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SUMMARY FINAL REPORT

ABSORPTIVITY/EMISSIVITY MEASURING SYSTEMS

By

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Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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FOREWORD

The basic optical and electrical system design during the breadboard phase was devised primarily by S. Aisenberg and V. Rohatgi with the assistance of J. Dodge. The prototype construction phase and mechanical design was directed by G. Kropa, while the reliability and program documentation was the concern of D. Cipolle. J. Newman with the assistance of J. Feather was concerned with the prototype electronics and the final assembly and testing. The prototype assembly was performed by R. Hopkins. The final calibration was done by J. Dodge and S. Aisenberg. The drawings and prints were made by C. Fong.

ABSTRACT

This report describes a flight instrument package designed for the study of the change of energy absorption (absorption, α) and the energy radiation (emissivity, ϵ) of vehicle surfaces during various phases of a space vehicle mission. The measurement is performed by having the test surface mounted on a sample drum and able to rotate into the interior of the measurement instrument where the visible and infrared reflectivity can be measured. The surface is then rotated back to the outside of the vehicle. The test surface spends a large majority of its time on the outside of the vehicle, and a relatively small fraction, 5%, of its time within the vehicle during the measurement cycle.

The technique for determining the α and ϵ consists of measuring the reflectivities of the surface in the visible and infrared range from which the emissivity and absorptivity are deduced. The instrument is designed to measure the total specular and diffuse reflectance in both spectral ranges simultaneously for the same surface. To measure the total reflected energy from the sample, an integrating sphere is used which permits a simultaneous measurement of absorptivity and emissivity for a single specimen without requiring separate optical systems for the two different wavelengths.

A special textured (faceted) and highly polished aluminum lining for the integrating sphere has been developed which acts to break the directionality of light after a minimum number of reflections. Because of the high reflectance of Al in the infrared (and moderately high reflectivity in the visible range), one textured integrating sphere can be used to measure absorptivity and emissivity at the same time.

The radiation source for the reflectance measurement consists of a tungsten filament lamp with a tuning fork chopper to modulate the incident light beam. Optical filters are used in front of each detector to separate the radiation in different ranges. A silicon diode is used for visible light (about 0.5 micron) detection, while the infrared in the 3 micron range is measured by a thermistor cell. High gain low noise tuned operational amplifiers are used to amplify the detector signals. An automatic gain control with feedback regulation is used to correct the changes of detector sensitivity. Operatinnal amplifiers with diode feedback are used to accurately convert the ac signal to the dc output.

An internal calibration surface for both the absorptivity and emissivity measurements and a calibration sequence before each measurement has been included to reduce the errors due to drift and component variations. Integrated circuits and operational amplifiers are used in the instrument to reduce weight, power, and size. Digital timing circuits are used to program the various sampling, calibration, and measuring cycles.

CONTENTS

Contents (Continued)

ILLUSTRATIONS

Illustrations (Continued)

TABLES

1. INTRODUCTION

The basic purpose of this program is to develop a flyable instrument designed to measure the absorptivity and emissivity of surfaces on vehicles in space. It is required that this measurement system works during the lift-off phase as well as the space phase of the vehicle flight. The purpose of this instrument package is to study the change of energy absorption (absorptivity) and energy radiation (emissivity) of various surfaces during various phases of the vehicle flight. It is particularly of interest to determine during which phases of the flight any changes of absorptivity/emissivity occur. The change in absorptivity/emissivity can result in undersired changes of vehicle temperature.

As a result of the development work on this absorptivity/emissivity system an improved integrating sphere system was conceived and has been described in a patent disclosure forwarded to NASA/Huntsville, November 2,1967 in accordance with the requirements of the new technology provision. In addition a paper describing the instrument system is being prepared for presentation at the 1968 meeting of the Instrument Society of America.

The instrument package is designed so as to mount flush with the surface of the vehicle without protrusions that could interfere with the normal air flow during the flight of the vehicle.

The efforts on this program were curtailed because of lack of funding. The Whittaker Corporation partially supported the effort to allow one bench model of the system to be delivered with a complete set of working drawings.

2. BASIC SYSTEM DESCRIPTION

The flight instrument package designed is for the study of the change of energy absorption (absorptivity) and the energy radiation (emissivity) of external surfaces of a space vehicle during various mission phases. The unit is designed to mount flush with the surface of the vehicle without protrusions that could interfere with the normal air flow during the vehicle flight. The surface measurement is performed by having the test surface mounted on a sample drum and able to rotate into the interior of the measurement instrument where it can be probed by means of the visible and infrared reflectivity measurement instrument and then rotated back to the outside of the vehicle. The test surface is planned to spend a large majority of its time on the outside of the vehicle, and a relatively small fraction, 1 to 10%, of its time within the vehicle during the measurement cycle.

The passive temperature control of a spacecraft in orbit is a serious problem. The change of vehicle surface properties in space (due to retro-rocket exhuast contaminants, due to prolonged ultraviolet radiation from the sun, and due to particle bombardment) can result in the loss of temperature regulation of the vehicle in space. From the energy balance conditions it follows that the steady state temperature of a body is governed by the optical properties of the spacecraft coating. In particular the ratio of emissivities of the surface in the visible and in the infrared range plays an important role in determining the temperature of the vehicle.

Considerable efforts[1][2] have been reported for the laboratory study of absorptivity α, and of the emissivity ϵ. The measurements of α/ϵ in simulated conditions are rather difficult and unreliable to the extent that the real space environments are unknown and cannot be easily reproduced in laboratories. Still more difficult is the problem of simulating the test surface with the actual flight history. Thus, to obtain more accurate information regarding the optical properties of the coatings, a system has been designed which can measure the α/ϵ of a test surface subjected to the space environment.

The system for determining α/ϵ consists of measuring the reflectivities of the surface in the visible and infrared range. From the measured reflectance, the emissivity and absorptivity are deduced assuming that there is no transmission loss. The instrument is designed to measure the total reflectance in both spectral ranges simultaneously for the same surface.

Figure 1 illustrates the design of the system. The test surface is a flat circular disk (about 0.5 inch diameter) mounted on a rotating sphere such that the surface is flush with the vehicle skin for most of the time except when it is withdrawn inside the vehicle for the measurement. Typically the sample stays in the exposed position (facing the space environment) for about 90% of the time, and in the measuring position for about 7% of the time, allowing 3% of the time in travel. After the reflectance measurement is made, the surface is returned to its original position.

On the same sphere is mounted another highly polished stainless steel surface at an angle of 120° from the test surface. This acts as a standard surface against which the exposed surface is calibrated. The sphere is turned (and returned) through only 120° so that the standard surface is never exposed to the outer space. In addition, light and dust baffles are provided to keep the steel surface and other optics free from contaminants. Normally the steel surface stays at the entrance of the integrating sphere and is used to permit the correction for the thermal drift and aging of light source, detectors, and amplifiers.

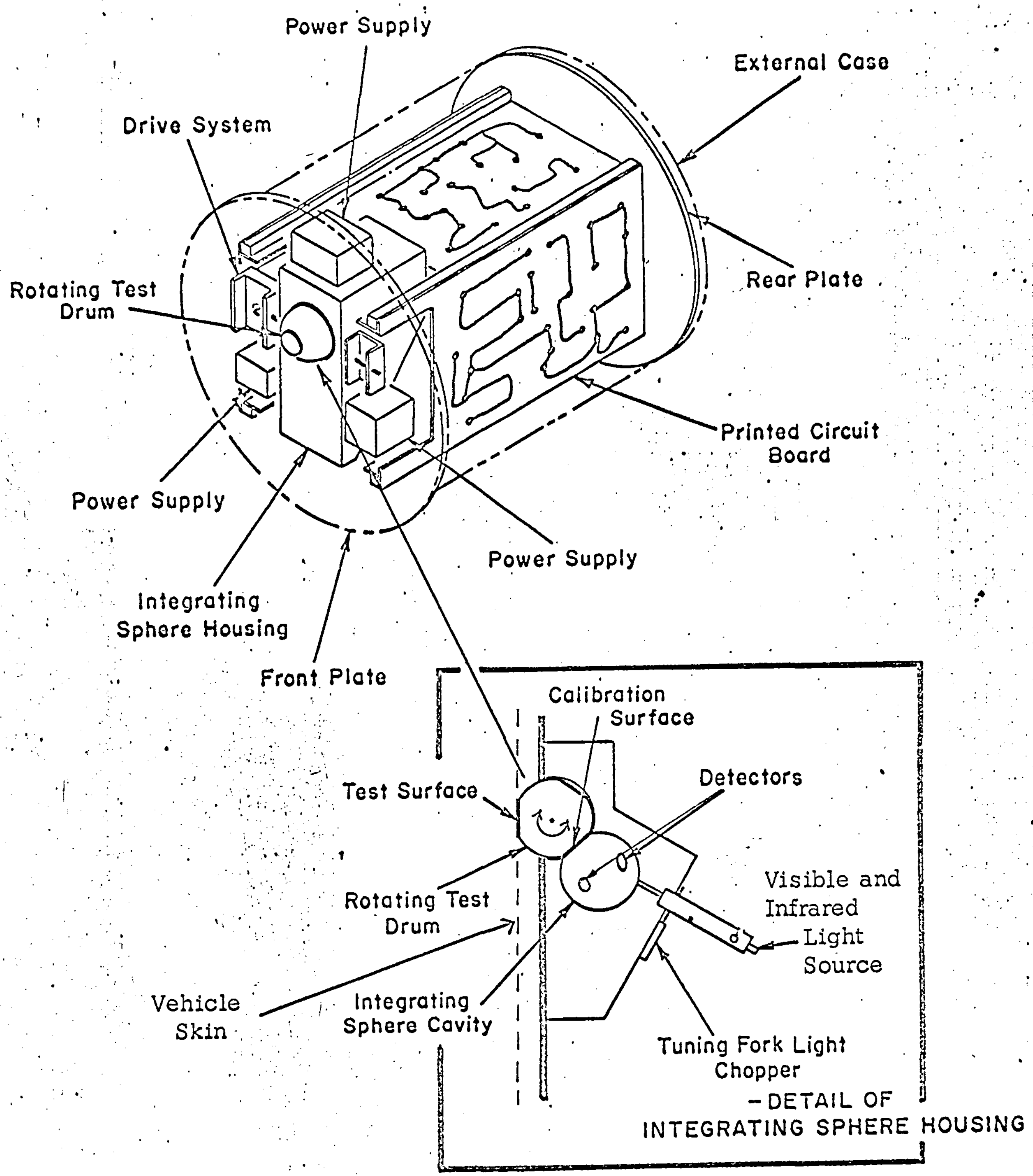

FIGURE 1.
EMISSIVITY AND ABSORPTIVITY MONITORING SYSTEM
(Visible and Infrared)

Since the object of these measurements is to study the balance of radiation emitted and absorbed at the surface, it is necessary that the total reflectance consisting of specular and diffuse reflections be measured. This is also important because during the flight, when the surface changes, it is possible that the ratio of specular to diffuse reflection may also change. Hence, to measure the reflected energy from the sample, a special integrating sphere is used. A two inch diameter integrating sphere with a textured metallic lining has been developed for this instrument. The advantage of an integrating sphere over a wide angle lens system is that an opening in the sphere has a high acceptance angle (180°) and collects the light reflected in all directions. This also permits a simultaneous measurement of absorptivity and emissivity for a single specimen without requiring complicated lens systems for two ranges of wavelengths.

The integrating sphere works on the principle that after a few reflections within the sphere, the light then becomes sufficiently randomized so that the light can be sampled from a small opening in the sphere(3). Thus, ideally an integrating sphere with a high reflection coefficient over a wide range (visible and infrared) is required for this purpose. The usual MgO coating was found unsatisfactory for the present application because of its low reflectance in infrared(4) and because a thick coating layer is unable to withstand vibration. A special textured (faceted) and highly polished aluminum lining has been developed which acts to break the directionality of light after a minimum number of reflections. Because of the high reflectance of Al in the infrared and visible range, one integrating sphere can be used to measure absorptivity and emissivity at the same time. The use of a textured metallic lining for integrating spheres has not been located in the published literature.

The light source for the reflectance measurement consists of a tungsten filament lamp. The filament operating at 2300°K radiates usable power of about 2% in the visible and 80% in the infrared range. The light beam passes through stops, a lens and a mechanical chopper before being incident on the test surface. The reflected light, after being randomized by the integrating sphere, is sampled by visible and infrared detectors separately. Optical filters are used in front of each detector to separate the radiation in different ranges. A silicon diode is used for visible light (about 0.5 micron) detection while the infrared in the 3 micron range is measured by a thermistor cell.

The low level, ac signal from each detector is passed into a low noise preamplifier tuned to the chopper frequency of 100 cps. After amplification by a variable gain amplifier, the signal goes into a superlinear demodulator designed to convert the ac signals into dc signals. Hence, the dc signal is related to the intensity of light reflected from the surface on the rotating sphere. A 100% reflecting surface gives a signal of 5 volts. The signal is then fed to telemetering as well as to logic gates which are used for the internal calibration.

The gains of the amplifier chains are electronically adjusted to give a standardized output when the internal calibration surface is in position: The gains are automatically frozen during the time that the calibration surface is briefly replaced by the test surface. Associated with the optical systems are integrated circuit timers and logic gates which control the individual measuring and calibration steps. Operational amplifiers and integrated circuits were extensively used in order to reduce cost, weight, and power requirements.

The actual rotation of the drum is accomplished by means of a permanent magnet stepper motor because it is free from difficulties associated with commutator brush operation under vacuum conditions. The relative phase of the excitation to the motor coils determines the sense of the rotation. A special drum drive logic system coordinated by the sequence timers is used to determine the rotation of the stepper motor.

By means of a special integrating sphere construction, valid for both visible and infrared light, it has been possible to reduce the weight, size and power requirements of the system package. Internal calibration for both the absorptivity and emissivity measurements has been included to reduce the errors due to drift and component variations.

3. OPTICAL FEATURES

The special optical features incorporated in the absorptivity/ emissivity measuring system are described in this section.

3.1 Choice of Integrating Sphere as Light Collector

In order to measure the energy balance or the energy acceptance of various surfaces, it is necessary to be able to measure both the specular and diffuse reflections. The surfaces that might be of use in space vehicles could consist of very shiny surfaces with a very high specular component or could consist of granular painted surfaces with a very high diffuse reflection coefficient. It is also possible that the surface may have a strong mixture of both specular and diffuse light reflection. This is also the case for the infrared range corresponding to the determination of the actual values of emissivity. It is, therefore, necessary that the system collecting the light reflected from the test surface be capable of collecting essentially all of the energy reflected specularly as well as diffusely. In order for this to be done effectively it is important that the collecting system have as large a solid angle as possible.

High collection efficiency using lenses requires that they have extremely large apertures; estimates based on only a 10% loss of diffuse reflection require f numbers of about 0.2 as computed from the Lambert cosine law (an analysis is presented in Appendix A). Available lens systems appear to be limited to f numbers of about 0.6 or 0.7. It therefore appears that if a lens system was used, there is a possibility of error in comparing the specular and diffuse reflection. If one is guaranteed that all of the energy is reflected specularly then this problem does not exist, since a moderately good lens should collect the reflected specular beam. If the energy is guaranteed to be all diffuse according to a cosine law then, again, the measurement can be made accurately since the error can be computed and a correction factor applied.

If the light reflected is an unknown mixture of specular and diffuse reflection, then it is difficult to determine the correction factor required without knowledge of the mixture of the specular and diffuse reflection coefficients. This information is not expected to be readily available. Even if it is available for certain materials, it will limit the variety of materials that can be studied with this measurement system.

For these reasons, the integrating sphere concept was improved and used. The advantage of the integrating sphere is that the opening has an acceptance angle of 180°. A properly designed integrating sphere will collect the light going in all directions, and, after a large number of reflections, will essentially randomize the light so that the light can then be sampled from the integrating sphere by a small opening at an appropriate point for the measurement. In this way, the light detected and measured by the detector is directly related to the light reflected from the test surface.

A very easy method of calibration, of course, is to put in a test surface with a known reflection coefficient. If the integrating sphere has a very high reflection coefficient, then the specular light and the diffuse light are equally well randomized and the conversion of reflected light, both specular and diffuse, to light coupled out in a detector is accomplished with equal efficiency. Therefore, the sampled light will be a measure of the total reflection coefficient, both specular and diffuse. Normally, one requires a reflection coefficient in the integrating sphere of about 97 or 98%, so that a very large number of reflections can be obtained before the reflected light drops by an appreciable fraction. In this way, the large number of relatively unattenuated reflections is responsible for very adequate mixing of the directions with the light collected by the integrating sphere. If the reflectivity of the interior surface of the integrating sphere is not large enough, however (of the order of 0.8 or 0.9), then a relatively small number of reflections can be obtained before the reflected light drops to the point where it can be considered negligible. Thus, the direction of the light is not adequately mixed, and then the coupling between the reflected light and the detector can be a function of the position of the detector and the position of the reflecting surface.

The light beam enters the integrating sphere for reflectance at a small angle with respect to the surface normal, so that any specular reflected light impinges on the sphere away from the entrance aperture and is therefore not immediately lost. The measuring aperture for the detector is placed so that it looks at an undisturbed portion of the interior of the integrating sphere.

A special improvement was made in the integrating sphere design so as to permit surfaces with relatively low reflection coefficients to be used satisfactorily as an integrating sphere surface. It appears that this method has not been used by others, and may become a contribution to others working in this field.

Since the system is designed to operate both in the visible and infrared ranges, one needs an integrating sphere lining which is a good reflector in both ranges. A material which is a good reflector in the visible range is magnesium oxide, which has a reflectinn coefficient of about 97 - 98%. Surfaces such as aluminum, copper, gold, etc. with very high conductivity have very high reflectivities in the infrared range (reflectivities of the order of 98%), so that these surfaces are quite good in the infrared system.

One possibility is to use an integrating sphere with MgO lining for the visible range and a metallic lining for the infrared range. This would require the use of two integrating spheres, two rotating spherical drums (one for the visible range and one for the infrared range) together with the use of separate infrared and visible sources that are separately chopped by Bulova tuning fork modulators. There is some question about the stability of the MgO lining under vacuum conditions. (The self-calibration feature of this measurement system would make slight variations of the integrating sphere relatively less unimportant.)

It was found possible to modify the integrating sphere coatings so that one could use one integrating sphere for both the visible and the infrared. Normally, one could not use the MgO coating for the infrared range since it was found by experimentation that an integrating sphere with MgO coating would work well in the visible range, but not in the infrared range. Presumably, this is because of the low reflectivity of the MgO coating in the infrared range. The reflectivity of MgO in the infrared range can be increased by using a very thick MgO coating. Unfortunately, however, such a thick coating probably would not withstand the shock and vibration conditions. It was found that an aluminum coating which has a high reflectivity in the infrared range, has a low reflectivity in the visible range, and therefore had a differential sensitivity to specular and diffuse reflection in the visible range. It was found by direct experiment that the use of a faceted aluminum lining in the integrating sphere gave sufficient directional mixing of the collected light in a relatively few reflections. Thus, in construction of the breadboard system, it was possible to use the faceted aluminum coating for the visible as well as the infrared system. Also one was able to use a simple drum with one test surface and a single integrating sphere. One light source was used together with one mechanical chopper. Two detectors, (an infrared and a visible one), were mounted at appropriate points on the integrating sphere.

The basic principle of the integrating sphere is that light going in any direction from the surface in the aperture of the integrating sphere suffers a large number of reflections off a high reflectivity wall, so that its original direction is randomized. In this way it is impossible to distinguish between specular and diffuse light reflected off the test surface in the aperture. The randomization requirement is that the light be randomized before the multiple reflections appreciably reduce the light intensity. There are two ways of doing this - one can use a smooth surface and depend upon a large number of reflections for the randomization, or one can use a surface which has a large number of facets in it so that after only one reflection from this faceted surface the light is largely randomized. Therefore, a relatively small number of reflections from a moderately reflective, faceted surface is capable of accomplishing the same randomization as many reflections from an unfaceted surface. It is necessary that the facet size be small (on the order of 1/10th of the size of the test surface) particularly for the specular component. The measurements that have been made to show the improvement that was obtained by using a faceted aluminum lining rather than a smooth aluminum lining in the integrating sphere are described in more detail in Section 6, where the calibration procedure is discussed.

3.2 Detectors

The detectors that were used are relatively compact and sensitive detectors. For the visible range an Edgerton, Germeshausen and Grier Photo Conductive Silicon Detector, Model #SGD-100 is used together with a stable very low noise 40 volt supply. The photo conductive current that flows is proportional to the photon flux in the visible range striking the detector. The voltage developed across a series resistor is a measure of this photon flux and is amplified by the low noise preamplifier. The spectral range is determined by the spectral characteristics of the light bulb, of the EG&G detector and of a filter placed in front of the detector. The overall system spectral sensitivity in the visible was computed to have 3db points at 0.49 and 0.65 microns.

The infrared detector is a Barnes Thermistor Detector which is designed to be sensitive to infrared radiation in the range from 1.5 microns to 20 microns. A germanium window lens is used over the detector for focusing the infrared radiation and increasing the sensitivity, and at the same time preventing the transmission of visible light. The Barnes Thermistor Detector consists of two thermistors connected in a bridge system. One of the thermistor resistors is exposed to ambient temperature changes as well as the incident radiation, while the other thermistor detector is exposed to ambient temperature changes but is shielded from infrared radiation. In this way the system is largely balanced against ambient temperature changes. The output impedance of this thermistor detector is about 100,000 ohms and the signal that is developed is amplified by the low noise preamplifier. The spectral characteristics of the infrared system is determined by the spectral output of the bulb and the detector characteristic. The overall system spectral sensitivity in the IR range was computed to have 3db points and is primarily limited by the infrared transmission of the bulb envelope.

3.3 IR Source

For the measurement of the reflection coefficient of the surface in the infrared range (which is related to the emissivity of the surface in this infrared range) it is necessary to provide a source of this infrared radiation. Since the available power for the whole instrument is low, it is anticipated that not more than 1 watt can be used for this infrared source. The usual infrared sources that are used in laboratories are large high-power heaters and cannot be used for this sophisticated flyable instrumentation package. It was ascertained, however, that a reasonably rugges light bulb will give a significant amount of infrared radiation through the normal glass envelope of the bulb. Thus with the use of appropriate filters at the detector, the infrared radiation can be separated from the visible radiation. The radiation that will be able to pass through the normal glass envelope of the small bulbs will be limited to wavelengths of about 3.7 microns or less. This is the infrared bulb source that has been used. Because of limitations on the funds available, the infrared radiation was not extended to the 5 to 10 micron range.

In order to obtain infrared radiation in the 5 to 10 micron range it would be necessary to modify these bulbs by removing part of their windows and replacing them with germanium, which is capable of transmitting the 10 micron radiation. Some bulbs utilizing germanium and Kodak Irtran windows have been made and tested at SSI and were shown to be satisfactory. The bulbs that were used, however, were initially of the larger filament size variety for ease of manipulation and fabrication. In order to use filaments which are resistant to shock and vibration it is necessary to use very small bulbs which are somewhat more difficult to fabricate. Modification of these vibration resistant bulbs would be necessary for a 5 to 10 micron range system. Additional testing would be necessary to verify the replacement vacuum seal and the life of the modified source.

4. MECHANICAL FEATURES

The pertinent mechanical features incorporated in the absorptivity/emissivity instrument are discussed in this section. A set of mechanical drawings have been supplied, separate from this report, in the event that more detailed design information is desired.

4.1 Package Design

The absorptivity/emissivity instrument is designed to withstand vibration and shock, and to operate for up to 1 year in a space environment. Special attention was given the design to produce a light weight package. Electronic components were selected to operate between -25°C and +85°C. The basic configuration is shown in Figure 1. Basically a circular base plate is used for mounting of the optical portion and the heavy electronic components. A set of struts is used to meet a backplate on which supply is fastened, and an aluminum shell is used to slip over the package which bolts to the front panel with the appropriate gasketing. This approach produces a lightweight rigid structure. To minimize vibration damage, it is intended to encapsulate the electronic assembly in a lightweight foam.

The input and output connectors are secured on the back of the package and is electrically isolated to minimize signal interaction. The electronics are mounted on epoxy printed circuit fiberglass boards which are fastened to the struts providing additional structural stiffening. The use of an internal strut structure which is fastened to the exterior aluminum shell gives a rigid but lightweight construction.

4.2 Epoxy Fabrication

In order to simplify the construction of the integrating sphere for the prototype units, the technique of epoxy encapsulation was used. The master block was made of epoxy using casting techniques. Once the master blocks were made, a set of RTV molds were fabricated. By using these molds, duplicates of integrating sphere blocks were cast out of a rigid epoxy in such a way as to minimize subsequent machining steps. It was found that once the first master and molds were made, subsequent blocks could be produced with little effort.

4.3 Stepper Motor for Drum Rotation and Locking

The mechanical portion of the absorptivity/emissivity measuring system consists of the basic structure and the system used to transfer the test surface from the exterior to the interior of the measuring module. It was desired to be able to rotate the drum 120° to bring the test surface into the instrument for measurement, then to let the drum remain stationary during the measurement phase and then to rotate the drum back 120° to replace the test surface at the outside of the vehicle. Since the instrumentation must be capable of withstanding significant shock and vibration, it was necessary to insure that the linear vibration would not cause the drum to rotate either during the measurement phase or during the calibration phase when the test surface is outside and the calibration surface is at the entrance to the integrating sphere.

Originally a rack and pinion system was planned utilizing a solenoid to drive the rack first in one direction and then in the other. It was decided to abandon this system in spite of its advantageous features of simplicity because of the susceptability of this system to linear vibration along the axis of the rack which could be converted into drum rotation. In addition, there was the complexity of requiring a certain amount of standby latching power to keep the drum against limiting stops so as to maintain its angular accuracy.

For this reason, a rotary motor drive was selected in order to make the system more immune to linear vibration. A simple DC motor designed for vacuum operation in space was considered because the control circuitry for driving the motor forward and reverse was quite simple. In discussion with manufacturers, it was found that the brush life on the commutators of DC motors is limited under vacuum conditions, and probably would not be much more than

50 hours. This lifetime is not satisfactory based on the design goal of one year of operation. There are no real difficulties anticipated with bearing or gear operation under vacuum conditions according to various motor manufacturers that were contacted. It was therefore decided to go to a motor which does not utilize brush commutators. This means that one would use electronic circuitry to take the place of the commutators. A stepper motor featuring a permanent magnet driven by a rotating vector generated by two phase excitation of fixed coils was decided to satisfy the requirements of long life under cacuum conditions and is used in the prototype units.

In order to rotate the drum to bring the test surface in and to return it to the outside, it was necessary that the stepper motor be reversible and operate both in the forward and reverse direction. This necessitated the use of a stepper motor inverter power supply which is then driven appropriately by the drum drive oscillator clock and controlled by a drum drive logic which steers the command pulses to the appropriate points for both forward or reverse rotation.

The mechanical drive system used with the stepper motor to drive the drum is a worm gear train. This system gives both increased torque and a self-locking system to the rotating drum. When the power is removed from the motor, the mechanical advantage of the worm gear prevents the drum from moving. Mechanical limit stops are adjusted to bring the desired test and calibration surface into position in the integrating sphere at the appropriate point for the measurement cycle.

The mechanical stop mechanism consists of a series of segmented washers which will allow 6 and 2/3 revolutions of the motor shaft. This in conjunction with the twenty to one worm gear ratio allows 120° rotation of the drum.

During the development phase, problems were encountered in the drum drive mechanism. To increase the reliability of the drum drive systems, extra pulses were supplied to the stepper motor. These extra pulses made it quite difficult to locate the drum within the required ±2°. The reason this occurred was because the added pulses at the end of the motor travel, after the worm hit the mechanical stop, tended to drive the motor in the reverse direction for two pulses, or as much as 180° of the motor shaft which could mean as much as 9° on the drum. During testing, a maximum of 120° of reverse movement was noted on the motor shaft due to motor reversal. To minimize the effect of this, the worm was slotted 150° and a pin was inserted in the motor shaft. This allows 150° movement of the motor shaft before the drum turns. Tests, that have been performed after this design modification, have demonstrated that the drum can be located within ±1° or a reversal of the worm of only 20°. This allows a minimum of signal change as a result of drum movement.

In future designs of a drive system, a solenoid system should be re-investigated. A system using solenoids could be designed that would not be effected by linear vibrations. Since the system being discussed is a two position system, a solenoid operated unit would be the simplest approach and would probably have increased reliability.

4.4 Chopper

The mechanical chopper for the optical beam is a Bulova Type 40 with a Type 4A driving circuit which is capable of interrupting the beam at a frequency of 100 cycles per second. The power requirements correspond to 28 volts at about 140 milliwatts.

5. DESIGN FEATURES OF THE ELECTRONIC SYSTEM

In this section a more detailed description is given of the various components of the electronic system. The interrelationship of these components is indicated in Figure 2 which outlines the basic measurement system and which describes the system components for the measurement of absorptivity and emissivity.

5.1 Low Noise, Tuned Preamplifier

A special preamplifier was designed and constructed for the amplification of the signals obtained from the infrared and visible detectors. The signals from the visible and infrared detectors are of the order of 100 to 200 microvolts. Figure 3 shows the circuit that is being used. A low noise operational amplifier was converted into a tuned amplifier by the use of frequency selective feed-back in the operational preamplifier. This system is adjusted so that the Q is not too high in order to maintain the bandwidth of about 10 cycles and to give a response in time of about 1/10th of a second. This is fast enough to make measurements during the short time that the drum is in position during the test surface measurement phase.

It can be seen that the preamplifier is a straightforward design and uses a relatively low noise, low power operational amplifier. The gain is about 250 and peaks at about 100 cycles per second. The measured rms noise level from this preamplifier with a 100K source impedance (IR detector), or a 1 meg source impedance visible detector is 1 microvolt rms or less. Two of the tuned preamplifiers are used, one for the visible signal, and one for the IR signal.

5.2 Second Stage Amplifier

The output of the preamplifier is further amplified by a 709 Type integrated circuit operational amplifier (A1) shown in Figure 4.

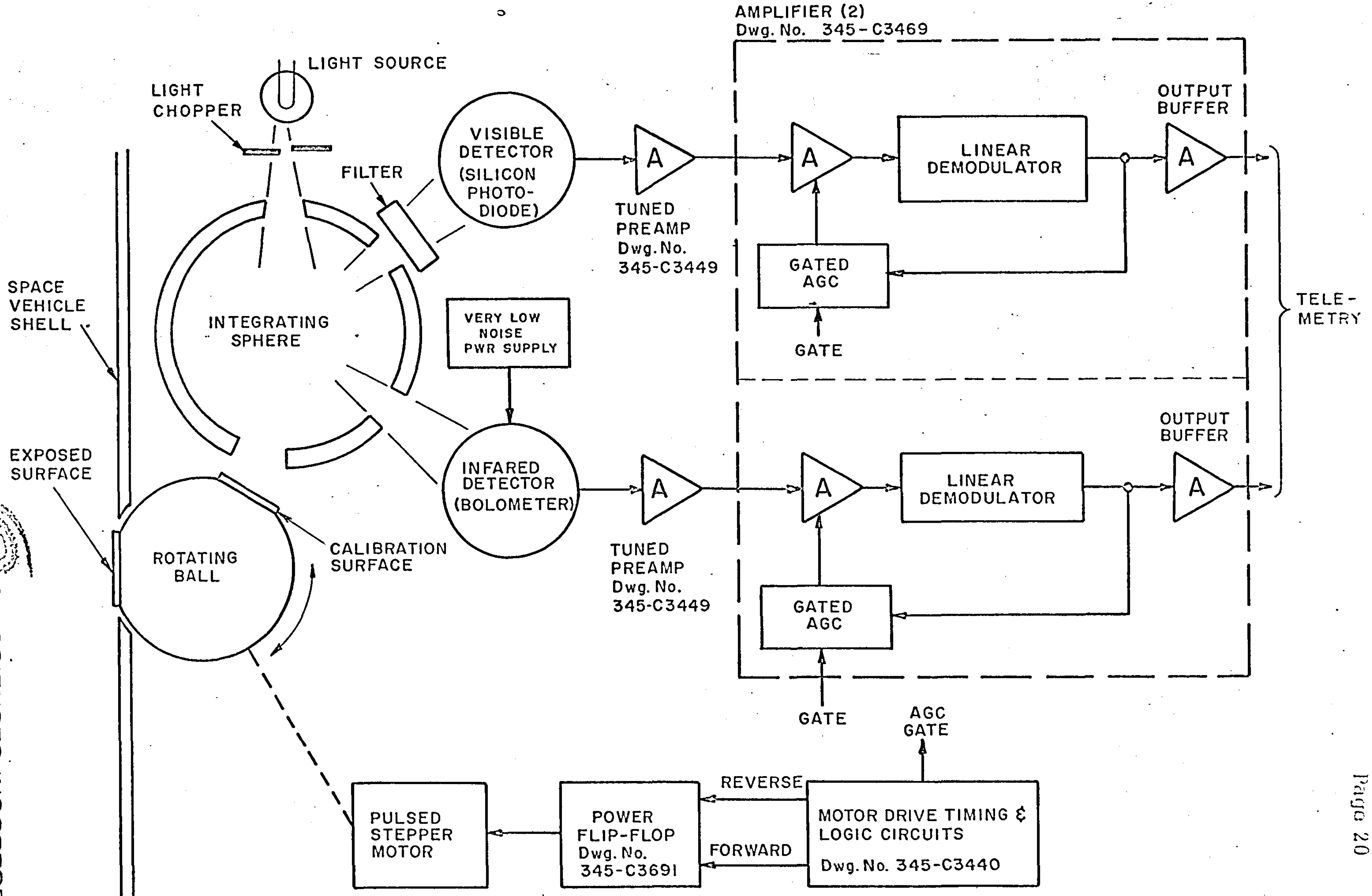

FIGURE 2
FUNCTIONAL DIAGRAM - ABSORPTIVITY/EMISSIVITY SYSTEM

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

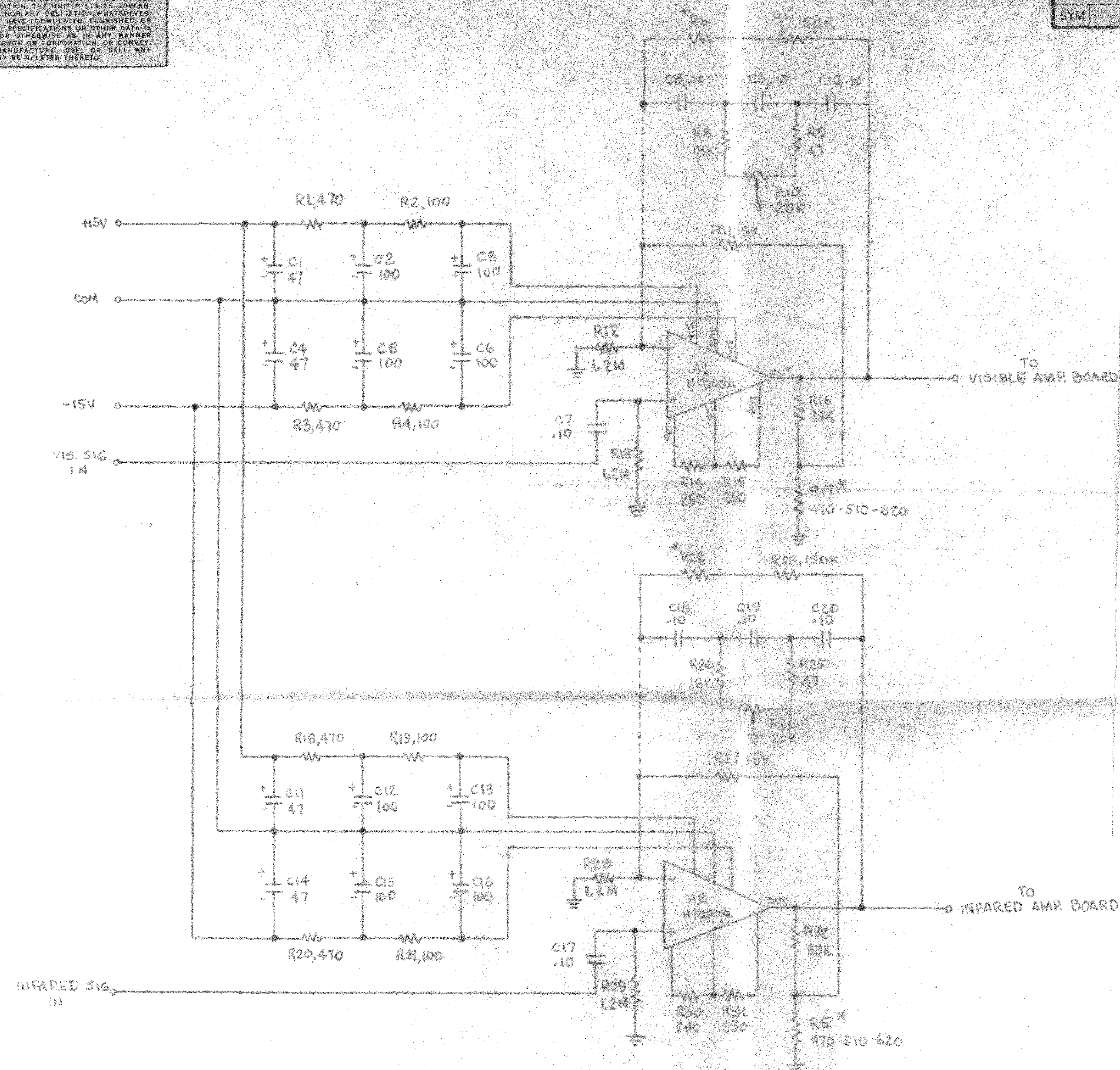

FIGURE 3.

NOTES:

1. * ARE RESISTORS SELECTED AT ASSEMBLY
2. ALL RESISTANCE VALUES ARE EXPRESSED IN OHMS AND ARE ±5%, 1/4 W.
3. ALL CAPACITANCE VALUES ARE EXPRESSED IN MICROFARADS.
4. CIRCUIT TO BE COMPLETED WITH A JUMPER WIRE DURING TEST ASSEMBLY.

ITEM NO.	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND/OR SPECIFICATION	REMARKS

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON
FRACTIONS — DECIMALS — ANGLES —

MATERIAL/HEAT TREAT/FINISH —

NEXT ASSY 345-D3448

DR Paul G. Day DATE 22 MAR 1968
CHK J.E. ... 3/22/68
APPROVALS
SUBMITTED
APPROVED

SPACE SCIENCES, INC.
WALTHAM, MASSACHUSETTS

TITLE
SCHEMATIC-PREAMPLIFIER

CODE IDENT NO. | SIZE C | DRAWING NUMBER 345-C3449 | REV -
SCALE — | WT | SHEET 1 of 1

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

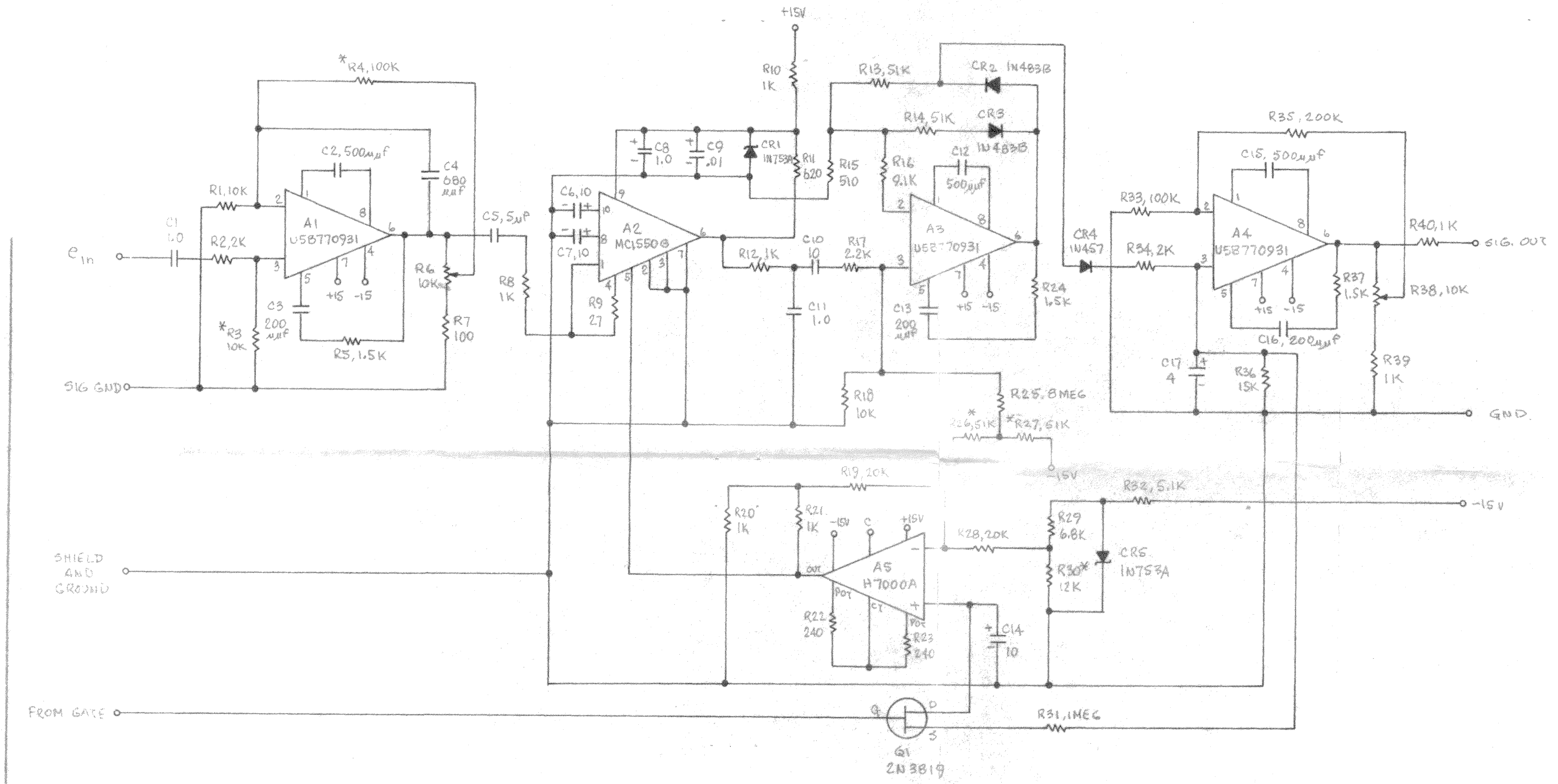

FIGURE 4.

NOTES:

1. UNLESS OTHERWISE SPECIFIED:
   ALL RESISTANCE VALUES ARE EXPRESSED IN OHMS, AND ARE ±5%, 1/4W.
2. ALL CAPACITANCE VALUES ARE EXPRESSED IN MICROFARADS.
3. ALL RESISTOR VALUES MARKED *, ARE NOMINAL, EXACT VALUE SELECTED AT FINAL TEST.

ITEM NO.	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND/OR SPECIFICATION	REMARKS

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS ± DECIMALS ± ANGLES ±

MATERIAL/HEAT TREAT/FINISH

DR [signature] DATE

CHK JZZ 5/16/68

APPROVALS

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APPROVED

NEXT ASSY

SPACE SCIENCES, INC.
WALTHAM, MASSACHUSETTS

TITLE SCHEMATIC - AMPLIFIER

CODE IDENT NO. | SIZE C | DRAWING NUMBER 345-C3469 | REV -

SCALE | WT | SHEET

FOLDOUT FRAME 4

FOLDOUT FRAME 5

FOLDOUT FRAME 6

5.3 Gain Control

In order to compensate for variation of detector sensitivity, or of light source output, a variable gain amplifier (A2) shown in Figure 4 was included to permit the overall system gain to be maintained constant when the calibration surface is in position. The gain of the system is "frozen" during the short measurement time when the external or test surface is rotated into position in place of the calibration surface. This method of substitutional calibration compensates for many possible sources of error or drift in the flight instrument. The variable gain amplifier is a very compact integrated circuit.

5.4 Superlinear Demodulator

In order to convert this ac signal related to the light incident on the detector into a dc signal, a superlinear demosulator was used. (The circuit is shown in Figure 4). By means of a diode rectifier network in the feedback loop of an integrated circuit operational amplifier (A3) it is possible to obtain rectification with considerable reduction of any difficulties due to the low level deficiencies of diode demodulators that are normally observed. The demodulator will operate nicely over a wide dynamic range without the usual difficulties that occur at signal levels of several tenths of a volt.

5.5 Output Amplifier

The dc output from the superlinear demodulator is fed to a buffer operational amplifier (A4) shown in Figure 4, to permit the adjustment of the output voltage to the correct value for telemetery. At the same time the output impedance is corrected to a sufficiently low value.

5.6 Gain Gating Circuit and Gain Holding Amplifier

Since the dc output from the also used to adjust the loop gain during the calibration part of the cycle but not during the measurement cycle, it is necessary to time multiplex the dc voltage. Figure 4 includes the circuit diagram to perform this function. An FET switch operated from the gate output of the timing logic circuit controlled the control signal fed into a holding capacitor and then into a feedback amplifier (A5) which controls the gain of the variable gain amplifier (A2).

During the measurement cycle, the FET gate opens and the last value of the gain required is stored in the holding capacitor. In order for the voltage to be held accurately (about 1% or better) for a period of about 0.5 second, the holding time constant should be large (about 100 seconds). For this reason a field effect operational amplifier (A5) was used as the amplifier following the holding capacitor. This operational amplifier was used in the non-inverting mode to retain the high input impedance.

5.7 Low Noise Filter Detector Supply

The Barnes infrared detector provided, requires a well filtered voltage source in order to reduce the noise contribution and to obtain a good signal-to-noise ratio. The Barnes detector is provided with a well filtered ±40 volt supply capable of driving the two thermistor detectors which have impedance of about 100,000 ohms. The EG&G visible detector is operated in the photo-voltage mode and does not require a power supply. The supply that is used consists of simple RC filtering circuits combined with Zener regulators, and dual Darlington transistors. The noise contributed by the detector power supply should be about 1 microvolt or less and was found to be quite small. Figure 5 shows the circuit in more detail.

5.8 Clock and Delay Timers

The measurement sequence for this system occurs as follows: At approximately ten second intervals a ten second clock will give a command pulse signaling the beginning of a measurement. This pulse will go to a delay timer for drum rotation which will generate a gate of about 0.2 or 0.3 seconds

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SYM	DESCRIPTION	DATE	APPROVED

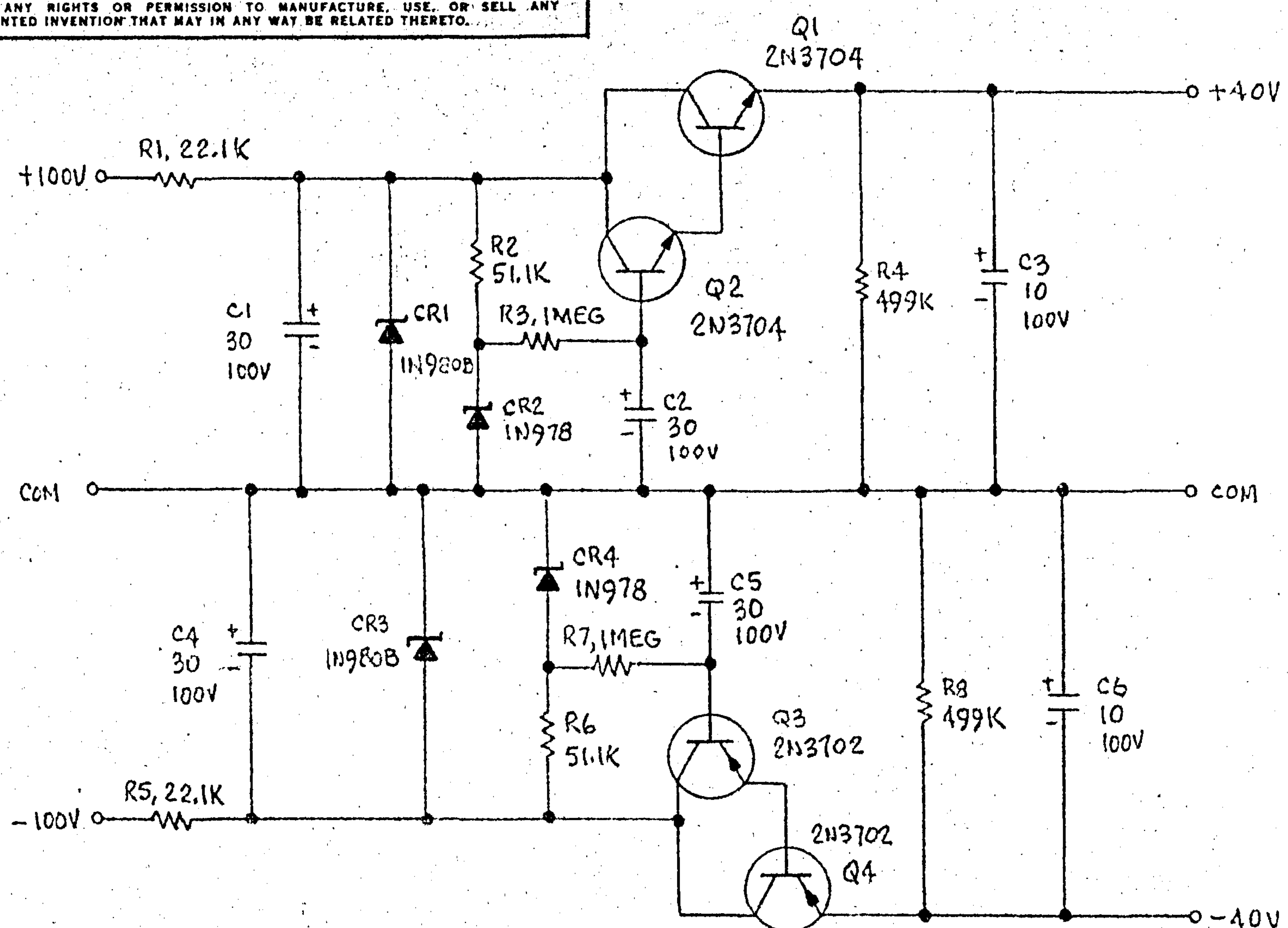

FIGURE 5.

NOTES:

1. UNLESS OTHERWISE SPECIFIED: ALL RESISTANCE VALUES ARE EXPRESSED IN OHMS AND ARE ±1%, 1/4W.
2. ALL CAPACITANCE VALUES ARE EXPRESSED IN MICROFARADS.

ITEM NO.	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND/OR SPECIFICATION	REMARKS

LIST OF MATERIALS

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MATERIAL/HEAT TREAT/FINISH —

NEXT ASSY

DR Carl G. Borg — DATE
CHK
APPROVALS
SUBMITTED
APPROVED

SPACE SCIENCES, INC.
WALTHAM, MASSACHUSETTS

TITLE SCHEMATIC- FILTER CIRCUIT

CODE IDENT NO.	SIZE	DRAWING NUMBER	REV
	B	345-B3459	—

SCALE — WT SHEET 1 of 1

FOLDOUT FRAME 1 FOLDOUT FRAME FOLDOUT FRAME 2 wide which will turn on the power supply for the motor drive oscillator and command a series of pulses at about 65 cycles a second to go to the input producing forward drum rotation. This will rotate the test surface of the drum from the exterior position to the interior measuring position.

The output at the end of the pulse generated by the first delay timer, will trigger the second delay timer which will be activated for a period of about 0.1 seconds corresponding to the actual measurement time. During this time interval, the motor drive will be stopped by turning off the series of pulses to the forward and reverse drive and opening the power conservation switch.

At the end of this measurement time interval, the third delay timer will operate and direct the drum oscillator clock signal to the reverse lead of the drum drive oscillator, and at the same time will turn on the power switch to the drum drive oscillator so that the drum will be rotated to bring the test surface back outside. At the end of this time, the feedback corrective loop will be reactivated, since the system detector is now looking at the internal test calibration system. The timing logic system is outlined in Figure 6 and is shown in more detail in Figure 7.

5.9 Motor Drive and Two Phase Reversible Oscillator

The rotation of the test surface into the measuring system and back out to the surface of the vehicle was a major source of difficulty. The problem was solved, and a discussion will be given here of some of the alternatives that were considered and the reasons for the final choice.

What is required is a system that will rotate the test surface in for the measurement in a small fraction of a second and will rotate the system back out again in a small fraction of a second, so that the actual measurement time will be less than a second. It is necessary that the system be relatively immune from vibration and shock which could move the surfaces away from their proper

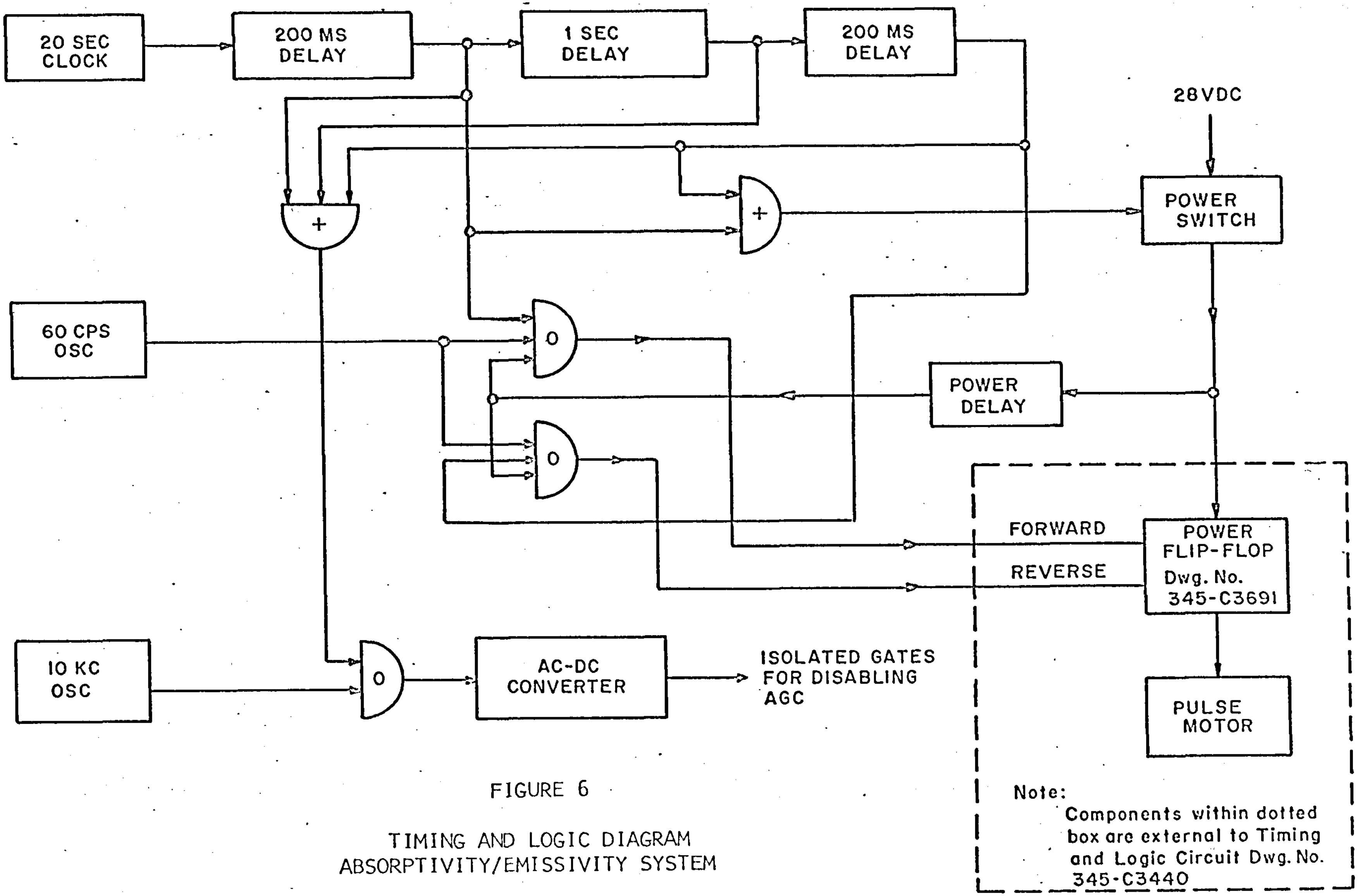

FIGURE 6

TIMING AND LOGIC DIAGRAM
ABSORPTIVITY/EMISSIVITY SYSTEM

GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ... PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY ... PROCUREMENT OPERATION, THE UNITED STATES GOVERNMENT ... NO RESPONSIBILITY NOR ANY OBLIGATION WHATSOEVER; ... THE GOVERNMENT MAY HAVE FORMULATED, FURNISHED, OR ... THE SAID DRAWINGS, SPECIFICATIONS OR OTHER DATA IS ... BY IMPLICATION OR OTHERWISE AS IN ANY MANNER ... OR ANY OTHER PERSON OR CORPORATION, OR CONVEY... PERMISSION TO MANUFACTURE, USE, OR SELL ANY ... THAT MAY IN ANY WAY BE RELATED THERETO.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

FOLDOUT FRAME 3

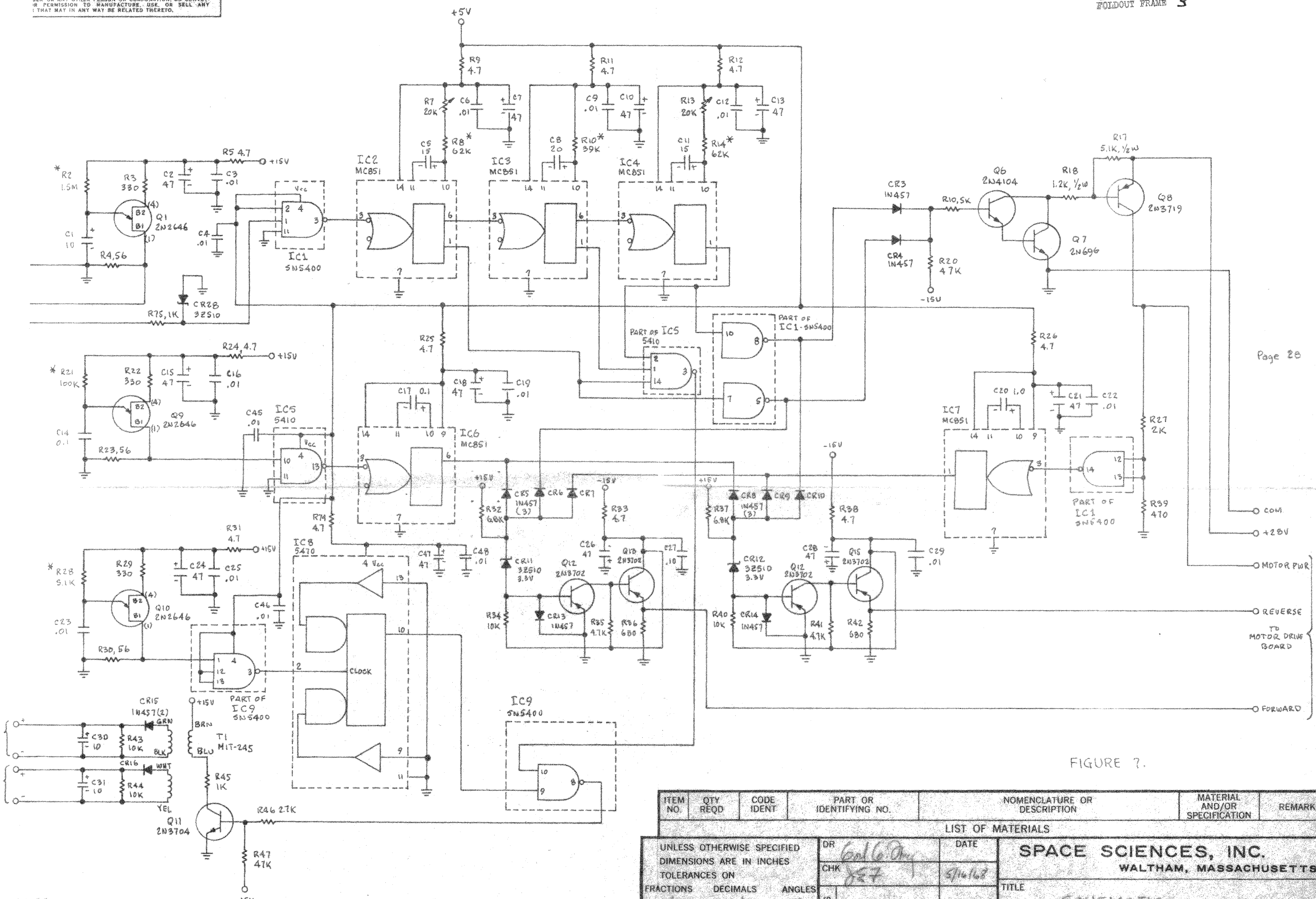

FIGURE 7.

ITEM NO.	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND/OR SPECIFICATION	REMARKS

LIST OF MATERIALS

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NEXT ASSY 345-D3481

SPACE SCIENCES, INC.
WALTHAM, MASSACHUSETTS

TITLE
SCHEMATIC-
MOTOR CONTROL CIRCUIT

CODE IDENT NO. | SIZE C | DRAWING NUMBER 345-C3440 | REV -

SCALE | WT | SHEET 1 of 1

NOTES:
1. UNLESS OTHERWISE SPECIFIED: ALL RESISTANCE VALUES ARE EXPRESSED IN OHMS, AND ARE ±5%, 1/4W.
2. ALL CAPACITANCE VALUES ARE EXPRESSED IN MICROFARADS.
3. * DENOTES RESISTORS SELECTED AT FINAL TEST.

FOLDOUT FRAME 4

FOLDOUT FRAME 5

FOLDOUT FRAME 6

position during measurement and during calibration. The low power availability meant that the mechanical activating system should only operate during the actual drum rotation, and should be turned off during the majority of the cycle. Since the power is turned off, it is necessary to insure that the system is sufficiently locked with zero power so that vibration will not result in drum rotation.

The initial system that was conceived consisted of a rack and pinion which converts linear motion of the solenoid into rotary motion of the drum. It was found that a single solenoid drive acting against a return spring would require too much power. A dual solenoid system was, therefore, tried, using one solenoid to rotate the drum one way and another solecnoid to rotate the drum back into position. In this way the drum was readily rotated with a small amount of power. Unfortunately the linear motion of the solenoid makes it susceptible to linear vibration and shock which could then be converted into drum rotation.

It would then be necessary to minimize this linear motion either by keeping the solenoid excitation on at all times which would be prohibitive from a power point of view, or else using special mechanical or magnetic latching systems which would keep the drum from rotating out of position, or else by using a symmetrical solenoid system balanced against linear vibration. The use of such mechanical or magnetic latching systems would increase the complexity and at the same time significantly increase the starting torque requirements of the solenoid.

The advantage of the solenoid drive is that a simple silicon controlled rectifier can be used to dump energy from a high voltage capacitor into the solenoid in a single pulse for the activation of the system. Since very large instantaneous currents can be permitted to flow through the solenoid, it would be possible to use very large voltage capacitors. The use of high voltage capacitors means that for a given energy storage the size of the capacitor is reduced, since the energy storage is proportional to the size of the capacitor and the square of the potential across the capacitor. This would reduce the weight and size associated with the capacity energy storage which is required for the solenoid drum activation. However, the complexity associated with keeping the solenoid from vibrating against linear motion prevented this approach from being pursued very far.

An alternative method of keeping the drum latched up is to provide a small standby current through the solenoid in addition to the actual turning pulses. This standby current would be much smaller than the actual current required for the actual drum rotation and could give a reasonable holding force against shock and vibration. However, it was felt that since this system is so susceptible to linear vibration, a rotary activating system would be preferable.

For this reason the next stage involved the use of rotary motor plus an appropriate gearing system to the drum. It was found that a DC motor could not be used because the brush life under vacuum conditions would not be long enough to give one a reasonable safety of margin. The alternative of closing the motor in a vacuum case and bringing the torque out through rings was thought of and abandoned, because this could add complexity and development difficulties. Although the use of DC motors is attractive in the sense that the excitation command signal to the motor is quite simple, the use of the brush commutators under vacuum prevented this.

It was therefore decided to use an AC excited motor which required the use of a small low power AC generator. The permanent magnet stepping motor was found to give very high torques for a given size and weight, and therefore was used. The use of the stepping motor requires the use of quadrature excitation of orthogonal coils, turning the rotary permanent magnet mounted on the armature shaft. The sense of rotation is controlled by controlling the relative phase between the excitation in the two coils.

A simple two phase oscillator to drive the stepper motor was supplied by the manufacturer of the stepping motor (Vernatron). But it was found that the actual delivery time of such a circuit by Vernatron would require many months of delay. For this reason it was necessary to build our own version of this oscillator based on their circuit. It was found that their circuit operation was not all that was desired so that the circuit was modified by the addition of transistors operated in the Darlington mode. This saved a delay of several months in the delivery of such a two phase oscillator. It was ascertained by conversations with Vernatron that the stepper motor could be lubricated for long life operation under vacuum conditions.

The two phase oscillator is shown in detail in Figure 8. The control logic is shown in Figure 7.

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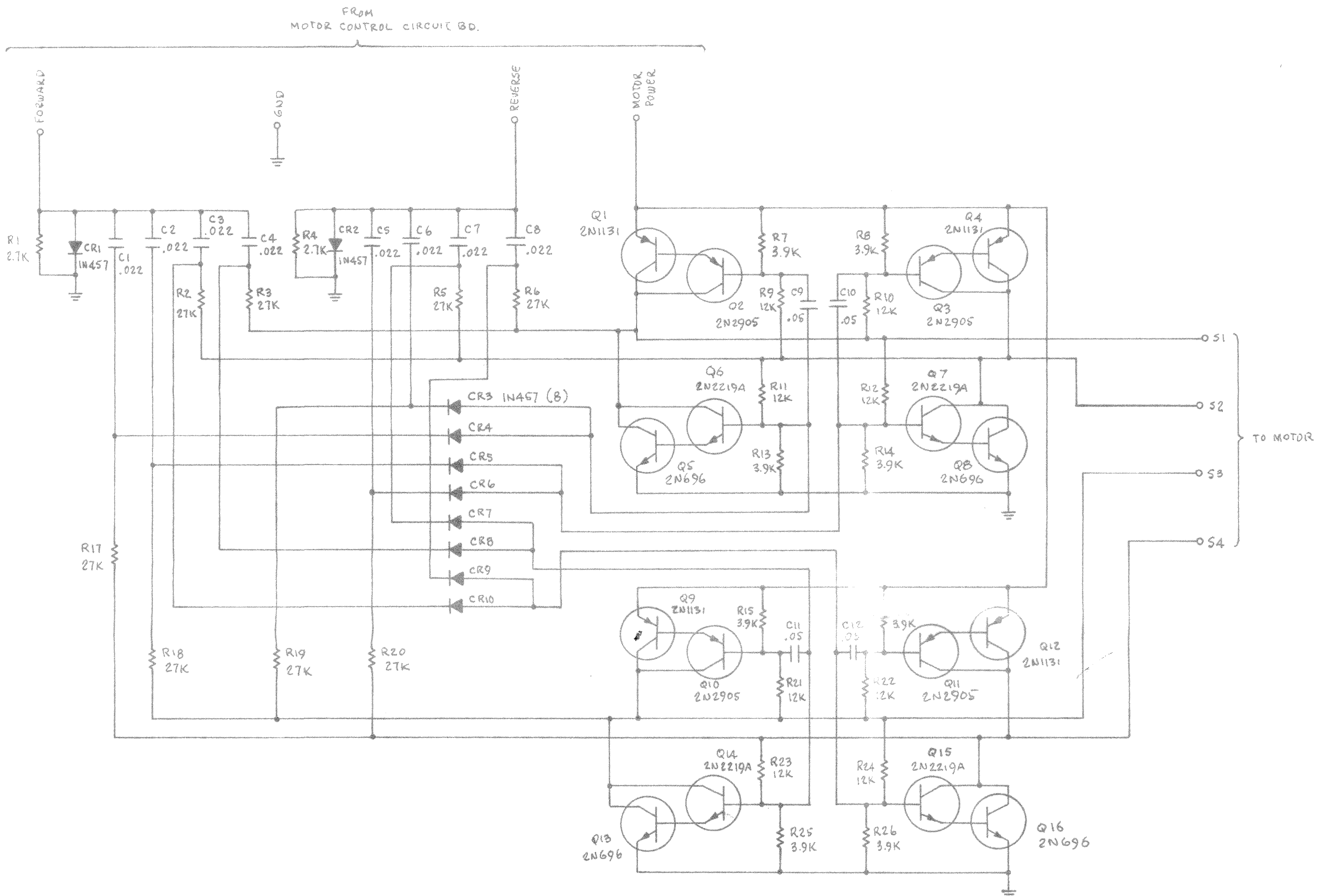
SYM	DESCRIPTION	DATE	APPROVED



NOTES:

1. UNLESS OTHERWISE SPECIFIED:
   ALL RESISTANCE VALUES ARE EXPRESSED IN OHMS, AND ARE ±5%, 1/4 W.

2. ALL CAPACITANCE VALUES ARE EXPRESSED IN MICROFARAD.

FIGURE 8.

ITEM NO.	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND/OR SPECIFICATION	REMARKS

LIST OF MATERIALS

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NEXT ASSY

DR Carl G. Davey
CHK JEZ
DATE 5/16/68
APPROVALS
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SPACE SCIENCES, INC.
WALTHAM, MASSACHUSETTS

TITLE
SCHEMATIC-
MOTOR DRIVE CIRCUIT

CODE IDENT NO. | SIZE C | DRAWING NUMBER 345-C3691 | REV

SCALE | WT | SHEET

FOLDOUT FRAME 4 · FOLDOUT FRAME 5 · FOLDOUT FRAME 6

6. CALIBRATION PROCEDURE

6.1 Introduction

One requirement of the system is that it measure the absorptivity/emissivity to 2% accuracy of full scale with a resolution of 1%. This means that in order to calibrate the system one must have surfaces whose absorptivity/emissivity in the visible and infrared range are known to an accuracy of better than 2%. While there is a great deal of information published in the literature quoting various absorptivity/emissivities of various materials, it should be noted that with the exception of a few materials, the absorptivity/emissivities measured by different researchers for presumably the same or similar materials are sometime significantly different from each other. In addition, it is noted that many of the surfaces experience progressive degradation or change of absorptivity/emissivity so that the actual value of the surface will depend on the time after it has been prepared.

In order to provide a stable reference or calibration surface for both visible and infrared on the calibration drum, a polished stainless steel surface was used. It is quite free from tarnishing problems.

In order to accurately calibrate this absorptivity/emissivity system it was necessary to devise, and construct laboratory calibration instrumentation that could be used to calibrate the actual surfaces that are being measured. The actual calibration of a specularly reflected surface can be done very accurately utilizing the system illustrated in Figure 9. The details of this system will be described in further detail in this section. The construction of a similar system for the measurement of diffuse reflection coefficients, however, is not as easy since it will require the use of a wide angle light collection system. The integrating sphere itself is such a wide angle light collection system. In other words, the integrating sphere can be used for the measurement of relative diffuse

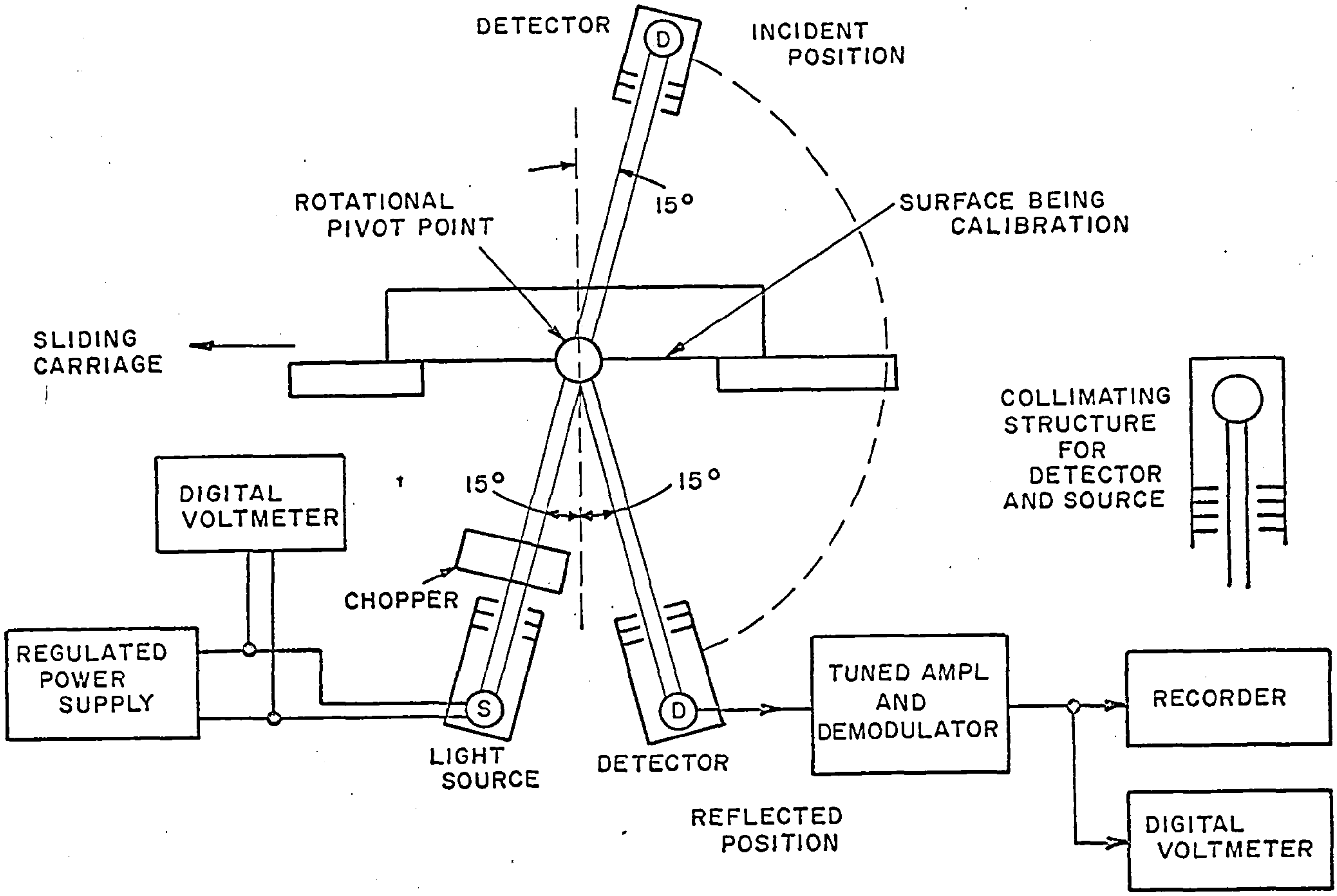

FIGURE 9

SPECULAR REFLECTION COEFFICIENT CALIBRATION SYSTEM reflection coefficients for various surfaces placed in the integrating sphere aperture. However, the absolute calibration can not be accomplished unless one places in the aperture a surface with a known absolute reflection coefficient.

The integrating sphere can be calibrated absolutely by means of a surface whose absolute reflection coefficient is known: Thus the integrating sphere is used in the comparison mode. It should be noted that since the integrating sphere is designed to have the same collection efficiency for both specular and diffuse light, the test surface used for the calibration of the integrating sphere can be a surface which is either completely specular or completely diffuse. Since the system shown in Figure 9 is a calibration jig for accurate specular reflection, the calibrated specular reflecting surface can be used for the subsequent calibration of the integrating sphere in the comparison mode.

The calibration procedure will then be to prepare calibration surfaces and to calibrate them on the specular jig shown in Figure 9 for both the visible and IR range. This permanent calibration surface is then mounted on the calibration position on the test drum. The linearity of the detector system and of the amplifier system then permits the calibration at intermediate points. The calibration can be verified by using other calibrated surfaces in the test position and by plotting the output voltage vs. the surface reflectivity.

In order to verify this calibration in the visible range an MgO surface can also be placed in the aperture of the integrating sphere for a measurement of its diffuse reflection coefficient. It is known that the visible reflection from MgO is essentially diffuse with a reflection coefficient of about 0.97 to 0.98%[5].

In order to utilize the integrating sphere for the measurement of specular and diffuse reflection, and in order to use the technique of a specular surface for the calibration of the integrating sphere, it is necessary to demonstrate that the integrating sphere has the same sensitivity to specular and to diffuse light.

Essentially the difference between the light entering the integrating sphere due to specular and diffuse reflection is due to the different paths that these light components will follow. The essential requirement is that the light going in any specific direction should be quickly randomized so that it is then impossible to distinguish between the light going in one direction from light going in the other direction.

Once this is done then it will not be possible to differentiate between specular and diffuse reflection because the major difference between specular and diffuse reflection is the direction distribution of the light coming off the surface before it enters the integrating sphere. Normally one depends on the integrating sphere to supply a large number of reflections to randomize the light direction with a minimum loss in signal intensity over the number of reflections required. If one requires a large number of reflections to randomize the light and the loss per reflection is not negligible, then the light being randomized in the last few reflections will be different from the light being partially randomized in the first few reflections. Therefore, light that is essentially random to begin with, such as diffuse reflection, will be more readily randomized in the integrating sphere than specular light which is highly directional to begin with. Thus, there will be a larger number of reflections required for specular reflections to be properly diffused, then for the diffuse reflection. The number of reflections required to randomize the light can be reduced if the interior of the integrating sphere itself is a diffuse surface so that right after the first reflection off of the surface the subsequent reflections act upon diffuse light rather than on specular light.

Of course, it should be noted that when light is reflected off of diffuse surfaces at very low angles, the diffuse surfaces act as if they were specular surfaces because the extreme angle minimizes the roughness factor of these diffuse surfaces. For this reason, even lining an integrating sphere with a diffusely reflecting surface will not be completely satisfactory in randomizing the light since a portion of the radiation is reflected as diffuse radiation and the portion at small angles is reflected as specular. A test jig shown in Figure 10 was used to measure the dependence upon the angle of the test surface. This differential sensitivity of the integrating sphere to specular and diffuse light is shown in Figure 11 which shows the angular dependence of the integrating sphere sensitivity for specular and diffuse test surfaces for a specular sphere lining. It can be seen that when the integrating sphere with a specular lining (polished aluminum) looks at the light reflected from a diffusely reflecting surface such as MgO and the angle of the test surface is changed slightly around the symmetry point (as is illustrated in Figure 11), the signal received by the detector is a symmetrical function of the displacement angle. This is what would be expected if the light reflected from the test surface is reflected diffusely and is properly mixed by the integrating sphere with a minimum number of reflections.

On the other hand, the curve in Figure 11 for a specular surface shows that the angular dependence of the integrating sphere sensitivity is not symmetrical and this suggests that the directionality of the specularly reflected light is not sufficiently randomized in the integrating sphere case for the polished aluminum surface. This means that a polished aluminum surface is not a satisfactory integrating sphere lining in the visible range for both specular and diffuse reflection, since there is a differential sensitivity to specular and diffuse reflection as is shown in the difference of the angular dependences.

It is anticipated that one way of utilizing a specular lining in the integrating sphere and still get satisfactory mixing of the specular and diffuse reflection is to use a specular lining with a very high reflection coefficient. Aluminum in the visible range has a reflectivity coefficient of 80 to 90% depending on its state of preparation and its aging. This is not really large enough to give a good mixing of the light direction. However, in the infrared range (from 2 to 10 microns) the reflection coefficient of freshly evaporated

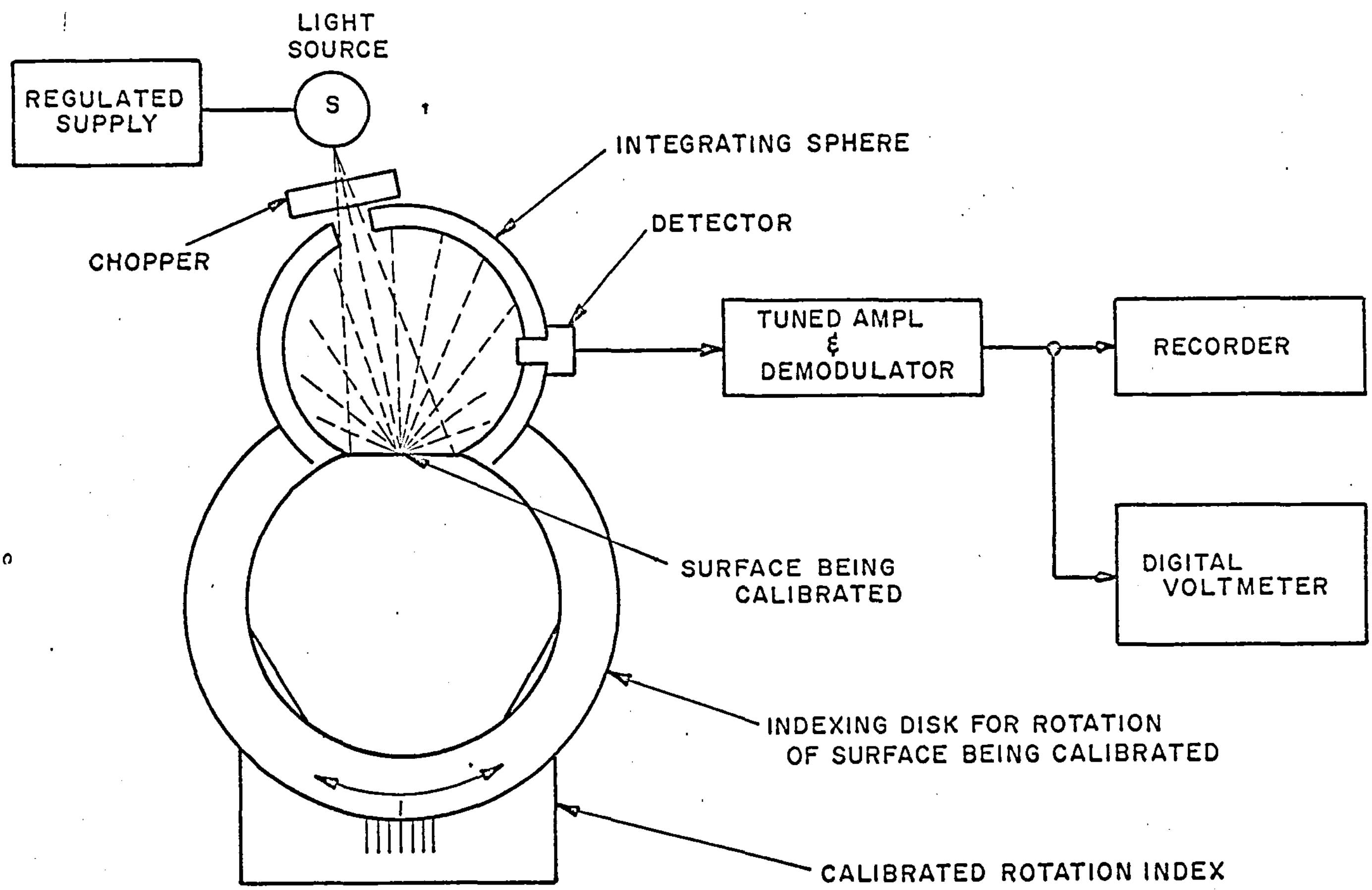

FIGURE 10

SYSTEM FOR MEASUREMENT OF
ANGULAR DEPENDENCE OF INTEGRATING SPHERE SENSITIVITY

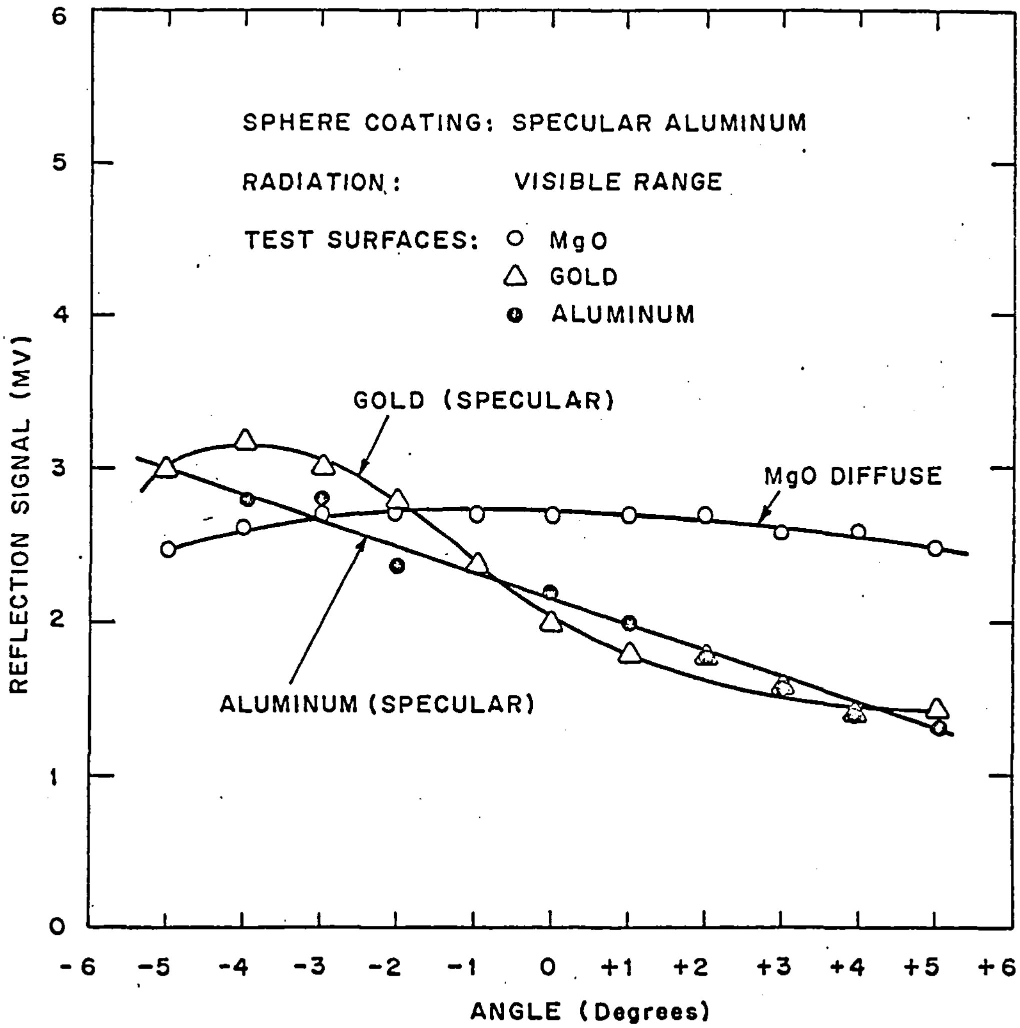

FIGURE 11

ANGULAR DEPENDENCE OF INTEGRATING SPHERE SENSITIVITY FOR SPECULAR AND DIFFUSE TEST SURFACES FOR A SPECULAR SPHERE LINING SHOWING THE ANGULAR DEPENDENCE DUE TO A LIMITED SPHERE COATING REFLECTIVITY IN THE VISIBLE RANGE.

aluminum is around 97 to 98%[6] and gold (from 0.7 to 10 micron) has a reflection from 97 to 98% because of the much larger ratio of wavelength to skin depth for infrared radiation. It is therefore predicted that for an infrared system an aluminum lining for the integrating sphere should be satisfactory and there should be no differential angular sensitivity for viewing both the specular and diffuse reflecting surface. Polished aluminum has a reported reflectivity 97% at 12 microns, but only 73% at 1 micron.

This leaves one with the problem of providing an integrating sphere coating which can be used in the visible range. MgO has a very high reflectivity in the visible range of about 0.97 to 0.98%[5] so that it is anticipated that a MgO coating for the integrating sphere should give the same angular sensitivity for specular and diffuse test surfaces. This result is shown in Figure 12, where it is seen that indeed the expected symmetry is obtained, indicating that MgO is a good coating for both specular and diffuse reflection in the visible range. However, it is found that the MgO coating is not a good reflector in the infrared range except for very thick (fragile) coatings. Therefore, one can not use the same coating for both the visible and infrared range in one integrating sphere unless one uses a special technique which has been devised by Space Sciences Incorporated specifically for this program.

In summary a proper mixing of the specular and diffuse radiation requires the use of integrating sphere coatings with high reflectivities for direction mixing in both the visible and the infrared range. An MgO coating will satisfy this requirement in the visible range but not in the infrared range, while a polished metal surface coating will satisfy this requirement in the infrared range but not in the visible range. It is desired to be able to use a single integrating sphere for both the visible and the infrared range so as to simplify the system, to reduce weight, and to reduce size.

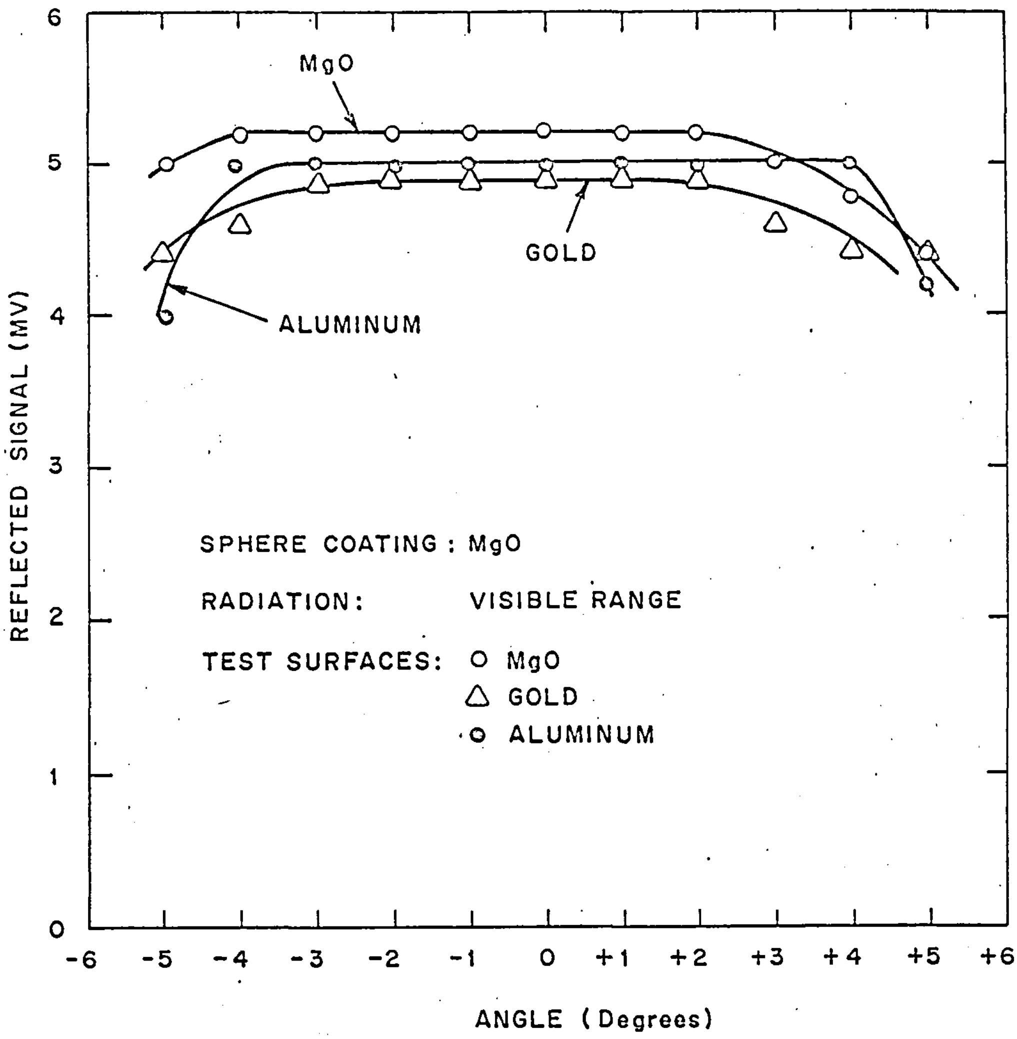

FIGURE 12

ANGULAR DEPENDENCE OF INTEGRATING SPHERE SENSITIVITY FOR SPECULAR AND DIFFUSE TEST SURFACES FOR AN MgO SPHERE LINING SHOWING THE ANGULAR DEPENDENCE FOR A HIGH REFLECTIVITY COATING FOR THE INTEGRATING SPHERE AND FOR BOTH SPECULAR AND DIFFUSE COATINGS IN THE VISIBLE RANGE.

If it were not possible to make one integrating sphere for both the infrared and visible range it would be necessary to mount two integrating spheres side by side and use an MgO coating or equivalent for one integrating sphere for the visible range, and a polished aluminum coating for the other sphere for the infrared range. This is one form of solution which is not particularly desired although it would work. Another possible disadvantage of using a MgO coating is that it may degrade under vacuum environmental conditions to the point where it could hurt the calibration. (It should be noted, however, that the self-calibrating feature of the system as devised by SSI would take care of reasonably small degradations of reflection coefficients for the integrating spheres.)

However, a much more attractive solution has been obtained to permit one integrating sphere coating to be used for both the visible and the infrared range. This solution revolves about the recognition that the purpose of the integrating sphere is twofold. One is to collect all of the light going in all directions so that its acceptance angle is essentially 180° and none of the light can escape. The second purpose is to take the light which has an arbitrary angular distribution depending upon whether it is specular reflection, diffuse reflection, or a mixture of the two, and convert it into a distribution of light within the integrating sphere which is completely isotropic so that the light can be sampled by viewing at an arbitrary point on the surface of the integrating sphere. In this way the relative amount of specular diffuse light will not matter, and the detector will measure only the total radiation.

The integrating sphere usually accomplishes this radiation randomization through a high reflection coating which results in a large number of reflections in the integrating sphere before the light is appreciably attenuated. These multiple reflections are then counted on to supply the randomization. If the coating of the integrating sphere is a diffuse surface rather than a shiny metal surface then the randomization takes place much more readily, since the specular nature of the radiation is lost after the first few bounces.

It should be noted however that this specular nature is retained for small angles even for a surface which is usually diffuse for normal incidence of radiation. The SSI solution to the problem is to provide a faceted or corrugated or textured metallic lining for the integrating sphere which acts to break up the directionality of the light after a minimum number of reflections. This method does not appear to have been used before, according to a study of techniques reported by various investigators[(5) (7 - 12)]. The fact that the surface is corrugated and reasonably reflective both in the visible and infrared range means that only a very few reflections are required and therefore it is not absolutely necessary to obtain as high a reflection coefficient as possible.

If one uses the textured aluminum foil liner for the integrating sphere then the metallic nature of the surface insures that the reflection coefficient in the infrared range will be very high and the infrared radiation will experience a large number of reflections before being appreciably degraded. The large number of reflections alone is sufficient to insure the randomization of the infrared radiation. The corrugation of the surface also insures that the directionality of the infrared radiation is very quickly destroyed. However, this corrugating is not really necessary in the infrared range because of the very high coefficient in this range. This additional randomization in the infrared range due to the corrugation, however, should not be ignored since it will add to the accuracy and has no disadvantage.

For the visible range the corrugation is absolutely necessary, since the reflection coefficient of aluminum in the visible range is not as high as it is in the infrared range. Thus, fewer reflections are available before the cumulative loss becomes intolerable. However, the corrugated nature of the reflecting surface insures that a small number of reflections will be required for the proper randomization. If the surface being viewed is about 1 cm in diameter so that the specularly reflected beam will be 1 cm in diameter or more, and if the facet size is made so that they are about several millimeters in size, then there will be approximately from 25 to 100 facets exposed within the first specular reflection from the test surface and the directionality of the reflected light will be very quickly lost after the first reflectinn. Other reflections will enhance this randomization even more.

The effectiveness of this approach is shown in Figure 13 for visible radiation, with a corrugated or faceted aluminum coating for both specular and diffuse test surfaces. It is seen that the angle dependence is symmetrical as is expected for the ideal integrating sphere.

6.2 Calibration Measurements

The actual calibration of the standard and test surfaces was done using the system shown in Figure 9. A modulated source of light with collimating apertures was used to project a beam at the receiving detector. When the test specular surface was slid into the optical path, the image of the probing source was reflected and appears at the appropriate mirror location. The detector is then moved (on a rotating arm with the pivot point at the mirror surface) so that the optical path to the detector remains the same in both the transmitted and reflected modes. The ratio of the reflected to the transmitted signals gives the specular reflection coefficient (at the system angle of incidence of about 15 degrees). The detectors are linear so that the signal ratio for both the visible and the infrared is equal to the light ratio. The use of a modulated light and an AC tuned amplifier eliminates the effect of stray light and of noise.

A number of measurements were made on each surface to get a good average value and a value for the probable error. A number of similar surfaces were used to check for material reproducibility. A great deal of effort was taken to polish the surfaces to optically flat conditions. Measurements were taken in the visible range (0.5 to 0.65μ) and in the infrared range (2.0 to 3.7μ). Four different surface

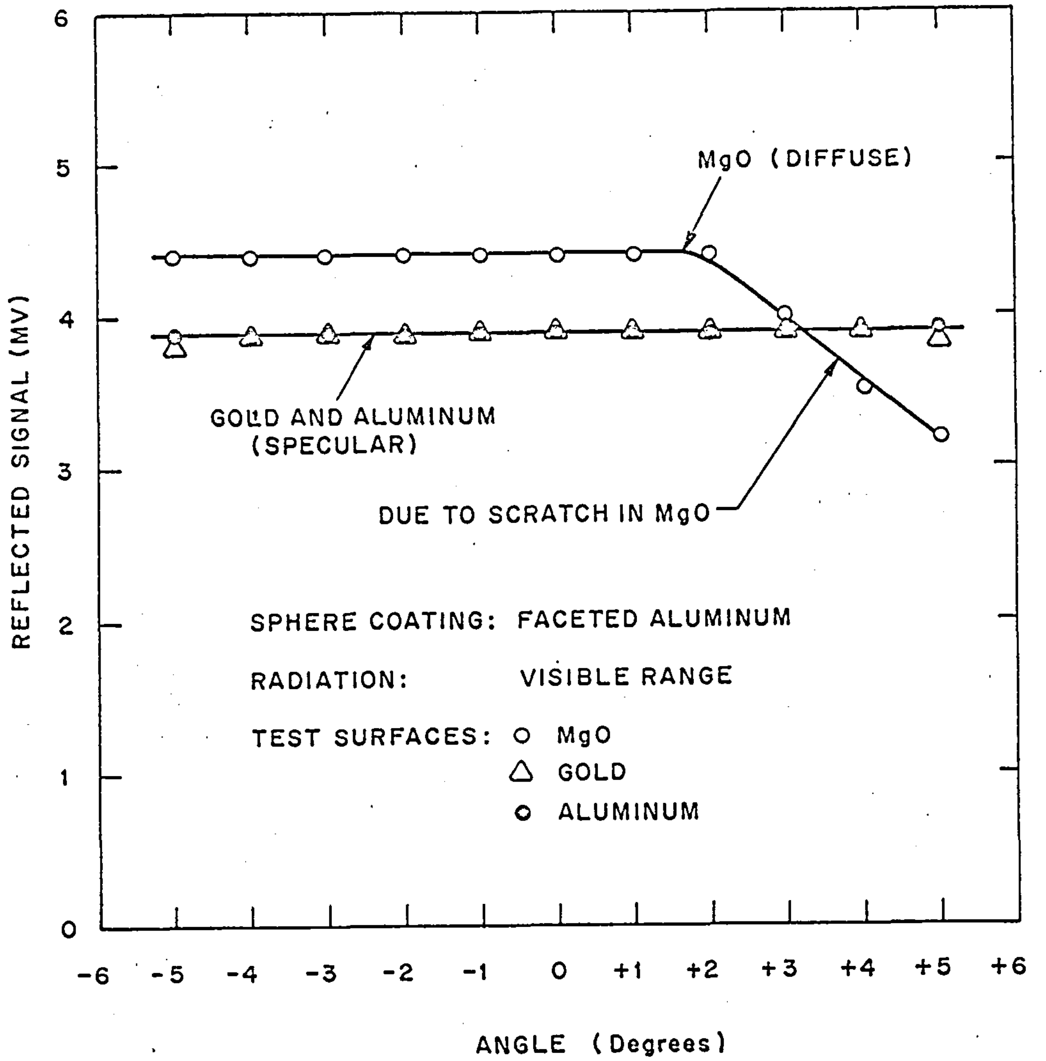

FIGURE 13

ANGULAR DEPENDENCE OF INTEGRATING SPHERE SENSITIVITY FOR SPECULAR AND DIFFUSE TEST SURFACES WITH A FACETED ALUMINUM SPHERE LINING SHOWING THE EXPECTED ANGULAR INDEPENDENCE FOR BOTH SPECULAR AND DIFFUSE TEST SURFACES AS A RESULT OF THE FACETING OF AN INTEGRATING SPHERE LINING WITH A LIMITED REFLECTIVITY (IN THE VISIBLE RANGE).

materials were measured: gold, brass, Al (Type 6061) and stainless steel (Type 304). The results are shown in Table 1 for the various surfaces and the different wavelengths. It can be seen that the individual uncertainty is small and that the agreement between different samples of the same material is better than 1%.

The stainless steel surface is used as the internal standard for the flight instrument. The system is adjusted so that an output of 5 volts corresponds to a reflectivity of 100% so that for the visible range the output for the stainless steel surface is 61.1% of 5 volts and for the infrared range is 78.4% of 5 volts.

The output voltage is proportional to the reflectivity. The emissivity can be computed from the reflectivity by means of the following simple argument. The sum of the absorptivity α and reflectivity R is unity so that

$$\alpha + R = 1 .$$

From the concept of detailed balance the absorptivity α is equal to the emissivity ϵ at that same wavelength. Thus, the emissivity α in the visible range is related to the reflectivity in the visible range R(V) and

$$\alpha(V) = 1 - R(V).$$

The emissivity in the infrared range

$$\epsilon\ (IR) = \alpha(IR)$$

and

$$\epsilon\ (IR) = 1 - R(IR).$$

Thus the absorptivity and emissivity can be computed from the reflectivity data according to the equations above.

Table 1

Summary of Calibration Measurements
of Specular Reflectivity for Various Samples and Materials

Sample	Infrared Range (2.0 - 3.7μ) Reflectivity (%)	Visible Range (0.49 - 0.65μ) Reflectivity (%)
Au 1	99.5 ± 0.4	81.0 ± 0.3
Au 2	98.7 ± 0.4	80.9 ± 0.5
Au 3	99.3 ± 0.6	80.9 ± 0.3
Au 4	98.5 ± 0.4	80.9 ± 0.3
Mean Au	99.0 ± 0.9	80.9 ± 0.5
Al 1	89.9 ± 0.3	72.1 ± 0.3
Al 2	89.6 ± 0.2	71.7 ± 0.2
Al 3	89.4 ± 0.3	71.9 ± 0.2
Al 4	89.6 ± 0.3	71.8 ± 0.1
Mean Al	89.6 ± 0.7	71.9 ± 0.7
304 SS 1	78.4 ± 0.2	61.3 ± 0.2
304 SS 2	78.4 ± 0.5	60.8 ± 0.1
Mean SS	78.4 ± 0.2	61.1 ± 0.5
Brass 1	93.0 ± 0.2	74.1 ± 0.5
Brass 2	92.7 ± 0.2	74.1 ± 0.2
Mean Brass	92.9 ± 0.3	74.1 ± 0.5

The accuracy requirements on the reflectivity can also be specified. If one requires an accuracy of 1% of full scale ($\alpha \pm 0.01$) in the deduced value of α (or of ϵ) the corresponding accuracy in reflectivity can be found from;

$$dR = - d\alpha$$

$$\frac{dR}{R} = - \frac{d\alpha}{R}$$

where $d\alpha = 0.01$ for 1% full scale accuracy. Thus the required dR/R can be specified as a function of α and of R and is shown in Table 2. Thus, for very low reflectivity surfaces or high emissivity surfaces the accuracy requirement in the reflectivity is less stringent.

The measurement system is adjusted so that an output voltage of +5.0 volts corresponds to a reflectivity of 1.00 both for the visible and infrared channel. Thus, as a check on the stability of the system the visible signal for the calibration portion of the cycle (the longer time period) should be 61.1% of 5 volts or 3.06 volts while for the infrared should be 78.4% of 5 volts or 3.92 volts.

If the system drifts so that the calibration voltage is not the expected value, but a new value V(cal, vis) the actual reflectivity can be obtained from this new value, the voltage corresponding to the test surface V(test, vis), and the visible reflectivity R(cal,vis) = 0.611. Thus the visible reflectivity of the test surface is;

$$R(\text{test, vis}) = V(\text{test, vis}) \frac{R(\text{cal, vis})}{V(\text{cal, vis})} .$$

Table 2

Required Accuracy in Measured Reflectivity for a 1% Full Scale Accuracy in α or ϵ

α or ϵ	R	dR/R (Percent)
1.0	0.0	---
0.9	0.1	10
0.8	0.2	5
0.7	0.3	3.3
0.6	0.4	2.5
0.5	0.5	2.0
0.4	0.6	1.7
0.3	0.7	1.4
0.2	0.8	1.3
0.1	0.9	1.1
0	1.0	1.0

Similarly for the infrared;

$$R(\text{test, IR}) = V(\text{test, IR}) \frac{R(\text{cal,IR})}{V(\text{cal,IR})}$$

where,

$$R(\text{cal,IR}) = 0.784.$$

A typical display of the visible and infrared output voltages is shown in Figure 14A, and also in Figure 14B with an expansion of the time axis to show more detail. The various portions of the characteristic are identified in the figure.

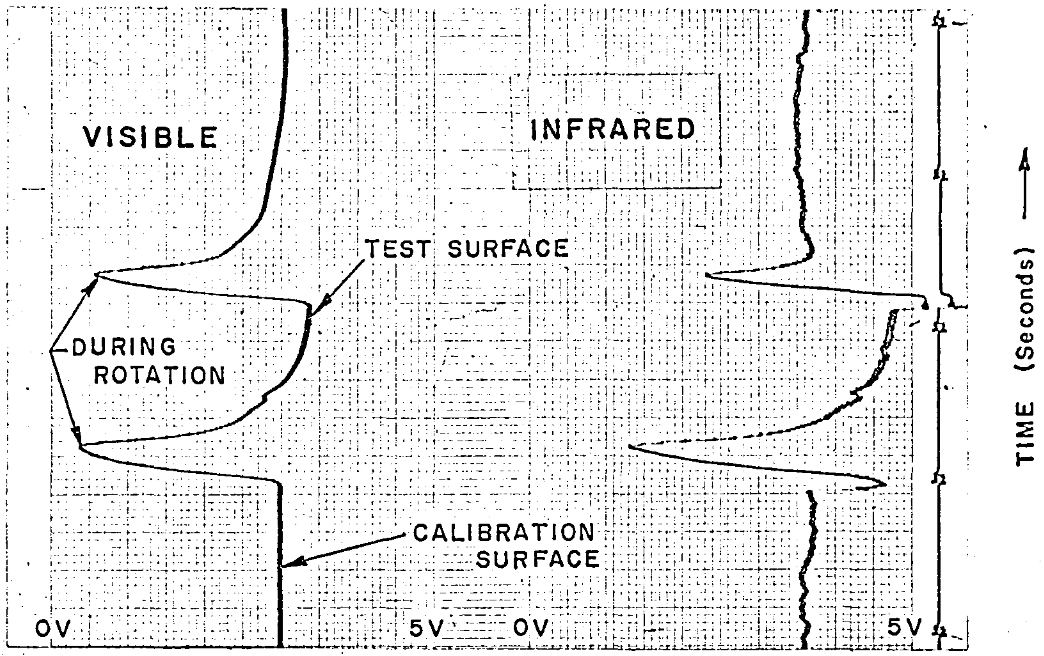

FIGURE 14A

VISIBLE AND INFRARED OUTPUT AS A FUNCTION OF TIME
SHOWING THE VARIOUS PARTS OF THE CALIBRATION AND MEASUREMENT CYCLE

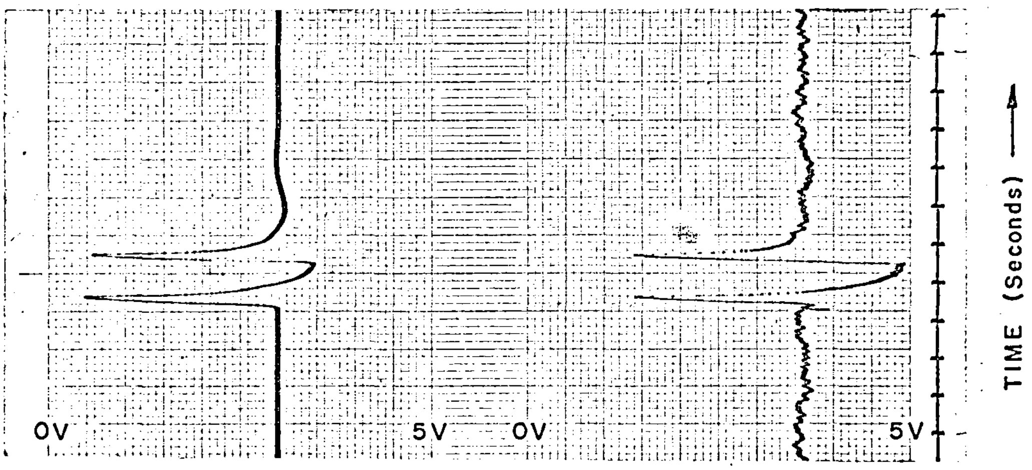

FIGURE 14B

FASTER TIME DISPLAY OF VISIBLE AND INFRARED OUTPUT SIGNALS

7. POWER SUPPLY AND POWER REQUIREMENTS

The power distribution and requirements of the various sections of the system are shown in the Power Supply Block Diagram, Figure 15. DC-DC converter power supplies are used where it is necessary to isolate system grounds from ships supply ground (Reference power supplies no.'s 5031,5032 and 5033). Noncritical circuits are connected directly to the ships supply except the lamp chopper which is connected through the RFI filter. An RFI filter is employed at the input of the converter supplies to keep source noise within acceptable limits. The overall efficiency of the converter type power supplies is much lower than anticipated being approximately 40% (versus the 70% design goal stated in previous reports) while the drive motor is quiescent and nearly 60% when in the drum rotation mode. Thus, overall power consumption is 14 watts quiescent and 21 watts in the drum rotation mode.

The IR sensor supply consists of two modules: (1) The converter (5031) and (2) a filter-regulator (3460) which is contained in a separate compartment of the 5033 regulated supply enclosure. Complete source isolation is achieved allowing optimum conditions for low noise operation.

A separate supply was deemed necessary for low noise operation of the tuned preamplifiers and therefore preamplifier supply (5032) was designed to fulfill the requirement. Source isolation and voltage regulation are the features of this supply.

A regulated supply (5033) with three isolated outputs is used to provide the power for the signal amplifiers, motor control circuit, and the lamp. This supply is a DC-DC converter and is pre-regulated. Electrostatic shielding is employed around the output winding of the signal amplifier section in order to reduce inter-coupling between supply sections.

In order to provide the option of testing the system while it is connected to ships supply but not energized by the ships supply, a separate pin (F) is provided so that 28 VDC test excitation can be applied as desired.

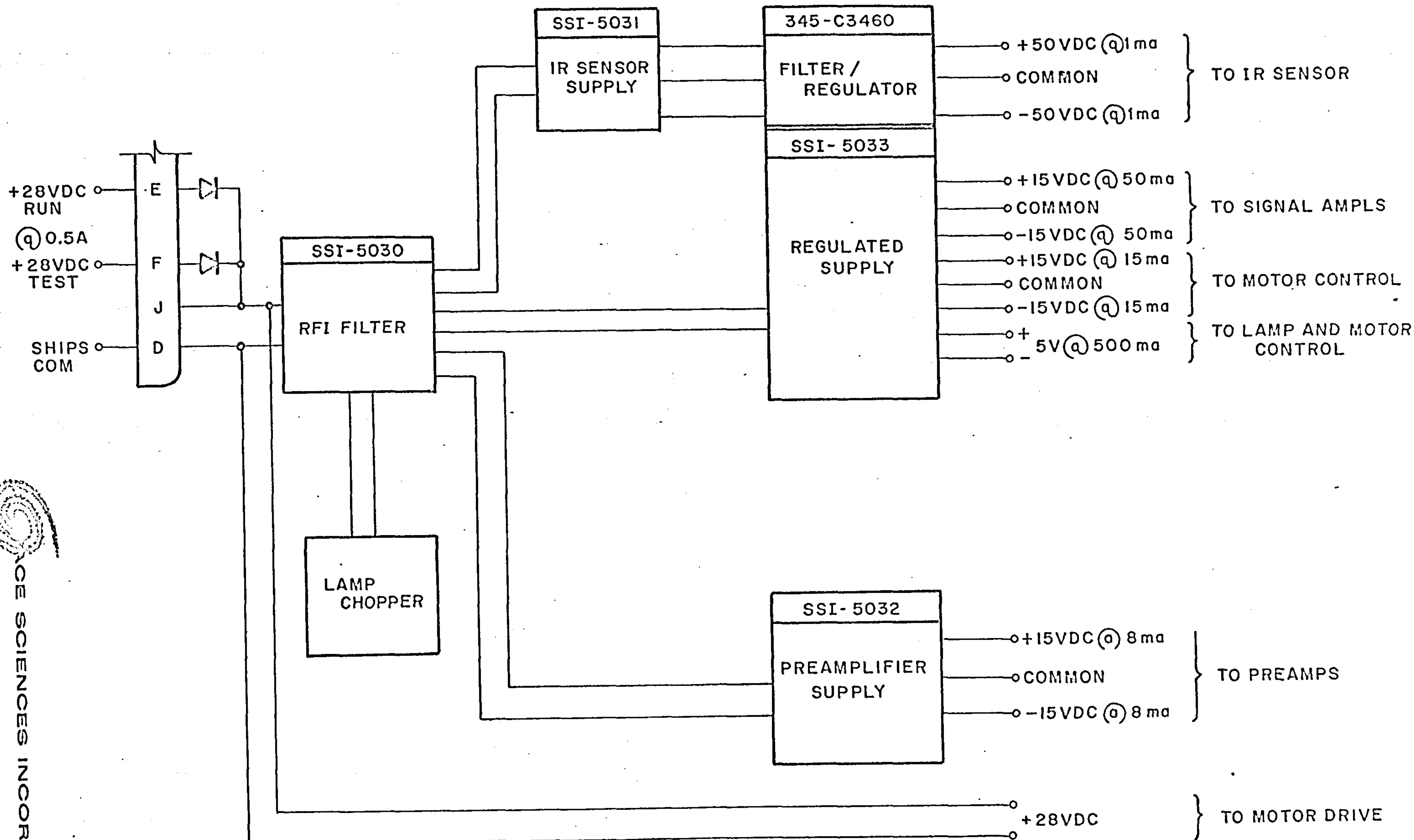

FIGURE 15

POWER SUPPLY BLOCK DIAGRAM - ABSORPTIVITY/EMISSIVITY SYSTEM

8. SYSTEM WEIGHT

The total weight of the absorptivity/emissivity instrument of the present design is approximately 4.2 kilograms. Further efforts towards a weight reduction were not undertaken at this time in the interest of program economy, but there are several areas in the system where it might be feasible for weight reductions. The weight reduction of heavier items such as the base plate, power supply, right and left sphere sections, the elimination of some amplifiers through circuit redesign, etc., could result in the weight reduction of 500 grams. The 4.2 kilograms represent the weight of the system minus the foam encapsulant around the system.

REFERENCES

(1) Katzoff, S., Symposium for Thermal Radiation of Solids (San Francisco, March 4 - 6, 1964) NASA-SP-55.

(2) Marshall, K. N., Douglas, N. J., Polland, H. E. and Rolling, R.E., "Laboratory and Flight Test Program to Evaluate the Space Stability of Highly Specular Reflective Surfaces," presented at Space Simulation Conference, Houston, Texas, September 7 - 9(1966).

(3) Wendlandt, W. and Hecht, H. G., Reflectance Spectroscopy (John Wiley and Sons, N.Y. 1966) p. 253.

(4) Wendlandt, W. and Hecht, H. G., Reflectance Spectroscopy (John Wiley and Sons, N.Y. 1966) p. 271.

(5) Wendlandt, W. M. and Hecht, H. G., Reflectance Spectroscopy (Interscience Publishers, N.Y., 1966) p. 264.

(6) American Institute of Physics Handbook, Second Ed. (McGraw-Hill, N.Y., 1963) p. 6-119 to 6-130.

(7) White, J. V., J. Opt. Soc. Amer., 54, 1332 (1964).

(8) Dunn, S. T., Richmond, J. C. and Parker, J. F., J. Spacecraft and Rockets, 3, 961 (1966).

(9) Bennett, H. E., Silver, M. and Ashley, E. J., J. Opt. Soc. Amer., 53, 1089 (1963).

(10) Moon, P. and Severance, D. P., J. Opt. Soc. Amer., 29, 21 (1939).

(11) Serlaut, G. A. and Krupnick, A. C., AIAA Journal, 4, 1227 (1966).

(12) Gibson, K. S., Spectrophotometry, National Bureau of Standards Circulat 484 (1949).

APPENDIX A

CALCULATION OF RADIATION COLLECTION EFFICIENCY FOR DIFFUSELY REFLECTED LIGHT AS A FUNCTION OF LENS f NUMBER

It will be shown that if high collection efficiency is required for the diffuse radiation then extremely small f numbers are required for the collection lens. This corresponds to a very large diameter lens with a very small focal length.

If the diffuse radiation is described by a Lambert cosine law according to;

$$R = R_o \cos\theta \qquad \text{(A-1)}$$

for the radiation per solid angle $d\Omega$ and the solid angle is given by,

$$d\Omega = \sin\theta \, d\theta \, d\Omega \qquad \text{(A-2)}$$

then the collection efficiency is given by;

$$R/R_o = \int_o^{\theta_{max}} \cos\theta \sin\theta \, d\theta. \qquad \text{(A-3)}$$

The angle limiting the maximum collection θ_{max} is described by;

$$\sin\theta_{max} = \frac{1}{\left(1 + 4f^2\right)^{1/2}} \qquad \text{(A-4)}$$

where f is the f number and is computed from the focal length F, and the lens diameter D according to

$$f = \frac{F}{D} . \qquad \text{(A-5)}$$

The values of diffuse collection efficients are given as a function of f number in Table A.

TABLE A

DIFFUSE COLLECTION EFFICIENCY, $\bar{R}/R_o$, AS A FUNCTION OF LENS f NUMBER

f Number	R/R_o
0.1	0.960
0.15	0.920
0.2	0.860
0.3	0.735
0.5	0.500
0.7	0.338
1.0	0.200
1.5	0.100
2.0	0.0588
3.0	0.0270

It can be seen from this table that for collection errors of less than 10% the f number must be less than 0.15. The smallest f numbers that have been encountered in lenses is about 0.6 to 0.7.

Thus it appears that accurate lens collection of diffusely reflected radiation is not possible except where the specular component is small enough to be neglected so that a lens correction factor can be used for the diffuse radiation. Alternatively, when the specular radiation is strongly dominant, the diffuse collection efficiency is not a serious problem since the diffuse radiation would only be a small correction factor.

APPENDIX B

CALCULATION OF TEMPERATURE DIFFERENCE BETWEEN DRUM FLAT AND VEHICLE SURFACE

The rotating drum assembly introduces a possible thermal discontinuity at the vehicle surface. The temperature difference between the drum flat and the vehicle skin has been estimated for several candidate drum materials and configurations. The results are shown in Table B along with the drum weight. The calculations assume the following:

1) Heat input is one solar constant,
2) drum is not rotating,
3) steady state conditions exist,
4) the heat conduction path in the solid sphere is simulated by an insulated pipe of length equal to the drum radius and cross-sectional area equal to the area of the drum flat, and
5) in the hollow sphere heat flows along the skin of the sphere.

All the assumptions are conservative; that is, they represent maximum possible temperature differences. From the results in Table B, it is evident that the temperature elevation (even for epoxy) is sufficiently low, and can be made even smaller by using an aluminum drum.

TABLE B

TEMPERATURE DIFFERENCE BETWEEN DRUM FLAT AND VEHICLE SURFACE

Drum Material and Shape	ΔT (°F)	W (lb)
Solid Epoxy	44°F	0.335
Solid Aluminum	3°F	0.410
Hollow Aluminum of Thickness 0.125"	6°F	0.134

ΔT = Temperature Difference Between Vehicle Skin and Drum Flat.

W = Drum Weight.