LITTLE "g": AN INTRODUCTION TO DROPPING THINGS

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in

Proceedings of the 1983 International School and Symposium on Precision Measurement and Gravity Experiment, Taipei, Republic of China, January 24 - February 2, 1983, ed. by W.-T. Ni (Published by National Tsing Hua University, Hsinchu, Taiwan, Republic of China, June, 1983)

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I would like to begin my third lecture in this school, noting that this is a school, by sharing with you some general thoughts on teaching and lecturing. This first slide (slide 1) comes from Joseph Priestley's very fine little book entitled, Advice to the Lecturer. The circled quotation offers an explanation of why cookies are often served before a colloquium (so students will come), and why I show cartoons in my talks (so they will stay awake).

The next slide (slide 2) addresses the teacher-researcher issue. The same issue stated in a somewhat different way is shown in slide 3. A confessional booth, incidentally, is a private little stall into which a person goes when he wishes to confess his sins to a priest. Now, in a certain sense, that is what universities should be, namely confessional booths. I shouldn't be afraid to confess something about which I'm not completely sure and you shouldn't be embarrassed to ask a question for fear that you're going to be laughed at. One should be willing to tell about not only the successful things he's done, but also the "sins" he's committed. The reason is simply that if you aren't aware of the less-than-obvious mistakes I've made, then you're likely to go out and repeat them.

Now before I arrived you had several lectures introducing you to gravimeters and gravity prospecting. The next slide (slide 4) (which was shown at the recent IAG meeting in Japan by Professor Torge of the University of Hannover, West Germany) summarizes how the accuracy of various types of gravity measurements has improved with time. A gal, incidentally, is a centimeter per second per second (presumably named after Galileo) and therefore a milligal, being 10^{-3} cm/sec^2, is about 1 part in 10^6 of g. Notice that pendulums seem to be limited to a few parts in 10^6 while relative (spring) gravimeters which are still extensively used have achieved a precision on the order of 1 part in 10^8. And finally, free fall methods appear to permit accuracies approaching a few parts in 10^9. Before discussing the method of free fall, let us talk briefly both about pendulums and about (relative) spring gravimeters.

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. The next slide (slide 5) is an engraving that shows both an overall view of Kater's apparatus and the technology of his day.

The most serious limitation 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; thus it would appear, save for the possibility of employing a magnetic suspension, that the use of pendulums for absolute (or even for relative) measurements has reached an impasse at somewhere in the range of a few parts in 10^6.

The use of spring gravimeters to carry out relative gravity measurements with a precision approaching one part in 10^8 followed the pendulum era. The next slide (slide 6) shows, at least conceptually, the inside workings of a spring gravimeter. Basically a gravimeter consists of a mass on a spring which, given a change in gravity, will result in a change in the length of the spring. This change in length is then read out as a change in g. The incredible thing is not that they work but that they work as well as they do. Their limitations have to do with both drift and sudden shifts in the spring length as well as linearity problems involving both the linkages and the reading screws.

The next slide (slide 7) shows a spring-type gravimeter being used in early (1952) field work. The thing you should notice in particular is that the apparatus is extremely small in comparison to the size of the truck. The point is that if the apparatus were somewhat larger, it wouldn't be all that bad, because you could still fit it into the truck. (As you will see later, our new absolute gravity apparatus is considerably larger than the relative gravity meter shown here; however, it still would fit nicely into this truck.) In recent years, the quest for greater stability and accuracy has led some workers to circumvent all of the aforementioned mechanical and materials problems by turning to the method of direct free fall.

Now let us begin by designing an apparatus to measure "g" using the method of free fall. The next three slides are from drawings made for me by Zdenek Herman, a visitor from Czechoslovakia who spent a year at JILA. The first of these slides (slide 8) shows the theorist's approach. And he's got everything right -- in principle. He has one student who drops an apple (for reasons of obvious significance), another student with a stopwatch to time the fall, and their professor to take the credit.

Now the problems should be obvious: a) you probably shouldn't use an apple; b) somebody had better catch whatever you drop at the bottom (or you're likely to need a new apparatus every time); and, c) you've got to get rid of the air resistance. How do you get rid of the air resistance? If you were a vacuum engineer, you might design an apparatus that looks something like this (slide 9). Somewhere in the picture is the actual apparatus, however it is dwarfed by the size of the vacuum system. This is a common problem in life: people tend to emphasize what they can do well. If they happen to be a specialist in vacuum systems, they build the world's greatest vacuum system, and somewhere, perhaps, the apparatus.

And, of course, if they are a computer expert (slide 10), they might have a very small vacuum pump and an insignificant mechanical apparatus, but have the world's largest computer. That's a failure mode that one needs to watch out for in designing experiments. An experimental physicist needs a good working knowledge of all aspects if he is to achieve the proper balance in any apparatus.

Now, before you go out and build a particular apparatus, it is also a good idea to make sure there isn't one available ready made that will do the job. I went to the literature to see what was available in terms of a free fall gravity apparatus and found (slide 11) that for only $752 you can buy one. It consists of an iron piece which on release (effected by turning off a holding electromagnet) free falls and at the bottom drops into a can of sand. The position timing is done with a high voltage spark which jumps between the dropped piece (as it falls) and the stand. This spark burns a hole every 120th of a second in a vertical strip of red paper tape which hangs along the stand. The resulting distance-versus-time record can then be analyzed to produce g. Unfortunately, the accuracy obtainable with this particular apparatus is only about 1%. The price and concept are right, but the accuracy of the result leaves much to be desired.

After World War II it was realized that the electronic technology which had been developed for measuring short time intervals would, at last, permit the use of the method of free fall for precise determinations of g. The earliest free fall measurements of g which were begun at this time used geometrical optics (rather than a spark) to accurately define the position of the dropped object as it fell. More recent work, starting with my Ph.D. thesis experiment, uses the methods and tools of optical interferometry to define the position of the freely falling piece as a function of time.

In principle, to measure "g" interferometrically, one need only drop one plate of a Fabry-Perot etalon and keep track of the central fringe count for two specified periods of time (slide 12). (If the plate could be released at a known time with zero initial velocity, it would only be necessary to do this for one period of time.) Anyone, however, who has ever worked with either a Fabry-Perot etalon or a Michelson interferometer will at once realize the immediate practical problem involved with this approach which results from the extreme sensitivity of the fringe pattern to the parallelism of the plates. (Recall from my first lecture the need for a worst-case analysis.) In order for the central fringe to remain unambiguously defined throughout the dropping period, the plates need to maintain their parallelism to better than a half-wavelength of the light used. If one side of the falling plate gets ahead of the other side by only $\lambda/2$ the modulation seen in the fringe pattern will be eliminated. In terms of the wavelength λ, the width of the plate W, and the angle of rotation ϕ, the requirement that must be satisfied (in order to insure a meaningfully modulated output) is

$$\phi W < \lambda/2 \quad .$$

Although for any amount of rotation there exists a plate width such that the above relationship is satisfied, it is highly unlikely (even if the resulting stringent requirements on motion to the side could still be satisfied) that one would be left with an area large enough to permit the use of a sufficient number of photons. Ideally one would like to have a system that is totally insensitive to rotations and to the horizontal motion of the falling mirror, for unavoidably on releasing the mirror a certain amount of angular momentum will be imparted to it together with a component of velocity in the horizontal direction.

A solution to this problem is the use of optical corner reflectors rather than plane mirrors (slide 13). With a corner mirror (triple mirror) the optical path (in and out measured from a fixed reference plane perpendicular to the incident ray) is unaffected by the rotation of the corner about its apex; with a solid glass corner prism, the optical path is affected only to an extent that is quartic in the angle of rotation of the prism about its optical center (the apparent position of the apex viewed through the glass). For interference between corner-type objects, the criterion that must be satisfied in order to avoid ambiguities in the pattern seen by a photomultiplier (which integrates the output light) is that:

$$\alpha\delta < \lambda/4$$

where now δ is the sideways motion and α is the half-angle of collimation. In practice, this criterion is easy to satisfy.

You might wonder how I ever got into this business of measuring little g in the first place. The next slide (slide 14) is an overall view of my thesis apparatus -- circa 1960. That first absolute measurement of the acceleration of gravity utilizing optical interferometry was made before the laser had been invented. To do this, a scheme was devised which resulted in the conditions for white light fringes being satisfied at three different positions in a modified Michelson interferometer. This scheme was used to provide the events between which one could measure the times precisely. To obtain a satisfactory signal-to-noise, the sun was used as the white light source. The resultant rms accuracy of the measurement was 7 parts in 10^7.

Not very many years after that, lasers came along; and as soon as the laser was available, life became somewhat simpler. Because the laser is monochromatic, you can have fringes over the entire dropping distance. Further, the available brightness, even using a 100 μWatt laser, is such that you can measure the position of the dropped object as it falls to the nearest one thousandth of a fringe.

The next slide (slide 15) shows a schematic drawing of a laser interferometer system. The optical system, as drawn, consists of a Michelson-type interferometer whose output is detected photoelectrically. Further, the measurement requires that at least one beam (the one in the free fall arm) be directed vertically. The "mirrors" of the interferometer are corner cubes. The reason the reference-cube arm is also drawn with a vertical orientation is so that the reference cube can be suspended from a spring for purposes of seismic isolation -- a subject which will be discussed shortly. To measure g, one cornercube is released and it free falls, giving rise to interference fringes -- a new one each time the cube falls another half a wavelength. The resulting sinusoidal fringe record, which starts at dc and goes up to about 10 MHz after about 20 cm, contains exactly the same little g information as was contained in the red sparked tape record but in this case with exquisite detail and precision.

The next slide (slide 16) shows the Ph.D. thesis apparatus of a former student of mine, Jim Hammond. This instrument, utilizing laser interferometry achieved a measurement accuracy of 5 parts in 10^8 (50 μgal) and was used in the late 1960's to make the first trans-Atlantic absolute gravity transfer as well as the first comparison of absolute measurements at the same site. The next slide (slide 17) shows the dropped object from this apparatus sitting at the bottom of its evacuated dropping chamber. I show this picture not so much because of what it shows, but simply because I see it as an example of "scientific art": it looks nice.

In this apparatus, the reference mirror rather than being rigidly attached to the interferometer base was suspended from a vertically hanging (long) spring -- just as was indicated earlier in slide 12. Why? Because the object that falls freely is completely decoupled from the Earth's (moving) surface during the drop. The reference cube, however, is not. It will experience accelerations due to motions caused by seismic or man-made noise which will increase the drop-to-drop scatter in the measurement. Hanging the reference cube at the end of a "long" spring permits us to inertially suspend it and by so doing to greatly reduce the scatter in the resulting data.

Now let me tell you about some of the problems with this kind of system. One problem is that to successfully avoid air drag, the free-fall section must be evacuated to a pressure of a few $\times 10^{-7}$ mm of Hg. That's an awkwardly high vacuum; not only does it severely restrict the materials you can use in it, but you can also get vacuum welding of sliding and contacting parts.

Another problem is, every time the free-falling object is dropped you have to catch it at the bottom and bring it back to the top (release position) again. My thesis advisor (Bob Dicke) used to talk about having small boys in apparatuses to perform the various needed tasks. But the truth of the matter is there are no small boys in physics. You ultimately have to build their mechanical equivalents and the high vacuum environment in this case only results in added complications.

Ten years later, another graduate student -- Mark Zumberge -- wanted to work on this problem, and we set out (successfully, as you will hear during the Symposium part of this conference) to develop a new instrument of considerably reduced bulk and weight which was intended to provide higher accuracy as well as greater mechanical reliability and markedly less set-up time at a given site. Furthermore, we designed and constructed a new type of "drag free" dropping chamber to correct the mechanical difficulties associated with the high vacuum environment required in Hammond's earlier instrument.

This involved dropping not only the cornercube-containing object but also its container so that air drag resulted only from the differential velocity between the dropped object and its container -- thus substantially reducing the vacuum requirement.

Our initial attempt at a dropping system -- prepare yourselves for a confession of sins -- is illustrated in the next slide (slide 18). The dropped object consisted of a cornercube mounted inside an aluminum body. Three spheres on this body served to kinematically position it in three corresponding v-grooves in the surrounding falling chamber, which was held to the top of a vacuum chamber by an electromagnet. An auxiliary mass hung beneath the dropping chamber on springs which pulled the falling chamber and its auxiliary mass together when the current to the electromagnet was interrupted. This resulted in the dropped cornercube "floating" inside the falling chamber as they fell together. Damped springs at the lower end of the vacuum chamber caught the falling chamber and a movable platform returned it to the electromagnetic support.

The behavior of this system was studied photographically. By triggering a flash at different stages during a set of drops a sequential series of photographs representing the evolution of a single drop could be assembled. From these it was determined that the falling object, in spite of the system's inertial design acquired a velocity relative to the falling chamber. However, when the electromagnet was replaced with a thin string that was burned to release the falling chamber, no relative velocity was produced. From this we inferred that eddy currents accounted for the relative velocity seen previously, and a purely mechanical release mechanism was built to replace the electromagnet. Eventually, this was made to operate satisfactorily, although the mechanical complexity had evolved to a level that we had hoped to avoid. Finally, we decided to investigate an alternative approach before committing ourselves to a successful but terribly clumsy mechanical system.

We wondered whether the falling chamber's descent could be actively controlled to follow that of the freely falling dropped object, and found it surprisingly easy (once we finally overcame our reluctance to try it) to servo a surrounding motor-driven chamber (which moves inside the main vacuum system) to the dropped object. The resultant system is schematically shown in the last slide (slide 19). The success of this drag-free approach not only eases the requirement for a high vacuum system (2 to 3×10^{-5} mm of Hg will now suffice as opposed to 10^{-7} mm of Hg), but as a bonus the same falling chamber can also be used electronically to gently arrest the descent of the dropped object and to swiftly return it to the starting position, thus increasing the rate of measurements. In retrospect, we should have tried the servo-driven drag-free approach much earlier in the development of the instrument. The reason we didn't was that we were afraid it would be much harder to do. But as is often the case in both science and life, hindsight is both cheap and easy.

Next Monday, in the symposium portions of this meeting, I'll talk more about this new instrument. Today's talk, I hope, will serve as a helpful introduction for you both to the field and to my talk next week. Thank you for your kind attention.

HIS DELIVERY

The most prominent requisite to a lecturer, though perhaps not really the most important, is a good delivery; for though to all true philosophers science and nature will have charms innumerable in every dress, yet I am sorry to say that the generality of mankind cannot accompany us one short hour unless the path is strewed with flowers.

In order, therefore, to gain the attention of an audience (and what can be more disagreeable than the want of it?), it is necessary to pay some attention to the manner of expression. The utterance should not be rapid and hurried, and consequently unintelligible, but slow and deliberate, conveying ideas with ease from the lecturer and infusing them with clearness and readiness into the minds of the audience.

(1)

... SO HE'S A GREAT TEACHER... WHAT HAS HE PUBLISHED??

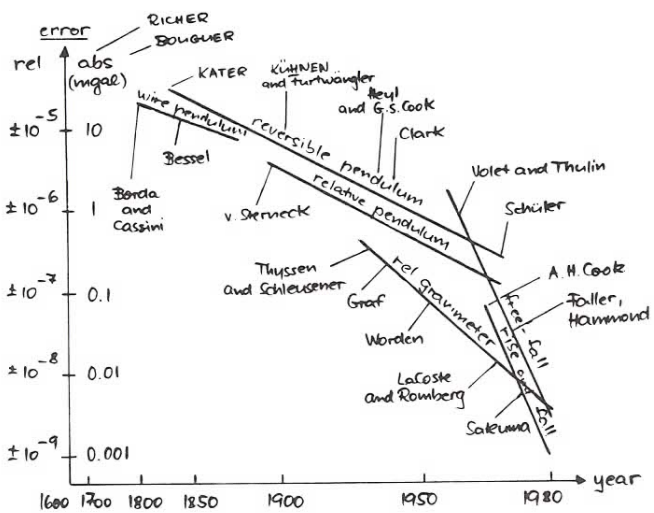
(2)

Tl

"Research is to teaching as sin is to the confessional: if you haven't done the first, you've no business doing the second."

In keeping with this maxim, David Starr Jordan is said to have threatened to fire any faculty member he found reading textbooks; they were to *write* textbooks. Students come to IU to learn from masters, not from "middle men." In a university where research is going on, there is "an

(3)



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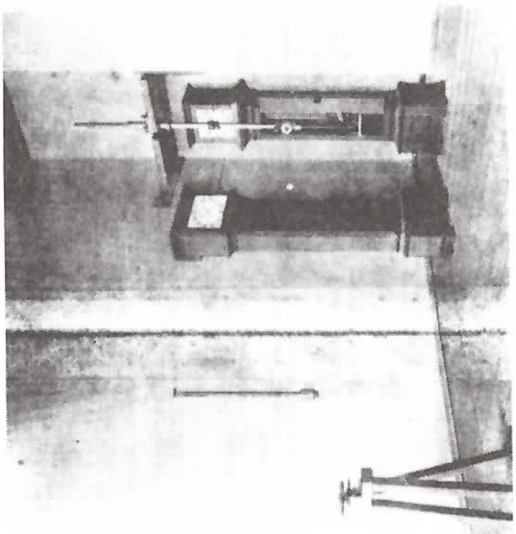

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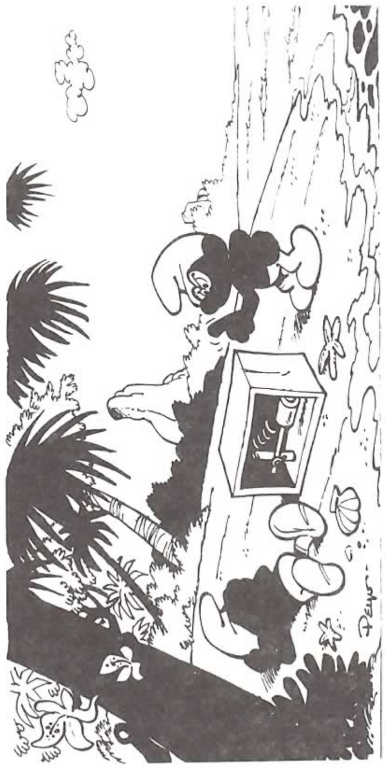

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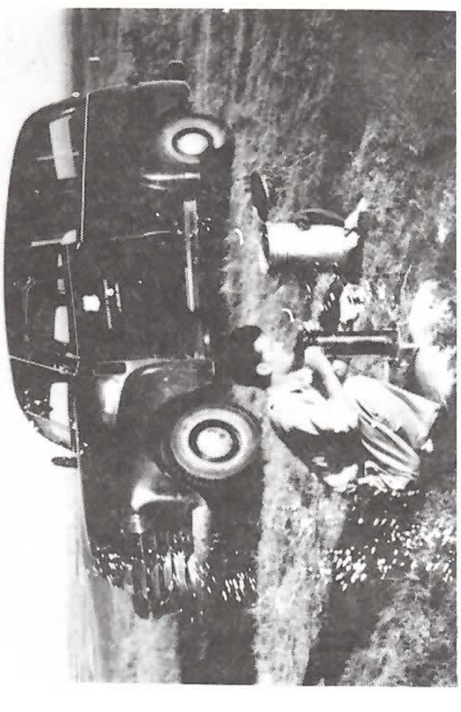

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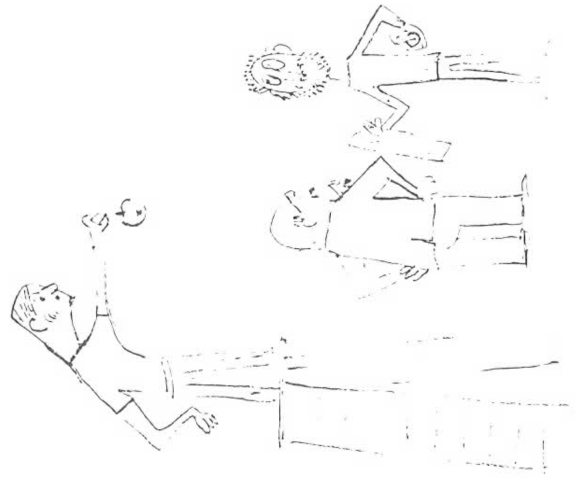

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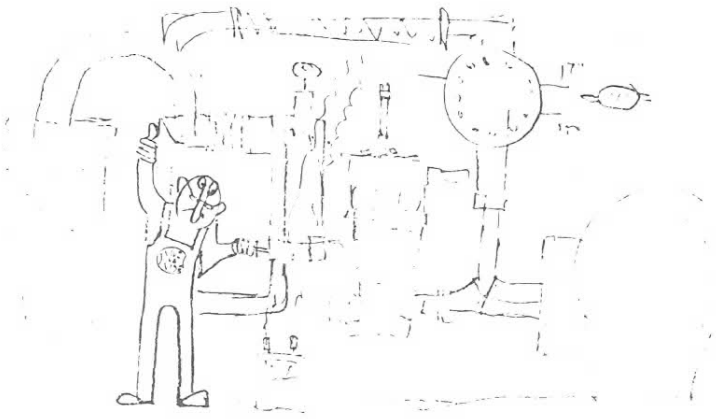

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(10)

BEHR FREE FALL APPARATUS

BEHR FREE FALL APPARATUS

For use in study of freely falling body, in particular, to measure g, acceleration due to gravity. In use, an object is allowed to fall freely, and its positions at end of successive equal intervals are recorded on coated paper strip by means of electric spark. From this data, graphs of distance time and velocity time are plotted. Acceleration is determined from slope of velocity time graph.

Apparatus consists of column, 148 cm long supported on heavy tripod base with leveling screws, an electromagnet for supporting and releasing cylindrical falling body, felt lined dashpot for receiving falling body, holder for 74900 002 Coated Paper and weighted paper clip to hold end of coated paper flat against column.

Electromagnet is energized by six volt DC source such as 79563 000 DC Power Supply or storage battery. Timed spark source similar to 74912 000 multi frequency Spark Timer is also required for producing spark record.

Complete as described with one roll of spark sensitive paper, auxiliary spark gap and operating instructions, but without dc source or spark timer.

74905-000 **$752-00**

(For experiments using this apparatus, see Selective Experiments 71991 124 and 71991 126)

00067-497 Replacement Free Fall Body **$34.50**

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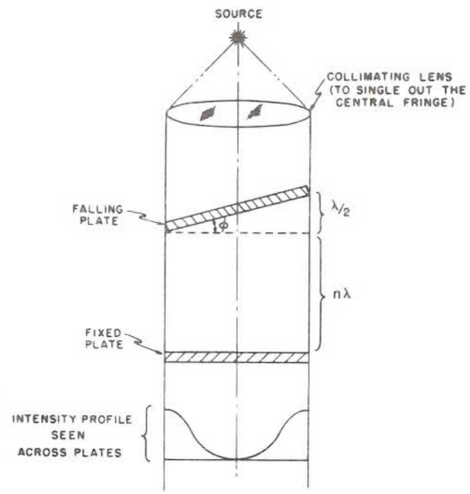

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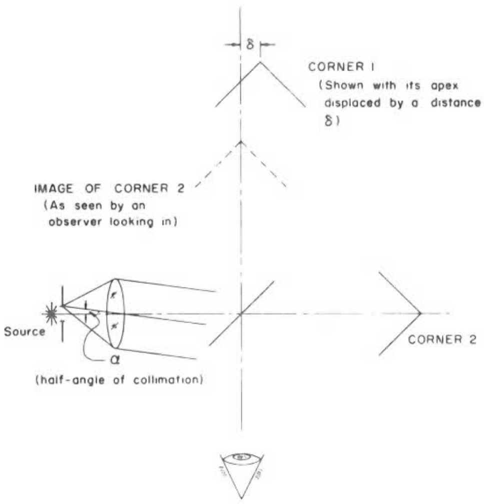

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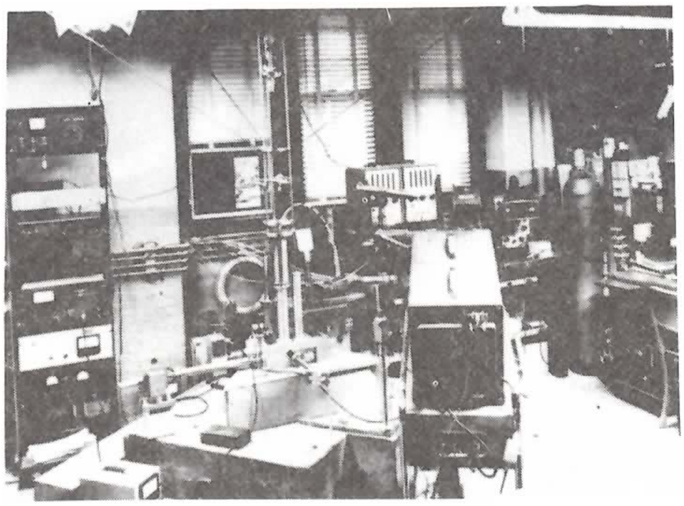

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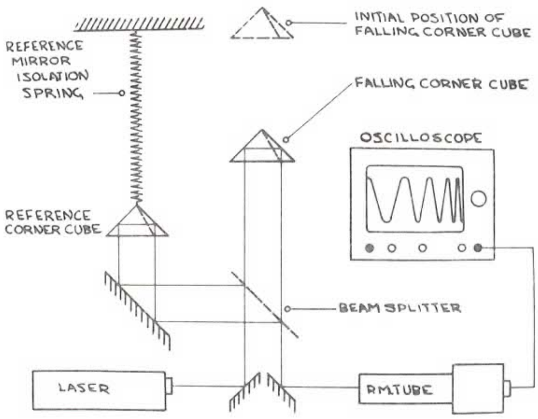

LASER INTERFEROMETER SYSTEM

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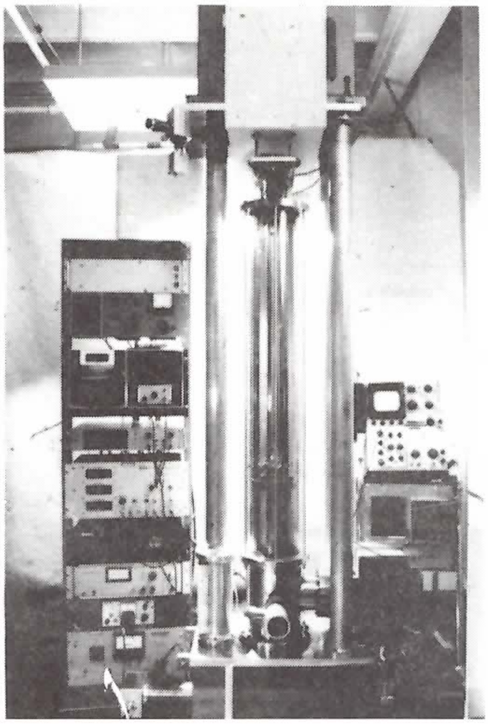

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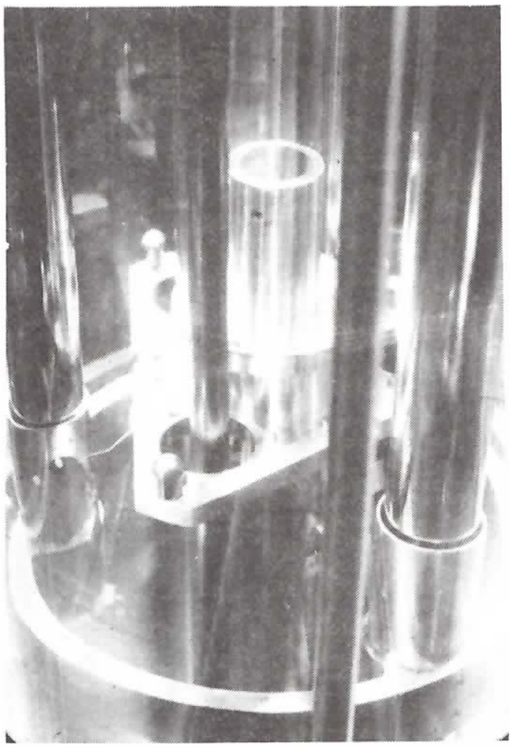

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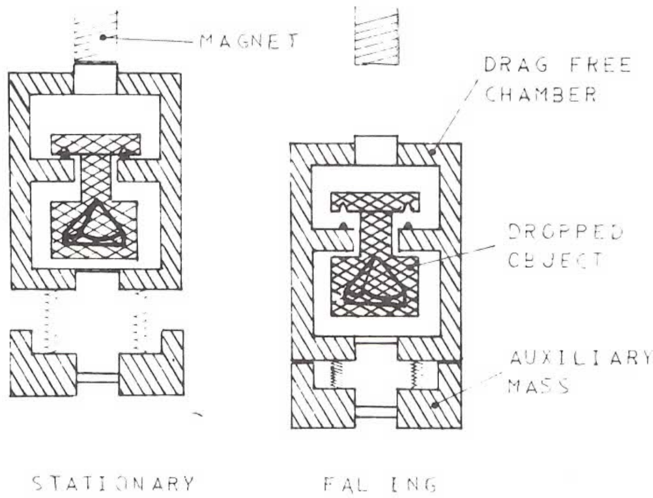
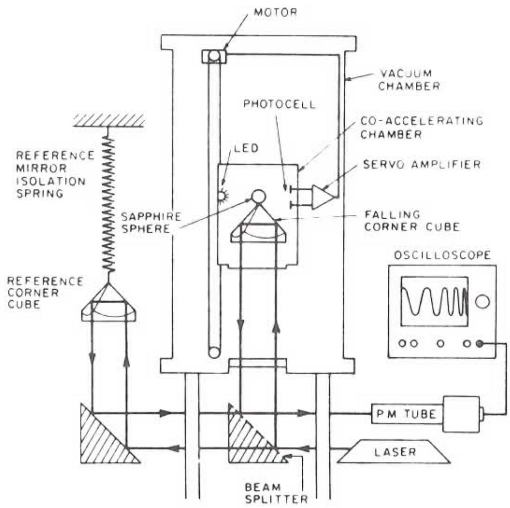

MAGNET
DRAG FREE
CHAMBER
DROPPED
OBJECT
AUXILIARY
MASS
STATIONARY
FALLING

(18)


MOTOR
VACUUM
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REFERENCE
MIRROR
ISOLATION
SPRING
SAPPHIRE
SPHERE
FALLING
CORNER CUBE
OSCILLOSCOPE
REFERENCE
CORNER
CUBE
PM TUBE
LASER
BEAM
SPLITTER

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