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A Prototype Rubidium Vapor Frequency Standard*

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INTRODUCTION

THE SEARCH for frequency standards of great stability has been pursued at a number of laboratories in recent times. This effort has led to techniques for constructing smaller and simpler devices, which in turn have resulted in demands for still smaller units with even lower power consumption. One application for small, light, low-power frequency standards is in a satellite measurement of the gravitational frequency shift predicted by the Theory of Relativity. In this experiment the frequencies of two identical standards, one on the ground and one in an earth satellite, would be compared. Since the experiment should last for a period of days or weeks, there is a major emphasis on the construction of a frequency standard with low-power drain. Since early 1959 the National Aeronautics and Space Administration has supported work at the Washington campus of the National Bureau of Standards to develop a prototype frequency standard suitable for satellite use employing optically pumped rubidium vapor.[1]

CONCEPT

Bender, Beaty, and Chi have reported data on hyperfine transitions in rubidium-87 vapor.[2] Of interest in frequency standard work is their result showing a Q of about 1.7×10^8 for the rubidium line at 6834.68 Mc which exceeds that of the 9192.63-Mc cesium line by a factor greater than 2. In a gas cell device, the microwave transition is detected by a reduction in the intensity of the optical radiation used for the pumping after passing through the gas cell or an increase in the scattering of this radiation perpendicular to its normal path. The magnitude of the effect is a function of the applied microwave frequency with a response resembling that of a single tuned LC filter. Such a relation is plotted in Fig. 1.

The microwave transition frequency can be used as a standard to allow correction of frequency deviations in an oscillator. If the oscillator output is slightly modulated in frequency and its harmonic is used to excite the transition, the light will be intensity modulated. If the frequency is varied about that of the peak of the response curve, Fig. 1, only even harmonics of the modulation frequency will appear in the light variations. If the average frequency of the oscillator is not a submultiple of the transition, variation of the light at the modula-

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[1] Other work in the field of alkali vapor frequency standards has been reported in the proceedings of the Signal Corps Frequency Control Symposia for the years 1957 to 1960. See also:

M. Arditi and T. R. Carver, "A gas cell 'atomic clock' using optical pumping and optical detection," 1958 IRE NATIONAL CONVENTION RECORD, pt. 1, pp. 3–9.

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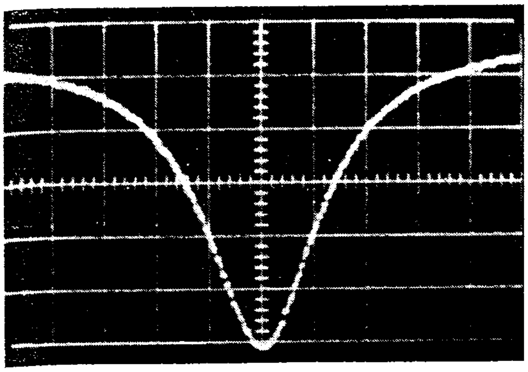

Fig. 1—The rubidium vapor transition line. The larger abscissa divisions are three parts in 10^9.

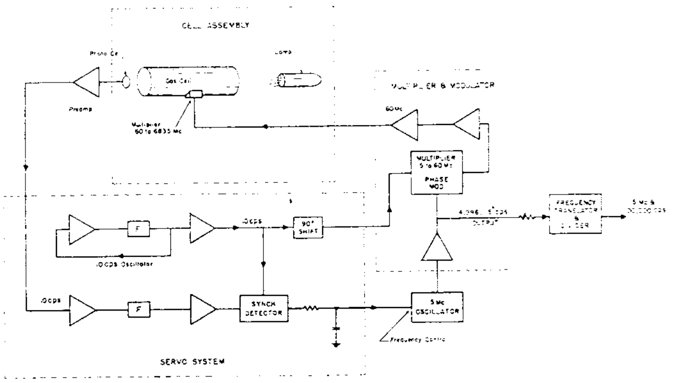

Fig. 2—Block diagram of rubidium vapor frequency standard.

tion frequency as well as at its higher harmonics will take place. The phase of the fundamental component of light intensity modulation indicates the direction of mistuning and can be used by a servo system to correct the oscillator frequency.

Since the gas cell is the heart of the system, some words on the stability of a device of this type are in order. Measurement of the relative frequencies of three similar gas samples over the period of more than a year has shown a drift of one part in 10^{11} or less per month. During the same period the drift of these samples relative to the Atomichron (R) cesium beam standard at the Naval Research Laboratory has totaled less than three parts in 10^{10}. The proper choice of the constituents and pressure of the buffer gas in the cell has resulted in a temperature coefficient of less than one part in $10^{11}/°C$. Investigation of the asymmetry of the transition line has indicated that this effect should not cause an uncertainty of as much as one part in 10^{11} in the determination of the frequency of the line. The transition frequency depends to some extent on the magnetic field intensity. The earth's field has been reduced to about 1 milligauss by shielding. This small field is negligible compared to the applied fixed field of 10 milligauss which produces a frequency shift of about one part in 10^{11}. The cavity is used only to increase the microwave field intensity so that mistuning will produce little error.

One should note at this point that mention has been made of the *stability* and not the *accuracy* of the rubidium gas cell unit. The actual frequency is highly dependent on the buffer gas, but once the cell is adjusted and sealed off, the frequency will remain highly stable.

EQUIPMENT

The prototype standard can be conveniently thought of as being divided into the sections shown in Fig. 2.

With the glass gas cell installed, the Q of the cavity is approximately 1000. The TE 0 1 1 resonant mode is used. The transmitted light method of detecting the transition is used, with the light passing along the axis of the cylindrical cavity resonator.

The light which has passed through the gas cell falls on a silicon photovoltaic cell, the output of which supplies the input to the frequency control servo system to be described later. The pumping light source is a Varian Associates type X49-900 rubidium vapor lamp, which uses two subminiature radio tubes as oscillators to excite the lamp. These are the only tubes in the standard. To improve the spectral characteristics of the emission of the lamp, a rubidium-85 filter cell is placed between the lamp and the gas cell located in the microwave field.

The radio frequency portion of the standard must produce a 6835-Mc signal of high spectral purity if a narrow transition line is to be observed. Since there is a high order of frequency multiplication in the RF section of the system, special effort must be expended to ensure that there is very little noise (especially FM) in the lower-frequency portion of the system.[3] Two types of 4,996,115-cps crystal controlled oscillators shown in Fig. 3 are available for use as the RF source for the system. One is designed by the Bell Telephone Laboratories and the other by Sulzer Laboratories. It is expected that the system will be operated with the ambient temperature controlled to plus or minus one degree Centrigrade, so the oven problem for the crystal oscillators is not severe. In the case of the Bell oscillator a simple proportional oven is used. The Sulzer oscillator does not use an oven; instead, a long thermal time constant is placed between the exterior of the unit and the crystal itself so that the rate of change of temperature at the crystal will be sufficiently low to allow the frequency control servo system to keep the crystal on frequency by comparison with the gas cell transition frequency. Both types of oscillator contain a voltage variable capacitor to allow variation of frequency by about a part in 10^7 per volt. This is used in the servo system.

The frequency of the oscillator output must be multiplied by the factor 1368 before application to the gas cell. Fortunately the rubidium transition requires very little microwave power for the observation of a narrow line. The frequency multiplication in the prototype unit is divided into two portions. In the first portion, Fig. 4, the output of the oscillator (about 1 mw) is

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[3] J. A. Barnes and L. E. Heim, Natl. Bur. of Standards, Boulder, Colo.; April 29, 1960. (Unpublished Rept.)

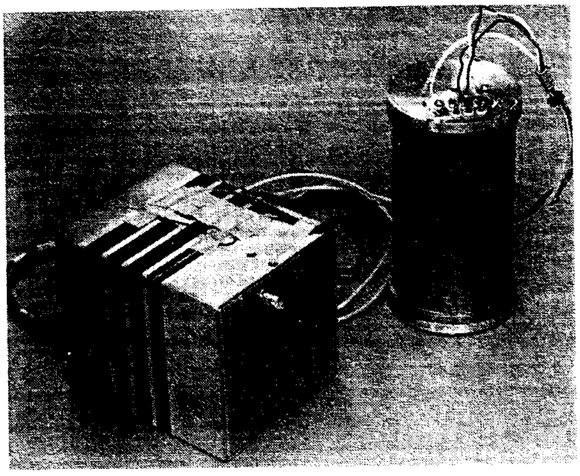

Fig. 3—The crystal oscillators. The 4×4×5 inch Sulzer unit is on the left and the Bell on the right.

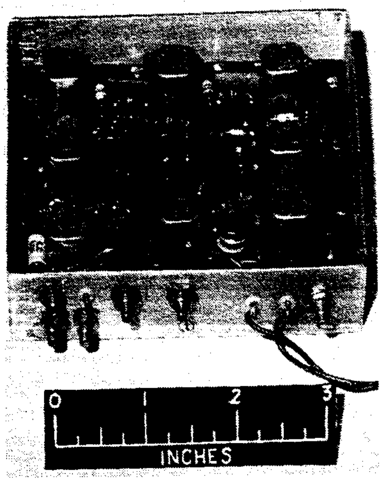

Fig. 4—The 5- to 60-Mc frequency multiplier-modulator.

amplified by a transistor to about 10 mw and divided between two outputs, one to the divider as the output frequency of the standard, and the other to the frequency multiplier proper. In this first portion the frequency is multiplied by the factor 12. The multiplication takes place in nonlinear capacitors. Since such units are most efficient at low orders of multiplication, three stages—×3, ×2, and ×2—are cascaded to provide the 12 times multiplication. The over-all efficiency of ×12 multiplication is about 5 per cent, or approximately the inverse of the multiplication factor.[4] The first stage, the tripler, is also used to phase modulate the signal to be further multiplied. The oscillator is not modulated directly, since modulation of the signal output is undesirable. The LF signal for the modulation is provided by the frequency control servo system. The output of the last doubler at about 60 Mc is at a rather low power level. Two stages of transistor amplification after the multiplier bring the output power level of this section of the multiplier chain to greater than 10 Mw.

The other portion of the multiplication, from the 60-Mc frequency to 6835 Mc, takes place in a single diode, which is mounted on the side of the resonant cavity housing the gas cell, Fig. 5. The order of multiplication in this diode is 114, and the conversion efficiency is about $1/(114)^2$. A "varactor" diode is used at this point, but the efficiency of energy conversion and the other operating characteristics of the multiplier lead us to feel that it is not truly acting as a varactor but more nearly as a nonlinear resistance device.[5] The frequency modulation deviation after multiplication to the 6835-Mc frequency is about 20 cps.

The output of the silicon photovoltaic cell sensing the light transmitted through the gas cell contains a small ac component which depends on the relation of the frequency of the crystal controlled oscillator harmonic to the transition frequency of the rubidium vapor. If the two frequencies are coincident the light will be modulated at only the second and higher harmonics of the modulation frequency in the incident RF field. If the two are not the same, a fundamental component will exist, and the phase of this component will differ by 180° on the two sides of the coincidence frequency. In the frequency control servo system, Fig. 6, the phase of the fundamental component of the light modulation is compared with the phase of the signal used to frequency modulate the RF signal to determine the sense of the frequency error. A large amplification is needed between the photocell and the phase comparator. The first part of this amplification takes place in a preamplifier produced by Varian Associates, while additional stages are provided in the servo system proper to bring the overall gain to about 140 db at the 10-cps modulation frequency. A narrow-band 10-cps filter is placed in the signal channel to insure that the phase comparison is made on the fundamental frequency only. A similar filter in the feedback path of an amplifier is used as the oscillator to produce the 10-cps signal to be used to modulate the RF. By using identical filters in the signal path and the oscillator, a considerable independence from degradation due to thermal drift of components is expected.

Before being applied to the phase comparator, the signal and oscillator (or reference) channel signals are converted to square waves. Since these signals are generally not truly square waves but are merely rectangular, the phase comparator has been designed to be insensitive to the symmetry of its inputs. The output of the phase comparator is a voltage of fixed amplitude, the polarity of which indicates the sense of the error between the crystal oscillator frequency and the rubidium

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[4] D. B. Leeson and S. Weinreb, "Frequency multiplication with non-linear capacitors—a circuit analysis," Proc. IRE, vol. 47, pp. 2076–2084; December, 1959.

[5] C. H. Page, "Harmonic generation with ideal rectifiers," Proc. IRE, vol. 46, pp. 1738–1740; October, 1958.

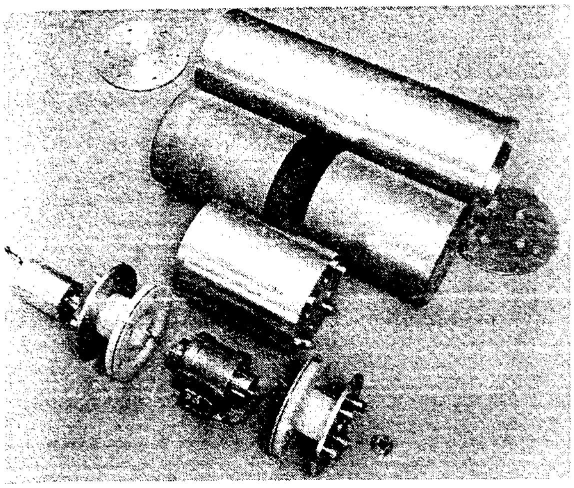

Fig. 5—The gas cell-cavity assembly, light source, and magnetic shielding. All are assembled in the 16-inch-long tube in the rear.

transition. The noise level in the system is about the same amplitude as the error signal with a frequency error of one part in 10^{10}. The output of the phase comparator thus contains random variations in the indicated sense of the error with small frequency errors. A long-time-constant low-pass filter placed in the phase detector output averages the output of the device and thereby removes the rapid variations in the indicated error, producing a proportional indication of error in the region in which the noise is equal to or greater than the error signal from the photocell. The output of the low-pass filter is applied to the crystal controlled oscillator to correct its frequency to that of a submultiple of the rubidium resonance. The low-pass filter also serves to stabilize the servo loop. It must have a sufficiently long time constant for stability of the feedback loop, and may be somewhat longer than this if the short-term variations in the output frequency of the system are to be a reasonable combination of noise fed back from the servo system and instability in the crystal oscillator. In practice a correction rate of about two parts in 10^9 per second is realized.

A further part of the system is a frequency divider to provide an output at 100 kc from the 4,996,115-cps signal. This unit was designed and constructed by Sulzer Laboratories.

A frequency translator to change the 4,996,115 cps to 5,000,000 cps is available for laboratory use.

The complete transistorized system, Fig. 7, uses about 7 watts of power input, with the additional requirement that the gas cell and crystal oscillator assemblies must be held at 45° ± 1°C. The lamp takes 6 watts of the input power and the remainder of the system uses the other watt.

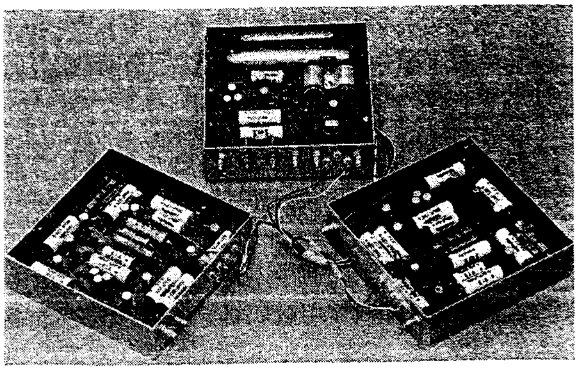

Fig. 6—The packaged servo system.

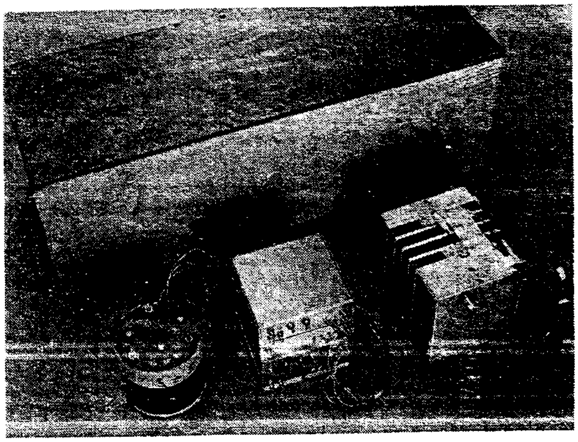

Fig. 7—The standard in its present form. The preamplifier in the left foreground will be repackaged in the standard 4×4×1 inch module.

CONCLUSION

The system described has been operated briefly with all components except the preamplifier and the servo unit in package form. The observed fluctuations from second to second were one to three parts in 10^{10}. We do not yet have sufficient information to predict the long-term stability.

ACKNOWLEDGMENT

Thanks are due G. F. Montgomery, chief of the Instrumentation Division of NBS, for his major part in the design of the servo system and for helpful suggestions on other portions of the system.