NBS ATOMIC FREQUENCY STANDARDS

R. C. Mockler and R. E. Beehler

The National Bureau of Standards, Boulder, Colorado

ABSTRACT

Two dissimilar cesium atomic beam frequency standards have been compared over the last several months. The zero field frequencies have a fixed difference of 1×10^{-11}. The precision of measurement is 2×10^{-12}. This represents the standard deviation of the mean for measurement times of a few hours. One of these machines has a separation of 55 cm between the oscillating fields of the Ramsey exciting system and a line width of 300 cps. The other machine has a separation of 164 cm between the oscillating fields and a line width of about 100 cps. The signal-to-noise ratio ranges from 100 to 400 in both devices. The largest contribution to the uncertainty in the zero field frequency comparisons results from peculiarities in the C field. The longer of the two machines is the present United States Frequency Standard; the shorter machine is an alternate standard. The assumed frequency for the $(F = 4, m_f = 0) \leftrightarrow (F = 3, m_f = 0)$ transition at zero field is 9192631770.0 cps. Corrections for the 60 kc standard frequency broadcasts of Station WWVB (formerly KK2XEI), Boulder, Colorado, are made about four times each week.

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Discussion

The problem of eliminating systematic errors in atomic beam frequency standards is a difficult one. It is of special concern because at the present time these instrumental errors limit the absolute accuracy of these devices. These errors are evident in experiments comparing different cesium beam standards. Such comparisons have been made by a number of laboratories. Those comparisons between devices in the same laboratory, rather than through propagation data, are of particular interest [1, 2, 3].

The results of Holloway, et al [1], showed agreement to about 2×10^{-10} (after certain corrections) between the commercial beam standards developed and manufactured by the National Company and the atomic standard at the National Physical Laboratory, Teddington, England.

Over the last several months comparisons have been made between two dissimilar cesium beam standards constructed at the National Bureau of Standards. Particular care was taken to avoid systematic errors. The devices were tested independently, the pertinent parameters were measured, and the frequency comparisons subsequently made.

The zero field frequencies of these two standards agree to 1×10^{-11}. (This is a fixed frequency difference.) The standard deviation of the mean of the difference frequency is 2×10^{-12}. This latter number represents the precision of measurement for measuring times of a few hours. The accuracy of these standards is considered to be $\pm 1.5 \times 10^{-11}$ taking into account certain uncertainties in the C field measurements to be discussed later in this report.

The NBS standards are shown in figures 1 and 2. Ramsey excitation is employed. The separation of the oscillating fields is 55 cm in the shorter machine (which we designate as NBS-I), and the oscillating field separation is 164 cm in the longer machine (which we designate as NBS-II). The line widths are 300 cps and 100 cps respectively. Typical signal-to-noise ratios are about 400 for NBS-I and 100 for NBS-II at the present time. The uniform C field is produced by a conducting trough which is surrounded by a mu-metal shield; a double shield is used in NBS-II. The beam dimensions are .003 inch x 0.100 inch (NBS-I) and .015 inch x 0.187 inch (NBS-II). The radiation field exciting the microwave transition is provided by a rectangular U-shaped resonant cavity. The beam passes through the two ends of the cavity just grazing the end walls. The purpose of this design is to assure identical phase at the two points where the beam passes through the cavity.

The most recent method of frequency measurement is shown by the block diagram of figure 3.

There are a number of uncertainties introduced into the absolute frequency measurements. The effects that we find contribute most significantly to these uncertainties are:

(a) the magnitude and non-uniformity of the C field including variations in the magnitude over long periods,

(b) a phase difference between the two oscillating field regions, and

(c) a lack of purity of the electromagnetic field exciting the atomic transition.

The magnitude of the C field is determined by observing a number of field sensitive microwave transitions, e.g., $(F = 4,\ m_f = 1) \longleftrightarrow (F = 3,\ m_f = 1)$. The low frequency transitions (for which $\Delta F = 0$, $\Delta m_f = \pm 1$) were used also to measure the magnitude of the field and in addition were used to measure the field uniformity. This was done by placing small coils at various positions along the beam in the C field region. A rotating-coil fluxmeter, sensitive to .002 oersted provided still another method for measuring the field and its uniformity. The field measurements indicate that the maximum C field variation along its length is ± .002 oersted. This non-uniformity can introduce at most an uncertainty of 4×10^{-12} in the measured frequency. At the time of the initial comparisons of the two standards the values of the C field magnitude as measured by the different methods agreed to within the precision of the measurements (±.002 oersteds) for both machines. Since that time, however, the shielding properties of the mu-metal shields have deteriorated to some extent, accompanied in the case of the longer machine by a discrepancy among the various types of field measurements of about .004 oersteds at a field of .080 oersted. In order to reduce the resulting uncertainty in the frequency measurements to below 1×10^{-11}, smaller C fields (about .020 oersteds) have been used in the more recent comparisons.

The microwave frequency measurements of the field are probably more reliable than the low frequency measurements because the low frequency transitions are much broader (about 30 kc) and more subject to distortion and power shifts. These discrepancies require further study. At any rate, the uncertainty is taken as ±.004 oersted corresponding to a frequency uncertainty of $\pm 7 \times 10^{-12}$.

Possible frequency shifts arising from neighboring lines in the spectrum have been calculated and found to be negligible. Frequency pulling of the resonant cavity also have been calculated and found to contribute an insignificant frequency shift in the spectral line measurement (assuming that reasonable care has been taken in tuning the cavity).

In order to test for phase differences between the two oscillating field regions of the Ramsey exciting structure, the U-shaped cavities of both NBS-I and NBS-II were designed so that they can be rotated 180°, i.e., the two oscillating fields can be interchanged. No frequency shifts were observable after rotation of the long cavity of NBS-II. A small shift was observable for NBS-I of about 5×10^{-12}. The precision of these measurements was $\pm 2 \times 10^{-12}$.

If the electromagnetic field exciting the transition is not pure - that is, if this signal is frequency modulated - rather large frequency uncertainties are possible in the measurements. The exciting radiation is ordinarily produced by frequency multiplication by a factor of 1836 from a stable quartz crystal oscillator. Sidebands in the power spectrum introduced in the oscillator or first stages of the frequency multiplier chain are enhanced significantly by the multiplication process. What is worse, sidebands resulting from frequency modulation are not, in general, symmetrically placed about the "primary" signal. The power spectrum of the exciting radiation for the NBS standards was examined using an ammonia maser stabilized frequency multiplier chain as a spectrum analyzer [4]. The signal was found to have a bandwidth of about 4 cps at 24, 000 Mc, was symmetrical, and contained no observable sidebands. Any shift introduced from this sour ce would be much less than the precision of measurement. In general, however, sidebands will be present to some extent.

A crystal oscillator in which the quartz crystal is emersed in liquid helium is presently used to drive the exciting chain instead of the oscillator described above with a 4 cps width to its power spectrum. A maser power spectrum of the helium oscillator is shown in figure 4. The sidebands are due to 60 cps frequency modulation. The factor of frequency multiplication is 2916. This unsymmetrical power spectrum would introduce an apparent frequency shift. In fact, shifts as high as 3×10^{-9} have been demonstrated experimentally. The undesired sidebands are eliminated by phase locking a simple single tube oscillator to the helium oscillator. Appropriate choice of the time constant of the phase locked system is, of course, necessary [4].

The effects discussed above are those that we consider to contribute most significantly to the uncertainty of absolute frequency measurements if adequate care is not taken in construction and testing. We have found it possible to reduce these uncertainties to a level below 1×10^{-11}.

Comparisons have been made through propagation data between the NBS standards, the British standard at NPL and four Atomichrons in the U.S.A. The propagation data was obtained from the regular reports of : S. N. Kalra of the National Research Council of Canada; J. R. Pierce of the Cruft Laboratories; NBS (Boulder); NRL (Washington); and NPL (Teddington, England). The results are compiled in the following table. In this table the designation M_4 is the mean of the zero field frequencies of Atomichrons 106, 112, 109, and 110.

Summary of 3-month Comparisons Between NBS II and NPL,
N.R.C. (Canada), and a Group of 4 Atomichrons
Data of Nov. 30, 1959 - Mar. 1, 1960

Comparison	Number of Daily Comparisons Used	Links Used in the Comparison
1. $(\text{NPL-NBS II})_{\text{av.}} = -0.1\times10^{-10}$ via N.R.C. (Canada)	34	a. WWVB-NBS II b. WWVB-N.R.C. c. MSF-N.R.C. d. MSF-NPL
2. $(\text{NPL-NBS II})_{\text{av.}} = +0.9\times10^{-10}$ via Cruft Labs	80	a. 106-NBS II b. WWV-106---(30 day averages) c. WWV-112 d. MSF-112 e. MSF-NPL
3. $(\text{N.R.C.-NBS II})_{\text{av.}} = +10.2\times10^{-10}$	22	a. WWVB-NBS II b. WWVB-N.R.C.
4. $(\text{M}_4\text{-NBS II})_{\text{av.}} = +1.0\times10^{-10}$ 106--Boulder 112--Cruft 109--WWV 110--NRL	70	a. WWV-106 b. 106-NBS II c. WWV-110 d. WWV-112 e. WWV-109

The results of the experiments show that beam devices of rather modest length (55 cm between oscillating fields) are capable of precisions of 2×10^{-12} for measurement times of one to a few hours. Apparently accuracies of 2×10^{-12} could also be obtained if the C field difficulties that we have experienced could be resolved. It seems likely that they can be. Longer beams would reduce the measuring time but also increase the C field difficulties. Professor P. Kusch has suggested the use of thallium instead of cesium. Thallium is particularly attractive, insofar as the C field is concerned, since the thallium transition of interest is 50 times less sensitive to magnetic fields.

The longer of the two machines (NBS-II) is the present United States Frequency Standard. The shorter machine (NBS-I) is an alternate standard [3]. The frequency assumed for the $(F = 4, m_F = 0) \longleftrightarrow (F = 3, m_F = 0)$ transition of cesium in zero field is 9192631770. 0 cps. The best comparison between cesium and Ephemeris time at present is that given by Markowitz, Hall, Essen, and Parry as 9192631770 ± 20 cps [5].

Corrections for the 60 kc standard frequency broadcasts of Station WWVB (formerly KK2XEI), Boulder, Colorado, are made each week and are available upon request.

We believe that the experiments demonstrate that with adequate care in construction and testing, atomic beam standards can be expected to agree in frequency without special recipes in design and indeed they behave precisely as one would predict from theory - one need only know the values of the pertinent parameters to sufficient accuracy. This information must be obtained from appropriate tests.

The authors wish to acknowledge the invaluable assistance of Mr. Charles Snider who helped with the many measurements, Mr. James Barnes and Dr. George Schafer, who contributed significantly to a number of the electronic problems, and Mr. Henry Salazar who built most of the electronic equipment. The beam devices were built in the NBS Instrument Shop. Thanks are especially due Messrs. John Carlson, Donald Harriman, Donald Penner, and Victor Schmitz. The helium oscillator employed in these experiments was designed by Mr. A. H. Morgan of the Broadcast Services Section of NBS. The quartz crystal itself was fabricated by the Bell Telephone Laboratories.

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[5] W. Markowitz, R. G. Hall, L. Essen and J. V. L. Parry, Phys. Rev. Letters 1, 106 (1958).

List of Figures

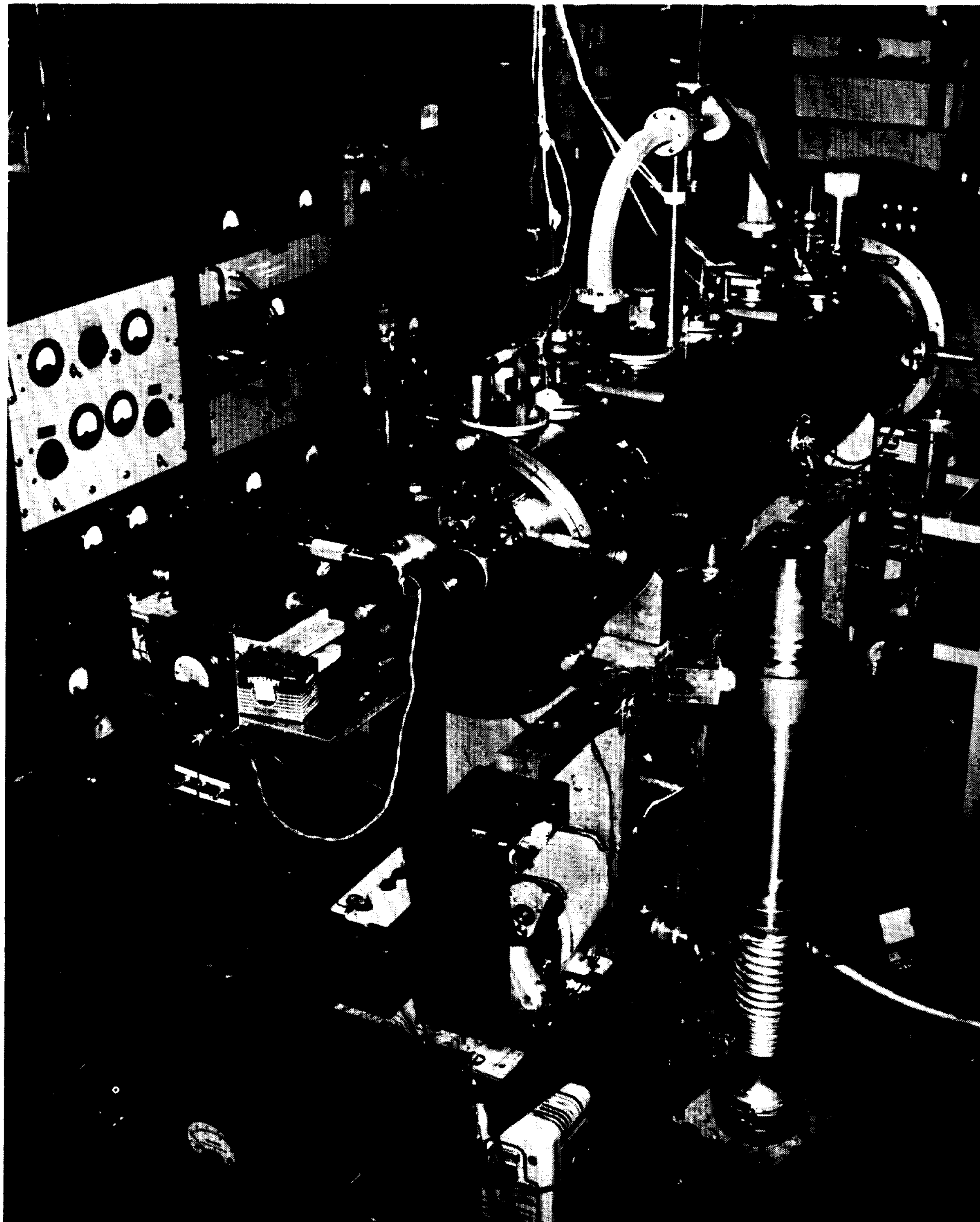

Fig. 1 Cesium Atomic Beam Frequency Standard (NBS-I).

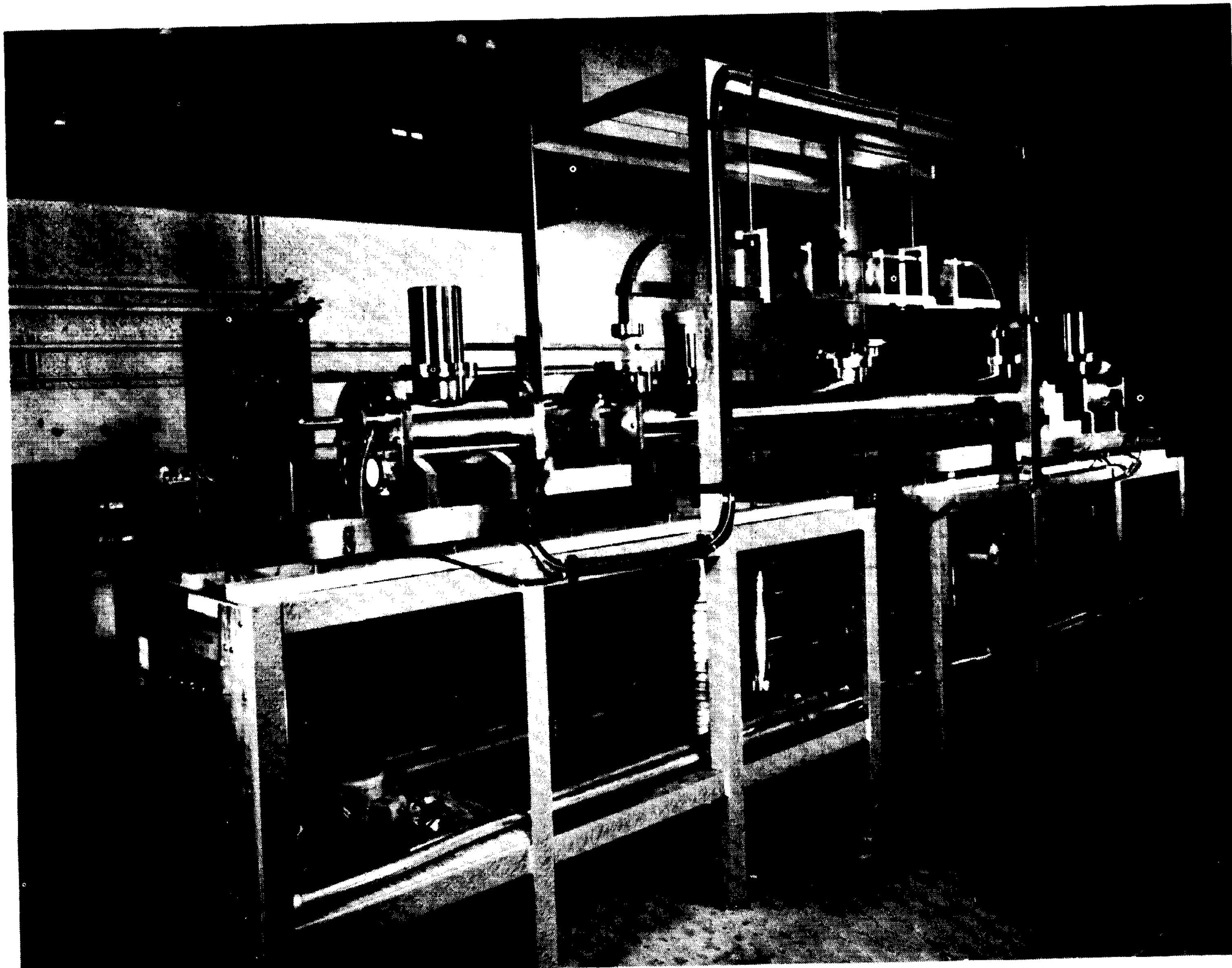

Fig. 2 Cesium Atomic Beam Frequency Standard (NBS-II).

BLOCK DIAGRAM OF SYSTEM USED TO COMPARE NBS I AND NBS II

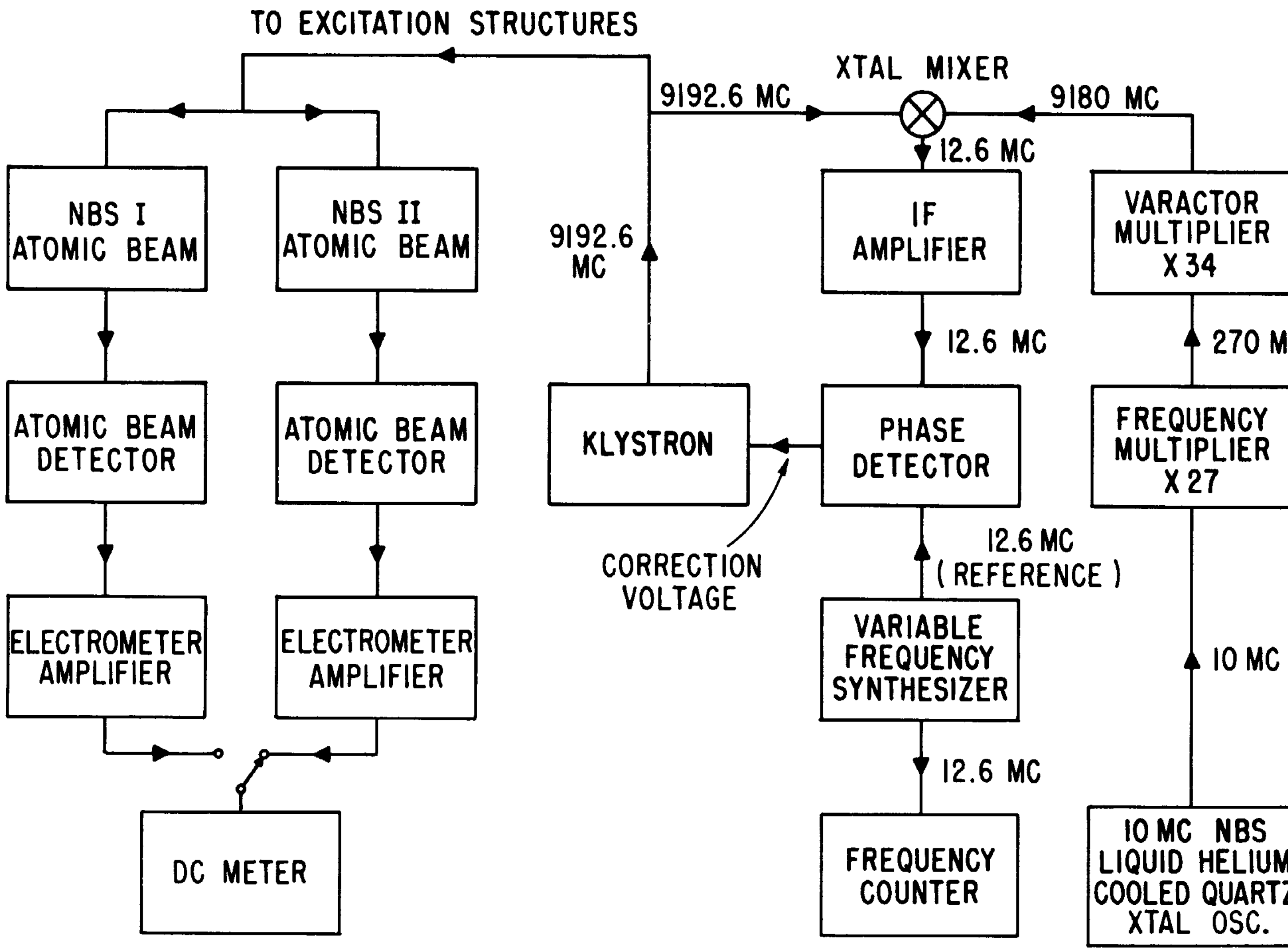

Fig. 3

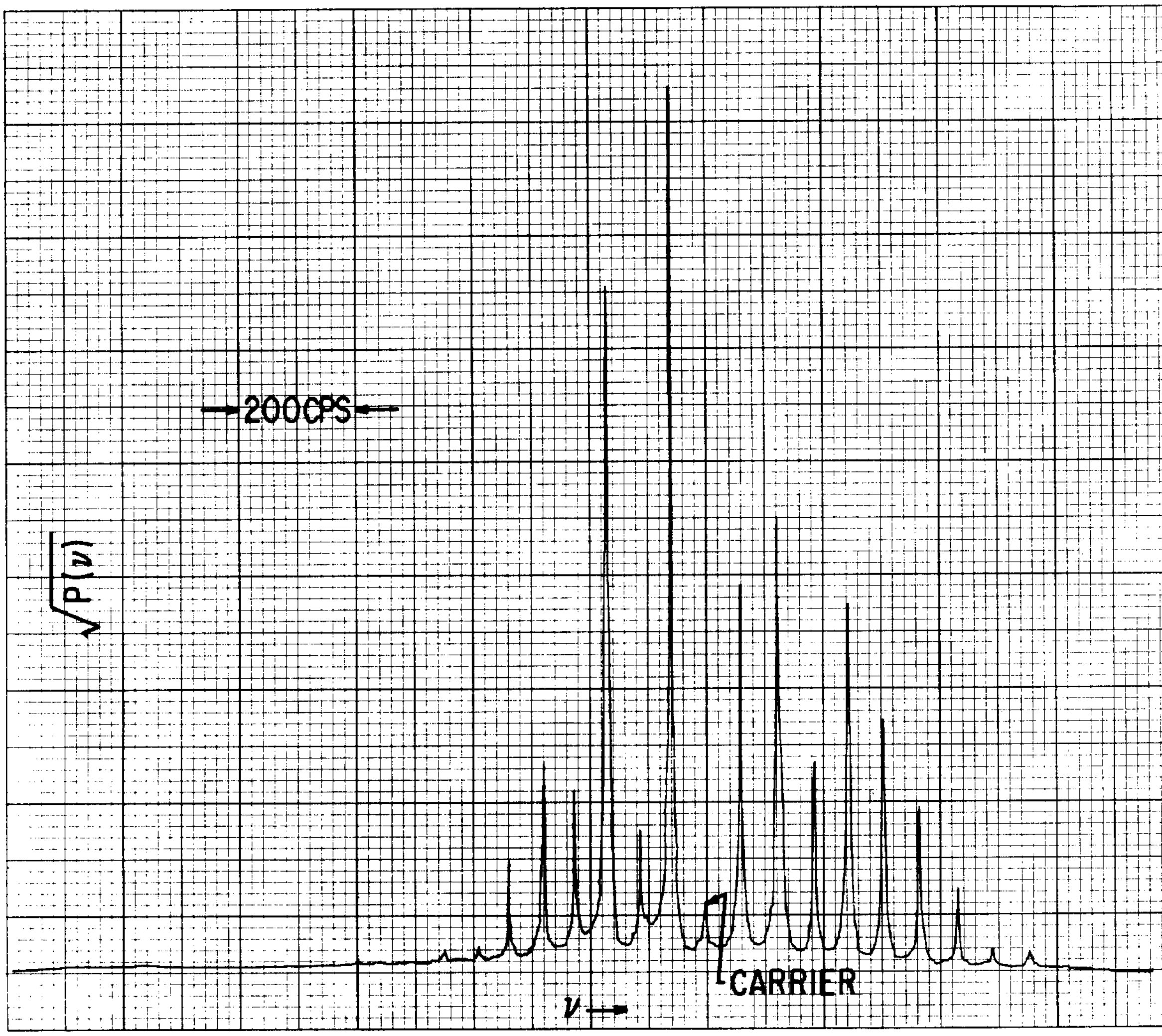

Fig. 4 A plot of the square root of the power spectrum of the output of a frequency multiplier chain driven by the helium oscillator. Multiplication factor = 2916.