2	0
−150	− 2		
+200	+ 1	+ 0·5	+0·5
−200	0		

(*g*) *Pressure in the beam chamber*

The pressure inside the beam chamber is measured by means of an ionization gauge, the electrodes of which are inside the actual chamber. The beam appeared at a pressure of about 1×10^{-5} mm Hg and increased in strength as the pressure was reduced to 1×10^{-6} mm Hg. Little further increase was observed as the pressure was reduced to 3×10^{-7} mm Hg.

The resonance frequency was measured at pressures between 8×10^{-6} and 3×10^{-7} mm Hg, and any change was less than 2 parts in 10^{10}, which represents the limit of accuracy of these measurements.

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Any pressure lower than 3×10^{-6} mm Hg is regarded as suitable for the operation of the equipment described, although a longer beam path would naturally require a correspondingly lower pressure. A pressure of 3×10^{-6} mm Hg is usually obtained after 3 h of pumping from atmospheric pressure and with the help of liquid air in the traps. After several days of pumping a pressure of 3×10^{-6} mm Hg is obtained by the pumps and refrigerated baffles, and it is an important feature that the standard can be operated for routine measurements without the use of liquid air. No severe vacuum problems were encountered in spite of the numerous soldered flanges, O-ring seals, and metal bellows, some of which could not be effectively cleaned after they had been soldered in position. Oil-diffusion pumps of the self-fractionating type (Metro-Vickers 03B) were employed with the silent type (DR1) backing pumps. Silicone oil is used in the diffusion pumps and it has not been changed throughout the two years of operation during which air has been admitted on many occasions while the oil was still hot. For leak detection a fine hydrogen jet is played round the suspected part and gives a change in the reading on the ionization gauge control panel if a leak is present. Plasticine has been found to be the most convenient means of effecting a temporary seal of small leaks. It adheres to the surface better than some materials prepared for this purpose.

It may be useful to mention one vacuum problem which gave trouble for some time. A persistent instability of the detector reading was finally traced to a small leak at one of the Kovar-glass seals from the detector wire. Although the leak was so small that it gave a barely detectable increase in the pressure readings the stream of molecules playing on the detector caused a serious deterioration in its performance.

(*h*) *Effect of other parameters of the beam chamber*

In the classical atomic beam experiments the r.f. field was produced by two parallel wires which were bent round at the ends to allow the beam to pass, and to lead from the chamber to the oscillator. At these bends there is a change in direction of the field and Millman (see Ramsey 1956) showed that a large distortion of the resonance curve could result. Any similar effect will clearly be very small with the cavity excitation, but there will be some distortion of the field at the slits. Experimental checks were made by altering the direction of the beam by adjustments of the oven and detector position. The beam would thus pass through different parts of the cavity slits, but no detectable frequency change was observed.

Measurements were also made with different widths of the collimating slit and with the detector set slightly off the best position and again no detectable effects were observed.

Doppler effects caused by the r.f. field being not quite at right angles to the beam direction would be expected to cause a broadening of the resonance without changing the position of the peak. Some experiments made by rotating the cavities through 3° confirmed this conclusion. It is clear from these tests that the conditions of mechanical alinement are not stringent, and that most of the adjustments provided in the experimental model could be omitted in future models.

Experiments were also made at different oven temperatures and with different fields in the coils of the deflecting magnets and no changes of resonant frequency could be detected.

5. Calibration of quartz clocks in terms of the caesium resonance

In addition to the experimental investigation described in the preceding section the caesium resonator has been used under standard conditions to calibrate the N.P.L. quartz clocks. The procedure of measurement is illustrated in figure 7, and sample results for two of the clocks, Q_{13} and Q_{26}, are given in figure 11. The direct measurement was usually made only on Q_{26}, the other curve being obtained from the difference between Q_{26} and Q_{13} which is obtained as a routine measurement in the quartz standards laboratory. The two curves are given to show that some of the small fluctuations from a straight line are due to variations in the clocks and not to errors of comparison with the caesium resonance. Including these deviations the total spread from straight lines is only ± 2 parts in 10^{10}. The results for these particular months are given because no experimental work was being done and the measurements were made in a routine fashion, by two different observers. The oven was fairly cool (170° C) giving an amplitude of resonance curve of 200 μA. The values are obtained as the mean of twenty settings to resonance occupying a time of 10 min.

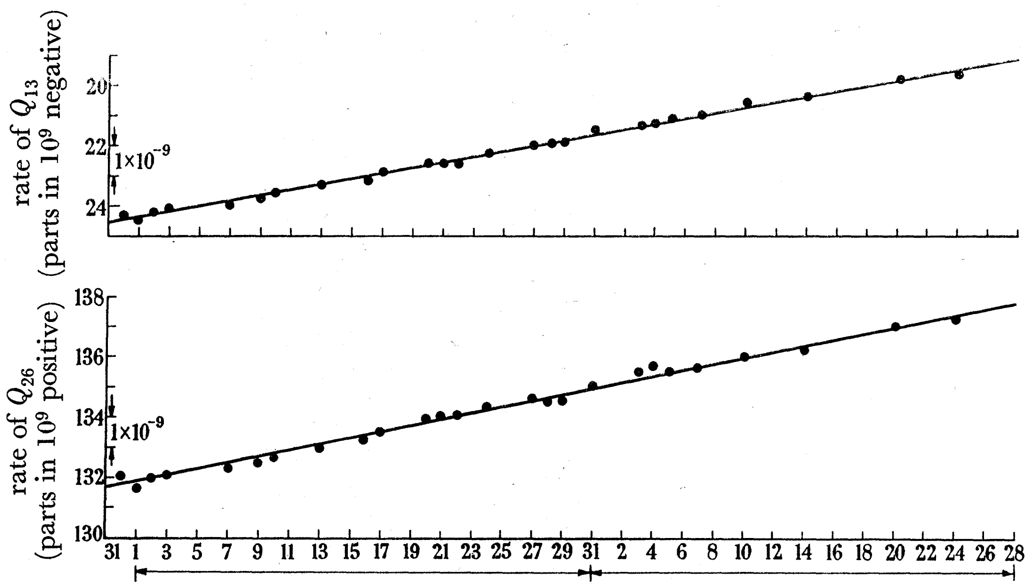

Figure 11. Rates of quartz clocks, Q_{13} and Q_{26}, for August and September, 1956.

The results illustrate the gradual drift in frequency of the two clocks. It is interesting to note, for comparison, how a calibration in terms of astronomical measurements would appear on the same diagram. If the astronomical observations of star positions were made with a transit instrument, having a standard error for the average of a night's readings of $\pm 0{\cdot}02$, the spread of the points would be 2000 times greater and they would still be at least 200 times greater if a photographic zenith tube (p.z.t.) were used. The accuracy of the average value of frequency is, however, increased by extending the astronomical measurements over longer intervals, and an accuracy of the order of ± 1 part in 10^9 would be expected from the p.z.t. observations in a period of 1 month. In practice, smoothing over periods of 1 year is required to eliminate the annual fluctuation in the period of the earth's rotation. The smoothing is carried out by quartz clocks which serve as the working standards of time. In figure 12 the continuous curve represents the frequency of clock

Q_{13} in terms of the value of the caesium resonance obtained in June 1955, the circles and triangles giving the value in terms of the finally corrected time signals of the Royal Greenwich Observatory and of the U.S. Naval Observatory respectively, as far as they are available. The results show that the frequency of the caesium resonance expressed in terms of the average unit of time for June 1955 to June 1956 would have been about 1·6 parts in 10^9 (15 c/s) higher than that expressed in the unit adopted in June 1955. They indicate that the smoothed astronomical time when finally corrected is uniform to ± 2 parts in 10^9, and that the earth's period at the beginning and end of the year was the same relative to the atomic unit within ± 2 parts in 10^9.

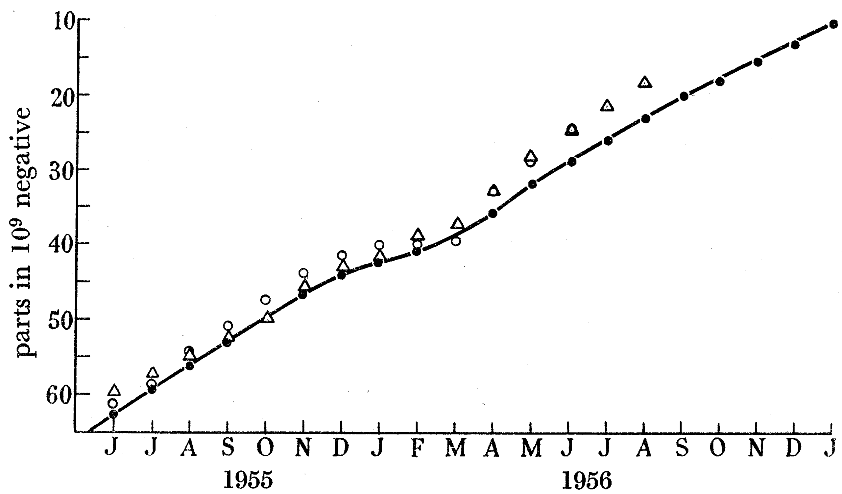

FIGURE 12. Rate of Q_{13} in terms of caesium and astronomical time. ●, caesium; ○, Royal Greenwich Observatory; Δ, U.S. Naval Observatory.

6. Frequency of the caesium resonance

The value previously published by the authors (Essen & Parry 1955) was 9192631830 $\pm$ 10 c/s, where the second was the value currently adopted by the Royal Greenwich Observatory in June 1955. The value in terms of the average second on the uniform time scale (UT2) for the period June 1955 to June 1956 would be 9192631845 c/s $\pm$ 2 c/s. The uniform time scale is based on the rotation of the earth on its axis; but it is now internationally recommended (Jones 1955) that the second of ephemeris time, which is based on the revolution of the earth round the sun, should be used for precise work. The caesium frequency in terms of this unit is being measured in co-operation with Drs W. Markowitz and G. Hall of the U.S. Naval Observatory and will be announced as soon as the astronomical data are available.

Sherwood *et al.* (1952) published the value 9192632000 $\pm$ 2000 c/s and Sherwood & Lyons (1956, private communications) have reported three values of 9 192 631 970 $\pm$ 90, 9192631800 $\pm$ 50 and 9192631880 $\pm$ 30 c/s. The results are stated to be not definitive and no corrections for time signals have been made. These values were obtained in 1952 and 1953, although they were not published, and they agree with the present value within the limits of accuracy given, and the uncertainty of the unit of time in which they are expressed.

7. Conclusion and future programme

The investigation described has shown that the present experimental model of the caesium resonator can be used to define frequency with a standard deviation of ± 1 part in 10^{10}; and that the quartz clocks calibrated by the caesium standard at intervals of a few days provide a continuously operating standard of frequency and time interval which is known in terms of the caesium resonance with a standard deviation of ± 2 parts in 10^{10}. These figures take account of estimated random and systematic errors due, for example, to uncertainties of magnetic field, errors of phase, and purity of the source used for exciting the resonance. They represent the accuracies of single measurements consisting of the mean of twenty settings to resonance and occupying a time of about 10 min.

The experience gained leads to the conclusion that a caesium resonator having a sharper resonance, less than 100 c/s wide, could be designed, built and operated without difficulty and that such a resonator could be used to define frequency by simple routine measurements with extreme limits of error of ± 1 part in 10^{10}. A design of such a resonator is now well advanced. It consists of a beam chamber about 14 ft long, mounted vertically. The outside walls of the chamber will be entirely free from vacuum seals so that it can be raised to expose all the internal components for mounting and servicing. It is planned also to use in this equipment or in the present experimental equipment an alternative atom, probably rubidium, to provide a second frequency standard for comparison purposes. It is hoped too to carry out a precise comparison between the caesium resonance frequency and that of the ammonia molecular resonance. This is of theoretical importance because the forces involved in the two transitions are of a different nature, and a comparison of the frequencies over long periods of time will be of interest.

The comparisons between atomic and astronomical time will be continued in order to reveal any variations between the two systems.

The authors wish to acknowledge the value of initial discussions on atomic beam techniques, in particular with Professor P. Kusch, Professor J. R. Zacharias and Dr H. Lyons in the U.S.A., and with Dr K. F. Smith at Cambridge. Mr J. McA. Steele, of the Electricity Division, National Physical Laboratory, is responsible for the maintenance and rating of the quartz clocks used in the comparisons and Mr E. G. Hope, of the same Division, carried out much of the detailed design and construction of the electronic equipment. Mr R. W. Donaldson assisted in the latter stages of the experimental work. The beam chamber was constructed from sketches by Mr A. Gridley, of the Metrology Workshop, Mr J. B. Thomas assisting with the mechanical work. The project was followed throughout with interest and encouragement by Sir Edward Bullard, F.R.S., at that time the Director of the Laboratory, and by Mr R. S. J. Spilsbury, Superintendent of the Electricity Division.

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