VI. MOLECULAR BEAMS

Prof. J. R. Zacharias  V. J. Bates  E. L. Kamen
Prof. J. G. King  D. A. Brown  F. J. O'Brien
Prof. C. L. Searle  R. Golub  J. E. Steelman
Dr. G. W. Stroke  W. D. Johnston  C. O. Thornburg
R. S. Badessa  R. Weiss

A. CESIUM BEAM TUBE INVESTIGATION

When the X-band excitation frequency of the atomic clock is at exact cesium resonance, theoretically a null should occur at the output of the 100-cps amplifier. In practice, we found that instead of there being a true null, the 100-cps signal merely goes through a minimum. This is the result of second-harmonic distortion in the frequency-modulation waveform. With a properly phased reference for the synchronous detector of the loop this 100-cps minimum causes no error, since it is in quadrature with the desired 100 cps that appears as a result of detuning the excitation frequency from the peak of the resonance. However, if the second-harmonic distortion is large, the stability of the clock will become a critical function of the phase drifts that might occur between the modulating signal and the synchronous detector reference, for any such drifts will disturb the quadrature relationship. A 10° shift in the reference phase, for example, would cause a detuning of several parts in $10^{12}$ if the second-harmonic distortion is 1 per cent. Drift might originate in the narrow-band 100-cps amplifier, or might be the result of changes in the temperature of the hot wire of the beam tube. Because a mechanical synchronous detector was used in the present application, we found it convenient to mount a "quadrature" brush electrically 90° away from the "in-phase" brush on the commutator. The dc voltage appearing at this quadrature brush is a measure of the magnitude of the quadrature component and hence of the second-harmonic distortion of the modulation. It was therefore used as an error signal in a second servo loop which, by injecting the precise amount of counteracting second harmonic, produced a true 100-cps null at the output of the 100-cps amplifier.

As a check on the ability of the quadrature loop to make the phase relationship between modulating signal and synchronous detector reference less critical, a phase shift of 17.2° was inserted at the output of the 100-cps amplifier. With the quadrature loop open, a detuning of five parts in $10^{10}$ was observed. With the quadrature loop closed, no effect was visible. With the quadrature loop open, a 10 per cent change in the current of the hot wire caused a detuning of six parts in $10^{11}$. Again, with the quadrature loop in operation, no effect was visible.

The desired stability of ± one part in $10^{12}$ has been observed occasionally over intervals of 10 minutes, but is generally an order of magnitude below this. Shift of the resonance characteristic of the beam tube with power level, an effect that is easily demonstrated, could be the predominant source of remaining drift.

R. S. Badessa, V. J. Bates
References

1. C. L. Searle, R. S. Badessa, and V. J. Bates, Quarterly Progress Report No. 64, Research Laboratory of Electronics, M.I.T., January 15, 1962, p. 54.


B. MEASUREMENT OF FREQUENCY STABILITY

The stability of frequency standards is usually expressed as the mean-square deviation in frequency or phase for several averaging times. It now appears that these specifications can be quite easily derived from the autocorrelation of the phase deviation. This provides a handy and unifying concept for the understanding of the specification of stability.

We are now trying to determine whether the autocorrelation can be computed with no more difficulty than the previous methods used for specification. Should this prove to be the case, the new method will be a practical means of measurement, as well as an aid to understanding. Part of the difficulty is that the autocorrelation $\phi(\tau)$ will be of interest out to a maximum $\tau$ of approximately 24 hours, and also for differential shifts $\Delta \tau$ of 2 seconds when $\tau$ is small.

D. A. Brown, C. L. Searle

C. VARACTOR MULTIPLIER STUDIES

In experiments with cesium atomic resonance devices a source of X-band signal is required, which must be highly stable in frequency and fairly stable in power. At present, this signal is obtained by direct multiplication to X-band of a stable crystal oscillator signal running at 16.415414 mc. System power requirements set the X-band signal level to be at least 20-40 $\mu$w. In the past, several varactor multipliers have been built which have satisfied the power requirement, but they have displayed typical varactor problems, such as critical tuning, day-to-day adjustment, sensitivity to shock and vibration, and severe drain on bias batteries.

A recently completed varactor multiplier chain of a balanced design (suggested by R. P. Rafuse) for the lower frequency doublers (Fig. VI-1) appears to have solved these problems, as well as yielded additional output power at X-band. This balanced design incorporates symmetry to decouple input and output circuits while suppressing the undesired third-harmonic signals and, with the use of iron-core coils, lends itself to a rugged mechanically stable design. This design also results in more stable electrical characteristics. For an input drive of 1.5 watts at 16.4 mc, an output power of 0.150 watt at 263 mc is easily obtained, this 150 mw level being determined by the
Fig. VI-1. Four-stage varactor multiplier (16.4-263 mc).
burnout power of the high-frequency varactor in the following stage. Battery bias drain was sharply reduced by using 1-megohm bias potentiometers. The factor of 35 from 263 mc to 9192 mc was accomplished in a single transmission-line circuit (Fig. VI-2). While development work is continuing on this device, results obtained already show an output power in excess of 100 μw for the 150-mw input signal. Replacement of Microwave Associates 4298 Varactor by a higher cutoff, higher power type should result in more signal.

A complete package was constructed containing a 16.4-mc transistor amplifier (Fig. VI-3) and the four doubler stages in a brass channel 1 1/8" wide, 3/4" high, 11" long.

V. J. Bates
D. SUPERCONDUCTING LEAD CAVITY

During the past quarterly period, the cryogenic system described in a previous report\(^1\) has been discarded and replaced by a double dewar system made by the Superior Air Company. In this design, the cavity holder is now submerged in helium.

The cavity was cooled to 4.2\(^\circ\)K and measurements indicated a \(Q\) of approximately one million. Then the Badessa oscillator\(^2\) was assembled with the superconducting cavity as the feedback element. The maximum stability of the oscillator was three parts in \(10^{10}\) for a 6-second averaging time.

The most likely cause of this instability is mechanical vibration. The cavity is made in two cup-shaped halves that are held together by a spring; thus a movement of \(3 \times 10^{-8}\) cm is enough to cause the instability observed. Therefore, welding or soldering the cavity into one piece seems to be necessary.

Temperature change was also considered, but the thermal masses and thermal time constants of the elements that determine the stability rule out this possibility. The temperature of the cavity also eliminates Johnson noise in the cavity as a possible cause of the instability.

Thus the cavity halves were soldered together with Wood's metal and a \(Q\) measurement showed a \(Q\) of only 100,000. Then the cavity halves were joined by fusing them together in two places. Again, the \(Q\) was low. A second cavity made from a purer sample of lead was also tried, and it seemed to have a maximum \(Q\) of about 70,000 — regardless of the surface treatment. Then the surface of the original cavity was machined smooth; the cavity was reassembled without soldering, and the \(Q\) was 90,000. After that, the cavity was chemically polished with a solution of 1 part 30 per cent hydrogen peroxide and 4 parts glacial acetic acid. Again the cavity was held together by springs only, and the \(Q\) was approximately 200,000. Then, without any further adjustments the \(Q\) increased to 1.2 million in a period of approximately 30 minutes. No explanation of this behavior has been found.

J. E. Steelman

References


E. MEASUREMENT OF THE VELOCITY OF LIGHT

This report summarizes the progress that has been made since the last report in preparation for actual measurement and evaluation of possible sources of error.

1. Pneumatic Measurement of Cavity Perfection

The pneumatic system previously described in Quarterly Progress Report No. 63 (pages 109-112) has permitted us to obtain the cavity topology shown in Fig. VI-4. The straightness of motion of the moving piston (on which the nozzles are mounted) was independently ascertained with the help of the alignment interferometer previously described. It accounts for approximately 1 fringe ($10^{-5}$ inch) of the curves in Fig. VI-4. The

![Fig. VI-4. Fused-quartz cavity topology with pneumatic detection. Curves show departures from straightness in $10^{-5}$-inch units along two diametrically opposed sections of the cavity. No correction was made for departure from straightness of travel of the moving piston. Independent interferometric measurements indicate that these errors could account for one-half of the departure from straightness.](image-url)
result is that the straightness of the cavity is more than satisfactory for the measurement of $c$ with an accuracy better than $10^{-6}$ without any corrections for dimensional perturbation, as we had hoped. This is particularly true also for the measurement of two diameters $90^\circ$ from each other which were found to differ only by approximately two and one-half fringes. The diameter measurement was carried out with a pair of nozzles, with the nozzles at opposite ends of a diameter. A more extensive series of measurements of cavity diameters will be undertaken with the help of an inner piston that has been finished for this purpose, rather than with the aluminum piston previously used, which required rather delicate temperature control.

2. Iris Dimensions for Cavity Excitation and Resonance Detection

Ideally, one would want to excite the cavity, as used in transmission, through irises without any losses in the cavity. Noise considerations, however, require a decoupling of no more than $\sim 40$ db. Figure VI-5 shows a number of experimental energy-drop

![Graph showing energy transmission of irises](image)

**Fig. VI-5.** Microwave energy transmission of irises used to excite the cavity and detect resonance. Graphs are shown for various iris shapes.
VI. MOLECULAR BEAMS

Fig. VI-6. Final iris shape transmitting 40 db at 9192 mc.

curves obtained by transmission through irises of various shapes. Figure VI-6 shows the final iris shape that was obtained. It has the smallest possible opening diameter at the cavity side for the desired 40-db decoupling. Two such irises are used, 90° from each other: one for cavity excitation, and one for resonance detection as previously described. This iris shape will be used in the optical plates that will be manufactured. A cavity of dimensions comparable to the actual cavity was used with a complete excitation and detection plate to verify the fact that the total transmission through the cavity was indeed the desired 80 db.

3. High-Speed Interferometer Length Measurement

In the past, it was considered that optical fringe counting and fractional measurement were restricted to the range from 2 to 10 fringes per second ($2 \times 10^{-5}$ inch per second), and would rarely exceed 20 per second, because of imperfections in the mechanical apparatus. This is the case for gratings ruling engines, for example. For our velocity-of-light apparatus, it appeared essential to strive for fringe rates in excess of 100 fringes per second, and possibly to work in the vicinity of from 500 to 1000 fringes per second, that is, up to the order of 1/100 inch per second. A resonance measurement could thus be completed in only a matter of minutes, with our apparatus, rather than in several days, as we thought when measurement on the M.I.T. ruling machine was first considered (see below).

We have indeed made considerable advances in measurement of high-speed optical fringe distance. Figure VI-7 shows an excellent example of a fringe signal obtained on our apparatus at 90 fringes per second. This was first recorded from a photoelectric multiplier tube on magnetic tape and then photographed on an oscilloscope screen. Figure VI-8 shows a fringe signal similarly obtained at 900 fringes per second. These remarkable results are due not only to the fine adjustment of the optical and electronic
Fig. VI-7. Interferometric fringe signal obtained at 90 fringes per second with velocity-of-light apparatus. (1 fringe $= 10^{-5}$ inch with green line of Hg$^{198}$ source used.) The photoelectric fringe signal shown here was recorded on magnetic tape and then displayed on the long-persistence screen of an oscilloscope. The superposition of fringes with very little relative shift is a measure of very good uniformity of the piston motion in our apparatus.

Fig. VI-8. High-speed interferometric fringe signal obtained for 900 fringes per second ($\sim 0.001$ in./sec) advance of moving piston with hydraulic control in the velocity-of-light apparatus.
Fig. VI-9. View of velocity-of-light apparatus used in our experimental work.
equipment but also, in particular, to the smoothness of motion and absence of any "stick-slip" in our hydraulic and mechanical piston advance mechanism. We recall that the moving piston that carries the moving plate of the interferometer is mounted on a cylinder, 20 inches long, sliding between brass ways. The entire piston and cylinder assembly rides on a hypodermic syringe assembly that governs the rate of piston motion. Considerable simplification has been achieved in the return motion of the cylinder. We are now in a position to raise the piston hydraulically in a matter of seconds, over the full course of 2 or 3 inches used in these experiments without introducing any air bubbles into the system. A maximum traverse of 6 inches can be made with the present syringe.

4. Thesis Research on Silver Conductivity and Cavity Diameter Measurements

Two theses have been completed in connection with this experimental work. Arthur T. Funkhouser has completed a Bachelor's thesis entitled "A Method for Measuring the Distance between Two Fabry-Perot Interferometric Plates," and J. F. Brenner has completed a Bachelor's thesis entitled "On Measuring the Electrical Conductivity of Thin, Deposited Metallic Films."

The results of this work will be used in our research and will be more fully described elsewhere.

5. Dry-run of Our Experiment

We have now chemically silver-plated our fused-quartz cavity and are proceeding with a dry-run of the entire experiment, including the mechanics, optics, microwave electronics, and recording of optical and resonance signals on magnetic tape.

A view of the apparatus used in these experiments is shown in Fig. VI-9.

6. Remark on This Experiment

This experiment was started in 1955 by Professor J. R. Zacharias, Dean G. R. Harrison, G. W. Stroke, Professor S. J. Mason and C. L. Searle. This measurement was proposed when there was a possibility of combining precise interferometric length measurements in terms of light waves (developed at the Spectroscopy Laboratory, M.I.T., by Dean Harrison, G. W. Stroke, and associates) with the precise microwave frequency standard of the Cs$^{133}$ atomic clock, developed by Professor Zacharias and associates, for the purpose of attempting a measurement of the velocity of light in terms of primary standards, in a microwave cavity resonance experiment.

The experiment was actively pursued by Zacharias, Searle, and G. W. Stroke until the end of 1958, by which time a precise fused-quartz cavity had been manufactured to optical precision by the Optical Shop at Boston University, and the mechanical parts of the apparatus had been built by the R. L. E. Shop. Microwave equipment for the cavity
Excitation and resonance detection had also been assembled, and a dry-run with an experimental Pyrex cavity carried out.

Work on the experiment was resumed in July 1961 by G. W. Stroke (Quarterly Progress Report No. 63, p. 105) and was devoted to assembly of optical parts and testing of the apparatus in preparation for an actual measurement. Dr. Stroke has accepted a position as Professor of Electrical Engineering at the University of Michigan and will complete the experimental work there.

G. W. Stroke, M. A. Yaffee, A. Funkhouser

References

1. J. R. Zacharias et al., Proposed measurement of the velocity of light in terms of two primary standards, Cesium (Cs\(^{133}\)) and Mercury (Hg\(^{198}\)), Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., January 15, 1956, pp. 59-68.