In its broader use, the typewriter control allows the user to load into the computer memory a detailed operating program. This program may be the one which will run the experiment for the next several hours or days or, alternatively, may represent a series of extremely complex test manipulations which may then be selected, started, or stopped by means of the station's communication switches. The experimenter is thus able to select, at will, the degree of automatic control he wishes to employ at any stage of his experiment.

The user is free to organize his program in any way he chooses. Normally, however, he reserves a portion of his allotted space for storing data. When he has accumulated a block of information he calls on the Multiple Spectrometer Control System to write it out on magnetic tape, properly arranged and identified. The magnetic tape records, which are centrally accumulated for all users, are in a form directly suited for entry into the laboratory's central computer complex. Alternatively, the user may wish to reread a portion of the data previously stored. In particular, the system provides the facility which enables him to retrieve information and display it on the console cathode ray tube for immediate analysis. A light pen is also provided.

Beyond its normal role of providing the medium for the "dialog" between the user and his spectrometer experiment, the typewriter also keeps the system operator alerted as to the status of the whole experimental complex. The operator is automatically informed of such things as overtime usage, error conditions, and equipment malfunctions. The typewritten sheets, therefore, represent a complete and accurate record of total-system usage and performance. A representative section of an output page is shown in Fig. 4. (The italicized comments do not, of course, appear on the record. The user's "shorthand" entries appear at the left, and the system's response appears in the second column.)

The Human Factor

At the beginning of this article I spoke of the young graduate student's training in computer science. A recent survey (*3*) indicated that, among a representative group of scientists, more than 90 percent wanted their students to learn to program a computer, although only about half of the scientists themselves knew how to do so. The older the scientist was, the less likely he was to be skilled in these new techniques. (Only one in ten of the men over 50 was able to program a computer.)

One effect of this is that those least likely to understand these new techniques are the ones most likely to have to pass judgment on them. The instability of this situation has produced a corresponding polarization in views, the "pro's" being unreasonably pro and the "con's" being unreasonably con. Unfortunately, because the techniques of laboratory automation are radical, it is difficult to write about them and to adequately describe their effects on research. (One of my colleagues—now an enthusiast—recently confessed that when he first read about on-line computers he thought the idea was "just plain crazy.")

I encourage the reader to go see for himself.

References and Notes

1. The work discussed was supported by the U.S. Atomic Energy Commission. Rather than pepper this article with references I have chosen to list only a few tutorial and survey papers that will further serve to introduce this field to the reader and will, in turn, lead him to the rather extensive literature. These papers are as follows: R. J. Spinrad, *Ann. Rev. Nucl. Sci.* **14**, 239 (1964); D. A. Cooper, *Intern. Sci. Technol.* **1964**, No. 36, 20 (1964); R. J. Spinrad, *Progr. Nucl. Techniques Instrumentation* **1**, 221 (1965); S. J. Lindenbaum, *Ann. Rev. Nucl. Sci.* **16**, 619 (1966); J. F. Davis, *Intern. Sci. Technol.* **1966**, No. 60, 40 (1966); J. A. Jones, *IEEE (Inst. Elec. Electron. Engrs.) Trans. Nucl. Sci.* **14**, 576 (1967); "Conference on Use of Computers in Analysis of Experimental Data and Control of Nuclear Facilities, Argonne, 1966," *Conf. No. 660527, U.S. At. Energy Comm.* (1967); R. J. Spinrad, *Sci. Res.* **2**, No. 8, 38 (1967).
2. D. R. Beaucage M. A. Kelley, D. Ophir, S. Rankowitz, R. J. Spinrad, R. Van Norton, *Nucl. Instr. Methods* **40**, 26 (1966).
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Precision Measurement of the Acceleration of Gravity

Measurements of *g* have always made maximum use of the available technology in measurement of length and time.

James E. Faller

The measurement of the acceleration of gravity (*g*) has long been a matter of scientific interest. Almost from the beginning of time, men must have noticed that things move faster and faster as they fall. Over 300 years ago Galileo, in studying how things fall, discovered that the motion is one of constant acceleration. He showed that the distance a falling body travels from rest varies as the square of the time. To show this, he used an inclined plane to slow down the motion (to "dilute" gravity); by thus extending the time scale of his experiments, he was able to make quantitative measurements with the limited experimental means at his disposal. In his *Dialogues Concerning Two New Sciences* (*1*, p. 178), Galileo depicts for us the technology of his day as he describes his experiments concerning motion on an inclined plane:

> A piece of wooden moulding or scantling, about 12 cubits long, half a cubit wide, and three finger-breadths thick, was taken; on its edge was cut a channel a little more than one finger in breadth; having made this groove very straight, smooth, and polished, and having lined it with parchment, also as smooth and polished as possible, we rolled along it a hard, smooth, and very round bronze ball. Having placed this board in a sloping

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position, by lifting one end some one or two cubits above the other, we rolled the ball, as I was just saying, along the channel, noting, in a manner presently to be described, the time required to make the descent. We repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse-beat. Having performed this operation and having assured ourselves of its reliability, we now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half of the former. . . .

For the measurement of time, we employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent, whether for the whole length of the channel or for a part of its length; the water thus collected was weighed, after each descent, on a very accurate balance; the differences and ratios of these weights gave us the differences and ratios of the times, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results.

On the basis of these experiments Galileo concluded that the motion of fall down an inclined plane is one of constant acceleration; and by extrapolating his observations to greater and greater slopes, he argued that there is also constant acceleration in the case of free fall.

His use of slopes of between 5 and 10 degrees (which extended the measurement time, over that of free fall, by a factor ranging from 10 to 6) indicates good experimental technique. Use of much greater slopes would have removed most of the timing advantage, while use of somewhat less of a slope would probably have yielded little except an unfavorable statement about the straightness of his inclined plane.

Perhaps Galileo's most noted conjecture was his surmise that in a perfect vacuum all bodies would fall at the same rate—that is, if they are released together, they will strike the ground together. In his *Dialogues* (*1*, p. 72) we read:

On the other hand the variation of speed in air between balls of gold, lead, copper, porphyry, and other heavy materials is so slight that in a fall of 100 cubits a ball of gold would surely not outstrip one of copper by as much as four fingers. Having observed this I came to the conclusion that in a medium totally devoid of resistance all bodies would fall with the same speed [together].

This conjecture, in combination with his observation that the motion of free fall is one of constant acceleration, results in the statement that all bodies fall with the same acceleration. This statement, which has proved to be one of the cornerstones of gravitational physics, has been tested many times—most notably in the experiments of Baron Rolan von Eötvös and in the recent extraordinarily precise experiments of R. H. Dicke and his colleagues (*2*).

The importance, for our purposes, of this miracle of physics (the physicist who does not delight in seeing a 50-cent piece and a penny fall together has no soul) is that it tells us that a body's weight (the earth's gravitational pull on the body) is proportional to its inertial mass—that is, to the resistance it offers to an accelerating force. The constant of proportionality is simply (from $F = ma$) the acceleration of gravity. Thus, g plays a dual role: the value of the acceleration observed in free fall (the acceleration of gravity) is also the constant of proportionality between mass and weight (the force of gravity per unit mass).

Though oftentimes thought of as a constant, g varies by about a half a percent with position on the earth's surface. This variation stems chiefly from the fact that the earth is rotating, and that, as a result, part of the earth's pull is expended in keeping objects rotating with the earth instead of flying tangentially off into space (as mud does off a wheel). It is this effect that is responsible for the bulge of the earth at the equator and the slight flattening at the poles. Local variations, nominally a few parts in 10^6, reflect variations in the density of the earth and changes in elevation. At any one place, g also varies with time. The tidal variation of several parts in 10^7, which results from the gravitational attraction of the sun and moon, is perhaps the most familiar example.

The interest in a precision measurement of g arises from the fact that the value of g is used in the determination of a number of physical, geophysical, and astronomical quantities (*3*). Because it is the constant of proportionality between mass and weight, its value in a particular laboratory provides the most accurate means of defining force (or pressure) in an absolute system of units. Though for most geophysical purposes relative measurements (measurements of differences in gravity) suffice, absolute measurements are useful, since they serve to establish precise gravity intervals over which one can check the accuracy of relative measurements made with fixed-length pendulums. Since the calibration of all spring-type gravity meters depends on relative measurements made with pendulums, a check on the reliability of pendulums for this purpose—as well as an increase in the accuracy of the gravity intervals—is highly desirable. The absolute value of g averaged over the surface of the earth is of interest in astronomy, since it relates to measurements of distances to artificial satellites, to the planets, and to our moon. Further, it is only with absolute measurements that one can hope to detect possible long-term variation in g. Finally, the precision determination of g is a measurement which has always presented man with a challenge—a mountain which each new scientific generation has attempted to climb not only because of a need to get to the top but also because of the challenge provided by the ascent to man's inventiveness and his technology.

Although techniques have been refined over the years, there are only two basic methods that have ever been used to measure the acceleration of gravity—timing freely falling bodies and timing falling bodies whose motion is constrained, as in the case of a pendulum.

Pendulum measurements of g (familiar to almost everyone who has taken an introductory course in physics) offer a distinct timing advantage over free-fall measurements. The constraint on the body's "free fall" both lengthens the time for a single drop and permits a large number of "drops" to be made during each measured interval of time. The price one pays for this gain is that, having introduced a constraint—the supporting wire or the knife-edge bearing used as a support—one needs to understand the effects of the constraint on the performance of the instrument. And here, with the problem of systematic errors, lies the difficulty in all high-precision measurements. The problem in measuring g is not just a question of precision of timing or one of measuring a length to a certain accuracy; it involves (for free fall) defining the time interval which is to be measured and (for a pendulum) determining the appropriate length to be measured. In addition, one must eliminate all extraneous effects from the experiment or *completely* understand them.

An example at this point is useful. Suppose that, during his studies of motion on the inclined plane, Galileo had actually measured g but had neglected to take into account the rotational inertia of the ball. The value he would have obtained would then have been low, since a ball rolling down a plane takes somewhat longer to reach the bottom than it would if it simply slid without friction down the plane, and this would make the acceleration of gravity appear to be less. For a solid ball, the measured value of g in this case would be just 5/7 of its true value.

We can also imagine that other scientists of Galileo's day would have made inclined-plane measurements of g, using balls of different sizes and a variety of slopes, in the expectation that by thus varying the conditions of the measurement they would discover any possible systematic effects. Making repeated experiments with different balls and with planes of differing slopes but neglecting rotational inertia would, however, have only served to confirm a false value (as expressed in familiar units) of 700 centimeters per second per second.

However, had one of Galileo's contemporaries timed the free fall of either of the two balls dropped from the tower in Galileo's famous "null" experiment, the value of 980 centimeters per second per second which he would have obtained for g would have pointed to a serious discrepancy between results of the free-fall and the inclined-plane methods. Eventually this would have drawn attention to the rotation of the ball. In a similar manner, precision free-fall measurements—which by their nature are free of many of the systematic errors that affect pendulum measurements—have served to confirm the existence of suspected systematic errors in pendulum measurements.

Pendulum Measurements

The first person to use the pendulum for measurements of g is said to have been Huygens, the Dutch astronomer and mathematician (1629–1695). Modern pendulum measurements are usually considered to date back to 1817, when Captain Henry Kater introduced the reversible pendulum for making absolute measurements. His intention was to use a pendulum having a half-period of exactly 1 second to provide a natural unit of length. Kater begins his paper "An Account of experiments for determining the length of the Pendulum vibrating seconds in the latitude of London" (*4*) with a statement of the basic problem in all pendulum measurements up to his time.

> To determine the distance between the point of suspension and centre of oscillation of a pendulum vibrating seconds in a given latitude, has long been a desideratum in science.

This same problem gives rise to a question often heard voiced in an introductory physics laboratory. The question goes something like this: "Sir, should I measure the length of my pendulum to the top, to the middle, or to just where on the ball?"

Kater provided a means of answering this question—of identifying the proper length. He did this by constructing a pendulum which could be hung from either of two fixed points of support. He was then able to show that, if the period of oscillation was the same about each of the points of support, the distance separating these points of suspension was equal to the length of a simple pendulum having the same period. The experimental problem, once the equality of periods has been established (by adjusting the position of attached weights), is then reduced to measurement of the common period and measurement of the distance separating the two supports.

Kater's measurements were carried out in the home of his friend Henry Browne, and here I cannot resist the temptation to quote from the original text.

> To the kindness of HENRY BROWNE, Esq. F.R.S., I am essentially indebted for the success of the experiments which form the subject of this paper. He most obligingly allowed me the use of his house, his excellent time-pieces, and transit instrument, assisting me with indefatigable zeal by his very accurate daily observations, and intermediate comparisons for determining the rate of the clock. The house is substantially built, and is situated in a part of Portland Place not liable to much disturbance from the passing of carriages. The room in which the experiments were made is the last of two on the ground floor, communicating with each other and facing the north. The temperature consequently is very steady, and if necessary, may be raised to any given degree by a fire in the first room. The clock with which the pendulum was compared was made by ARNOLD; and in addition to the gridiron compensation for temperature, its pendulum is suspended by a spring, the strength of which is so adjusted, that the vibrations in different arcs are performed in equal times. Near to this, on the wall which is at right angles to the recess, is fixed another time-piece by CUMMING, which was the property of the late GENERAL ROY, and is considered by Mr. BROWNE to be the best in his possession. Respecting this clock, it will be sufficient to remark, that three tenths of a second was the greatest variation in its daily rate from the 22d February, when the observations commenced, to the 31st July; and consequently the deviation from its mean rate during that period, did not exceed 0.15 of a second per day. This clock has been used as the standard of comparison, the time having been taken from the transit instrument by a chronometer of ARNOLD'S. With such advantages it will be confessed that there can be little chance of error arising from the rate of the clock. . . .
>
> Since the mean results of three several sets of measurements [of the distance between the knife edges—approximately 1 meter] are within one ten-thousandth of an inch of each other, and the different methods employed, preclude, it may be presumed, any accidental coincidence, we may with confidence infer that the error in the distance of the knife edges, cannot amount to one ten-thousandth of an inch.

Figure 1 is an engraving showing an overall view of Kater's apparatus—and the technology of his day.

Though his basic standards would have permitted him to achieve an accuracy of a few parts in 10^6, the accuracy of Kater's measurement has proved to be not much better than 1 part in 10^4. In spite of the fact that Kater did not fully understand the role of the surrounding air or appreciate the influence of pendulum flexure on the measurement, still a giant step had been taken: by introducing the reversible pendulum, Kater had provided an answer to the difficult question "What length?"

It was with reversible pendulums that Kühnen and Fürtwangler (*5*) made their measurements at the Geodetic Institute in Potsdam during the period 1898 to 1904. Their work is noted for the serious effort which was made to identify the various sources of error and make allowances for them. The value of g that they obtained is still used as a reference throughout the world today in the so-called Potsdam system of gravity values. Though subsequent measurements have shown their value to be in error by more than 1 part in 10^5, it has been decided to continue with this system until there is certainty that a revision which is accurate to at least 1 part in 10^6 can be made.

Following the Potsdam measurements, some 30 years passed (partly because of the intervention of World War I) before two new absolute determinations were embarked upon—one in the United States, by Heyl and Cook working at the National Bureau of Standards (*6*), and one in England, by Clark at the National Physical Laboratory (7). A better treatment of a number of systematic problems, together with improvements in the available technology (they could work at pressures such that all systematic effects due to the air density were negligible), resulted in values which agree with recent free-fall measurements to within a few parts in 10^6.

The most serious limitation today on the use of pendulums appears to be one of understanding the conditions at the knife edge. The length one measures is ambiguous because of compression, and, further, the actual behavior along the contacting region of the knife edge involves a difficult problem in surface physics. Though a number of theories have been put forward to account for the behavior of the knife edge, none to date seems to be totally satisfactory, and it would appear, save for the possibility of using a magnetic suspension, that the use of pendulums for absolute measurements have reached an impasse at an accuracy somewhere in the range of a few parts in 10^6.

Free-Fall Measurements

In recent years the quest for greater accuracy has led workers to circumvent the knife-edge problem by turning to direct free-fall measurements. (This development is reminiscent of Kater's circumventing the length-definition problem by introducing a new type of pendulum.) After World War II it was realized that the electronic technology which had been developed for measuring short time intervals would, at last, permit use of the method of free fall for precision determination of g. Accordingly a number of free-fall experiments, in which the length of the drop ranged from 1 to 2 meters, were begun at various laboratories around the world (8).

In 1957—a few years prior to the invention of the laser—I started work on a free-fall determination of g at Princeton University, under the guidance of R. H. Dicke. In that experiment (9), one element of an optical interferometer was dropped. The design of the instrument was such that fringes in white light (familiar as the colors seen in thin films) were ob-

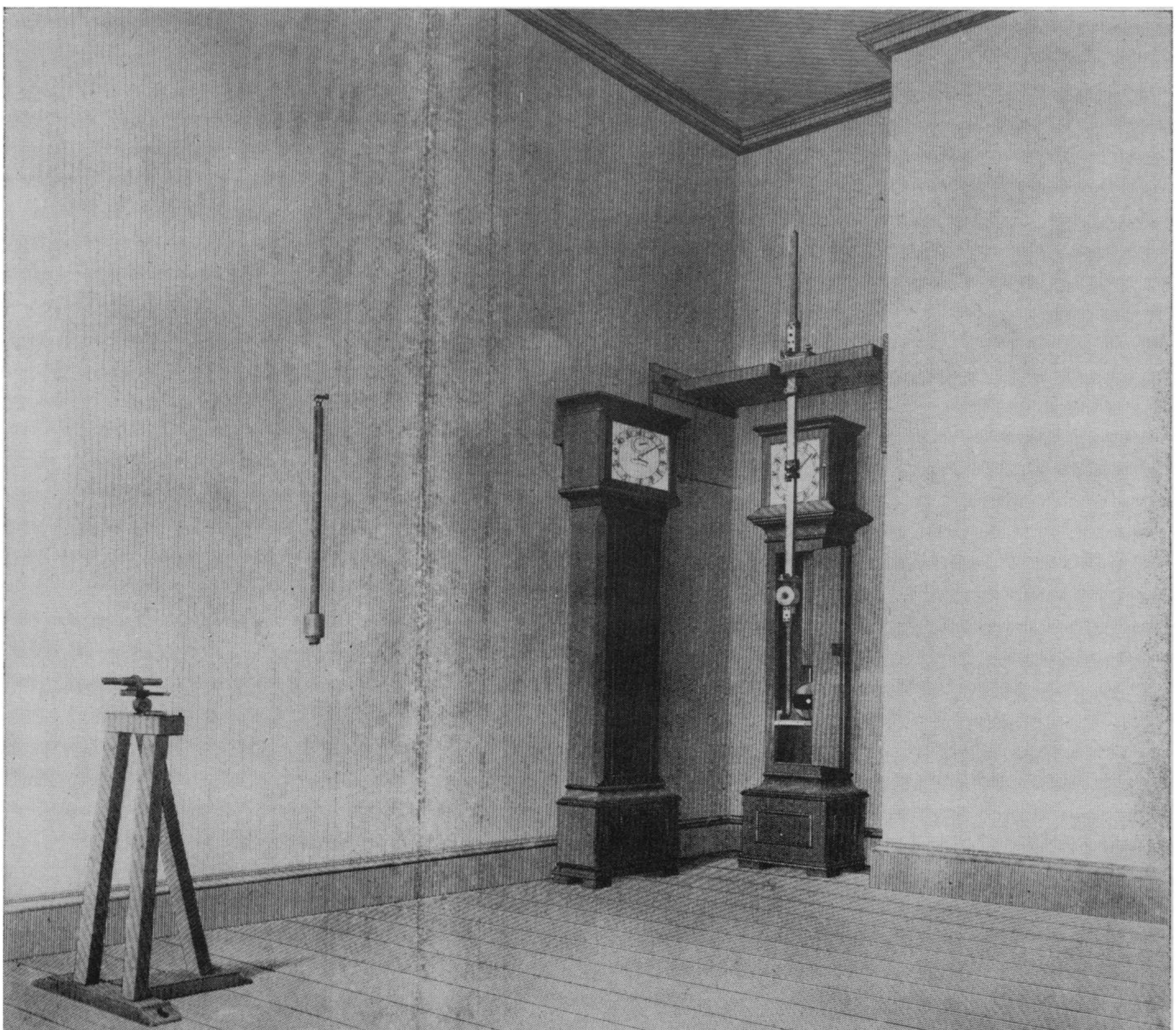


Fig. 1. An overall view of Kater's apparatus. [From *Phil. Trans. Roy. Soc. London* (4)]

tained at three separate regions along the drop. Through use of these interference fringes, it was possible to determine the position of the object as it fell to an accuracy of 5×10^{-7} centimeter (a fiftieth of a fringe). For reasons of mechanical and optical convenience, the actual dropping distance selected was only a little over 5 centimeters. A measurement, based on the use of white-light fringes, in which the dropping distance is considerably greater (40 centimeters) is at present being worked on at the Bureau Gravimétrique International in Paris (*10*).

The 1963 measurement of g made at Princeton, for which the standard deviation was 7 parts in 10^7, has been found to be in good agreement with results of the recently completed free-fall experiments of Alan Cook (*11*) at the National Physical Laboratory in England and of Douglas Tate (*12*) at the National Bureau of Standards in this country. For Cook's results, the standard deviation was 1.3 parts in 10^7; for Tate's, 3 parts in 10^7. Comparison of measurements requires a knowledge of the gravity differences, and for this reason such comparisons are at present limited to an accuracy of 3 or 4 parts in 10^7. As the precision of individual measurements rapidly approaches 1 part in 10^7, this problem of comparison is becoming acute. To fully assess the true accuracies of different experiments—to discover their "knife edges"—the differences in gravity between sites will need to be known to an accuracy of at least 1 part in 10^7. Since this degree of precision seems beyond the capabilities of either relative-measurement pendulums or spring gravimeters (except in the case that the gravity interval is very small), the desirability of developing a high precision yet portable free-fall instrument has become clear.

In both Cook's and Tate's experiments—as in the free-fall experiments completed earlier at Sèvres (*13*), Leningrad (*14*), and Ottawa (*15*)—the methods of geometrical optics were used to define the position of the falling object. In Cook's experiment, a glass ball (2 centimeters in diameter) was catapulted upward approximately 1 meter; position measurements were made on its way up as well as on its way down. During its passage between pairs of horizontal slits the ball, acting as a lens, imaged light from one slit onto a phototube located behind the other slit. The moment of passage through the plane de-

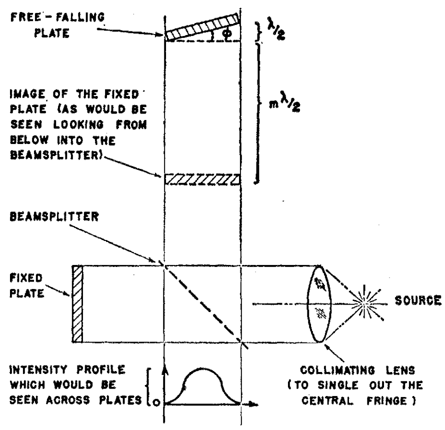


Fig. 2. Free-fall interferometer method. Note that in the situation shown the integrated light output would be constant (unmodulated).

fined by the two accurately parallel slits was then determined in relation to the center of the output pulse from the photomultiplier. In Tate's apparatus, three holes whose lower edges were bounded by carefully made knife edges of metal were located at carefully measured spacings on a meter-long rod. As the rod fell, they let through a collimated light beam and generated photoelectric pulses which were used to start and stop scalers. A 10-megahertz clock was counted to determine the measurement times.

Though the uncertainties in both of these experiments are smaller than the uncertainty of my Princeton measurement, the nonetheless respectable precision of that experiment (a precision which was achieved with a 5-centimeter dropping distance, as contrasted with dropping distances of 100 centimeters or so in other experiments) served to demonstrate both the feasibility and the accuracy of the interferometer method. In view of the potential of this method, there seems to be little doubt that the next generation of absolute g measurements will consist of free-falling interferometer determinations.

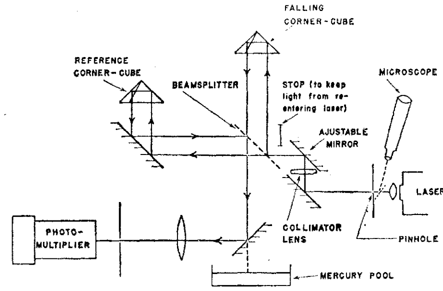


Fig. 3. Schematic diagram of the optical system of the laser-interferometer apparatus.

Interferometric Method

Let us now turn to a discussion of the interferometer method itself. In principle, to measure g interferometrically, one need only drop one mirror of a Michelson interferometer and keep track of the central fringe count for two different periods of time measured from the same starting time (see Fig. 2). (If the plate could be released at a known time with zero initial velocity, it would be necessary to count fringes for only one period of time.) However, anyone who has ever worked with an interferometer of this type will at once realize the immediate practical problem resulting from the extreme sensitivity of the fringe pattern to the parallelism of the plates. If one side of the falling plate gets ahead of the other side by only half a wavelength (3×10^{-5} centimeter), the output of the photomultiplier, which integrates the light over the entire fringe pattern, will no longer be modulated. In terms of the wavelength of light, λ, the width of the light beam, W, and the angle of rotation, ϕ, the requirement that must be satisfied is

$$\varphi W < \lambda/2.$$

For a light beam 1 centimeter in diameter, the permissible angle through which the mirror could rotate is 3×10^{-5} radian—the angle subtended by a dime at ⅕ of a mile (3/10 of a kilometer).

Ideally one would like a system that is totally insensitive to rotation and to horizontal motion of the falling mirror, for, unavoidably, when the mirror is released, a certain amount of angular momentum will be imparted to it, along with a component of velocity in the horizontal direction.

A solution to this problem is the use of optical retroreflectors, "mirrors" whose reflection properties are independent of their orientation. Beaded motion picture screens, "Scotch light," and reflective highway "Stop" signs all make use of this type of optical device.

Three mirrors at right angles to one another (a corner mirror), one corner of a glass cube (a corner cube), and the paraxial portion of a glass sphere of refractive index $n = 2$ are all retroreflective; they send an incident ray (or plane wave) back on itself. Further, each possesses a so-called optical center—a point about which it can be rotated without altering the optical path (the effective distance traveled) of a reflected beam.

If one replaces the plane mirrors of Fig. 2 with corner reflectors, the criterion that must be satisfied in order to have a usable (modulated) photomultiplier signal is

$$\alpha \delta < \lambda/2.$$

Here δ is the difference in the sideways displacement of the two corner reflectors from the center line of the incident light beam and α is the angular spread in the light incident on the interferometer. For a collimation angle of 10^{-3} radian (such as was used in the Princeton determination), the tolerance on the relative displacement δ is about 0.025 centimeter—a requirement that was easily satisfied in practice. In the case of a plane wave "of diameter D," α is approximately λ/D. With a beam diameter D of 1 centimeter (which makes $\alpha = 5 \times 10^{-5}$ radian), the tolerance on δ is almost half a centimeter!

Laser-Interferometer Apparatus

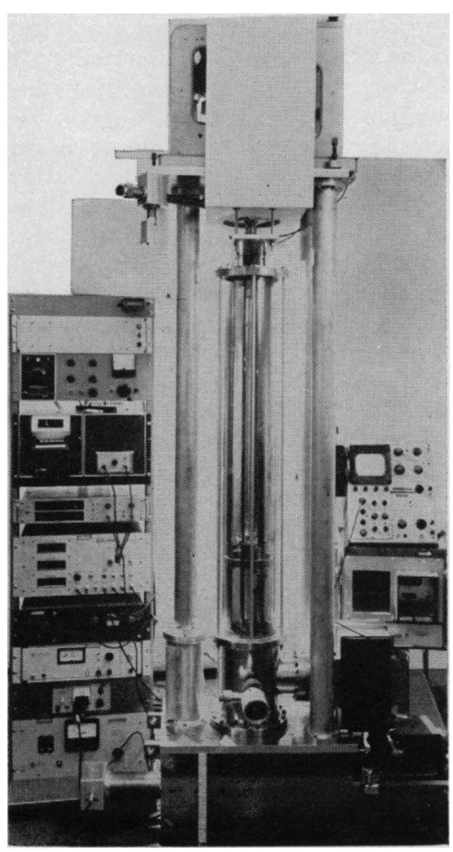
In practice, our free-fall apparatus will then consist quite simply of a Michelson-type interferometer constructed with corner cubes (or their equivalent) rather than with plane mirrors. A schematic diagram showing the optical system of a new apparatus on which I am at present working with James Hammond at Wesleyan University is shown as Fig. 3. A stabilized helium-neon laser provides the brightness and coherence required to achieve high-quality fringes over a 1-meter dropping distance. The total free-fall time for this dropping distance, corresponding to 3×10^6 fringes, is about ½ second. The characteristic time of the experiment—the time it takes the falling corner to move one fringe—is about 10^{-7} second. The high brightness of the laser, which gives rise to approximately 10^5 photoelectrons per fringe at the cathode of the photomultiplier, permits the dynamic length measurement to be made to 3/1000 $[1/(10^5)^{1/2}]$ of a fringe. By comparing the laser wavelength with the orange (6056-angstrom) line of krypton-86—the internationally agreed-on standard for length—a length-scale accuracy of 1 part in 10^8 can be achieved. The time base for the electronics is obtained from a highly stable 5-megahertz crystal oscillator (the drift rate is given as parts in 10^{10} parts, per day) whose frequency is compared with the standard radio frequency broadcast by WWVB, the frequency standard service at 60 kilohertz of the National Bureau of Standards. Utilization of present-day high-speed electronics results in a timing accuracy of about 1 nanosecond (10^{-9} second). We have purposely made the instrument (Figs. 4 and 5) portable, designing it for disassembly into units which are light enough to be carried by one or two men. Thus it will be possible—for the first time—to make absolute measurements with the same apparatus at a number of different sites.

To eliminate air resistance, the free-fall section of the apparatus is evacuated to a pressure of less than 5×10^{-7} millimeter of mercury. The relatively new ion-type pumps are ideally suited for this purpose, since they afford freedom from both mechanical vibration and unwanted vapors which might, over a period of time, impair the quality of the optical surfaces. The wall of the vacuum chamber is a glass tube 18 centimeters in diameter.

Though we are no longer troubled by the carriages of Kater's day, trucks and automobiles as well as student traffic in the building itself combine with the general ground unrest (the microseismic background) to create disturbances which can cause the earth's surface to move by as much as one fringe. This, in turn, gives rise to a scatter in the data, since, during the time the dropped object is falling (toward the center of the earth), the other components of the interferometer rest on—and move with—the surface of the earth. The long-period seismometer mounted above the instrument (Figs. 4 and 5) monitors these seismic disturbances, permitting us to make corrections for them. We are in the process of attaching the fixed cube directly to the "stationary" mass on the seismograph; by thus inertially suspending it, we can avoid these problems of the earth's surface motion by, in effect, tying the reference cube to the center of the earth.

Figure 6 shows the dropped object resting on the carriage, as it rests during its ascent to the top of the chamber. The stationary rods which run through the holes in the dropped object serve, at the lower end, to hold the spring-mounted catching platform. During free fall there is a separation of about half a centimeter between the dropped object and these stationary rods.

In a cycle of operation, the dropped object is carried to the top of the vacuum chamber by the mechanical carriage, which is driven, through a magnetically coupled feedthrough, by a direct-current motor outside the vacuum chamber. The motion of the carriage is automatically controlled by a circuit which incorporates position-sensing switches located in the chamber.



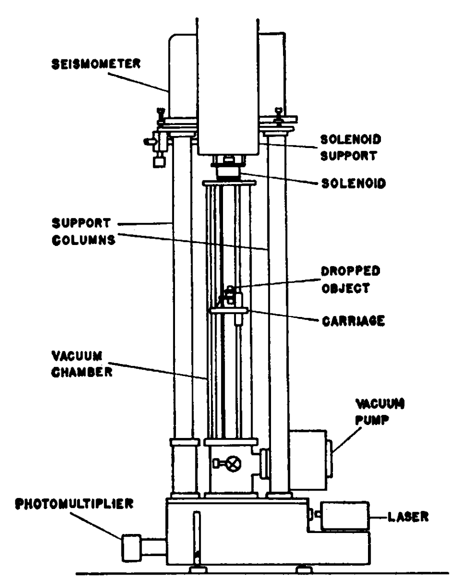


Fig. 4 (left). An overall view of the laser-interferometer apparatus.

Fig. 5 (top). Diagram of the apparatus.

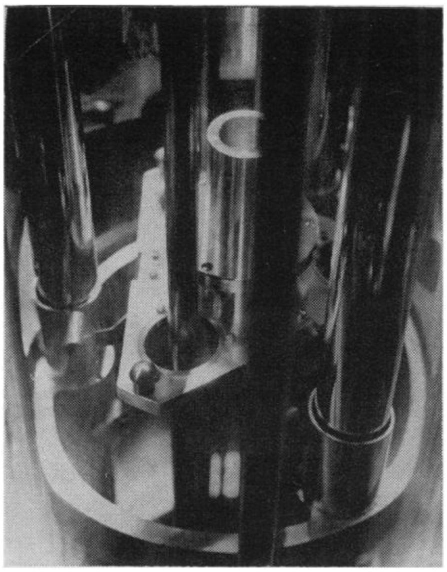


Fig. 6. The dropped object on its carriage.

At the top, the three spring fingers on which the dropped object rests on the carriage are cocked, so that when it is lifted up they move out of the way. A solenoid at the top of the chamber serves as a magnetic hand to lift and then hold the object in position by "grasping" a small piece of soft iron located in its top. After a few seconds the current in the solenoid is turned off; this releases the object.

The arresting mechanism—a vacuum pillow—is designed to minimize the shock on landing. After a measurement has been completed the carriage is returned to the bottom of the chamber, where it again picks up the dropped object; at the same time the electronics are reset for the next measurement.

The actual measurement is started after the object has fallen about 10 centimeters. The output of the interferometer is a sinusoidally varying intensity which ranges in frequency during the measurement from about 4 to almost 20 megahertz. Fringes are counted for two different distances, the longest of which is approximately 1 meter. Two distances are required, since the initial velocity is unknown. The expression for g in terms of the wavelength λ, the two time intervals τ_1 and τ_2, and the corresponding fringe counts m_1 and m_2 is

$$g = \frac{\lambda(m_2 - m_1 \cdot \tau_2/\tau_1)}{\tau_2^2 - \tau_1\tau_2}$$

This is simply derived by applying $s = \frac{1}{2}g\tau^2 + v_o\tau$ to the two intervals and solving for g. Here s is the distance—in terms of the fringe count m $(\lambda/2)$; τ is the time interval; and v_o is the initial velocity.

The basic electronics required for the acquisition of data is shown in block diagram form in Fig. 7. A time-delay generator is triggered when the dropped object is released at t_0, and it generates in turn pulses at times t_1, t_2, and t_3. The first of these pulses turns on both channels of a dual scaler, while the pulses at t_2 and t_3 turn off channel A and channel B of the scaler, respectively. The readings on the dual scaler, representing the fringe counts for the preset time intervals, together with the actual time interval $\tau_1 = t_2 - t_1$ and $\tau_2 = t_3 - t_1$, constitute the required data. Fractions of fringes are determined by electronic measurement of the time interval from the moment a scaler is gated on (or off) until the discriminator sees the next fringe.

Preliminary measurements with this apparatus suggest that the instrument is capable of a precision approaching 1 part in 10^8. The sources of errors associated with the free-fall method—any one of which could prove to be the real limitation on the realizable accuracy—fall into essentially three categories: errors in the basic length and time standards; errors due to nongravitational forces such as electrostatic forces, magnetic forces, and gas drag; and possible systematic effects, such as might result from the seismic shock initiated by the release of the object itself and which is thus phase-related to the actual measurement.

The method effectively utilizes the most precise standards at present available for the measurement of length and time. The uncertainty in the discrimination time which results from shot noise on the fringe signal is less than 10^{-9} second. That this length error translates into a timing error which is essentially identical to the timing uncertainty caused by "jitter" in the electronic circuits means that the brightness provided by today's laser is as high as can be effectively used in the laser-interferometer apparatus without further improving the associated state-of-the-art electronics.

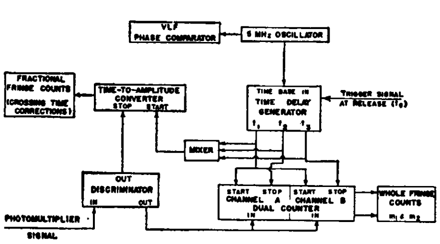


Fig. 7. Block diagram of the electronics of the laser-interferometer apparatus.

In the design of our apparatus every effort was made to avoid the other types of errors listed. Further, the ability to vary the conditions of the measurement by simply changing the time settings on the digital time-delay generator provides an invaluable means of discovering any possible errors which may be present. The portable nature of our apparatus, which permits direct comparison with other determinations, should greatly assist in arriving at a judgment of the absolute accuracy achieved.

Final Words

The history of precision measurements of the acceleration of gravity is a story of man's ingenuity in utilizing the technology of the day both to quicken the response of his eye and to increase the resolution capabilities of his hands. Certainly the centimeter (finger-width) uncertainties in length and the tenth-of-a-second (not more than a tenth of a human pulse) timing limitations of Galileo's day present a sharp contrast to the better than centifringe (3×10^{-7} centimeter) and nanosecond (10^{-9} second) capabilities which we are using in the laser-interferometer method of today.

As for the future, it is not unreasonable to speculate that, before many years, free-fall measurements will achieve an accuracy of 1 part in 10^9. At this level of precision, a number of effects of geophysical and possibly cosmological origin may be expected to appear. The need to disentangle these effects and to understand and correct for the various sources of error should provide a challenge for the future—an era in which precision measurements of g could prove to be an exciting *new* tool for furthering our understanding of the world on which we live.

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Concept of a National Measurement System

The systems approach is being applied to improve understanding of the nation's measurement activities.

R. D. Huntoon

Concurrently with the growth and industrialization of this nation, there has developed within it a vast, complex system of measurement which has made possible the very growth that brought the system into being. This National Measurement System (NMS) stands today as one of the key elements in a worldwide measurement system that links all major nations together in a consistent, compatible network for communication and trade.

Our National Measurement System is one of a number of mutually interacting systems within our technologically based society that form the environment in which the individual citizen must live and function. Familiar examples are the communication, transportation, educational, medical, and legal systems, all of which may be included under the general heading of social systems.

In view of the demonstrated value of the systems approach for the understanding and improvement of hardware such as computers and weapons, some of these social systems are being subjected to the same type of analysis. The National Measurement System, which evolved in this country with little formal recognition as a system, is now being examined in this way at the National Bureau of Standards (NBS) which undertook the study of NMS partly because of a growing realization of the all-pervasive nature and great economic importance of the nation's measurement activities, and partly because of the challenge to NBS in putting its splendid new facilities to optimum use for the benefit of the nation. Such optimum use can be approached only when NMS, of which NBS is a central element, and the services it requires for effective operation are sufficiently well understood.

The magnitude and scope of NMS appear to justify such a study. All of us make measurements and use them; within the United States, this activity is roughly estimated at some 20 billion measurements per day. In the industrial sector, we find (from 1965 data) that the industries that account for two-thirds of the gross national product ($400 billion) invest annually about $14 billion of operating expenditures and 1.3 million man-years in measurement activity. We have about $25 billion invested in instruments for measuring, and we are increasing this investment at the rate of $4½ billion per year. Another $20 billion is invested in completed data on properties of matter and materials, and we are adding approximately $3 billion per year to this amount. Those industries that are growing most rapidly in their contribution to the gross national product are generally those that invest the most in measurement in proportion to output. Hence, the growth sectors of the economy are those that are technologically more sophisticated and therefore more directly dependent upon an advanced measurement capability.

If we judge the value of a service by what the user is willing to pay for it, then the value of the National Measurement System to the nation is in excess of $15 billion a year. More than 90 percent of this cost is paid by NMS through charges to the user in the marketplace; the federal government contributes by providing a central facility for measurement standards (NBS) and the national standards upon which NMS is based.

Like other social systems, the National Measurement System consists of two basically different interacting structures which we designate as the "conceptual system" and the "operational system." In general, the conceptual system is a rational, ordered structure of rules, definitions, laws, conventions, or procedures which provides the fundamental basis upon which the operational system can be built. It is universally applicable, like the laws of physics and chemistry. The International System of Units (Système International

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