NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT 8400-12-84104

October 5, 1959

NBS REPORT 6075

*AN EVALUATION OF A CESIUM BEAM FREQUENCY STANDARD

by

R. C. Mockler, R. E. Beehler, and J. A. Barnes

*To be printed in the proceedings of the conference on Quantum Electronics - Resonance Phenomena, Office of Naval Research, Bloomingburg, New York, September 14-16, 1959.

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
Boulder, Colorado

IMPORTANT NOTICE

TABLE OF CONTENTS

List of Figures

List of figures, continued:

AN EVALUATION OF A CESIUM BEAM FREQUENCY STANDARD

R. C. Mockler, R. E. Beehler, and J. A. Barnes

ABSTRACT

A cesium atomic beam frequency standard constructed at the National Bureau of Standards has been tested for reproducibility and accuracy. The estimated standard deviation of the frequency measurements is 8.5 parts in 10^{11}. Measurements and control of the various parameters affecting the measured frequency indicate that the accuracy of the machine falls within the precision, i.e., within 8.5×10^{-11}.

Comparisons with other cesium standards have been made. Agreement is satisfactory in view of the uncertainties incurred by the method and circumstances of comparison.

An unsymmetrical power spectrum of the radiation exciting the cesium transition would, in general, give a different frequency measurement for a spectral line than would monochromatic radiation. Power spectra of the multiplied frequencies of several crystal oscillators were observed using a maser stabilized frequency multiplier chain in the spectrum analysis. In some cases the power spectrum displayed large asymmetries. Certain inferences are made concerning the effect that the power spectrum of the exciting radiation of an atomic beam device can have on the measured frequency of the atomic resonance.

1. INTRODUCTION

A cesium atomic beam frequency standard constructed at the National Bureau of Standards has been tested for reproducibility and accuracy. The estimated standard deviation of the frequency measurements is 8.5 parts in 10^{11}. Measurements and control of the various parameters affecting the measured frequency indicate that the accuracy of the machine falls within the precision, i.e., within 8.5×10^{-11}.

Comparisons with other cesium standards have been made. Agreement is satisfactory in view of the uncertainties incurred by the method and circumstances of comparison. Relative frequency excursions of several parts in 10^{10} between Atomichrons introduce uncertainties in these comparisons.

An unsymmetrical power spectrum of the radiation exciting the cesium transition would, in general, give a different frequency measurement for a spectral line than would monochromatic radiation. Power spectra of the multiplied frequencies of several crystal oscillators were observed. In some cases the power spectrum displayed large asymmetries. Furthermore, the spectral asymmetry was observed to change in time for one particular oscillator. It seems essential -- for a reliable standard -- that the exciting radiation be without frequency modulation, or -- if frequency modulation is needed for servo purposes -- the modulating signal should be introduced into an otherwise clean spectrum. Multiple frequency modulating signals introduce assymmetrical character to the power spectrum.

2. THE EXPERIMENTAL APPARATUS

The NBS cesium beam frequency standard (hereafter referred to as NBS-1) employs Ramsey type excitation, has a spectral line width of 300 cps (at 9192.631 Mc), and provides a signal-to-noise ratio in the range 100 to 400. The atomic beam is produced by heating pure cesium metal to 150° C and allowing it to effuse from the oven through a channel 0.038 inch long with a cross-section of 0.003x0.100 inch^2. The beam is detected by a surface ionization detector. The hot wire is made of a platinum -- iridium alloy (80% Pt; 20% Ir). The ion current is measured with an electrometer. Typical values of the undeflected beam current fall in the range 1 to 3×10^{-11} amperes.

The beam excitation is derived from a quartz crystal oscillator (10.317...Mc). The output of this oscillator is multiplied in frequency up to the cesium transition by the scheme shown schematically in Fig. 1. The exciting radiation is swept in frequency over the width of the spectral line by tuning the 10.317...Mc crystal oscillator by means of voltage sensitive capacitors in the crystal circuit. The detected beam signal is applied to the y-axis and the analog output of a frequency counter is applied to the x-axis of a x-y plotter. A Ramsey line shape plotted in this manner is shown in Fig. 2. The frequency scale on the x-axis is linear. This allows the position of the peak of the line to be determined by taking the average of the frequency of two points on opposite sides of the central peak, both points having the same value of y. Several averages of this sort are made for each line trace. The line is swept in both directions and a linear interpolation is made. This compensates for delays that occur in the detecting circuit.

The Ramsey excitation structure consists of a long electroformed resonant cavity of rectangular cross-section bent into the shape of a U. The Q of this cavity is about 6000. It is symmetric about the coupling iris and operates in the $TE_{1,0,60}$ mode. The beam passes through the two ends of the cavity -- which are separated by 56 cm -- and just grazes the end surfaces. Frequency shifts incurred through frequency "pulling" of the cavity are given approximately by

$$\Delta\nu_R = \left(\frac{Q\ \text{cavity}}{Q\ \text{line}}\right)^2 \Delta\nu_c$$

where $\Delta\nu_R$ is the shift in the peak of the atomic resonance response, and $\Delta\nu_c$ is the difference in frequency between the peak of the cavity response and the peak of the atomic response. Q_{line} is the Q of the atomic response. $\Delta\nu_R$ is negligible for this machine for reasonable values of $\Delta\nu_c$. Consequently, temperature variations which shift the cavity resonance only tend to vary the intensity of the exciting radiation. No measurable shift in frequency is observable for variations in radiation intensity.

The "C" field is ordinarily adjusted to .080 oersted and is produced by a brass strip parallel to the atomic beam through which a current is passed. The uniformity of the field is determined by measuring the low frequency transitions in the beam (~28 kc) induced by small coils placed at different positions along the "C" field. The measured uniformity is within ±.003 oersted. The "C" field region is magnetically shielded from external fields by a mu-metal shield.

3. ACCURACY

The accuracy of the machine depends upon the precision to which certain parameters can be controlled (and/or measured).

The uncertainty in the measured magnitude of the "C" field is ± 0.003 oersted. This corresponds to an uncertainty in the microwave frequency measurements of 2×10^{-11} -- well within the precision.

There is an uncertainty introduced in the measured frequency if the phase relation between the two oscillating fields of the Ramsey exciting structure is not precisely known. In the machine described here, a single resonant cavity is used. Consequently, the phases are precisely the same at the two cavity ends. The beam passes through these two regions of identical phase. As further evidence of phase identity, the cavity can be rotated 180° (except for the shorted ends) and the two measured transition frequencies compared. A lack of phase identity in the two oscillating field regions can also be detected by observing the symmetry of the line shape. The absence of perfect line symmetry implies unequal phases in the two regions. The degree to which the inaccuracy can be determined by this kind of observation is limited by the signal-to-noise ratio to a greater extent than by comparing the frequencies for one orientation of the waveguide structure and the inverted orientation. However, if the line breadth is 300 cps and the signal-to-noise ratio is 400, this method permits the inaccuracy in the frequency to be specified within about 1.4×10^{-10}. No asymmetry is observable in the line traces.

Any frequency shift caused by electric fields has been shown by Haun and Zacharias (1) to be negligible for magnitudes of the electric field intensity that would be expected in the "C" field region. They have found that the frequency shift in the cesium line is

$\Delta \nu_o = 1.89 \times 10^{-6} E^2$ cps, where E is the electric field intensity in volts/cm.

The microwave frequency magnetic field is polarized parallel to the static "C" field. Under these circumstances the most important selection rule is $\Delta M_F = 0$. There are seven transitions in cesium for which this selection rule applies. It can be shown that these are sufficiently well resolved at .080 oersted so that the resonant peak of interest is not shifted beyond the present uncertainties in measurement by the overlapping of neighboring lines.

Uncertainties can be introduced by the exciting radiation. If this radiation consists of more than one signal and if these signals are not symmetrical in frequency and amplitude about a frequency that is an integer multiple of the primary crystal oscillator driving the multiplier chain, then erroneous line frequencies will obtain (2).

---

(1) R. D. Haun, Jr., and J. R. Zacharias, Phys. Rev. 107, 107 (1957).
(2) N. F. Ramsey, Phys. Rev. 100, 1191 (1955).

It is not unusual to find unsymmetric power spectra of this sort from frequency multiplier chains (Section 5), and large errors could result. The square root of the power spectrum of an oscillator identical to that used in NBS-1 is shown in Fig. 3. Notice that the spectrum has no sidebands and any asymmetry of the central peak will be of no consequence since this peak is much narrower than the spectral line breadth. Other tests were made on the NBS-1 oscillator to show that its spectrum was similar to that of its twin (Fig. 3) -- in particular, no low frequency sidebands were detected in the multiplier chain output. This spectral character will provide accurate frequency comparisons. The usual assumption that the median frequency of a frequency multiplier is an exact integer multiple of the primary oscillator is an accurate assumption for the sort of spectrum displayed in Fig. 3.

Considering the various sources of inaccuracy and the results of their study, we believe -- with some confidence -- that the accuracy of the machine falls within the precision or $\pm 8.5\text{x}10^{-11}$.

4. THE MEASUREMENTS

The reproducibility of the cesium standard (NBS-1) was determined by comparison with a 10 Mc quartz crystal oscillator in which the quartz crystal and associated crystal circuit are emersed in liquid helium. The stability of this oscillator over periods of several days is 3 to $5\text{x}10^{-11}$* -- a figure determined from a continuous comparison with an Atomichron (106) during periods of good behavior. This Atomichron, even though large excursions in frequency occur in short time intervals (Fig. 4b), has excellent stability when averaged over time intervals of 1 minute or more. Periods during which the helium cooled oscillator and Atomichron (106) showed no significant

---

* The aging rate of the helium cooled oscillator appears to be less than $1\text{x}10^{-11}$ per day.

variations relative to each other were considered best to determine a reproducibility figure (precision) for NBS-1.

The helium oscillator has also been demonstrated to be stable to 2-4x10^{-11} over periods of 1/2 second to 6 hours by comparison with a maser stabilized frequency multiplier chain (Fig. 4a).

In handling the data, the mean of a single day's measurements is considered one piece of data. An estimate of the standard deviation was obtained from successive differences. Let

$$\delta^2 = \sum_{i=1}^{n-1} \frac{(x_i - x_{i+1})^2}{n}$$

where x_i is the frequency measurement for the ith day and x_{i+1} is the frequency measurment for the (i+1) day; n is the total number of data points (or days). The estimate of the standard deviation by successive differences is given by

$$\sigma\,(\delta) = \sqrt{\frac{\delta^2}{2}}^{\dagger} \quad .$$

For our set of data δ = 1.1 cps and σ (δ) = 0.77 cps which is 8.5x10^{-11} of the cesium frequency. Successive differences are likely to be random even though certain systematic changes may occur. These systematic changes are small when data is taken on succeeding days but nevertheless still exist. It is impossible to attribute these variations to the Atomichron, the helium cooled oscillator, or NBS-1, or to a combination when the variations are small. Actually the standard

---

† R. H. Kent and J. Von Neumann have shown that $\overline{\sigma^2(\delta)} = (\sigma')^2$ where σ' is the true standard deviation.

deviations estimated from successive differences is almost the same as that estimated in the usual way. In fact, this standard deviation,

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{(\bar{x} - x_i)^2}{n}} ,$$

is .5 cps or $\overset{5.4}{\cancel{6}}\text{x}10^{-11}$.

The data show Atomichron (106) to be lower than NBS-1 by 3.6 cps for the week of August 30. The mean of all the data taken over the months of July and August show about the same difference. Data of one day was deleted from the average because the Atomichron (106) made a large excursion, $8\text{x}10^{-10}$, just prior to a general retuning. The excursion was verified by NBS-1, the helium-cooled oscillator, the masers and Cruft Laboratory data.

In addition to the tests carried on at the Boulder Laboratories to determine precision and accuracy, frequency comparisons were made between NBS-1 and other cesium standards in the United States and England. The comparisons were made through propagated signals between the different locations.

In the discussion that follows, the following designations will be used to identify the various cesium standards:

Designation	Location
NBS-1	Cesium resonator, NBS, Boulder, Colo.
106	Atomichron, NBS, Boulder, Colo.
109	Atomichron, Station WWV, Beltsville, Md.
110	Atomichron, Naval Research Laboratories, Washington, D. C.
112	Atomichron, Cruft Laboratory, Cambridge, Mass.
M4	The mean of 106, 109, 110, 112
NPL	British cesium resonator, Teddington, England

Table I (1 unit = $1\mathrm{x}10^{-10}$)

1.	(NBS -1) - 106 = +3.9[*],	mean over July and August 1959.
2.	M4 - 106 = +4.2,	6 month mean for the period Sept. 1958 to March 1, 1959.
3.	M4 - (NBS-1) = +0.3	
4.	NPL - M4 = +1.5,	6 month mean for the period Sept. 1958 to March 1, 1959
5.	NPL - (NBS-1) = +1.8	

It should be emphasized that this comparison assumes that 106 had the same mean frequency during July and August 1959 as it had during the 6-month period September 1958 to March 1959. The accumulated data over the past two years indicates that the Atomichrons tend to wander in frequency. In fact, Atomichrons 112, 106, 110 were in rather good agreement during March 1959 -- differing by probably less than $2\mathrm{x}10^{-10}$. This comparison was made by a single Atomichron transported by air to each of the locations to provide a more direct comparison between the different units.[†] The relative frequencies of Atomichrons 112, 106, 110, 109 have changed considerably between March and July according to the propagation data of July. During the month of July 1959, 112 differed from 106 by about $1\mathrm{x}10^{-9}$ and it differed from 110 by several parts in 10^{10}. Other variations of this nature are evident from the various data including the direct comparison data made at Boulder between 106, NBS-1, and the helium-cooled oscillator.

---

[*] A positive sign means that the first standard is higher in frequency than the second.

[†] The experiment was performed under the auspices of the U. S. Signal Corps by Dr. J. H. Holloway from the National Company.

Table II

(1 unit = 1×10^{-10})

Date	(NBS-1) -106	112 - 106	112 - 109	112-110	(NBS-1) - M4
July 8	+ 4.5	+ 8.6	+ 4	+ 7.6	+ 0.9
July 9	+ 2.5	+ 9.3	+ 5	+ 8.4	- 1.1

The link between Boulder and Cruft Laboratory is through the 60 kc transmission of station KK2XEI at Boulder. This transmission is reported to be very weak, and comparison with it difficult. Recently, new alternatives for comparison through radio signals have come into being. High power VLF stations are presently propagating signals of sufficient stability for highly accurate frequency comparisons.

5. THE POWER SPECTRUM OF THE EXCITATION RADIATION-- ITS EFFECT ON THE MEASURED FREQUENCY

For the purpose of understanding the detailed nature of extremely precise microwave frequency measurements, it is necessary to investigate the power spectra of the radiation from frequency multiplier chains used in such measurements. This is especially important in atomic frequency standards where a quartz oscillator is compared with an atomic resonance through a frequency multiplication process. The multiplier chain measured output frequency would be some sort of average -- depending upon the method of measurement. If the power spectrum were unsymmetric this average would not be an exact integral multiple of the primary crystal oscillator frequency.

In the method of observing the power spectrum used here, the output signal of the multiplier chain to be investigated is mixed with an essentially monochromatic signal. This relatively pure signal is obtained from an ammonia maser stabilized chain (Fig. 11). In this fashion the power spectrum is shifted to low frequencies -- in fact, audio frequencies -- where it can be conveniently examined with a variable frequency narrow band filter (amplifier). In the experiments, 100 kc, 10 Mc, and 5 Mc crystal oscillators -- and chains -- were investigated (Fig. 3, 5, 6, 7, 8, 9, 10). The frequency multiplication factors used were 1458 for the 10 Mc oscillators, 2916 for the 5 Mc oscillators, and 145,800 for the 100 kc oscillators. Direct multiplication of these oscillators by these factors would give the frequency 14,580 Mc. The most prominent features of the observed power spectra are the 60 cps (the commercial power frequency) and the harmonics of 60 cps sidebands. These sidebands are enhanced very significantly by the multiplication process -- in fact, by a factor of roughly the frequency multiplication. These sidebands are apparently introduced through frequency modulation in the crystal oscillator, buffer amplifiers and the first stages of frequency multiplication. The existence of limiters in the frequency multipliers removes practically all of the amplitude modulation. One would expect the 60 cps (and harmonics of 60 cps) sidebands of an amplitude modulated signal to be symmetric in their amplitude about the central peak. This is not necessarily true of frequency modulated signals -- provided that the primary signal is modulated with two or more modulating signals. Thus unsymmetric power spectra are expected -- under certain circumstances -- when frequency modulation occurs in frequency multipliers. Suppose that the output frequency of such a frequency modulated chain were measured. Suppose this is done by beating it with a known and relatively monochromatic signal, and the beat note is measured with a counter. The counter would measure the center of gravity of the power spectrum and this frequency will not be an integer multiple of the basic quartz oscillator (unless the power spectrum is symmetric). Furthermore, if this radiation were used to excite the atomic transition in an atomic beam frequency standard, the measured frequency of the spectral line would be different than that measured if the multiplier chain output were monochromatic. In general the frequency measured by the spectral line will be different than that measured by the counter under the unfavorable --but not unusual -- conditions discussed above. Elimination of the sidebands and the reduction in the frequency multiplying factor is the best cure -- and also a possible cure for these difficulties.* If the power spectrum is symmetric, regardless of whether the frequency is measured by a spectral line or a counter, the measured frequencies will be the same so long as the receiver amplifier is not extremely narrow banded.

In the investigations described here, power spectra for the 5 Mc helium-cooled quartz crystal oscillator, taken at different times, showed large changes in appearance and symmetry for no known reason. See Figures 7 and 8 - notice that one of the sidebands is missing in Figure 8. This particular oscillator has been shown to have a maximum deviation in frequency of about 2×10^{-11} over a six hour interval (by comparison with the maser stabilized chain) during periods of a fixed power spectrum. Variations of this sort in the power spectrum would undoubtedly produce a corresponding change in the "fixed" frequency of an atomic frequency standard.

---

* See Fig. 3.

The extremely sharp spectrum (1 cps or less at 14, 580 Mc) shown by the 5 Mc crystal oscillator -- desregarding the 60 cps sidebands -- suggests that the high stability feature of quartz crystal oscillators has not been completely exploited. The width of the peaks in the spectrum of the 5 Mc helium cooled oscillators is not perceptible with the dispersion used in our experiments. However, the width is observable in the square root of the power spectrum of the 9.835 Mc oscillator shown in Fig. 3 in which the crystal circuit is maintained at 46° C. Perhaps this suggests that this width is due to fundamental noise in the quartz crystal and crystal circuit. The extremely narrow spectrum of a helium cooled oscillator (< 1 cps) implies that crystal oscillators could be used in atomic beam frequency standards for line widths less than 10 cps. Evidently, when the breadth of a spectral line is less than the breadth of the power spectrum of the exciting radiation, a plotted resonance curve will have a width determined primarily by the breadth of the radiation spectrum. Fig. 9 shows the square root of the power spectrum for a 100 kc oscillator and multiplier chain. If this spectrum were used to excite the transition in NBS-1 (line breadth = 300 cps) the Ramsey pattern would be completely obliterated leaving only the broad Rabi line shape. This has actually been observed to occur (3). It is for this reason that higher frequency oscillators are used in atomic standards. As a matter of interest, this 100 kc oscillator has a frequency stability of 1-2x10^{-10} per day.

---

(3) R. C. Mockler, R. E. Beehler, and J. A. Barnes, "A Practical Limitation to the Length of an Atomic Beam Machine," to be published.

Fig. 5 and 6 display the square root of the power spectrum of the 10 Mc helium-cooled crystal oscillator used in the frequency comparison with NBS-1. The spectrum is quite complex and is also unsymmetric. It provides a superb signal for frequency comparisons (Fig. 4a) but would not be useful as a signal source to induce the atomic transition (4). The square root of the power spectrum of the 5 Mc oscillator belonging to the NBS Atomichron (106) is shown in Fig. 10. The spectrum is symmetric. In spite of its complex character it provides a uniform averaged frequency over long periods of time.

In establishing the performance of an atomic standard it is important to know the spectral character of the excitation. A clean spectrum is likely to give the most reliable behavior.

6. CONCLUSION

The agreement between the NBS cesium atomic standard frequency and a mean frequency of four Atomichrons (M4) is rather good -- within $\pm 1 \times 10^{-10}$. This agreement may be fortuitous, however, because there is considerable disagreement among the Atomichrons used in determining the mean frequency M-4. The comparison between the NBS atomic standard and that of England [NPL-(NBS-1) = +1.8] may be more meaningful.

The variations between atomic standards seem to be quite real and remain unexplained. The source of disagreement can only be determined by test experiments on the individual machines.

At the present time a new cesium resonator is being put into operation at the Boulder Laboratories. This machine will have a line breadth of 90-100 cps.

---

(4) A more detailed report on the power spectra is in preparation by two of the authors.

7. ACKNOWLEDGEMENT

The authors acknowledge with gratitude a large amount of work on the cesium beam by Mr. Lowell Fey during the initial stages of the experiment. Mr. Henry Salazar constructed most of the electronic apparatus. Mr. John Carlson and Mr. Donald Harriman constructed the cesium beam and maser apparatus. We further recognize the invaluable cooperation of Messrs. A. H. Morgan, J. Shoaf, V. E. Heaton, and especially, P. Simpson of the Radio Broadcast Service Section to whom belong the helium-cooled oscillators and Atomichron 106 used in the experiments.

FIGURES

Pages 16 through 26

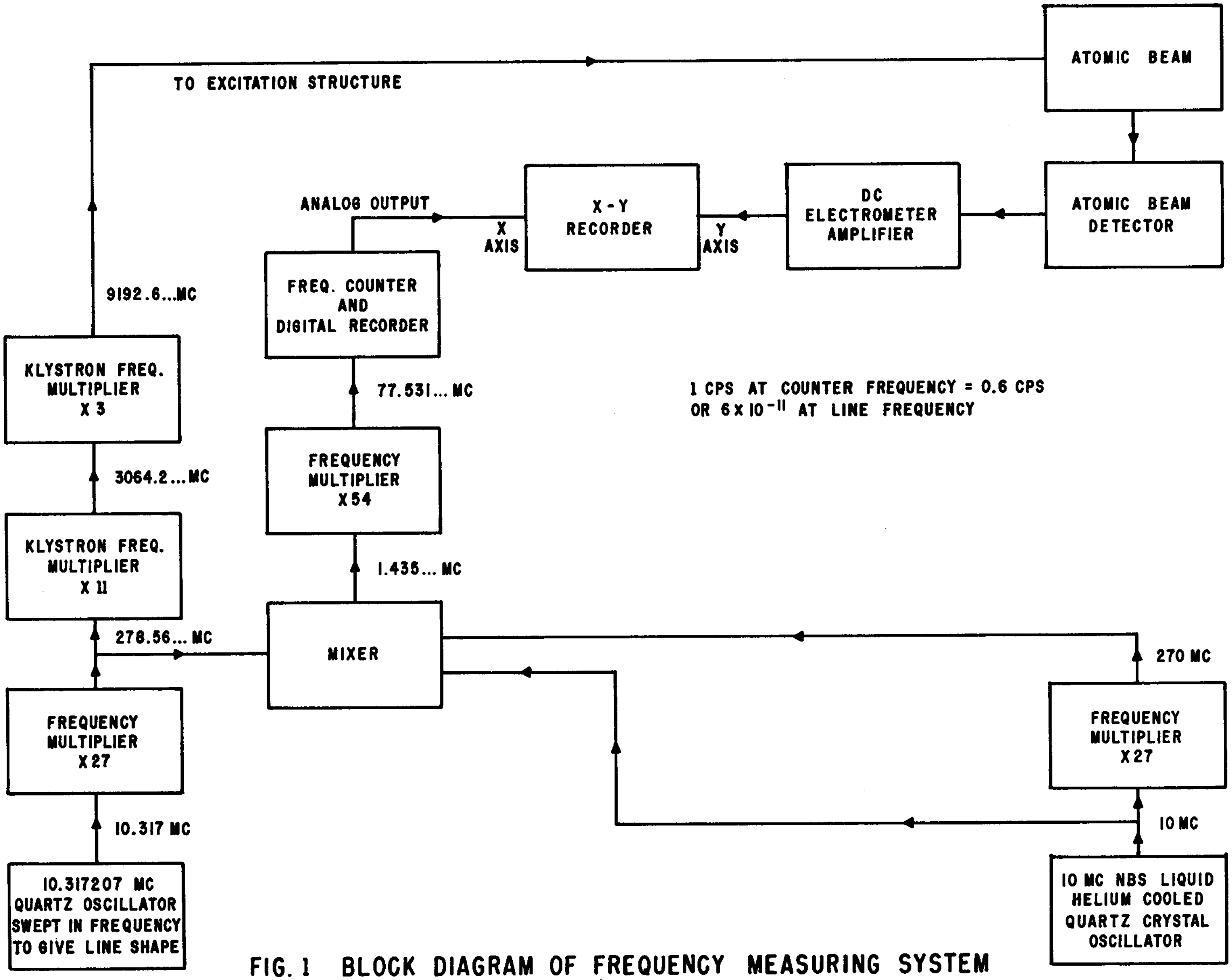


FIG. 1 BLOCK DIAGRAM OF FREQUENCY MEASURING SYSTEM

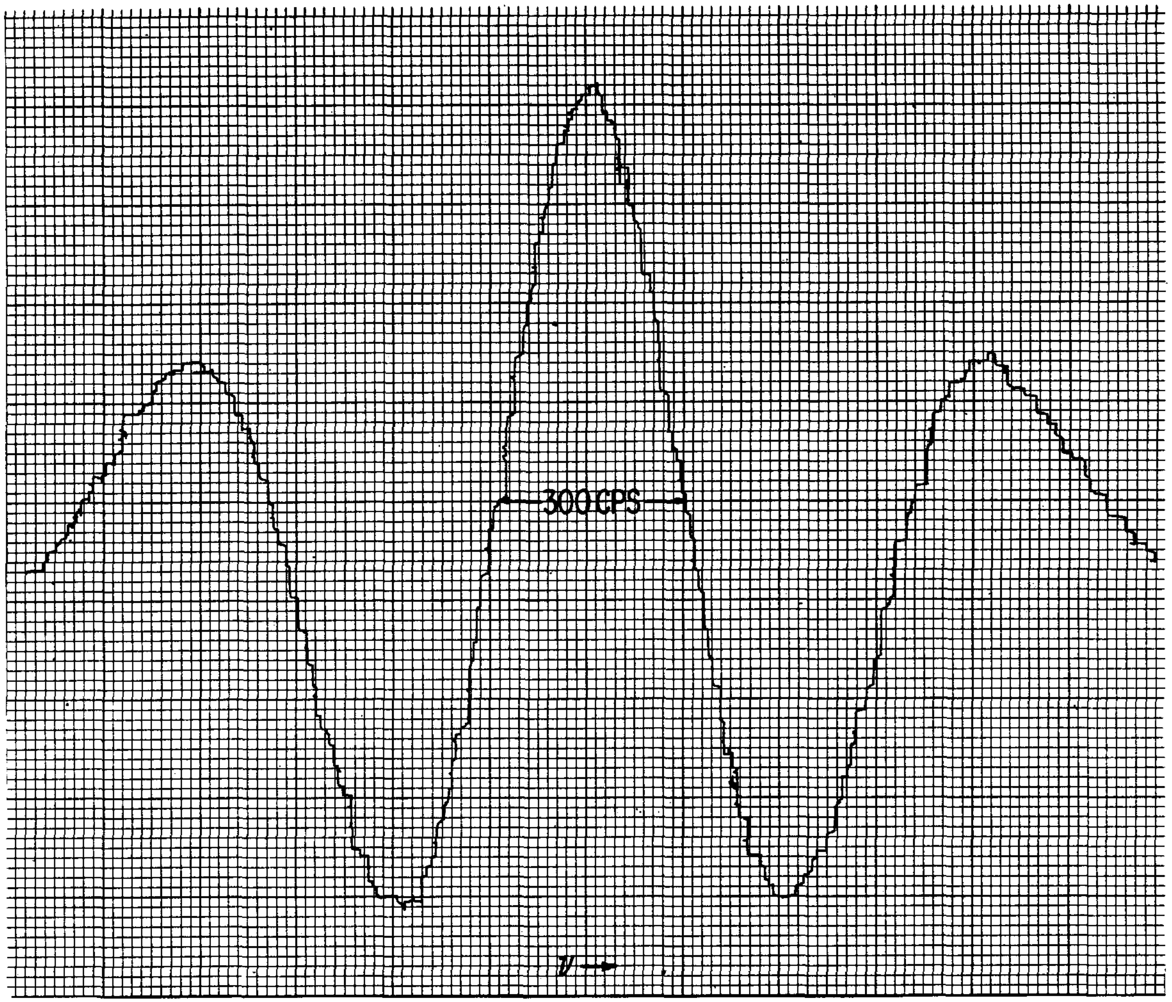


FIG. 2 RAMSEY LINE SHAPE OF THE $(F=4,\ M_F=0) \leftrightarrow (F=3,\ M_F=0)$ TRANSITION. THE TRACE HAS BEEN MADE ON AN X-Y PLOTTER. THE X-AXIS SWEEP IS DERIVED FROM THE ANALOG OUTPUT OF A FREQUENCY COUNTER. THE STEP VARIATIONS IN THE CURVE OCCUR BECAUSE OF THE STEP BEHAVIOR OF THE COUNTER OUTPUT.

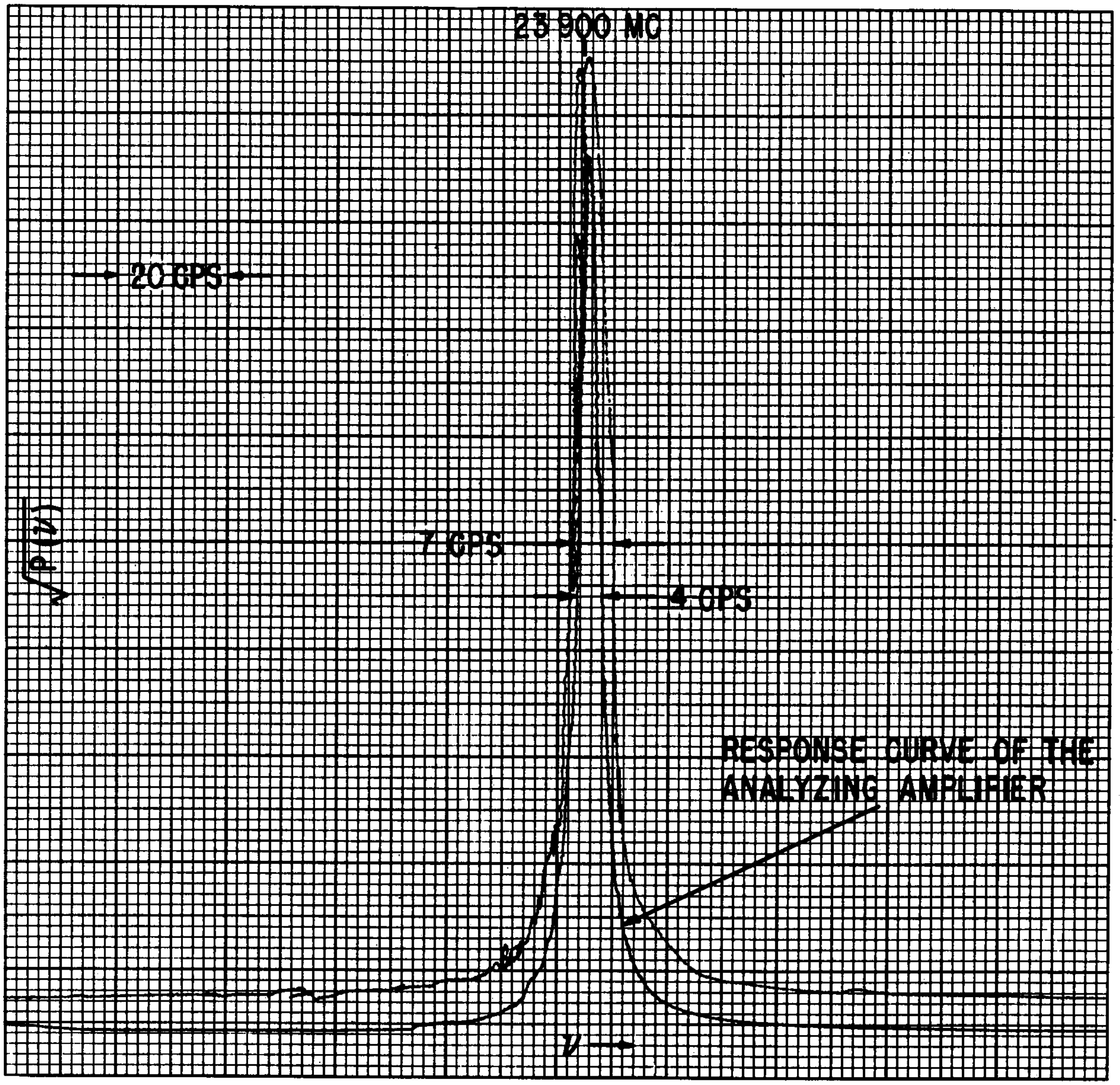


FIG. 3 $\sqrt{P(\nu)}$ VERSUS FREQUENCY FOR A 9.835...MC CRYSTAL OSCILLATOR MULTIPLIED IN FREQUENCY 2430 TIMES.

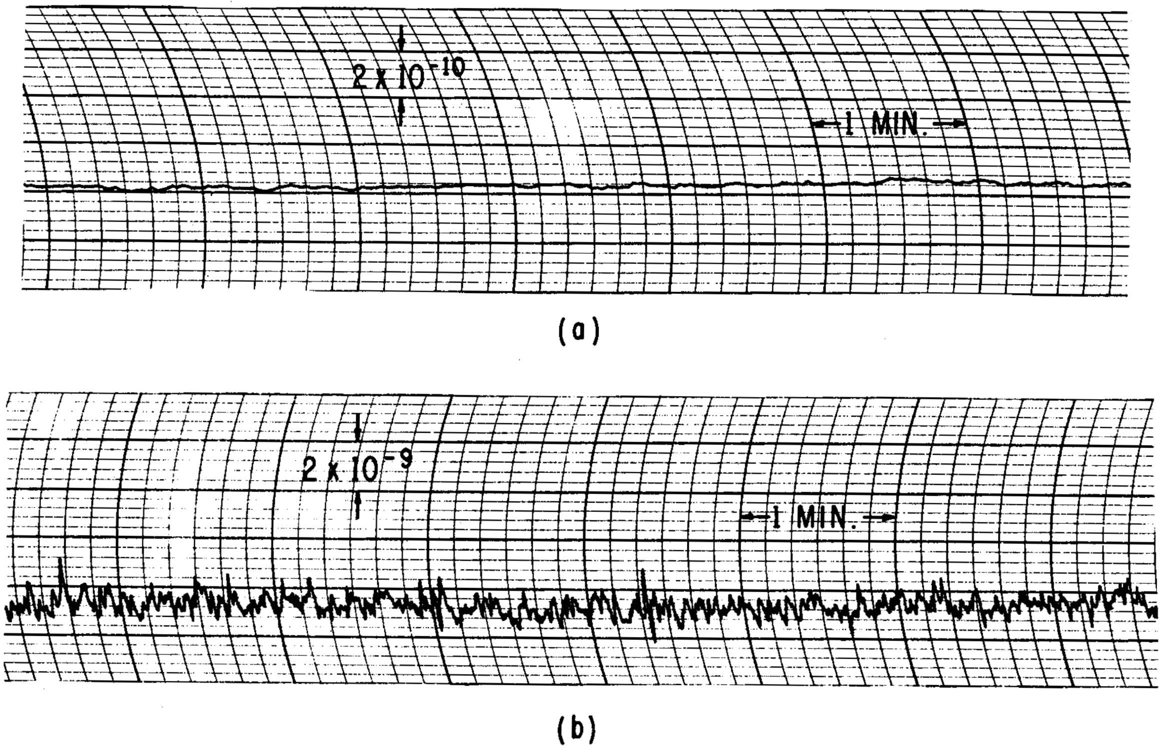


FIG. 4 (a) MASER STABILIZED CHAIN COMPARED WITH 10 MC HELIUM COOLED CRYSTAL OSCILLATOR. THE RECORDER PLOTS THE ANALOG OUTPUT OF A FREQUENCY COUNTER VERSUS TIME. THE COUNTING PERIOD IS 1 SECOND AND THE DISPLAY TIME IS 1 SECOND.

(b) MASER STABILIZED CHAIN COMPARED WITH 5 MC ATOMICHRON CRYSTAL OSCILLATOR. IN THIS TRACE THE DIFFERENCE SIGNAL IS MEASURED WITH A FREQUENCY METER, NOT A COUNTER. THE TIME CONSTANT FOR THE METER IS ABOUT 1/2 SECOND. NOTE THE CHANGE IN FREQUENCY SCALE BETWEEN (a) AND (b).

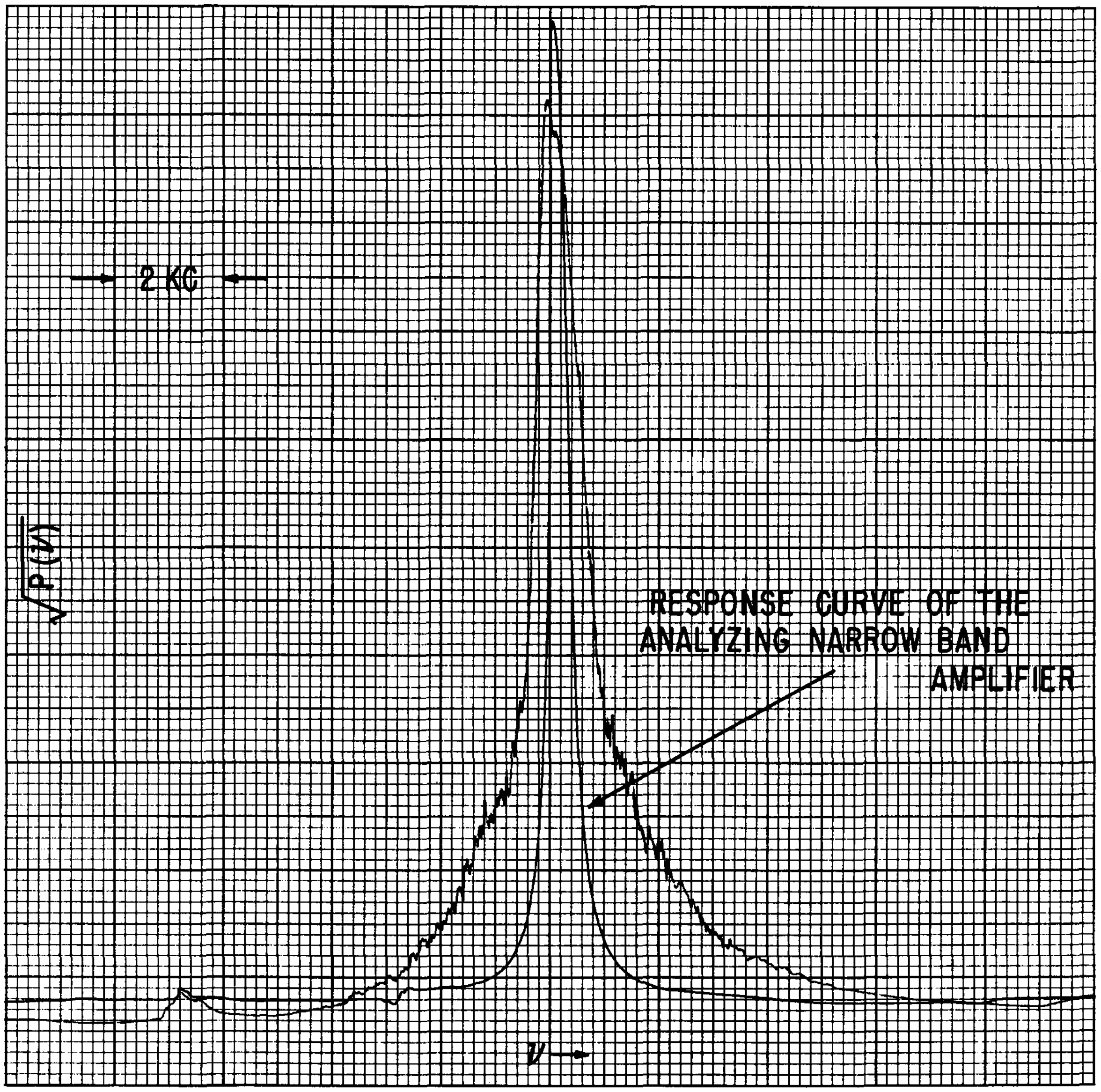


FIG. 5 $\sqrt{P(\nu)}$ VERSUS FREQUENCY FOR A 10 MC HELIUM COOLED CRYSTAL OSCILLATOR MULTIPLIED IN FREQUENCY 1458 TIMES.

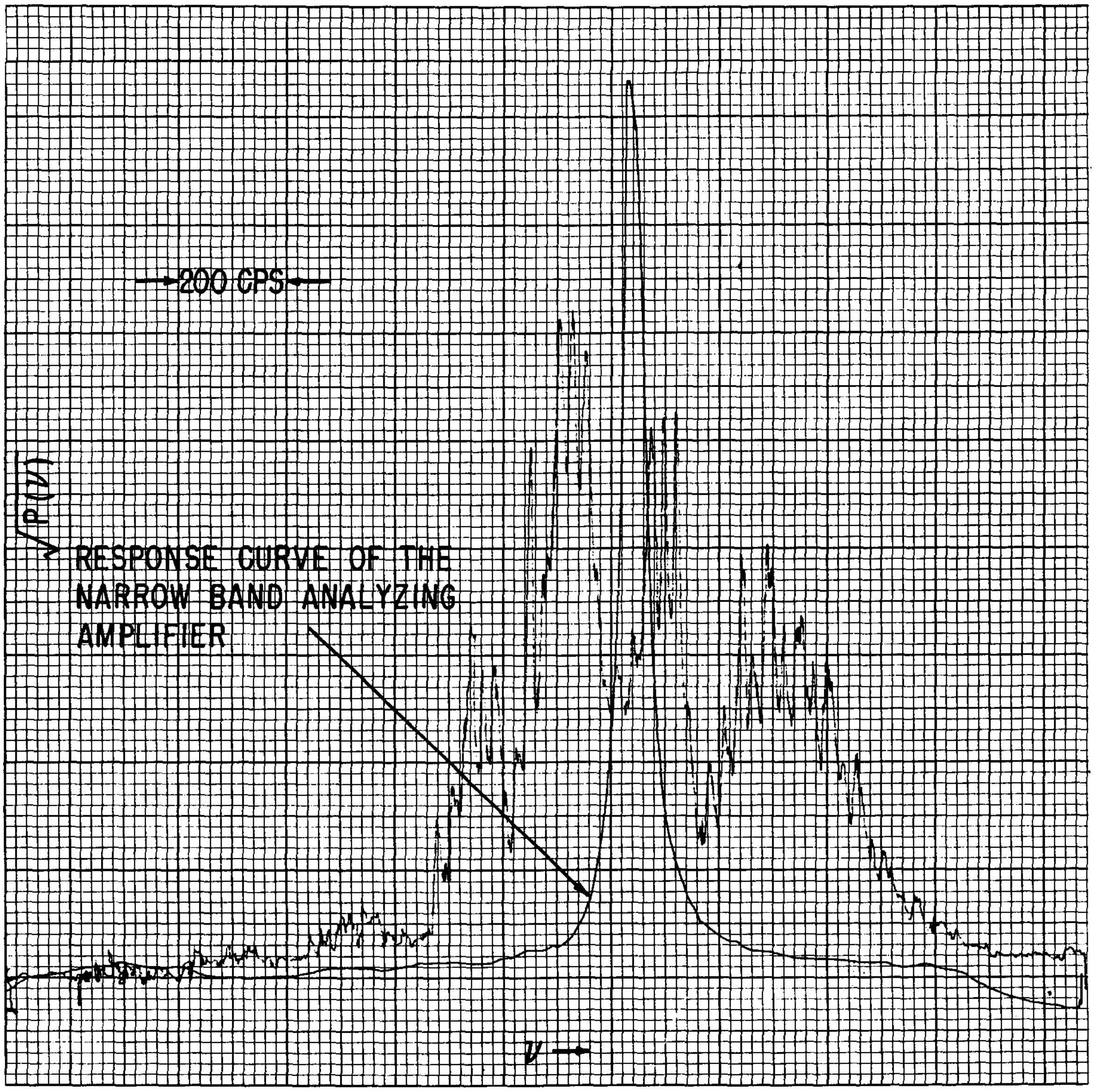


FIG. 6 $\sqrt{P(\nu)}$ VERSUS FREQUENCY FOR A 10 MC HELIUM COOLED CRYSTAL OSCILLATOR MULTIPLIED IN FREQUENCY 1458 TIMES.

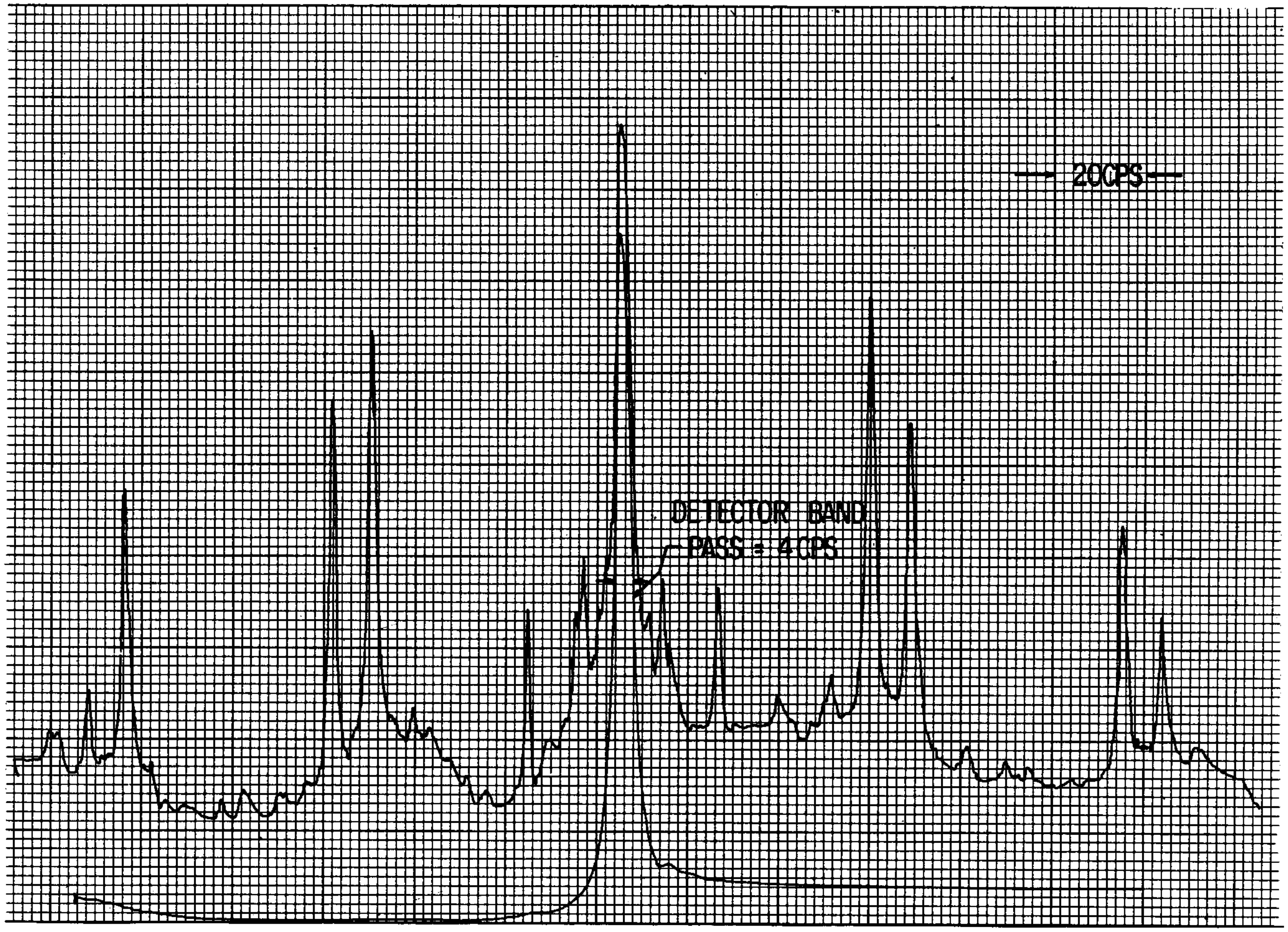


FIG. 7 5MC HELIUM COOLED CRYSTAL OSCILLATOR POWER SPECTRUM.
MULTIPLICATION FACTOR = 2916.
THE DETECTOR BAND PASS ~ 4 CPS.
THE INDIVIDUAL PEAKS IN THE SPECTRUM HAVE A WIDTH LESS THAN 1CPS.

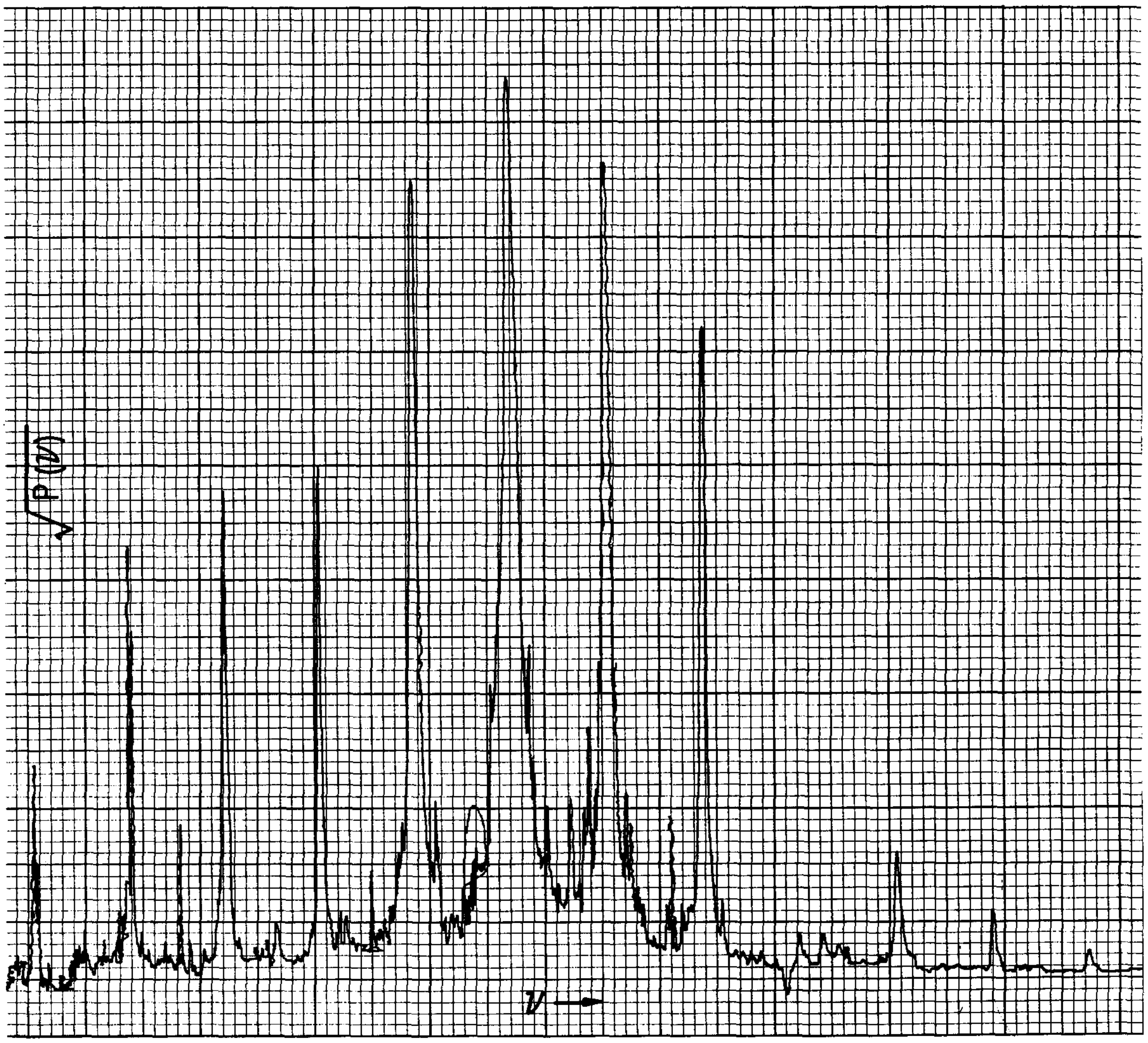


FIG. 8 THE POWER SPECTRUM OF A 5MC HELIUM COOLED QUARTZ CRYSTAL OSCILLATOR MULTIPLIED IN FREQUENCY 2916 TIMES. THE PROMINENT SIDEBANDS ARE DUE TO FREQUENCY MODULATION OF 60CPS AND HARMONICS OF 60CPS. NOTE THAT THE SPECTRUM IS UNSYMMETRIC. THE CENTER OF GRAVITY OF THE SPECTRUM HAS BEEN SHIFTED 41CPS IN THE MULTIPLICATION PROCESS FROM THE VALUES IT WOULD HAVE HAD, HAD THERE BEEN NO SIDEBANDS.

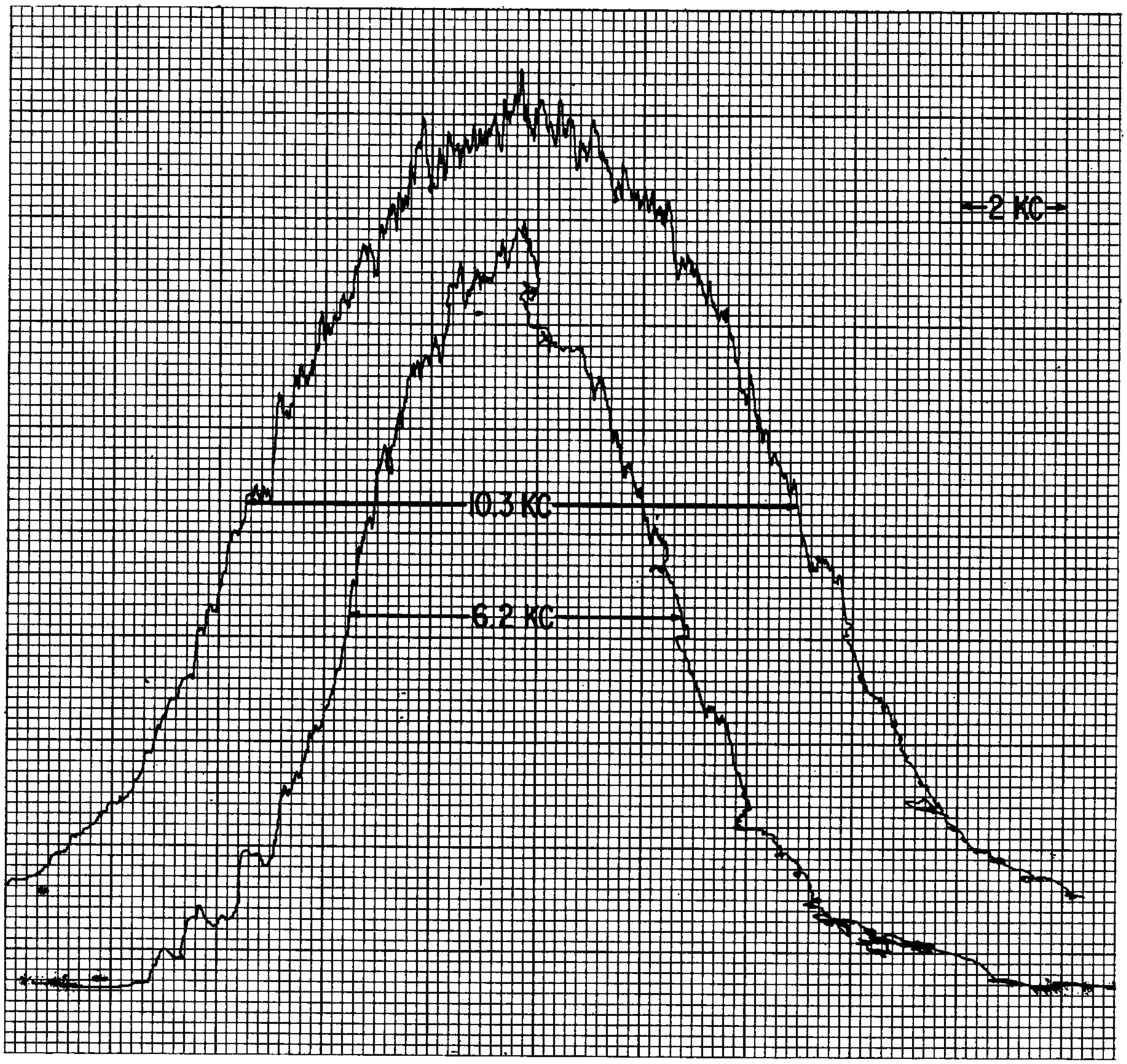


FIG. 9 100KC GT CRYSTAL OSCILLATOR. MULTIPLICATION FACTOR = 145,800. THE TWO TRACES DIFFER IN THAT THE UPPER TRACE WAS OBTAINED 1 HOUR AFTER THE MULTIPLIER CHAIN WAS SWITCHED ON, AND THE LOWER TRACE WAS OBTAINED 6 HOURS AFTER THE CHAIN WAS SWITCHED ON.

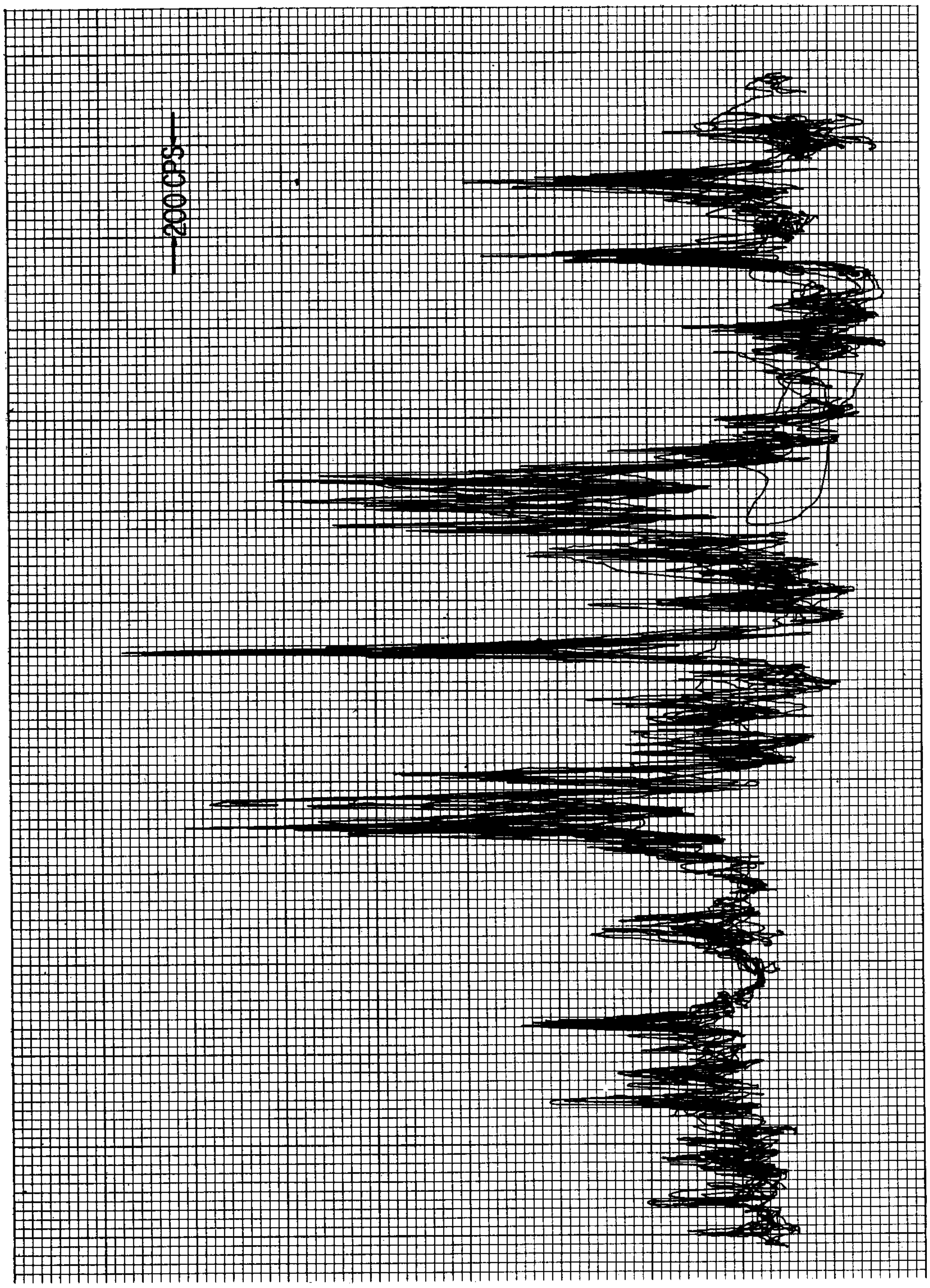
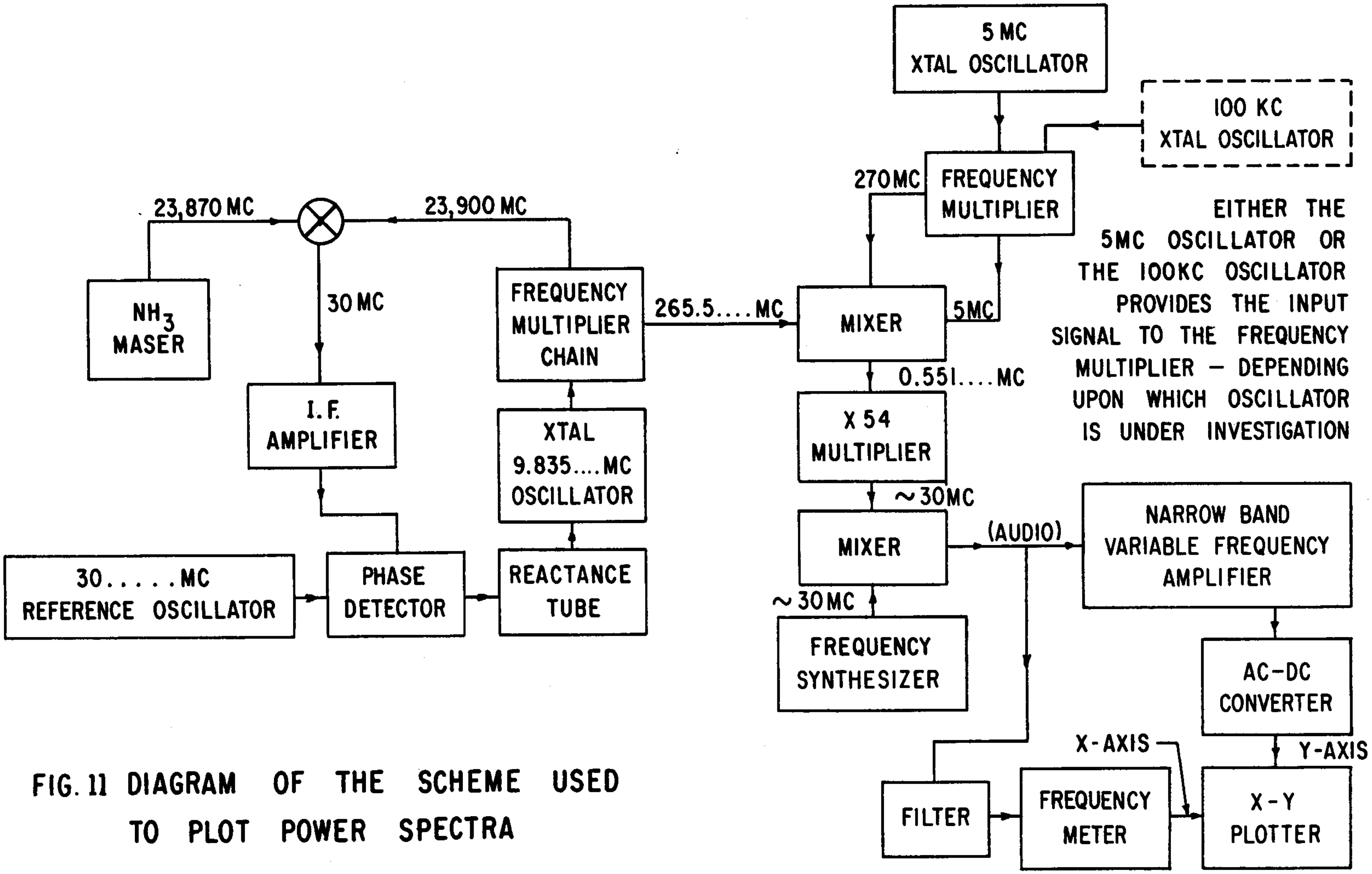


FIG. 10 POWER SPECTRUM OF THE 5MC CRYSTAL OSCILLATOR OF AN ATOMICHRON (MULTIPLIED BY 2916)



EITHER THE 5MC OSCILLATOR OR THE 100KC OSCILLATOR PROVIDES THE INPUT SIGNAL TO THE FREQUENCY MULTIPLIER – DEPENDING UPON WHICH OSCILLATOR IS UNDER INVESTIGATION

FIG. 11 DIAGRAM OF THE SCHEME USED TO PLOT POWER SPECTRA
`