APPLICATION OF HIGH PERFORMANCE CESIUM BEAM FREQUENCY STANDARDS TO VLBI

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I. INTRODUCTION

Inherent to any VLBI experiment or observation is the use of independent frequency standards at both elements of the interferometer. These standards generate the signal for the local oscillator (LO) used to convert the observed RF frequencies to a video signal which is then recorded on magnetic tape. They also furnish the reference time recorded along with the observations made by each station. These tapes are then brought together at a later time for cross-correlation in order to determine the interferometric observables.

The stability requirements of the frequency standards used for VLBI experiments are very demanding. Figure 1 illustrates the relative frequency stability required to insure 90° radio phase stability as a function of time interval for several representative observing frequencies. Until this time, only rubidium frequency standards and hydrogen masers have been used for most VLBI experiments. Usually rubidium standards are used when hydrogen masers are unavailable. MacDoran et. al. (1975) have reported the successful use of a HP 5065A rubidium standard at S-band (2.3 GHz) for the ARIES project. They also make the conjecture that sufficient stability might be obtained for X-band (8.4 GHz) by slaving a rubidium to a cesium frequency standard with a phase-lock loop.

As this last statement implies, the typical commercially available cesium standard does not have sufficient intermediate term frequency stability, i.e., for periods of time less than or equal to 1000 secs, to be of use as a VLBI reference oscillator. Because improved cesium standards, such as the HP 5061A with option 004, High Performance Cesium Beam Tube (HPCBT), approach the short and intermediate term stability of a typical rubidium standard, it appeared that they might be successfully applied in some VLBI experiments. In addition, the availability of several HPCBT cesium standards which had been specially modified and which appeared to have better short and intermediate term stabilities than rubidium standards (Alley, 1975) led the Naval Research Laboratory and the Naval Observatory to undertake a joint program to test and evaluate their use for VLBI applications.

The program consisted of evaluating the laboratory behavior of the specially modified HPCBT frequency standard and then utilizing it and an "off-the-shelf" HPCBT HP5061A (004) in a VLBI experiment. Participation in the VLBI experiment was to be on a standby basis so as not to interfere with the major goal of the experiment. After sufficient observations had been made using a hydrogen maser as the principal reference standard, the test oscillators were switched into the system.

II. STABILITY MEASUREMENTS

CS 1025, an HPCBT cesium beam frequency standard which had been specially modified was selected for this experiment. The modifications consisted of:

1) increased oven temperature in order to obtain a larger beam flux;

2) a second order control loop; and

3) a special HP proprietary modification.

A system consisting of:

1) Dual Mixer Time Difference System, Model 106, manufactured by Boulder Scientific R&D Laboratory, Inc. (as described by Allan, 1976);

2) HP 5360A Computing Counter;

3) HP 5376A Programmer;

4) HP K01-5360B Serial-to-Parallel Converter; and

5) HP 5050B Digital Recorder

was used to measure phase differences between CS 1025 and a hydrogen maser and to calculate the Allan variance (Allan, 1966). A beat frequency of 1 Hz was obtained using an HP 106 crystal oscillator. System measurement noise is plotted in Figure 2 along with the results obtained for the Allan variance of CS 1025 versus the hydrogen maser and typical stability curves (Walcek, 1976) for a rubidium frequency standard (HP 5065A), a HP 5061A and a HP 5061A (option 004) cesium frequency standard.

It was not possible to independently determine the Allan variance for the hydrogen maser used in this experiment. Therefore, the contribution of the hydrogen maser to the "CS 1025 versus hydrogen maser" data could not be removed. Consequently, this curve can be looked upon as an upper limit for the Allan variance of CS 1025. It is important to note that, at this time, it would be erroneous to consider this curve as typical. It is very good and represents a selected clock. More such clocks will have to be evaluated in order to determine the reproducibility of this curve.

Inspection of Figure 2 shows the improvement of this specially modified HPCBT cesium standard over a rubidium standard (HP 5065A), especially in the 1000s region. This strongly indicates that these devices should be of value in VLBI experiments where rubidium frequency standards were applicable and possibly of use in additional areas.

III. VLBI MEASUREMENTS

In March 1976, observations were made at 22.235 GHz of the strong water vapor maser associated with W3(OH)*. The interferometer elements were the 85 foot antenna at NRL's Maryland Point Observatory located at Maryland Point, Maryland, and the 130 foot antenna of Owens Valley Radio Observatory at Big Pine, California. This baseline has a length of 3547 kilometers, corresponding to a minimum fringe spacing of 0".0008. The data were recorded using the Mark II VLBI system of the National Radio Astronomy Observatory at a bandwidth of 2 MHz. The local oscillator was successively derived from a hydrogen maser frequency standard, a rubidium frequency standard (HP 5065A, Serial #161), and a cesium frequency standard (HP 5061A(004), Serial #871) for two successive periods of 15 minutes each to generate the local oscillator at Maryland Point Observatory. At Owens Valley the local oscillator was always derived from a hydrogen maser frequency standard.

The data were reduced on the NRAO Mark II processor in Charlottesville, Virginia (Clark 1973). The output from the processor was a series of 96 point cross-correlation functions at intervals of 0.2 seconds. These were fourier

*a known water source associated with an HII region.

transformed with uniform weighting on a general purpose computer to give a series of cross power spectra having a spectral resolution of 50 kHz or 0.7 km s^{-1}. The cross power spectra were coherently averaged for one second. A fringe rate was removed from the strongest cross power spectral feature in W3(OH) in order to rotate the fringe phase to zero. The complex fringe phase and amplitude, for the one second averages over a time interval of sixty seconds, were fourier transformed to evaluate the frequency stability of the local oscillators. The phases are displayed in Figure 3. Figures 4-6 show the frequency stability of the hydrogen maser, rubidium and cesium derived local oscillators, respectively. The frequency stability ($\frac{\Delta f}{f}$) of the local oscillators can be estimated as $\leq 8.1 \times 10^{-13}$ for the hydrogen maser, $\sim 1.6 \times 10^{-12}$ for the rubidium standard and 9×10^{-12} for the cesium standard. This is simply the frequency width of signal in the frequency domain divided by the observing frequency (22235 MHz). The integration time is 60 seconds. These frequency stabilities correspond to the 5061A cesium and 5065A rubidium standards displayed in Figure 2. The cesium standard used was a 5061A(004), and the main peak in the frequency display for this oscillator is quite narrow but has many harmonics. The observing procedure was again repeated in September 1976, comparing the frequency stability of the hydrogen maser frequency standard with another HP 5061A(004). The results were the same as those reported for March 1976.

An experiment using the specially modified HPCBT 5061A-(004) at a frequency of 1.670 GHz was attempted between Maryland Point Observatory, the National Radio Astronomy Observatory in Green Bank, West Virginia, and Vermillion River Observatory in Danbury, Illinois. The station at Green Bank, West Virginia failed due to an unstable second local oscillator. The data between Maryland Point Observatory and V.R.O. has not yet yielded successful fringes. However, during the experiment the 5 MHz signal from the hydrogen maser, rubidium standard (HP 5065A, Serial #161) and the specially modified cesium standard (5061A(004), Serial #1025) were compared at Maryland Point Observatory. This was done by mixing the signals from two of the oscillators and studying the resulting signal. The frequency stability of the HP 5065A (Serial #161) and HP 5061A (Serial #1025) duplicated those displayed in Figure 2.

IV. CONCLUSIONS

The typical performance curves for the rubidium standard (5065A) and the HPCBT (5061A(004)) show close agreement, with the rubidium standard exceeding the HPCBT in performance between 1 and 100 seconds. These curves are so close together that a specially selected HPCBT may exceed the typical performance of the rubidium standard, as does the curve for the specially modified 5061A(004). Similarly, a specially selected rubidium standard may exceed this curve. However, at integration times exceeding 300 seconds, the performance of the rubidium standard, as shown in the typical curve, is limited by flicker noise. For integrations exceeding 300 seconds, therefore, a specially selected HPCBT should prove to be superior to the rubidium standard. However, from the VLBI observations discussed in this paper, at 22 GHz, this does not prove to be the case. These observations were made at a very high radio frequency that necessitates very good performance, i.e. $\frac{\Delta f}{f} = \leq 10^{-12}$ on a 10 second time scale (integration) to avoid loss of coherence (i.e., a phase rotation of 90°). The frequency stability of the two HPCBT (5061A(004)) used in these observations may be typical, as is shown in Figure 1. At radio frequencies that are ten times below this, i.e. 2.2 GHz (S band), the frequency stability $(\frac{\Delta f}{f})$ required to prevent loss of coherence on short time scale is $\sim 10^{-11}$. At integrations exceeding 300 seconds or more, the frequency stability of the HPCBT should prove to be superior to the rubidium standard, as is shown in Figure 2. Therefore, it is our conclusion that at low frequencies, i.e. $<$ 2.5 GHz, for integrations greater than 300 seconds, the HPCBT should yield superior performance in VLBI phase stability to a rubidium standard. However, neither the rubidium nor cesium standards yield, within an order of magnitude, the phase stability offered by a hydrogen maser. More tests of the stability of the HP 5061A(004) need to be made under VLBI conditions to verify the curve shown in Figure 2.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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CAPTIONS FOR FIGURES

Figure 1	Relative frequency stability as a function of integration time required to avoid loss of coherence, i.e., a phase rotation of 90°, during a VLBI experiment.
Figure 2	Allan variance as a function of time interval for several different classes of frequency standards.
Figure 3	Phase of most intense spectral feature in W3(OH) versus time for a local oscillator derived from a cesium (HPCBT), rubidium and hydrogen maser frequency standard.
Figure 4-6	Fourier transform of the complex fringe Amplitude and phase displayed in Figure 3. The distribution of amplitude versus frequency illustrates the frequency stability of the local oscillators for a 60-second period.

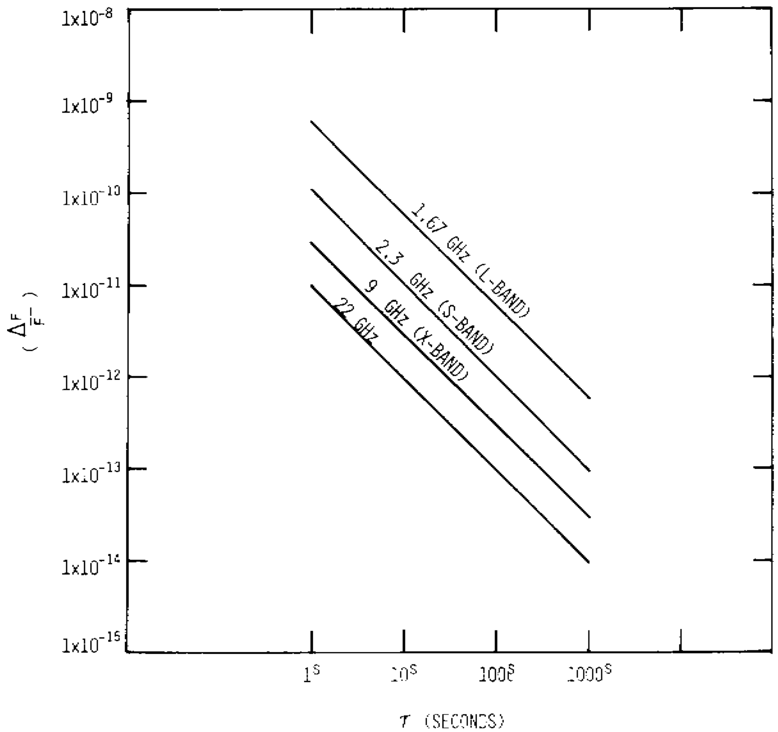


Figure 1

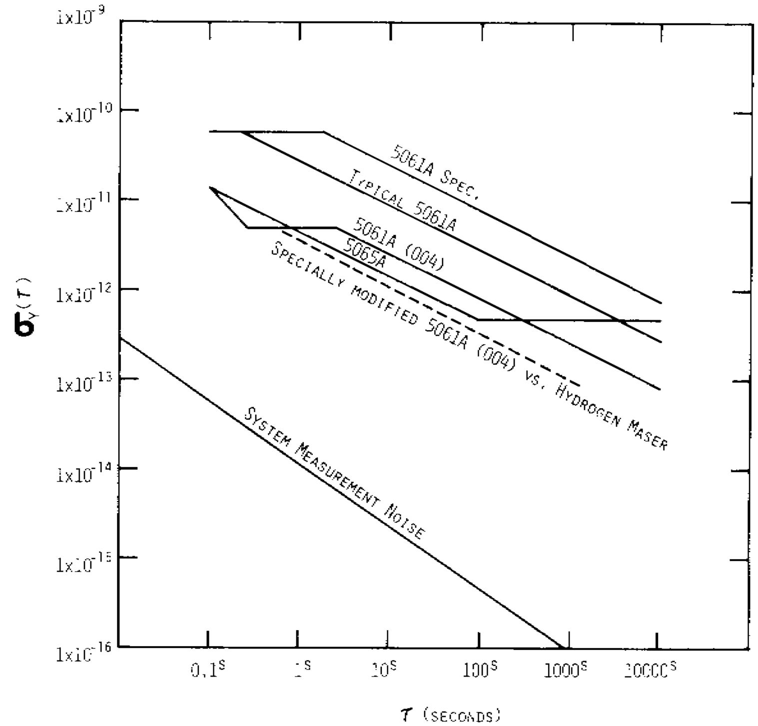
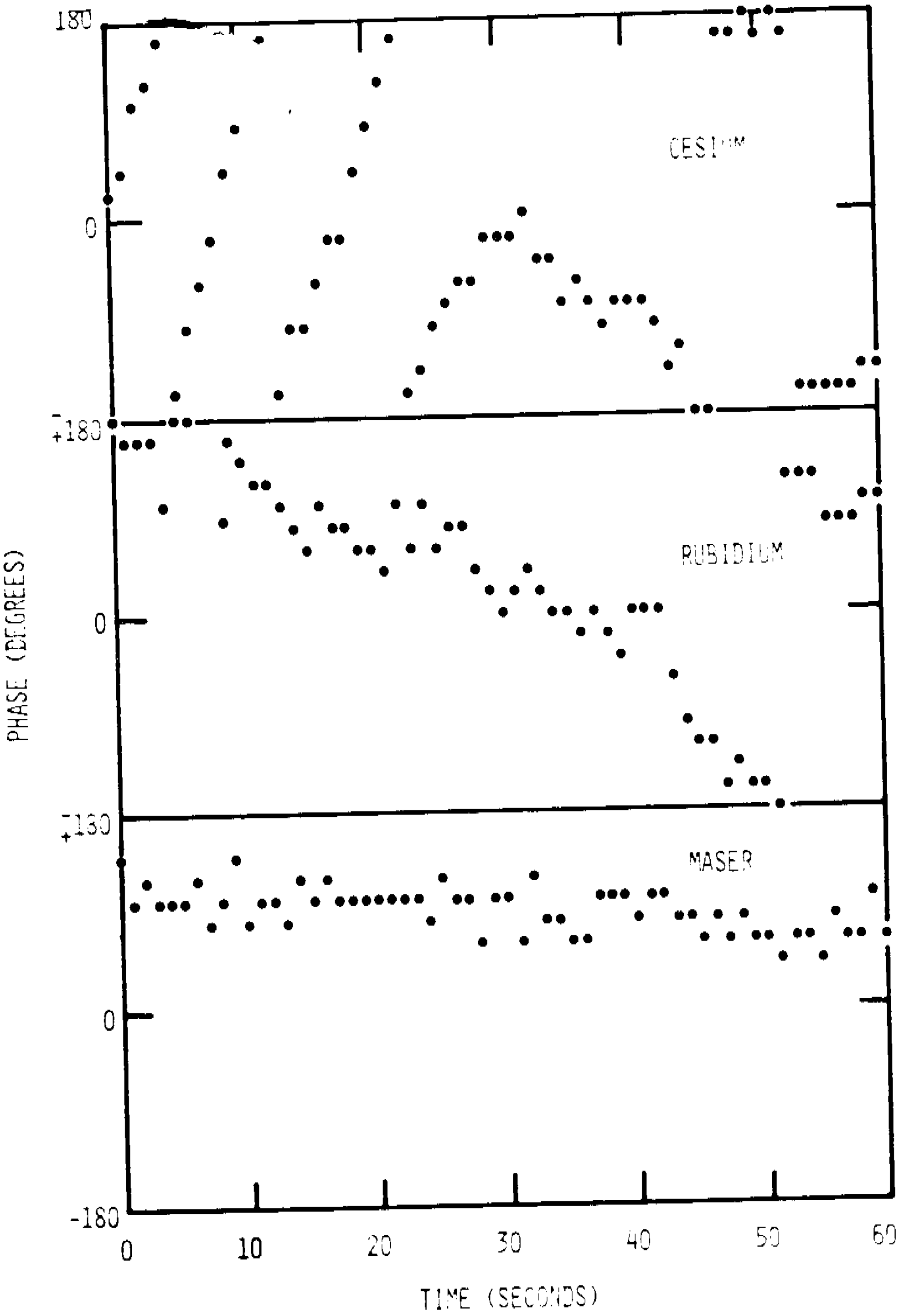


Figure 2



180
0
-180
+180
0
-180
+180
0
-180
0
10
20
30
40
50
60
PHASE (DEGREES)
TIME (SECONDS)
CESIUM
RUBIDIUM
MASER

Figure 3

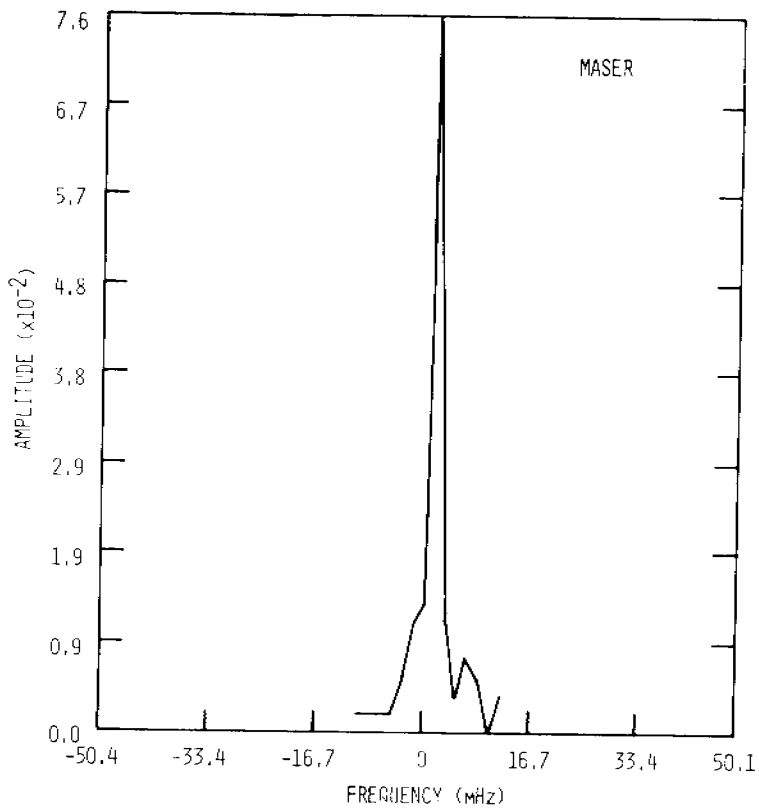


Figure 4

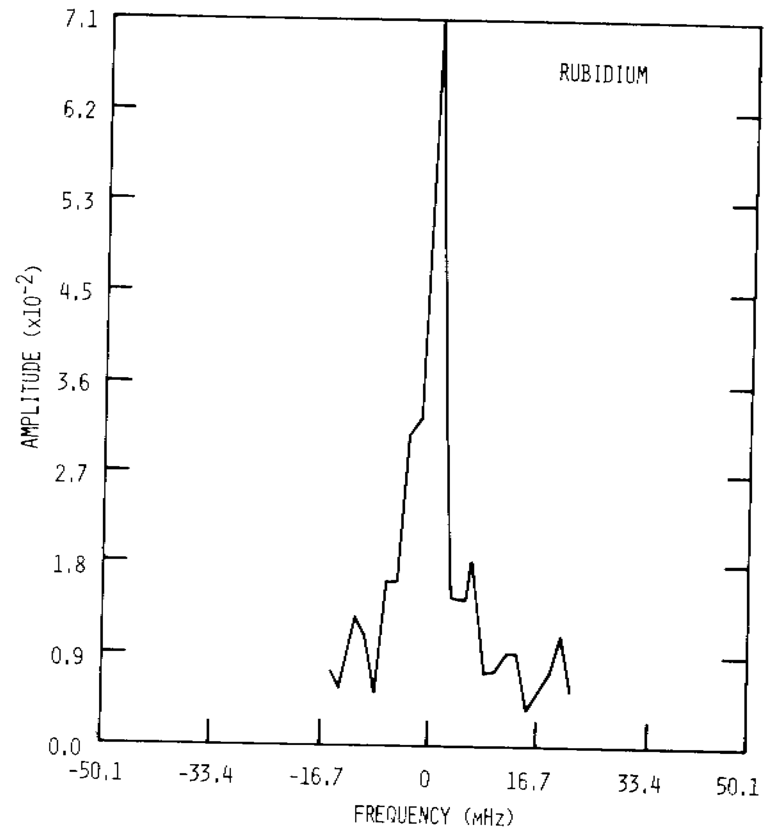


Figure 5

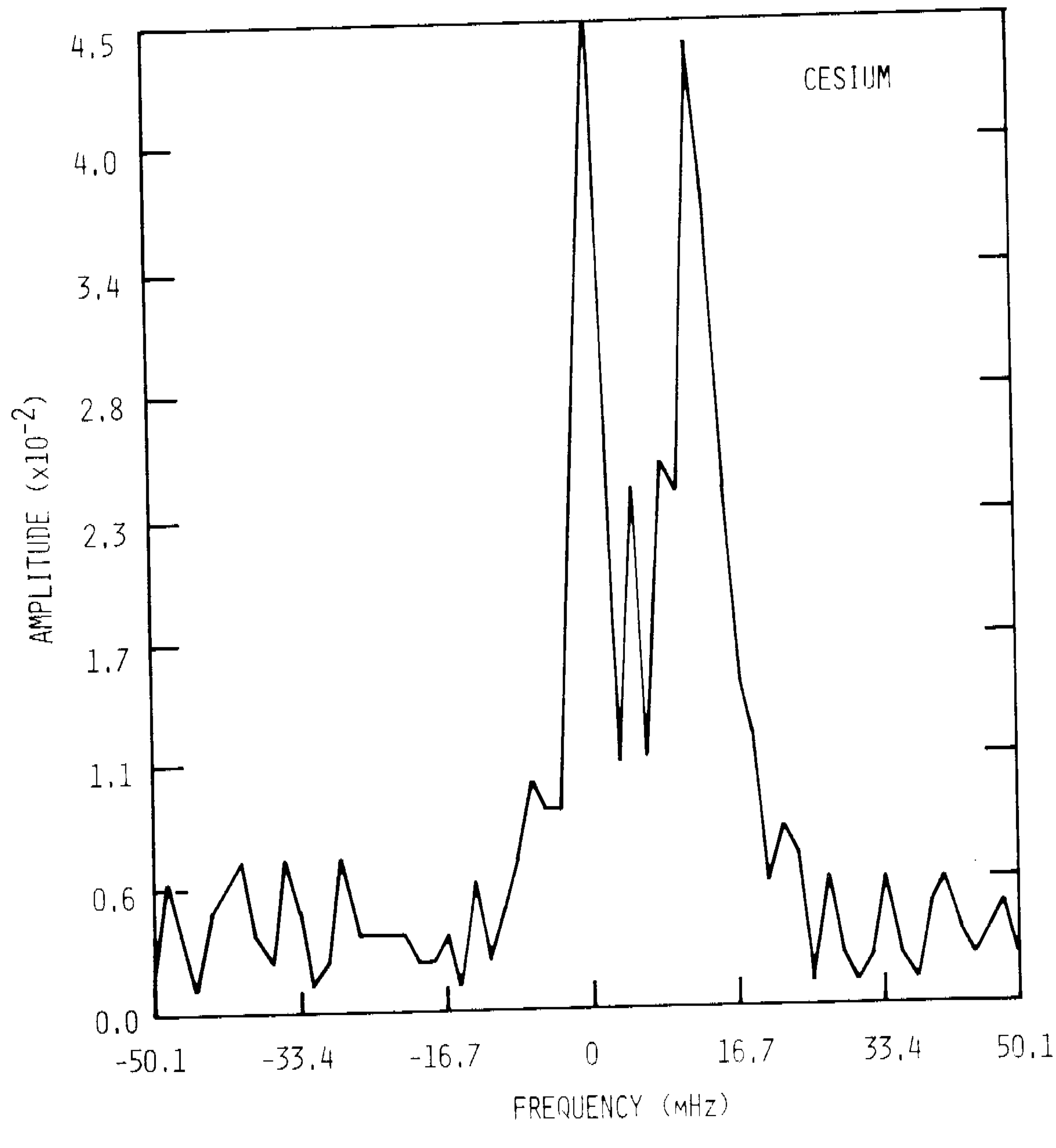

CESIUM
AMPLITUDE (x10-2)
4.5
4.0
3.4
2.8
2.3
1.7
1.1
0.6
0.0
-50.1
-33.4
-16.7
0
16.7
33.4
50.1
FREQUENCY (mHz)

Figure 6