PERFORMANCE OF A DUAL BEAM HIGH PERFORMANCE CESIUM BEAM TUBE *

Gary A. Seavey
Hewlett-Packard Company
Santa Clara, California

ABSTRACT

The dual beam high performance cesium beam tube general design and operation is discussed. Computer generated theoretical performance predictions are compared to typical performance measurements on a large sample of tubes. Improvement in cesium oven design and a configuration change of the tube's cesium detector is presented. A few tubes were subjected to adverse environments and the beam tube performane after these tests is discussed. Also, a slightly modified dual beam high performance cesium beam tube was subjected to high level random vibration and its performance before and after the vibration is presented. The possibility of achieving greater than typical performance for relatively short periods of time, for special applications, is discussed. Measurements of accuracy, stability for various time periods and stability in dc magnetic fields carried out on HP 5061A primary frequency standards equipped with dual beam high performance cesium beam tubes is presented. The frequency stability of various types of atomic frequency standards is compared to the typical frequency stability of a HP 5061A primary frequency standard equipped with a dual beam high performance cesium beam tube.

INTRODUCTION

The dual beam high performance cesium beam tube was developed by Hewlett-Packard Company in 1971. During the past three years Hewlett-Packard has been producing the tube to be sold as an option (designated option 004) with the HP 5061A primary frequency standard.[1] Figure 1 shows the high performance tube and an HP 5061A. Utilization of the option

* This paper was presented in part at the 30th Annual Frequency Control Symposium

with the HP 5061A allows one to realize improved short-term stability, reproducibility, settability, and decreased sensitivity to dc magnetic fields.

General Design and Operation

The dual beam high performance cesium beam tube is a passive atomic resonator whose internal components are shown in Figure 2 and are: a cesium oven, which forms and aims the two cesium beams; the state selector magnets, which by means of a magnetic field gradient, spatially separate the atoms of each beam into two energy groups; the microwave cavity, in which an energy state change of the atoms is induced; the hot-wire ionizer, which ionizes the atoms that have undergone an energy state change; the mass spectrometer, which separates the cesium ions from unwanted noise contributing ions; the electron multiplier, which converts the ions to electrons and amplifies the electron current to a level compatible with subsequent electronics; the ion pump, which maintains a high vacuum within the tube; magnetic shielding, which minimize effects of external magnetic fields; solenoid type windings, which produce the homogeneous magnetic field "C-field" over the region of the microwave cavity and for degaussing the beam tube magnetic shields. Also the tube contains gettering material which collects and traps the unwanted expended cesium atoms.

The primary life limiting elements in cesium beam tubes are the cesium supply and the gettering system. The cesium supply and gettering system in the dual beam high performance cesium beam tube have been designed for a five year operating life, as has the standard tube.

The cesium oven or cesium source forms and aims the two cesium beams by means of a multi-tube collimator. We use dual beams primarily to double the output signal to the ionizer which gives a $\sqrt{2}$ increase in the Signal-to-Noise ratio at the input to the electronics. A second advantage of the dual beam, which has been designed in, is relative immunity to acceleration effects. The cesium beam intensity is controlled by the temperature to which the cesium is heated by the oven. Additionally there are intentional conductance limitations in the oven and collimator which reduce the beam intensity. These conductances within the oven are designed to prevent liquid cesium from escaping the oven.

The state selection magnets produce an inhomogeneous, 10^4 gauss peak, magnetic flux density. The beam comprised of cesium atoms in two energy level groups, as depicted in Figure 3, passes through this large magnetic field gradient. Since:

1. an atom's energy is dependent on magnetic field intensity;

2. the magnetic field intensity is dependent on position in the state selector magnet gap;

3. physcial systems tend to the lowest potential energy possible;

then the atoms experience a force in the direction of the magnetic field gradient. The atoms in the levels of F=3 and F=4, m_F=-4 group are deflected towards stronger magnetic fields. The atoms in the remaining F=4 levels are deflected towards weaker magnetic fields. Hence the atoms of each of the two beams are spatially separated into two energy level groups.

The first state selector magnet separates the atoms into two energy level groups such that the F=3 levels and F=4, m_F=-4 level are directed through the microwave cavity while the remaining group of the F=4 levels is prevented from passing through the microwave cavity.

The second state selector magnet separates the cesium beam which has traveled through the microwave cavity into two groups, the atoms that have not undergone a transition to the F=4 group are directed away from the hot-wire ionizer and the atoms that have undergone a transition to the F=4 group are deflected onto a path toward the hot-wire ionizer. Thus the majority of atoms that are ionized by the hot-wire ionizer are atoms that have experienced an energy transition while traveling through the microwave cavity.

The microwave structure first proposed by Professor Ramsey is a center feed, U-shaped microwave cavity which is machined to close tolerances from oxygen-free copper. The outside configuration of the microwave cavity is fabricated in such a way that it positions the C-field windings and the C-field magnetic shield.

The hot-wire ionizer is a flat tantalum ribbon running at approximately 1000° Celsius. The cesium atoms which have undergone an energy transition in the microwave cavity are directed toward the ionizer by the second state selector magnet. The atoms intercepted by the ionizer first stick, then are ionized, and finally evaporated and accelerated into the mass spectrometer.

The mass spectrometer spatially separates the cesium ions from any other unwanted noise producing ions, such as potassium, and focuses the cesium ions into the electron multiplier.

The electron multiplier, which is of the box and grid design, converts the 1×10^{-11} ampere ion current to an electron current and then amplifies the electron current to approximately 10^{-7} amperes which becomes the input for the signal processing electronics of the HP 5061A.

Figure 2 depicts the paths of the cesium atoms through the beam tube. The solid lines indicate the path of the atoms that contribute to the signal and the dashed lines indicate the path of the atoms that do not contribute to the signal.

Comparison Theoretical Vs. Actual Performance

A computer program was developed to model the dual beam high performance cesium beam tube and the theoretical performance was calculated based on this model.[2] The pertinent parameters obtained from the computations are as follows:

1. Total beam intensity arriving at the hot-wire ionizer, 7.2×10^{7} atoms/sec. (1.15×10^{-11}a)

2. Linewidth of the field independent transition ($F=3$, $m_F=0$ to $F=4$, $m_F=0$) is 327 Hz.

3. Figure of merit, 31

An initial production group of approximately 30 tubes was produced that exhibited performance somewhat less than predicted. An investigation was carried out to determine the cause of this disagreement. A cesium source problem was discovered as was an improvement in the detector configuration.

The cesium source or "oven problem" which caused erratic beam intensity performance and some very early failure, due to decreased signal level, required a redesign of the cesium oven. This has long since been completed, and since we have seen no recurrences we feel confident that the problem is cured.

In Figure 4 the shaded area depicts the figure of merit of the initial group, and the outlined area, the figure of merit of the most recent 150 units. The figure of merit increased 44% to a mean value of 24.

Typical performance after the modifications as measured on over 150 tubes:

1. Total beam intensity, 1×10^{-11}a

2. Linewidth, 358 Hz

3. Figure of merit, 24.

The most important of these parameters in characterizing overall tube performance is the figure of merit. The figure of merit is defined to be the beam tube output signal to noise ratio as measured in a ¼ Hz bandwidth, divided by the linewidth of the field independent transition. Figure 5 depicts the pertinent measurements and their relation to the figure of merit.[3]

Typical Performance in an HP 5061A

Figure 6 is a frequency offset histogram of HP 5061A option 004 based on final test data for over 100 instruments.

The frequency stability specification for the 5061A option 004 is based on a realized figure of merit of 10. The high performance tube figure of merit mean of 24, if realized in the environmental and instrument conditions prevailing, would give a 100 second stability of 3.5×10^{-13}. Published data of NBS shows a realized stability of 5×10^{-13} at 100 seconds. The specification sheet calls for less than 8.5×10^{-13}. These NBS data also indicated that the $\tau^{-\frac{1}{2}}$ relation holds past 10^4 seconds, giving 5×10^{-14} at 10^4 seconds.[4]

The specification limit for sensitivity to magnetic fields is $\pm 2 \times 10^{-13}$ for a 2 gauss field in any direction. A typical measurement yields:

side to side	$\pm 1 \times 10^{-13}$
top to bottom	$\pm 5 \times 10^{-14}$
front to rear	$\pm 5 \times 10^{-15}$

The reproducibility specification of 3×10^{-12} is obtainable when the HP 10638A Degausser is used with the HP 5061A Option 004. This reproducibility is shown by the accuracy histrogram Figure 6. The function of the degausser is to relax the magnetic domains of the inner shield to an equilibrium magnetization after a change in the "C-field" current. The degausser accomplishes in 20 minutes the relaxation that might otherwise proceed for weeks causing a shift in frequency as the "C-field" changes. A high level degaussing is recommended at turn on, and can be performed as the oven is heating. Low level degaussing can be performed without causing the instrument to unlock, and is recommended after changes in "C-field", or magnetic environment changes are made. Reproducibility is defined as the independently set up instrument frequency comparison to the NBS frequency standard.

The settability specification of $\pm 1 \times 10^{-13}$ requires the use of the degausser. Settability or calibration refers to the ability to make relatively small, predictable changes to the output frequency of the standard. One minor division on the "C-field" control corresponds to a nominal change of 5×10^{-14} in output frequency and 2 in the logging numbers on the "C-field" dial which reads from 0 to 1000.

Typical performance with regard to settability is 1×10^{-14} which includes control linearity, operator, beam tube and degausser effects.

Operating life data are still scarce, but recently two early tubes were returned at end of life after more than 4 years in service. These tubes were of the old oven design.

Frequency Stabilities of Various Types of Atomic Frequency Standards

Before the development of the high performance cesium standards, the commercial rubidium standards exhibited superior short-term stability by an order of magnitude when compared to commercial cesium standards. The high performance cesium standard exhibits typical short-term stability approximately equal to the short term stability of commercial rubidium standards.

Figure 7 is a graphic representation of the measured frequency stability of various types of atomic frequency standards.[5] The shaded area labeled High Performance Commercial Cesium represents the realizable frequency stability range for $\pm 1\sigma$ of the measured figure of merit for a sample of over 150 dual beam high performance cesium beam tubes. The mean of this range corresponds to a figure of merit of 24.

High Level Vibration

A dual beam high performance cesium beam tube was modified for the Global Positioning System evaluation program.[6] The modifications were to strengthen it structurally and change the internal wiring so that the tube could be subjected to high level random vibration and not experience mechanical or electrical failure.

The random vibration characteristics were: acceleration spectral density of 0.35 G^2/Hz from 125 Hz to 1200 Hz, below 125 Hz and above 1200 Hz the vibration spectral density decreases by 6 dB/octave until a total frequency band of 20 Hz to 2000 Hz is reached. Figure 8 is the plot of acceleration spectral density vs. frequency for the above mentioned vibration. This vibration characteristic integrates to approximately 25 g rms.

The tube was measured in an HP 5061A frequency standard prior to the vibration, then subjected to the vibration while non operating and then remeasured in the same HP 5061A frequency standard. A comparison of this electrical performance before and after the vibration is tabulated below:

	Accuracy	Short Term Stability (10 second averaging)
before vibration	4.5×10^{-14}	1.33×10^{-12}
after vibration	11.1×10^{-14}	1.68×10^{-12}
specification	$300. \times 10^{-14}$	2.70×10^{-12}

Modified Performance for Special Applications

The figure of merit (stability) of a cesium beam tube is determined, as mentioned previously, by the signal-to-noise ratio, the linewidth and curve shape factor. In any given beam tube the linewidth and curve shape are relatively constant, but the signal-to-noise ratio can be changed within limits by changing the beam intensity, i.e. oven temperature. Since the vapor pressure of cesium doubles for approximately a 10° Celsius increase in oven temperature one expects such a change to give a doubling of cesium beam intensity, a $\sqrt{2}$ improvement in figure of merit and a doubling of consumption of cesium, or halving of operating life.

Cesium beam tubes have been operated with oven temperatures increased 12° Celsius from nominal for periods of hundreds of hours. If the cesium vapor pressure is made too great scattering occurs in the beam which adversely affects the curve shape and linewidth which shorten the operating life and yield no benefits.

Similarly a reduction in cesium oven temperature will give reduced beam intensity, cesium consumption, and figure of merit with expected longer life. The initial limitation here would be the need for a detectable signal level which would set a low temperature limit.

Adverse Environments

Randomly chosen tubes have been subjected to adverse environments. One such test was to subject a tube to high level shock. The test called the "hammer blow" is carried out by mounting the tube to a large steel carrier and then striking the carrier with a 400 lb. hammer. The hammer swings through 1, 3, and 5 foot drops in each of three axes for a total of nine blows. The 5 foot drop generates shocks on the order of 1500 g at the table. The tube successfully passed this shock test without mechanical or electrical damage, or measurable change.

Acknowledgements

The author wishes to express his appreciation to L. F. Mueller, R. C. Hyatt, R. F. Lacey, D. W. Allan for discussions invaluable in the preparation of this paper and to Sal Blas and Liz Cypert for their efforts in preparing the illustrations and manuscript.

References

1. R. C. Hyatt, L. F. Mueller, T. N. Osterdock "A High Performance Beam Tube for Cesium Beam Frequency Standards," Hewlett Packard Journal, September 1973, p. 14.

2. Unpublished work, L. S. Cutler, R. F. Lacey

3. R. F. Lacey, A. L. Helgesson, J. H. Holloway "Short Term Stability of Passive Atomic Frequency Standards," Proc. IEEE, 54, 2, p. 170, February 1966.

4. H. Hellwig, D. W. Allan, F. L. Walls "Time and Frequency," Proc. Fifth International Conference on Atomic Masses and Fundamental Constants (AMCO-5) June 1975.

5. Helmet W. Hellwig "Atomic Frequency Standards: A Survey," Proc. IEEE, 63, 2, p. 214, February 1975.

6. Contract No. N00173-75-C-0471 (NRL).

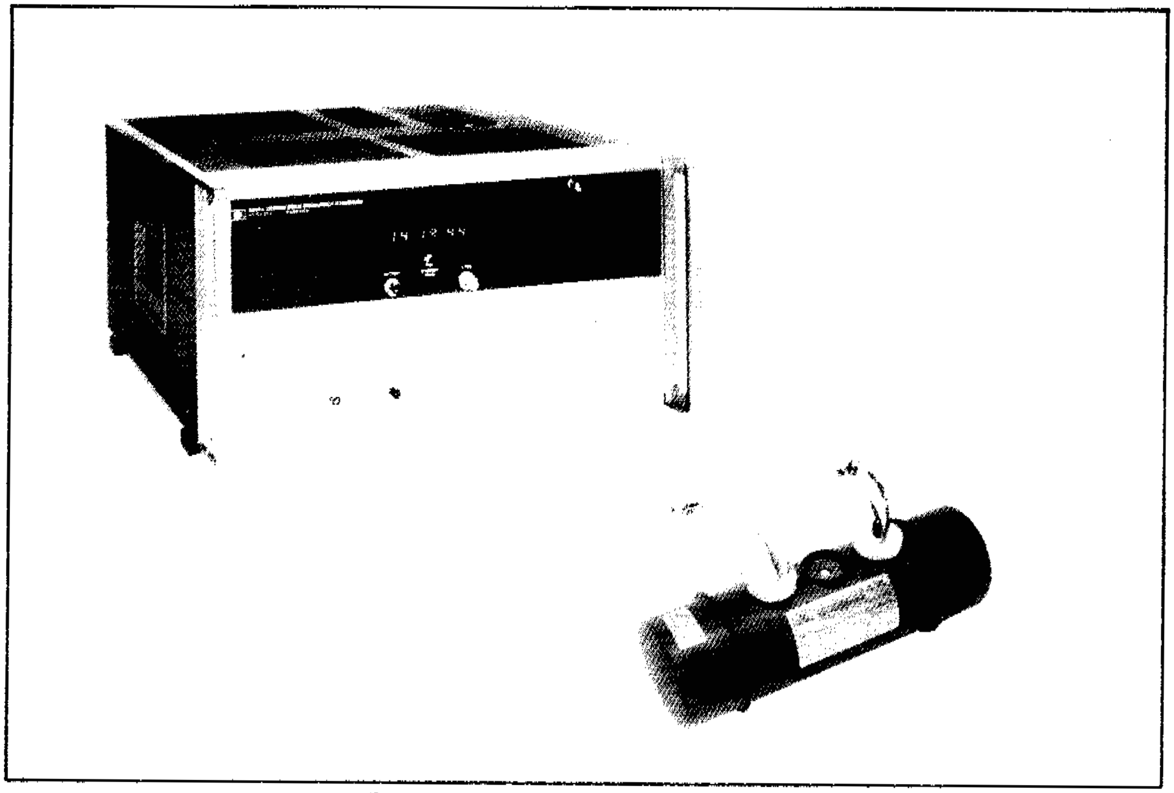

Figure 1. HP 5061A and High Performance tube

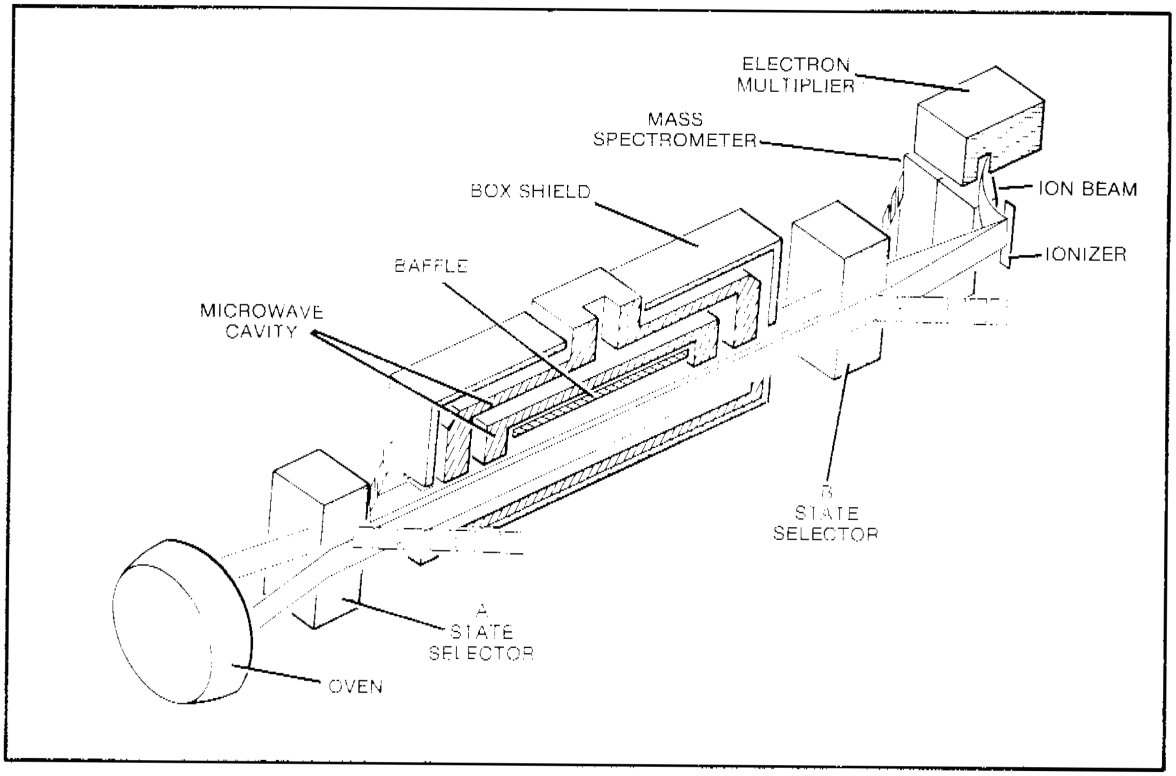

Figure 2. Pictorial representation of Dual Beam High Performance

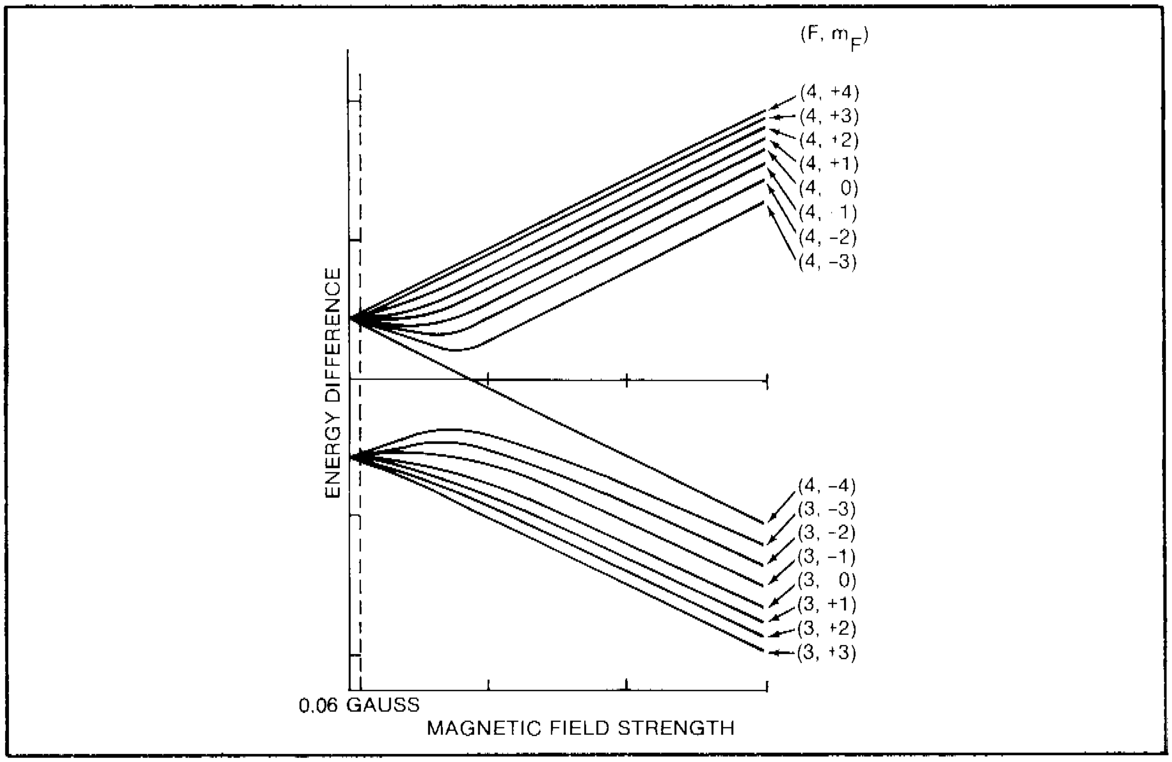

Figure 3. Energy Level Diagram of Cesium 133

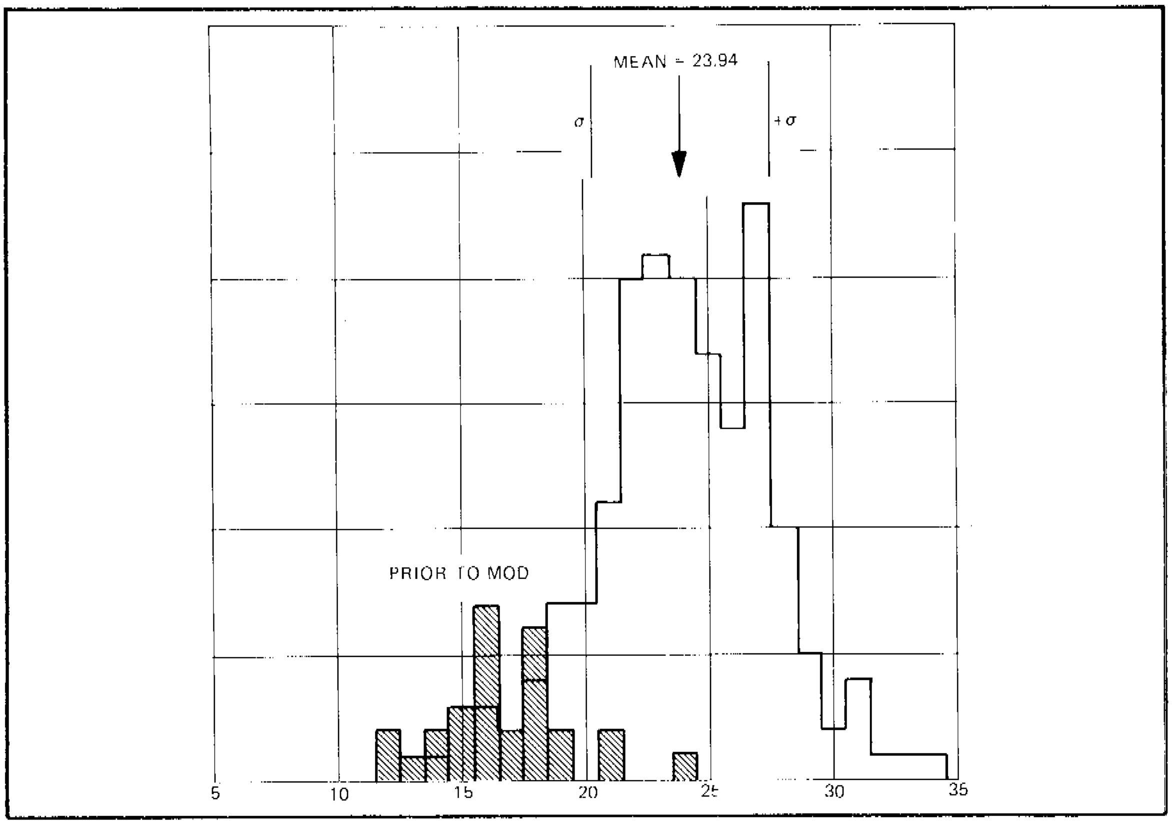

Figure 4. Figure of merit Histogram

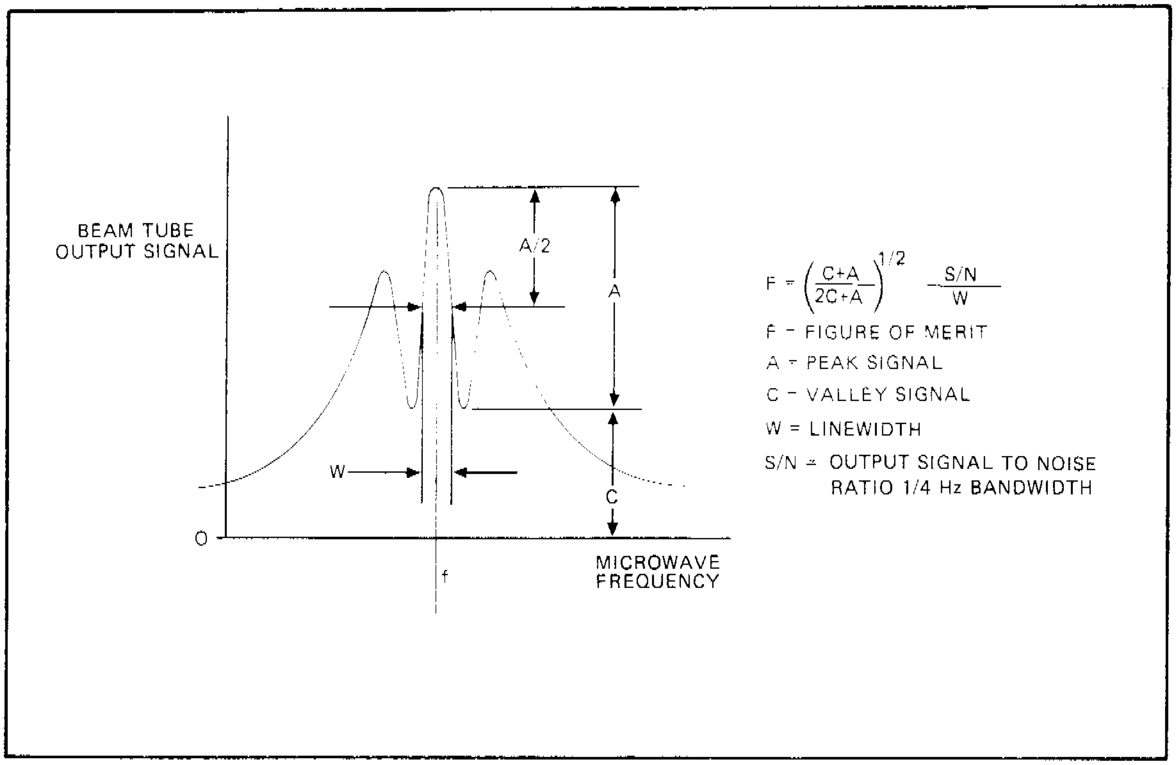

Figure 5. Figure of Merit

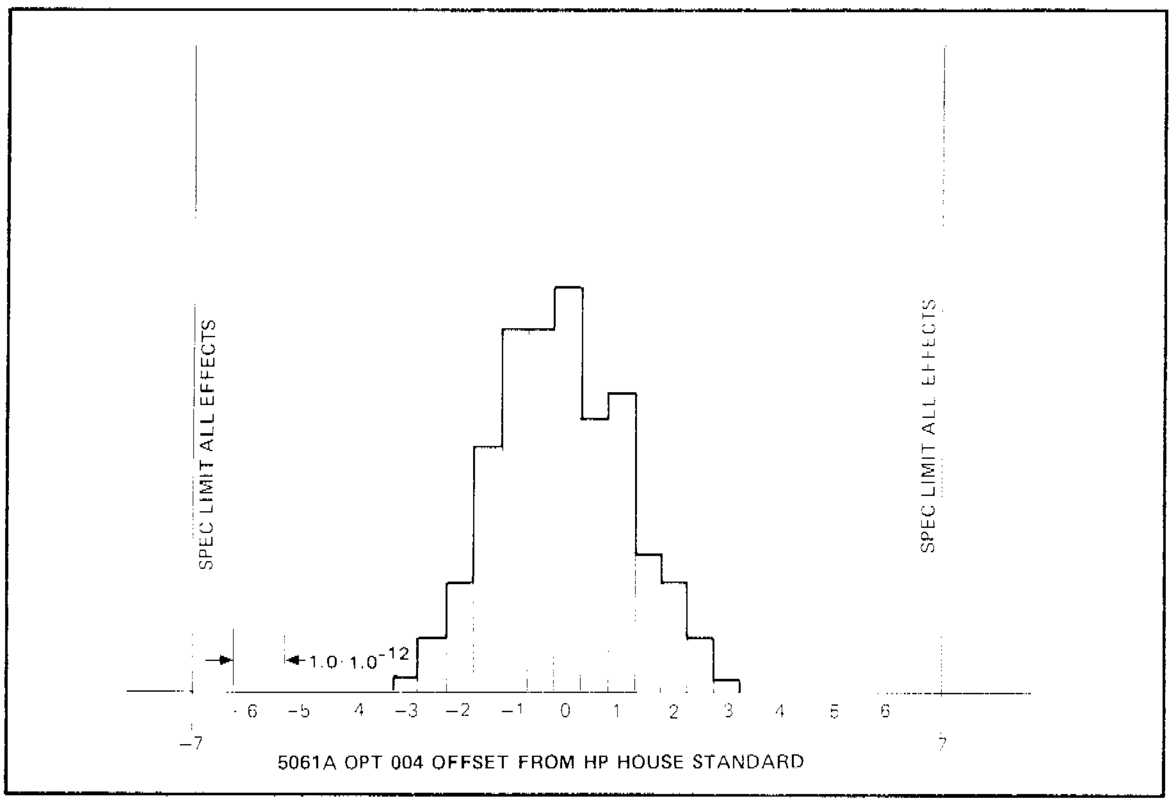

Figure 6.

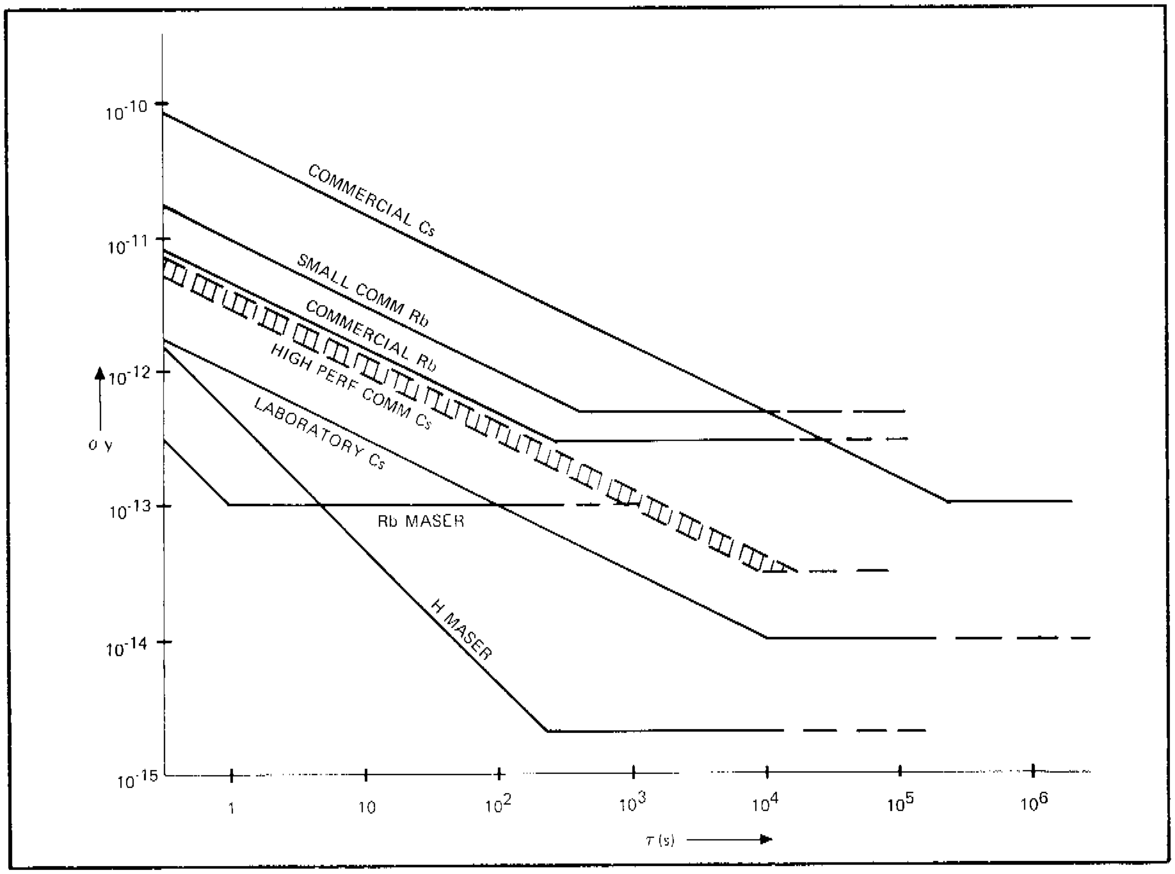

Figure 7. Frequency stabilities of various types of atomic frequency standards

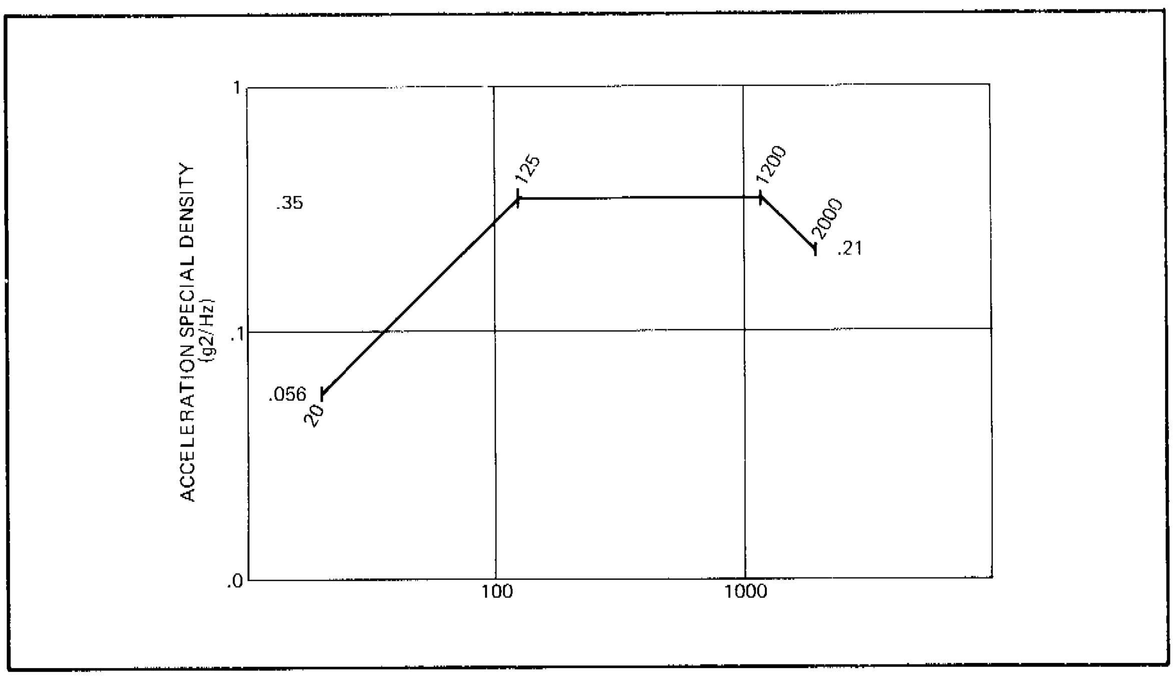

Figure 8. Acceleration spectral density