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TECHNICAL DOCUMENTATION FOR THE MARK I MODEL OF THE LASER ABSOLUTE GRAVIMETER

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16. Abstract This report is a documentary on the laboratory work performed in trying to perfect a laboratory model absolute gravity meter (gravimeter). Included are the following results: the measurements taken with this device of acceleration due to gravity, the vibration isolation tests performed on the air table used to support the gravimeter, and the measurements of the transmissive properties of the optical components used in the gravimeter.

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TECHNICAL DOCUMENTATION OF THE LASER ABSOLUTE GRAVIMETER

SUMMARY

A machine to measure the absolute acceleration due to gravity is investigated. The gravity meter (gravimeter) is of the falling-mass type. The falling mass is the moving mirror of a Michelson interferometer. The interferometer, with a highly stable He-Ne laser as the light source, is used to measure length. Time is measured using a 1-MHz oscillator as a time base for two time-interval counters.

The results of the acceleration measurements show a dependency upon the system used to release the mass. Two types of release systems were used in this investigation. One type employed a pneumatically operated swing arm; the other, a hydraulically retracted spring. Data obtained from the same path lengths were compared; the standard deviation of all the measurements was higher, and the values of acceleration due to gravity were 20 to 30 milligals* lower with the hydraulic release than those values obtained with the pneumatic release. For the longest path lengths in both systems, the average value of the acceleration due to gravity was 979.580 cm/sec^2 for the pneumatic release and 979.566 cm/sec^2 for the hydraulic release. The correct value, as determined by relative gravity meters, is 979.637 cm/sec^2.

For both systems, the standard deviation (considering all the drops) gets higher as the path length over which measurements are made gets shorter. Also, the average acceleration values show a dependency upon path length. For the pneumatic release, the acceleration values that differed the least from the correct value, disregarding the standard deviation, were obtained from a path length one-eighth as long as the path length from which the most accurate values should have been obtained. It is believed that a large part of this

* A gal is one cm/sec^2.

dependency of the acceleration values upon path length is due to the motion of the gravimeter that results because of the air cushion used to vibrationally isolate the gravimeter.

The motion resulting from this air cushion, or air spring, is that of a spring supported mass with damping. This motion causes an error in the acceleration values from the gravimeter because the acceleration is being measured relative to the table on which the gravimeter is supported, and the motion, which has a period of about 0.4 seconds, is not damped out over the time during which a measurement is made.

The results of tests to measure the dependency of the period of this motion upon the type of gas used for supporting the table top are not consistent with theoretical calculations. This inconsistency has not yet been fully resolved.

It was found that the best optical system is one that uses a polarizer, a collimating lens, a spatial filter, a fifty-fifty beam splitter with very little absorbing properties, and corner cubes for the mirrors in the interferometer. However, the intensity of the light sources prevented the use of the spatial filter on this gravimeter.

Errors in the value of the acceleration measurement result mainly from the following: the high seismic noise level in the room where the gravimeter was housed, the beam splitter and stationary mirror not being in vacuum, the motion due to the air cushion, the vibration introduced into the gravimeter system by the release system, and, possibly misalignment of the beam to the bird. (This beam should be parallel to the local "g" vector.)

INTRODUCTION

The laser absolute gravity meter discussed in this paper is the invention of O. K. Hudson, and the work described was carried out under his supervision. Its principle of operation is described in his working paper [1]. This paper summarizes the work done on the first (Mark I) laboratory model of this gravimeter and is intended primarily for those people who will be connected with the next model gravimeter. The Mark I has been disassembled and is being modified so that the error sources resulting from specific sources identified in the Mark I will be reduced.

Much of the work done toward identifying error sources was qualitative; that is, the source was identified and its influence on the gravimeter results noted. Measurements of the amount of error caused by some of the sources could not be made because of a lack of equipment or the inability to isolate the noise produced by the source.

The gravimeter is basically a Michelson interferometer. The moving mirror of the interferometer is allowed to free fall in vacuum, and, as it falls, the distance is measured as a function of time. The falling mirror and its housing will be referred to as the "bird" throughout the paper.

That portion of the path the bird traverses as it falls and the portion over which measurements are made is referred to as the path length. Path lengths consist of two equal, consecutive intervals over which distance is measured as a function of time. Generally, when speaking of the distance covered by a path length, only the length of one measuring interval is given. The length of the interval is usually stated in terms of the number of fringes it contains. This number is usually stated in binary form since the fringes are counted binarily. Table 1 gives the conversion from binary form to the total number of fringes and to the path length.

In connection with the bird, the term "release" is used to designate the operation of removing the support from the bird so that it may begin its free fall. The expression, "dropping the bird," is also used to designate this operation.

The whole operation of releasing the bird and letting it fall is referred to as a "drop." This term is usually applied to those times when data are collected for a calculation of acceleration.

The measurement of "g" is dependent upon counting a given number of fringes. Any disturbance that causes extra fringes to be formed and counted, or that causes the fringes to be counted too fast or too slow, is termed "noise" and results in an error in the calculated acceleration value.

TABLE 1. CONVERSION OF PATH LENGTH FROM FRINGES TO CENTIMETERS

Binary Measuring Interval (2^n fringes)	Number of Fringes in Binary Measuring Interval	Path Length (cm)
2^{20}	1 048 576	33.18698
2^{19}	524 288	16.59349
2^{18}	262 144	8.29674
2^{17}	131 072	4.14837
2^{16}	65 536	2.07418
2^{15}	32 768	1.03709
2^{14}	16 384	0.51854

SECTION I. DATA

The Standard Value of "g"

At the gravimeter site (Spaco, Inc.), the acceleration of gravity established by relative meters is 979.637 cm/sec^2. The determinations of several people using different meters were used to establish this value. The seventh figure (tenths of milligals) differs for each experimenter. The value is tied to the Potsdam system and has been corrected for altitude. When comparing data, this value will be used as the standard, although it is generally agreed that the Potsdam system values are high by approximately 15 mgal.

Sources of Error

Data for the measurement of the acceleration due to gravity have been taken under a variety of conditions. The measurement intervals have been varied from 2^{20} fringes to 2^{15} fringes with the most repeatable "g" values coming from the longer path lengths, and, in general, with the most accurate value coming from the shorter path lengths. Measurements have been made at all times of the day using different detection systems, two release systems, and several optical systems.

The noise level (that is, fringes other than those caused by the fall of the bird) associated with the Mark I model has been extremely high. However, the major causes of the noise fringes have been identified. As a result of the experience gained from the Mark I, noise contributions from these sources can be reduced considerably in future models.

Errors in the value of "g" result either from extra fringes being counted or from fringes that are not counted. Both effects are present in the Mark I because of the large amount of extraneous vibration to which the stationary interferometer parts are subjected. Errors due to electrical noise in the electrical equipment are negligible compared with the errors resulting from these vibrations. The sources that cause the most vibrations are the forepump, the air compressor in a nearby room, the air table reaction to the release of the bird, and, in the case of the pneumatic release system, the operation of the release mechanism.

Smaller errors were caused by air pressure changes in the reference arm, seismic movement of the floor, acoustic vibrations impinging on components not in vacuum, noncoincidence of the center of gravity of the mirror housing and the optical center of the corner cube, and, in the case of the pneumatic release system, misalignment of the beam direction to the bird.

Absolute error values cannot be given because no accurate measurement of noise fringes was performed. The difficulty in making these measurements lies in separating the noise fringes from the regular fringes. Only about half the total error can be accounted for because of the lack of definitive noise measurements.

Measurements of the number of noise fringes occurring under normal conditions and caused by disturbances other than alignment and release (Section VII) show that, on the average, 5.149 fringes occur each second. This can be translated into an approximate error by assuming the fringes are uniformly distributed over the measuring intervals and by using the error equation

$$\frac{dg}{g} = \frac{d\lambda}{\lambda} - \frac{2dn}{n} + \frac{dN}{N} + 2\frac{df}{f} + \theta\, d\theta \quad . \tag{1}$$

Then, with the pneumatic release, the error in "g" caused by these noise fringes amounts to 0.810 mgal for two measuring intervals of 2^{20} fringes and 1.106 mgal for intervals of 2^{19} fringes. For the hydraulic release, the error for 2^{19} fringes amounts to 0.822 mgal.

For the pneumatic release, an angular deviation of 7.5 minutes occurred between the beam direction to the bird and the vertical. This translates into an error in "g" of 4.66 milligal. Both these errors are small compared with the total error experienced by the values of "g" found with the Mark I.

The largest error found was a result of the springlike action of the air table when the bird was released. Figure 1 is a record of the output of an accelerometer placed on the table top. It shows the acceleration experienced by the 600-lb table top. Errors in "g" result from this action because the gravimeter is measuring acceleration of the bird relative to the table top and not to a fixed point on the earth's surface. The magnitude of the error resulting from this while using the pneumatic release and measuring intervals of 2^{20} fringes amounted to approximately 22.1 mgal. For 2^{19} fringes it amounted to approximately 35.4 mgal. With the hydraulic release and a fringe measuring interval of 2^{19} fringes, the error is approximately 55.2 mgal. It was assumed in the calculation of the error for the hydraulic release that the table does not start its movement before the bird clears the end of the release shaft.

The higher errors in "g" values occurring with the hydraulic release, compared with those experienced with the pneumatic release, result from a longer drop before fringe counting begins. Consequently, the bird has a higher velocity at the beginning of the measuring period and passes through it faster. Hence, the time interval during which the motion of the table top is important is shortened. Less acceleration of the table top is cancelled by its up-and-down motion; thus, the error in "g" is higher. For the longer path lengths for both release systems, the directions of motion and the sign of the acceleration of the table top were such that the erroneous accelerations resulted in low "g" values.

Summary of Data

Figures 2 and 3 are histograms arranged according to measuring interval of the data taken under normal conditions with the pneumatic release system. Normal conditions are pressures of 10^{-4} mm Hg or lower, using the all delrin bird and with no drop delays. It should be noted that only one set of drops was made in a pressure greater than 10^{-5} mm Hg. Figure 4 is a histogram of the data taken under normal conditions while using the hydraulic release.

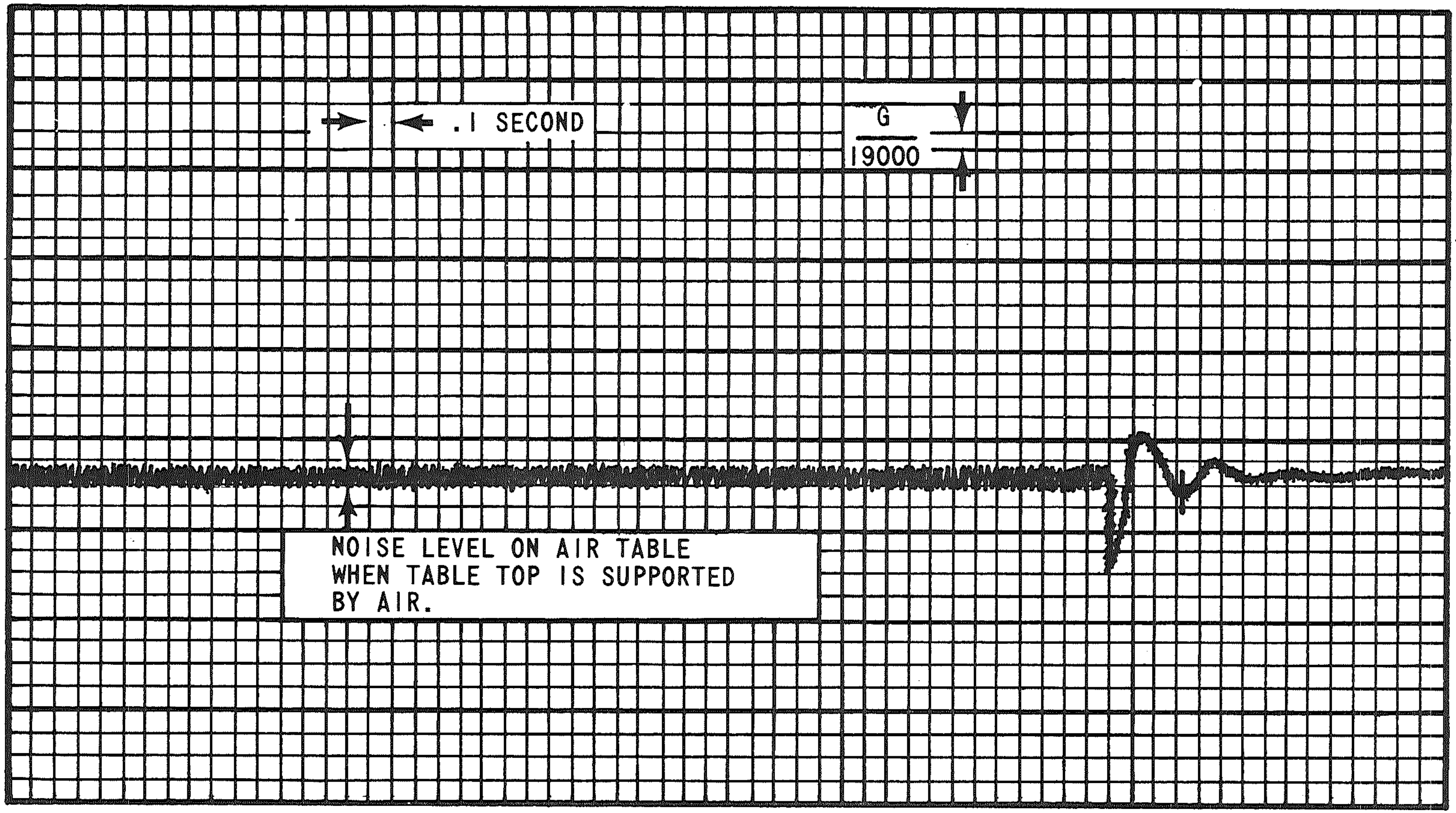
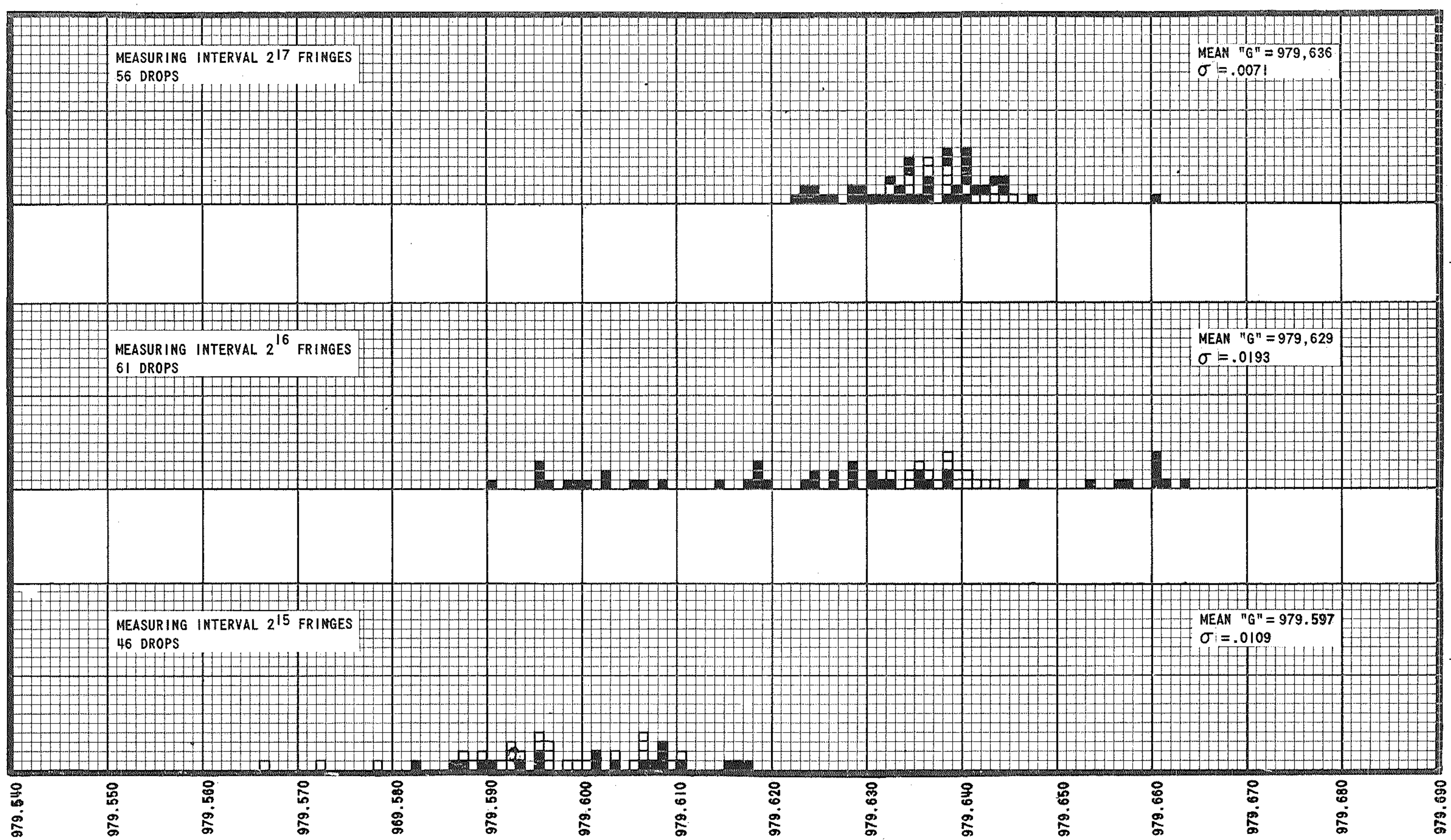


Figure 1. Acceleration experienced by air table top when bird is released.
(weight of table top = approximately 600 lb)



□ DATA OBTAINED WITH PLATE BEAM SPLITTER
■ DATA OBTAINED WITH CUBICAL BEAM SPLITTER

Figure 2. Histogram for data obtained while using the pneumatic release.

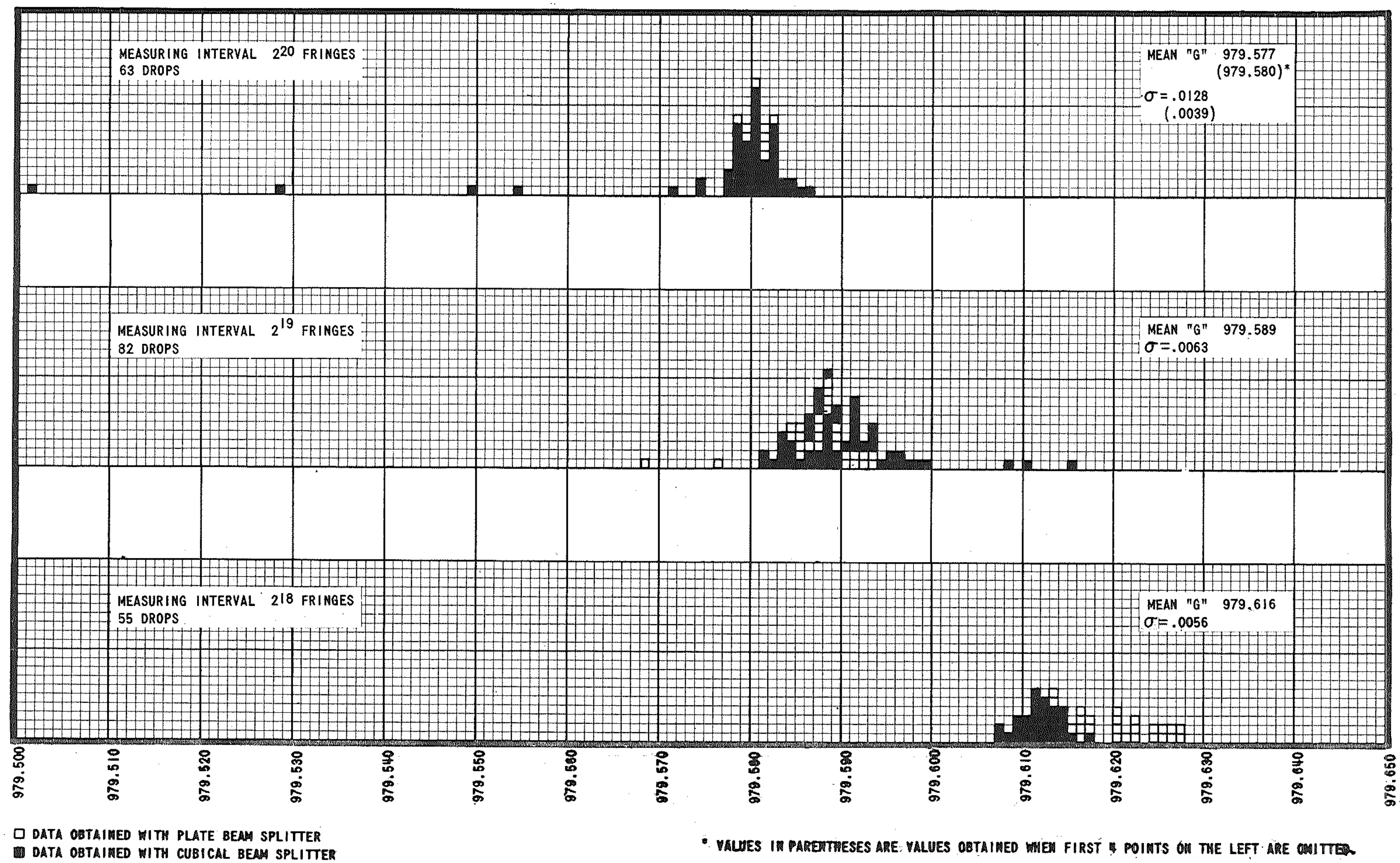
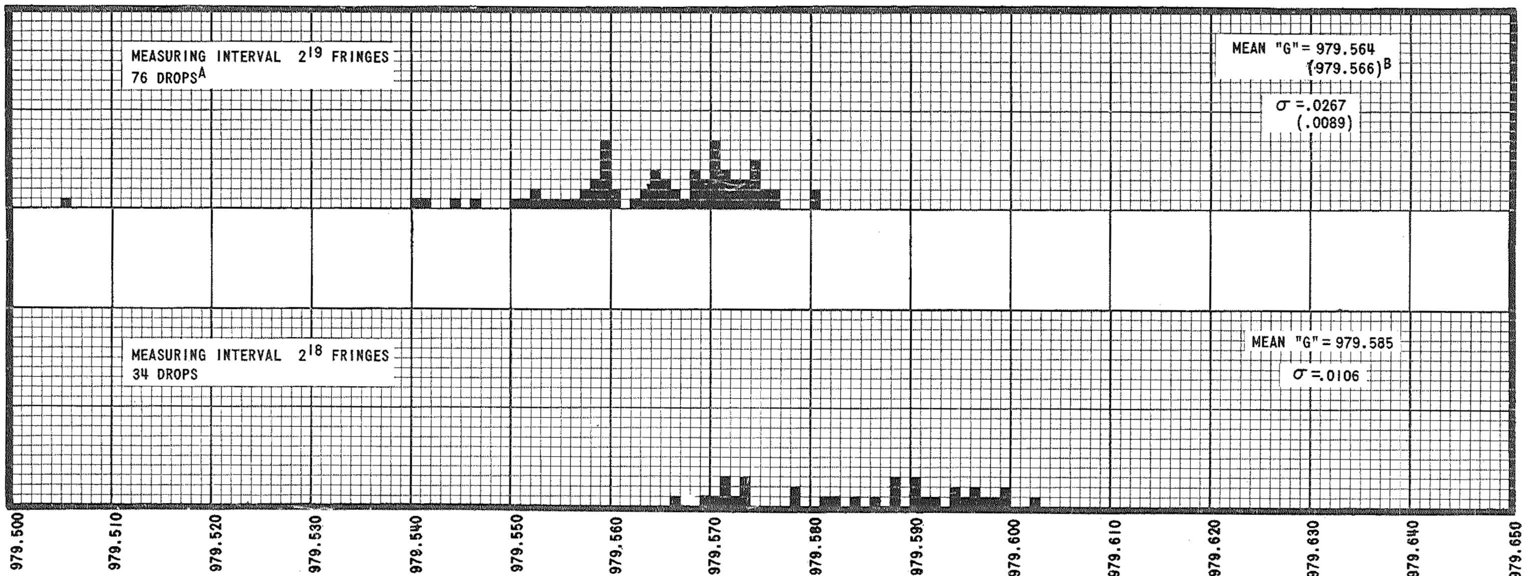


Figure 3. Histogram for data obtained while using the pneumatic release.



A. ONE VALUE 979.777 COULD NOT BE INCLUDED DUE TO SPACE AVAILABLE
B. VALUES IN PARENTHESES ARE VALUES OBTAINED WHEN FIRST POINT ON LEFT AND POINT IN A ARE OMITTED

Figure 4. Histogram for data obtained while using the hydraulic release. (cubical beam splitter was used for all values)

Several fringe detection systems were used for the data for measuring intervals of 2^{20} fringes before one was obtained that gave satisfactory performance (Section VI). However, the values obtained from all systems, with one exception, were approximately the same. The "g" values from four drops using the Lawrence Radiation Laboratory equipment were low and widely scattered. The four extreme left points of the 2^{20} fringe data in Figure 2 are the values obtained with this equipment. Although these were the only drops recorded, they were not the only ones made, but the "g" values and the scatter are representative of all the data obtained with the 7326 phototube. Because of the uncertainties connected with these data, mean "g" and standard deviation values obtained by omitting these four points are in parentheses.

The only two values of all the data that can be considered as spurious data were both obtained while using the hydraulic release and 2^{19} fringe measuring intervals. These points are noted in Notes A and B of Figure 4. The values of mean "g" and standard deviations obtained by omitting these points are given in parentheses.

Since theoretically the longest path lengths will yield the most accurate results, it is of interest to compare the average values obtained from the gravimeter for these path lengths with the standard value. The comparison will be made with the gravimeter data corrected for table top motion and the standard value corrected by 15 mgal.

If the gravimeter values are corrected for air table movement as previously noted, the mean "g" values would be 979.602 cm/sec^2 for pneumatic release and 2^{20} fringe-measuring intervals. For the hydraulic release and 2^{19} fringe-measuring intervals, the value would be 979.621 cm/sec^2. There is a difference of 19 mgal between the values for the pneumatic and hydraulic releases, it is believed it can be attributed to the higher noise level in the pneumatic release. The standard value, corrected by -15 mgal, would be 979.622 cm/sec^2. Note the apparent improvement that occurred when the pneumatic release system was replaced with the hydraulic release. However, neither the larger scatter associated with the hydraulic release nor the uncertainties associated with the errors stated for the gravimeter data should be forgotten.

The average "g" values in Figures 2 and 3 change with a change in measuring intervals. This shift is a result of the table top motion and also of the reduced time spent by the bird in the shorter measuring intervals. An increase in standard deviation with decreasing measuring intervals also occurs because of the increased uncertainties connected with the detecting and counting equipment caused by the shorter times involved and the smaller number of fringes being counted. It is believed that in the pneumatic release system, the shift is also due to an increased effect of release noise for the shorter measuring intervals. There is not enough data available to determine the size of this effect with the hydraulic release.

The hydraulic release data (Fig. 4) has a larger standard deviation than the pneumatic release data for the same path lengths. It is believed that this scatter in the standard deviation will be reduced after the hydraulic release system has undergone further usage.

Table 2 shows the "g" values obtained when the fringe counting is delayed long enough for the bird to fall through the given distances. This is called a drop delay. The general trend of these values is to decrease with decreasing drop delay to approximately a 20-cm delay, then to increase with decreasing drop delay. This effect is also a result of the table movement.

Table 3 shows the data obtained while using the metal bird. (Actually, only the bottom of the bird is metal, al-mag 35.) Generally, the "g" values run approximately 50 mgal higher than with the all delrin bird. It was noticed that the level of the noise that occurred while the metal bird was suspended on the release arm was also higher than with the delrin bird. The "g" values ran higher, probably because of the increased motion of the table top. This increase in motion resulted from the increased weight of the metal bird. No satisfactory explanation was found for the higher static noise level, but it is believed that the weight of the metal bird was a contributing factor.

Table 4 gives the average "g" value for a set of drops that took place in vacuums of less than 10^{-4} mm Hg. The effect of air resistance would result in low acceleration values. This effect is apparent in Table 4. However, because of uncertainties in the gravimeter, more tests should be conducted to quantitatively determine the effect of air resistance on accuracy.

SECTION II. OPTICAL SYSTEM

The optical system, basically a Michelson interferometer, is comprised of a laser, a beam-processing system, a beam splitter, Brewster windows, a corner cube reflector in the stationary mirror and in the bird, and an aperture. A detailed description of this system may be found in Reference 2.

TABLE 2. VALUES OF "g" OBTAINED WITH DROP DELAYS

MEASURING INTERVALS (FRINGES) \ DROP DELAYS (CM)	50		40		30		20		10		5		2		1	
2^{18}			979.587	979.588	979.584		979.555		979.567	979.571	979.586	979.588	979.603	979.602	979.608	
STANDARD DEVIATION (MILLIGALS)			4.4	3.3	5.4		3.8		4.3	4.4	4.2	2.0	1.2	3.4	3.4	
2^{17}	979.605		979.588	979.588	979.523		979.581		979.576		979.607		979.615		979.624	
STANDARD DEVIATION (MILLIGALS)	16.6		1.11	36.0	35.4		8.4		9.8		5.3		3.2		3.2	
2^{16}			979.633		979.555		979.586		979.610		979.592		979.625		979.625	
STANDARD DEVIATION (MILLIGALS)			38.8		15.4		21.6		10.1		13.2		6.6		5.1	
2^{15}							979.559		979.630		979.599		979.647		979.610	
STANDARD DEVIATION (MILLIGALS)							56.9		56.9		17.4		12.5		7.9	

NOTE: 1. ALL VALUES ARE THE MEAN OF 10 CONSECUTIVE DROPS EXCEPT 2^{15}, 20cm DELAY WHICH IS MEAN FOR 9 DROPS.

2. ALL DROPS WERE PERFORMED WITH THE PNEUMATIC RELEASE AND WHILE USING THE CUBICAL BEAM SPLITTER.

TABLE 3. VALUES OF "g" OBTAINED WITH THE METAL BIRD

Number of Drops	Mean "g" (cm/sec^2)	Standard Deviation (mgal)
9	979.681	5.2
10	979.685	4.0
10	979.682	4.9
10	979.654	5.1
16	979.674	9.1

The mean "g" for all drops was 979.675 cm/sec^2. The following conditions were obtained for all drops:

1. measuring intervals = 2^{16} fringes
2. vacuum = 10^{-5} mm Hg
3. pneumatic release
4. cubical beam splitter.

TABLE 4. VALUES OF "g" OBTAINED IN VACUUMS OF LESS THAN 10^{-4} mm Hg

Number of Drops	Mean "g" (cm/sec^2)	Standard Deviation (mgal)	Pressure (mm Hg)
9	979.525	35.51	1.5×10^{-1}
6	979.547	10.06	$< 2\times10^{-2}$
10	979.551	9.70	$< 10^{-3}$

The following conditions were obtained for all drops:

1. measuring intervals = 2^{20} fringes
2. pneumatic release
3. cubical beam splitter.

Laser

Two lasers have been used in the Mark I gravimeter. Both are uniphase, frequency-stabilized He-Ne lasers. The wavelength (in vacuum) of the light from these lasers is 6329.9147 Å. The wavelengths of these lasers have not been measured, but, from factory guarantees and Reference 3, the wavelength stated above is assumed to be accurate to 1 part in 10^7.

Both lasers and control units are equipped with servo loops that stabilize the laser and reduce changes in the wavelength by controlling the cavity length. The lasers can be operated in either mode, that is, with or without the servo control. Stated stability of these lasers is 75 MHz per day without the servo loop and 1 MHz per day with it.

The lasers were seldom operated in the servo-locked mode, since, on a drop-to-drop basis, the fractional error in "g" due to the drift of the laser is negligible compared with other errors. When the accuracy, on a drop-to-drop basis, reaches 1 part in 10^6, then the servo loop will have to be used.

A Spectra-Physics 119 laser was used until it became inoperable because of diffusion of gas into the plasma tube walls.

The beam divergence of the SP 119 is rated at 10 milliradians, but it was never directly measured since a collimating system has always been used with the laser. The power output of the laser is factory rated at 100 microwatts and has been measured to be this value. However, because of the large losses associated with the optical system, the voltages at which the PM tube could be operated, and the operating requirements of the fringe counter, this power was marginal.

A Perkin-Elmer 5800 laser was obtained to increase the power transmitted through the optical system. The SP 119 was not replaced with the PE 5800 until after it became inoperable. Power output of the PE 5800 is rated as "greater than 250 microwatts" and has been measured at values greater than 300 microwatts. However, power output after the laser temperature has stabilized is 300 microwatts. The divergence of the beam from this laser is rated at 2.5 milliradians. Latest measurements of the divergence show it to be about 1.4 milliradians; however, this laser will also always be used with a collimating system.

Beam-Processing System

Four beam-processing systems have been used with the SP 119 laser and three with the PE 5800. The systems used with the SP 119 had rigid mountings and were attached to the laser; those used with the PE 5800 were not attached to the laser, and mountings were somewhat improvised. Each component had to be aligned manually; consequently, it is felt that the power transmission and stability of alignment of these parts can be improved only when the system used with the PE 5800 is attached rigidly to the laser.

The Spectra Physics 310 polarizer rotator was employed in three of the systems used with the SP 119 laser and all those used with the PE 5800 laser. Its function was to vary the percentages of the incident beam intensity reflected and transmitted by the beam splitter to compensate for the difference in loss that occurs in each arm of the interferometer. The compensation is necessary to obtain the optimum fringe contrast. Contrast is defined as the ratio of the difference between the maximum intensity and the minimum intensity of the fringes to the maximum intensity. The contrast is a maximum when the amplitude of the beam from the bird and the beam from the stationary mirror are equal. This condition is obtained by equalization of the intensities (at the detector) of each beam, which, in turn, is accomplished by varying the direction of polarization of the light incident on the splitter.

Losses in power can be great and depend upon the orientation of the polarizer. However, in practice, the loss in the polarizer was small since the best balance of the beam intensities was obtained close to the orientation of the polarizer at which maximum power transmission occurs. But, even at the point of best balance, the intensities were not quite equal.

A rotatable Brewster window was used in front of and attached to the stationary mirror to equalize the intensity of the beam from the bird and from the stationary mirror. Rotation of this window varied the intensity of the beam from the mirror, allowing the intensities to be equalized at the expense of a small loss of power ($\approx$ 8 percent of incident power). The rotatable Brewster window was used in all the optical systems except for the early ones that will be discussed later.

The beam-processing system used most frequently was the combination of the polarizer and SP 330 collimating lens. This was the only system used with the SP 119 laser that enabled enough power to be transmitted through the rest of the optical system to cause operation of the fringe counter. The power output of this system with the SP 119 was 95 microwatts and was concentrated in a beam 0.625 cm in diameter.

This particular beam-processing system was not used with the PE 5800 laser because the 330 lens, when used alone, or with the polarizer, was unable to collimate the beam from this laser. No explanation has been found for this.

However, the SP 330 lens, when combined with the polarizer and SP 332 spatial filter, did collimate the beam from the PE 5800 laser. This system was the best of the systems used with the PE 5800 laser in terms of beam diameter and power transmitted through the rest of the optical system, although the power loss was large. The beam diameter of this arrangement was 1.25 cm. The power transmitted by this system was sufficient to operate the fringe counter. Since the spatial filter and 330 lens were not designed to be used together, their interface was faulty and unusually large power losses resulted. The power loss cannot be attributed entirely to the spatial filter. It is caused by the beam from the spatial filter not being centered on the entrance aperture of the lens. This, in turn, is caused by the exit aperture of the spatial filter and the entrance aperture of the lens not being in line, or the axis of the lens not being parallel to the direction of the beam from the spatial filter, or both.

Because of power losses, this arrangement could not be used with the SP 119 laser. Approximately two-thirds of the power from the PE laser was lost in this beam-processing system. The same loss was experienced with the SP 119 laser, whose power was marginal. After this loss the remaining power was sufficient to operate the counters.

The power arriving at the detector from the polarizer-spatial filter-beam expander (SP 331) combination was too low for counter operation even with the PE 5800 laser. This was due not so much from loss incurred, as with the previously discussed system, as from a decrease in intensity because of a larger beam diameter. Whereas the diameter of the beam from the other systems is on the order of 1 cm, the diameter of the beam from this system was 4 cm. The power is spread over a larger area; that is, the intensity is lower and, since only that portion of the beam that fills the effective aperture (1.5-cm-diameter) of the corner cubes is used, the power reaching the detector is reduced proportionately. With the PE 5800, under the best conditions, 220 microwatts is the output power of this system. Because of the Gaussian distribution of the intensity, most of the power in the beam is concentrated in an area around the center. The portion of the beam that was actually used was taken from slightly off-center, due to alignment problems, resulting in an even lower intensity at the detector. It is felt that even in the center of the beam emitted from the beam expander, the intensity at the detector would not be satisfactory.

This system, although not adequate for data taken, is highly satisfactory for purposes of alignment of the beam to the bird. The beam diameter of this system is large enough that a movement of the beam splitter and laser does not affect the image reflected from the suspended bird. However, experience has shown that it is not desirable to use one system for alignment and then change to another beam-processing system. In changing systems, the beam direction is changed, making realignment mandatory.

An attempt was made to use the 330 lens alone as a beam-processing system. With the SP 119 laser, losses were lower than with other systems, and beam collimation was good; however, the intensity of the beams in the two arms of the interferometer could not be equalized, even with the use of the Brewster window at the stationary mirror.

It should be noted that the fringe contrast obtained from the beam-processing systems that utilized the spatial filter was much better than that obtained from those systems in which the spatial filter was not used.

Power Loss in System After Beam-Processing

Power loss in the optical system after the beam-processing is large. In the optical system, consisting of the SP 119 laser, polarizer-330 lens combination, the cubical beam splitter, and an 0.030-in.-diameter aperture, the power at the detector was, at most, 1 microwatt. The power was not any greater with the PE 5800 laser because of the problem with lens alignment in the beam-processing system. Table 5 is a summation of the transmission properties of each component of the optical system.

Beam Collimations

Several methods were used to achieve collimation of the laser beam. One method was to direct the beam from the lens system into the receiving end of a telescope focused at infinity and to adjust the lens system until the diameter of the beam emerging from the eyepiece was a minimum. Although

TABLE 5. TRANSMISSIVITY PROPERTIES OF COMPONENTS OF THE OPTICAL SYSTEM

Component	Incident Power Not Absorbed (%)	Incident Power Absorbed (%)
SP 310 Polarizer Rotator	87.50	12.50
SP 330 Collimating Lens	87.99	12.01
SP 331 Beam Expander	92.59	7.41
SP 332 Spatial Filter	86.36	13.64
Cubical Beam Splitter Used in Gravimeter	45.96	54.04
Extra Cubical Beam Splitter	89.31	10.69
Plate Beam Splitter	60.00	40.00
Pellicle	95.83	4.17
Brewster Windows	94.88	5.12
Corner Cubes[a]	90.00	10.00

[a] The corner cubes in the stationary mirror and bird are a matched pair. The transmission was measured only on the corner cube that was in the stationary mirror. It is assumed that the one in the bird has similar properties.

probably the most accurate, this method was the hardest to use because of the lack of proper equipment. It also requires the certain knowledge that the lens system is capable of collimating the beam.

Another method was to place an optically flat piece of glass in the beam, usually between the lens system and the beam splitter, and to adjust the lens system for the maximum width of the fringes in the reflection from the glass. This method is not as certain as the telescope because of the problem of judging the fringe width.

Collimation was also achieved by adjusting the lens system until the diameter of the beam at the lens and the diameter of the beam some distance from the lens (approximately 25 ft) were equal. This method provides a check for the other two methods and is itself a simple, quick method for accomplishing collimation; consequently, it was the preferred method.

Beam Splitters

As can be seen from Table 5, the largest loss in the system occurs in the beam splitter, except for the pellicle. Three types of beam splitters have been used in the gravimeter: cubical splitters, consisting of two glass prisms glued together, a plate beam splitter, simply a glass plate with a partially reflecting surface; a dielectric film, 1 to $1\frac{1}{2}$ microns thick, called a pellicle.

A 2-in. cube, made in the optical shop of the Astrionics Lab, MSFC, was used in the first phases of the project. However, the reflecting qualities of the cube deteriorated rather quickly and voids formed in the glue between the prism. It should be noted that this cube was the first such splitter ever made by the optical shop. This cube has recently been remade, but its optical properties have not yet been determined. Also, during the first phases of the project, the bonding glue in commercially made 25-mm cubical splitters presented some problems. Voids formed in the glue, and the prisms came apart. Two cubical splitters were obtained from the manufacturer and are now over a year old; no indications of deterioration are visible. Only one of these has been used in the gravimeter, and almost all the data presently available were taken while using an optical system that included this splitter.

As can been seen from Table 5, this was the wrong splitter to use as far as light loss and split is concerned. These properties were originally assumed to be the same, and only since the disassembly of the Mark I gravimeter has the difference been discerned.

The beam split afforded by these cubes is supposed to be a fifty-fifty split; that is, as much light is reflected as is transmitted at 6328 Å. Table 6 is a summary of the beam split afforded by the three types used. As can be seen, the split of the cubical beam splitter used in the Mark I gravimeter is, in round numbers, 70-30 (70 percent transmitted, 30 percent reflected). This split is performed on the 45.96 percentage of the light that is not absorbed in the splitter.

TABLE 6. SUMMARY OF REFLECTING AND TRANSMITTING PROPERTIES OF THE THREE TYPES OF SPLITTERS

Type Beam Splitter	Power Reflected After Loss in Splitter (%)	Power Transmitted After Loss in Splitter (%)
Cubical	30.60	69.40
Cubical (Spare)	46.14	53.86
Plate	77.78	22.22
Pellicle	76.53	23.47

Refraction effects in the cubical beam splitters cause deviation of the direction of the light beam. The deviation is not a parallel displacement effect. The direction of the beam out of the cube is at an angle to the incident direction. The faces of the splitter used were not parallel (Fig. 5). Measurements of the angles of the cube and nonparallelism of the faces were made by the optical shop of the Astrionics Laboratory. Deviation in the vertical direction is 1.34×10^{-3} radian (≈ 4.6 min). Deviation in the horizontal plane is 0.516×10^{-3} radian (≈ 1.77 min), but this measurement has much more error associated with it since there was not as much effort made to keep a constant incidence angle in this plane as in the vertical plane.

Initially, the alignment procedures were impaired by this deviation. The Hg pool could not be used as a standard to determine the direction of the local "g" vector (vertical direction), since the direction of the beam out of the cube differed from the incident beam direction. Rather than correct for the effect, another method for alignment was found which is described in Section III.

The plate beam splitter that was used is a partially reflecting front surface mirror but is of poor quality. Although it is free of the effects that cause deviation of incident beams, it does have macroscopic ripple. Also, it is constructed so that the stationary mirror beam passes through the plate three times, whereas the beam reflected to the bird only traverses the plate once. The unequal number of passes through the plate increases the loss in the stationary mirror beam; that is, the intensities of the two beams are made unequal.

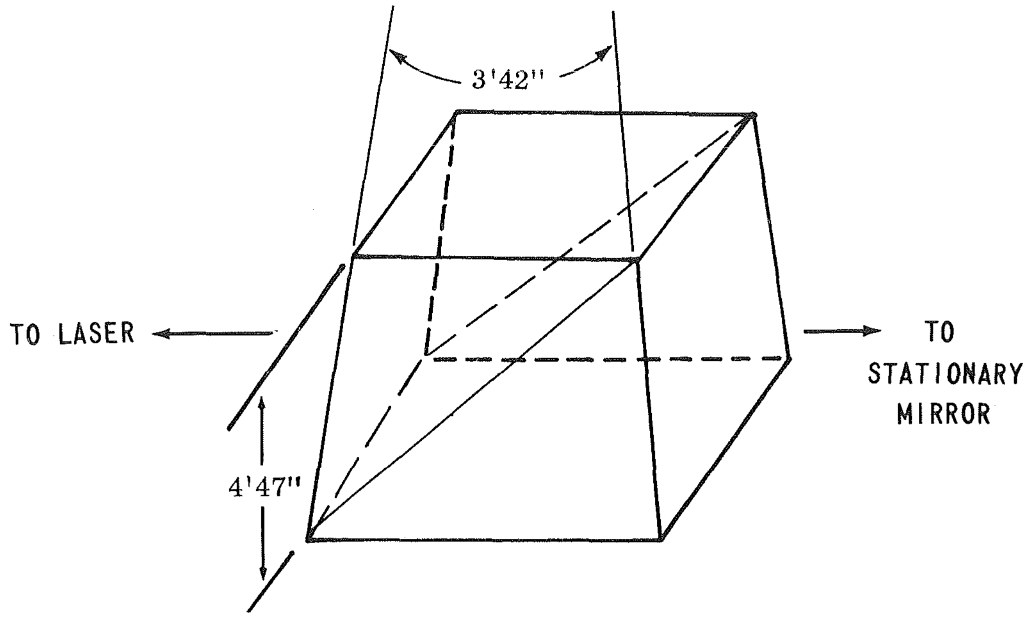


Figure 5. Schematic of the angles between the faces of the cubical beam splitter.

An unusual fringe pattern was obtained with the plate beam splitter (Fig. 6). Circular fringes were obtained in all other systems. This unusual pattern is caused by the macroscopic ripple on the front surface. Because of this pattern, the plate splitter was used very little, although data have been obtained while using it. The plate beam splitter could be used in conjunction with the Hg pool to establish the vertical direction because it is free of the deviation effect.

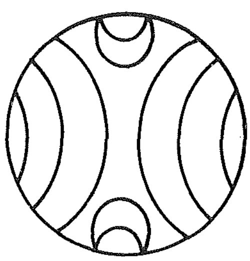


Figure 6. Representation of the fringe pattern obtained with the plate beam splitter.

The pellicle can be used also with the Hg pool since no deviation is introduced into incident beams. Light loss associated with the pellicle is low (Table 5). With regard to deviation and light loss, the pellicle is the ideal beam splitter. Unfortunately, the pellicle is a stretched film and as such acts as a drumhead. As a result, it is fragile and very sensitive to acoustical and mechanical vibration. In the Mark I, the beam splitter and stationary mirror are not in vacuum and are susceptible to acoustical vibrations. The sensitivity of the pellicle to vibrations was clearly shown by the fact that visible stationary fringes were not observed with the pellicle. Its vibratory motion caused the fringes to move back and forth so rapidly that the eye could not detect them. Thus, while alignment could be effected, there was no possibility of taking meaningful data.

Brewster Windows

The Brewster windows have presented no problems. All windows, except the one between the beam splitter and stationary mirror, should be oriented so that maximum light transmission is effected.

Corner Cubes

Only corner cube reflectors have been used in the bird. (All the corner cubes used in the Mark I are of 2-second accuracy; that is, the incident and reflected beam directions are parallel to within 2 arc seconds.) Corner cubes have the property that the direction of the reflected beam is parallel to that of the incident beam. Within limits, this characteristic is independent of rotation of the corner cube. The limits are greatest when the rotation takes place about the optical center of the corner cube. To take full advantage of this independence, the center of gravity of the bird and optical center of the corner cube should coincide. This has not been the case with the birds used so far, but the accuracy of the data has not been sufficient to determine experimentally how much, if any, error is introduced by this effect. The longitudinal separation of the two points was calculated to be 3 mm; the lateral separation is unknown.

A plane front-surface gold mirror was the first reflector to be used in the reference arm of the interferometer, that is, as the stationary mirror. However, small rotational movements of a plane mirror have relatively large effects in an interferometer. Also, the power loss in this plane mirror was not as great as in corner cubes, and, as a result, the intensity of the beam from the bird was lower than the intensity from the plane mirror. This difference in intensity could not be removed from the polarizer rotator in the beam-processing system. For these reasons the plane mirror was replaced with a corner cube and a rotatable Brewster window.

No noticeable improvement in image quality or fringe contrast resulted from using a matched pair of corner cubes in the bird and stationary mirror. However, they were left as a matched pair to avoid any effects that could arise because of different reflection characteristics (polarizations, power loss, etc.).

The orientation of the corner cubes with respect to each other has an effect on fringe quality. The images from both corner cubes of the intersections of the reflecting planes should be coincident. Also, there is a preferred angular orientation of the images from the corner cubes at which the best fringe quality, as judged by the eye, is obtained. This orientation is found by rotating the stationary mirror corner cube, after its image and the image from the bird have been made coincident, in increments of 120 degrees until the best fringe quality is obtained.

The intersections of the reflecting planes in the corner cubes produced diffraction effects in the reflected beam (the corner cube image). The larger the distance from the corner cube to the viewing screen, the more pronounced the effect. For this reason, the image of the bird corner cube is more degraded than that of the stationary mirror when both are viewed at the detector. Simple, practical solutions to this problem are not readily available. However, it is a minor problem and can be tolerated over the distances used in the Mark I.

Aperture

Fringe resolution was obtained by the use of an aperture. Aperture diameters from 0.635 cm (0.25 in.) to 0.0594 cm (0.0234 in.) were used in an attempt to find the optimum size. The best results were obtained with an aperture 0.119 cm (0.0469 in.) in diameter. This, of course, is less than the fringe width. A completely opaque material must be used as the aperture plate or the detector will see the full image of the coincident beams, which will destroy the resolution.

For the optimum performance of the fringe detecting system, the aperture has to be the last element in the optical system; that is, it has to be just over the detector and capable of adjustments in two perpendicular directions, which, in turn, are perpendicular to the beam direction. This allows that portion of the image of the coincident beams to be chosen that will give the best signal from the detector.

Optical Feedback to Laser

The construction of the Michelson interferometer allows the interference pattern to be observed at the light source as well as at the detector. When the laser is operated with the servo control, this effect manifests itself as optical feedback to the laser. It is evident from observations of the behavior of the SP 119 laser that the servo loop is not capable of handling this feedback when the bird is falling. As a result, the wavelength stability of the laser is destroyed. This effect has not been observed in the PE 5800 because the laser has yet to be operated with its servo control. Elimination of the optical feedback was achieved by adding another aperture to the system and also by placing a stop so that only one-half the beam traversed the system (Fig. 7).

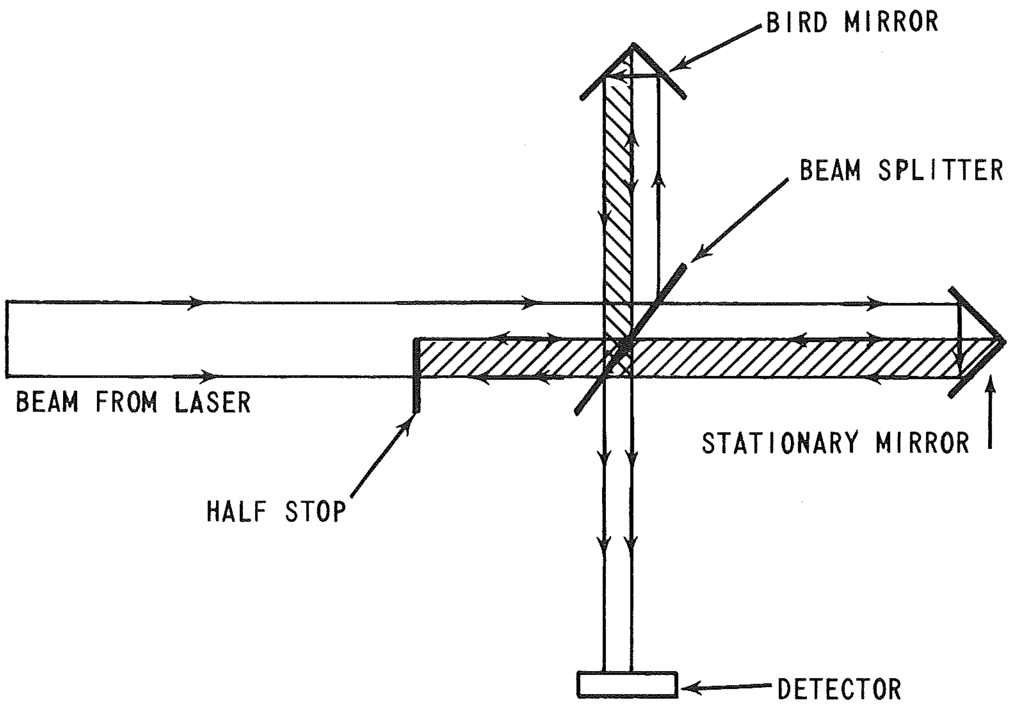


Figure 7. Schematic of the half-stop method used for the elimination of optical feedback.

The aperture was placed between the beam-processing system and the beam splitter. A great deal of power was lost because the aperture diameter was 0.75 mm and the incident beam diameter was 6.25 mm. A maximum aperture diameter of half the diameter of the effective aperture of the corner cubes can be used. The reflected and incident beams in the two arms cannot be coincident (that is, return on themselves) but must be displaced in the corner cubes. (The points at which the beam enters and leaves the corner cube must be different.) When this condition exists, the return beams impinge on the aperture plate and are not returned into the laser.

An alternate method allowed the beams to be coincident. An opaque material placed between the beam-processing system and the beam splitter served as a stop. It was positioned so that only the top half of the beam was incident on the corner cube. Since the corner cubes reverse the images incident on them, the half beam was displaced, and, on its return, was stopped at the aperture plate (Fig. 7). However, like the aperture, this method reduces the power transmitted through the system and causes diffraction effects in the transmitted beam. The half stop, as it was used, cut off half the maximum power available in the beam. An aperture of suitable size can be positioned to transmit the center of the beam and, thus, the maximum power.

The feedback and the power loss due to the aperture and the stop can be eliminated as follows:

1. By using a beam-processing system that produces a beam whose diameter is at most half the diameter of the effective aperture of the corner cubes.

2. By displacing the reflected beam by an amount equal to the diameter of the beam.

Recommendations for Future Model Gravimeters

Because of the large light loss in the Mark I system, it is recommended that the higher power laser be used. However, if losses in the system can be reduced, or a more sensitive detection system devised, the low power laser can be used.

The beam-processing system should include a polarizer rotator, a spatial filter, and a collimating lens. These components should be compatible so that power losses are minimized. The diameter of the beam from this system should be at most half the diameter of the effective aperture of the corner cubes, and all the power available from the laser should be concentrated in this beam. The optical system, with the exception of the laser, beam-processing equipment, and aperture, should be placed in vacuum. For a laboratory model, the pellicle beam splitter (in vacuum) should be used. For portable models, a cubical beam splitter of good optical qualities should be used.

The corner cubes should remain a matched pair to keep the intensities in the two beams as nearly equal as possible. The optical center of the corner cube and center of gravity of the bird should be made to coincide as nearly as possible.

The optimum aperture size for fringe resolution will vary, depending on the size of the fringes. The aperture diameter should be smaller than the width of a fringe. Ideally, the size of the aperture would be adjustable. Feedback to the laser should be eliminated by using a beam of the size recommended above and displacing the beams in the corner cube.

SECTION III. ALIGNMENT

General

Alignment is concerned with orienting the laser, beam splitter, air table, and vacuum chamber so that the direction of the beam reflected to and from the bird is parallel to a local "g" vector (that is, vertical). This is also the direction the center of gravity of the bird will follow if no momentum is transferred to it during release.

Calculations have shown that the fractional error in "g," for an angle of one second between the beam direction and the vertical, is on the order of 10^{-10} [1]. Although much larger angles were encountered in the Mark I, the errors resulting from them were small compared with the total error in "g" values actually obtained. A detailed description of alignment procedures is given in Reference 2.

Vacuum Chamber

For proper alignment, the vacuum chamber has to be positioned so that a plumb line that defines the local vertical (the direction of the "g" vector) suspended at the release system will pass through the center of each of the openings through which the beam from the bird traverses. Once the chamber of the Mark I was plumbed accurately, no replumbing was necessary. It therefore appears that the adjusting legs can be eliminated and the chamber rigidly attached to the air table after initial alignment.

Initial Laser Orientation

The plumb line is also important in the first positioning of the laser. The laser is oriented so that the plumb line is in the center of the laser beam, and the beam falls on the stationary mirror which is positioned in the center of its travel. Although it is not generally desirable to move the laser once it is in position, it is sometimes necessary to achieve the proper alignment. The laser beam must be collimated before the alignment process is started.

Spectrometer Table

At first, orientation of the beam splitter was accomplished by manually moving the beam splitter and by adjusting the spectrometer table upon which it rested. No provisions were made on the original spectrometer table for lateral movement of the cube; tilt and height adjustments were very crude and hard to effect. The beam splitter orientation was considered critical, so a new spectrometer table was designed and built to provide for all the necessary adjustments (height, rotation, tilt in two planes, translation in two perpendicular directions) and allows them to be made with the beam splitter firmly clamped to the spectrometer table. As a result of this change, alignment was much easier to accomplish. The new table is also smaller and will be more compatible with future models. Caution must be exercised while working around this table because the tilt adjustment in the plane defined by the two arms of the interferometer is one of the most critical adjustments on the spectrometer table.

Oscilloscope Traces

Oscilloscope traces of the signal from the detector served as a check on the alignment. A flat trace of the proper length was taken as a standard for proper alignment. Figure 8 is the form of the trace that was sought. At first it was assumed that the frequency response of the equipment used was such that no decrease in signal amplitude would occur. This was not the case, however, and a large amount of time was wasted trying to obtain a better adjustment when the alignment was actually adequate. Despite this, the traces are a necessary and invaluable help.

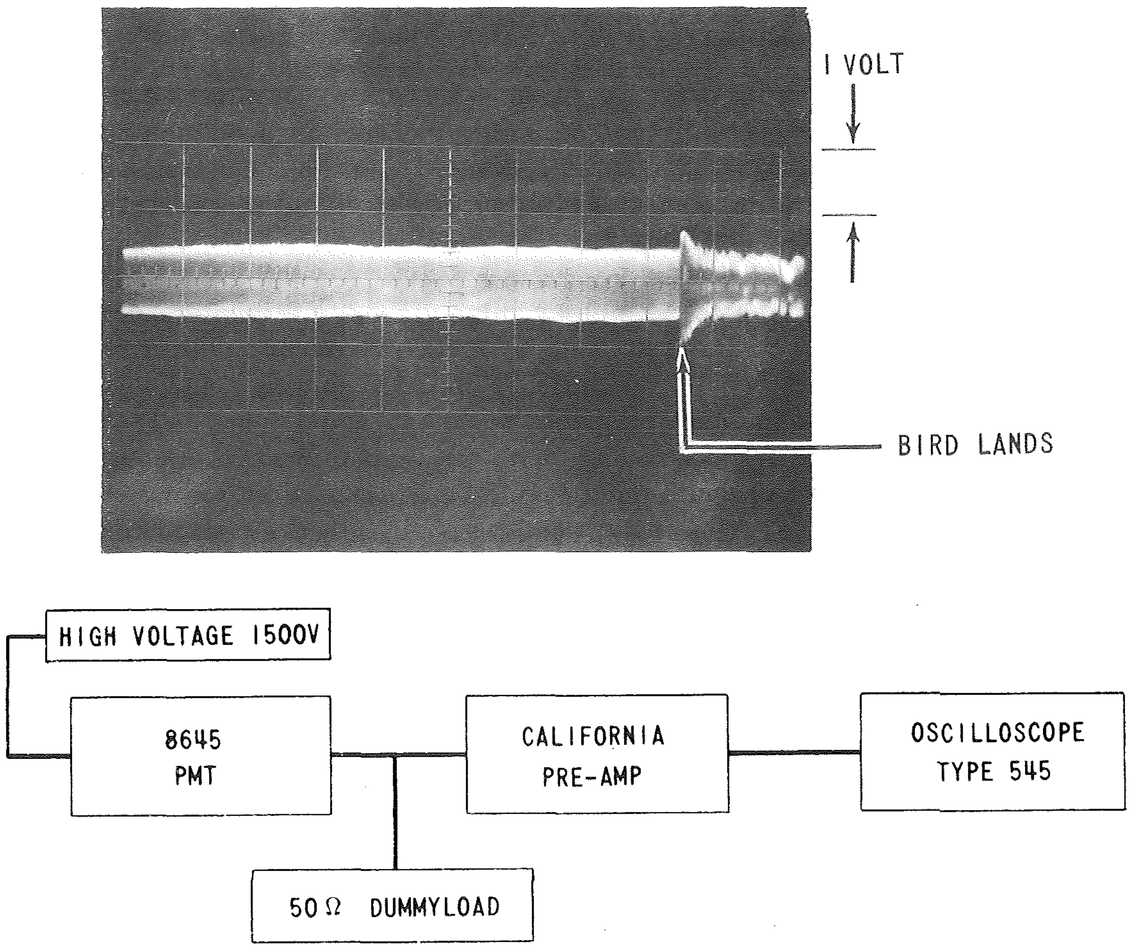


Figure 8. Signal trace obtained from California preamp.

The Determination of Vertical

Two methods have been used for determining when the bird beam direction is vertical. Actual alignment procedures revolved around these methods but were generally the same in each case.

The original method used a Hg pool as a first surface mirror since its reflecting surface is, for large enough pools, perpendicular to the local "g" vector. In this method, the beam from the bird passed through an aperture below the position of the photodetector and was reflected back to the aperture plate by the mercury. If the optical system above the aperture plate does not introduce deviation effects, then when the reflected beam passes back through the aperture, the beam direction is vertical. The aperture was circular and its diameter was made coincident with the diameter of the first diffraction maximum at the Hg pool. Accuracies to within one minute can be achieved with the naked eye by this method. This can be improved by using a telescope to monitor the area around the aperture. No telescope was used with the Mark I because the Hg pool was eliminated shortly after its first use for reasons that will be discussed later.

A thin oil layer of Molvac A, a clear, high viscosity diffusion pump oil, was used to cover the pool and to dampen surface waves [4]. Test results show that the oil is very effective in dampening the surface waves and, also, that the oil does not introduce any noticeable error into the determination of the vertical. One problem directly concerned with the Hg pool was the cleanliness of the mercury surface. Even with the oil on the surface, oxidation occurred and the Hg had to be cleaned frequently. The Hg pool method for alignment was abandoned when it was discovered that the cubical beam splitter changed the direction of an incident beam. A precision beam splitter that was free of the deviation effect was not readily available at the time of this discovery, so another method to determine the vertical was devised.

The second alignment method, called the "no-walk" method, was based on the fact that for the return beam to remain in a fixed position in space, the direction of the incident beam and the path executed by the center of gravity of the bird as it falls must be parallel. Some rotary motion of the bird can be tolerated because corner cubes are being used as reflectors. At first, the movement of the beam from the bird was judged visually with a screen at the photodetector. Visual problems associated with this and problems associated with the screen position made the job of alignment tedious. (The screen was in a position so that it was difficult to view the screen and make adjustments to the spectrometer table simultaneously.) An image converter borrowed from Astrionics Laboratory remedied the situation. With the image converter, the beam image is magnified and displayed on a special oscilloscope screen. Using this arrangement, one could position himself comfortably near all the necessary adjustments.

Measurements made with the pellicle beam splitter and the pneumatic release showed that alignment using the no-walk condition did not necessarily result in a beam direction parallel to the "g" vector. By using the Hg pool to establish the vertical direction, the direction of the beam aligned by the no-walk condition was shown to be inclined at an angle of 7.5 min to the vertical direction in the right-left plane and 1 min in the front-back plane. This was taken as an indication that the release system was imparting momentum to the bird. To reduce the amount of momentum imparted to the bird during release, a new release system was designed and built (Fig. 9).

Alignment of the Hydraulic System

It was quickly discovered that the new release system itself had to be oriented so that its center of gravity and the center of gravity of the bird were along the same vertical line. When oriented in this position, the imparted momentum is a minimum.

Orientation of the release system was accomplished using a 36X telescope placed approximately 15 feet from the release shaft to monitor movement of the shaft resulting from the release. Small weights on the release system were positioned so that no movement of the shaft was visible through the telescope upon release. This indicated that the bird was falling straight off the release shaft and that the horizontal force components were also at a minimum.

During the use of this release system, no exact measurements were made with which to compare the directions of the beam resulting from alignment with the no-walk criteria and with the Hg pool. Quick looks have indicated that the directions are not the same, but it is believed that these quick looks were made at a time when the release shaft was not properly aligned.

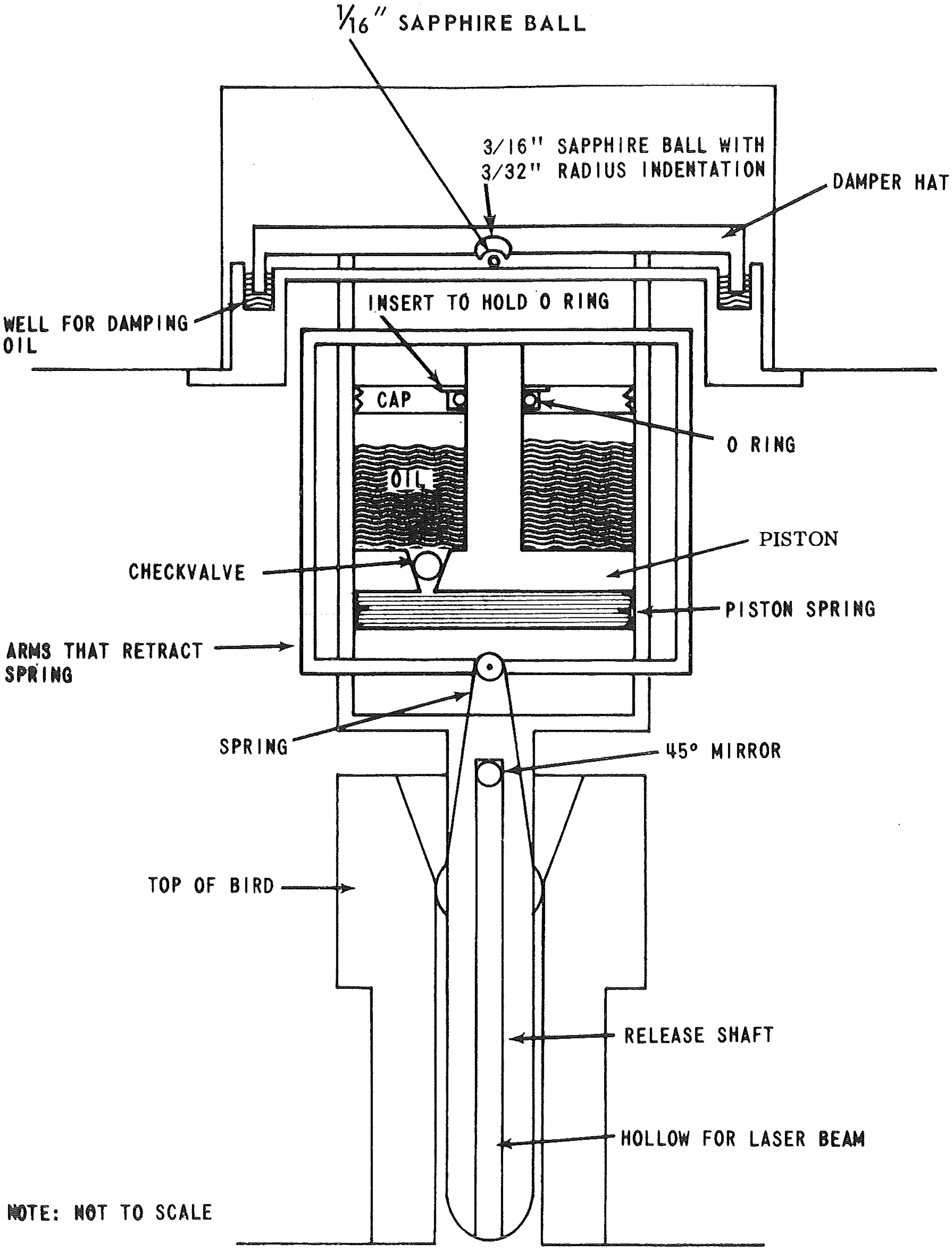


Figure 9. Cutaway view of hydraulic release system.

Other Methods

An alignment scheme using an autocollimating telescope was considered. However, those positions of the telescope that would allow the autocollimation to be performed properly required that the vacuum chamber be modified and also depended upon the position of another mirror. Since this was not desirable at the time, no attempt was made to implement this method.

Recommendations

The new spectrometer table should be used in the Mark II because of the ease with which adjustments can be made and because it is small. However, the tilt adjustment on this table should be made tighter.

Tests should be conducted, or some method devised, to determine if the bird experiences any rotary or lateral motion as it falls, and, if there is such motion, the amount should be determined. Tests also should be conducted using the hydraulic release system to determine if the beam direction as determined by the no-walk condition is vertical.

If alignment using the no-walk criteria does result in a vertical beam, a method of automatically aligning the air table utilizing the photodetector and the movement of the beam from the bird should be devised. A screen should be provided at the detector that will aid in viewing the movement of the bird image. The vacuum chamber should be rigidly attached to the air table with the axis of the chamber perpendicular to the table. A representative photograph of the oscilloscope trace of the signal from the detector should be made for each set of drops.

SECTION IV. VACUUM SYSTEM

General

The vacuum pumping system is comprised of a mechanical pump, oil diffusion pump, three pneumatically operated valves, one manually operated vent valve, a cryo-baffle (cold-trap), and associated plumbing, electrical and electronic equipment. A detailed description may be found in Reference 2.

Vacuum Monitoring Equipment

The pressure in the vacuum chamber is monitored by an ion gage and a thermocouple. A thermocouple also monitors the pressure in the backup system for the oil diffusion pump. The thermocouples used in this system were calibrated against the ion gage. This monitoring system is capable of measuring pressures from 2 torr to 2×10^{-10} torr.

Leak Test Results

Leak tests, conducted with a CEC model 24-120B helium leak detector, borrowed from and operated by Test Lab, MSFC personnel, revealed the presence of small leaks around all the flanges and around the viewing ports of the vacuum chamber. The tests were conducted with a pressure of 10^{-5} torr in the chamber. Absolute leak rates were not measured, but the rate of the leaks detected represented a small load to the pumping system. Since there did not appear to be any disrupting air flow and a sufficient vacuum (10^{-5} to 10^{-6} torr) could be obtained, it was decided that these leaks could be tolerated, at least until problems in other areas were solved.

No leaks were found in any of the flanges downstream from the vacuum chamber or around or in any of the associated valves.

Only two major leaks developed in the vacuum system and both were repaired. One was in the rubber "adapters" in the line from the mechanical pump to the hard plumbing of the valves. All four rubber adaptors leaked. The leaks were caused by disassembling and reassembling of these parts without proper cleaning and greasing. A thorough cleaning of the parts and a new application of vacuum grease reduced these leaks to a tolerable level. The line after this could hold a 10^{-3} torr vacuum for about a 24-hour period.

The other major leak was located around the base of the fitting for the ion gage. Aging and temperature changes caused the glyptal paint used on the threads of the fitting to crack and allowed air to enter the chamber. A new coating of glyptal eliminated the leak.

Performance

The lowest pressure recorded for the system was 2.4×10^{-7} torr and was obtained while using liquid nitrogen (LN_2) in the cryo-baffle. Normally, the system was operated without LN_2, and pressures on the order of 10^{-6} torr were obtained. In a later test, the pressure was not appreciably lowered by the use of LN_2, so, there was no further attempt to use it. It is speculated that in the first test, the system had completely outgassed, whereas, in the second, the outgassing process had not been completed.

Ambient temperature also has an effect on the pressure in the chamber. At temperatures above 75° F, the pressure in the chamber rises. This is caused by expansion of some of the sealing surfaces in a way that breaks the seals and allows air to leak into the chamber.

At the time the Mark I gravimeter was disassembled (October 9, 1968) so that work on the Mark II model could begin, the equilibrium pressure in the chamber was 1×10^{-5} torr. The ion gage was not degassed for these pressure readings because in the replacement of a burnt ion gage Apiezon L vacuum grease was used to help close the seal around the gage. The heat from degassing the ion gage or long periods of operation caused the grease to boil off, resulting in a rise in chamber pressure. No attempt was made to remedy this since the tube was not operated for long periods and the vacuum was sufficient for tests conducted up to the time of disassembly.

Problem Areas of the Vacuum Equipment

The vacuum pumping system has been dependable. Neither the mechanical pump nor the oil diffusion pump has given any trouble. However, the oil (Convoil 20) used in the diffusion pump has exhibited a bubbling effect upon its first exposure to vacuum. The peak of the bubbling activity occurs at a pressure of 500 microns and rapidly decreases as the pressure decreases. This activity is attributed to outgassing of contaminants in the oil. It presents no real problem, except in the damping system for the bird (See Section V), since the effect is negligible after the oil has undergone the first exposure to vacuum.

Vibration problems resulted from not being able to disconnect the mechanical pump, the LN_2 bottle, and the circulating water from the air table. All three represent a connection of the air table to the ground.

The solenoids of the pneumatically operated valves were another source of vibrations. These solenoids originally operated on alternating current and caused vibration problems by chattering. The chattering of the solenoids was eliminated by changing the voltage supplied to them from ac to dc. Three 12-volt car batteries were used to provide the power for the solenoids and were in almost constant use. A charging unit had to be connected to each battery and a constant charge supplied to them to ensure that enough power was available to keep the valves open. A constant check had to be made on the water level in the batteries to prolong their life.

Recommendations

The need for the continuous operation of the mechanical pump should be eliminated. This can be achieved by replacing the oil diffusion pump, which needs a backing pump, with a titanium sublimation pump.

The pneumatically operated valves should be eliminated and replaced with manually operated valves; the requirement for circulating water should be eliminated; and the fitting for the ion gage should be changed to one that is an integral part of the vacuum chamber and does not require the use of glyptal or any other thread sealant.

Celvacene, or a similar high-vacuum grease, should be used where high vacuums and temperatures above 30° C are encountered, as well as on the outside of the chamber and on fittings connected with the mechanical pump.

Apiezon L vacuum grease should be used on the o-ring seals and components that are used in the vacuum chamber. (Note that the maximum temperature at which this grease can be used is 30° C.) The pumping system should be capable of holding the chamber pressure in the low 10^{-7} torr range and should be made more compact to facilitate handling.

SECTION V. RELEASE SYSTEM

Pneumatic System

Two types of release systems have been used in the Mark I gravimeter. One is a pneumatically operated swing-arm system; the other is a self-contained hydraulic system. The pneumatic release has the advantage that the bird can be dropped arbitrarily; this is not possible with the hydraulic system. The hydraulic release is a low noise system. A detailed description of the pneumatic system is given in Reference 2.

Measurements made from high-speed motion picture photographs, which were made by personnel of the Photographic Branch of the Technical Services Office, MSFC, have shown that the swing arm has a peak acceleration of 69.15 g. The first detectable acceleration is 34.83 g. The motion pictures also show that the arm does not interfere in any way with the fall of the bird. The arm is almost completely through its cycle before bird motion can be detected.

In the first model of this release system, there were no provisions for damping the motion of the bird while it was suspended on the arm. An oscillatory motion resulted from the hanging operation, and, since the bird was in a vacuum environment, the motion was very lightly damped, and, if present before release, persists in the bird after release. Because of this behavior, it quickly became apparent that some sort of damping mechanism was required to allay this motion. Figure 10 is a schematic of the pneumatic release after the damping mechanism was added. With this mechanism, the oscillatory motion of the bird that is present while it is supported by the swing arm is damped to a tolerable level after 30 seconds. High-speed photographs made after the damping mechanism was added show no abnormalities in bird motion after release.

False fringe counts were caused by the plunger that operates the release arm slamming into the structure supporting the release system. Vibrations from this were transferred to the air table top and subsequently to the beam splitter and to the reference arm of the interferometer. Figure 11 is a photograph of the signal obtained from the detector when only the release arm is actuated. The amplitude of the signal caused by these "false fringes" was large enough to trigger the fringe counter.

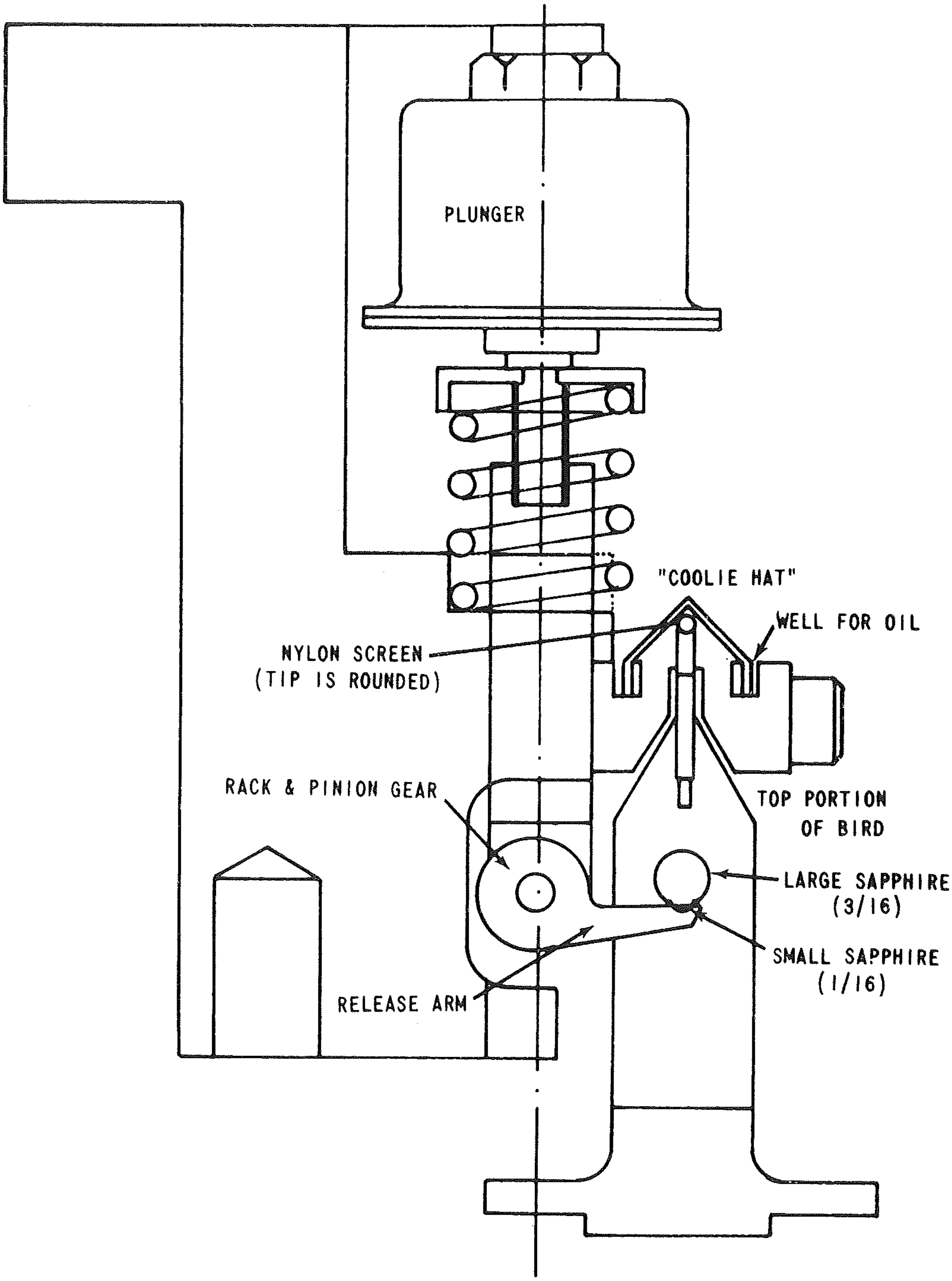


Figure 10. Damping mechanism of the pneumatic release.

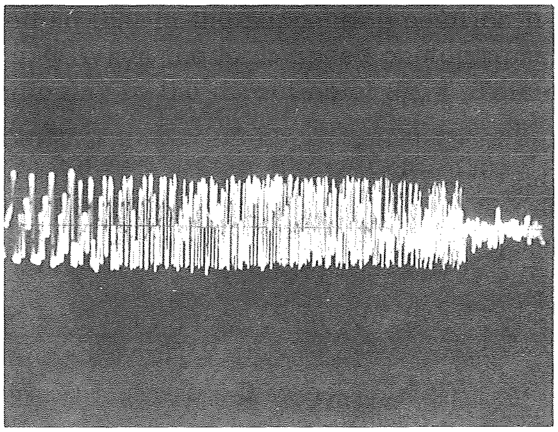


Figure 11. Noise in signal caused by actuating release arm (the bird was not dropped)

A small amount of noise (false fringes) was introduced into the interferometer by the action of the rubber air lines to the release system. These lines relaxed when the release system was actuated (pressure is reduced) and tensed again after the actuation (pressure builds back up). This action caused the lines to pull on the top of the vacuum tank, resulting in false fringes. The rubber lines were replaced with copper lines to eliminate the noise introduced into the gravimeter.

The angle that existed between the verticals, as established by the two alignment methods (no-walk and Hg pool) when using a beam splitter that causes no deviation of the beam, indicated that a large amount of momentum was imparted to the bird on release (assuming the vertical established by the Hg pool to be correct). This is in direct contradiction to the results obtained from the high-speed photographs.

To keep the imparted momentum to a minimum, the swing arm must be perpendicular to the "g" vector when supporting the bird. Sometime after making the high-speed photographs and during the course of making fine adjustments to other parts of the release system, the swing arm was unintentionally moved so that in the supporting position it was not perpendicular to the direction of "g." When the high-speed photographs were made, it was very closely perpendicular to the direction of "g." This difference in supporting positions was the reason for the difference. Because of the noise caused by the plunger of this system, a new release system was designed and built.

Hydraulic System

The second release system is self-contained in that no external connections are required. Since this system has not as yet been described in the literature, a brief description of its operations will be given here. Figure 9 is a cutaway view of the system.

When the bird is suspended, the springs holding the bird are in the position shown (exerting pressure on the bird). The piston is also in the position shown with the oil on the top side of the piston. A spring beneath the piston exerts an upward force on the piston compressing the oil. Leakage of the oil back to the side containing the spring allows the piston to rise slowly, the rate depending upon the leakage. As the piston rises, the arms connecting it to the bird spring slowly pull the spring up, causing it to retract; when the spring is retracted, the bird falls. The release shaft is long enough so that perturbations of the bird, resulting from differences in retraction times of the two sides of the bird spring, are stabilized as the bird falls. This effect is somewhat like the ejection of a bullet from a gun barrel and requires that the shaft be accurately directed. Alignment of the shaft is accomplished by the adjustment of small balance weights attached to the release system and is performed as described in Section III.

The operation of hanging the bird is essentially the reverse of that for releasing it. Passage of the oil from one side to the other during this process is much faster than during the release process because of the check valve.

In the hydraulic system, the bird is rigidly attached to the release system, which is allowed to hang freely from the supporting structure. The reverse was true in the pneumatic release. Support of the release system is accomplished by using the same sapphire balls as were used for support of the bird in the pneumatic system. The damping process is similar to that used in the pneumatic system, except that, in the hydraulic system, the whole release mechanism is subjected to the damping force and the damping hat is rigidly attached to the system. As in the pneumatic system, oscillations are damped to a tolerable level after approximately 30 seconds.

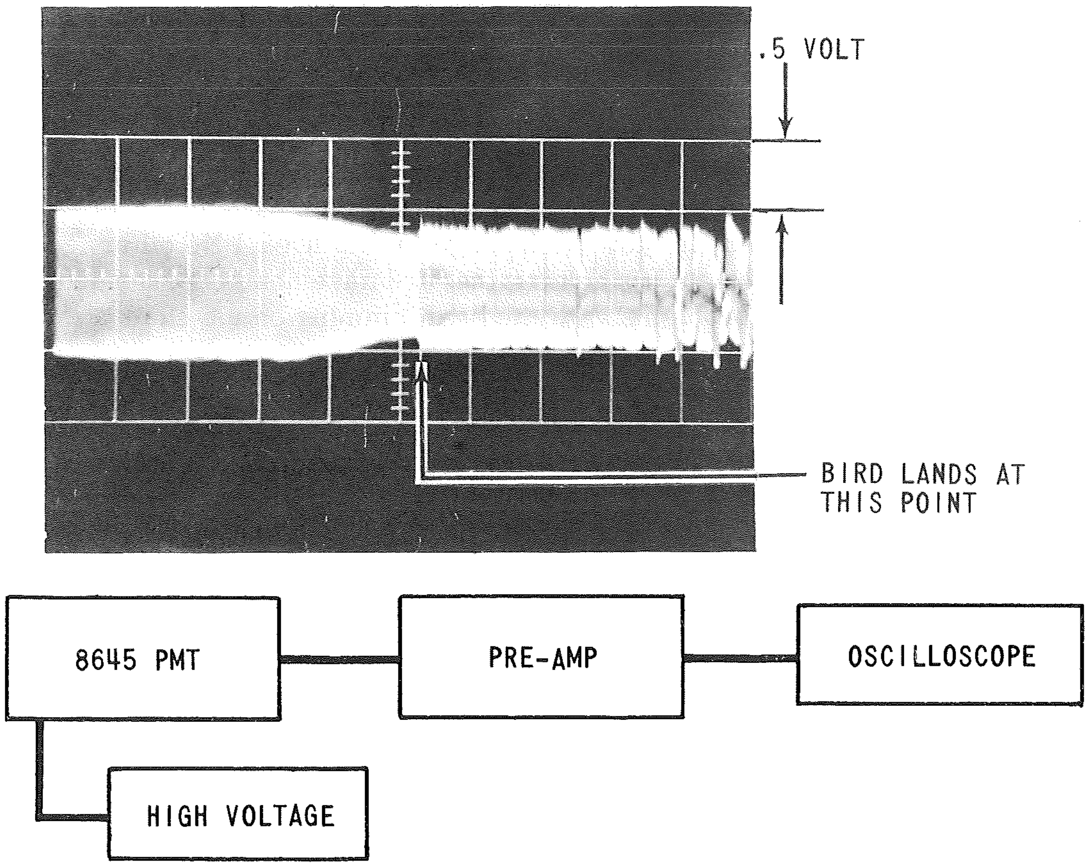
When this system was first installed, some trouble was experienced with its operation in vacuum. At atmospheric pressure the system worked quite well, but, at pressures of 100 microns and less, the oil in the piston cylinder leaked out through the o-rings around the piston rod and out through the side of the cap. Actually, the oil was pushed out while the system was being cocked, that is, as the bird was being hung. As a result, the release springs instantly retracted, dropping the bird. Another complication was the bubbling effect of the oil previously mentioned. Convoil 20, a diffusion pump oil, was used in the cylinder and in the damping mechanism.

The problem of the bubbling oil was solved by using oil that had been exposed to vacuum. The problem of leakage in the piston cylinder was solved by the addition of an insert with which pressure is exerted on the o-ring, creating a better seal around the piston rod and in the cap. The cap was soldered around its periphery to stop the leakage in this area. No other problems concerning the system not holding the bird have been experienced. However, there have been problems with the bird jamming on the shaft and with release times.

In vacuum, the release times varied considerably, partly because of the temperature-dependence of the oil. At lower temperatures (ambient below 70° F), the oil flowed slowly, and thus the time that elapsed from hanging to release (release time) was longer. Release times became shorter as the room warmed up. The release system was modified so that release times could be varied by controlling the distance that the piston is pushed down during the hanging operation. The use of temperature-independent oils will eliminate problems associated with the temperature dependence of the oil viscosity.

Differences in the coefficient of expansion between brass (the release shaft) and delrin plastic (the bird) have created the greatest problem. When the ambient temperature in the laboratory was below 70° F, the fit between the bird and release shaft was so tight because of the differences in the coefficients of expansion that the bird failed to fall, even after the spring was completely retracted. This problem was partially solved by directing a heat lamp at the release system. However, the heat lamp was slow and cumbersome, and, if left on too long it heated the oil in the damping system causing it to expand and leak down onto the release shaft. Oil on the shaft also causes the bird to jam and has to be kept off the optical components; therefore, extreme caution must be exercised in using the heat lamp.

In a laboratory environment where the ambient temperature can be kept above 70° F, this situation can be avoided. However, in a field environment, steps will have to be taken to avoid ambient conditions that aggrevate this problem. Figure 12 is a photograph of a typical oscilloscope signal trace obtained with this release.



NOTE: TRACE SHOWN IS THAT PORTION OF THE SIGNAL THAT OCCURS AFTER THE FIRST TIME INTERVAL COUNTER HAS CEASED OPERATION

Figure 12. Signal trace from LRL preamp after modifications.

Recommendations

The hydraulic release, or a system equivalent to it, should be used in future models since it is a self-contained, extremely low noise system. A temperature-independent oil should be used in the release and damping mechanism. The environment around the release system should be controlled, at least as far as temperature is concerned, that is, if the materials presently used in the components are to be used in future models. A modification to accurately control release times should be included in the release system.

SECTION VI. FRINGE DETECTION

General

Two photomultiplier tubes (PMT) and a photodiode have been tested for use as fringe detectors. One PMT and the photodiode were placed in separate but identical modules that were compatible with the mercury tank [2]. A preamp was included in the module for the photodiode, but the preamp (cable driver) for the PMT's had to be installed outside the module as an extra piece of equipment. In this document, the combination of the detector and preamp is considered to be the fringe-detecting system.

Detectors

A Philco L4503 photodiode was the only solid-state detector tested. In preliminary tests, adequate outputs could not be obtained from the photodiode system. At the time of the test, it was thought that the light intensity was lower than the minimum intensity required by the photodiode for operation. It is now thought that the preamplifier contributed to the situation because of an inadequate design. The photodiode was not used in any other test so the cause of the nonoperation has not been properly resolved. The photodiode detector system is being rebuilt for use in future model gravimeters.

An RCA 8645 PMT was used in the second module. This tube has been used almost exclusively for all attempts at "g" measurements with the Mark I.

It has been used with a number of preamps and has been operated with voltages from 1100 to 1600 volts, depending upon the aperture size and preamp. Most data were obtained with the supply voltage in the 1200- to 1350-volt range. In this range, the current amplification is from 1.2×10^4 to 3.3×10^4. A typical signal level from this PMT is 20 millivolts.

An RCA 7326 photomultiplier tube and associated preamp were borrowed from Lawrence Radiation Laboratories (LRL). A red filter was used to reduce the light intensity entering the 7326 because of its sensitivity. The RCA 8645 did not require a filter. The 7326 tube was operated with 1800 volts. Current amplification at 1800 volts is 1.5×10^5 and at 1200 volts is 7×10^3. This system was supposed to have a flat frequency response from dc to 15 MHz.

Preamps

The operation of the PMT's was satisfactory, but the preamps used with them created several problems.

The oscilloscope traces of the signal from the fringe-detecting system were, in general, obtained using a Techtronix 535 scope (frequency response from dc to 15 MHz). The maximum frequency of the signal from the detecting system is about 12 MHz, so there should be very little visible fading of the signal because of the frequency response of the scope. Also, the signals were generally obtained with a 0.031-in.-diameter aperture placed directly over the PMT.

The first fringe-detecting system with which results were obtained employed the RCA 8645 PMT. The preamp was a wide-band commercial model pulse amplifier made by RHG. While having plenty of gain, the preamp had frequency response problems. Figure 13 is a typical example of the trace first obtained with this system. The response goes almost to zero at about 1.5 MHz and then increases again. Also, clipping of the bottom portion of signal at 5.26 MHz and greater is evident. Although these and other problems were corrected, the performance of this preamp was not at any time satisfactory.

The LRL equipment was used in an attempt to find a better fringe-detecting system. The LRL system was thought probably to be a better system than the 8645-RHG combination.

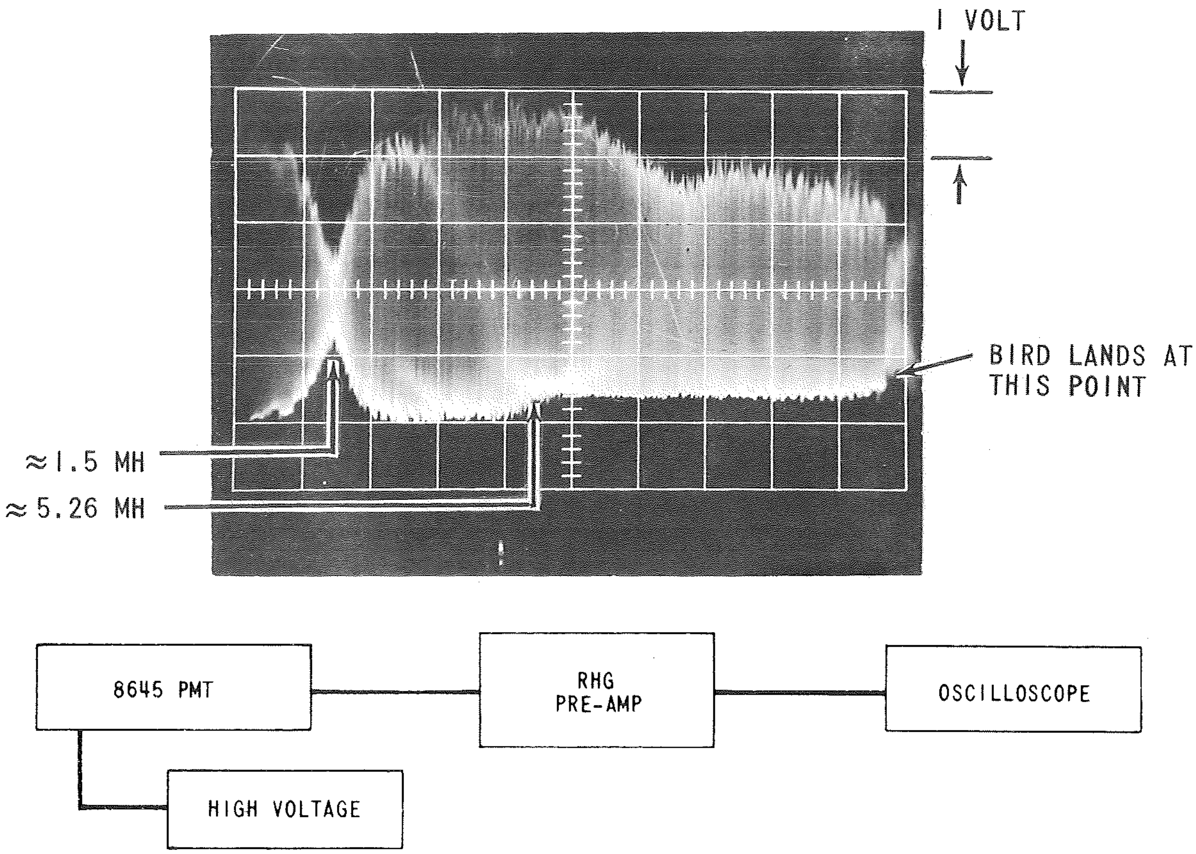


Figure 13. Signal trace from RHG preamp.

Figure 14 is a photograph of a typical trace obtained with this system. Normally, the trace should be smooth and continuous. It is felt that large amounts of spurious noise were present because of the way this system was interfaced with the gravimeter. (The detecting system sat on the floor and was subject to all the floor vibrations.) As a result, the trace is not as it should be. One characteristic of the trace that stands out in the photograph is a dc shift in the signal. This is not present in any of the other photographs.

Since the 8645 PMT did operate satisfactorily, it was decided to continue using it and to find a satisfactory amplifying system. The 7326 PMT and preamp were returned to LRL, and a preamp similar to the one borrowed from LRL was fabricated by Spaco.

Figure 15 is a trace of the signal obtained using the circuit shown in the schematic. The traces are reasonably flat after an initial decrease in amplitude, but beats were produced somewhere in the system. This was not

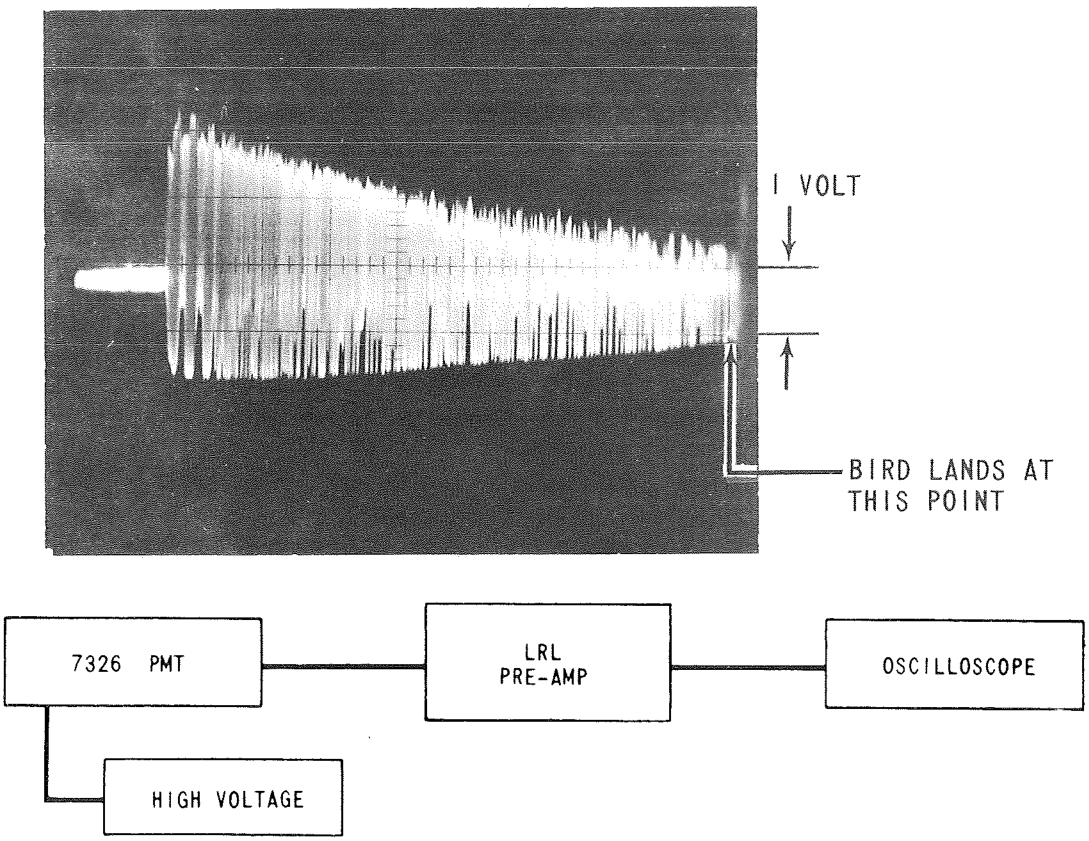


Figure 14. Signal trace from LRL equipment.

adequately checked before the preamp had to be returned. No photographs were made of the signal trace obtained while using the replica preamp. However, during its use with the RHG, it was discovered that self-oscillations were produced in the RHG. It is believed that the beats visible in Figure 15 resulted from these self-oscillations. Thus, the RHG preamp was abandoned because of its problematic history, its size, and its voltage requirements. The RHG operated on 110 VAC, whereas all the other preamps, with one exception, were battery operated (13.5 volts) and all were, at most, half the size of the RHG.

The one exception to the battery operation was a unit built by Photometrics specifically for use on the gravimeter. This unit is called the "California Preamp." It also operated on 110 VAC; it was supposed to have a gain of 200 and operate on a 20-millivolt input; its frequency response was supposed to be flat from dc to 20 MHZ. Since the gain specifications were not met by the unit when received, some modifications were made. The gain was

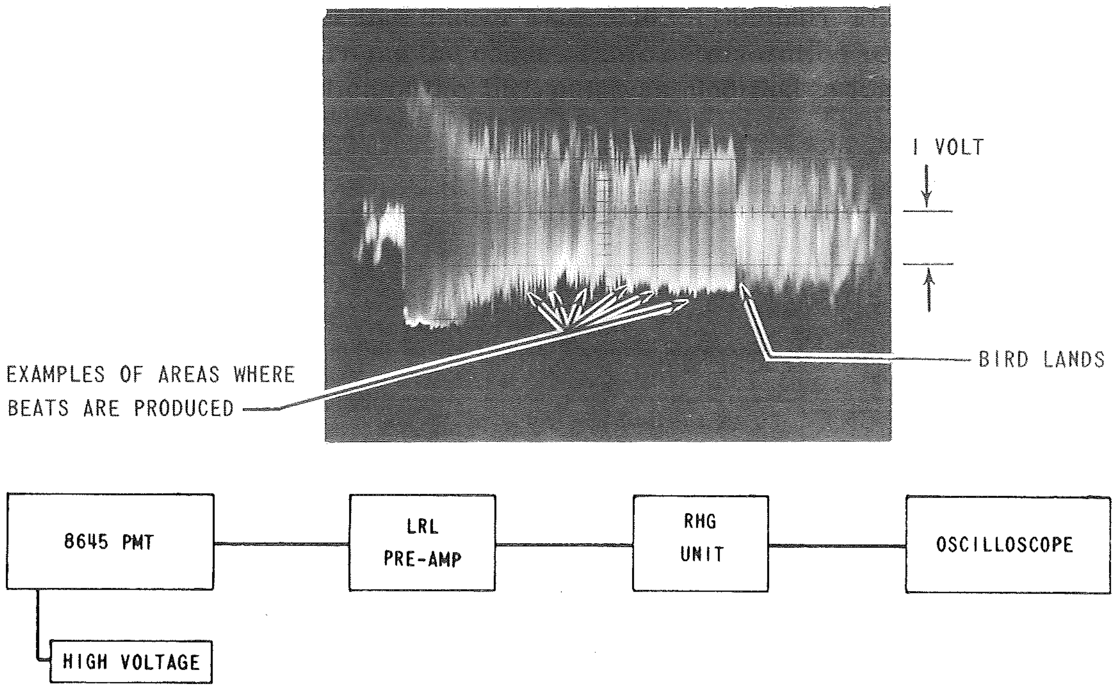


Figure 15. Signal trace obtained from 8645, LRL, and RHG preamp.

increased at the expense of the frequency response for low frequencies. The unit blocked out frequencies below several hundred Hz after the modifications. In the initial use, the output of the LRL preamp was used as the input to this unit. However, it quickly became apparent that the frequency response of this system decreased rapidly with increasing frequency.

The LRL unit was removed from the system, and the PMT output used as the input to the California preamp. Figure 8 is a photograph of the trace obtained from this arrangement. The oscilloscope used in this case is a 545 model. This trace has the ideal form, flat all the way across. However, its amplitude (1.25 volts peak-to-peak) is marginal. Unfortunately, the frequency response and gain of this unit deteriorated after some use. Figure 16 is a trace of the signal straight from the PMT, and Figure 17 is a trace of the signal from the California amplifier, obtained after it had been used for some time, with an input like that of Figure 16. (Compare Figs. 8 and 17.) Tests conducted to determine the cause of this deterioration revealed nothing. For this reason the replica of the LRL unit was modified to improve its gain

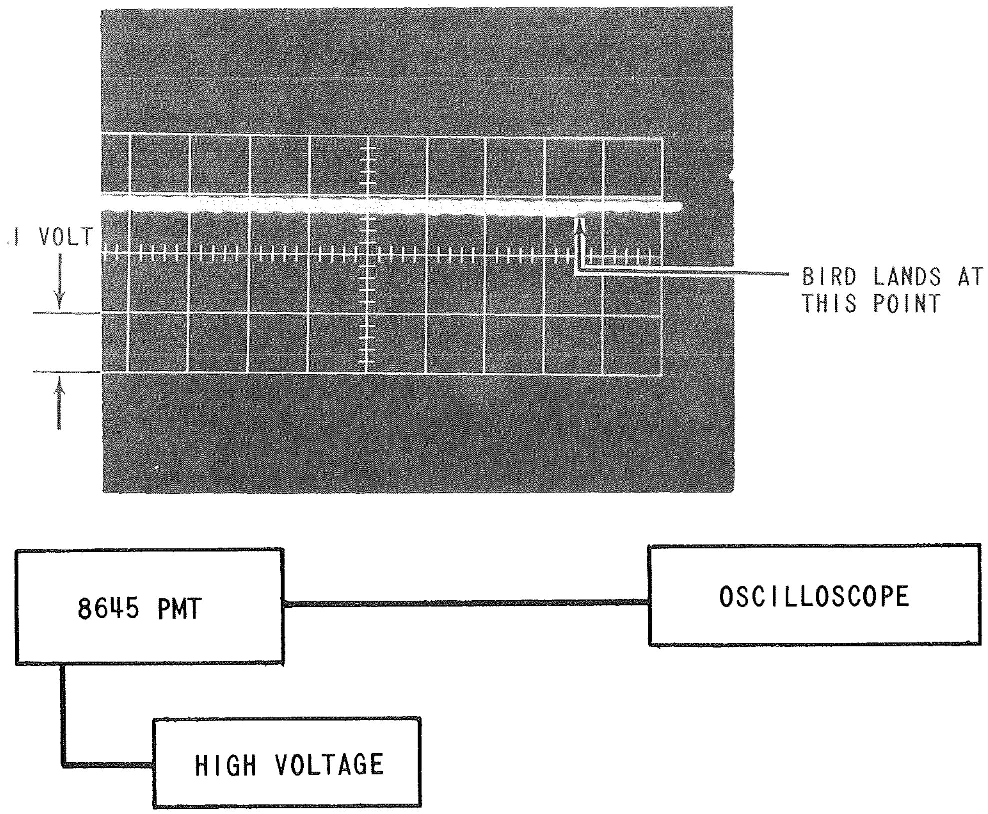


Figure 16. Signal trace obtained from PMT.

and frequency response. Although the gain increase resulting from the modification was sufficient, more was desired. The frequency response of the modified LRL unit has been questioned several times, but in each case frequency response tests have shown its response in the range of 200 Hz to 27 MHz to be flat within ± 3 dB. A 3 dB-limit is evidently too large when working with signals whose amplitudes are marginal. Further modification of the unit was made just before the gravimeter itself was disassembled. These changes increased the frequency response at the higher frequencies (around 10 MHz). Figure 12 is a typical trace obtained after the last change, which, by the way, is the only one of the traces shown in which the hydraulic release system was used. (The pneumatic release was being used during the time Figs. 13 through 17 were made.) Also, the fact that the amplitude does not begin to decrease until the end of the drop indicates that the frequency response of one or some of the components in the test system was not as great as it should have been.

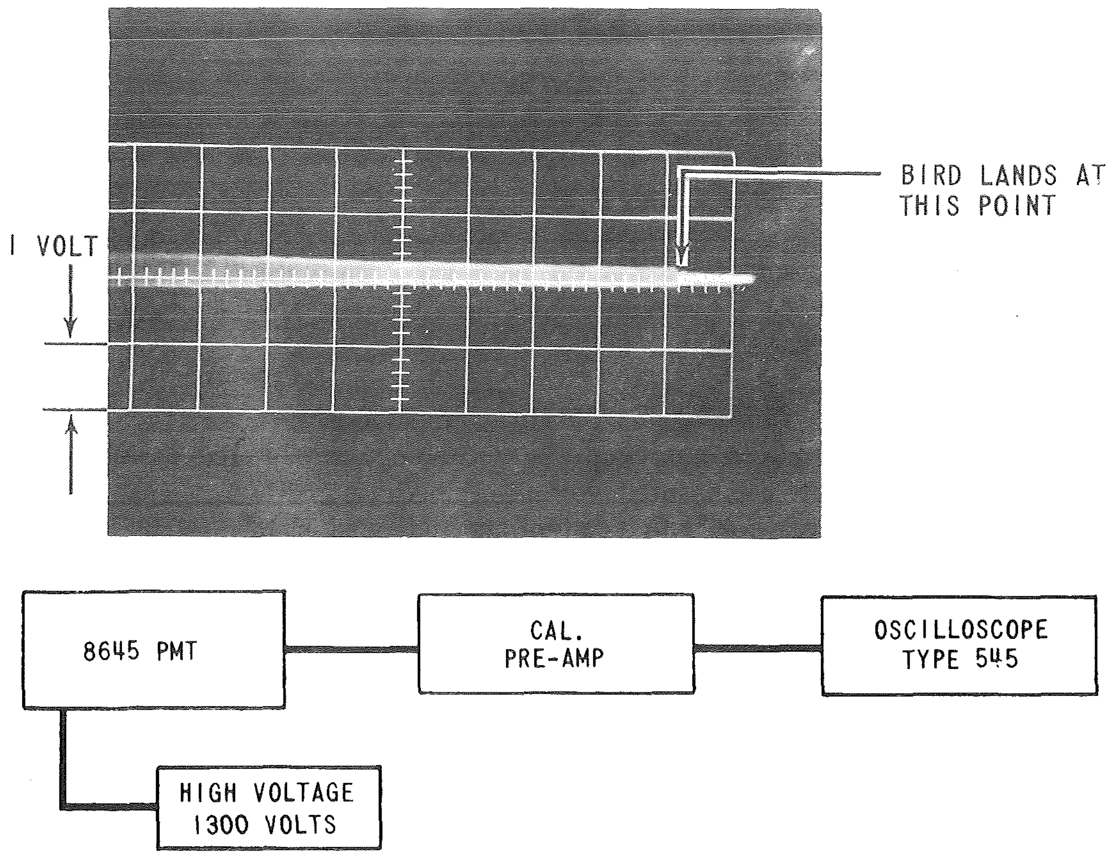


Figure 17. Signal trace obtained from California unit after deterioration.

Recommendations

A solid-state detector should be used because of its ruggedness and because it does not require a high-voltage power supply. A preamp of suitable size and sufficient gain and frequency response should be used. It should also be battery operated (less than 15-volt or, ideally, independent of any power supply). The intensity of the light incident on the detector should be increased.

SECTION VII. VIBRATION ISOLATION

General

Vibration isolation is achieved through use of an "air table" made by Barry Controls. Each leg of the table incorporates an air chamber and piston arrangement that provides support to the table top. The table top is a large steel plate that supports the gravimeter. A detailed description of the support table is given in Reference 2.

The air table arrangement is set up so that the gravimeter is effectively supported by an air spring. Servo valves, whose sensing mechanism is connected to the table top by means of a thumbscrew and lever arrangement, keep the height of the air columns constant and independent of the load supported by the air columns.

Since the table top orientation is dependent upon the height of the air columns with respect to ground, the orientation is also constant. It can be preset by adjustments of the thumbscrews. Experience with the Mark I gravimeter arrangement has shown that in the absence of sudden and extensive changes in the supported load, the table top orientation does not change by more than 30 seconds of arc over a 24-hour period.

Isolation Ability

The seismic vibration isolation provided by the air table is limited to the vertical components. Horizontal components of the vibrations affect the gravimeter only in that the table top is moved laterally. Since this movement is small, there will be little effect upon the fringes produced by the interferometer.

The ability of the table to vibrationally isolate the gravimeter was somewhat impaired by the connections from the LN_2 Dewars when they were used and from the forepump. These connections provided a bridge by which seismic noise could bypass the air columns. However, even with these connections a good deal of isolation was obtained.

A rough measurement of the extent of vibration isolation was made by monitoring the fringe movement that occurred with normal activity around the gravimeter. The vacuum equipment was on, but no drops were made, and there was very little movement in the room. Each time a fringe passed over the aperture used, it was counted as one. The direction of the fringe movement was inconsequential. Counts were made with the table on air (isolated) and with no air support (not isolated). The results are given in Table 7.

TABLE 7. FRINGE MOVEMENT RESULTING FROM TABLE TOP VIBRATION

Time For Counts (minutes)	Not Isolated (counts)	Isolated (counts)
11	39,486	3070
10	34,167	3418

This shows approximately a 10 to 1 reduction in fringe movement, or a 10 to 1 reduction in table top vibration resulting from isolation provided by the air columns assuming a linear relationship between table top vibration and fringe movement.

This measurement was made on March 1, 1968. More recent measurements made after the gravimeter was disassembled also show the isolation ability of the table. The measurements were made with an accelerometer arrangement devised by Bob Jones of Space Sciences Laboratory, MSFC. In these measurements, noise levels should be lower than in previous measurements since the table top had no connections to the ground and the forepump was not operating. Under these conditions, there is a factor of three difference in peak-to-peak acceleration experienced by the accelerometer when sitting on the floor and when on the table supported on air (Figs. 1 and 18), the table being the least noisy. These same measurements show an increase by a factor of at least three in floor activity when an air compressor in a nearby room is running, compared with measurements taken when it is not operating.

These and other seismic measurements made by Bill Greene, et al of Space Sciences Laboratory, MSFC, show that the gravimeter is in a high noise area. They also show that the forepump and the air compressor make large contributions to this noise.

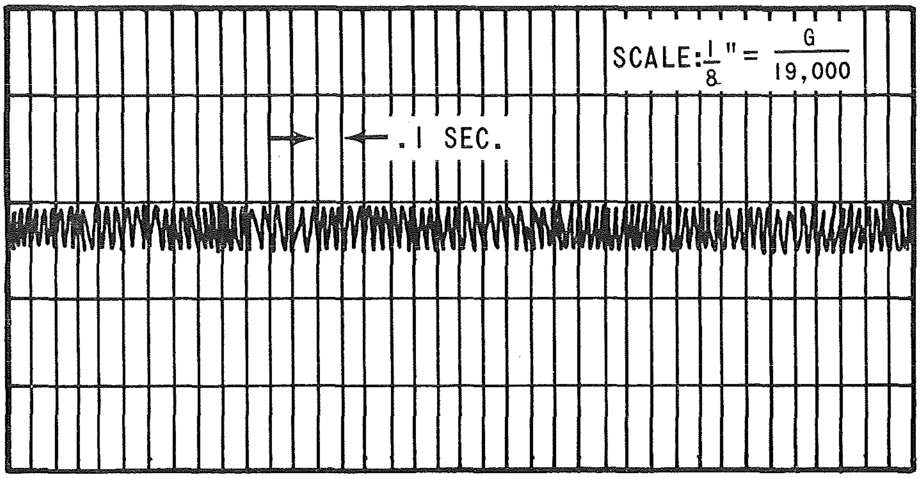


Figure 18. Noise level on the floor. (forepump and air compressor are not in operation)

Table Top Reaction When Bird is Released

The most important measurements made with the accelerometer were those of the acceleration experienced by the table top when the bird is dropped from it. Since the table is effectively supported on a spring, the decrease in the supported mass that occurs when the bird is dropped causes the table to undergo oscillatory motion. The servo control system of the table top dampens this motion.

The measurement of this motion is important since it identifies a large source of error that, until this time, had not been considered significant. The acceleration experienced by the table top, unless it averages out over the time of the measurement, will result in erroneous "g" values, since the acceleration is detected by the interferometer.

The size of the error that would have occurred in the "g" values can only be calculated since the amplitudes of the accelerations are dependent upon the mass on the table top and the measurements were made after the gravimeter was disassembled. But, for the table top alone (≈ 600 lb.), the peak acceleration is 0.000263 g. (Fig. 1). Since both negative and positive accelerations are experienced, the resultant acceleration experienced by the table during the time in which a "g" measurement is made is the resultant error in "g" caused by table motion. These errors are discussed in Section I.

If the response of the air spring is linear, the peak acceleration experienced by the assembled gravimeter ($\approx$ 1400 lb.) was $\approx 11.272 \times 10^{-5}$ g.

Since this source of error had to be eliminated, an experiment was conducted to determine the peak acceleration and the period of oscillation as a function of weight supported and the type of gas used for support. Four gases were used: compressed air, nitrogen, CO_2, and freon 12. The results showed that the initial peak acceleration experienced by the table top decreased with increasing load, but it was independent of the gas used for support, as expected. But, from the test results, the period is approximately independent of the type of gas used for support (see Table 8).

It can be shown that the natural undamped frequency of the nonservo controlled table is proportional to the square root of the ratio of specific heats, γ [5]. The period is therefore proportional to $\frac{1}{\sqrt{\gamma}}$. Table 8 gives the calculated periods for the undamped table motion and the measured periods for each gas used. Note that the measured period for each gas is roughly half the calculated period and that there appears to be a slight decrease in measured periods for a decrease in γ. The amount of decrease in the period is comparable to the inherent error of the method used to determine the period.

It has not been shown, but it is believed that the measured periods are approximately independent of the type of gas used for support because the servo control system handles the table quite well at these frequencies and driving forces. Thus it appears that nothing would be gained by using a gas other than air for support.

Recommendations

The air table should be made as independent of connections to the ground as possible. A low seismic noise environment should be used for laboratory measurements. Some method should be found to eliminate the effects on "g" values of the motion of the air table. Continuous records should be made of the seismic noise occurring at the floor during measurements and also of the movement of the air table.

TABLE 8. CALCULATED AND MEASURED PERIOD OF TABLE TOP

Gas	$\gamma = \frac{C_p}{C_v}$ *	Calculated Period (sec)	Measured Period** (sec)
Air	1.40	0.854	0.413
Nitrogen	1.40	0.854	0.433
Carbon Dioxide	1.29	0.890	0.427
Freon 12	1.13	0.950	0.398

* These values are for 1 atmosphere pressure and 300°K, except for Freon 12, which is for 1 atmosphere and 283°K.

** These are the average values of all measured periods for each gas.

SECTION VIII. DATA COLLECTION

General

The data collection system consists of a fringe counter, a logic circuit, a 1-MHz oscillator, and two time-interval counters. A detailed description of this system is given in Reference 2.

Operation of Fringe Counters

The fringe counter uses a tunnel diode arranged so that its output voltage changes states each time the sinusoidally varying signal voltage from the detector is large enough. A 1-volt RMS signal from the detector is required to operate the tunnel diode. The pulse generated in this manner by this circuit represents one fringe.

This system is among the last being evaluated. The evaluation has not been completed. However, when possible, a commercial zero-crossing discriminator will be used to evaluate the switching capabilities and switching repeatability of the tunnel diode system. It is believed that the system will be found to be quite adequate.

The output of the tunnel diode operates the binary counters located in the logic circuit. The initial fall distance and the fall distances over which measurements of "g" are made are determined in the logic circuit. The initial distance is determined by the manner in which the binary counters are reset prior to a "g" measurement. For the pneumatic release this distance was 2^{14} fringes. This had to be changed with the installation of the hydraulic release to $2^{16} + 2^{17}$ fringes because of the length of the release shaft (~ 2 in.). The prefall is required because the bird has to be free of the shaft before "g" measurements can begin.

The longest fall distance available in the logic circuit is 2^{20} (1,048,576) fringes. Since two consecutive measuring distances are needed, a path length of 2^{19} fringes is the longest possible fall distance with the hydraulic release because of the length of the release system. With the pneumatic release, the full 2^{20} fringe path length could be utilized.

The measuring intervals can be varied from 2^{20} fringes on down in integral powers of two by disconnecting the appropriate binary counters. However, this is a cumbersome job and is hazardous to the adjacent wiring in the logic circuit since the connections are soldered and are often inaccessible.

1-MHz Oscillator

The 1-MHz oscillator is used as a time base for the time interval counters. It is a Hewlett-Packard 101A oscillator whose long-term drift is stated as 5 parts in 10^8 per week, its short term drift as 3 parts in 10^8.

After a considerable number of hours of operating time, the frequency of the oscillator was checked against a rubidium standard and found to be within 1 to 2 cycles of 1-MHz. (These measurements were performed by Astronics Laboratory personnel.) Its drift rate at the time of the frequency check and before adjustments was about 8.3 parts in 10^8 per sec. After adjustments the frequency was 1-MHz. A drift rate of 8.6 parts in 10^{10} per sec was measured after adjustments. This deviates grossly from the stated drift rate. However, since no gross errors in the frequency have been indicated, it is felt that the time over which this measurement was made, 15.14 hours, was not long enough for accurate measurements of long term drift.

Time-Interval Counters

No problems have been associated with the time-interval counters. All indications are that they are working properly and accurately.

The data collection system as a whole has operated satisfactorily and without any major breakdowns.

Recommendations

Tests should be made to determine the switching capabilities and dependability of the tunnel diode fringe-counting system.

A cesium beam standard should be used either as the time base for the time-interval counter or as a standard arranged to provide a continuous check on the frequency of the 1-MHz oscillator. (The cesium beam standard is recommended over a WWV receiver to avoid reception problems and the need of an antenna.) A cesium beam standard has been obtained and is presently being repaired.

A switch arrangement should be installed in the logic circuit to facilitate changes from one path length to another.

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APPROVAL

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TECHNICAL DOCUMENTATION OF THE LASER ABSOLUTE GRAVIMETER

By Paul Craven and O. K. Hudson

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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