Some Recent Progress in Microwave Frequency and Time Standards at the National Bureau of Standards

D. W. Allan, R. J. Besson*, G. Busca**, R. M. Garvey,
H. Hellwig, D. A. Howe, S. Jarvis, A. Risley
S. R. Stein, F. L. Walls, D. J. Wineland

Frequency and Time Standards Section
National Bureau of Standards
Boulder, Colorado 80302

ABSTRACT

Research and advanced development at the National Bureau of Standards (NBS) in the area of microwave frequency and time standards is discussed. New insights into the causes of flicker noise and long-term instability of cesium standards are discussed. A new cesium beam tube configuration is described with a potential accuracy of $\sim 10^{-14}$. Results and design of a passive hydrogen maser system are given showing stabilities of better than 10^{-14}. Causes for frequency instabilities in rubidium gas cell standards and on line-asymmetries are described. New quartz crystal standards and special purpose atomic standards for field use appear possible. Excellent short-term stability can be realized by superconducting cavity and quartz crystal oscillators.

INTRODUCTION

It is the intent of this paper to summarize and review efforts at the National Bureau of Standards (NBS) in the area of advanced development and improvement of microwave frequency and time standards. These efforts are aimed at fundamental improvements of accuracy, short- and long-term stability, environmental insensitivity, and practical utility for both laboratory and field applications. They are motivated by scientific and engineering opportunities uncovered within and outside of NBS as well as by the needs for improved primary frequency and time references and the demands of modern navigation and communication systems.

Progress in the area of traditional atomic standards is being made, opening up new capabilities for cesium beam, hydrogen maser, and rubidium gas cell standards. Coupling new electronic servo principles with one of the best known quantum electronic resonances, the inversion transition in ammonia, has demonstrated the feasibility of atomic standards of modest performance but of small size and a high degree of ruggedness. Advances in quartz crystal standards and

* Ecole Nationale Superieure de Chronometrie et de Micromecanique de Besancon, Cedex, FRANCE.

** Laval University, Quebec, CANADA.

superconducting cavity oscillators are opening up new performance levels in short-term stability. In addition, long-term stabilities in novel crystal standards may soon rival those of some atomic standards, and atomic standards may improve because of better slave (crystal) oscillators.

Cesium Beam Standards

One of the fundamental limitations to the accuracy of cesium beam frequency standards is the Ramsey cavity phase shift (1st order Doppler shift). The performance of commercially available cesium standards as well as laboratory standards is significantly affected by this effect. A novel approach to remove this limitation has been conceived at NBS [1] and is now being investigated experimentally.

Rather than attempt to adjust to zero the relative electrical phase of the two cavity arms, two separate cavities with slightly different microwave frequencies are employed. In this way, the relative cavity phase continually changes, producing a signal envelope free from the effects of cavity phase shift. For cesium beams with broad velocity distributions, little loss in signal linewidth is incurred.

Not only may the accuracy of the standard be improved but the stability may also be increased by the reduction of effects (as cavity phase shift) which couple device parameter changes (as velocity distribution) to frequency changes.

It is important not only to investigate fundamental improvements but also to study limitations of the existing concepts. Of particular practical importance in clock applications is an understanding (and cure!) of those parameters which adversely affect the long-term stability of cesium beam clocks [2,3]. Changes of frequency have been correlated with changes in velocity distributions, changes in microwave power, changes in voltages at the cesium beam detector, changes in polarity of the C-field current, and changes in temperature.

A novel way of controlling the microwave power is being developed which should reduce the sensitivity to temperature variations. Figure 1 illustrates for a high performance commercial tube the microwave power dependence of the amplitude of the signal at the detector, of the most probable transition velocity, and of the Ramsey pattern side-lobe peak frequency. Figure 2 more graphically indicates the sensitivity of the side-lobe peak frequency with microwave power. A 1% duty cycle sampling of the side-lobe frequency with respect to the Ramsey center peak would allow one to control the power to about 0.01 dB. Such a servo may reduce, to first order, effects on frequency caused by changes in the Ramsey pattern; e.g., velocity distribution, microwave power, velocity selection at the detector, etc.

Hydrogen Maser Standards

Theoretical and experimental work at NBS is aimed at developing a clock with substantially less long-term time dispersion than the best present clocks. This has been accomplished by developing new electronic servo concepts and applying them to a passively operating hydrogen maser [4,5].

Using this new technique the microwave cavity is locked with great precision to a probe signal which is in turn accurately locked to the hydrogen resonance line. There is no need for a second reference maser as previously required. This new ability to accurately control the cavity frequency permits one to correct for environmental perturbations to the cavity and also to greatly simplify the mechanical, thermal, and electrical designs.

Since the passive maser does not oscillate, one is even able to reduce the hydrogen density, thereby reducing spin exchange frequency pulling and the size of the vacuum pumps, and to increase reliability. Moreover, the traditional bulky microwave cavity (~30 cm dia) and separate internal quartz bulb can be replaced by a small (15 cm dia) dielectrically loaded cavity with an integral storage bulb.

The results obtained with the first prototype passive hydrogen maser frequency standard are shown in figure 3. Once calibrated, the low drift of less than 6×10^{-16}/day and the excellent long-term stability of this new standard yield an unsurpassed potential memory of the SI second.

Upgraded and reliable electronics are now being completed which should allow us shortly to begin operating a passive maser in the NBS time scale and also in the International Atomic Time scale. Progress is also being made on two small dielectrically loaded cavity units.

Rubidium Gas Cell Standards

Frequency measurements versus microwave power ($P_{\mu\lambda}$) and lamp temperature (T_L) of a passive Rb^{87} frequency standard have been made. This is the first report of the frequency sensitivity as a function of $P_{\mu\lambda}$. The basis for the sensitivity to $P_{\mu\lambda}$ and T_L has been shown to be the spatial inhomogeneities related to high buffer gas density. The type of Rb gas cell studied was an NBS-purchased, commercially available, integrated cell. It must be realized that the data reported herein are for a single unit, and that the coefficients stated below may change markedly for different settings of the microwave power, of the Rb excitation lamp temperature, and of the temperature of the gas cell. In fact, turnover points were found which, of course, greatly reduce the frequency sensitivity to changes in that particular parameter. The following coefficients only give a general value for nominal operating conditions: for microwave power, $\sim5\times10^{-11}$/db; for lamp temperature, $\sim7\times10^{-11}$/C°; and for gas cell temperature, $\sim4\times10^{-10}$/C°.

The overall results of this work gave some very interesting insights into the causes of frequency instabilities in rubidium gas cell standards. Most importantly, a possible method of avoiding some of the key problems was suggested by this work and will be investigated [6].

Ammonia Frequency Standard

The feasibility of a special purpose frequency standard based on microwave absorption in ammonia gas has been investigated [7]. Such a device could potentially fill a need in certain communications and navigation applications for an oscillator which has medium stability, and greater accuracy ($\sim10^{-9}$) than that provided by crystal oscillators, but a cost significantly smaller than that of more sophisticated atomic frequency standards. A device was constructed* using a stripline oscillator at ~0.5 GHz whose multiplied output was frequency locked to the absorption of the 3-3 line in $N^{15}H_3$(~22.8 GHz). An output between 5 and 10 MHz was provided by direct division from the primary oscillator. Observed stability was $2x10^{-10}$ from 10 to 6000 s, and reproducibility (accuracy) is estimated to be $\pm$ $2x10^{-9}$. The unique features of this device include: 1) realization of a high performance stripline oscillator; 2) use of digital servo techniques; 3) unique oscillator cavity servo; 4) pressure shift compensation scheme; 5) and the potential for high acceleration insensitivity.

Quartz Crystal Standards

Quartz crystal controlled oscillators, because of their small size and weight, low power consumption, and commercially unexcelled, short-term stability, have been used as the basic frequency reference in literally millions of systems. Their main limitations have been the sensitivity of the quartz resonator to shock and vibration, temperature variation, changes in driving amplitude, and long-term aging.

Recent advances in quartz resonator design promise to greatly reduce all of these effects, although perhaps not simultaneously. Of particular importance are the new SC, TCC and electrodeless crystals [8,9,10,11]. Several laboratories, including NBS, are developing new electronic circuits which will more fully exploit these new advancements in resonators. Acceleration sensitivities of less than $1x10^{-10}$/g, 10 second frequency stabilities $\sigma_y(10s) < 1x10^{-13}$ and aging rates of less than 10^{-12}/day now appear feasible. Frequency retrace after turn-off/turn-on are also much improved.

If one were to optimally lock a quartz crystal controlled oscillator with excellent short-term stability ($S_\phi(f) \approx -180$ dB, 1 kHz $\leq f \leq$ 100 kHz) to a resonator or oscillator with the above expected performance, the resulting standard would be more stable than most present atomic standards for a very large range of sample times, τ. The main limitation would be in the absolute accuracy.

The use of such a hybrid quartz controlled oscillator as the reference oscillator of atomic standards would greatly improve the combined, overall performance including the vibration sensitivity. For example, such an oscillator locked to a commercial cesium device would yield a stability of better than a few $x10^{-13}$ for all measurement times longer than $\approx$.02s. Therefore, we expect quartz crystal controlled oscillators based on these new resonators, possibly in combination with presently available oscillators, to play an important role in the following areas: frequency metrology, oscillators for field use, reference oscillators for atomic standards, and spectrally pure sources for high order multiplication applications, plus low temperature.

Superconducting Cavity Oscillator

Another nonatomic device with very interesting properties is the superconducting oscillator. The frequency determining element is a superconducting microwave

*This research was supported by the Advanced Research Project Agency of the Department of Defense and was monitored by ARPA under Contract #3140.

resonator. At 10 GHz, superconducting niobium cavities can be fabricated with Q-actors up to 10^{11}. In addition, these resonators have much smaller nonlinearities than quartz resonators and can be operated with very large internal stored energy. Since the white frequency noise of an oscillator is inversely proportional to both the stored energy and the Q, and the additive white phase noise is inversely proportional to the power delivered to the load, such an oscillator should have excellent spectral purity. Using reasonable parameters, the theoretical noise limit has been predicted to be [12]

$$S_\phi(f) = 10^{-20} f^{-2} \mathrm{Hz} + 2\mathrm{x}10^{-18} \mathrm{Hz}^{-1} .$$

Since the resonators are mechanically and electrically very stable and the linewidth is very narrow, superconducting oscillators achieve state-of-the-art medium-term stability. For averaging times between 10s and 1000s, the demonstrated stability is $\sigma_y = 6\mathrm{x}10^{-16}$ for one type of oscillator which used the cavity as a passive frequency discriminator [13].

The high frequency and potential spectral purity of superconducting oscillators make them very desirable for use in frequency multiplication. One of the goals of NBS is to synthesize frequencies from the infrared to the visible with the full accuracy and stability of the primary cesium standard. If suitable nonlinear elements were available, then it would be theoretically possible to multiply the signal from a superconducting oscillator all the way to the visible without loss of the carrier. Other fields can also utilize the high frequency and stability of superconducting oscillators. For example, millimeter wave VLBI and deep space tracking could both utilize the increased coherence time (low flicker noise floor) of superconducting cavity stabilized oscillators.

Conclusion

We believe that our work, as part of other advanced activities in the United States and many other countries of the world, adds credibility to the following predictions: commercial cesium standards with accuracies approaching 10^{-13} may become widely available while laboratory devices may reach 10^{-14}. Long-term stabilities over days and weeks of cesium and hydrogen standards in reasonably protected environments may reach reliably 10^{-15} resulting in time dispersions of less than 10 ns in 10 days. Rubidium and quartz crystal standards may become available with significantly reduced frequency drift; i.e., much less than 10^{-13} per day for rubidium and less than 10^{-12} per day for crystal standards. Clocks and frequency standards for special applications under severe operational or environmental constraints could be developed. Such devices could be based on new quartz resonator types of configurations, and/or on quantum electronic resonances such as rubidium or ammonia.

Devices could be built based on a systems integration of two or more concepts featuring exceptional stability over a large range of averaging times. Examples are a crystal oscillator servoed to a crystal resonator (projected performance: 10^{-13} for $0.1\mathrm{s} \le \tau \le 10^5\mathrm{s}$) or a superconducting cavity oscillator servoed to a passive hydrogen maser (projected performance: 10^{-15} for $1\mathrm{s} \le \tau \le 10^6\mathrm{s}$).

Finally, it must be realized that the above only touches those possibilities which appear realizable with devices based in the rf and microwave region. In numerous laboratories and organizations, including NBS, research and advanced development are carried out on novel standards and metrology in the far infrared,

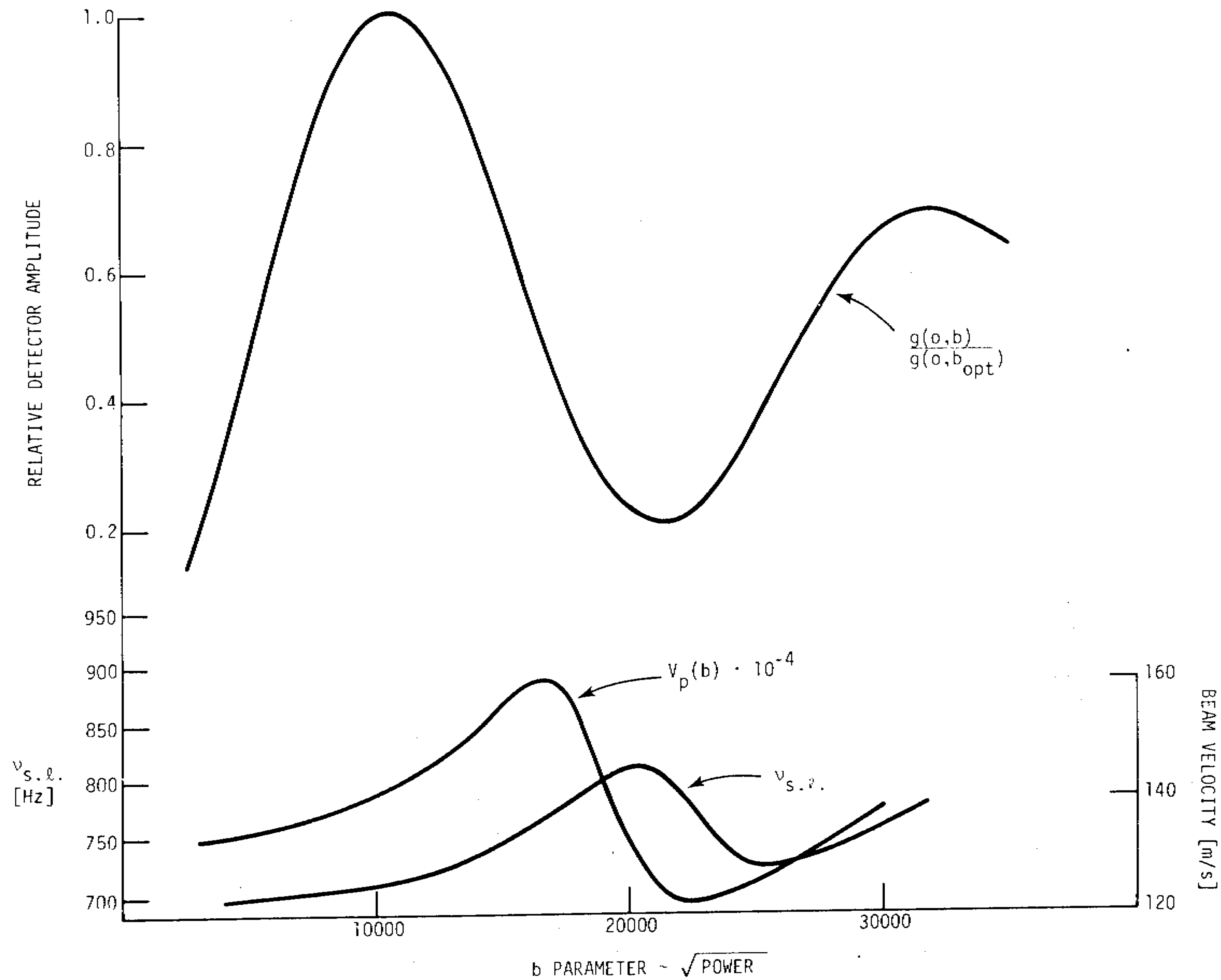

Fig. 1-The dependence of the amplitude of the detected signal $(g(o,b)/g(0,b_{opt}))$, of a most probable transition velocity $(V_p(b) \cdot 10^{-4})$, and of the frequency displacement of the first side peak or side lobe with respect to the center peak $(\nu_{s.1.})$ as a function of the b parameter (a parameter proportional to the microwave power) in a high performance commercial cesium standard.

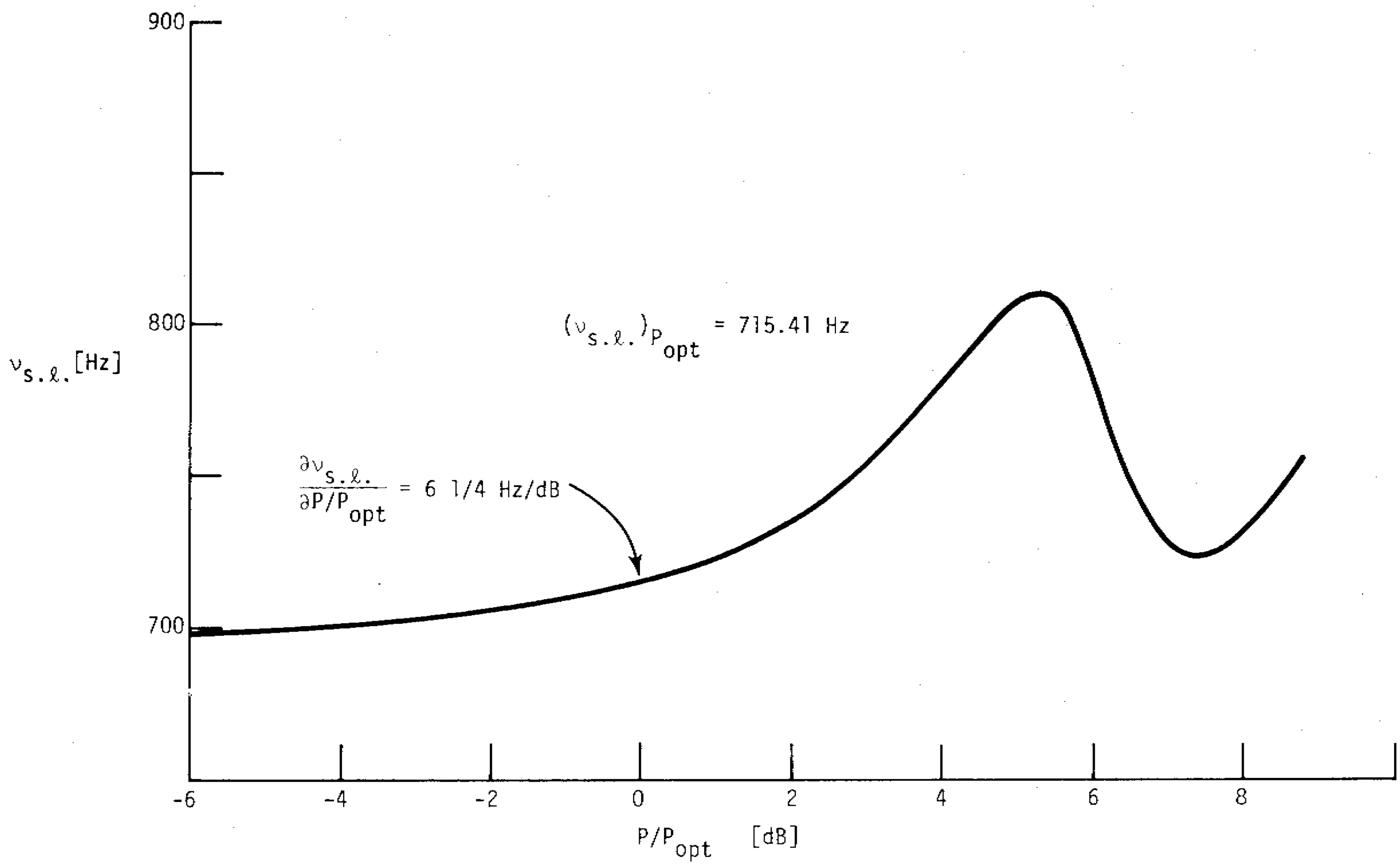

Fig. 2-The dependence of the Ramsey pattern side lobe frequency offset from the center peak as a function of microwave power for a high-performance commercial cesium standard. Optimum power (P_{opt}) is the power setting for maximum signal at the cesium detector.

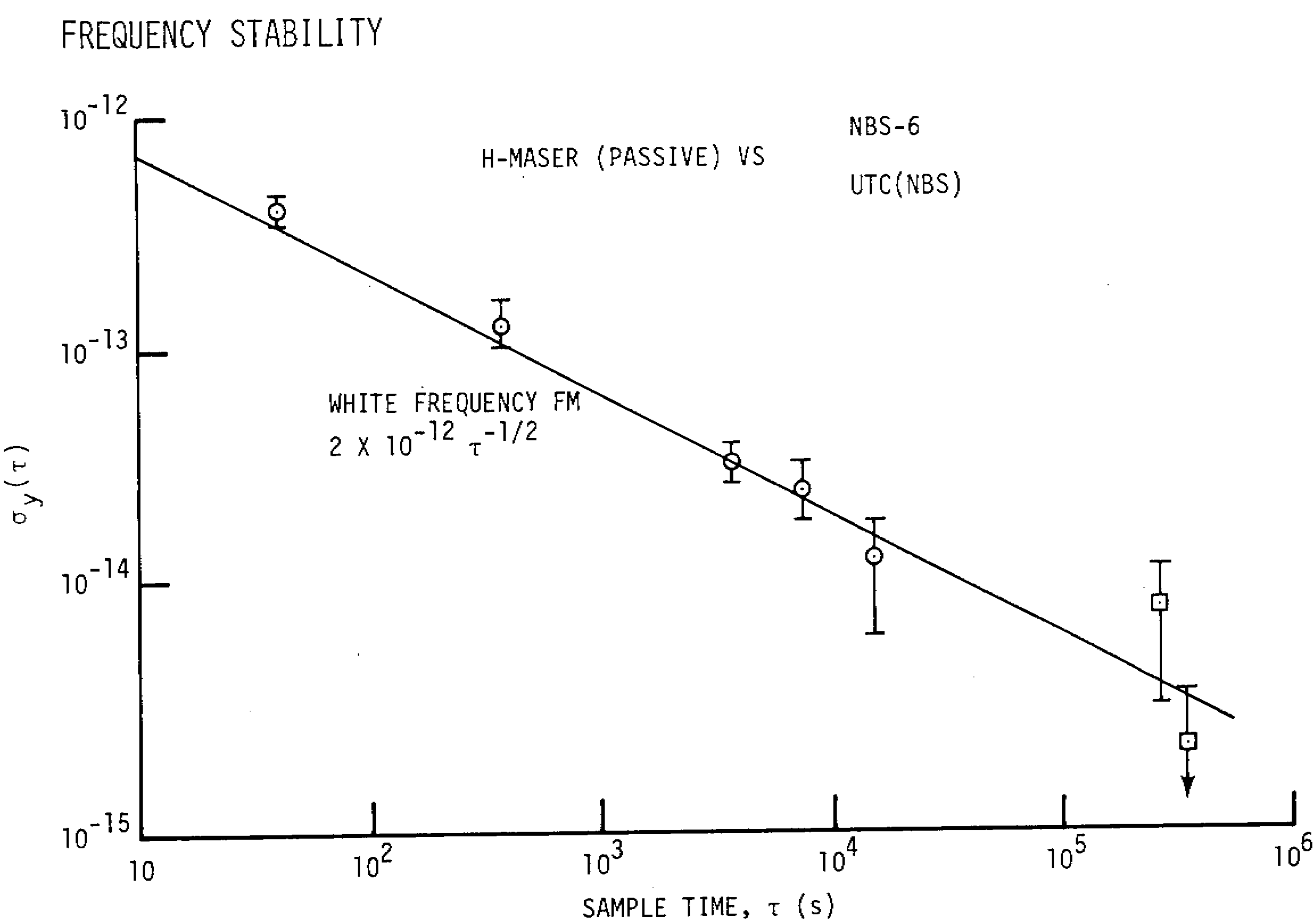

Fig. 3-Frequency stability measurements of an NBS prototype passive hydrogen maser frequency standard--showing no apparent flicker floor at well below 10-14.

QUESTIONS AND ANSWERS

DR. JACQUES VANIER, Laval University:

You mentioned accuracy for rubidium, and you mentioned at the same time a breakthrough to get this accuracy. Could you elaborate on this?

MR. ALLAN:

No. I would rather let the investigators have their chance. They have to do their thing before it can be talked about.

MR. ANDREW CHI, NASA Goddard Space Flight Center:

I notice that the data that you give in the last slide is a mix between projected and present-day performance. In the projected data, for instance, the cesium stability for 10 days is approximately 1 part in 10^{15}. Can you state at what time you can anticipate that performance?

MR. ALLAN:

On NBS-4, we have already seen 7 parts in 10^{15} flicker floor at sample times approaching 10 days. For commercial standards, I would project that we would see consistent stabilities below 1 part in 10^{14} in the next three or four years.

MR. CHI:

Was this measured by two cesium standards or just one?

MR. ALLAN:

It depends. There are several ways you can do it, of course. If you have a very good standard, you can use just one standard as the reference. Let me mention specifically that the measurements on the passive hydrogen maser were extremely difficult--it took a whole ensemble just to measure that one device. Our net assessment was that the passive hydrogen was as good as our whole clock ensemble--maybe better.

DR. ROBERT VESSOT, Smithsonian Astrophysical Observatory:

I think the acceleration question is probably the key to how you treated the temperature coefficient, because it is a question of engineering. I remember vividly when we were testing the Probe, we had to estimate the effect of gravity. So we turned it upside down and measured the two g effect. And it was a good deal less than a part in 10^{11} per g, and we did that just by making sure that the end plates and the cavity were about the same weight so they sagged by the same amount.

I should think the same sort of tricks could be done with cesium. And in the case of quartz, it is obvious that the device is in fact a mechanical thing and therefore subject directly to stress of gravitational loading, and the same with the superconducting cavity. So, I think you are right in saying you have to take it with a grain of salt.

DR. REINHARDT, NASA Goddard Space Flight Center:

The fact that some of the standards use phase lock loops and some use frequency lock loops greatly changes their sensitivity to crystal effects used in the VCO. I don't think in the hydrogen you can say that there is an actual frequency offset due to crystal effects--A phase shift, yes, but not a frequency offset.

MR. ALLAN:

In the oscillator?

DR. REINHARDT:

Yes, due to the crystal oscillator being stressed.

MR. ALLAN:

Right. Of course, even in the passive hydrogen, if you have a tight locked loop, you only see the output frequency move by one over the loop gain times the natural frequency change of the quartz oscillator. So it probably could be much less than the coefficient shown in the slide also--in other words, not limited by the quartz but by the atomic resonance.