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FINAL REPORT

PORTABLE LASER ABSOLUTE GRAVIMETER STUDY

Prepared under Contract No. NAS 8-21157

Chester A. Savelle
Wade Ewing

SPACO INCORPORATED
3022 University Drive
Huntsville, Alabama 35805

for

NASA
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

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Chester Savelle
Wade Ewing

SPACO, INC.
Huntsville, Alabama
July 1969

1.0 INTRODUCTION

The Laser Doppler Gravimeter discussed herein is an instrument for use as a means of measuring gravitational field strengths of the moon and other extraterrestrial bodies. A secondary purpose is for use as a standard for precision measurements of the gravity of the earth. The method of accomplishing this measurement is based on a principle conceived by Dr. O. K. Hudson of the NASA Marshall Space Flight Center. The feasibility of this principle has been proven by development and tests of a Laboratory Model of the Gravimeter.

The next logical step in the exploitation of this gravity measurement principle is the design and development of an Engineering Model of the Gravimeter. The Engineering Model of the Gravimeter should be a transportable unit which can be used to measure the force of gravity at various locations in the United States (or the world if so desired). The requirements for achieving portability of the Engineering Model are discussed in the Technical Discussion of this report. In addition, the work accomplished on the Engineering Model should lead to and establish design criteria for a third model, designated as the Flight Model, which would be suitable for use in exploration of the moon and other extraterrestrial bodies to be explored in the United States space program.

SPACO, INC. has been studying and solving the various problems associated with development of the Laboratory Model for about 2-1/2 years under contract to NASA. During this work, concepts for the Engineering Model have been developed. The discussion of concepts contained herein is based on the concepts derived from the work on the Laboratory Model.

2.0 TECHNICAL DISCUSSION

2.1 General

It should be remembered that the one and only end result required for the Gravimeter is the measurement of a gravitational field with an accuracy having a known degree of certainty. Secondary improvements must be subordinate to this function. One example of a secondary function is in the generation of interference fringes by the system which are necessary to the gravity measurement. Academically and scientifically, it would be satisfying to have "perfect" quality of the fringes which cause 100 percent modulation of the light. However, the attainment of such fringes might adversely affect the achievement of the required end result, because the attainment of "perfect" fringes might very well reduce the light intensity to a level where they cannot be satisfactorily detected. Therefore, a general policy for the work discussed herein is: Except when accuracy is affected, less than perfect results for any function will be accepted so long as the results are sufficiently good as to adequately perform the function required.

The objectives of the Engineering Model, as compared to the Laboratory Model are:

(1) That the Engineering Model be designed for transportability where the Laboratory Model was designed for a permanent setup primarily to prove feasibility of the principle.

(2) That the Engineering Model achieve better accuracy and repeatability than is practically attainable with the Laboratory Model.

(3) That the Engineering Model achieve optimum solutions for problems encountered on the Laboratory Model; and the design work on the Engineering Model develop and establish design criteria for a Lunar Model to be used on the moon's surface.

The discussion that follows describes the various problems associated with the attainment of these objectives and proposed solutions to these problems. It should be noted that the proposed solutions are based on knowledge of methods known to work; and with several exceptions, it will not be necessary to prove feasibility of these methods. By following several principles of design, based on knowledge from work on the Laboratory Model, the problem of developing the Engineering Model is primarily a procedure of straightforward design.

2.1 General (continued)

Mistakes made on the Laboratory Model need not be repeated. There were many excellent methods of operation derived for the Laboratory Model, and these methods should be carried forward to the Engineering Model.

During work on the Laboratory Model, it was found that a drop length of about sixty centimeters was the minimum that could be used to attain an absolute accuracy of one part per 10^8 when measuring earth gravity. Therefore, the physical size of the drop tank must remain as large as that of the Laboratory Model. The design of the mounting can result in a reduction in overall size of the unit to facilitate transporting and setup. Even so, thoughts of reducing the overall unit to "suitcase" size, for an earth gravity unit, are not considered feasible. Such a reduction in size for a Lunar Model needs further study at this time; and this study should be accomplished during work on the Engineering Model. An objective of the follow-on work is to achieve a practical and feasible size and weight reduction.

There are several terms, used in subsequent discussion, which should be explained at this time as follows:

Bird: The falling mass to which is attached the moving reflector of the interferometer system.

Fringe(s): The variations in light intensity at a point in the area of the light beam. The variations are caused by the light wave interference due to the interferometer principle.

2.2 Principle of Operation

The effects of a gravitational field are designated as the acceleration of any mass freely falling in a vacuum environment. The Laser Doppler Gravimeter was conceived to measure the acceleration directly in terms of time and distance in terms of the known stable wavelength the light generated by a Helium-Neon Laser.

The Gravimeter operated as a dynamic Michelson interferometer as illustrated in Figure 1. Mirror B is fixed with its surface plane perpendicular to the light beam. Monochromatic light of very high purity at a precise wavelength is produced by a Helium-Neon Laser. The laser beam is passed through a beam splitter which directs half of the incident light perpendicular to the incoming beam direction.

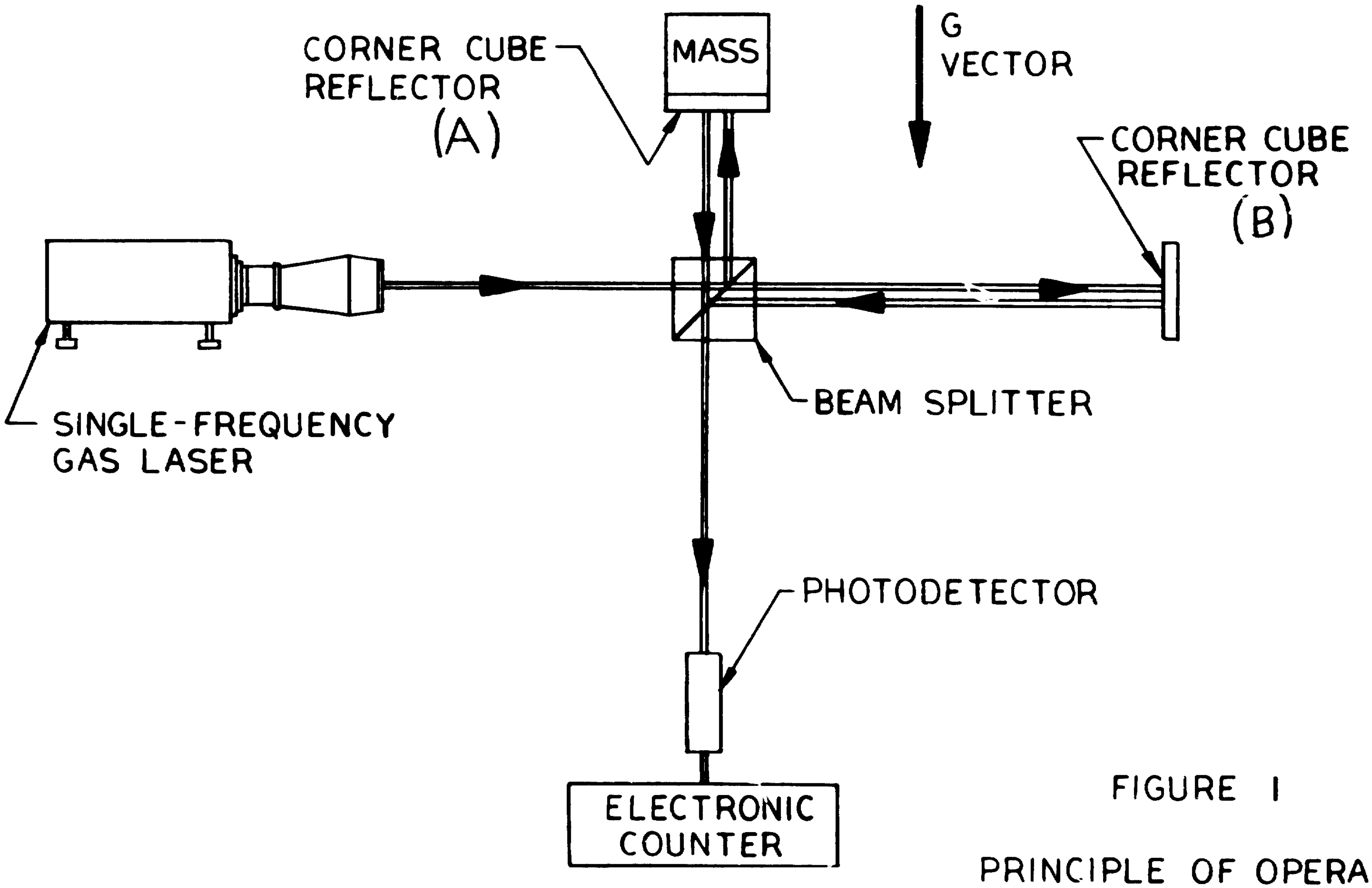


FIGURE 1

PRINCIPLE OF OPERATION
OF LASER GRAVIMETER

2.2 Principle of Operation (continued)

The transmitted half of the beam is reflected back from Mirror B, half of which is reflected down to the photodetector. The reflected half of the original beam is reflected back from Mirror A which is attached to a free falling mass, which is being accelerated by gravity. The reflected beam is partially transmitted back through the beam splitter and onto the photodetector. Interference maxima and minima as a result of the change in relative light path are counted with respect to time, yielding a value of average velocity of the moving mirror. This velocity measurement is made in two adjacent time spans, resulting in a value of acceleration.

The light source is a Helium-Neon continuous wave laser which emits radiation at a wavelength of .63299147 microns. The light from the laser is highly collimated, having a beam divergence of 10 milliradians. This is further reduced by use of a collimating lens mounted on the laser. The laser is capable of frequency stability of ± 1 mc per day by means of a servo control system.

2.3 System Accuracy

It would be desirable for the subject Gravimeter to serve as a reference standard for the measurement of gravity. The ideal standard would make measurements by the use of physical phenomena, the parameters of which are unvarying and precisely known. Unfortunately, the subject Gravimeter can only approach the ideal, and there will always be some degree of uncertainty in the measurement. Only if the degree of uncertainty of the Gravimeter substantially is smaller than other methods of measuring gravity can it be considered a standard.

In examining the degree of uncertainty of the Gravimeter, it is necessary to examine the worst case effects of variations that may occur in the parameters used for measurement. The following considerations are necessary:

(1) Vacuum Environment: It is necessary to evaluate the effects of having a vacuum environment that is less than perfect. At the present time, a thorough analysis of uncertainty caused by this condition is much too complex and beyond the scope of any immediate subsequent investigations.

2.3 System Accuracy (continued)

(2) Distance Measurement: The distance used for the measurement is defined by a number of the half-wavelengths of helium-neon laser light which has a good but less than perfect wavelength stability. The laser, when manufactured and adjusted in a specified manner, has a natural wavelength of 632.99147×10^{-9} meters or a frequency of 473.94×10^{12} Hz. Adjustment of the wavelength can be maintained to within 1×10^{6} Hz per day, which is a frequency or wavelength stability of 2.11×10^{-9} Hz per day. Thus, the wavelength uncertainty of distance due to stability should be no worse than 2.11 parts per 10^{9}. The fringes produced during a bird drop occur at rates that are well within the state-of-the-art for detection and counting, provided the light intensity is of sufficient magnitude to produce an adequate signal-to-noise ratio. It is necessary to count a minimum of two distance intervals. For practical reasons, the two intervals defined by 2^{20} fringes (or roughly 1×10^{6} fringes each) are used. A variation that can occur in the distance measurement is due to variations in the detection of the zero-axis crossing point of the light signal. These variations can amount to several parts per 10^{7} and thus, are greater than variations due to wavelength stability. The light signal-to-noise ratio affects the accuracy with which the zero-axis crossing point can be detected. The effects of the signal-to-noise ratio must be investigated more extensively.

(3) Time Measurement: A resolution of about 3×10^{8} parts can be attained. The absolute accuracy stabilities of 5 parts per 10^{11} for the frequency, upon which time measurement is based, can be attained with commercially available frequency standard instruments.

(4) Other Error Sources: Other possible error sources are as follows:

(a) The reflective coating on the bird corner cube reflector is necessarily a metallic substance. The movement of this metallic coating through any magnetic field will generate forces affecting the drop of the bird. Analysis of these forces would be very complex, but should be briefly examined to the extent necessary to determine if the uncertainty factor, due to minute forces, is likely to be within tolerable limits.

2.3 System Accuracy (continued)

(4) Other Error Sources:

(b) The drop of the bird through electrostatic fields can cause errors. Again, as in (a) above, analysis would be complex and could not be tested inasmuch as the effects of magnetic and electrostatic fields cannot be separated from the effects of gravitational fields.

Obviously, all of the possible error producing phenomena cannot be completely analyzed. The alternative is to analyze and minimize those for which analysis is feasible and/or possible, and to minimize, by design judgment, those that are not subject to analysis.

Tentatively, it appears that the limiting factor for the accuracy of a practical gravimeter system is the distance measurement and a practical drop distance limits the accuracy to several parts per 10^7 with a possible repeatability of several parts per 10^8. Thus, it is doubtful if the subject system, at the present time, could be developed as a reference standard. However, the Gravimeter is capable of making readings at about ten-second intervals, and hundreds of readings can be obtained during periods required for one measurement in some of the other methods of measuring gravity. Thus, minute variations in gravity that would be integrated by slower methods can be detected with the Gravimeter.

2.4 Optical System

The optical system of the Gravimeter is based on the helium-neon laser which has a wavelength stabilized light emission. The wavelength of the laser is nominally 0.63299147
warm-up and stabilization, the eight-hour drift rate does not exceed two parts per 10^9. These conditions have been verified by operation of the Laboratory Model, and are sufficient to obtain the target value for the accuracy of the Engineering Model.

An interferometer requires nearly monochromatic light if the path length difference is more than a few wavelengths of the light used. An ideal monochromatic light source emits light of only one wavelength; any real near-monochromatic source emits over a small band of wavelengths. The bandwidth may be expressed in terms of length, wavelengths, or frequency.

2.4 Optical System (continued)

Coherence length may be defined as the distance over which fringes will be visible in an unequal pathlength interferometer. Fringe visibility decreases from unity at a path difference equal to zero, to zero at path difference equal to the coherence length. If we divide the total change in pathlength (0.6 M) equally so as to achieve a maximum pathlength difference of 0.3 M, and arbitrarily limit ourselves to one-fourth the coherence length, then the required minimum coherence length would be 0.3M/1/4 = 1.2M.

Coherence length may be calculated by squaring the wavelength and dividing the bandwidth (in units of length). Some typical sources and their coherence lengths are:

(1) One line of discharge-tube monochromatic source:

Wavelength: 500×10^{-9} M

Bandwidth: 0.1×10^{-9} M

Coherence length= 2.5×10^{-3} M = 2.5 millimeters

(2) A non-coherent light-emitting solid-state diode:

Wavelength: 670×10^{-9} M

Bandwidth: 40×10^{-9} M

Coherence length = 11.22×10^{-6} M = 0.01122 millimeters

(3) A coherent (laser) light-emitting diode, pulsed operation:

Wavelength: 900×10^{-9} M

Bandwidth: 4×10^{-9} M

Coherence length = 202.5×10^{-6} M = 0.2025 millimeters

2.4 Optical System (continued)

(4) A helium-neon laser:

Wavelength: 628×10^{-9}

Bandwidth: 1.31×10^{-18} M approximately

Coherence length = 305×10^{3} M = 305 kilometers

(Bandwidth was given as 1000 Hz or better; relative bandwidth would be 1000 Hz/frequency = $1000 \times 628 \times 10^{-9}/3 \times 10^{8}$ = 20.93×10^{-15}; bandwidth = 1.31×10^{-18} M)

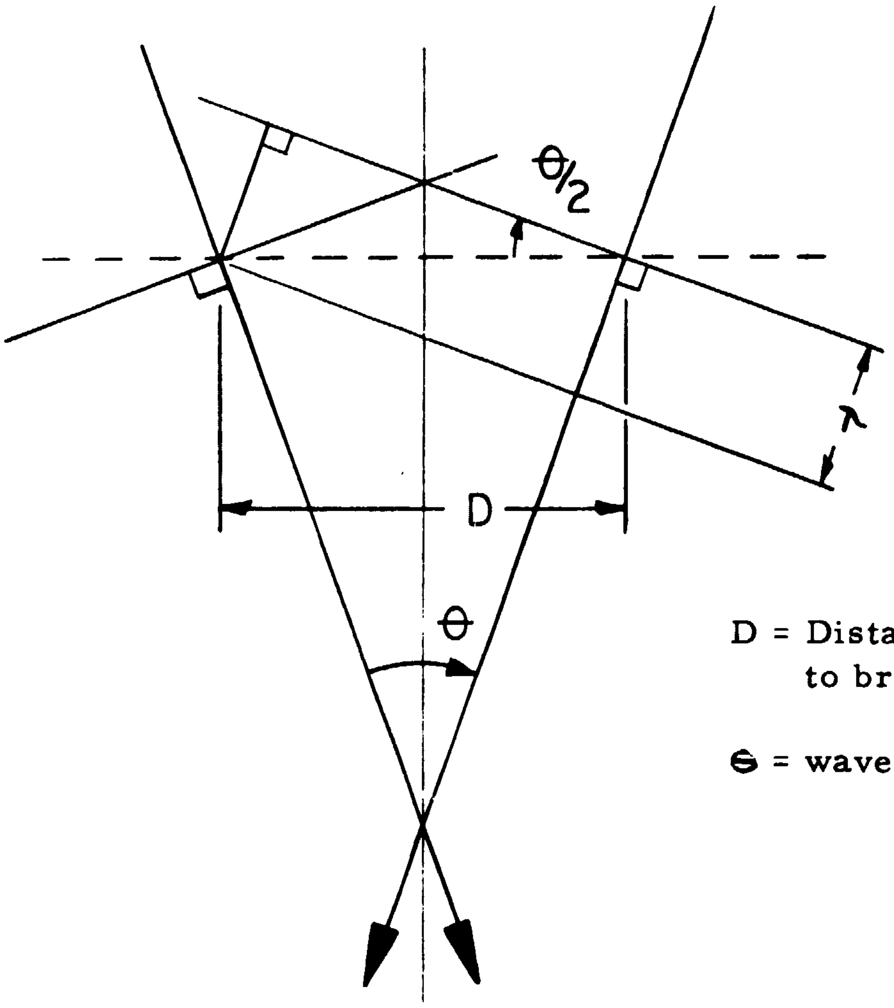
It is apparent, then, that a helium-neon laser far exceeds the coherence length requirements, whereas none of the other sources would be at all suitable.

One of the major problems encountered on the Laboratory Model was the low light level at the fringe sensor. The level of the light striking the .5 millimeter diameter sensor was approximately 10×10^{-9} watts. This level resulted in a marginal signal-to-noise ratio when using a photomultiplier sensor, and an unacceptable ratio when using a solid-state sensor. The laser light beam output of 250 microwatts was filtered, collimated, and expanded to a diameter of about seven millimeters. The resultant light output was about fifty microwatts. After passing through the optical system, the total level of the seven millimeter light beam was about one millimeter thus dictating that the sensor diameter does not exceed .5 millimeter. One of the major objectives of the design of the Engineering Model must be to obtain a light level sufficient for an excellent signal-to-noise ratio at the sensor.

The attainment of an improved light level will require an intensive analysis of the fundamental requirements of the system with optimum trade-offs between ideal and practical solutions of various problems revealed by detailed analysis. The fundamental purpose of the optical system is to produce the fringes necessary for measurement of the acceleration of the "bird". Ideally, the fringe would be a single light spot which goes from full light to full dark during the movement of the "bird" through a one-half wavelength ($\frac{\lambda}{2}$) of the light beam. In this

case the fringe <u>width</u> must be equal to the beam diameter. The width of the fringe is a function of the accuracy of alignment of the two interferring light beams. A computation of this alignment is shown in Figure 2. It can be seen that the required alignment angle (Θ) to obtain desired fringe width (D) may be computed by $\Theta = \frac{3.34' \text{ (minutes of arc)}}{D}$.

For two coherent wavefronts interfering, with axis of propagation differing by small angle θ:



D = Distance from bright to bright

θ = wavelength

$$\sin \frac{\theta}{2} = \frac{\lambda}{D}$$

for D = 1 mM, = 633×10^{-9} M

$$\sin \frac{\theta}{2} = \frac{\theta}{2} = \frac{633 \times 10^{-9}}{1 \times 10^{-3}} = 633 \times 10^{-6} \text{ (radians)}$$

since 1 second of angle = 4.848×10^{-6} radians
(continued)

Figure 2
Fringe Width vs. Alignment Light Beam

Figure 2
Fringe Width vs. Alignment Light Beam
Computation (continued)

$$\theta = 2 \times \frac{633 \times 10^{-6}}{4.848 \times 10^{-6}} = 261.14 = 4' \; 21.1''$$

This would be sufficient for a detector diameter of 0.5 mM = .020''

For a .040'' detector, θ would be half as much.

2.4 Optical System (continued)

Thus, the feasibility of obtaining the ideal fringe becomes one of the practical problems of obtaining and maintaining the necessary limits of alignment angle variations. The discussion later in this report describes the design features and methods that should accomplish the required angle variation limits.

The quality of the fringe may be defined as the ratio change of the light striking the sensor from maximum to minimum. In terms of electrical analogy, it is the percentage of modulation of the light, and this term will be used for simplification of discussion. The light modulation is affected by characteristics of the light beam and the transmission characteristics of the optical system. The pertinent characteristics are coherency, chromaticity, and beam divergence or convergency. The light coherency and chromaticity are fixed and governed by the laser characteristics and, thus, are beyond the scope of the recommended work except when or if lasers with better characteristics become available. In any event, the Laboratory Model has demonstrated that commercially available helium-neon lasers are capable of producing excellent modulation of the fringes. The Gravimeter optical system does affect the convergence and divergence of the light beam, and control of these factors falls within the scope of the recommended work.

During work with solid-state fringe detectors, SPACO obtained results which indicate that 100 percent modulation of the light is not necessary and may even be undesirable. This study is not complete, but a preliminary analysis has been made based on known facts about the light detectors. The light-detecting devices, whether photomultiplier or solid-state have an effective electrical impedance and, thus, are subject to both shot-noise and the self-generated Johnson noise. Apparently, an ambient light level tends to either swamp the noise or reduce the device impedance which reduces the Johnson noise. Since a less than 100 percent modulation would then effectively add to the ambient light intensity, and even though the overall electrical signal-out would be smaller than with 100 percent modulation, the effective signal-to-noise ratio might be improved. This phenomenon was observed with an avalanche photo-diode which has a photon to electron gain similar to the photomultiplier tube. Any noise generated within the diode or by the light source was amplified by the diode, but an increase in ambient light level only, with a resultant small decrease in modulation percentage, gave a better signal-to-noise ratio. This phenomenon should be further studied during the recommended work.

2.4 Optical System (continued)

The light beam divergence or convergence will affect the light modulation after the beam splitter as illustrated in Figure 3. A diverging (or converging) light beam is a cone; and assuming perfect alignment of the two cone axes, after the beam splitter, the light between the beam splitter and sensing plane will be concentric cones. Only the two light beams contained within the inner cone will generate interference fringes, and the area between the inner and outer cones will reduce the modulation caused by the fringes. The effective modulation is a function of angle and the relative distances D_1 and D_2. This effective modulation can easily be calculated. The angle might be reduced by optical devices, but any gains obtained by reducing the divergence angle might be more than offset by light power losses within the angle reducing optical device. Since lasers are available with a divergence angle not exceeding 10 milliradians, a very careful analysis of the Gravimeter optics is required to establish the most desirable trade-off between modulation reduction due to beam divergence and light power loss due to an optical collimator.

Several trade-off decisions must be made during this recommended development, and a typical analysis that provides trade-off evaluation information is included here as illustration. It will be noted that the analysis required, in most cases, does not require much time, but it must be done for proper evaluation.

2.4.1 Beam Divergence vs. Collimation:

Referring to Figure 3, if the laser beam is not collimated, $\theta = .01$ radians and $\frac{\theta}{2} = .005$ radians r_2 is radius of the spot from the further mirror. The optical system can be arranged so that the maximum difference in the distances that will occur during a drop is 30 CM (1/2 drop distance of 60 CM). Thus, the two beams will be diverging at a rate of .005 radians per CM; so at the end of the drop with a distance difference of 30 CM, r_2 will be $30 \tan \theta = 30(.005) = .15$ greater than r_1. The ring of light represented by $r_2 - r_1$ cannot produce fringes so it is essentially a loss in light intensity and modulation. The ratio of light loss to light used is a ratio of the area (A_r) of the ring defined by $r_2 - r_1$ and the area (A_2) of the smaller light spot having a radius r_1. If r_1 is one unit value, then:

$$\frac{A_R}{A_2} = (r_2 + 1)(r_2 - 1) = (1.15 + 1)(1.15 - 1) = .3225$$

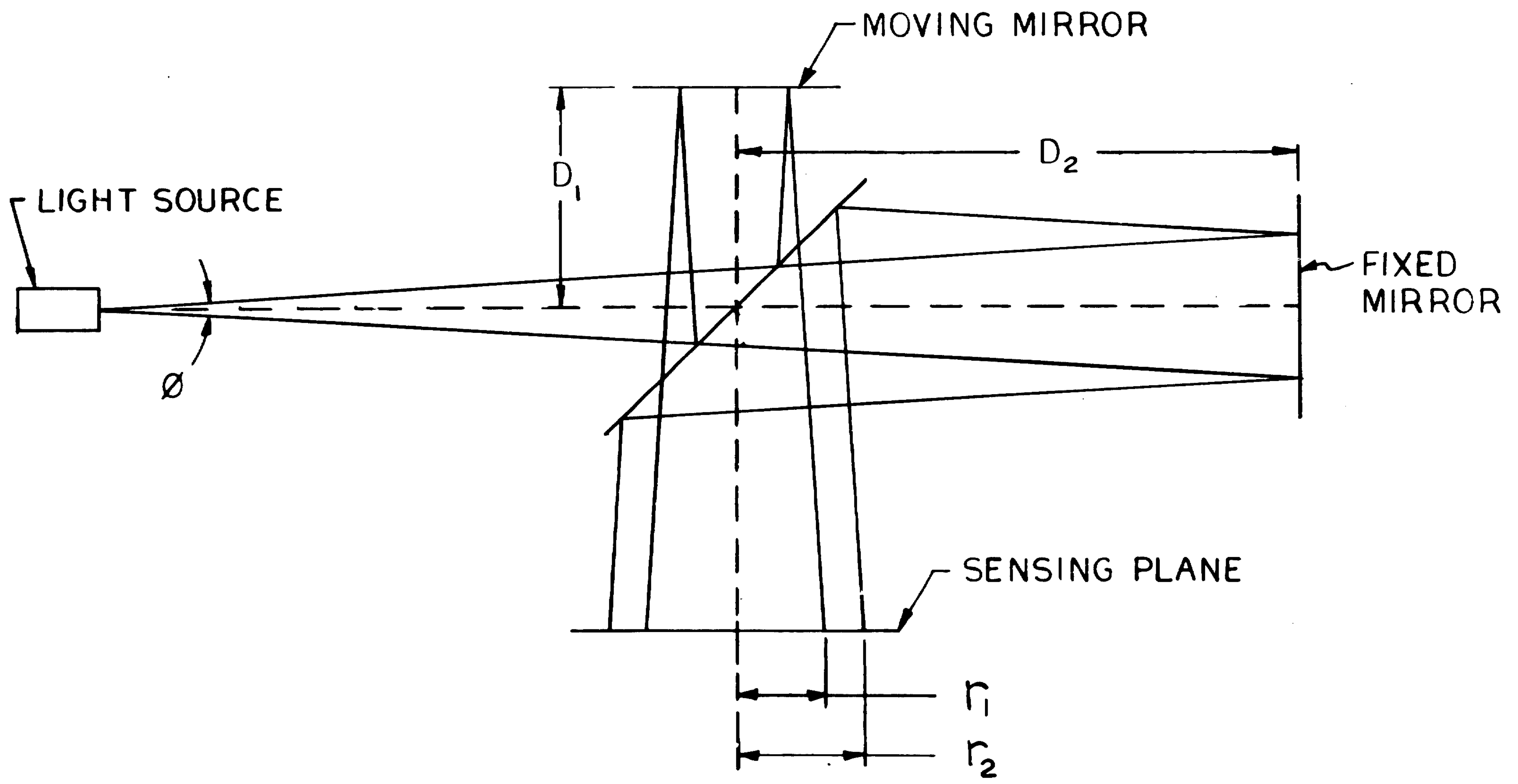


Figure 3
Effect of Diverging (or Converging) Light Beam

2.4.1 Beam Divergence vs. Collimation: (continued)

Thus, 32 percent of the light contained in the beam does not produce fringes; and the quality of the fringes is proportionately reduced. Typical high quality optical collimators are rated to transmit 90 percent of the incident light. It is obvious that the proper choice of the diverging beam versus collimated beam is the selection of the collimated beam.

There are several other optical devices which will alter the characteristics of the light beam including a polarizer and filters. These devices inherently cause a loss in light power; so again, a careful evaluation of the devices must be made to establish the most desirable trade-off between loss of light power and fringe improvement.

Other optical devices that are essential for the Gravimeter optical system are Brewster's angle windows, beam splitters, and reflectors.

The Brewster's angle windows are required for the purpose of transmitting the light beam through the walls of the vacuum chamber enclosing the "bird" drop path. Since these windows cause light power losses, the ideal situation would be to have the entire Gravimeter optical system within the chamber. However, the laser cannot, at the present time, be operated within a vacuum; and because of other problems, several windows will be necessary, but their use should be kept to a minimum. In no case should a Brewster angle window be used simply for balancing the light beams from the fixed and moving reflectors. Instead, the ratio of the light division by the beam splitter should be used for light balancing purposes.

Several beam splitting devices are available, but the one that shows most promise is a Pellicle beam splitter as manufactured by the National Photocolor Corporation for this purpose. Experience with the Laboratory Model has shown that an analysis of trade-offs would most likely favor the Pellicle. The analysis of this device should be made during the follow-on work.

Reflectors, fixed and moving, will most likely be corner cube types as used on the Laboratory Model. Again, the relative merits of other types of reflectors will be considered. Unless definite advantages can be proven analytically, changes will not be made.

In summary, the design of an Engineering Model Optical System will lean rather heavily on the results obtained from the Laboratory Model.

2.4 Optical System (continued)

Any changes that are made will be only for the purpose of obtaining second generation improvements in the optical system. One such improvement that is considered necessary is an increase in light intensity at the fringe detector. It should be noted that the purpose of increasing light intensity is to increase reliability, repeatability of readings, and possibly accuracy. In no case should changes be made that will affect the attainable optimum accuracy of the Gravimeter measurements.

2.5 Problem Areas

During the development of the Laboratory Model, a series of technical problems were encountered and resolved. At the time some of the problems were encountered, the basic concept of the Gravimeter had been developed and hardware fabricated. Major modifications or complete redesign was not feasible, so "patch-up" type solutions were required. As a result, optimum performance of the system was difficult to maintain. In the design of an Engineering Model, the knowledge of these problems is now available and must be considered during the derivation of initial concepts. The resultant concepts should be aimed at achieving a unified solution to these problems. Remembering that the basic function of the Gravimeter is the measurement of gravity, peripheral functions must be subordinate to this basic function. The following paragraphs discuss the problems that were encountered and the action taken.

2.5.1 Light Intensity: The optical system design of the Laboratory Model resulted in a very low light intensity striking the fringe detector. This light intensity was measured and found to be about 1.0×10^{-6} watts in the light spot of about five millimeters in diameter. The fringe width was about one millimeter so the light sensor diameter could not exceed 0.5 millimeter. The light intensity striking the sensor was about 10×10^{-9} watts. No measurement of the signal-to-noise ratio could be made. In an effort to determine where the light loss or attenuation was occurring, several measurements were made using a commercially available light meter calibrated in units of 1×10^{-6} watts. The direct output of the laser beams, without optical devices, was measured and found to be 250×10^{-6} watts. Several optical devices had previously been mounted at the output of the laser for the purpose of improving the "quality" of the fringes. These devices were reinstalled, and the light beam intensity was found to be 50×10^{-6} watts. This is an attenuation of 5:1 for the fringe improving optics. The attenuation of the Gravimeter optics was 50:1; and the total attenuation from laser to sensor location was 250:1.

2.5.1 Light Intensity: (continued)

The low light intensity at the sensor presents the problem of obtaining a signal-to-noise ratio that was considered adequate. A test method for measuring effects of noise, derived by SPACO, (discussed later in this report) indicated that the signal-to-noise ratio is probably more stringent than was originally thought required.

A major objective of the Engineering Model design must be to obtain an increased light intensity at the fringe detector. This should be done by careful analysis of the optical system and use of the best options in trade-off evaluation. Only the absolutely essential loss producing optical devices should be used. In addition, the optical system concept should be aimed at concentrating the available light energy into the smallest feasible beam diameter.

2.5.2 Siesmic Vibrations: Any vibrations that are transmitted from earth into the Gravimeter structure will result in vibrations in the various portions of the structure. These vibrations will not be of equal frequencies or amplitudes, and will cause changes in the relative lengths of optical Path A and Path B (Figure 1). The path length changes will be several light wavelengths in amplitude so interference fringes will be generated solely from the siesmic vibrations. There are several methods of eliminating these spurious fringes One would be to build such a rigid structure that path length changes would not occur. This is not feasible for a portable model. A more feasible method is the isolation of the entire structure from the siesmic vibrations with devices which absorb and attenuate the transmission of siesmic vibrations to the structure. Unfortunately, the use of this method creates an additional problem.

2.5.3 Jump-up: By definition,the vibration damping devices must be non-rigid and have some value of spring constant. A force equal to the weight of the structure is applied by the vibration damper to the structure for support. When the bird is dropped, the removal from the structure of even so small a relative weight as the bird will result in the vibration damping devices applying a force which is greater than that required to support the structure. As a result, an upward movement of the structure supporting the optical system will occur. The amplitude of this motion will be the order of several wavelengths of light.

Referring again to Figure 1, envision that the bird reflects as a fixed point in space. Any motion upward of the optical system will

2.5.3 Jump-up: (continued)

shorten optical Path a, a- fringes will be generated. These fringes are due only to the motion of the optical system and, consequently, are spurious. For want of a better term, the motion of the optical system due to removal of the bird weight is called "Jump-up".

A solution to the problem of Jump-up used on the second version of the Laboratory Model was the physical separation of the structure supporting the bird and the structure supporting the optical system; and this is the only solution that has been devised to date. When the structures are separated, the Jump-up of the bird structure is not transmitted to the optical structure, and no relative motion of bird-to-optics occurs due to Jump-up. The physical separation of the structure requires an additional set of vibration dampers to reduce the effects of siesmic vibrations.

The physical separation of structures results in the addition of three problems which are:

(1) Increased difficulty in attaining and maintaining optical alignment.

(2) Additional optical devices which further attenuate the light intensity. The problem of attaining and maintaining alignment of the optical system is illustrated in Figure 4(a).

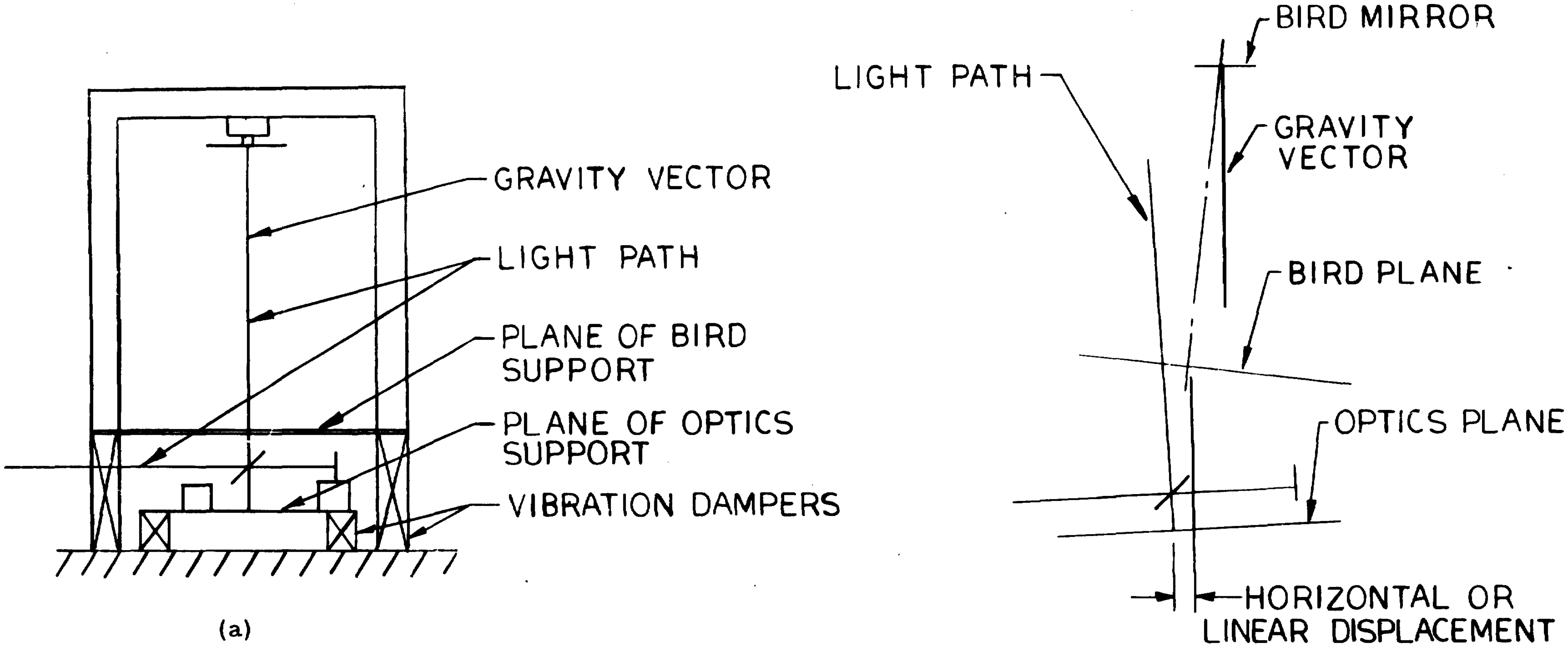
(3) Two supporting planes supported by vibration dampers are shown in a condition of perfect alignment. For this perfect alignment, the following conditions are required:

    (a) The two planes must be parallel;

    (b) The two planes must be perpendicular to the gravity vector;

    (c) A specific point on both planes must be aligned horizontally with the gravity vector.

Figure 4(b) illustrates schematically the effects of any vibrations from the above required conditions. It can be seen that adverse effects from misalignments of the two planes are additive for any variations from perfect alignment that might occur in the two structural positions.



(a)

Separate Structures
Perfect Alignment

(b)

Separate Structures
Angular and Linear Mis-alignment

Figure 4
Effects of Misalignment of Separate Structure for Bird and Optics

2.5.3 Jump-up: (continued)

The problem is aggravated by the fact that the vibration dampers must be non-rigid and are, thus, subject to causing drift in the relative linear positions of the structures.

2.6 Problem Solutions

Spurious fringes due to siesmic vibrations and Jump-up introduce errors into the desired measurement of gravity. These errors must be eliminated or controlled within tolerable limits. Vibration damping and physical separation of structures must be included in the system concept until better concepts are developed.

To derive a concept for solutions of the previously discussed problems, consider the following conditions for a perfect system:

(1) The function of this system is to measure the force of gravity. This force has a direction called gravity vector.

(2) The free-falling mass (bird) used for the measurement will, by natural laws, fall in a direction coinciding with the gravity vector.

(3) The light path used for measuring the bird fall must coincide with the gravity vector.

It will be noted that the gravity vector appears in all of the above considerations so it follows that a good concept for the Gravimeter system would result from utilization of the gravity vector in the solutions to problems. The concepts discussed subsequently are derived from attempts to do just that.

A non-excited pendulum having a frictionless flexible support would eventually come to rest in exact alignment with the local gravity vector. With ideal damping the pendulum would maintain alignment with changes in the gravity vector which occur over a length of time sufficient for the force of gravity to move the pendulum. It follows that the gravity vector would be useful, in the Gravimeter system concept, to assist in alignment of the optics with the gravity vector.

A requirement for using the pendulum is a frictionless, flexible support. Air bearings have a very low friction value, which are constant and irreducible below that constant level. Also, an apparent friction develops from minute forces developed from

2.6 Problem Solutions (continued)

non-uniform gas flow rates in different locations within the bearing. These considerations plus the operational and maintenance problems indicate that other devices should be considered. Some types of "flexures" exhibit, at low deflection angles, an even lower value of friction than air bearings. To reduce the friction forces in flexures becomes then a problem of reducing the deflection angle. Figure 5 illustrates a straightforward concept for accomplishing friction reduction in a flexure. The pendulum (Gravimeter) supporting flexure is supported by a rigid structure whose position, relative to the gravity vector. can be changed with the leveling devices. Strain gages (or other suitable sensors) are mounted on the flexure to sense deflections in the flexure. The output of the strain gages control a servo system which drives the leveling devices until the flexure has the minimum attainable deflection. Thus, the flexure friction is reduced to its minimum possible value, and the pendulum is almost completely free to achieve alignment with the gravity vector.

Damping of the pendulum motion is required to reduce the time required for the system to come to its gravity vector aligned rest position, to prevent external forces from setting the pendulum into motion, and to prevent oscillation conditions from occurring. At the time of this writing, it is proposed to use eddy current principles for this damping. No physical contact between the pendulum and damper is required with eddy current damping. The damping force can be controlled by controlling the strength of an electromagnetic field. Damping force can easily be removed during the bird drop.

Within the limits of a study already performed, it appears that the pendulum concept advantages outweigh the disadvantages; and though many problems have been anticipated and recognized, they do not appear to be unsolvable.

The effects of siesmic vibrations must be minimized, so the use of vibration damping devices is inescapable without better alternative concepts. Referring again to Figure 5, the vibration damping devices can be located as shown. With the concept shown, drift in vibration damping devices would be compensated for by the leveling devices.

Separation of the optical system from the bird supporting structure is an absolute requirement in the system concept. The alignment problems encountered have been previously discussed.

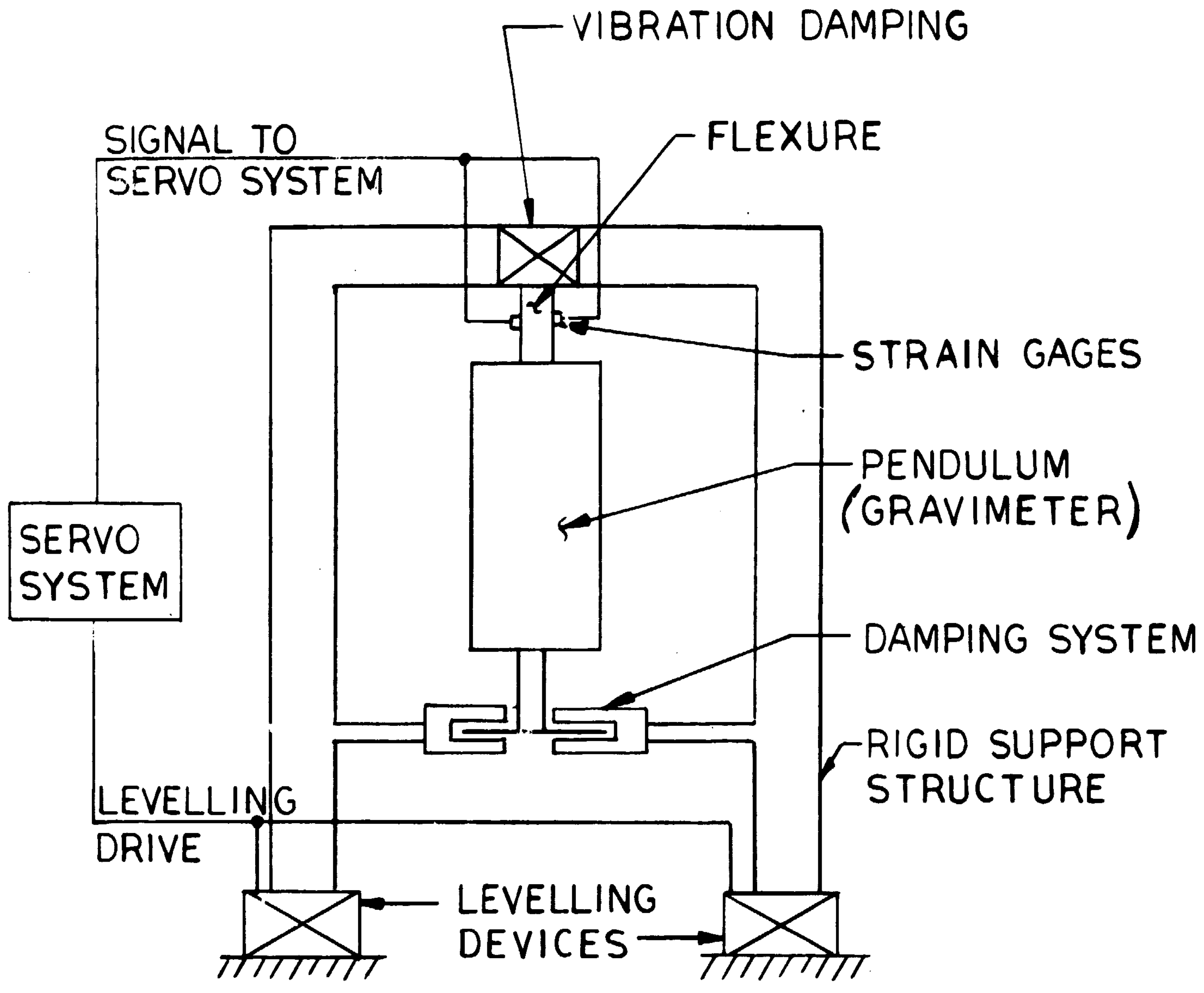


Figure 5
Pendulum and Friction Reduction Concepts

2.6 Problem Solutions (continued)

SPACO has selected an approach which minimizes the alignment problems while retaining the elimination of Jump-up errors. This is illustrated in Figure 6(a). The optical system is the same as previously discussed except the reference light beam is deflected to a direction which is parallel to the light beam along the gravity vector. The reference reflector is located normal to this beam and is mounted on a structure which, because it is separate from the bird support structure, is not subject to movement due to Jump-up of the bird structure. To understand how this concept compensates for Jump-up, envision the bird reflector and the reference reflector both at points fixed in space. When Jump-up occurs, the path length between the beam splitter and the bird reflector is shortened; but at the same time the path length between the beam splitter and the reference reflector is shortened an equal amount. Fringes can only be generated by changes in relative lengths of the paths between the beam splitter to bird and to reference reflectors. Since no change will occur in these relative lengths, no fringes will be generated due to Jump-up. It does not matter if the bird is dropping while the reference reflector is still fixed in space because at any instant of time, the relative positions are fixed with respect to any movement of the beam splitter at the same particular instant of time. The use of the SPACO concept requires that the reference mirror mounting must also be equipped with vibration damping devices and (ideally) be perfectly aligned with the gravity vector.

At the first thought, it would appear that the SPACO concept does not simplify the problem of maintaining alignment between two structures supported by a non-rigid or "soft" device. Detailed analysis will show that the concept does simplify the alignment problem. Referring back to Figure 4, illustrating the previous concept, it will be seen that misalignment of either structure will result in both an angular and a linear displacement of the light beam relative to both the bird starting position and the gravity vector. Angular displacements by each structure are always additive, and such angular displacements have an adverse effect on the width of the fringes obtained. With the SPACO concept, the angular relationship between the beam splitter and the bird starting point is fixed by a rigid structure. Assuming alignment with the gravity vector, as previously discussed, the bird will fall along the light path with no angular displacement between bird fall path and light beam centerline. To eliminate the alignment problems between the beam splitters and the reference reflector, the pendulum concept can again be used. The reference reflector can be suspended by a flexure from the rigid support structure with the flexure isolated from siesmic vibrations with a vibration damping device. It would be possible

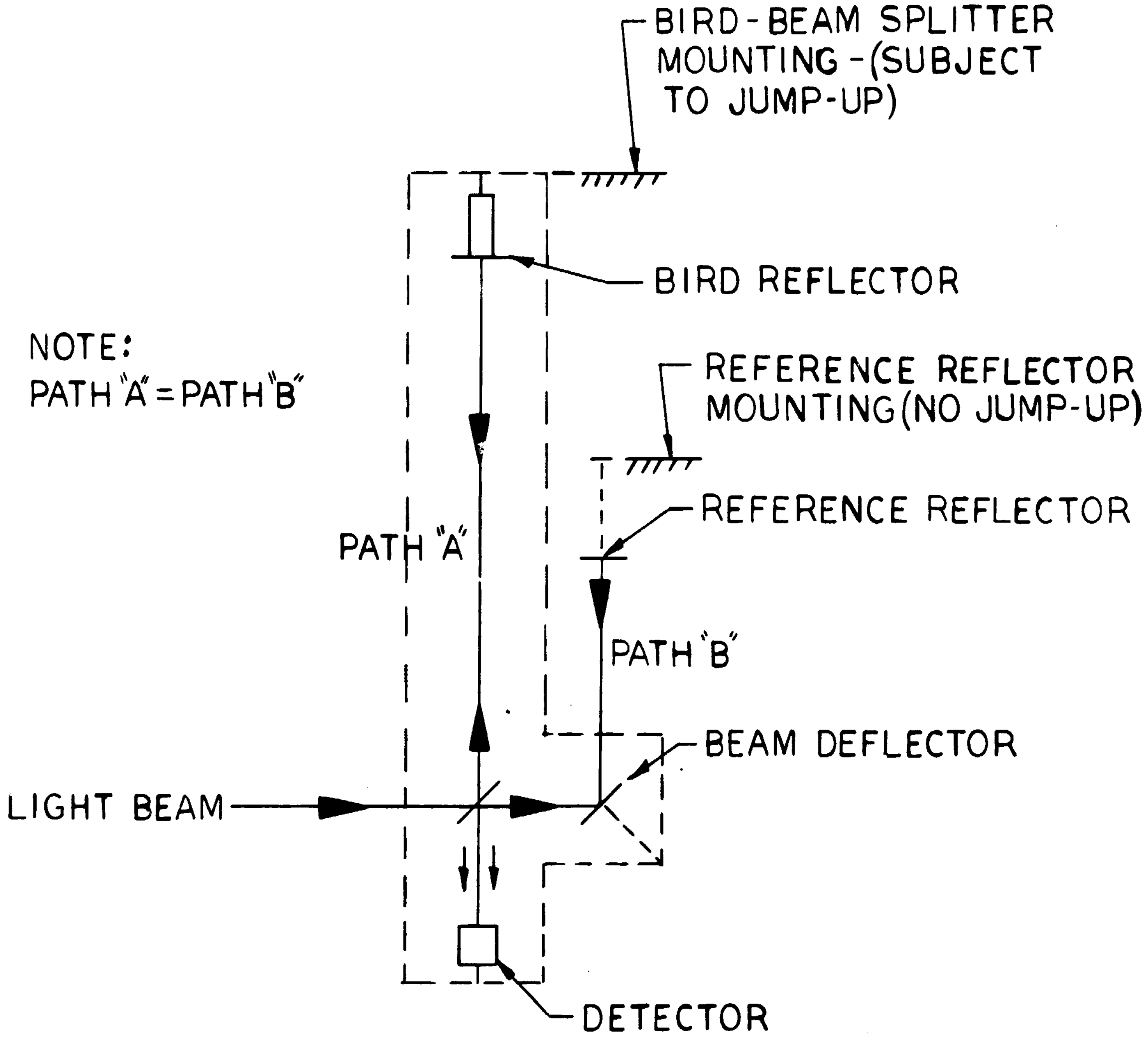


Figure 6
Optical System Concept Compensation
For Jump-up

2.6 Problem Solutions (continued)

to remove any angular deflections from this flexure if found necessary. This can be done by the same methods as previously discussed. The SPACO concept substantially simplifies the alignment problems traceable to the jump-up effect. Linear deflections can occur in a direction normal to the light beam, but it is felt that they can be reduced to a tolerable value. It should also be remembered that angular errors in the system reduce the width of the fringes whereas the linear (direction normal to light beam axis) displacements affect only the quality of the fringes. With a fixed size and location for the fringe detector, the variations in fringe quality are more tolerable than are the variations in fringe width. It is, therefore, logical to favor angular alignment over the reduction or elimination of linear displacement.

It is recommended that these basic principles, which have been described and discussed, be used for the design of the Engineering Model of the Gravimeter; but with the understanding that the principles selected may be changed as desired or required so long as the results obtained are equal to or better than the results that were or would be obtained by the use of the suggested principles.

3.0 MECHANICAL STRUCTURE

3.1 General

The concept for the design of the mechanical structure has been discussed. The structure must perform four functions as follows:

(1) Provide a vacuum environment for the bird drop path.

(2) Provide support for the bird handling mechanism, laser, optical system, and periphery equipment as required.

(3) Achieve and maintain alignment of the bird/optical system with the gravity vector.

(4) Isolate drop mechanism from external physical perturbations.

The following general problems and solutions must be considered in the design of the structure:

(1) Weight must be considered because of the transportability requirement. Extensive use of aluminum should be made because higher stiffness to weight ratios can usually be achieved with aluminum than with other metals. Also, aluminum is very nearly non-magnetic, and extraneous magnetic fields would be minimized. A disadvantage of aluminum is its relatively large coefficient of expansion with temperature.

(2) Considerations of large temperature changes must be made inasmuch as the Engineering Model is likely to be operated in locations of widely varying ambient temperatures. Extensive use of symetrical parts and other standard methods of compensating for expansion and contraction will accomplish adequate compensations for the temperature variations of the structure.

(3) Stiffness of the structure must be adequate to maintain alignment of the optics but must be used with caution in some parts of the structure. Considerations of siesmic vibrations will enter strongly into the design of the stiffness of some parts of the structure.

(4) The non-magnetic characteristics of aluminum are good. The effects of a magnetic field on the bird drop cannot be precisely determined. It is, therefore, considered desirable to reduce possible magnetic fields to a minimum. The use of plastics has been considered, but electrostatic fields are difficult to eliminate. It is felt that electrostatic fields would probably affect the bird drop more seriously than would magnetic fields.

3.2 Vacuum System

The methods used on the Laboratory Model are considered, at this time, to be satisfactory and little, if any, change would be required.

3.3 Support and Alignment Structure

The design of this structure is the area in which most of the changes from the Laboratory Model are required. The primary function is to support the required bird handling mechanisms, the required optical system, and to provide leveling so that the optical system is aligned with the bird drop path. The concepts adopted for this function will be aimed at the achievement of desired objectives and the achievement of solutions to problems found on the Laboratory Model as previously discussed.

The proposed concept for the Gravimeter structure has been tentatively evaluated and is considered to achieve a reasonable trade-off between favorable and unfavorable factors involved in accomplishing the requirements for the Engineering Model.

The concept has the following features:

(1) The supporting structure will be three legged (which gives the advantage of not requiring an absolutely flat surface for solid footing). The three legs relative to four legs crease the problems of leveling, but the increase is not excessive nor does it involve unsolvable problems. One of the legs will be equipped with a manually operated device for varying the length of the leg. The other two legs will be equipped with servo motor driven leveling devices. The tank containing the bird and optical system is to be suspended from a flexure for sensing the position of the three-legged support structure relative to a level position. Sensors will be used to sense strains or deflections in the flexure which suspends the tank. The output of these sensors will be used to control the servo system which levels the support structure. The leveling accuracy will be a function of the relative accuracy and stability of the sensors which sense the flexure deflection, rather than the absolute accuracy and stability of the sensors. This will reduce the sensitivity to varying environmental conditions, and enhance the accuracy of the levelling system. This leveling concept does not involve any state-of-the-art

3.3 Support and Alignment Structure (continued)

(1) concepts. Levelling accuracy that is well within the previously discussed alignment requirements can be attained. The leveling system would be turned off during the bird drop.

There are several methods of suspending the bird-optics tank so that it will effectively be a pendulum which will align the bird drop path with the local gravity vector. Among these are air bearings and flexures. Preliminary study, including consultation with specialists in the flexible device field, indicate that when the angle of deflection is small, the flexure has decided advantages over the air bearing. As the angle of deflection approaches zero, these advantages increase rapidly. The leveling system, previously discussed, will reduce the angle of deflection to a very small value. The extent to which the angle may approach zero is a function of the hysteresis of the servo system which can be a very small value.

(2) One of the problems anticipated in suspending the bird-optics tank is tank oscillation during setup and levelling and possibly during intervals between bird drops. Such oscillation cannot be tolerated during bird drops. A damping system is included beneath the tank to stop any tendencies to oscillate. A candidate for this damping system is electrical eddy current damping. This method has the disadvantage of requiring electrical power but has the important advantage of requiring no mechanical contact between the bottom of the tank and the support structure. In addition, the amount and direction of damping forces applied can be controlled with the electrical current generating the magnetic field. Also, the forces opposing motions of the tank are a function of velocities attained by the tank, i.e., the greater the tank velocity, the greater the force opposing the direction of the velocity. During the drop of the bird, the eddy current magnetic field will be turned off.

3.3 Support and Alignment Structure (continued)

(3) The bird-optics tank must be carefully balanced so that the center of gravity lies on the desired drop path of the bird, which is along the gravity vector. A study must be made of the desired vertical location of the tank center of gravity with the viewpoint of minimizing oscillations and enhancing damping.

(4) The reference reflector is suspended as a pendulum from the support structure and has siesmic isolation from the structure. The design of this reference mirror suspension probably presents the most difficult design problem thus far discussed. The feasibility of attaining the previously discussed objective for this particular reference reflector mounting method affects the design of the entire Gravimeter system. Therefore, the feasibility must be studied and attainment of objectives proven early in a further development program.

3.4 Optical Alignment

Attainment and maintenance of near perfect optical alignment is one of the most important functions of the structure. Ideally, the best method of attaining adequate alignment would be to have all parts affecting alignment machined so precisely that alignment would be attained upon assembly. The required machining and assembly accuracies are not economically feasible. so some adjustments must be included. Inherently, adjustment devices have a tendency to be too flexible, and locking devices upset the adjusted position of the device. For many years, the optical industry has been developing, designing, and building adjustment devices aimed at minimizing the adverse effects of these characteristics. The general concepts for attaining and maintaining optical alignment have the following features:

(1) Machining of the structural components will be to the best accuracies that are economically feasible.

(2) A good, coarse alignment will be achieved during assembly of the structure. When the desired coarse adjustment has been obtained, dowel or taper pins will be used to maintain the obtained alignment after any necessary disassembly of components.

3.4 Optical Alignment (continued)

(3) Fine adjustment ranges will only be of sufficient amplitude to cover the range of errors that could not be eliminated during coarse adjustment.

(4) Resolution of the adjustment will be very high so that many actuations or revolutions of the adjustment control device will be required to achieve small angular or linear displacements. Backlash or hysteresis in the adjustment must be almost completely eliminated. A reasonable amount of friction is desirable in the adjustment mechanism, so backlash or hysteresis can be reduced to an almost insignificant amount.

(5) Locking devices will generally be applied to drive portions of the adjustment mechanism. Techniques are readily available for avoiding adjustment upset by the locking device.

(6) Adjustment mechanism will be of rugged construction to avoid alignment variations during both operation and transportation of the Gravimeter.

There are many factors that must be considered during the design of the subject instrument, and not all of them can be anticipated or discussed here; but a thorough study of factors and trade-offs required will result in minimizing problems and tend to make problem solutions easier. Alternate solutions are considered during initial design and provisions made, where possible, for taking these alternate routes even after fabrication. A minimum of waste and rework will be achieved, if the alternate method is chosen in this manner.

4.0 BIRD DROP MECHANISM

4.1 General

It is desirable, from the system operation viewpoint that the bird be held in its start-of-drop position until a drop is desired, at which time the drop mechanism would be actuated by an electronic signal to release the bird. An absolute requirement for the mechanism is that no acceleration and/or gyration forces be applied to the bird during release. All concepts for such positive actuation mechanisms that have been studied to date will impart accelerations and vibration forces to the bird structure during actuation. Spurious fringes are produced similar to those from siesmic vibrations.

SPACO developed a bird release mechanism which is self-actuated and does not impart any forces to the bird upon release or cause vibrations in the structure. But a signal cannot be obtained from the device as to the exact time which bird release occurs. Unless a better concept is derived, this latter mechanism should be used; and a light beam interruption be used for obtaining a start-drop signal.

4.2 Bird Catcher and Return Mechanism

The bird catcher and return mechanism need not be changed, in principle, from that used in the Laboratory Model. Sufficient redesign should be accomplished so as to make the mass of moving parts symetrical about the vertical axis of the unit. This will avoid asymetrical forces, during accelerations of the return mechanism, that might tend to upset the level position of the bird-drop tank.

The design of an improved bird drop and catcher mechanism, using established principles, should present no very difficult problems.

4.3 Portability

To meet the requirements of transportability, the tank and other free-swinging mechanisms must be securely clamped to restrain motion during transportation. These clamping devices must be easily installed and removed to facilitate setup at desired locations.

4.4 Electronic System

The electronic system of the Gravimeter consists of the fringe detector (probe), counting, time base generator, and readout. The electronic system used in the Laboratory Model, with exception of the probe, has been completely satisfactory. The basic principles should be carried forward to the Engineering Model.

4.4.1 Probe: The probe in the Laboratory Model uses a photomultiplier tube as a sensor for the fringes. The photomultiplier tube has the advantage, over other light sensors, of having available a very high photon/electron gain within the tube itself. However, a careful study must be made of the signal to noise ratio at the probe output. SPACO developed a method for making such a study with exact indications of errors due to noise. This method is illustrated in Figure 7.

Referring to Figure 7, a light signal is generated by a light-emitting diode (LED) which is energized by a variable voltage DC supply to set the ambient light-emitting level of the LED. The AC voltage from the signal generator modulates or varies the intensity of the light from the LED. Thus, the light signal generated by the Gravimeter fringe is simulated with the LED. The average light level and the modulation can be varied to duplicate the Gravimeter fringe levels. The light from the LED is optically coupled to the fringe sensing probe whose AC output is fed to the zero-crossing detector which feeds the counting input of an electronic counter. A signal coming directly from the signal generator, through a signal conditioner, is fed to the external time base input on the counter. This signal is "clean" inasmuch as it has a very high signal-to-noise ratio. If an error-free signal (from the zero-crossing detector) is received at the counting input of the counter, then the number of counts equals the number of cycles coming into the time base input; and a reading of "one" followed by all "zeros" will be obtained on the counter. The number of "zeros" is dependent upon the counting time interval selected. If the time interval is selected for 10^8 counts, the reading would be 100,000,000. If no error counts are present from the zero-crossing detector, then this reading will always be obtained regardless of frequency. If a reduction in the signal-to-noise ratio occurs at the input to the zero-crossing detector, a point will be reached where the highest amplitude noise pulses plus signal will trigger the zero-crossing detector, and extra output pulses will occur. For example, if 12 noise pulses were of sufficient amplitude (plus signal) to trigger the zero-crossing detector, then a reading of 100000012 would be obtained, indicating errors of 12 parts per 10^8. Further reduction of the signal-to-noise ratio will cause progressively larger errors. If the signal-to-noise ratio is not large enough to reliably trigger the zero-crossing

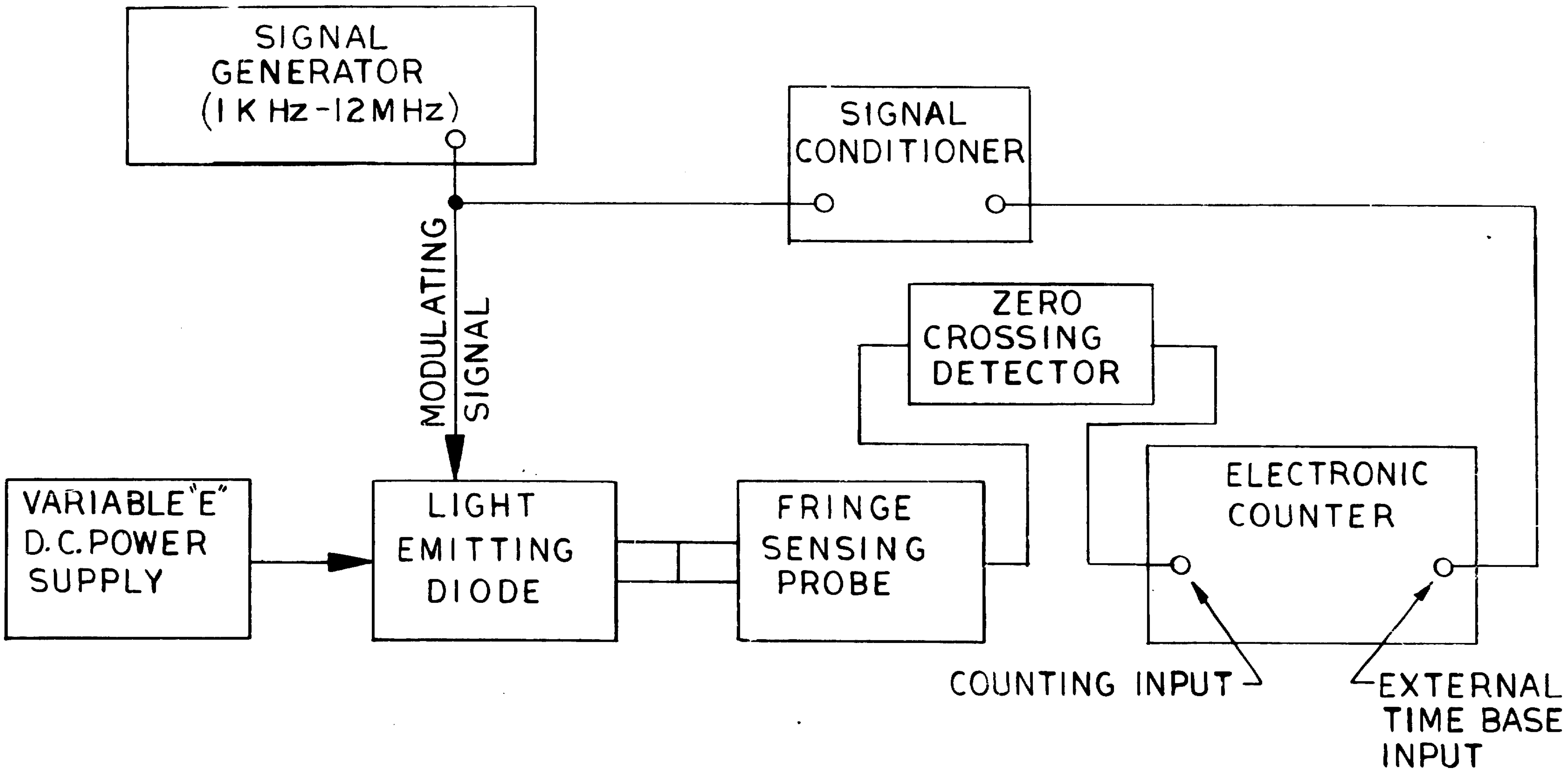


Figure 7
Detection of Errors Due to Noise

4.4.1 Probe: (continued)

detector, then readings such as 099,999,321 would be obtained. A frequency-sweeping signal generator can be substituted for the signal generator shown with the same readings resulting on the counter. This would more closely simulate the operation of the Gravimeter. The zero-crossing detector output could also be fed into the "gravity" computer and readout circuits. A direct comparison can be made of errors in counts from noise and errors in "gravity" readout.

An intensive study should be made of the effects of noise. A determination of the signal-to-noise ratio required for error-free (from noise) operation of the Engineering Model should also be made.

4.4.2 Counting Circuits: The function of the counting circuits is to detect the number of zero crossings of the signal generated by the fringes, and count two equal number of fringes: for example, two counts of 2^{20} fringes representing two equal distances measured in light wavelengths. These circuits work very well on the Laboratory Model and require little, if any, change unless substantially superior concepts are developed.

4.4.3 Timing Circuits: The function of the timing circuits is to measure the length of time required for the drop of the bird through the two previously discussed distances. This timing was accomplished initially on the Laboratory Model with two electronic time interval meters. Later, a system was added to compute the value of gravity and provide a direct numerical readout. This direct readout system essentially duplicated the function of the time interval meters, so these latter meters should be eliminated from the Engineering Model system, and replaced with the direct readout computing system.

Timing of the bird drop requires a very accurate time base generator or frequency standard. The most accurate and stable frequency standards operate a 1 MHz. Crystal controlled standards are available with one week stabilities of several parts per 10^{11} and predictable drift rates. Somewhat better stabilities may be obtained with cesium beam standards, but they cost an order of magnitude more than crystal standards. Considering the factors of cost and transportability, the crystal standard along with a means of frequency comparison with WWV should be used in the Engineering Model.

4.4.3 Timing Circuits: (continued)

The desired resolution of the Gravimeter requires that the time base frequency be 100 MHz. In the Laboratory Model this frequency was obtained by using frequency multipliers driven by the 1 MHz standard. Frequency multipliers have inherent characteristics which may cause possible errors in the 100 MHz frequency. An alternate method should be used for the Engineering Model. This method is shown in Figure 8. A voltage controlled oscillator (VCO), with its center frequency at 100 MHz, supplies the clock frequency. The VCO also feeds divide by 100 circuits which feed one input to a phase comparator. The 1 MHz standard feeds the other input to the phase comparator. The phase comparator output is a DC signal whose polarity and amplitude is a function of the phase relationship of the two input signals. Since the VCO is phase-locked to the 1 MHz standard, it is forced to oscillate at exactly 100 times the frequency of the standard.

4.4.4 Computer: The function of the computer is to provide a direct reading of the value of "g". To do this the computer must count the clock pulses occurring during the first bird drop distance (time t_a) and the pulses during the second distance (time t_b). The computer must then solve the equation:

$$g = 66.37396636 \frac{t_a - t_b}{t_a t_b (t_a + t_b)}$$

Techniques are readily available for solving the equation, and the solution is least cumbersome with binary circuits. Therefore, the counting should be done with binary circuits. It was found on the Laboratory Model that conversion of the Time Interval Meter binary coded decimal output was more cumbersome than duplicating the Time Interval Meter functions and counting in straight binary. So, the Time Interval Meters are not required on the Engineering Model.

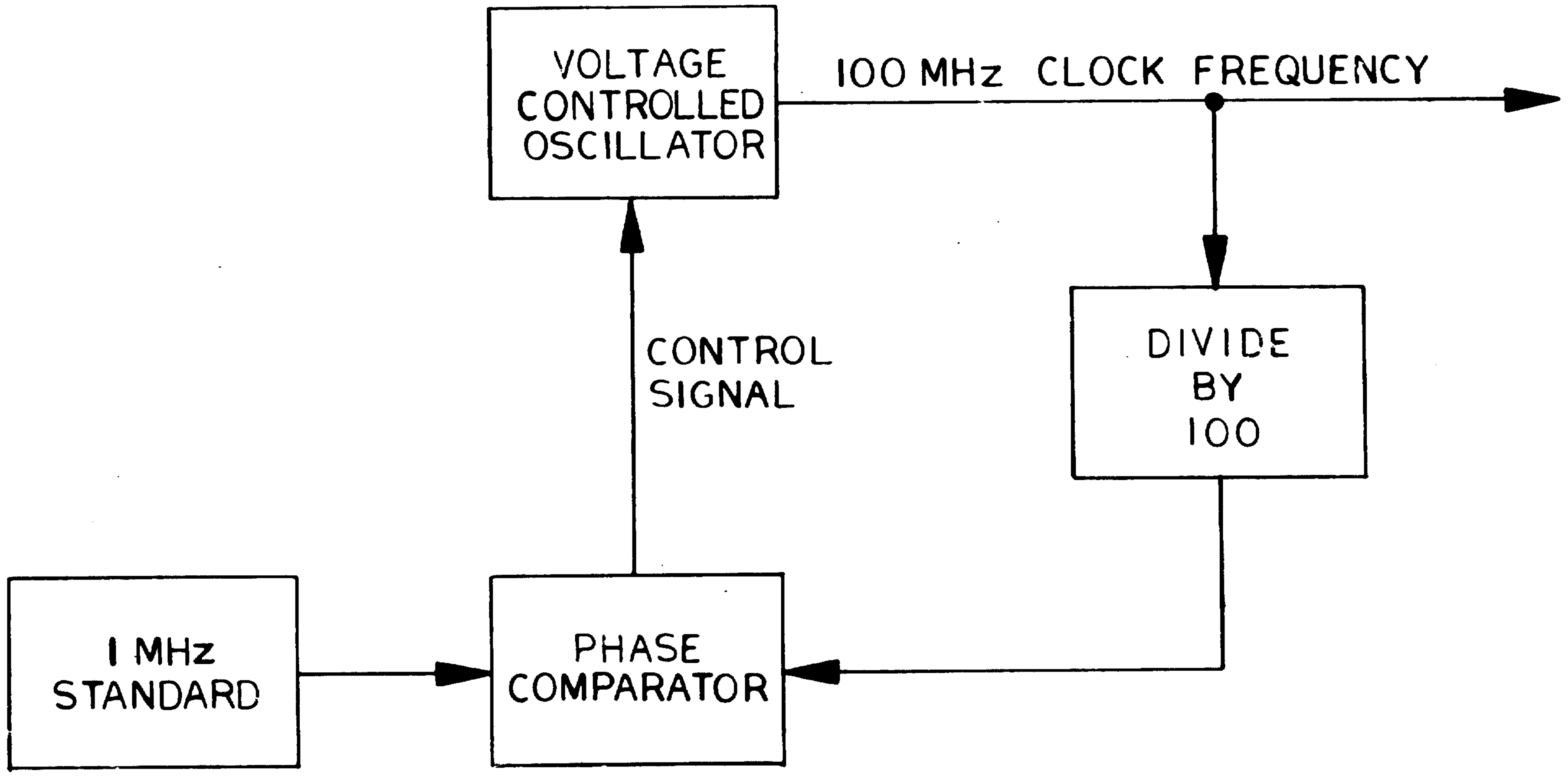


Figure 8
Generator for 100 MHz Clock Frequency

5.0 PACKAGING

The exact methods of packaging should be determined during design. Some parts of the electronic system, i.e., the probe, must be mounted on the Gravimeter structure, while other parts will function better if on the structure. The remainder may be mounted in the most feasible manner, taking into consideration the factors of cost, transportability, ease of setup, and maintenance.

6.0 PROBE

Final results obtained with an avalanche diode were not adequate to operate on present light level. Tests indicated that five to ten times the present light level would provide satisfactory operation. The Probe was left set up for the avalanche diode, but the diode was broken during a re-mounting operation. The Hewlett Packard 4204 diode (same one used for light level measurement) was then installed in the Probe. Insufficient light was available to operate the Probe with this diode. See Figure 9.

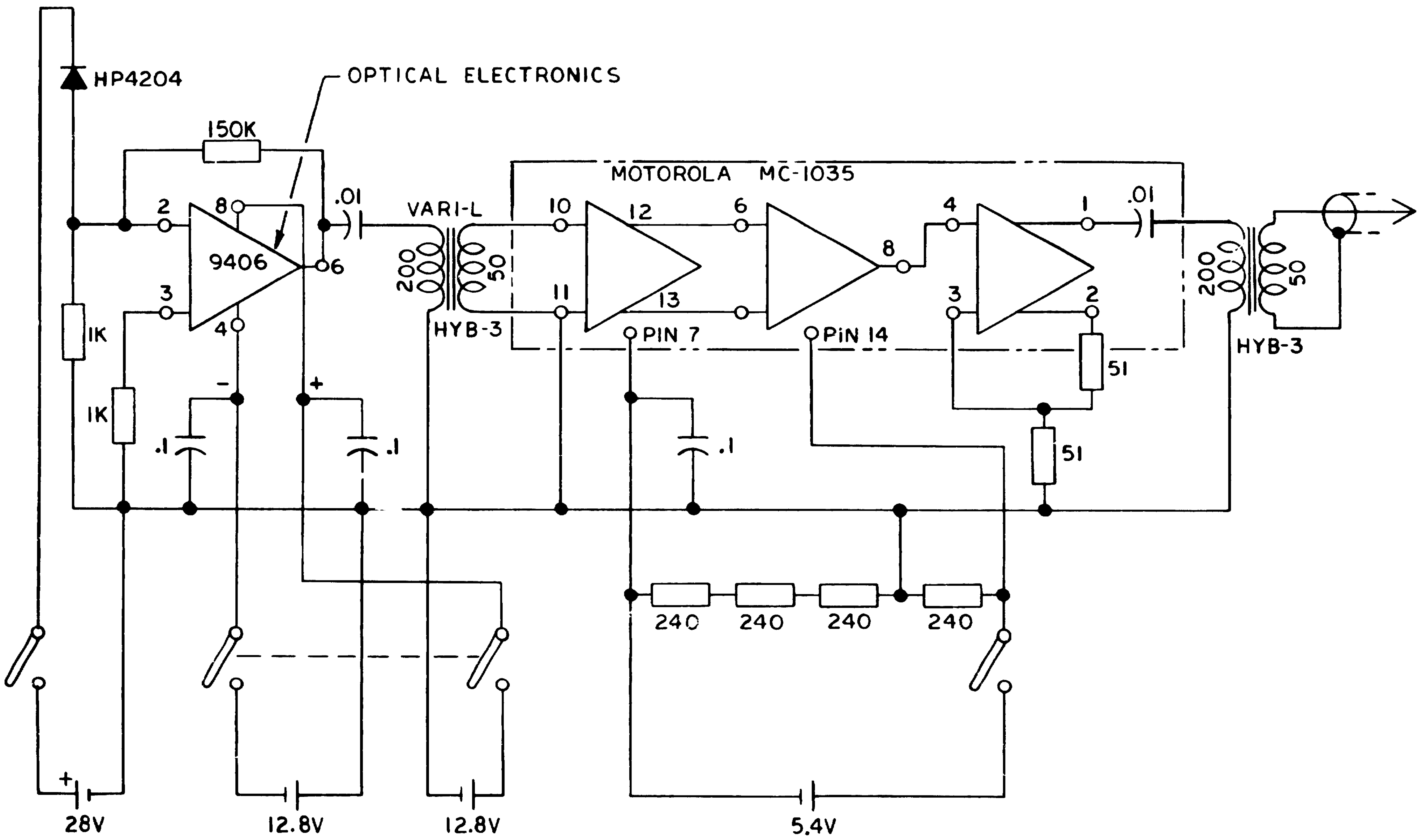
7.0 LEVELLING SYSTEM

The function of the levelling system is to maintain the vertical axis of the Gravimeter in line with the local gravity direction. This is accomplished by sensing the deviation of the line of fall of the bird, corresponding to the local gravity vector, from the vertical axis of the instrument. The block diagram of the levelling system is shown in Figure 10.

The sensor is a two-axis, light-sensitive diode with a pair of proportional outputs aligned with the XX axis and a second pair of outputs aligned with the YY axis. If the light spot falling on the diode is not centered geometrically, an error signal will be generated which is fed through preamplifiers to the appropriate integrator circuits. The light falling on the diode has been reflected from the corner cube in the bird. Thus, if the bird falls off to one side, corresponding to an error in the alignment of the vertical axis of the instrument, then the appropriate error signal will be generated.

This error is stored on a gated integrator circuit. No levelling action is allowed to take place until the bird has completed its fall. The completion of the fall is determined by the Sequence Generator which operates from signals available in the fringe counting circuit, (discussed elsewhere). At the appropriate time when all action is complete, the voltage on the integrator circuit is allowed to operate the Motor Relay Driver. This is a three-state relay driver circuit which permits bi-directional control of the motor. If the stored integrator voltage is positive and above the threshold of the relay driver circuit, then the motor will be driven to decrease this voltage the next time the bird falls. The alternate relay is operated if the stored voltage on the integrator is negative.

The system is to be adjusted if necessary so that the error is corrected by approximately one half of the measured value. This is



PROBE SCHEMATIC

Figure 9

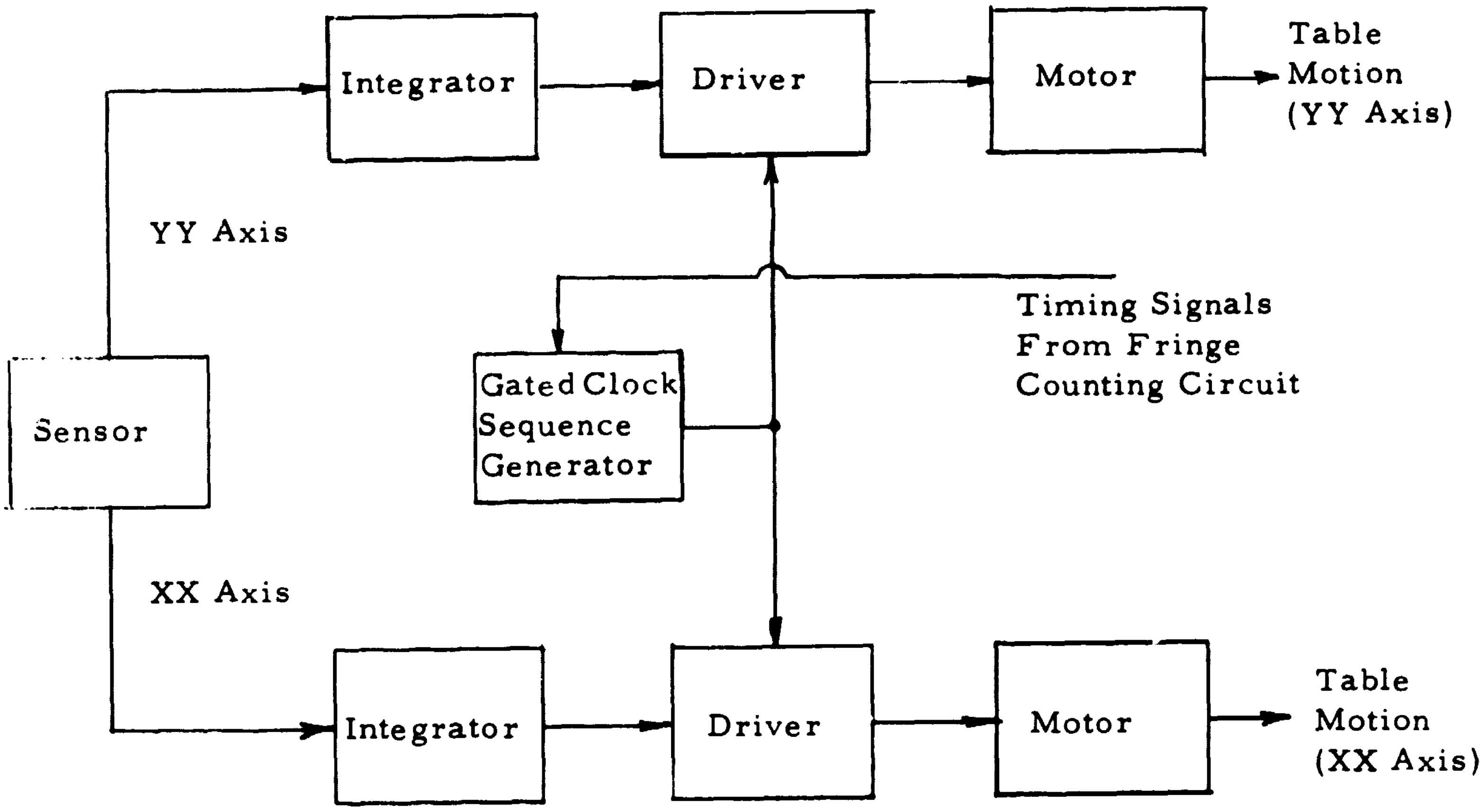


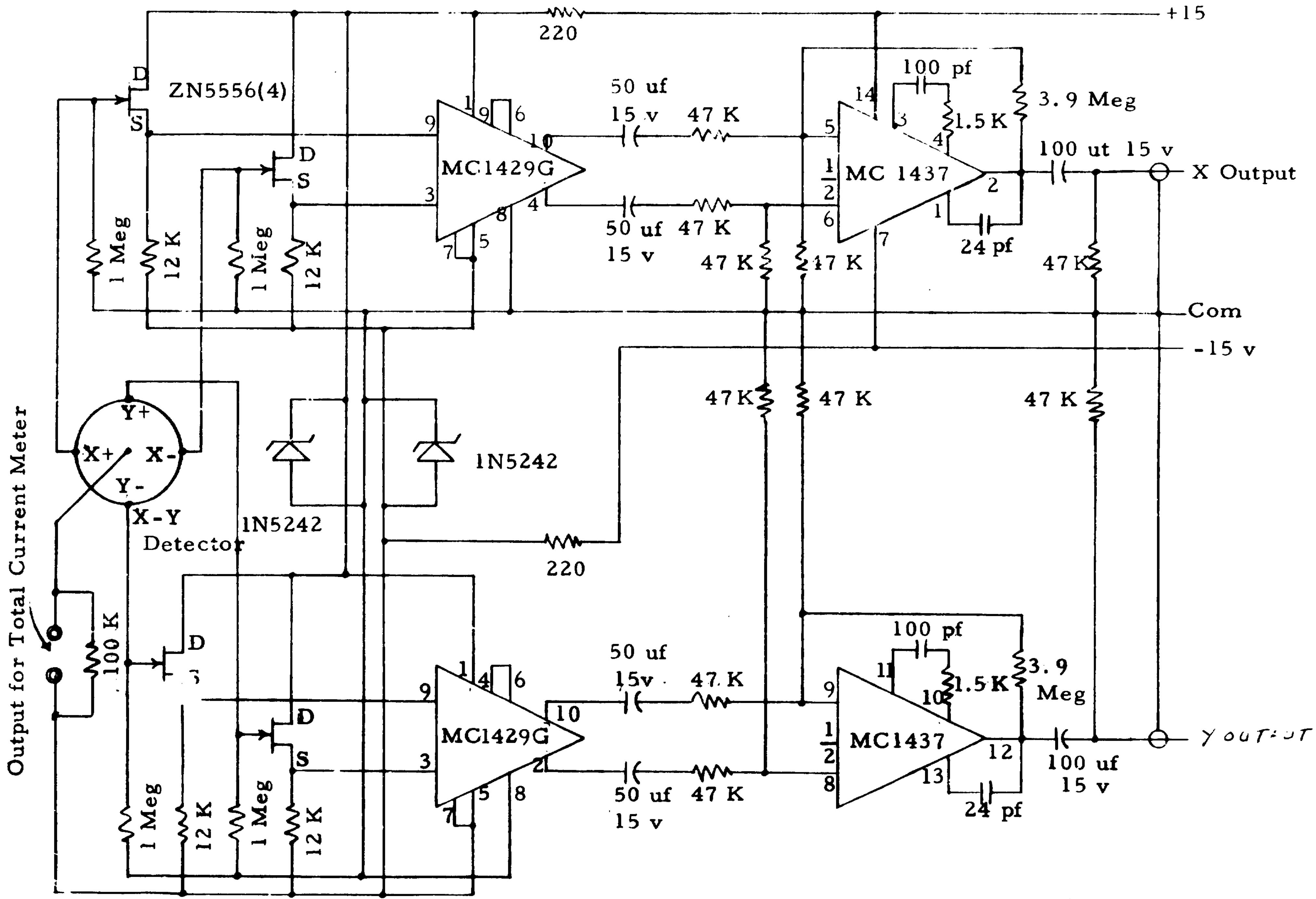
Figure 10

Block Diagram of Levelling System

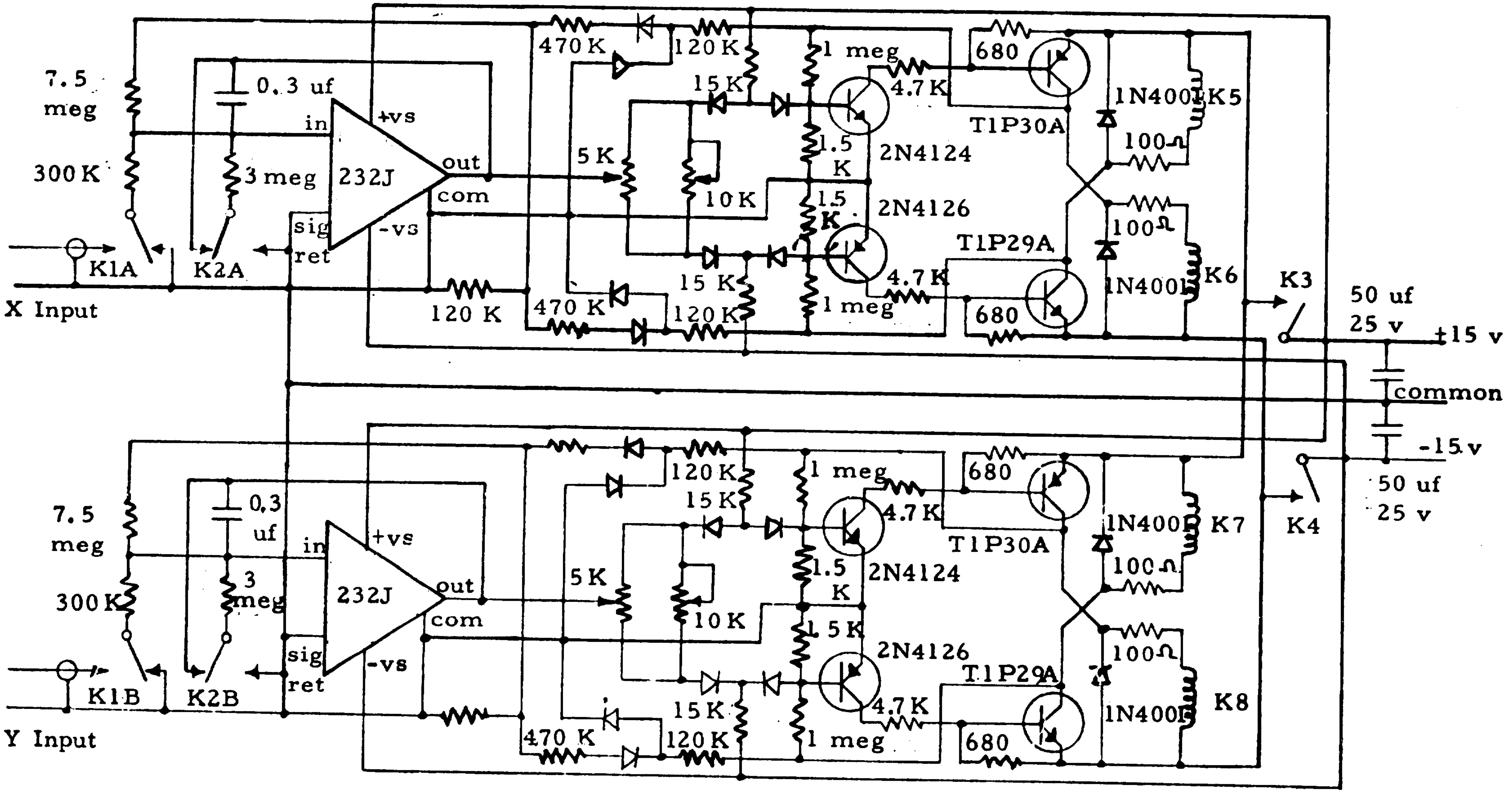
7.0 LEVELLING SYSTEM (continued)

accomplished by changing the integrator cancellation time-constant by changing the value of the 7.5 meg. ohm resistor. By allowing the error to reduce slowly to zero, problems that might be associated with hunting or instability are reduced.

The motors are mounted on the Servo Table and control the vertical alignment of the instrument by means of a pneumatic servo system. The levelling system was breadboarded from the sensor through the integrator feedback and relay driver. This included a sensor, an integrator, a Gated Clock, a Sequence Generator, and a test fixture for simulation of the bird fall. One complete system, for either an XX axis or a YY axis, was assembled and checked out. Both axes are identical. Tests showed that the system worked as planned. As the light moves across the sensor, a sawtooth voltage is generated. At time t_1, K_1 picks up and the integrator begins to charge to some level which is a function of the amplitude of the sawtooth voltage. Two hundred milliseconds later, at t_2, K_1 drops out, and the integrator holds. Six hundred milliseconds later, at t_3, the motor relay driver is energized, depending on polarity and magnitude of the integrator voltage, and the appropriate levelling motor is driven. The relay driver also feeds back a current tending to cancel the integrator charge. At time t_4, the integrator voltage has been cancelled and the relay driver drops out, de-energizing the levelling motor. The time interval that the levelling motor is energized is a function of the integrator charge which in turn is a function of how far the light spot moved. If the integrator charge has not been brought to zero after 12.8 seconds, the Sequence Generator shuts off the motor drivers and discharges the integrator. The Gated Clock and Sequence Generator apply the proper signals to the levelling system so as to synchronize its operation with the bird drops.



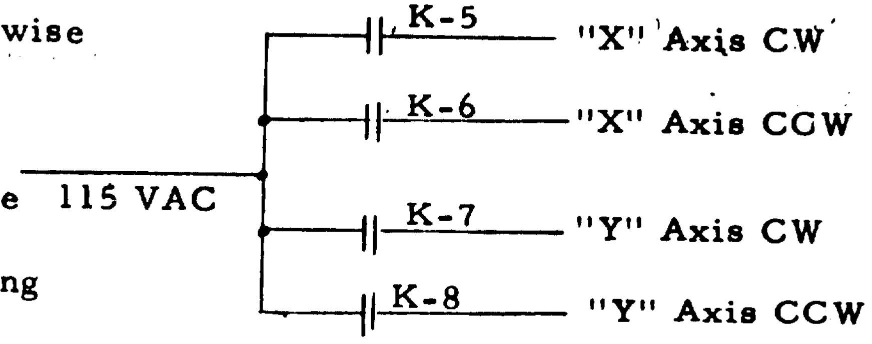
Leveling System
Detector and Pre-Amp
July 1969 W. Ewing



All diodes 1N4148 unless indicated otherwise

Op-Amp is Analog Devices Model 232J

Note: It may be necessary to interchange motor leads or rotate sensor 180 degrees to achieve correct levelling



NOTE:

IC1, IC4 - Texas Instrument
SN7493N

IC2: Motorola MC846P (or 849P)

IC3: Motorola MC1808P (or 1809P)

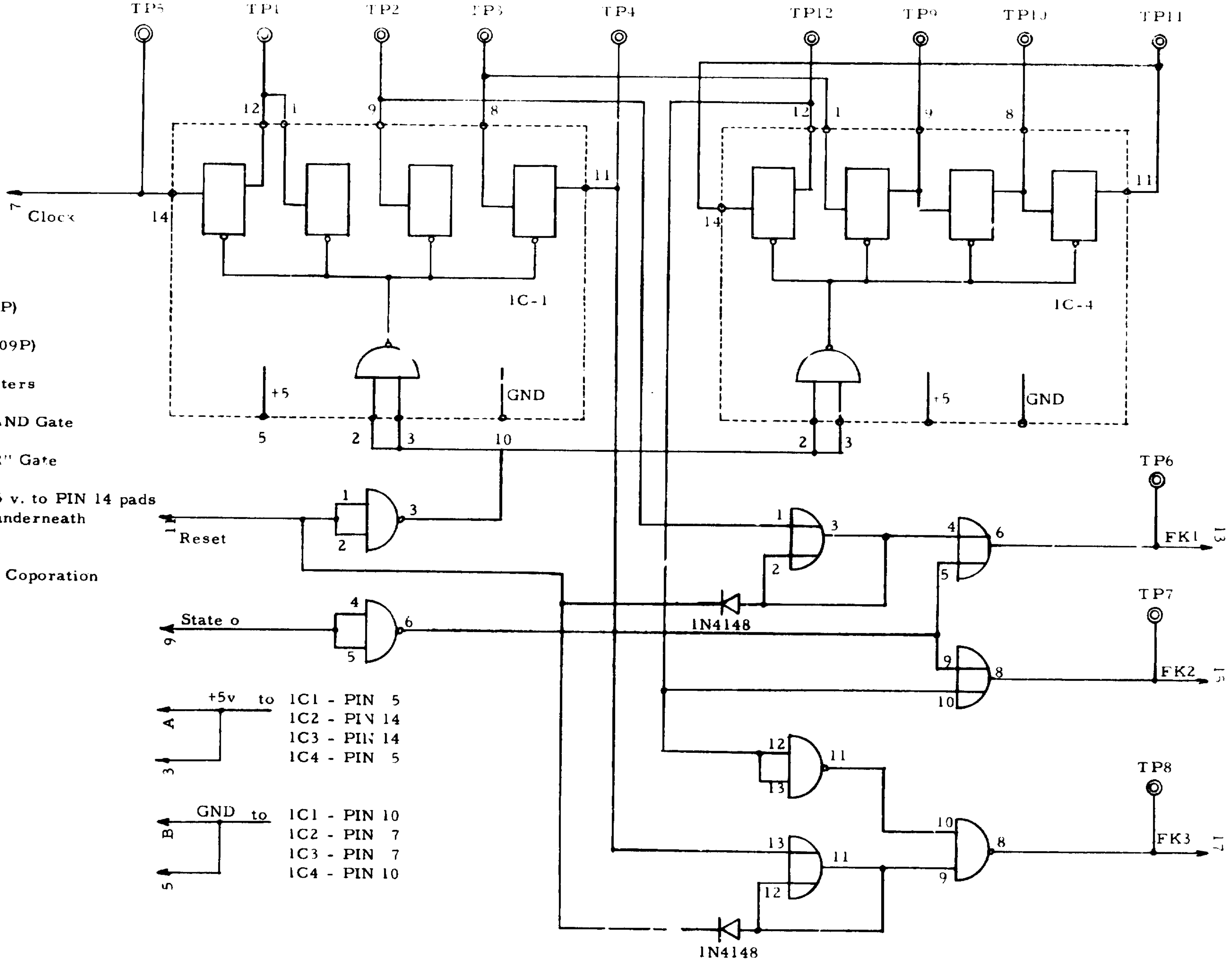
IC1 IC4 are divide-by-16 counters

IC2 is a quadruple, 2-input "NAND Gate

IC3 is a quadruple, 2-input "OR" Gate

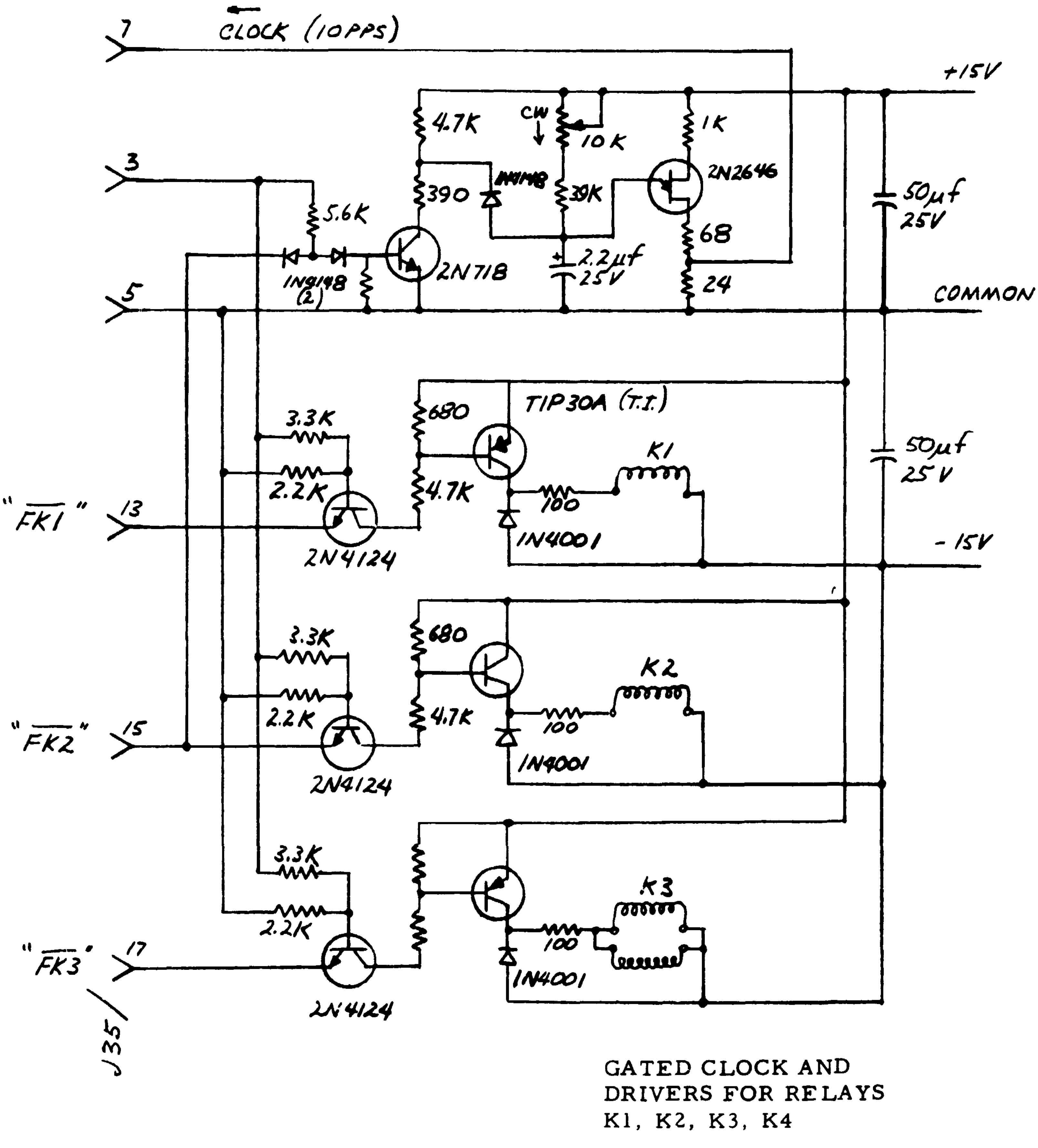
Note: Printed leads carrying +5 v. to PIN 14 pads for IC1 and IC4 are cut underneath the IC's.

Constructed on Data Technology Coporation card #593



SEQUENCE GENERATOR
FOR RELAYS K1, K2, K3, K4

JUNE 26, 1969 W. EWING



GATED CLOCK AND
DRIVERS FOR RELAYS
K1, K2, K3, K4

JUNE 1969 W. EWING

APPENDIX I

Progress Report on Gravimeter Probe and Levelling System

MEMORANDUM

SPACO, INC.

6 May 1969

TO: Dr. O. K. Hudson
FROM: Chester Savelle

SUBJECT: Progress on Gravimeter Probe and Levelling System

Probe

As previously reported, an extensive investigation had been made of the effects of noise on the probe performance at a frequency of 1 MHz. It was found that an input level of about 600 microvolts was necessary to obtain less than one part per 10^7 error due to noise. It was felt that the performance of the probe must be checked at 10 MHz, but due to the counter limitations, a frequency divider was necessary.

A circuit was designed using inexpensive IC logic devices to obtain a frequency division in steps of 1, 2, 2.5, 10, 20, 25, 50, and 100. These division ratios give a maximum flexibility with a minimum of cost, and permit the probe tests to be extended to the 10^9 range. This range is necessary to meet the requirements set by Dr. Hudson of no error due to noise greater than 1 part per 10^8. A chassis and package was fabricated (no contract cost) and the unit was assembled with a self-contained battery (30 to 40 hrs.) for power. The switching was arranged to remove power from the IC when it is not being used for frequency division. The unit was tested and performed satisfactorily.

Tests were made on the probe at 10 MHz and it was discovered that an input level of only 90 microvolts was required for less than 1 part per $\underline{10^9}$ errors due to noise. Furthermore, it was found that as the voltage level was reduced, extra counts of about 50 per 10^8 were obtained, and further reduction resulted in less than the number of counts that should have been obtained. This result has been defined as negative counts, and probably results from erratic triggering by the low signal level with the noise being of lower frequency than 10 MHz. However, an explanation of the wide disparity of performance between 1 and 10 MHz was not immediately apparent.

Then a test was made for which no logical reason could be justified technically, but would require only about ten minutes; so it was tried anyway. The resistor-capacitor coupling between the first and second amplifier stages was replaced with an available transformer (100 KHz to 500 MHz frequency range).

The impedance ratio is 50 ohm to 600 ohm, and the transformer was first connected in a voltage step-down configuration with the step-down ratio being $\sqrt{12}$: 1. At 1 MHz and at 10 MHz, the input level required for error free output (less than $1/10^8$) was 250 microvolts. This was a substantial improvement. Furthermore, no positive counts were obtained, as reductions in input level simply resulted in negative counts as previously described. These results were very encouraging, and for no logical reason other than curiosity the transformer was turned around to obtain a voltage step-up ratio of $\sqrt{12}$: 1. At 1 MHz, error free triggering was obtained at an input level of 60 microvolts, and at 10 MHz the required level was 180 microvolts. Again, no positive counts were obtained, but negative counts were obtained with reductions in input levels. This result is significant, inasmuch as it indicates that additional amplifier gain can be used before the noise again causes extra counts. This additional gain will further reduce the input level required for error free operation. It was decided to install an additional amplifier stage giving more than optimum gain, and then experimentally reduce the overall gain until no extra counts in 10^8 parts are obtained. This point is then the optimum gain level, and based upon the levels previously obtained, the input required will be less than the theoretical output of the avalanche diode.

Over the weekend (no contract cost), the probe was disassembled and mechanical modifications were made to the chassis. In addition, improvements in power supply lead shielding, decoupling, and returns were made. The chassis grounding system was also revised. These changes were necessary because at the gain level to be used initially, oscillation would occur without the precautions being taken. Reassembly of the electrical circuits has been started but is not complete at this writing. However, it is felt that, based on previous results, there is now about a 95% chance of obtaining a workable solid state probe.

Levelling System

Progress on the levelling system has not been as good as we had hoped. Primarily, the reason is that, in the excitment of the positive results that have been obtained on the probe, we have neglected, to some extent, the levelling system. However, the two special chassis for the light sensor amplifiers were fabricated (no contract cost) and the assembly of light sensor and amplifiers is completed and "smoke" tested. Complete tests require a dynamic test with a moving light spot. Over the past weekend (no contract cost), work was accomplished on the dynamic test setup. The mirror was cemented to the speaker cone and the speaker mounted at 45° to the light path. The light sensor (with amplifiers) was mounted. Still remaining is the mounting of the light source, arrange for adjustment of light spot size on the sensor, and determine the drive voltage required for the required spot deflection of 0. 1 inch. The design of the light sensor provided for rotating the sensor to simulate different vector motions of the light spot under different levelling requirements. It is anticipated that this test setup will be completed this week and dynamic tests will be performed. Progress cannot be expedited by additional manpower inasmuch as the system is to the point that checkout and analysis of performance by the design engineer is required.

The chopper stabilized integrator op-amp has not yet been received. The unit was due to be shipped on April 18, 1969. Preparation of this report stimulated follow-up on this unit and Analog Devices was contacted by phone. It seems that they have been having production problems with this particular op-amp, and the man contacted was going to check and give us an answer today (May 6, 1969). Analog Devices has been pretty reliable (not like TI) on calling back, so we expect to get an answer shortly.

Chester Savelle

Chester Savelle
Program Manager, Gravimeter

cc Mr. Green (NASA)
Mr. Hatch
Mr. Scates
Mr. Thomas
Mr. Ewing

APPENDIX II

Report on Gravimeter Work

SPACO, INC.
3022 University Drive
Huntsville, Alabama 35805

TO: Dr. O. K. Hudson
FROM: Chester Savelle, Jr.
DATE: 15 April 1969

SUBJECT: Report on Gravimeter Work

The following is a summary of work that has been performed on the Gravimeter since 10 March 1969:

A. RFQ

A specification and request for quote for a solid state probe was prepared and sent to 54 possible suppliers.

B. Probe

Since the last report, much work has been accomplished on the problem of building a solid state probe. Several answers have been obtained, even though these answers are negative in the sense that they indicate that the problems are greater than thought before.

An analysis of the essential probe performance was made and the following guidelines were developed for the probe:

1. The basic purpose of the probe is to sense the fringes and produce an electrical output signal suitable for counting the fringes. Any auxiliary functions such as light balancing, observing the fringe wave shape, etc. are non-essential to the basic function; and in view of the difficulty of the problem these auxiliary functions may compromise the performance of the basic function and. thus, should be eliminated.

2. At the time the bird has stabilized, dropping through $2^{15} + 2^{16}$ fringes, the frequency of the fringes has reached 1 MHz. Thus, if the probe has a sharp cutoff below 1 MHz, the preliminary $2^{15} + 2^{16}$ fringes do not have to be counted, and a frequency range of 1 MHz to 11.5 MHz is sufficient, with no degradation of the accuracy of the gravimeter readings.

3. Since the basic function of the probe is counting, then a pulse output from the probe is satisfactory to perform this function.

B. Probe (continued)

4. For design purposes, the probe must perform with a diode current swing of 2.3 x 10^{-9} amperes. At the best tradeoff of diode element size (governs sensitivity) and shunt capacitance, (limits upper frequency range) a shunt capacitance of 2 picofarads is about the lowest limit available. With this shunt capacitance, the maximum diode load resistance, for an upper frequency limit of 11.5 MHz, is 2 K ohms. Thus, the diode output (signal) would be 4.6 microvolts. Photodiodes have an inherent high signal to noise ratio; thus, this 4.6 microvolt signal is practically noise free. With an avalanche photodiode, it is feasible to obtain a practically noise-free photon/current gain of 100. This volt/volt gain of 100 would result in a signal level of .460 millivolts with only the Johnson noise of the diode load resistor (2K) added to the signal thus far. The theoretical Johnson noise plus shot noise of the load resistor should still result in a signal-to-noise ratio of 30-60 db.

With the above guidelines, the probe concept was redesigned to the circuit shown in Figure 1. Several problems were encountered and solved. A major problem encountered was oscillation of the circuit. This was solved by building a new chassis (no contract cost) which provided excellent isolation between the stages to prevent feedback from the output to the first amplifier input. The initial tests were made using a signal generator in place of the diode, as shown in Figure 2, and looking at the output on a scope. It was found that a signal level of 70-100 microvolts would trigger the circuit, and we were elated. After all, we could possibly have a diode signal of 460 microvolts with a very good signal-to-noise ratio. Some jitter was noted, and this was caused by inherent noise coming from within the amplifier, but it was felt that some jitter could be tolerated.

In order to measure the effects of jitter, the test setup in Figure 2 was derived. The signal from the generator was fed through (co-axially) the input to an amplifier and to the probe input. The output of the amplifier was fed to the external standard jack on the electronic counter, and the output of the probe was fed to the trigger input on the counter. Thus, if the output of the probe exactly equals the signal generator output, the counter reading is 1 x 10^6 (1 second time interval) or 1 x 10^7 (10 second time interval). With a 460 microvolt input to the probe, readings of 1 x 10^6 + 500 (approx.) were obtained. This indicated that about 500 extra counts were being caused by noise. As the probe input signal was

B. Probe (continued)

increased, the extra counts dropped off and at an input signal level of 920 microvolts no extra counts in a total of 1 x 10^7 were present. At this time we weren't very elated, as this is twice the diode signal we can expect to have available, and there would be some noise in this signal.

In an effort to ascertain what was happening, with respect to noise, the hysteresis of the Schmidt trigger (without the amplifier) was measured and found to be 11 MV RMS. The amplifier was reconnected and its input was shorted. Thus, only the noise generated in the amplifier was available to trigger the Schmidt trigger. Using the counter, on internal standard, several (random number) counts were obtained during one (1) second counting intervals. These counts could only be attributed to noise. Using the hysteresis of the trigger and the amplifier gain, (previously measured at 200) the relative peak values of signal and noise were calculated.

Figure 3 illustrates the reason that noise-caused triggers occur in varying numbers of pulses in the presence of a signal. Traditionally, noise values are defined by RMS values with respect to a signal. Statistically, a large majority of the noise "pulses" (for want of a better term) have an amplitude equal to or less than this value. In a linear radio or audio frequency application, this definition is adequate. However, statistically, there will be some "pulses" coming through that are, in varying amplitudes, greater than the defined RMS noise value. In the probe system, when a signal begins to build up, at some signal level, the peak value of the signal plus the largest noise pulse will be sufficient in level to actuate the trigger "on". If during the positive signal excursion a negative going pulse comes along (prior to negative signal excursion), then the level is sufficient to actuate the trigger "off" and so on. This is what happened during low signal levels. It was possible to adjust the signal level to get one or two extra counts per 1 x 10^7 , and maintain this condition for several counting (10 second) intervals. For the gravimeter readout, these extra counts are intolerable.

Supposedly, higher signal levels should make it possible for lower level noise pulses to actuate the trigger, but this isn't true. Figure 4 illustrates one of the reasons. Two signal levels with respect to a noise level are shown plotted as amplitude versus time. It can be seen that the lower level signal required a longer time to exceed the noise pulse level than does the higher level signal. Thus, there is a shorter time available for noise pulses to get through and cause extra trigger actuations, and the higher signal "swamps" the noise in a shorter time. Incidentally, the photomultiplier signal has noise in it; and it is possible that this noise

B. Probe (continued)

is injecting extra counts into the readout system. If so, the gravity readings should be higher than anticipated. It could be that the extra counts, due to noise (probably random), are contributing to the variations that are occurring in the 6th, 7th, and 8th significant figures in the readout.

Now that the problem with respect to noise has been further defined, further solutions are being sought. Apparently, the original concept of a 30 db signal-to-noise ratio is no longer valid. It appears that for the gravimeter, a signal-to-noise ratio of about 120 db is required. A digital filter is being considered as a method of removing the extra pulses, but no answer as to feasibility is presently available. It is likely the only other alternative is a very narrow band (10-100 Hz) tuned synchronous filter to reject the noise.

C. Leveling System

Work has been proceeding on the leveling system concurrently with work on the probe.

The amplifier for the light sensor has been designed and will be fabricated within a few days. The light sensor is illustrated in the sketch below Figure 1. The sensor itself is difficult to illustrate inasmuch as it is one light sensitive diode with five terminals arranged as shown in the sketch. If the light moves on the surface of the diode, an unbalance in current between the opposite terminals (outside) occurs. A measure of this unbalanced current is the position indication. The circuit shown, shows one output amplifier for one terminal. The circuit consists of an identical amplifier for each of the terminals.

The subsequent amplifiers, integrators, and relay drivers have been designed, and it is planned to test the system operation next week.

CRSavelle, Jr.

C. R. Savelle, Jr.

cc Mr. Greene - NASA
Mr. Hatch
Mr. Scates
Mr. Thomas

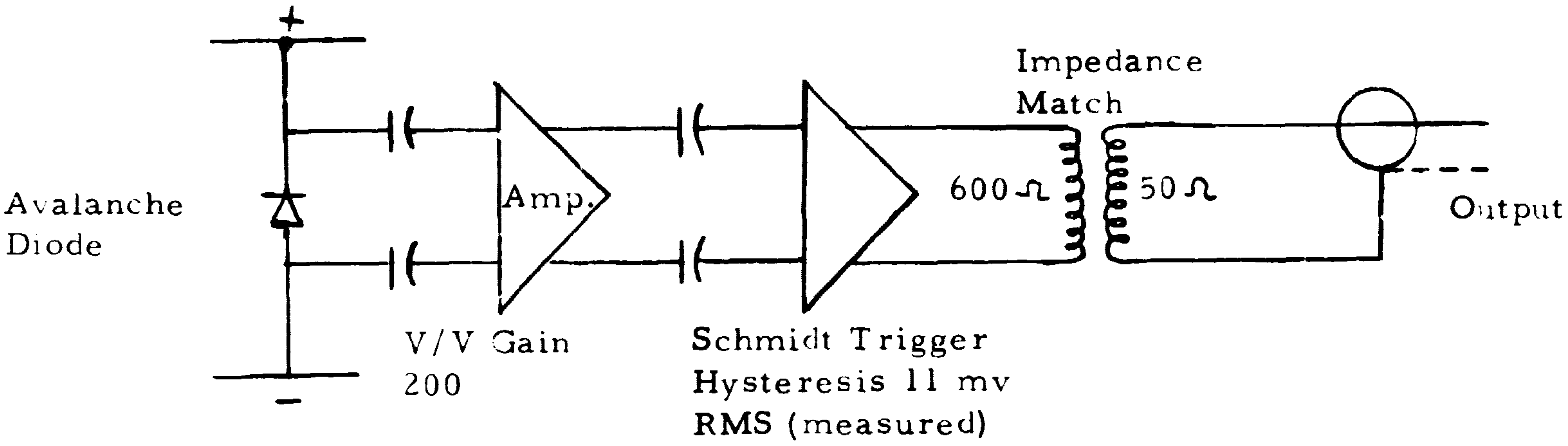
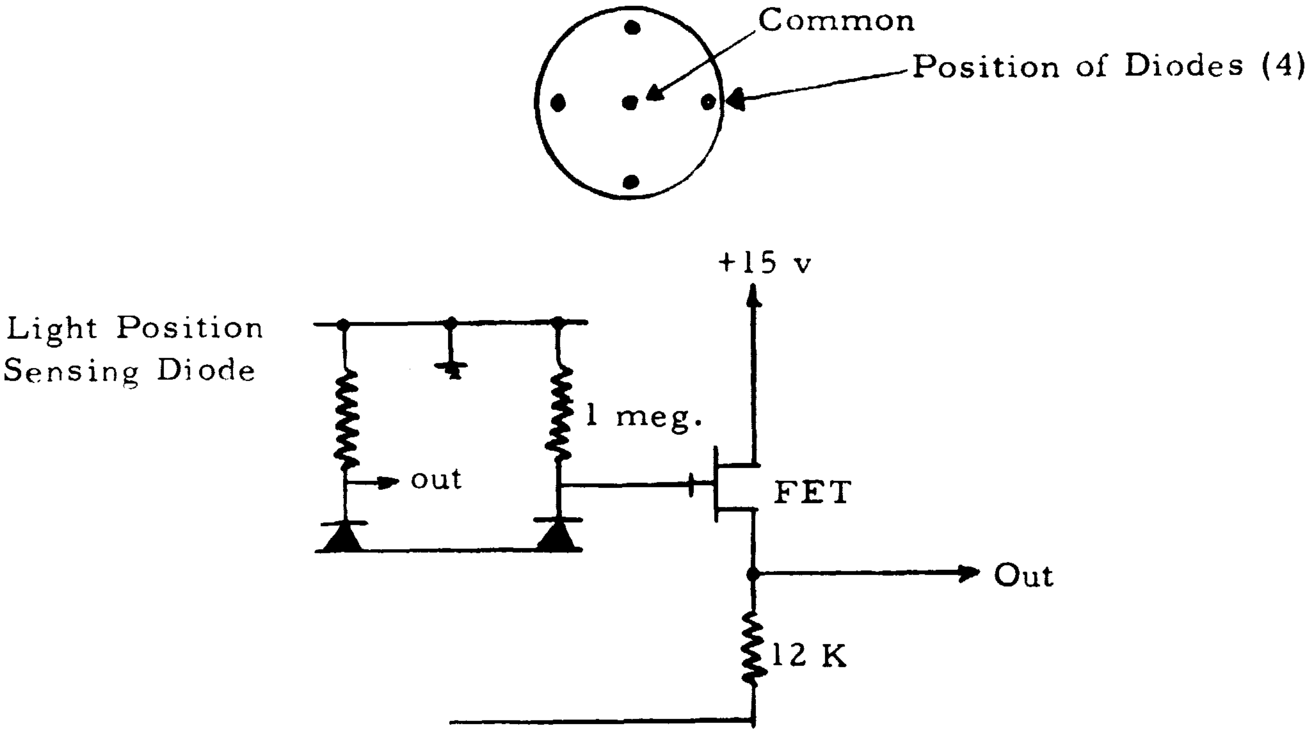


FIGURE 1



LEVELLING SYSTEM SENSING

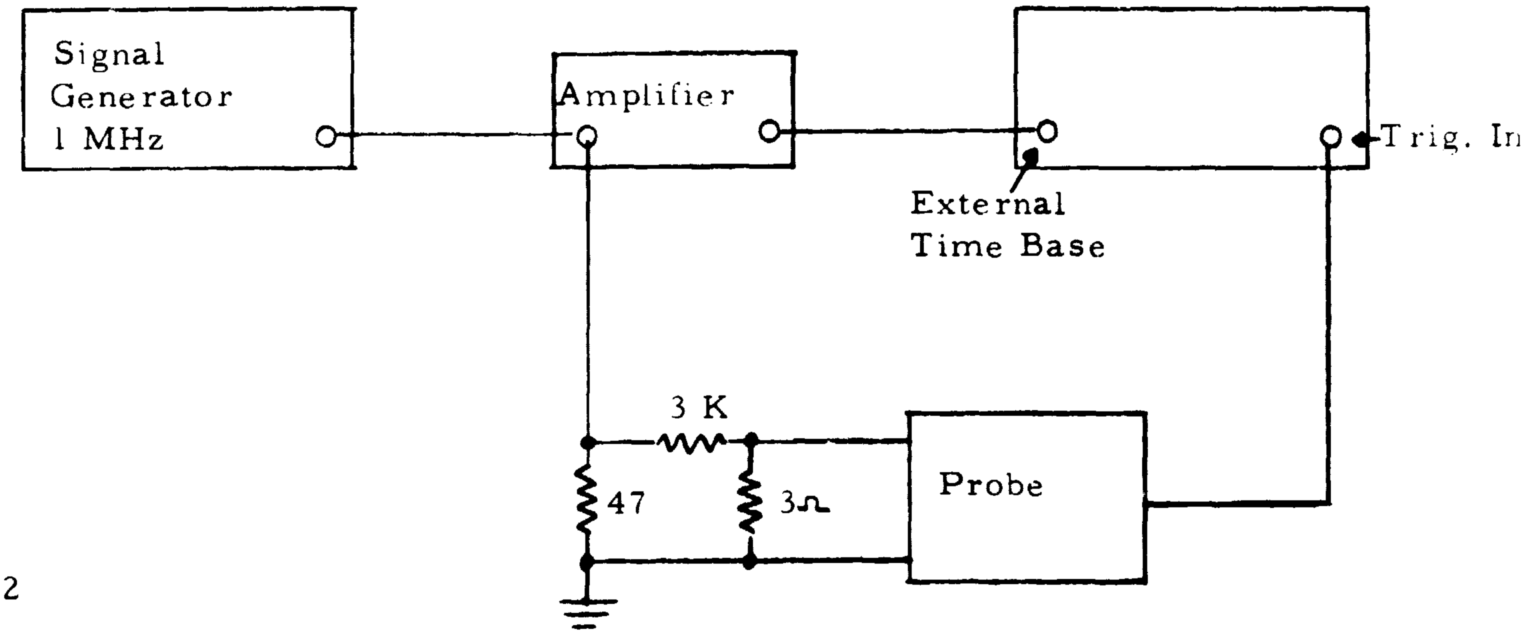


FIGURE 2

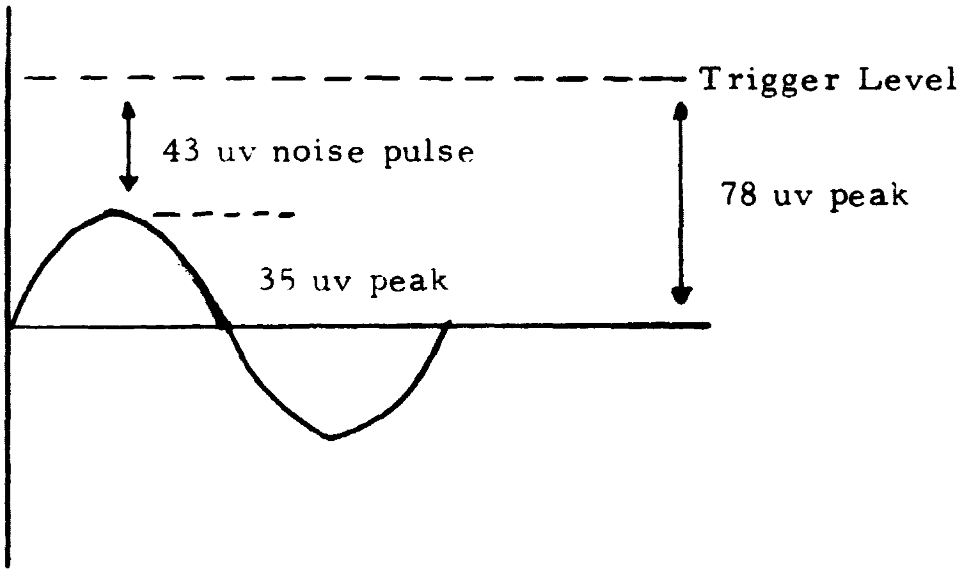


FIGURE 3

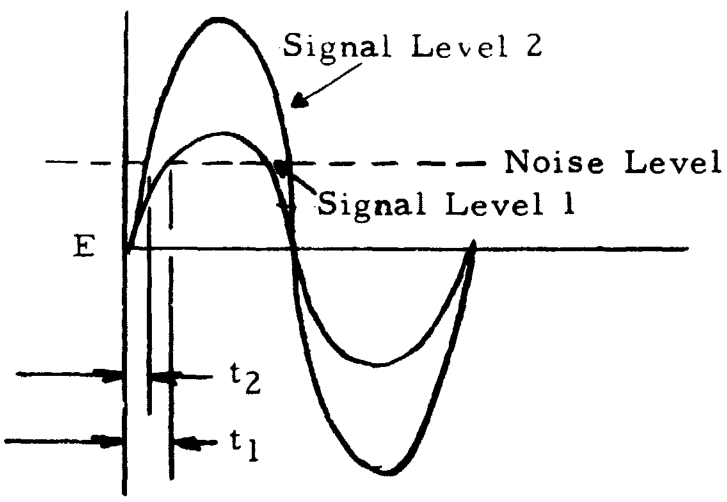


FIGURE 4

APPENDIX III

Solid State Probe Gravimeter

MEMORANDUM

SPACO, INC.

March 4, 1969

TO: Dr. O. K. Hudson

SUBJECT: Solid State Probe-Gravimeter

ENCLOSURES: 1) Design Calculations

2) Tests on Solid State Probe

Enclosed are copies of the design calculations and results of tests on the solid state probe for the Gravimeter. On February 28, we were able to get an indication that the probe was sensing the fringes. This is encouraging, but whether enough extra output can be squeezed out remains a question. Present efforts are directed in that direction.

Chester Savelle, Jr.

Chester Savelle, Jr.
Program Manager

mbm

cc Mr. Green - NASA
Mr. Hatch
Mr. Scates
Mr. Thomas

DESIGN CALCULATIONS

GRAVIMETER SOLID SATE PROBE

1. Light Sensor - Diode - Hewlett-Packard Type 4204

2. Characteristics

(a) Sensing Area - 2×10^{-3} CM ^{2}

(b) Sensitivity - = .3 μa/μw @ λ = .633 microns

3. Amplifier Design

(a) Input Voltage

From data on previous sensor, it is estimated that the light level is approximately:

15 μw with 100 μw laser
30 μw with 250 μw laser

So:

I_L = Light Current
= (.3 μa/μw) 15 = 4.5 μa (100 laser)
I_L = (.3 μa/μw) 30 = 9.0 μa (250 laser)

$I_D = 100 \times 10^{-12}$ a (ID = dark current)

Since dark current is very low w.r.t light current the peak to peak current is:

$I_{(p-p)_1}$ = 4.5 (@ 15 μw)
$I_{(p-p)_2}$ = 9.0 (@ 30 μw)

A load resistor = 1000 , for the diode, is about the best compromise for optimum voltage E out noise at input to amplifier.

$E_{(pp)_1} = I_{(p-p)_1}\ R_L = 4.5 \times 10^{-6} \times 1 \times 10^{3} = 4.5$ mv
$E_{(pp)_2} = 9.0 \times 10^{-6} \times 1 \times 10^{3} = 9.0$ mv

Input Noise

The theoretical minimum value for input noise vs bandwidth for an amplifier is given by the equation:
$I\ (\text{Noise}) = 4 \times 10^{-12}\ A/\sqrt{(\text{Hz})}$ ~~1/2~~

This equation was taken from noise current vs resistance curves published by Quan-Tech Laboratories, for the 1 K ohm load resistor used for the photo diode.

The subject amplifier is to have an output low-pass filter with a low cut-off frequency of 20 Mhz.

Bandwith (Hz) = 20×10^6

$= (4 \times 10^{-12})(20 \times 10^6) = (8 \times 10^{-9})\sqrt{5} = (17.89 \times 10^{-9})$ A.

For worst case signal to noise ratio use 4.5 μa diode current swing:

Signal to noise ratio $= \frac{4.5 \times 10^{-6}}{17.89 \times 10^{-9}} = .252 \times 10^{-3} \cong$ 47 db

Total Noise Voltage :

$E_N = I_N R_L = (17.89 \times 10^{-9}) \times (1 \times 10^3) = 17.89$ μvolt

Required Gain (G) for 1 volt RMS Signal output:

$G = \frac{1.4}{\frac{4.5 \times 10^{-3}}{2}} = \frac{1.4}{2.25 \times 10^{-3}} = 622$

Noise output for perfect amplifier (ie-no noise generated by amplifier). At 1 volt RMS signal output:

E_N (out) $= 622\,(17.89 \times 10^{-6}) = 11.13$ millivolts

Actual amplifier noise = $.5 \times 10^{-4}$ volts

En(amp) $= 622\,(.5 \times 10^{-4}) = 31.1$ millivolts

Total noise out:

En (total) $= \sqrt{(31.1)^2 + (11.13)^2} = 33.04$ millivolts

Signal to noise ratio:

at 1 volt out $= \frac{1}{33.04 \times 10^{-3}} = 30.26 \cong 30$ db.

The digital logic trigger circuits will function properly at a 1 volt signal level, but will not be triggered by the 33 millivolts of noise. Therefore the amplifier design should be satisfactory.

Tests on Solid State Probe - Gravimeter

February 24, 1969

On February 22 and 23 an assembly was designed and fabricated to adjust the 45° mirror on the probe. The probe was taken to Test Division and tried on the Gravimeter. Due to the location of the photo diode, recessed about 3/16 inch in the diode holder, it could not be determined if the fringe pattern was striking the diode sensing element. It was determined by test that the mirror adjustment range was adequate. No fringes were detected during tests.

February 25, 1969

During the evening of February 24, the diode holder was revised to bring the diode out in front of the probe surface where it is visible for alignment purposes, and a holder was constructed to mount the probe in a vertical position on the floor under the gravimeter. In this way, the fringe pattern falls directly on the diode, without the mirror in place. This facilitates testing of the probe by temporarily eliminating alignment problems. The probe and fixture were taken to Test Division, but tests were in progress with the photo multiplier probe, and there were not interrupted.

In addition to the probe, a light intensity measuring device was fabricated and taken to Test Division. This device consisted of a Philco L4503 photo diode connected across a 0-20 microampere meter. The Spectra-Physics laser (100 μw) was turned on and the output of the laser was measured with the Spectra-Physics light meter. The output of the laser was measured at 50 microwatts. The SPACO light meter was used to measure the same output, and a meter reading of 15 microamperes was obtained at the 50 microwatt laser output.

Attempts were made to measure the light level striking the probe on the gravimeter. The Spectra-Physics light meter was used to measure the output of the 250 microwatt Perkin Elmer laser now installed on the gravimeter. The light meter indicated an output power level of 25 microwatts. The light meter probe was then moved to the gravimeter probe position. No movement of the light meter probe could be observed indicating that the light level at the gravimeter probe is less than 0.1 microwatt. Inasmuch as the solid state probe was designed to operate at about 15 microwatts of light level swing (dark to light), it was obvious that the probe would not have an output sufficient to drive the logic circuits.

February 26, 1969

A test setup was fabricated, at SPACO, to test the probe with varying light levels. The setup consisted of a type 47 pilot lamp energized with a 6.0 volt battery, with the lamp mounted behind a 20 blade fan turning at about 3000 RPM. The fan served as a light interrupter. The light assembly was mounted on a plywood base which was equipped with two runner strips to align and locate the probe. The distance between the light and probe was varied to vary the light level striking the probe diode. The light level was measured with the SPACO light meter previously calibrated against the Spectra-Physics light meter. At a light level of about ten microwatts, the probe output was about two volts peak-to-peak. This performance is about what was expected from the probe design calculations.

February 27, 1969

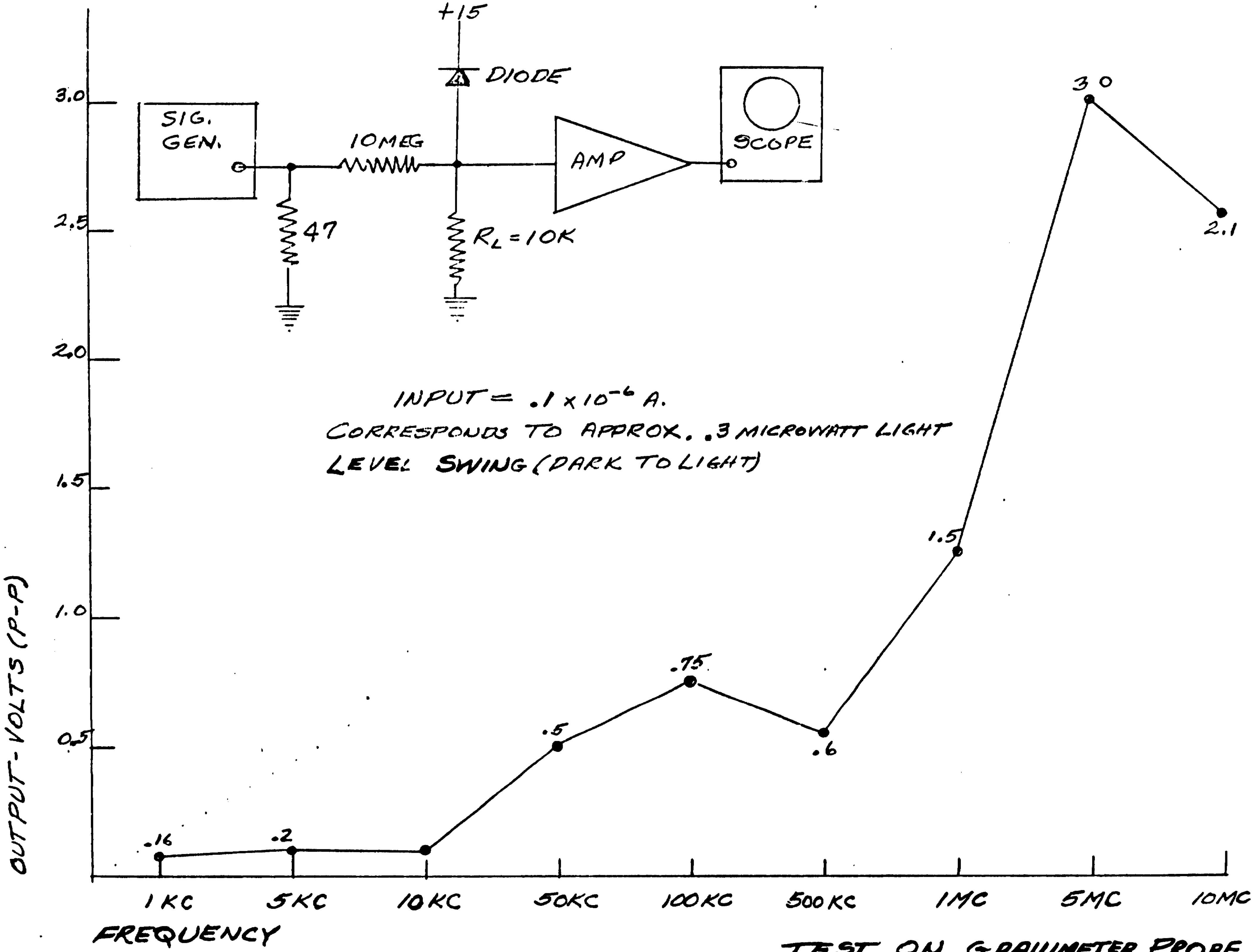
In previous tests of the probe, a 1000 ohm resister was used for the diode load, and the amplifier gain was adjusted to 1000. A diode load of 10,000 ohms has previously been considered as this should theoretically increase the voltage swing output by a factor of ten while increasing the Johnson thermal noise by a factor of $10^{1/}$~~1/2~~. Thus a net gain of signal-to-noise ratio would be obtained. However, based on the values of diode and amplifier shunt capacitance, it was feared that the 1 Khz to 10 Mhz bandwidth would not be achieved. However, it was decided to test the probe with a 10 K ohm diode load resistor.

The test setup shown on the attached data sheet was arranged. The 47 ohm resistor serves as a load for the signal generator, and the 10 megohm resistor is used to establish a constant current source. The probe diode is left connected in the circuit for it's shunt capacitance, but the diode has no light striking it. The diode load resistor was 10,000 ohms. It can be seen that the 10 K load resistor did not limit the bandwidth of the probe to below 10 megacycles. It can also be seen that about 1.5 microwatts of light is required on the diode to obtain a 1 volt peak-to-peak output from the probe. The output noise level measured with this setup was about 200 millivolts peak-to-peak.

After these tests were completed, the probe was restored to its operational configuration and tests were made with the interrupted light source previously discussed. The light level on the probe diode was adjusted to about 1.5 microwatts using the SPACO light meter, previously discussed. Output from the probe with this light level was 2 volts peak-to-peak. Noise was measured at 200 milliwatts peak-to-peak. The light interruption was occurring at a rate of about 1000 hz. This performance of the probe was demonstrated to Mr. Bill Green who was present at SPACO at the time of these tests.

February 28, 1969

The revised probe was taken to Test Division for tests on the gravimeter. The probe, less the mirror assembly, was mounted vertically on the floor and carefully aligned with the light segment carrying what was visually the best fringe. Several bird drops were made and an indication of fringe detection was obtained as observed on the oscillioscope. However, the signal level observed was about the same level as the noise (about 200 mv) and would not trigger the logic circuits. It was observed that the light sensing element of the photo diode was larger in diameter than the fringe width so some integration of dark and light levels was occurring. It is planned next week to fabricate several apertures with accurately aligned holes to sense only the fringe width. Attempts were made to measure the light level at the probe position, but this level is something less than 0.1 microwatt and cannot be sensed with the Spectra-Physics light meter. All of the optics, except the collimater, were removed from the laser, and the laser output was measured at 225 microwatts. Again, no indication could be obtained on the light meter at the probe position. An indication of fringe detection could be obtained from the solid state probe under this light condition, but there was no significant improvement over the previous fringe detection. These tests concluded the work for the week.



INPUT = $.1 \times 10^{-6}$ A.
CORRESPONDS TO APPROX. .3 MICROWATT LIGHT
LEVEL SWING (DARK TO LIGHT)

TEST ON GRAVIMETER PROBE
FEB. 27, 1969

APPENDIX IV

Report on Gravimeter Work

March 11, 1969

TO: Dr. O. K. Hudson

FROM: Chester Savelle, Jr.

SUBJECT: Report on Gravimeter Work

Attached is a report on work accomplished on the Gravimeter Leveling System, prior to the stop order, and work accomplished on the Gravimeter Solid State Probe during the period of March 3 through March 10, 1969.

Chester Savelle, Jr.
Program Manager

cc: Mr. Greene - NASA
Mr. Hatch
Mr. Scates
Mr. Thomas

/ec

REPORT ON GRAVIMETER WORK

Prior to March 3, 1969 (Leveling System)

On February 20, a meeting between Dr. Hudson and Wade Ewing took place at Test Division relative to the auto-leveling system. It was suggested to Dr. Hudson that work could be done on the leveling system concurrently with work on the probe. This suggestion was made because SPACO felt that the auto-leveling system might help maintain alignment on the Mark II Gravimeter, and thus expedite test operational status of this model.

During the meeting, SPACO expressed concern about the problems that might be encountered in leveling the two separate tables. Dr. Hudson quickly eliminated this concern by specifying that SPACO need design a system only for leveling the optical table.

On February 24, a suitable sensor for the light spot position was located and placed on order. A thorough discussion of the system concept was held between two SPACO engineers and work was started on detail design. It was found that, based on 0.1 μw of light level, the leveling system electronics must respond to a signal swing of 60 nanoamperes of current from the light position sensor. Several methods of achieving sufficient signal amplification were studied and a method that seemed suitable was selected. A breadboard of the circuit was constructed, but tests were not completed during the week. A signal integrator circuit is required for the system, and it is required that this circuit hold an attained voltage constant for several seconds while the leveling motors are driven. A breadboard integrator circuit was tested for drift, and it was found that the circuit held constant, within satisfactory limits, for periods of several minutes provided no abrupt temperature changes of the integrator circuit occurred during the period. The integrator must be shielded from abrupt temperature changes, but does not need an expensive temperature control system. During the week several components were received for the leveling system. Work was also accomplished on a laboratory (SPACO) test setup for the leveling system. The concept of the test system is illustrated on the attached sketch. With this setup a movement of the light spot can be obtained on the sensor that almost exactly simulates any movement caused by the bird drop, and the system can be tested and de-bugged prior to installation on the optical table.

March 3, 1969

In a telephone conversation between Dr. Hudson (NASA) and Mr. Ellis (SPACO), it was directed that work be stopped on the leveling system. This was done immediately.

Work was accomplished on a test setup for obtaining a controllable level modulated light source for testing the gravimeter probe.

March 4, 1969

The mounting device for the light sensing diode was revised to bring the Hewlett-Packard 4204 diode out to the front of the front plate of the probe in order to make the diode visible during tests with the gravimeter. This new mounting method is shown on the attached sketch. A feature of the method is the accurate alighment of the diode sensing element (.020") in the center of the 0.5 inch hole in the front plate. The external flange also provided for later addition of an aperture if this was found to be desirable. Incidentally, the machining and materials for this mount were accomplished at no cost to the contract. In addition, a light shield, as shown, was added to shield the diode from ambient room light during sensitivity and bandpass tests.

An informal report was carried to NASA/SSL, and a discussion between Dr. Hudson (NASA), Mr. Greene (NASA), Mr. Ellis (SPACO), and Mr. Savelle (SPACO) resulted in a decision for SPACO to prepare a specification for sending out RFQ's on a solid state probe in the event the SPACO probe cannot be made sensitive enough to detect the gravimeter fringes. Work was initiated on this specification upon return to the SPACO plant.

March 5, 1969

The light modulator assembly for probe sensitivity and bandwidth tests was completed and checked out. The light assembly is shown on the sketch with the diode mounting method. The light assembly slides over the diode light shield, mounted against the aperture ring, and completely shields the diode from room light. This was necessary because increased performance of the probe made it very sensitive to the 60 cycle modulated light from fluorescent lamps.

Modifications were accomplished on the probe to increase gain and to increase the voltage output from the diode. Several possible sources of noise were reworked.

March 6, 1969

In a telephone conversation with Mr. Hatch (SPACO), Mr. Greene (NASA) requested that SPACO measure the light level at the gravimeter probe position. Dr. Hudson (NASA) was contacted by Mr. Savelle (SPACO) regarding availability of equipment to measure the light level. Dr. Hudson suggested that the Hewlett-Packard 4204 diode current be measured and the light level computed by using the diode specifications. This would give a light level relative value that would be adequate for preparing specifications for a solid state probe. SPACO has an electronic microammeter (HP425A) which is suitable for this purpose and it was decided to modify the probe circuit to perform these tests. Prior to probe modification, a test to obtain range data was made with a spare diode, but this diode was inadvertently overloaded during the tests, and although current range data was obtained, the diode was no longer useful.

Inasmuch as very careful adjustments had been made to the probe circuits for increased sensitivity, it was decided to postpone modifications for light level tests until after the planned bandwidth and gravimeter tests had been made on the probe. Bandwidth tests, using the modulated light source, were made and the probe was found to have a flat response from 1 Khz to 10 Mhz with the H-P diode. The amplifier gain was increased to 10,000 and the noise level in the output was 500 millivolts (peak to peak). It was apparent that some of the noise was originating from a nearby radio station, and this noise source should decrease at the Test Division location. So, it was decided to leave the probe in this configuration and make tests with the gravimeter.

March 7, 1969

The probe with the following configuration, was tested with the gravimeter:

1. Diode - HP 4204
2. Load Resistor - 10K ohms
3. Amplifier Gain - 10,000
4. Aperture - None
5. Room Lights - Off
6. Ambient Light - Some (level unknown) from windows through holes in cabinets
7. Probe Position - In fixture on floor facing up into light beam

With the bird in the catcher, fringes were observed in the brightest sector to be about 1 mm wide, and of reasonably good definition. Fringe movement was occuring due to vibrations of unknown origin. This fringe movement was observed on the oscilloscope monitoring the probe output. Several bird drops were made, and definite indications of fringe detection were observed on the scope, but the amplitude of the output would not trigger the counting circuits. It was interesting to note that the probe output noise had decreased as anticipated to a value slightly less than 400 millivolts peak to peak, and the noise was apparently not triggering the counter. One difficulty in the test was that of aligning the diode sensitive area in the best position in the brightest sector. Even though the diode was exposed (with the new mounting), it was difficult to see the diode in the illumination from the fringe light spot. Also, it was felt that the ambient light, noted above, may be striking the diode and "swamping" the fringe detection. For these reasons, it was decided to fabricate an aperture to assist in diode alignment, and to shield the diode from all light rays except those from the gravimeter.

March 8, 1969

At no cost to the contract, an aperture was fabricated as shown on the diode mounting sketch. The diode sensitive area is 0.020" dia. so the aperture was made 0.040" dia. to allow for small mis-alignment errors. At present, the aperture simply snaps on and off of the nylon diode mounting flange. When the probe performance is improved enough to trigger the counter, a more permanent arrangement will be made.

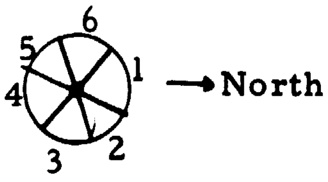
March 10, 1969

The probe circuit was modified to measure the gravimeter light level, and the measurement was made at Test Division by Mr. Page Evans (NASA), Mr. Wade Ewing (SPACO) and Mr. Savelle (SPACO). The test setup, test results data, and computations of light level are shown on the attached data sheet. The previously discussed aperture was used to locate the diode in the brightest portion of each of the six segments, but it should be noted that the aperture does not attenuate the light level inasmuch as the aperture has twice the diameter of the diode sensitive element and the laser light is collimated and coherent. The light level in the brightest segment was computer (4204 Diode Specs attached) to be 0.0092 microwatts. In a conversation with Dr. Hudson (March 6) it was anticipated that the light level swing (modulation) between "light" (no fringe) and "dark" (fringe) would be about 50%. Therefore the anticipated light swing on the diode is 0.0092/2 = 0.0046 microwatts (peak to peak), which results in a current swing (diode output) of 0.0024 microamperes. The present probe amplifier has a 6.0K ohm input impedance. The current of 0.0024 microamps across 6.0K results in a voltage swing of 14.4 microvolts (peak to peak). To achieve a 2.8 volt peak to peak (1.0 volt RMS) output from the probe, a gain of 200,000 will be required. To achieve the 3.0 volts RMS output desired by Dr. Hudson will require a gain of 600,000.

The light level tests verified that the aperture simplifies alignment with the light beam, and it verified that the aperture is required for eliminating "swamping" by any stray light.

March 1969

TEST - LIGHT LEVEL AT GRAVIMETER PROBE POSITION



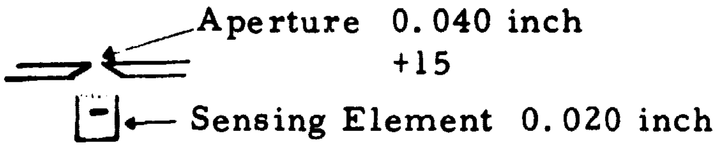
Segment

PK	1	2	3	4	5	6
	3.3×10^{-9}	2.0	4.8	2.4	2.9	1.9

Room Light + 0.2×10^{-7}
meter + 10×10^{-12} offset

0.5 Low Level* (approximate)

*Note: The low level could not be easily measured because the gravimeter fringes would not stay over the aperture for sufficient time to allow the meter to drop to the lower reading.



HP 4204 has sensitivity or output of 0.5 ua/uw of light.

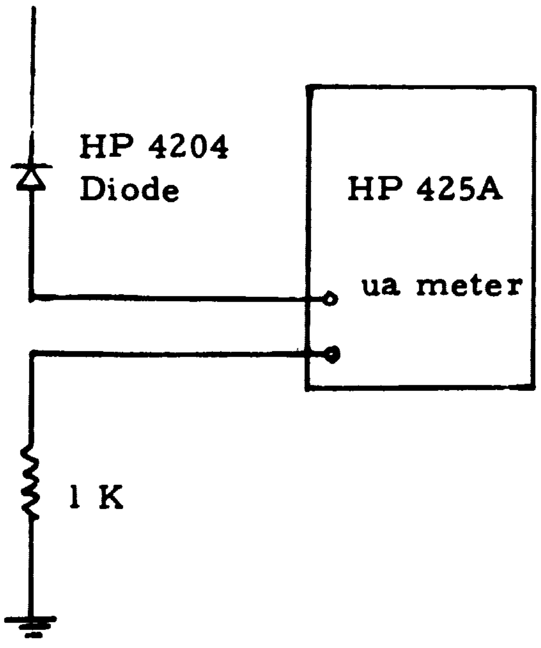
$$\text{Light uw} = \frac{I}{0.5 \times 10^{-6}}$$

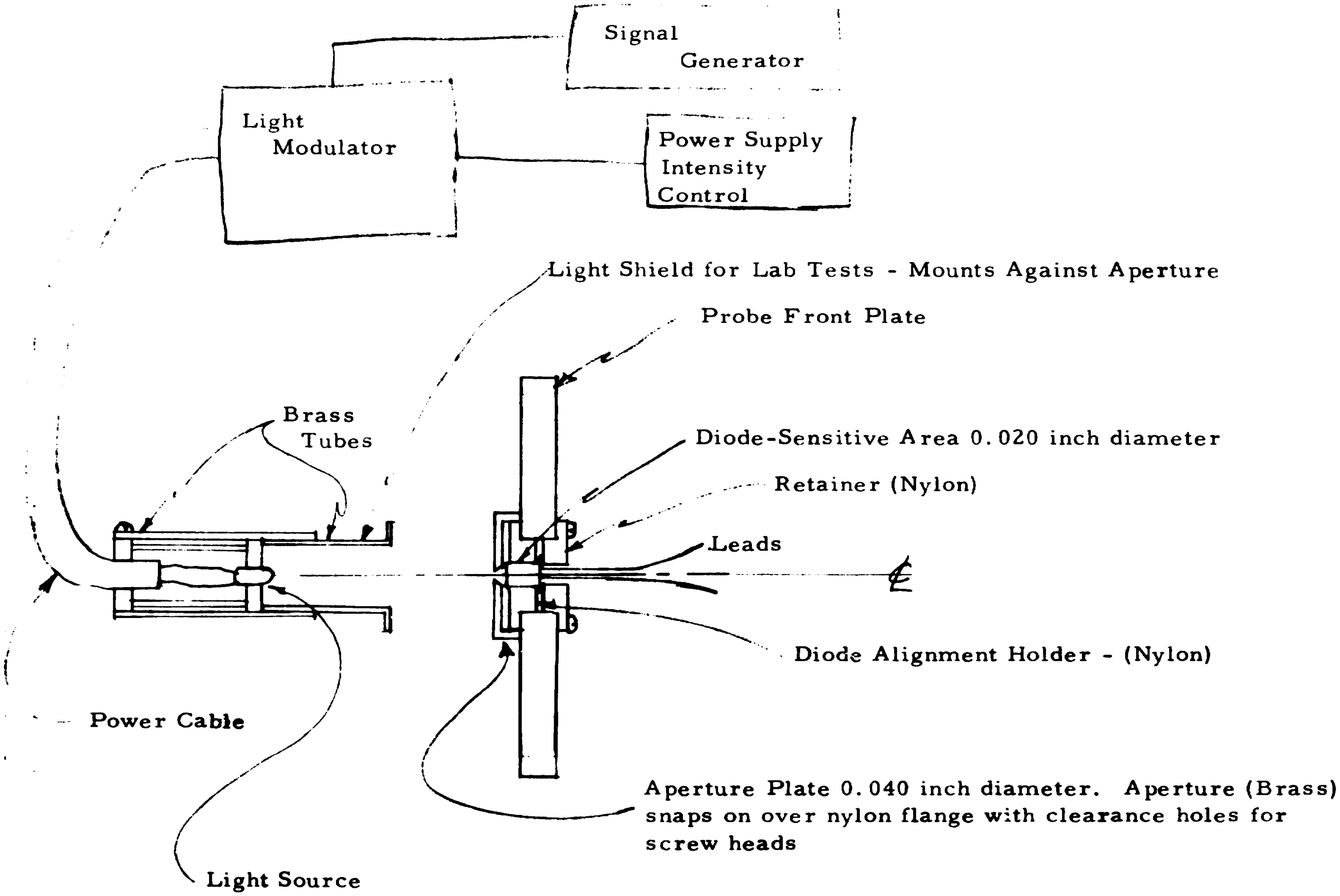
For Segment 3:

$$\text{Light uw} = \frac{(4.8 - 0.2) \times 10^{-9}}{0.5 \times 10^{-6}}$$

$$= 9.2 \times 10^{-3} \text{ uw}$$

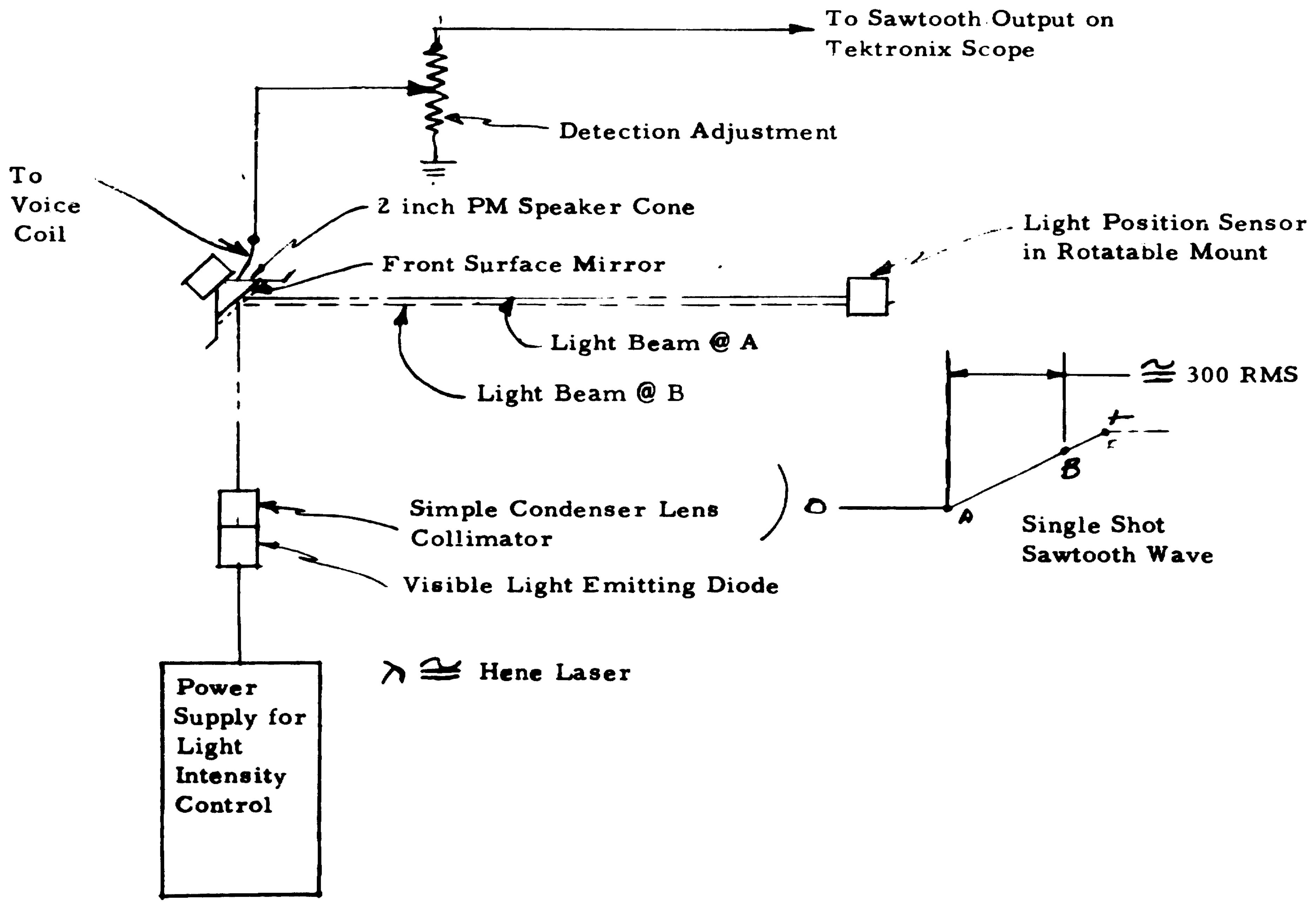
therefore, light level equals
9.2 nanowatts or .0092 microwatts





GRAVIMETER PROBE
DIODE MOUNTING AND LIGHT
SOURCE FOR TEST

MARCH 1969 Chester Savelle, Jr.



TEST SETUP
GRAVIMETER LEVELLING SYSTEM

FEBRUARY 1969 Chester Savelle