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on a

Space Background Study

Contract DA-30-069-ORD-2803

EK/ARD ED-692

For the

Army Rocket and Guided Missile Agency
U. S. Army Ordnance Missile Command
Redstone Arsenal, Alabama

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ABSTRACT

This document describes the progress of work for the period January 1, 1961 to July 1, 1961, on the Space Background Study conducted by the Eastman Kodak Company for the Army Rocket and Guided Missile Agency under Contract DA-30-069-ORD-2803. A review of the work conducted on the initial phases of this contract are presented as well as the general technical approach for future endeavors.

Operating principles and details of design and construction of the infrared stellar photometer are discussed. A tentative observing program utilizing the Mount Wilson telescopes is also presented.

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I. INTRODUCTION

The Eastman Kodak Company and its subcontractor, the Ohio State University Research Foundation, have been given the assignment, under contract with the Army Rocket and Guided Missile Agency, to investigate and characterize the space background problem as faced by optical space defense systems, with primary emphasis on the infrared spectral region.

Optical sensors for space applications must of necessity work in the presence of a background consisting of a multitude of point sources on the celestial sphere. This has presented a serious challenge to the designer of military systems to develop discrimination techniques for detecting essentially point targets against a stellar background. Further, the targets of interest are relatively cold bodies (300°K) with most of their emitted energy concentrated in the far infrared. The aim of this investigation is to locate and identify by theory and direct observation all thermal sources in space, stellar or otherwise, which will produce irradiances comparable to the irradiance from a relatively cold body at long range.

Phase I of the Space Background Study, which was essentially completed during the first year, was devoted to an intensive literature search and to the development of a theoretical model of the infrared stellar background. The results of this phase are summarized in the second semi-annual report dated July 1960 (reference 1) which presents the model of the stellar background as computed from the theoretical blackbody extrapolation of visible and near infrared stellar data. The stellar magnitudes considered were limited to 1/10 the apparent magnitude of an assumed target (2 square-meters projected area, 300°K surface temperature, at a distance of 500 nautical miles). The total number of interfering stars was found to decrease from the order of one hundred thousand in the visual region (for the foregoing target sun-illuminated) to only several hundred for the infrared beyond 7.5 microns when the target radiation was considered as purely self emitted. Star maps of the celestial sphere and a table of 185 stars in the order of their infrared magnitudes are presented.

The encouraging results of this study are, however, based on the following two assumptions:

1) The stars radiate at longer infrared wavelengths as they would if they were blackbodies at the temperature deduced from their radiation in the visual and near infrared regions of the spectrum.

2) The "infrared stars", that is to say, those sources which are too cool to radiate measurably in the visible, are not present in sufficient numbers to significantly affect the conclusions drawn from the data available for the visible stars.

It was considered imperative that a planned program of infrared stellar photometry be initiated to rigorously test the foregoing assumptions. This would provide a more precise and sound specification of the space background in wavelengths never before accurately observed and measured. In the total astronomical effort of others to date, the brightness of approximately 70 stars have been measured in the lead sulfide region, but beyond a wavelength of about 3 microns the only sources studied have been the sun, moon, Mars and Venus.

The Army Rocket and Guided Missile Agency has therefore extended the original contract to provide for the implementation of a planned program of infrared stellar measurements. The specific contract requirements are as follows:

1. The contractor will design and construct an infrared stellar photometer using the best available cooled photoconductive detectors and electronic techniques which will be capable of making measurements of intensity of infrared radiation from stellar objects in the following spectral regions: 2 to 2.4 microns; 3.4 to 4.1 microns; 7.5 to 13.5 microns.

2. The contractor will install and maintain the photometer on the 69-inch reflecting telescope at the Perkins Observatory, and later at the Lowell Observatory, or in the interim on the 32-inch reflecting telescope at the Perkins Observatory.

3. The contractor will conduct a measurement program so as to specify more completely the nature of the infrared stellar background. This measurement program will include infrared measurements made in the wavelength regions specified in (1) above on known sources approximately in the order of their brightness, and unknown sources approximately in the order of their likelihood of observation.

4. The contractor will present the information in a fashion suitable for use by the designer of infrared anti-missile and other space body defense systems.

II. TECHNICAL SUMMARY

Under a continuing contract with the Army Rocket and Guided Missile Agency, the Eastman Kodak Company and the Ohio State University Research Foundation have embarked on an intensive program of stellar measurements in the infrared spectral region. The measurement program is designed to supplement the study program and literature search carried out during the first phase of the contract.

An experimental infrared stellar photometer constructed during the first year of the contract was operated on a regular biweekly schedule in conjunction with the 69-inch Perkins reflector at Delaware, Ohio, up to March 10, 1961. After some modification, this experimental instrument produced some very excellent results, including the first narrow spectral band data ever obtained in the 3.2-4.2 micron region. The irradiances of approximately 30 stars have been measured in the atmospheric windows at 2.0-2.4 microns and 3.2-4.2 microns and the results have been shown to be in good agreement with the results of two other recent stellar measurement programs in the 2.0-2.4 micron region. However, the data show a marked divergence from the theoretical model for some of the cooler stars, particularly the long period variables. Apparent infrared magnitude scales have been established for each band, and color indices have been calculated and compared with the theoretical color index values derived in the first phase.

In parallel with this preliminary measurement program, a new and improved stellar photometer was designed which employs the best in infrared detectors for the wavelengths of 2 to 2.4 microns, 3.2 to 4.2 microns and 7.5 to 13.5 microns. This instrument will be ready for observational use by July 1961, and, when coupled with a large aperture telescope, will result in an infrared system with an overall sensitivity far superior to any military hardware now under development. This provides a large degree of assurance that state-of-the-art advances will not vitiate the results of this investigation, and that the stellar measurements data obtained by this instrument will be of great value to system designers for years to come.

The previous semi-annual report (reference 2) discussed at length the considerations leading to the design of the new photometer. This report describes in detail the design of the optical-mechanical and electronic elements of the photometer system. These include dichroic beam splitters, a visual tracking eyepiece, pre-aligned detectors including helium cooled (4°K) doped germanium, a narrow-band chopping frequency centered at 480 cps, and integrating circuits timed to produce an effective bandwidth of as little as .001 cps.

The new photometer is being equipped and designed to fit not only the 69-and 32-inch Perkins-Flagstaff telescopes, but also the 60- and 100-inch Mt. Wilson telescopes.

III. TECHNICAL APPROACH

The designer of an optical system for space surveillance or navigation is interested in the infrared stellar background only to the extent of being informed as to which celestial objects will produce signals exceeding the noise in his system and how large these signals will be. In other words, he needs to know the location and the irradiance of each object on the celestial sphere that his optical system is likely to "see".

The goal of this program is to provide such information in a form which will be usable by future system designers. To this end, a theoretical model of the infrared stellar background has been developed which can be used to predict the irradiance of any star in any infrared wavelength band, provided only that its visual magnitude and its spectral type (effective temperature) are known. If the validity of the model can be established, or if a more valid model can be developed, the results should be far more valuable than a compendium of irradiance values for a multitude of stars in a few specific wavelength bands.

The first part of the measurement program is designed to test the validity of the infrared model by systematically measuring the irradiances of known stars in three distinct wavebands in the infrared spectrum. An experimental photometer mentioned in the technical summary has been used with the Perkins 69-inch reflector to obtain data in the 2.0-2.4 and 3.2-4.2 micron bands. The new photometer described in this report will have the additional capability of extending the infrared measurements to the 7.5-13.5 micron band, with a threshold detectivity of less than 10^{-18} watts/cm^2 referred to the aperture of the 69-inch Perkins reflector for the shorter infrared wavebands. This new photometer has been designed for use with a number of the largest telescopes in the country, the Mt. Wilson 60- and 100-inch reflectors and the Perkins-Flagstaff 69- and 32-inch reflectors.

Beyond the initial stages, results can only be speculated, but the observations and measurements will be of a fundamental and exploratory type, capable of shedding light in an as yet unpredictable way, on important astrophysical problems such as:

a) The structure of the Galactic nucleus.

b) The law of interstellar reddening, and consequently the constitution of interstellar material.

c) The existence of proto-stars, heretofore only hypothesized. Located probably in young star clusters, their infrared brightness and spatial distribution is now a critical missing datum in the problem of stellar evolution.

d) Certain peculiar stars suspected to have large infrared components.

e) The infrared energy distribution associated with extraglactic nebulae and selected radio sources.

IV. THE INFRARED STELLAR PHOTOMETER

A. GENERAL DESCRIPTION

The previous semi-annual report (reference 2) discussed at some length the considerations leading to the design of the improved stellar photometer. This included areas such as the effect of atmospherics on an infrared stellar image, the suitability of selected photoconductive detectors, methods of achieving background-limited detector operation, and so on. The system which has been devised basically resembles the experimental photometer, but includes a number of new features found desirable from the experience gained in operating the earlier instrument or as a result of the analysis of the system parameters.

The final arrangement of the photometer head is shown in Figure 1. Stellar radiation enters from the telescope tailpiece (1) or from the side at 1A, and is reflected alternately by the chopping mirror (6) and the stationary mirror (5) known as the "background mirror", to the visible-infrared dichroic (8). The visible light is transmitted through the dichroic to a diagonal mirror and then to the tracking eyepiece (9) for visual observation and guidance purposes. The infrared radiation is reflected from the dichroic to an off-axis ellipsoid (10) which reimages the stellar image onto plumbide and Cu:Ge photoconductive detectors after splitting into the proper wavelength bands at the NIR-FIR dichroic (11). Alternatively, the

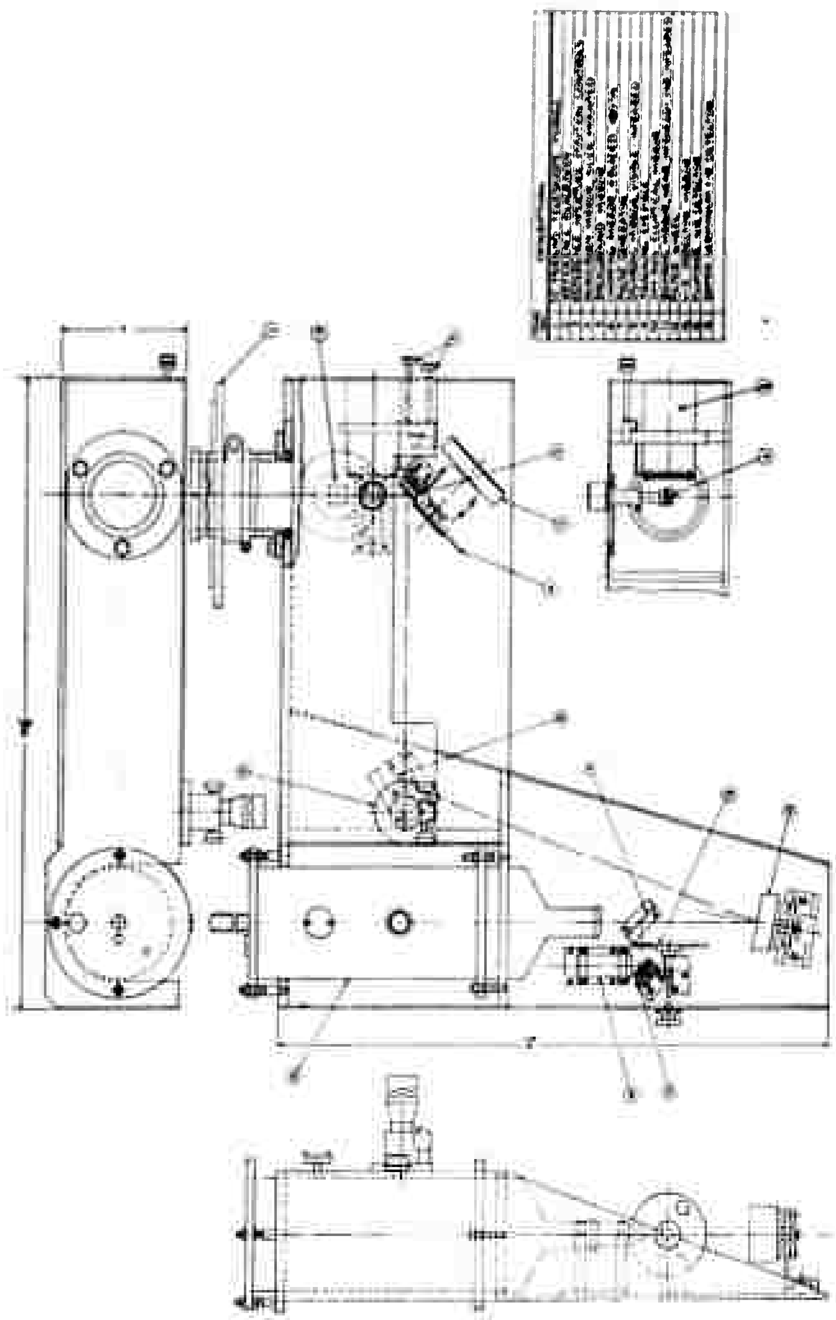


Figure 1. INFRARED STELLAR PHOTOMETER

reference blackbody can be imaged on the detectors via the same optical train by interposing a diagonal mirror (4). By reflecting the radiation alternatively off the rotating chopper mirror and the background mirror, the detectors look alternately at the star and the sky background adjacent to the star. This produces a periodic interruption of the stellar radiation while radiation from the background remains essentially unmodulated. This technique has been found to substantially enhance the star-to-background contrast.

The electronic system makes use of an ac signal preamplifier and amplifier, a synchronous demodulator, a reference signal generator, an integrator with timer, and a recorder. This combination of chopper modulator and synchronous demodulator is sometimes called a homodyne amplifier. A block diagram of the system appears in Figure 2 and includes the waveforms produced by the system elements.

The details of the electronic system are discussed in Section IV C but several features will be noted here. An adjustable phasing control has been provided in the reference frequency generator to compensate for differences in the time constants of the plumbide and Cu:Ge photoconductive detectors. The integration system provides for timed intervals of one and five minutes, corresponding to system bandwidths of 0.02 and 0.004 cycles/sec respectively. Bandwidths as small as 0.001 cycles/sec may be obtained by manual operation of the integrator over a fifteen or twenty minute interval.

The improved photometer provides a considerable improvement in detectivity over the experimental photometer as well as extended spectral

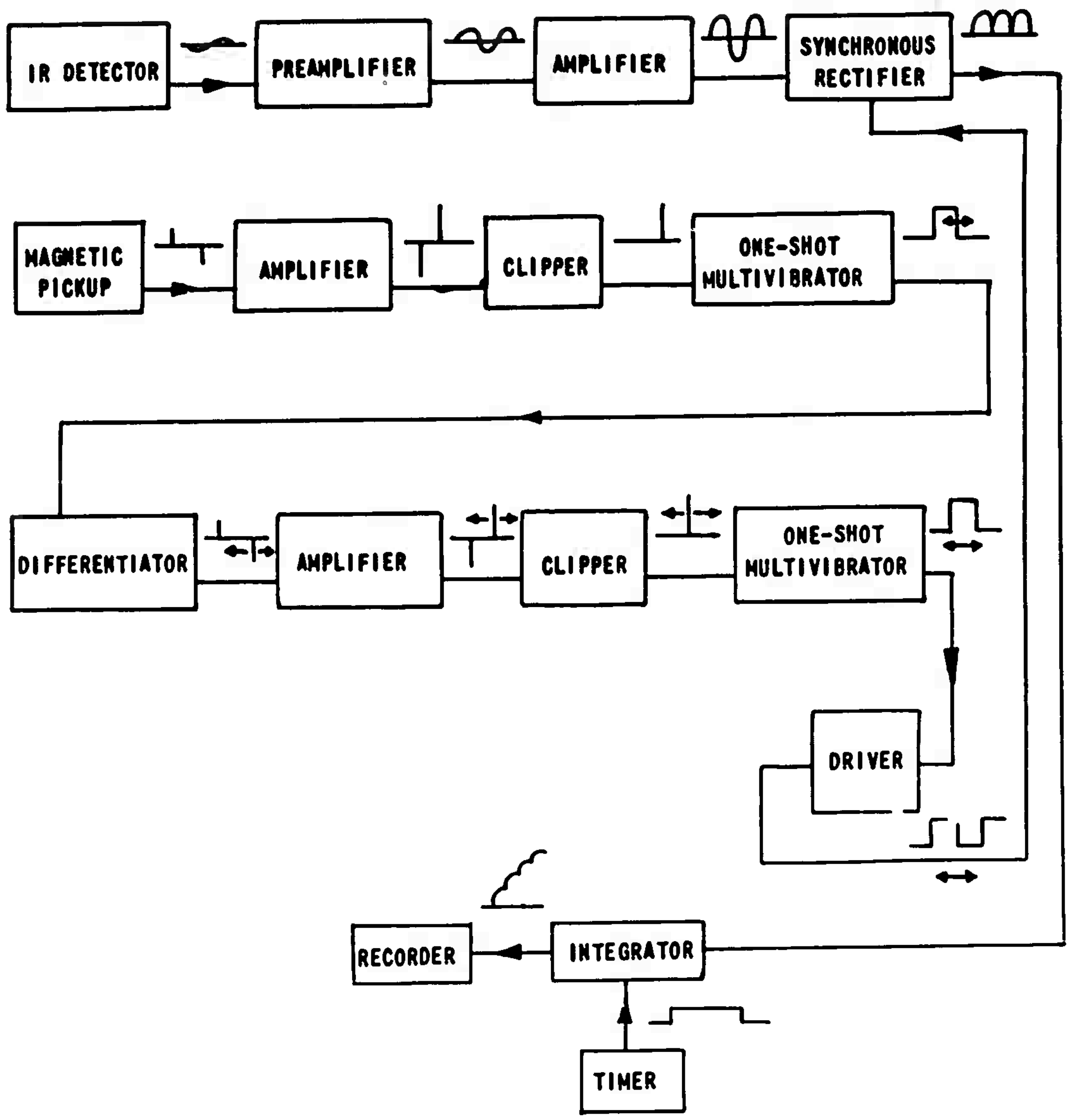


Figure 2. ELECTRONIC SYSTEM BLOCK DIAGRAM WITH WAVEFORMS

response to the longer wavelengths. The experimental photometer had a minimum bandwidth of 0.2 cycles/sec and a theoretical NEPD of 10^{-17} watts/cm^2 for infrared wavelengths to 4 microns with the 69-inch Perkins telescope. The observed stellar signals with this instrument were as small as 5×10^{-17} watts/cm^2 in the 3-4 micron band, and the observed NEPD approached 2×10^{-17} watts/cm^2. The improved photometer is expected to have an NEPD approaching 7×10^{-19} watts/cm^2 in the 3-4 micron band with the 69-inch Perkins telescope, or an improvement in detectivity of a factor of about fourteen. This presumes the use of a twenty minute integration interval and an effective bandwidth of about 0.001 cycle/sec.

B. PHOTOMETER HEAD

Detectors

Two photoconductive detectors which have the highest state-of-the-art spectral detectivity have been selected to cover the 2 to 14 micron infrared wavelength interval. They are chemically deposited plumbide (a lead sulfide variant) cooled to 77°K with liquid nitrogen to cover the 2.0 to 2.4 micron and 3.2 to 4.2 micron atmospheric windows with filter programming, and copper-doped germanium cooled to 4°K with liquid helium to cover the 7.5 to 13.5 micron window. The spectral detectivity, D*, within these windows will be about 1.5×10^{11}, 7×10^{10} and 1.5×10^{10}, respectively (normalized for a detector area of 1cm^2 and a bandwidth of 1 cycle/sec).

An analysis of the effect of atmospherics on the stellar image was presented in the previous semi-annual report (reference 2) and it was concluded that under poor seeing conditions the refractive power of the atmosphere may produce stellar images as large as 8 to 10 seconds of arc in diameter (reference 2). These images will be in the neighborhood of 3 to 4 millimeters in diameter at the Cassegrainian focus of the 69-inch Perkins reflector for the infrared wavelengths of interest. Optical image reduction has been provided by an off-axis elliptical mirror in the photometer system re-imaging at a 4:1 ratio to approximately "fill" the smallest practical size detector. State-of-the-art techniques limit the doped germanium crystals to a minimum face area of 1 x 1 mm determining the optical reduction for this system. It should be noted that a system designed purely for the shorter wavelengths covered by the plumbide detector, could employ a reduction of the image to as small as 0.1mm in diameter to match practical lower limits in size for this type of detector.

Dewars and Cryogenics

The copper-doped germanium infrared detector requires cooling to liquid helium temperature. A specially designed dewar must be used as a reservoir to hold the coolant and also to hold the detector and cooled filter assembly. The following requirements have been established for this dewar.

1. A holding time of at least eight hours is necessary to permit filling the dewar at the liquifier prior to each observing night. This will reduce the helium transfer loss to a minimum and permit uninterrupted operation of the photometer.

2. The dewar must withstand tilting 45° from the vertical without coolant spillage.

3. The dewar must be sufficiently rigid to prevent lateral shifts of the detector of more than about 0.1mm when the photometer is tilted 45°.

4. A heavy mounting flange, suitable for holding a precision semi-kinematic mount, must be provided. This will permit removal of the dewar and subsequent return with the detector still in optical alignment.

The dewar requirements were discussed with a member of the engineering staff of the Hofman Laboratories, Hillside, New Jersey. It was felt that all requirements could be met without any unusual design problems. The dewar would be fabricated from standard spinnings to avoid undue manufacturing delays. The Hofman Laboratories suggested a modification of one of their existing designs to obtain a 1.2 liter helium capacity and a 2.1 liter nitrogen capacity. This provides a hold time of better than 8 hours. The outer walls of the nitrogen chamber are extended about 2 inches and the top is covered to prevent nitrogen spillage when tilted. A detailed drawing of this dewar is shown in Figure 3.

The top cover also serves to stiffen the assembly and prevent flexure of the internal vessel holding the helium and the detector assembly when the photometer is tilted. Two thermocouples are installed in the liquid nitrogen compartment to act as high and low nitrogen level indicators, since with the top cover on the dewar, the level cannot be observed. The nose section of the dewar is demountable so that detectors can be changed easily.

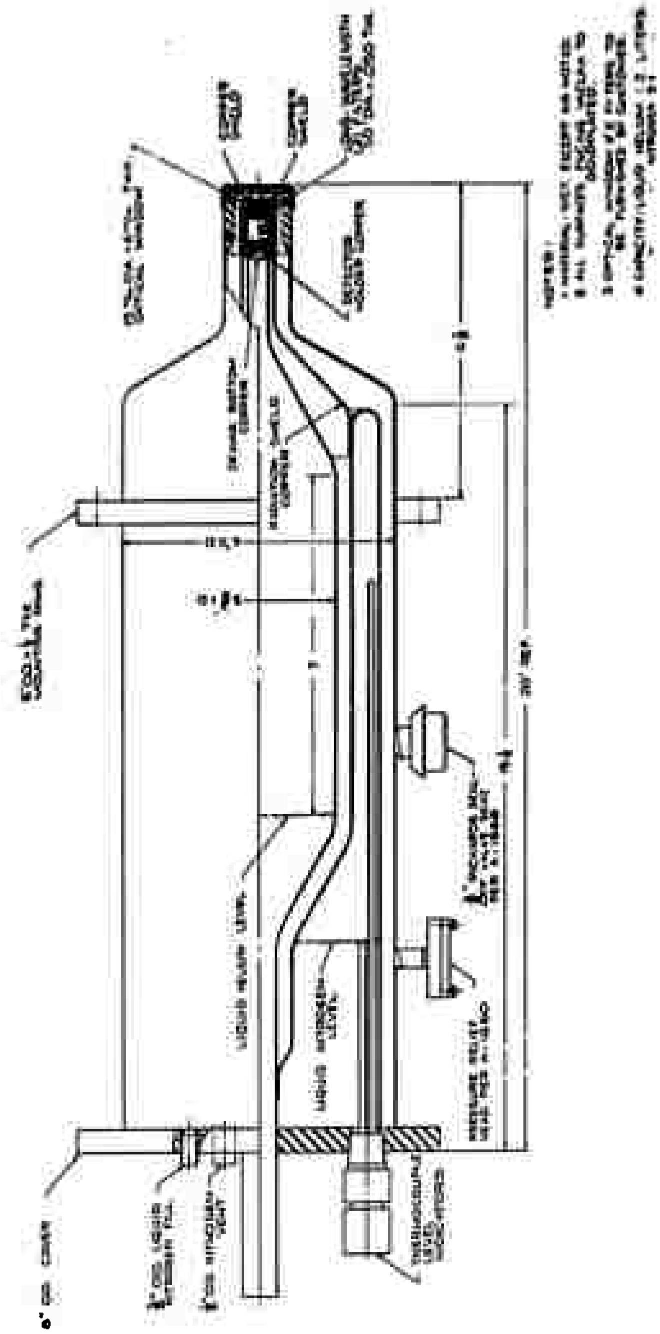


Figure 3. HOFMAN LABORATORIES INC. HELIUM RESEARCH DEWARS
MODEL HO-33-IW-16-316

A high-vacuum valve, which is an integral part of the dewar, facilitates pumping down and sealing off the vacuum chamber. Once pumped to the required vacuum of 10^{-5} mm, it should hold for a period of about 6 months.

The shorter wavelength plumbide detector must also be cooled, but only to liquid nitrogen temperatures. A recent development by the Eastman Kodak Company in cooling chemical lead sulfide detectors of this type will be of value on the stellar photometer. In the past it has been necessary to periodically vent the small dewar containing the lead sulfide or plumbide cell because the chemical film is not vacuum stable. Now however, the detector has been mounted on a copper block at the end of a phenolic tube which fits into the unevacuated cooling finger of a small double window dewar. This dewar is permanently evacuated, but the detector will not deteriorate with time because it is at atmospheric pressure. Furthermore, the new dewars have the cooling finger accurately concentric with the outer dewar wall, thus simplifying the optical alignment. The new configuration is shown in Figure 4.

Optics

The discussion on background limited detector operation presented in reference 2 has shown the importance of the choice of the radiation chopping frequency. The plumbide detector is dominated by 1/f noise up to about 100 cycles/sec and the typical noise power spectrum of a Ge:Cu detector has a dominant 1/f component below about 200 cycles/sec. There is a relatively wide latitude in the choice of a chopping frequency because Johnson noise

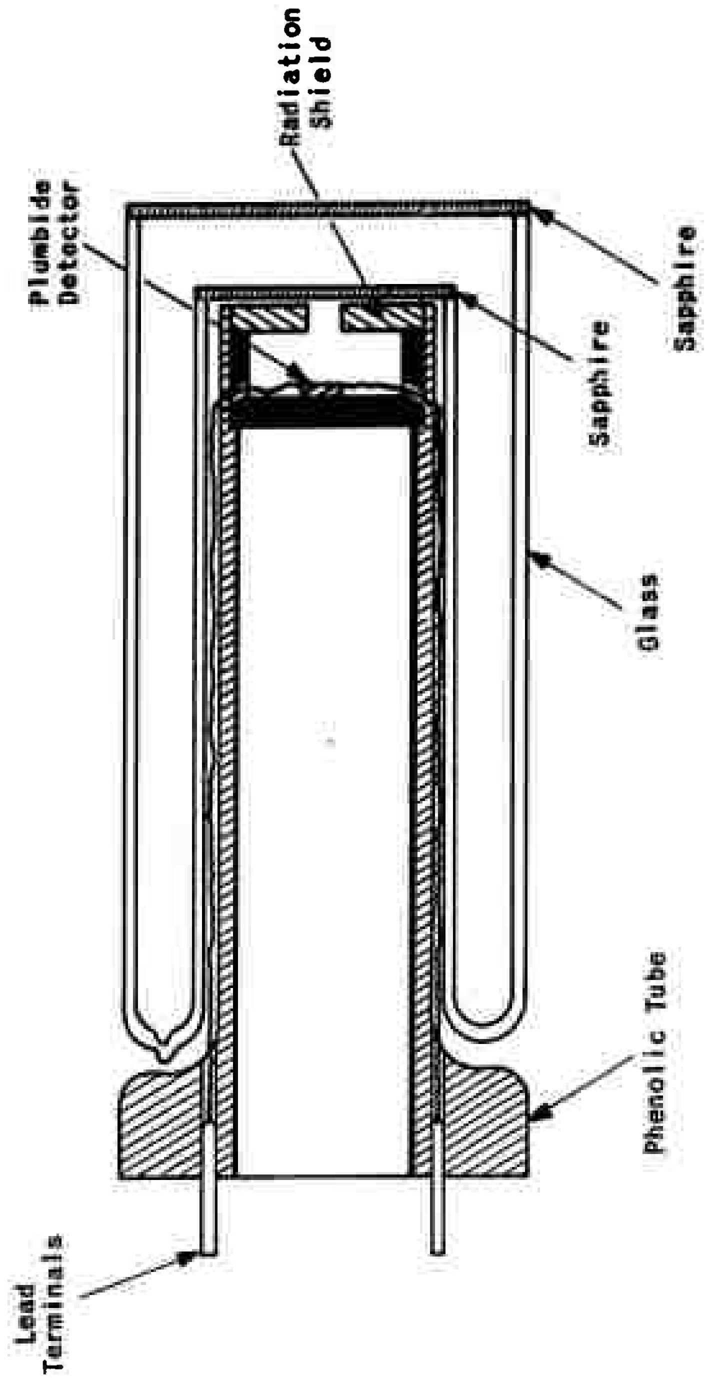


Figure 4. NEW DEWAR CONFIGURATION FOR NITROGEN COOLED PLUMBIDE DETECTOR

does not dominate either detector below about 2000 cycles/sec. A chopping frequency in the neighborhood of 500 cycles/sec is the most desirable compromise; accordingly, 480 cycles/sec was selected as the most convenient to obtain with a 60 rps synchronous motor and an 8-bladed glass mirror chopper. A view of the front section of the photometer is shown in Figure 5 illustrating the arrangement of the chopper and "background" mirrors, and the reference blackbody with aperture positioning slides.

The following requirements are imposed on the means of chopping:

1. There should be equal on and off times with as rapid a transition as possible between the two states in order to give a detector output signal with the maximum possible energy.

2. As the star image wanders about the sensitive area of the detector, due to atmospheric shimmer, the signal must remain in-phase with the reference ac signal supplied to the synchronous demodulator or rectifier, as it is phase-sensitive. Therefore, if the phase shifts through 360 degrees, the dc output of the demodulator will decrease to zero, become negative, and return through zero to its original value.

3. The stellar radiation only should be chopped and not the sky background radiation, since chopping the background produces spurious signals which give rise to erroneous radiation measurements.

Of the various methods by which chopping may be effected, the one selected as most suitable is shown in Figure 6. This system fulfills the foregoing requirements most effectively. In one position of the chopper, a star image is in focus on the detector; in the other position, the background radiation falls on the detector from the fixed mirror. Although it is not in best focus, the irradiance of the detector is the same as if it were in focus.

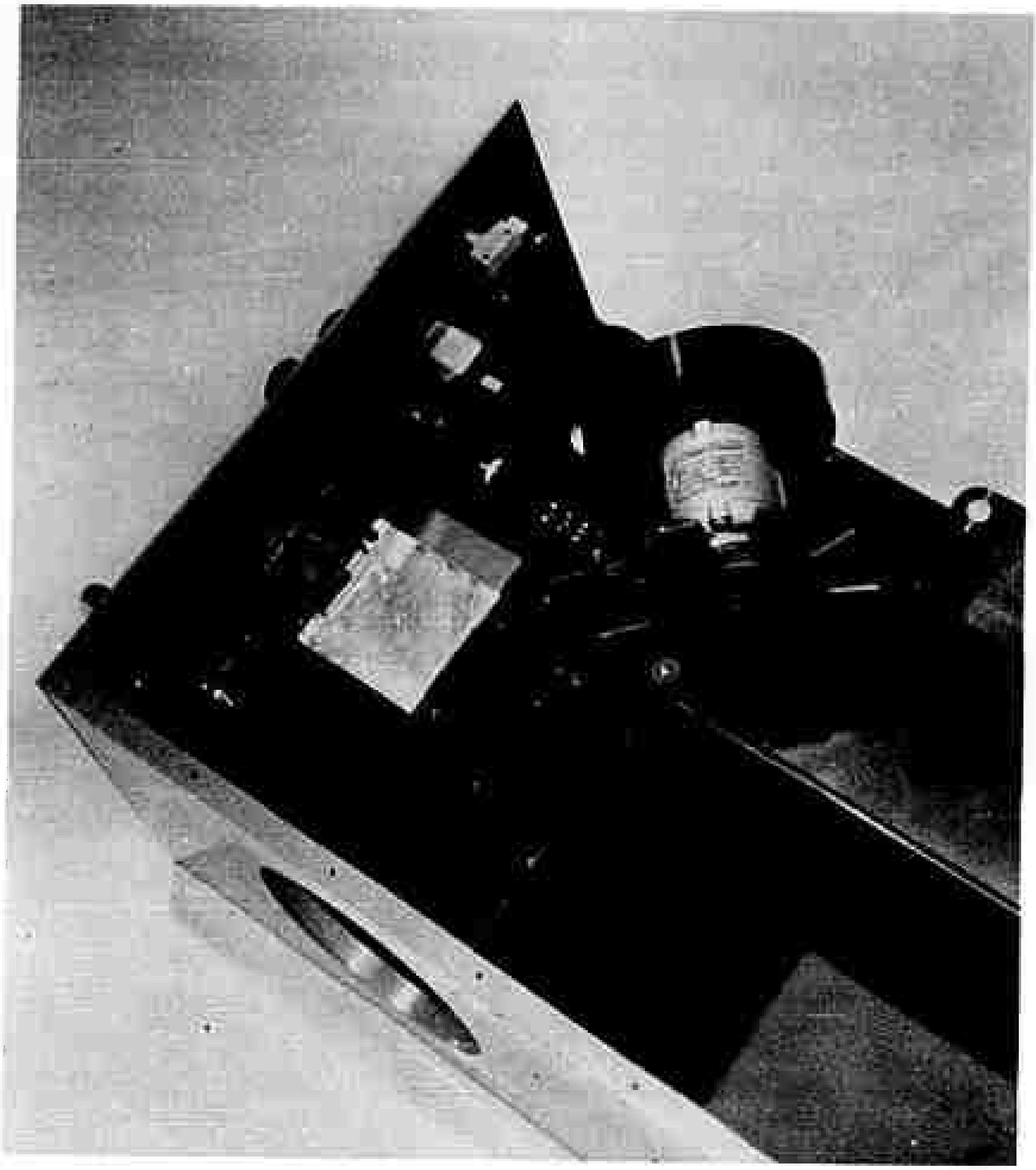


Figure 5. TWO MIRROR CHOPPING SYSTEM AND REFERENCE BLACKBODY

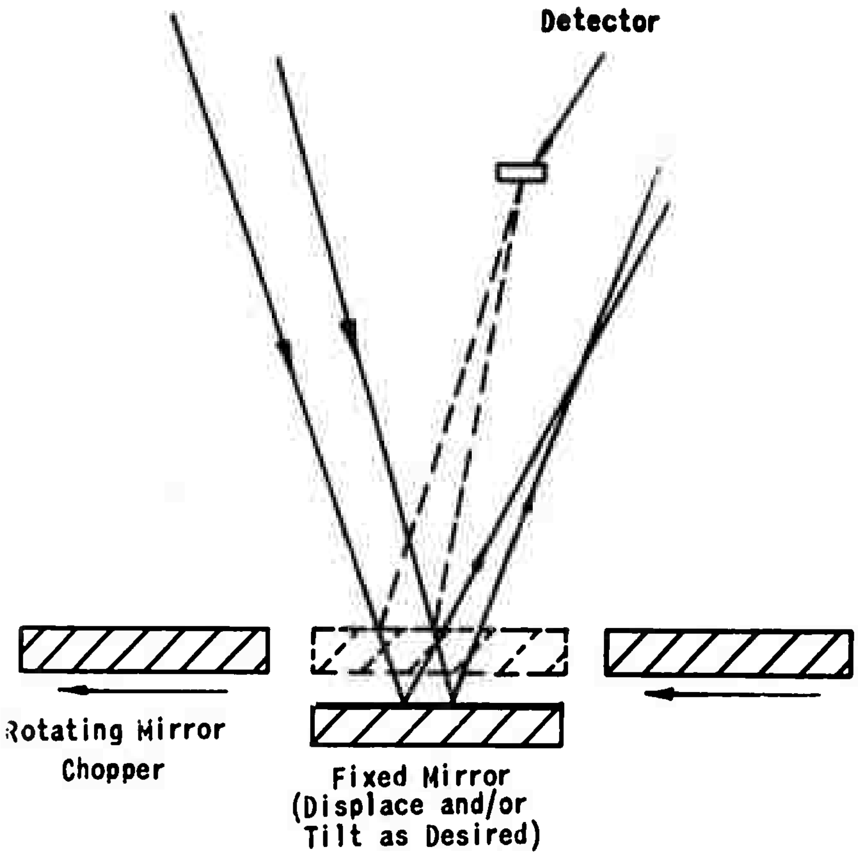


Figure 6. IMAGE DEVIATION CHOPPING

Therefore, the background radiation is not modulated. The sectors of the mirror chopper should ideally be made much larger than the bundle of radiation which it displaces so that there will be long dwell times during which the image is fully on or off of the detector.

This method of chopping has the advantage of using mirrors rather than infrared transmitting elements, and a multi-sectored wheel can easily produce the high chopping frequencies required.

The radiation is directed from the chopping mirror to a visual-infrared-plane-parallel dichroic mirror using conventional crown glass as a substrate for the multi-layer evaporated coatings. This mirror and the associated visual tracking eyepiece may be seen in Figure 7, an overall view of the photometer with the front panel tipped back. It will be noted that the tracking eyepiece is mounted in a rack and pinion holder on the panel, along with the preamplifier with plug-in modules and the reference blackbody selector mirror in a slide.

Another overall view is presented in Figure 8 which clearly shows the preamplifier arrangement on a hinged sub-panel, as well as a better view of the tracking eyepiece and the control knob for the selector mirror. It should be noted that the large helium detector dewar has been omitted from both of the overall views.

The re-imaging off-axis ellipsoidal mirror, near-and-far-infrared dichroic mirror, filter wheel, and plumbide detector in a nitrogen-cooled dewar are shown in Figure 9. The ellipsoidal mirror is of very high

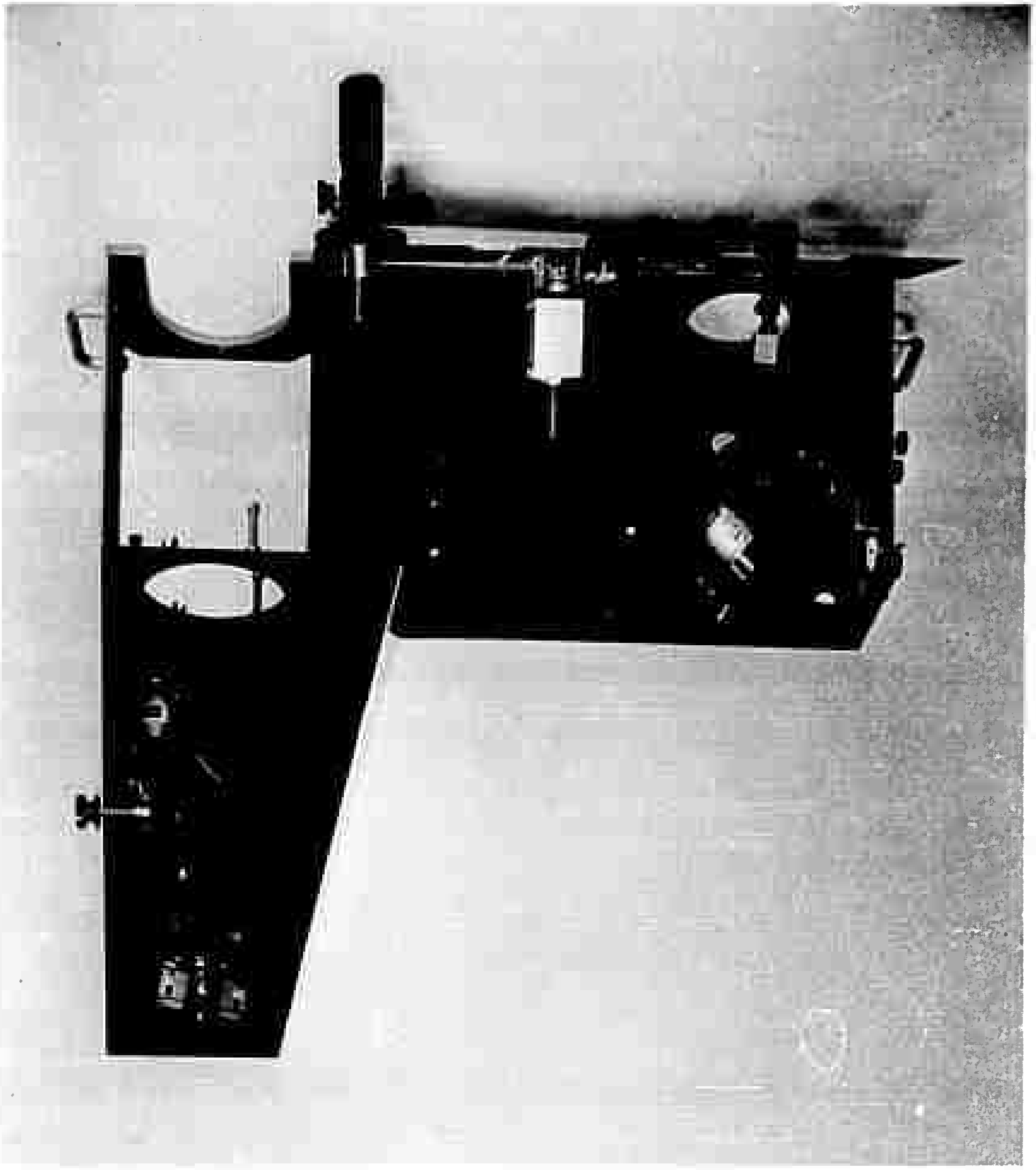


Figure 7. PHOTOMETER HEAD WITH FRONT PANEL TIPPED BACK

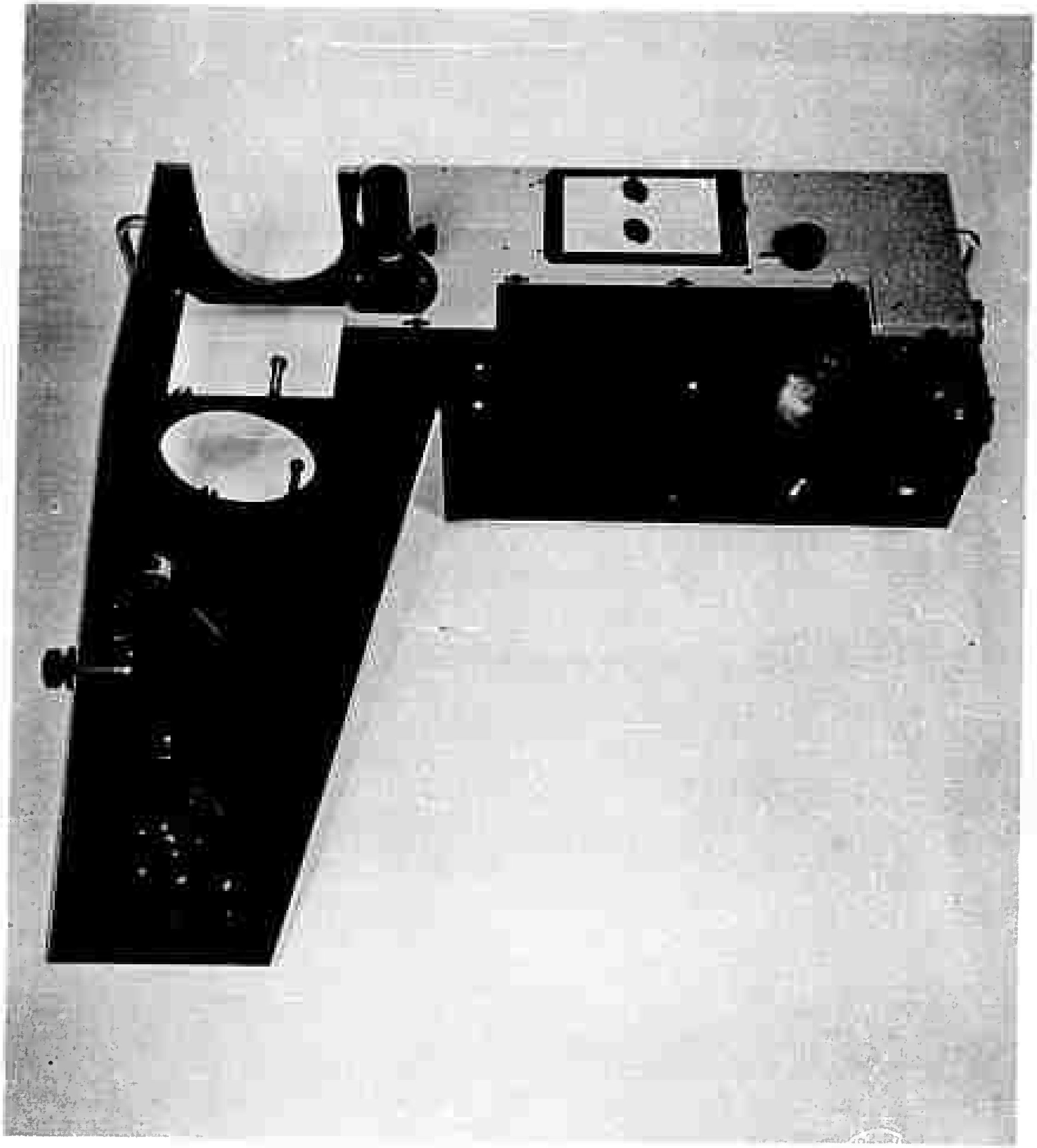


Figure 8. PHOTOMETER HEAD WITH COVERS REMOVED

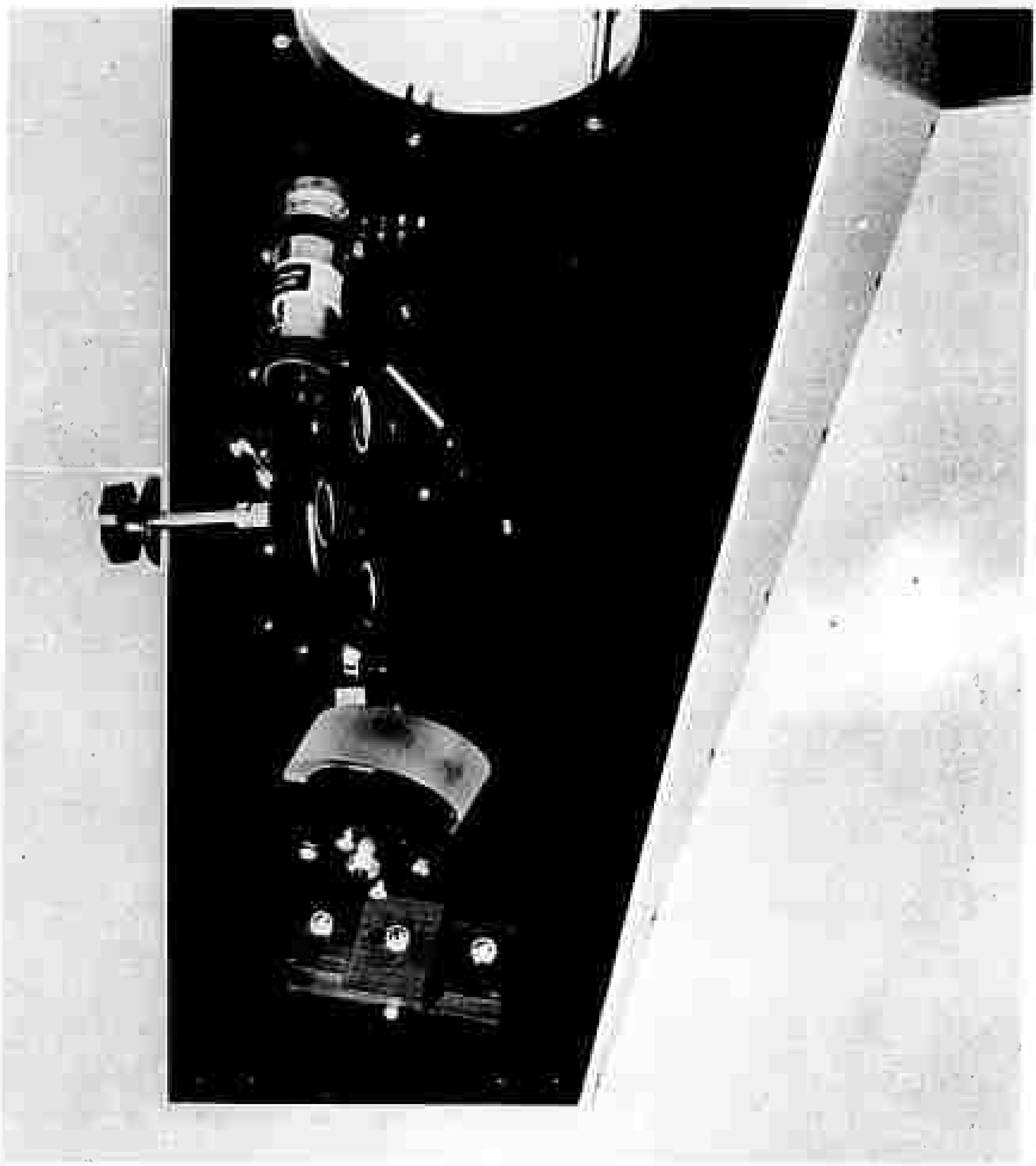


Figure 9. CLOSEUP OF DETECTOR SECTION OF PHOTOMETER HEAD

optical precision, first-surface gold coated, and has an aberration blur circle which is very nearly diffraction limited. This mirror is working at 20° off-axis with 4:1 optical conjugates. The NIR-FIR dichroic is a plane parallel mirror of Irtran II glass with multi-layer coatings. Light is directed from the mirror to a filter wheel containing the 2.0-2.4 micron and 3.2-4.2 micron interference filters which are manually positioned ahead of the plumbide detector. Far infrared radiation which passes through the dichroic mirror is filtered by a cooled 7.5-13.5 micron filter in the helium dewar and finally strikes the doped germanium detector.

The ac signals generated by the fixed detectors are conducted by low noise cabling to separate preamplifiers for initial amplification before further processing in the remote electronic system. The details of this system are described in the following section.

C. PHOTOMETER ELECTRONIC SYSTEM

The function of the photometer electronic system is to take the electrical outputs of the infrared detectors in each of the two channels and obtain from them a permanent record of voltage levels which correspond to the intensities of the stellar infrared radiation impinging on the detectors in their particular infrared bands. For many stellar measurements of interest, the electrical output of the detector is so small that it is of the same order of magnitude as the noise. The signal-to-noise ratio must therefore be improved before recording by reducing the electrical bandwidth of the signal in the signal processing system to suppress the noise level. The specific requirements set forth for the signal processing system are determined by the characteristics of the infrared detectors selected and are discussed below.

The frequency at which the system operates must be high enough to permit the detector to operate above its 1/f noise region but not be so high as to have the signal reduced in amplitude by operating above the cut-off frequency limit imposed by the detector time constant. A representative curve of the signal-to-noise ratio of a liquid nitrogen cooled plumbide detector is given on page 62 of the previous semi-annual report (reference 2). This indicates that our 480 cps chopping frequency is within the optimum range of this detector. It is near the lower limit of operation of the doped-germanium detector.

The detectors when cooled to their respective operating temperatures will each have a resistance of about 2 megohms, and when ballasted, their source impedance, viewed from the preamplifier input, will be about one megohm. This is an impedance level suited to the operation of low noise vacuum tube circuits, but the input leads must be kept short to eliminate the possibility of any noise pickup in the wiring.

The signal-to-noise ratio at the detector terminals may be less than one because the detectors operate over a much wider electrical bandwidth than is needed for this type of measurement. In order to obtain good data, the noise must be reduced by narrowing the electrical passband to improve the signal-to-noise ratio.

When the bandwidth is reduced, however, some of the Fourier components which make up the signal will be eliminated along with noise. As harmonics of the fundamental chopping frequency are eliminated, the signal waveshape changes and it becomes a sine wave. If the electrical bandwidth is narrowed beyond this point, the steady state waveshape cannot suffer further change in shape but remains sinusoidal. However, there are anharmonic components of the signal that are generated when the sine wave signal starts, stops, or changes in amplitude. These components are infinite in number, and their amplitude distribution about the signal frequency is a function of how rapidly the signal envelope is changing in amplitude. Rapid changes yield high amplitude components spread over a wide band of frequencies about the fundamental. Slow amplitude changes produce high amplitude components closely grouped about the fundamental. Consequently, very narrow bandwidths accept only those components which go to make up a signal that is changing in amplitude very slowly. This then is the price paid for reducing the noise; the response time of the equipment becomes very long.

Since we are taking readings from objects which appear to remain stationary against their background, we may readily spend considerable time in taking each reading. During this time the telescope must be sidereally driven to follow the object across the sky and keep the image on the detector. Also, the atmospheric transmission must not change during this time due to the passage of clouds. A practical limit on the length of time that may be taken for any one reading may be about 15 or 20 minutes. This produces an effective system bandwidth of about 0.001 cycle/sec.

The electronic system which best meets the requirements of the measurement task is a homodyne type amplifier using an electro-mechanical chopper demodulator followed by an integrator. The homodyne amplifier has been used by astronomers for many years in photoelectric photometry because of the facility with which signals may be separated from noise (references 3, 4, 5, 6 and 7). In essence, it is an ac carrier amplifier with a synchronous demodulator. The synchronous demodulator, or phase-sensitive detector as it is often called, translates the modulation frequencies or sidebands from their position centered about the chopping or carrier frequency to a new position centered about zero frequency. When the modulation frequencies are centered about zero, they may be limited in bandwidth by a simple low-pass r-c filter. When centered about the carrier frequency, a complex band-pass filter would be required. For very narrow bandwidths, the low pass filter remains simple in configuration but with a longer time constant, while the band-pass filter grows more complex and eventually becomes impossible to achieve as the bandwidth narrows further.

The type of image chopping used in the photometer produces an amplitude modulated ac signal. However, in the absence of an image there is no carrier and both a positive or negative signal can produce an ac signal of the same amplitude. This is characteristic of a suppressed carrier amplitude modulated signal. The carrier frequency is absent but both upper and lower sidebands are present.

Therefore, when the frequency is changed (from the chopping frequency to zero) not only must the proper frequency be supplied to produce a zero frequency beat, but this frequency must also be in exactly the same phase relationship with the sidebands as the carrier frequency which has been eliminated. When this has been done, the original dc signal polarity can be recovered at the output of the demodulator. If this frequency, called the reference frequency, shifts from its proper phase, the demodulated output voltage of the system changes its amplitude and polarity, the amplitude passing through zero as the polarity changes. The reference frequency should be obtained from a generator coupled to the chopper blade shaft so that the phase and frequency remain constant, fulfilling the two requirements.

The phase sensitive detector is an electromechanical switch which reverses the polarity of the signal and noise in synchronism with the polarity reversals of the signal. This process converts the signal to a unidirectional voltage, but the periodic reversals of the random noise fluctuations still leaves the fluctuations random, having an average value of zero. Integrating the output of this demodulator will steadily build up the dc signal but not the random noise. The integration process can be continued until the signal is sufficiently greater than the noise fluctuations to allow a reliable reading to be recorded.

The use of an electromechanical switch rather than a ring demodulator composed of semiconductor or vacuum diodes is imperative in this application where the signal-to-noise ratio is one or less than one. The nonlinearity of the diode circuits causes the generation of cross products or beats between the various components of signal and noise yielding signal times signal, signal times noise, and noise times noise voltages. This increases the number of noise components within the passband, reducing the signal-to-noise ratio when the signal is equal to or less than the noise (references 8 and 9). The electromechanical switch on the other hand is strictly linear and does not produce the unwanted cross products which degrade the system performance.

The reference frequency is used to actuate the driving coil of the switch, causing the polarity reversals to take place at the instant when the ac signal voltage goes through zero. Since the two detectors used in this instrument will have different time constants, the ac signals produced by each will go through zero at different times, requiring reference frequencies having a different phase for each of the channels. In the previous instrument, the proper phase was obtained by adjusting the position of a magnetic pickup around the periphery of the rotating steel sector disc mounted on the chopper wheel shaft. An oscilloscope showed the waveform and indicated when the correct position was reached. This adjustment, rather difficult and time consuming in the experimental model, would require more precision due to the greater number of blades on the chopper disc. Therefore, in this present model a new reference generator circuit has been incorporated to allow for phase adjustment instead by the turn of a knob on the panel of the amplifier and reference generator chassis.

Signal Amplifier

The main amplifiers and recorder are mounted in two desk-type relay rack cabinets as shown in Figures 10 and 11. The preamplifiers, as seen in Figure 12 are located on the photometer itself, near the detectors. This is necessary, for in some telescope installations, the photometer as mounted, may swing in an arc which would require as much as 50 feet of connecting cable.

The detectors are biased by batteries mounted nearby in a shielded compartment and ballasted by wire-wound resistors for minimum noise. The circuit utilizes switching which will localize sources of excess noise quickly. Switch position 1 grounds the input eliminating input circuit noise, leaving noise sources located in the plate circuit of the preamplifier tube, the cable, and main amplifier. Position 2 returns the input circuit to the normal high impedance disclosing any noise sources in the grid circuit or electric field pickup. Position 3 turns on the polarizing batteries but replaces the detector with a resistor, revealing noise due to faulty batteries. Position 4, or normal operating position, switches the detector into operation so that its noise can be compared with that of the resistor in position 3.

Figure 10. AMPLIFIER RACK

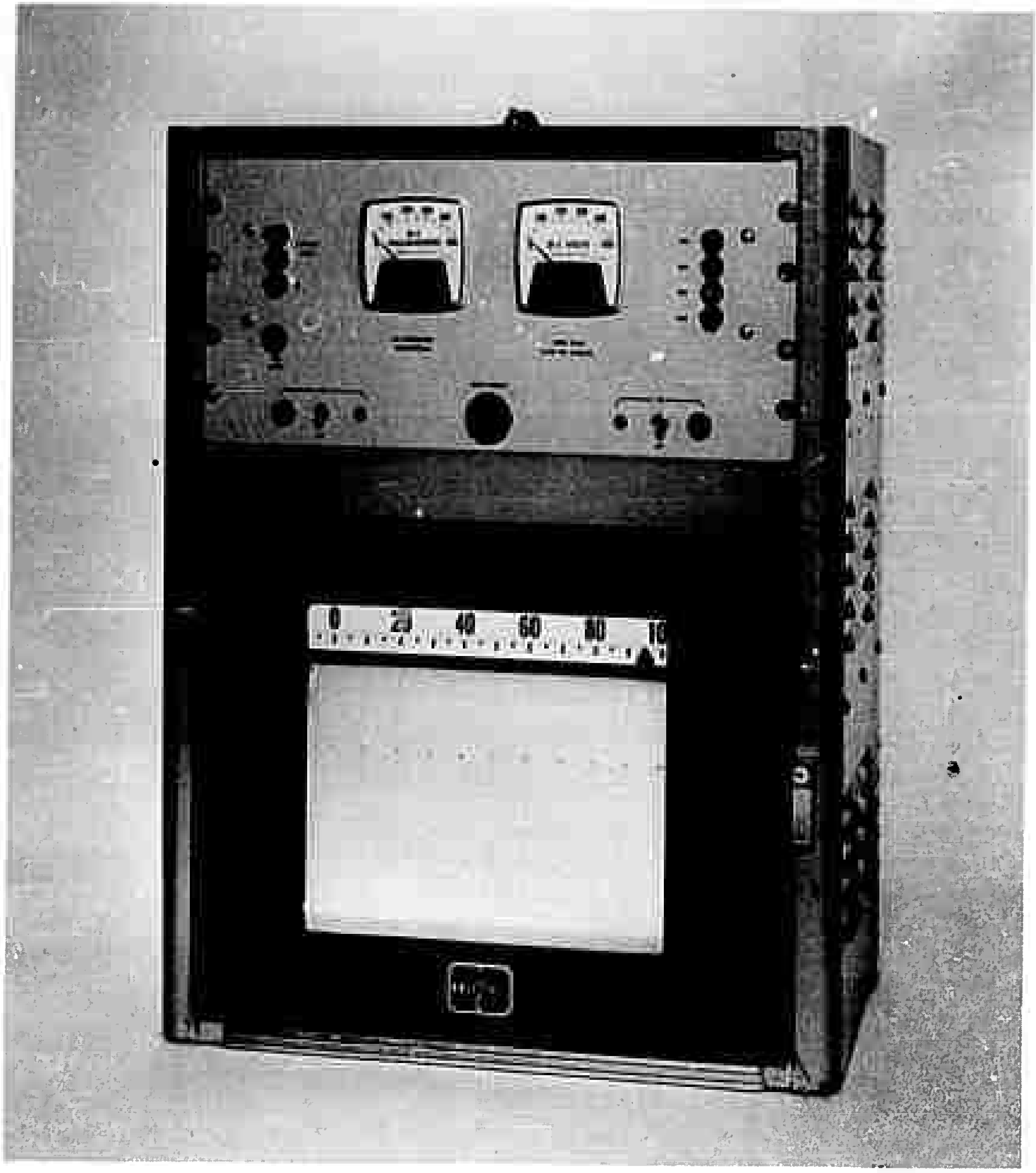


Figure 11. RECORDER RACK

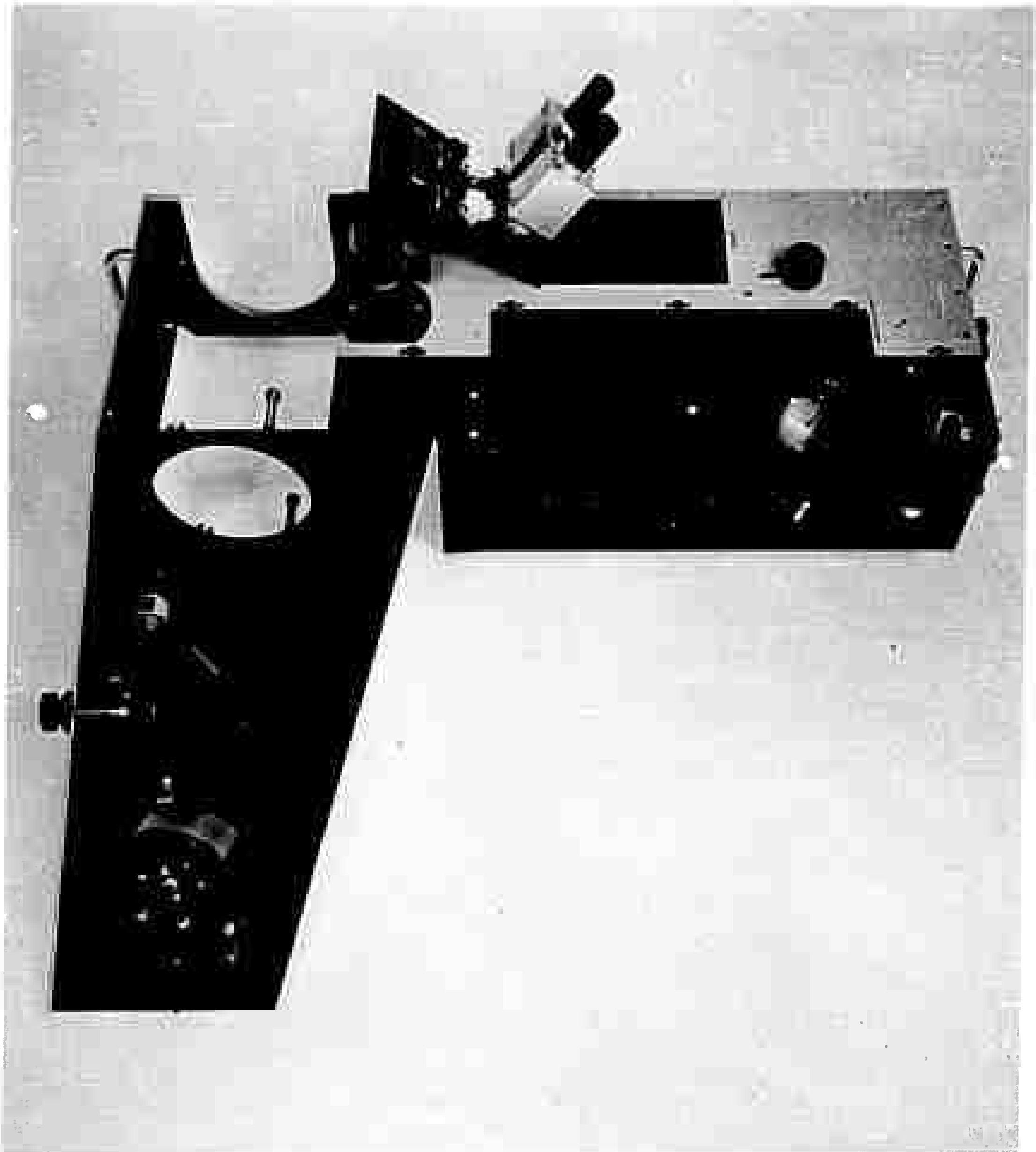


Figure 12. PHOTOMETER HEAD SHOWING PREAMPLIFIERS

The preamplifier makes use of a cascode circuit to achieve low noise operation (references 10, 11, and 12). Direct current is used to supply the tube heaters, and wire-wound resistors are used wherever possible. The plate supply voltage is kept below 100 volts so that residual gas in the tube will not be ionized and become a source of excess noise. Figure 13 is a schematic of both the preamplifiers and the input switching system.

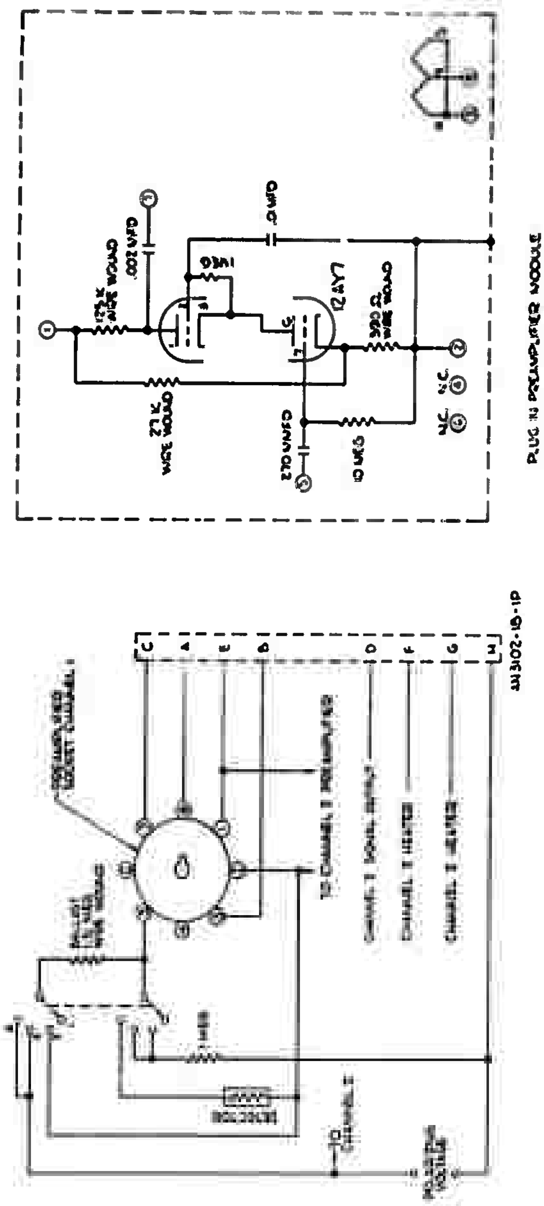
The main amplifiers and attenuators are located in the relay rack. There is a continuously variable attenuator and a step attenuator in each channel. The attenuator steps are 4 decibels each which correspond to one half of a stellar magnitude.

The output stage is a chathode follower transformer coupled to the chopper demodulator. The transformer allows the output to be completely isolated from or balanced to ground, if a different mode of output signal processing should be desired. The signal when rectified by the chopper, is then integrated to allow the low-level signals to be brought up out of the noise.

Figure 14 is a photograph of the chassis containing the signal amplifiers and the reference generator, while Figure 15 is a schematic of the same unit.

Integrator

The integration is performed with the aid of a Philbrick K2-W operational amplifier, stabilized by a model K2-P chopper amplifier in the



SWITCH POSITION:
1-INPUT SHORTED
2-INPUT OPEN
3-POLARIZING BATTERY TEST
4-OPERATE

NOTES:
1. SCHEMATIC SHOWS ONLY CHANNEL 1. CHANNEL 2 IS IDENTICAL AND IS ALSO ON THE SAME CHASSIS.

Figure 13. PREAMPLIFIER SCHEMATIC

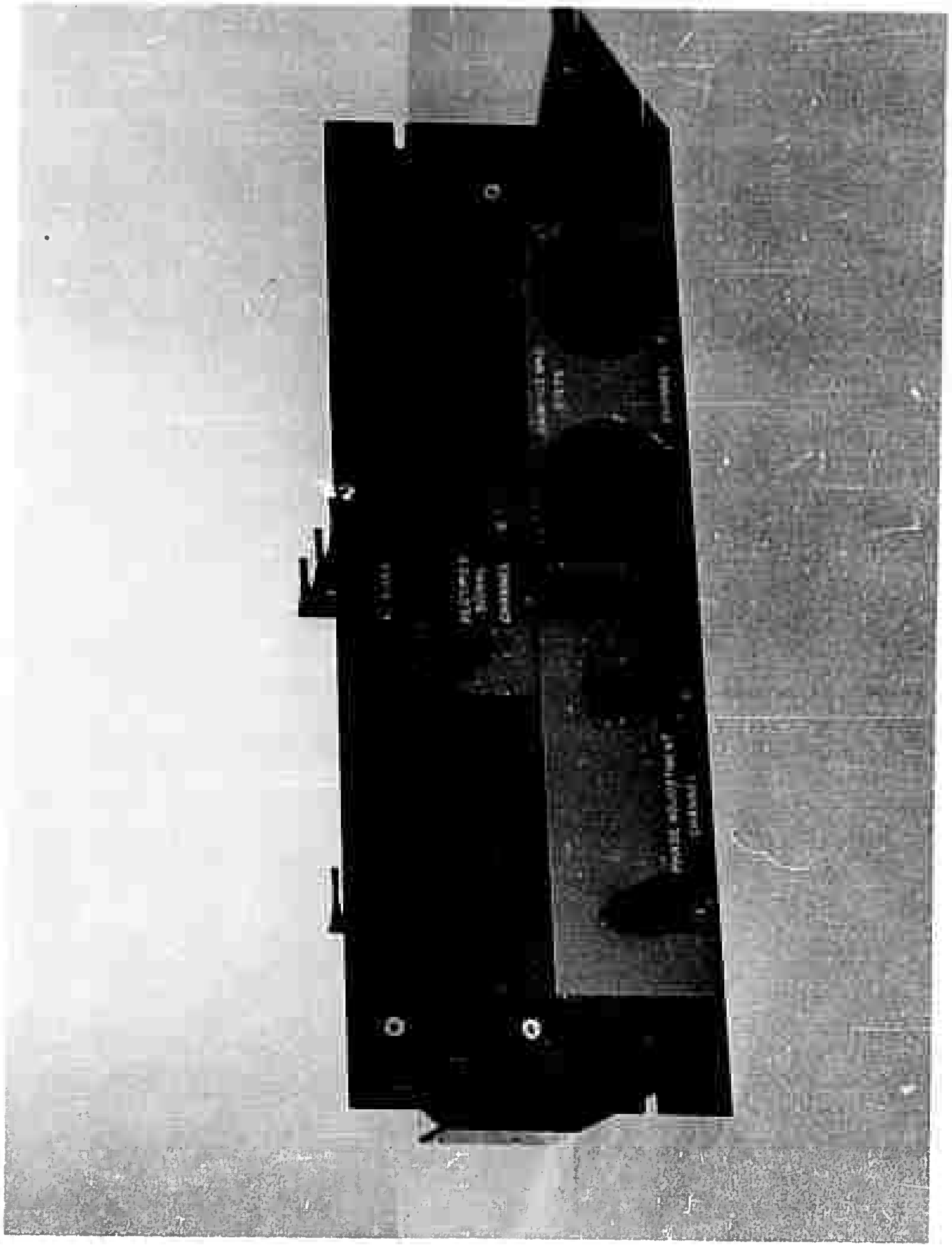


Figure 14. SIGNAL AMPLIFIER AND REFERENCE GENERATOR CHASSIS

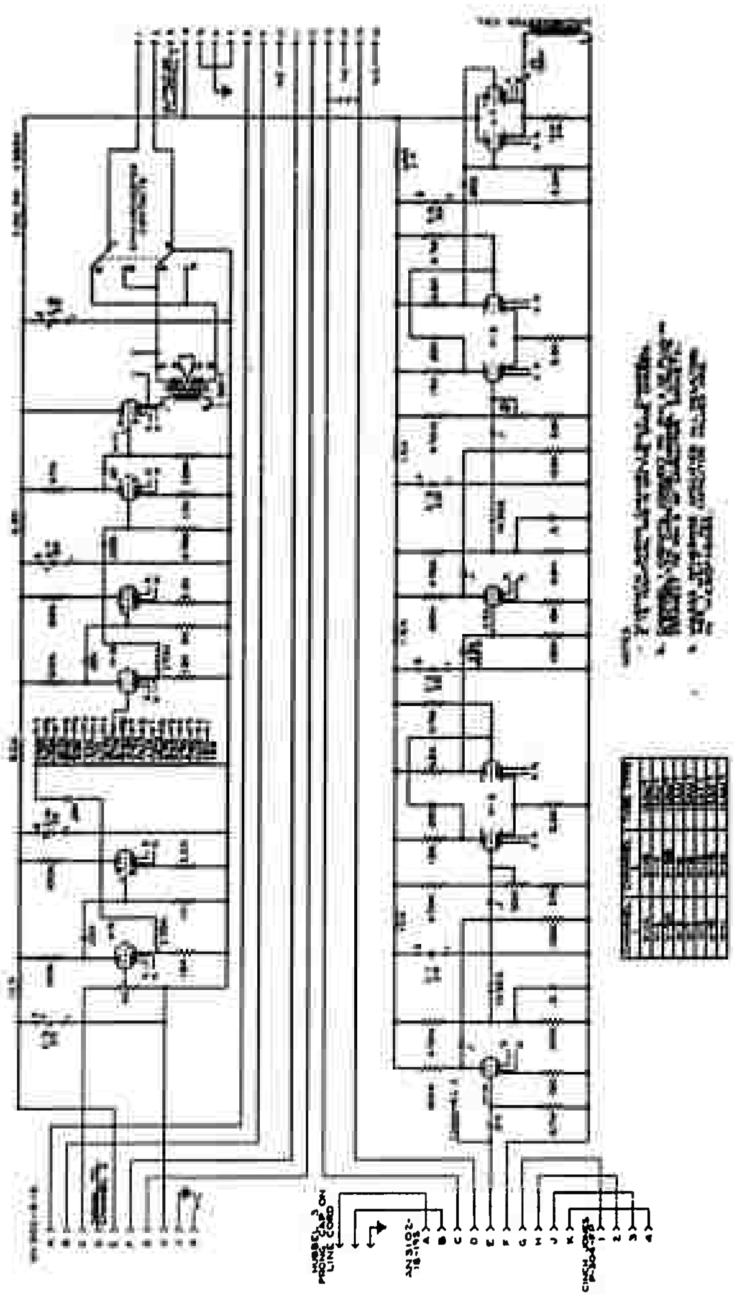


Figure 15. SIGNAL AMPLIFIER AND REFERENCE GENERATOR SCHEMATIC

direct biasing connection. The circuit used can be seen in the Integrator and Timer Chassis Schematic (Figure 16). The capacitor used in the feedback network is a one microfarad polystyrene dielectric capacitor having very low leakage and dielectric absorption. The time of integration is automatically controlled by actuating either a one-minute or a five-minute synchronous motor driven clock timer. If shorter or longer times are required, these may be had by manually starting and stopping the integration cycle with a panel switch. Figure 17 is a photograph showing the integrator and timer chassis, with its front panel controls.

Another K2-P and K2-W amplifier combination is used to amplify the signal so that it may also be recorded while it is being integrated. Then, when the integration is concluded, the recorder is automatically switched over to record the result. In this way, the presence of any interfering transient disturbances or spurious signals is indicated. The response of this signal amplifier can be adjusted to suit the signal to-noise-ratio of the signal involved. Large signals that do not require integration may be recorded directly if desired.

Reference Generator

The reference generator must supply a square wave to the chopper driving coil in order to operate the switching contacts at the proper instant in each cycle. The frequency is synchronous with the chopping of the radiation on the detectors, and the phase must be constant, but adjustable.

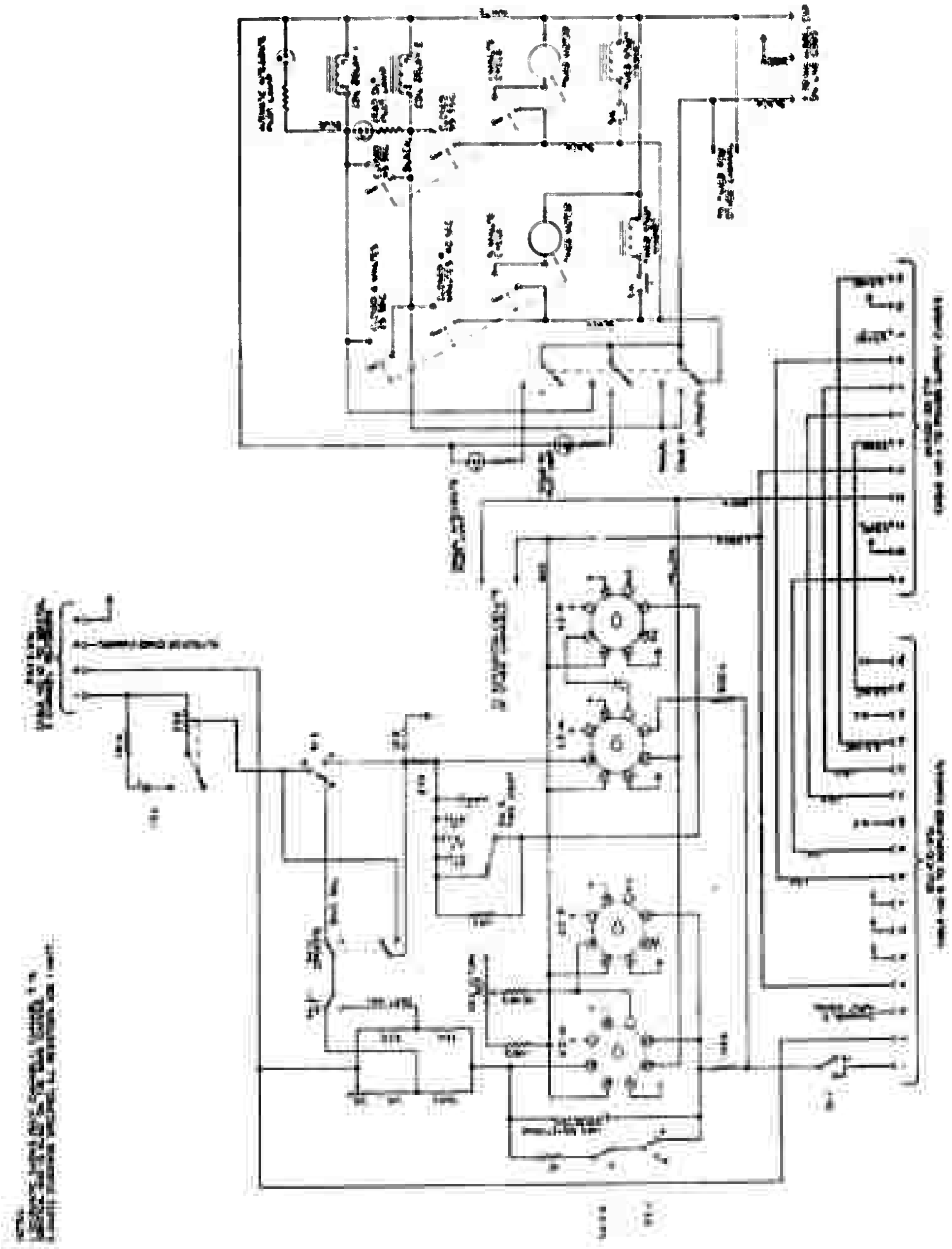


Figure 16. INTEGRATOR AND TIMER SCHEMATIC

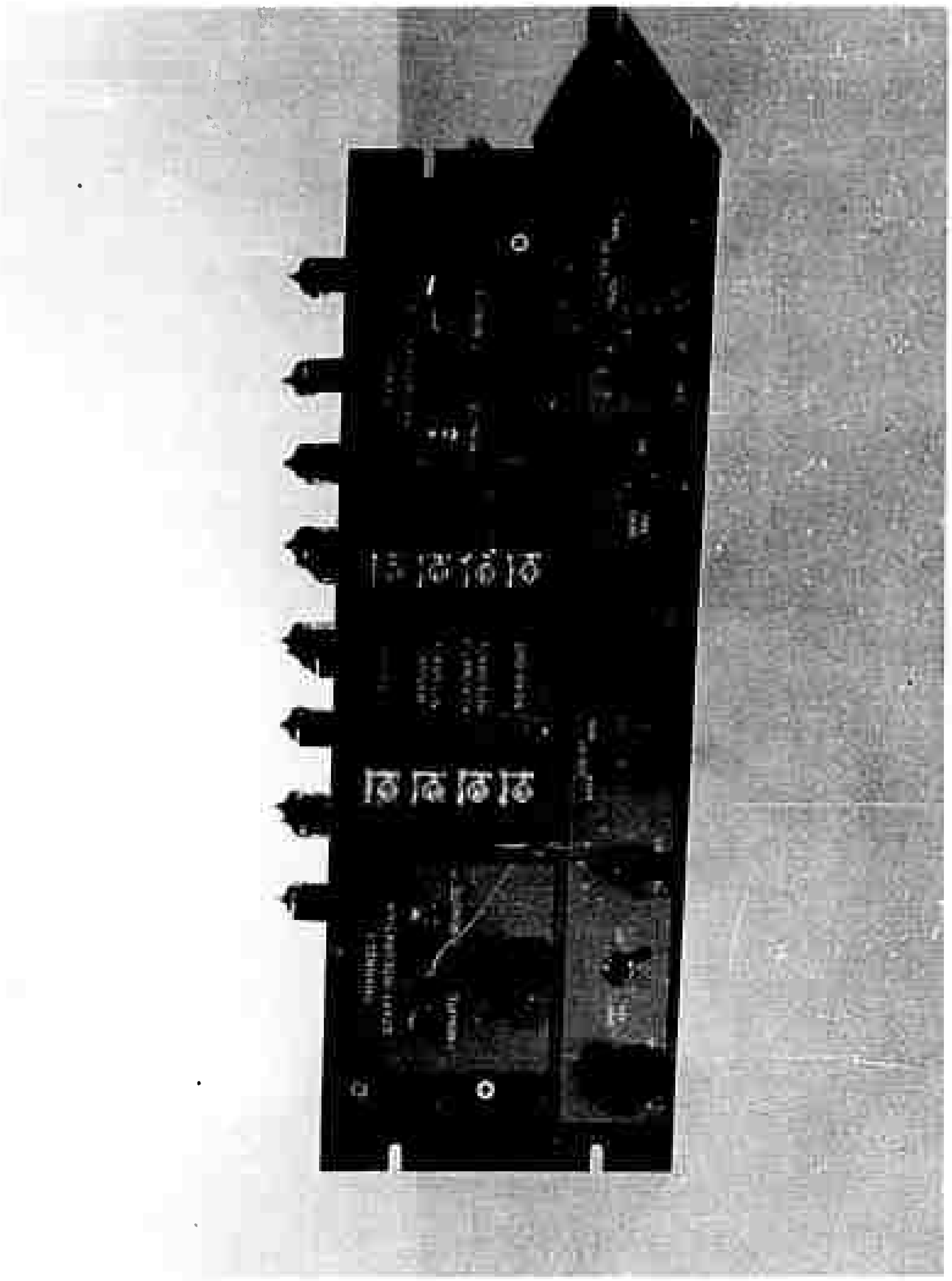


Figure 17. INTEGRATOR AND TIMER CHASSIS

A magnetic pickup, composed of a coil of wire wound on a magnetized pole piece, generates a positive and negative pulse as each sector of a soft steel disc comes into and out of the field of the pole piece. Since the steel sector disc is mounted on the same shaft as the optical chopping disc, it produces pulses in synchronism with the radiation pulses falling on the detectors.

The pulses are amplified to over 30 volts in order to actuate a one-shot multivibrator. The one shot is triggered by a positive pulse and in turn produces a single positive square wave. The start of the square wave coincides with the trigger while the length or end of the wave is a function of the grid bias applied to one of the two triodes comprising the one shot. A wide range of square wave durations is obtained by this method. The bias control is mounted on the front panel of the reference generator and is the phase control. The negative pulses are removed before reaching the one shot by a silicon diode clipper. The waveforms existing at each stage in the circuit are shown on the block diagram of Figure 2.

The square wave pulses produced by the one shot are then differentiated to give a positive impulse at the beginning and a negative impulse at the end. The positive pulse then is stationary while the negative shifts position with the controlled bias. The pulses then go through an amplifier to invert their polarity so that the movable pulse is positive and can trigger another one shot. Another diode clipper again removes the negative pulse. The next one shot also has an adjustable bias. This control is a screwdriver adjustment and is used to make the on and off times of the square wave pulse equal. This second one shot produces a square wave which can be shifted back and forth in time or phase by the bias control of the first one shot. It merely remains to take this square wave and amplify it so that it can be used to energize the driving coil of the chopper rectifier.

Power Supply

Two voltage regulated power supplies are provided to furnish the positive and negative 300 volts needed for the integrating circuits. Good regulation is needed to keep the phase of the reference frequency constant, since it is a function of the bias voltage. A schematic of the negative supply is given in Figure 18, while Figure 19 is a photograph of this supply. The front panel of this chassis also has the photometer master switch and a 24-hour digital readout clock mounted on it.

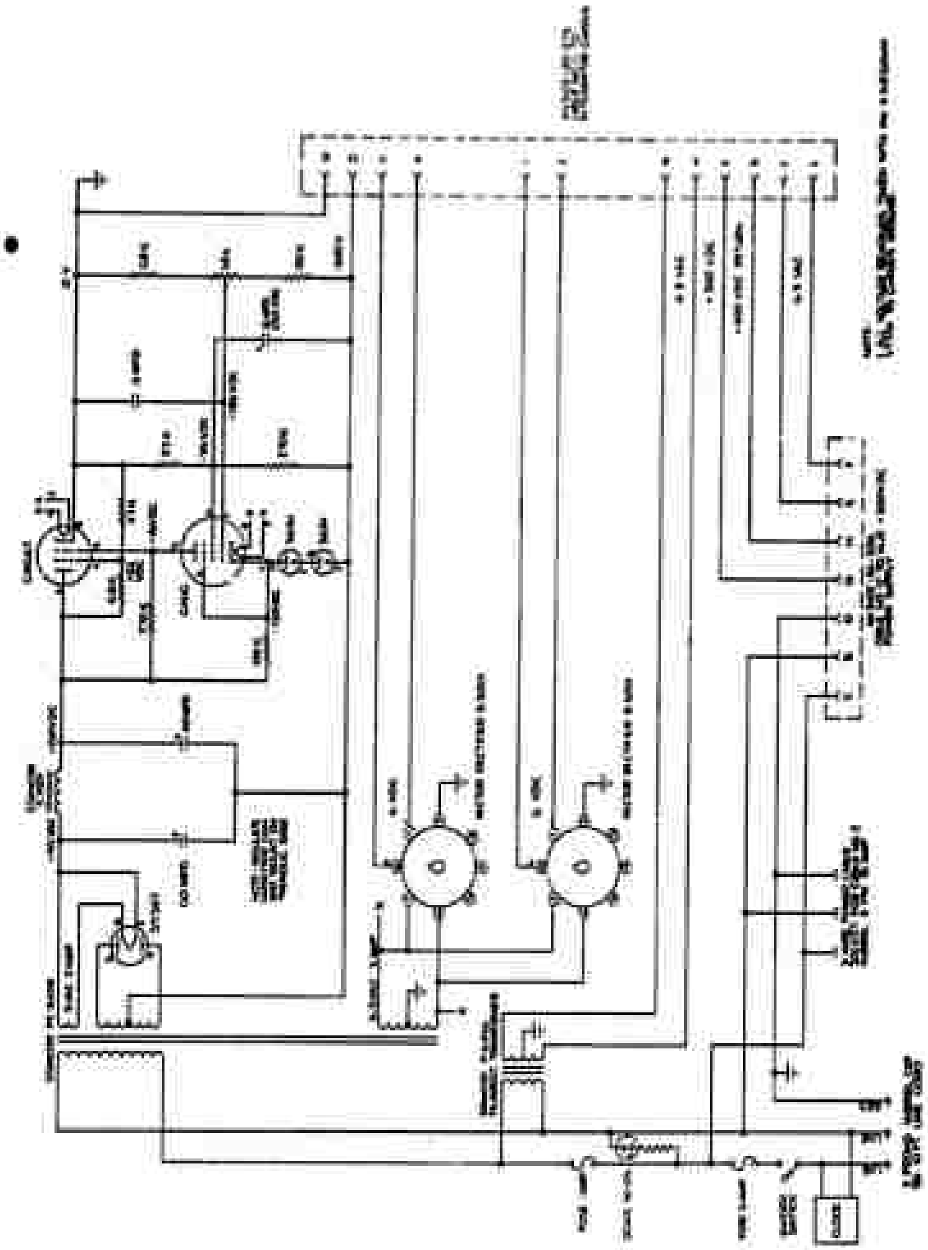


Figure 18. POWER SUPPLY SCHEMATIC

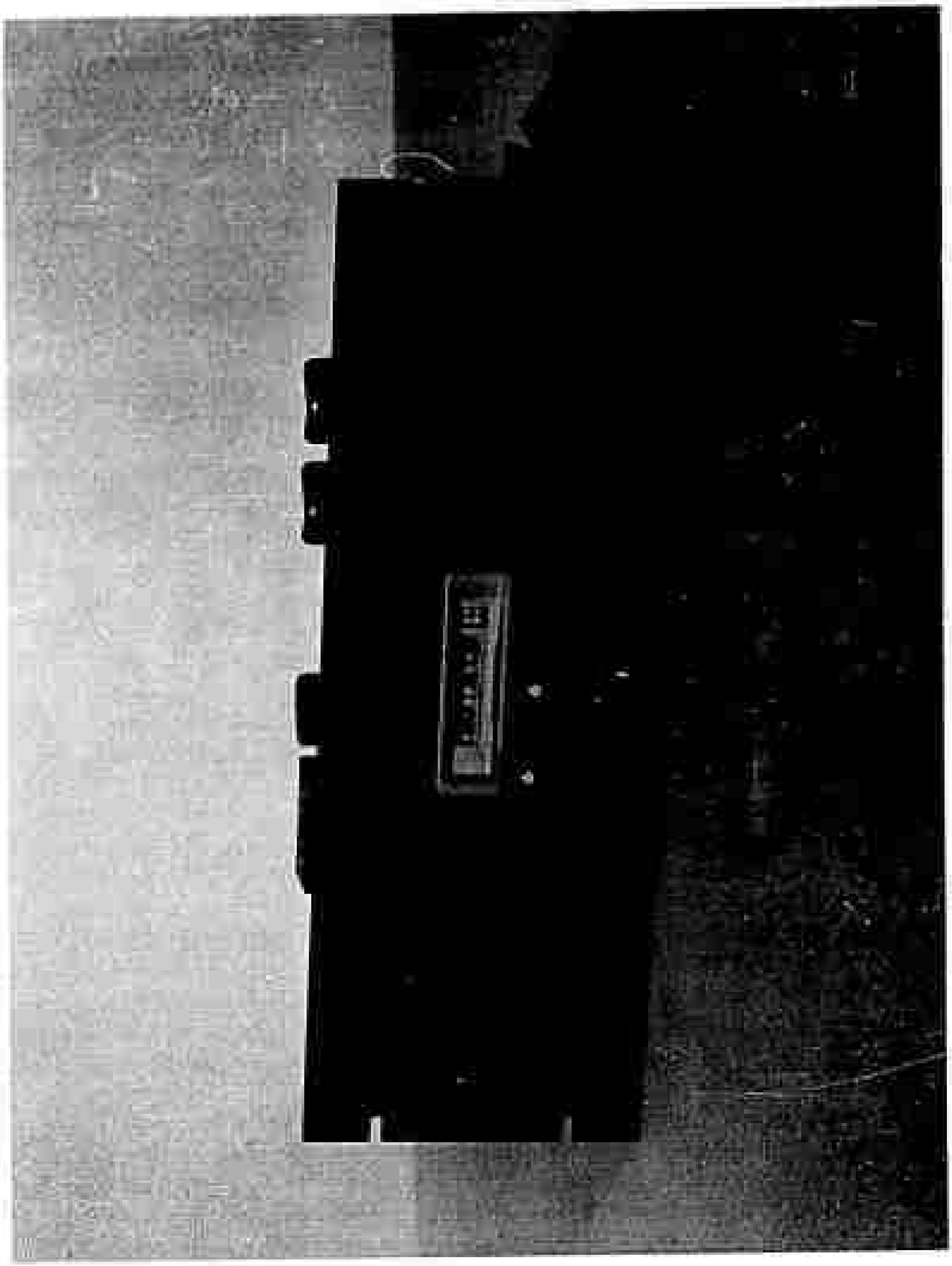


Figure 19. POWER SUPPLY CHASSIS

V. THE OBSERVING PROGRAM

The Perkins Observatory observing schedule was terminated on March 10, 1961, for the purpose of dismantling the 69-inch reflector in preparation for the transfer of the telescope to Flagstaff, Arizona. Therefore, the observing effort was confined to the first seventy days of the year. The experimental photometer telescope time allotment was increased during this period to allow as great an opportunity as possible to obtain data before the telescope shutdown.

The experimental photometer was installed on the telescope on each of the more than twenty scheduled nights and the astronomers were on duty each night. However, weather in the form of clouds and/or extreme cold, precluded obtaining any stellar data on all but part of two nights. The 69-inch telescope log which dates back 35 years shows no other January-February period during which so few observations were obtained because of bad weather. This is, however, an indication of why the large reflector is being moved to Arizona.

The 69-inch telescope is now in Flagstaff and installation in the new dome is proceeding. There has been some delay because the polar axis bearings were found to be badly worn and are being replaced. Installation of the 32-inch reflector at Delaware has been delayed in order to refigure the secondary mirror. Final completion of this installation will be on or before October 15, 1961.

The observing effort for the remainder of the contract period will be confined to the 60-inch and 100-inch telescopes at the Mt. Wilson Observatory. The infrared stellar photometer is presently scheduled for eight consecutive nights on the 60-inch instrument starting July 18, 1961, with at least four more nights later on. The 100-inch schedule is not definite as yet but four to six nights of observing time have been tentatively allotted to the infrared photometer between August 14 and August 24. A somewhat ambitious observing program has been planned for the session on Mt. Wilson. The details of the program are as follows:

A. Observe the 45 or 50 stars currently available in the sky and on the IR list in 3 wavelength regions to determine characteristics.

  a. Observe the non-variables (10-12) every night to set up a standard IR sequence.

  b. Observe as many non standards each night (as time permits) as possible, from the list of 235.

  c. Observe stars of particular interest as the occasion arises.

B. Observe at least 1 star each night (for first several at least) at a number of zenith distances to obtain the effects of atmospheric absorption.

  a. Use all filters.

  b. Use the Plumbide detector on each elevation, unfiltered, to get an idea of the effects outside the spectral windows.

C. Observe into the dawn on as many mornings as the observers can take it. Determine the daytime limits for the photometer.

D. Observe a few "peculiar" objects to try to detect IR emission from them.

a. Ring Nebula

b. M 13

c. Cass A

60-inch Telescope (12-15 nights)

Night 1 - July 18: Photometer Shakedown

S	α Boo	14:13
S	α Ser	15:42
S	α Her	17:12
S	α Lyr	18:36
	X Oph	18:36
	δ Sge	19:45
S	α Cyg	20:40
	μ Cep	21:42
S	β Peg	23:01
	δ And	0:37

Night 2 - July 19: Those labelled (S) plus:

ε Boo	14:43
30g Her	16:27
δ Dra	17:55
δ Lyr	18:53
δ Aql	19:44
δ Sge	19:56
δ Cep	22:27

Night 3 - July 20: All labelled (S) plus:

	β UMi	14:51
	30g Her	16:27
	β Oph	17:41
S	δ Dra	17:55
	R Aql	19:04
	χ Cyg	19:49
	υ Del	20:43
	W Cyg	21:34
	18 Cep	22:02
	λ Aqr	22:50

Night 4 - July 21: All labelled (S) plus:

	W Boo	14:41
	RR UMi	14:57
	ι Dra	15:24
	T CrB	15:57
	π Her	17:13
	104 Her	18:10
	R Lyr	18:53
S	α Aql	19:49
	ϵ Cyg	20:44
	T Cep	21:09
	μ Cep	21:42

Night 5 - July 22: All labelled (S) plus:

S CrB	15:19
T CrB	15:57
α Sco	16:26
X Oph	18:36
R Lyr	18:53
χ Cyg	19:49
3 Aqu	20:45
μ Cep	21:42
L Cep	22:09
χ Aqu	23:14

Night 6- : Cover all objects missed on nights 1-5

Night 7- : Repeat night 2

Night 8- : Repeat night 3

Night 9- : Repeat night 4

Night 10- : Repeat night 5

Night 11- : Cover missed objects nights 7-10

Night 12- : Recovery night - objects insufficiently covered during observing session.

100-inch Telescope (4-6 nights)

Night 1 - : Concentrate on fainter objects.

W Boo	14:41
S CrB	15:19
α Ser	15:42
α Her	17:12
β Oph	17:41
α Lyr	18:36
X Oph	18:36
δ Aql	19:44
α Aql	19:49
χ Cyg	19:49
α Cyg	20:40
W Cyg	21:34
ζ Cep	22:09
β Peg	23:01
71 Peg	23:31
ψ Peg	23:55
ζ And	0:37
β And	1:07
δ And	2:01
α Ari	2:04
o Crti	2:17
N Per	2:47

Night 2 - : Concentrate on fainter objects.

ε Boo	14:43
ι Dra	15:24
α Ser	15:42
π Her	17:13
104 Her	18:10
α Lyr	18:36
X Oph	18:36
δ Sge	19:45
α Aql	19:49
α Cyg	20:40
ε Peg	21:42
18 Cep	22:02
δ Cep	22:27
β Peg	23:01
71 Peg	23:31
ψ Peg	23:55
ζ And	0:37
β And	1:07
δ And	2:01
α Ari	2:04
o Ceti	2:17
η Per	2:47

Night 3- : Observe objects missed on 1 and 2

Night 4- : Repeat night 1

Night 5- : Repeat night 2

Night 6- : Observe objects missed on nights 5 and 6

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