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A differential electronic photometer and polariscope with negative feedback

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ROGERS — DIFFERENTIAL ELECTRONIC PHOTOMETER

A DIFFERENTIAL ELECTRONIC PHOTOMETER AND POLARISCOPE WITH NEGATIVE FEEDBACK

By

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CHAPTER I

INTRODUCTION

Purpose of the Instrument

In connection with a program of research in the physics of the atmosphere, a need has arisen for a sensitive differential photometer which would be adaptable to balloon-borne operation. This paper describes a prototype of such an instrument. The present photometer is constructed for preliminary investigations to be carried out in the laboratory, but with light-weight components used in the design except for the power supply and the main structural frame. Consideration is given to these latter features to the extent that the entire equipment is designed for operation from power sources which can be directly replaced by small light-weight battery packs. The optical components are all replaceable by equivalent ones of smaller size, and the metal parts of the frame can be replaced almost entirely by fibre or plastic materials.

Effect of Polarization

The instrument as designed is sensitive to polarization of the light source used. Therefore care must be taken to neutralize the effects of polarization. However, this same feature gives the photometer another use: the

determination of the orientation of the plane of polarization of a light source. The reasons for this will be made apparent in Chapter II where the details of construction of the photometer are described. This feature is valuable in applications such as the study of polarization of the light of the night sky.

CHAPTER II

DETAILS OF THE DIFFERENTIAL PHOTOMETER

General Principles

The comparison of two sources of light is made by combining beams of light from two apertures at different locations into a single beam which is then projected into a multiplier phototube. By means of a shutter mechanism the two apertures are alternately opened and closed so that the illumination on the photocathode has an alternating component proportional to the difference in intensity of the two light sources. At the same time an electronic switch is operated synchronously with this shutter mechanism to provide a standard reference for phase detection of the signal from the multiplier phototube.

An electronic system translates the fluctuation in illumination of the photocathode into a feed-back current which moves an opaque vane to open or close one aperture, as is required to minimize the fluctuation. This same current also operates the indicator, which allows a reading of the difference in intensity at the phototube from the two beams.

The Optical Receiving System

The front elevation of the receiver unit is shown

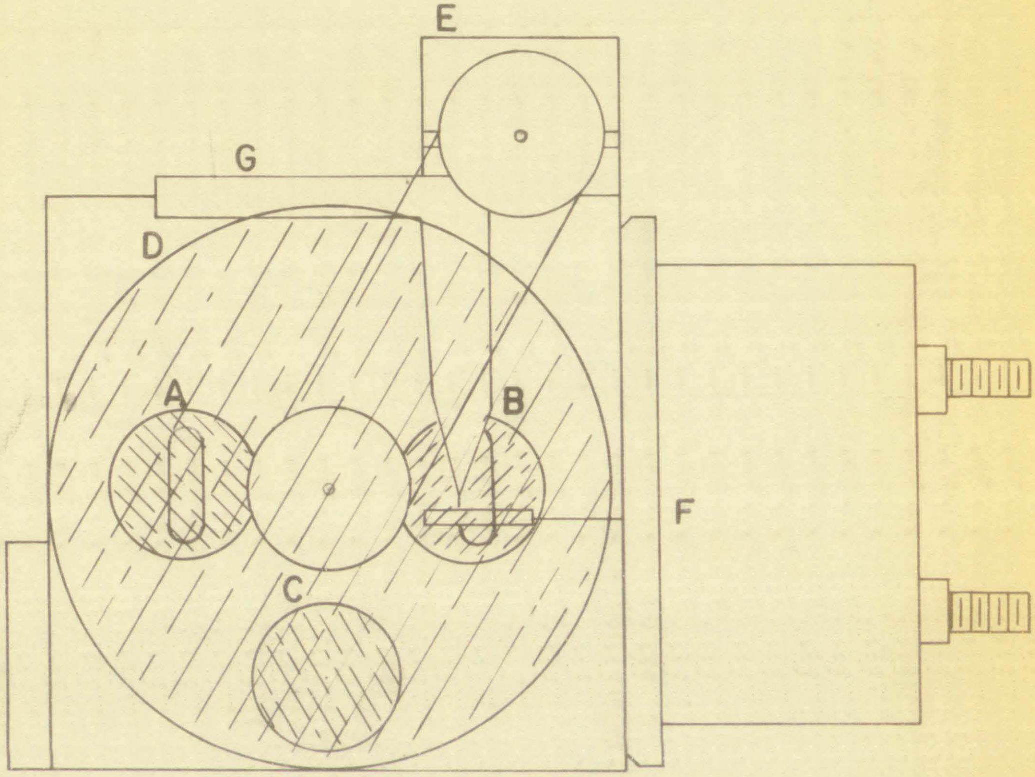

Fig. 1

Front Elevation of Optical Receiving Unit

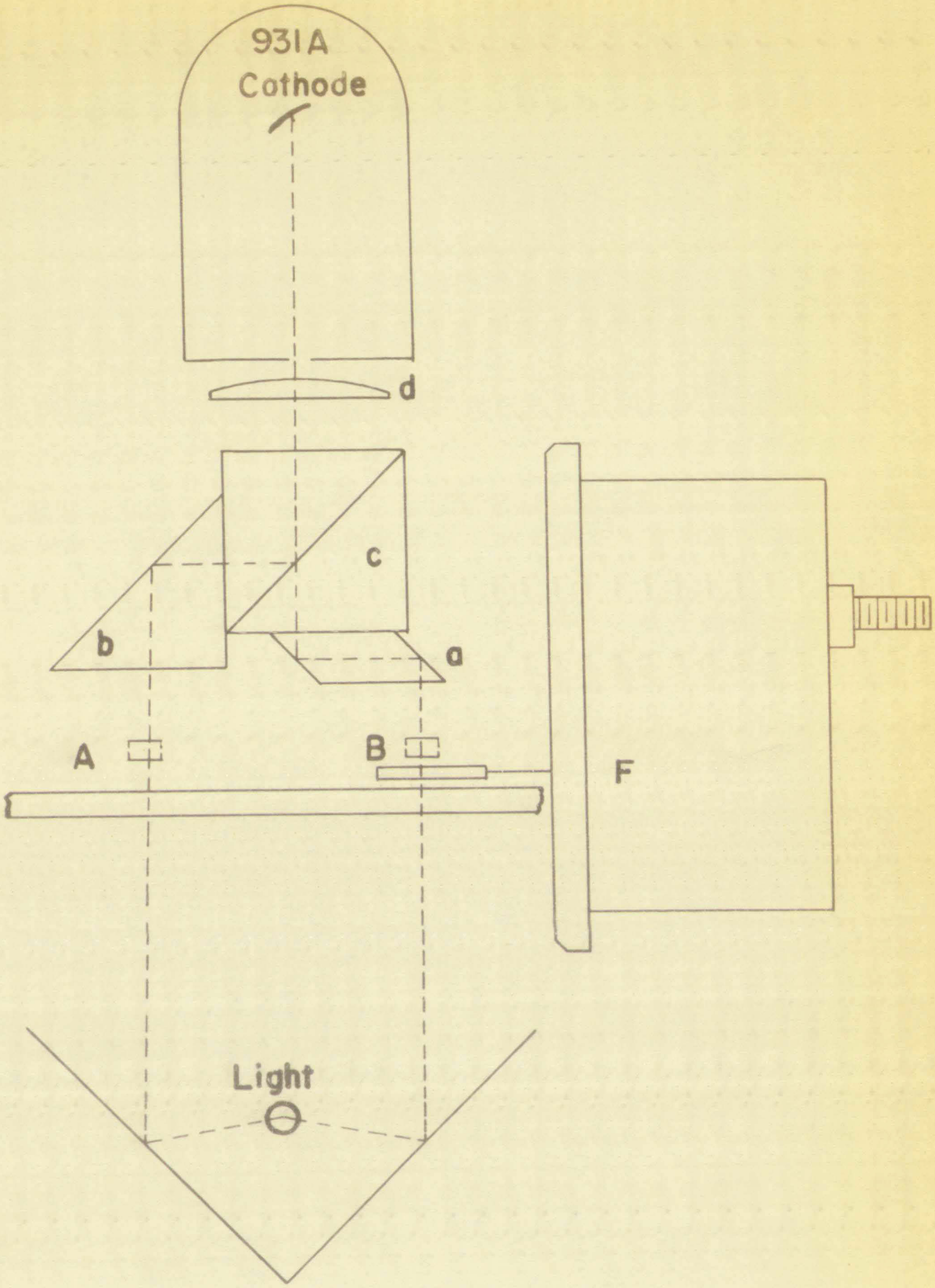

Fig. 2

Plan of Optical
Receiving Unit

in Figure 1. At A and B are the two apertures through which light is admitted to reach the cathode of the multiplier phototube Type 931A. In A there is a polaroid aperture with its transmission axis fixed. In B there is a similar polaroid aperture fixed with its transmission axis perpendicular to that of A. One large polaroid disk, D, is mounted on a central shaft in such a way that it overlaps both A and B. By means of a pulley and belt drive from the motor at E, this large disk is rotated at a constant speed of approximately 1500 r.p.m. This rotation produces a sinusoidal variation in the total light transmitted through A and B separately. Moreover, the two apertures are opened and closed in this manner alternately, due to the fact that their transmission axes are mutually perpendicular. Thus, when the two beams of light are superposed by the optical train shown in Figure 2, the resulting single beam has an alternating component at a frequency of approximately 50 c.p.s. and an intensity equal to the difference between the variations of intensity of A and B separately.

The optical train in which the two beams are merged into one is shown in plan in Figure 2. It consists of the 45° rhomboid prism a, the isosceles right-angle prism b, and the cubical beam-splitter c. The emergent beam is then collected by lens d onto the photocathode of the 931A phototube.

The Phase Reference

In order to provide a phase reference of fixed relation to the signal it is necessary to derive the reference from the same motion that governs the opening and closing of A and B. To accomplish this with a minimum of added weight for parts or power supply, further use is made of the rotation of the transmission axis of the disk, D. A third aperture is provided at C and fitted with a polaroid which is fixed in position. In front of this aperture there is mounted a 6 volt lamp bulb operated by the same battery that powers the motor. Behind the same aperture is a Type 934 phototube, for which the only power requirement is a source of anode potential capable of supplying a few microamperes through the anode load resistor.

The Electronic System

Figure 3 shows in block diagram the nine vacuum tube stages, two crystal diodes, two resistance-capacitance filter sections, feedback, and indicator units which comprise the electronic system. The circuit diagram corresponding to this system is shown in Figure 4.

The phase reference derived from the phototube behind aperture C is amplified in the one stage phase reference amplifier, PRA, and then applied through a grid limiting resistor to the grids No. 1 of both phase detector, PD, stages in synchronism. This provides rapid

switching of the plate circuits of these stages at intervals of one half the signal period. This completes the requirements for the synchronous switching as mentioned in the first paragraph of this chapter.

The signal derived from the 931A multiplier phototube is amplified in the two stage signal amplifier, Sig. A-1 and Sig. A-2, and then applied directly to the grid of the phase inverter, PI-1, which is in turn cathode-coupled to the other phase inverter stage, PI-2. These two stages in cooperation divide the signal into two equal signals of opposing phase. The phase inverter output from PI-1 is applied directly to grid No. 3 of the phase detector PD-1, while the output from PI-2 is applied similarly to PD-2.

By adjusting the orientation of the polaroid aperture at C in Figure 1 the phase reference applied to the grids of the phase detector stages is timed to be precisely in phase with the comparison signal in one of these stages while opposing it in the other.

Since all the grids of the phase detectors are usually greatly overdriven, the applied signals are equivalent to large square topped pulses. The two pulses thus applied to one tube are in coincidence while in the other tube they are in anticoincidence. In the stage where the grid pulses are in coincidence, the plate circuit has a signal in the form of square waves

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of about 15 volts amplitude. In the other phase detector stage at the same time there is no signal at the plate because the pulses on grids one and three effectively cancel each other at all times.

The position of the coincidence changes from phase detector 1 to phase detector 2 when the signal at the grid of the first signal amplifier, SA-1, is inverted. Such an inversion takes place in operation when the relative illuminations of the apertures A and B of Figure 1 are interchanged. Thus at any time only one of the phase detector stages has an output. The choice as to which of the two stages this is depends on which of the apertures A and B is more intensely illuminated.

The negative pulses from the plate of that phase detector stage which is conducting are transmitted through the crystal diode, either D-1 or D-2, into the corresponding filter unit, F-1 or F-2. These filter units convert the 50 c.p.s. signal into direct current. They are coupled directly to the grids of the respective direct current amplifiers and also to a common bias source.

The two direct current amplifier stages, DCA-1 and DCA-2, have a common cathode resistor and a common plate potential source. The two tubes are as nearly identical as is reasonably practicable, and the two load resistors in the plate circuit are nominally of the same value. The plate circuits terminate in opposite ends of a

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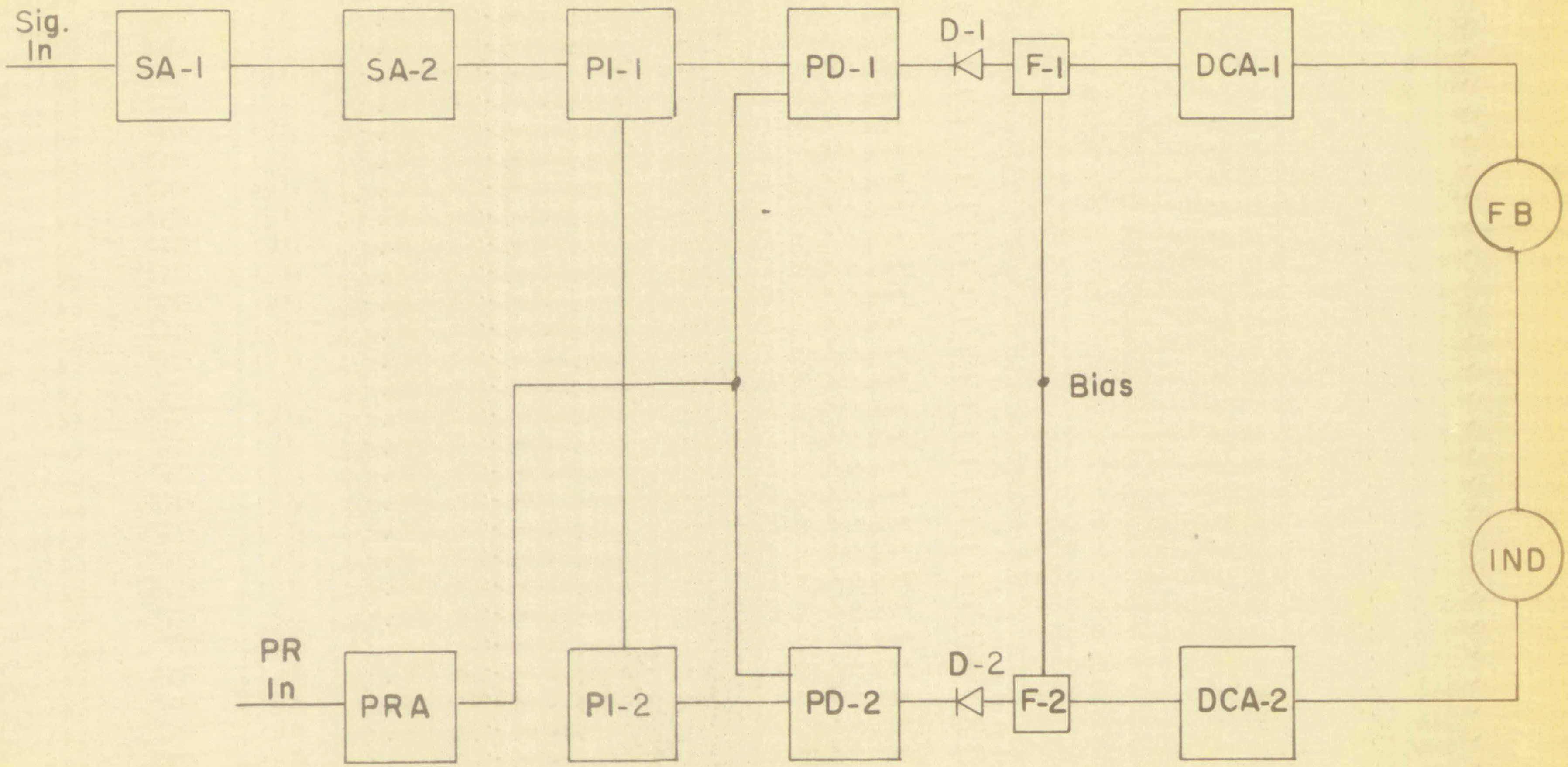

Fig. 3

Block Diagram of Electronic System

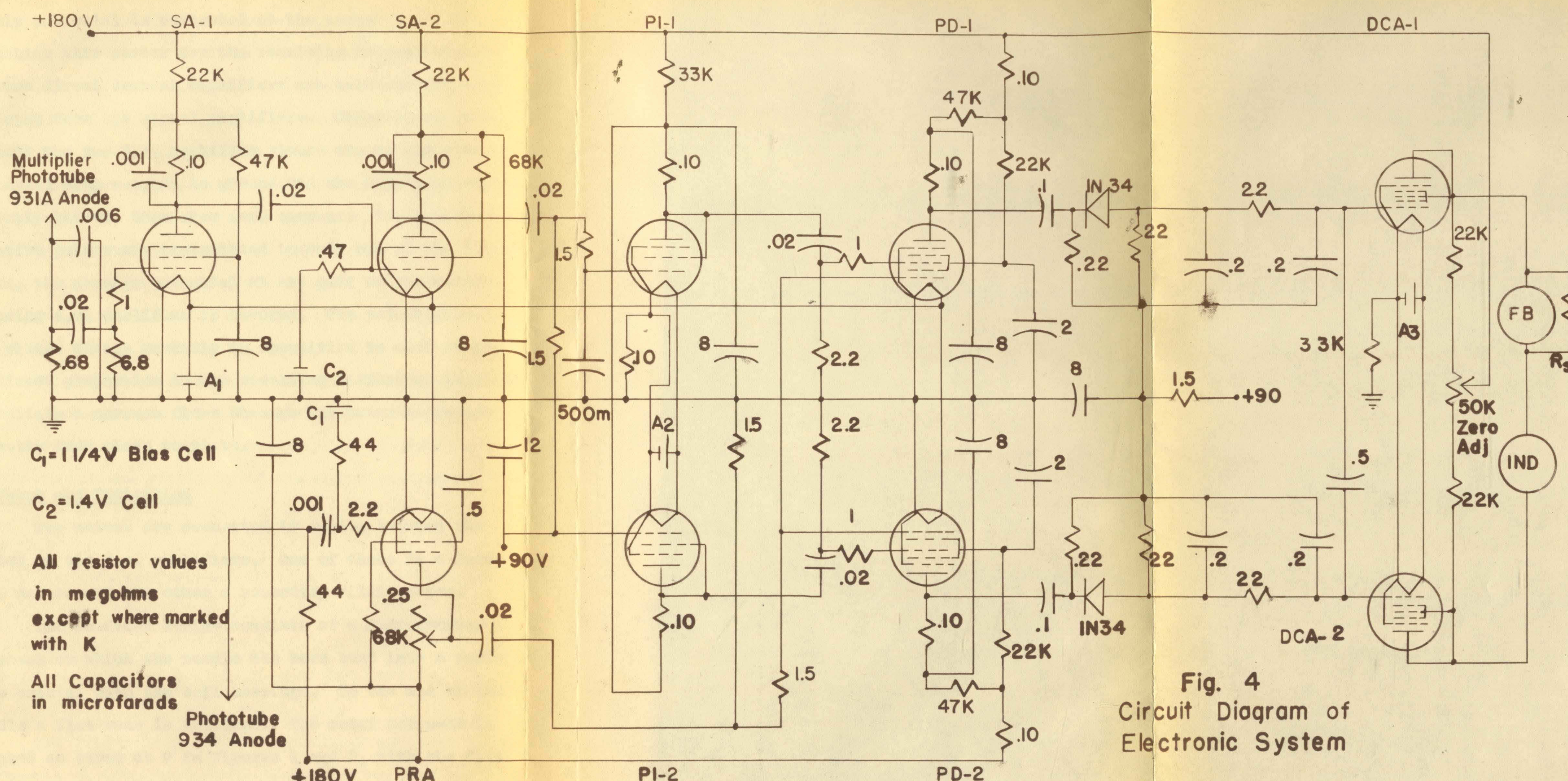

Fig. 4
Circuit Diagram of Electronic System

potential divider, marked Zero Adj., to which the plate supply potential is connected at the center tap. By adjusting this center tap the remaining inequalities in the two direct current amplifiers are balanced out with no input from the signal amplifiers. Under these conditions the two d.c. amplifier plates are at the same potential with respect to ground and the meters connected directly between them show zero current. If, subsequently, negative pulses are transmitted to only one of the filter units, the average potential at the grid of the corresponding d.c. amplifier is lowered. The potentials at the plates change markedly in opposition to each other. In direct proportion to the resulting difference in plate potentials a current flows through the meter connected directly from plate to plate.

Feedback and Indication

Two meters are connected in series between the plates of the d.c. amplifiers. One of these is a feedback device and the other a recording milliammeter.

The feedback device consists of a microammeter movement on which the needle has been bent into a position coaxial with the coil bearings. To the end of the needle a flat vane is attached. The meter movement is mounted as shown at F in Figures 1 and 2, with the flat vane projecting across the aperture at B. The meter is then connected between the plates of the d.c. amplifiers

in such a way that darkening of aperture A results in a rotation of the feedback meter movement which places the flat vane more nearly parallel to the surface of the polaroid in B. This automatically darkens B to compensate for the darkening at A. If the illuminations at A and B are initially and always nearly enough alike so that the difference between them can be compensated by rotating the flat vane in front of B, the photometer will automatically compensate all changes and simultaneously indicate the extent of the difference in terms of the current required to rotate the flat vane to the proper position.

The entire photometer comprises a closed signal circuit with negative feedback resulting in nearly 100% degeneration of the signal at the input. This feature results in extreme stability of the system as a whole.

CHAPTER III

OPERATIONAL BEHAVIOR OF THE PHOTOMETER

Sensitivity

Several tests of sensitivity were made with the photometer comparing the illumination of two white screens by a small light bulb placed between them. In these tests the screens were adjusted to make the difference in light intensity at the apertures A and B come within the range of control of the feedback system and the indicator was set to an arbitrarily chosen current reading. Then small variations were introduced at aperture A by obstructing the light path through it.

The objects used for the sensitivity test were single pieces of wire placed horizontally across A. The obstructed areas were approximately 2%, 1%, and 0.5% with the three sizes of wire used.

In a typical test of this kind the 0.5% change caused a change in indicated current of 250 microamperes with a response time of about one minute. Under the same conditions the 1% change caused an increase of 500 microamperes and rotated the vane on the feedback meter to the position of maximum shadow on B.

The sensitivity of this photometer is controlled by several factors considered in the design of the instrument.

The rest position of the vane on the feedback meter influences the sensitivity due to the fact that for small rotations the variation in the width of shadow projected on aperture B is proportional to the sine of the angle between the flat surface of the vane and the surface of aperture B. This one factor is adjustable in three ways: By removing the meter from its position (F in Figure 1) and twisting the vane at the point where it is anchored to the meter needle; by removing the meter movement from its case and setting the position of the coil by means of the original meter zero adjustment; by adjusting the Zero Adjust control shown in Figure 4.

The ratios of vane width to thickness and vane area to aperture area also affect the sensitivity. In the instrument constructed the vane is a strip of aluminum foil of 1.25 mm. width and 0.11 mm. thickness. The ratio of vane area to aperture area is about one to ten.

In view of these factors the vane is set to rest at an angle of about 20 degrees with the surface of the polaroid in order to afford maximum sensitivity together with a range of operation sufficient for the expected conditions of use.

Sensitivity and zero point reading are both found to be essentially independent of operating characteristics of the electronic system over a sufficiently large range

to allow dependable operation. However, filament voltages must be kept well above the minimum 1.25 volts indicated for the tubes.

Sensitivity is most reliably changed over large ranges by substitution of different shunts across the feedback device. The indicator sensitivity varies inversely to the value of the feedback shunt. The numbers given above for sensitivity test were obtained with a seven-ohm shunt. A similar test with a ten-ohm shunt showed an indicator sensitivity approximately half as great.

Finally the sensitivity is dependent on the size of the signal applied. For small signals such as should ordinarily be encountered this effect is completely unimportant, but if there is a possibility of sudden large changes in illumination it should be noted that the response of the electronic system is not linear.

Stability

As a test of stability, the photometer was put into operation, set to a particular indication, and left on for several hours. It was observed that as long as there was no change in relative illumination nor appreciable loss of terminal voltage by the filament batteries, the zero point did not vary by more than 20 microamperes over a period of several hours.

Response Time

The response time is determined primarily by the circuit constants involved in the filter units. In all tests it was observed that the time required for noticeable drifting to stop after producing a sudden definite change in the illumination of the photometer apertures was approximately one minute. This time was nearly independent of the size of the disturbance provided that it lay within the range of the linear feedback characteristic. The single element that most effectively controlled the response time was the capacitor connected directly between the grids of the d.c. amplifier tubes. When this was completely removed the response was almost immediate, but the indication became uncertain due to hunting and noise disturbances over a range of about 50 microamperes. With the 0.5 microfarad capacitor shown, this fluctuation disappeared entirely. The indicated uncertainty was then the long term variation of about 20 microamperes in zero point as mentioned above.

Rough Adjustment

Due to the fact that beam-splitting cubes were not available which transmit and reflect equally at the interface, it was necessary to provide some means of compensating for the difference in the loss of light from A and B at this point in the optical path. In the

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beam-splitter used in the present photometer the ratio of transmission to reflection is nearly two to one. Consequently B appears much brighter than A as seen from the multiplier phototube when the two apertures are equally illuminated. To compensate for this difference a manually adjustable stop was provided. This is shown in Figure 1 as the channeled slide G with a vane projecting over part of the aperture at B. This was set for zero signal in the signal amplifier while the feed-back vane was somewhere near its normal operating position and disconnected from the d.c. amplifiers.

<u>Operation as a Polariscope</u>

If the photometer is directed at a single source of plane polarized light of uniform intensity instead of two separate sources, the transmission at A will in general be different from that at B because of the difference in the angles which the transmission axes of these polaroids make with the polarization vector of the source. Equal transmission will be obtained at the two windows only when the polarization vector of the source light bisects the angle between the transmission axes of the two apertures. As shown in the diagram of Figure 5 equal transmission at the two apertures identifies the polarization vector as either P or P'. A slight clockwise rotation will then result in more light through A if P is the true source polarization vector, but in more

light through B if P' is the true vector. Since the instrument detects variations of less than 0.5% in relative transmission through A and B it should afford reliable measurement of the polarization direction within 0.1 degrees.

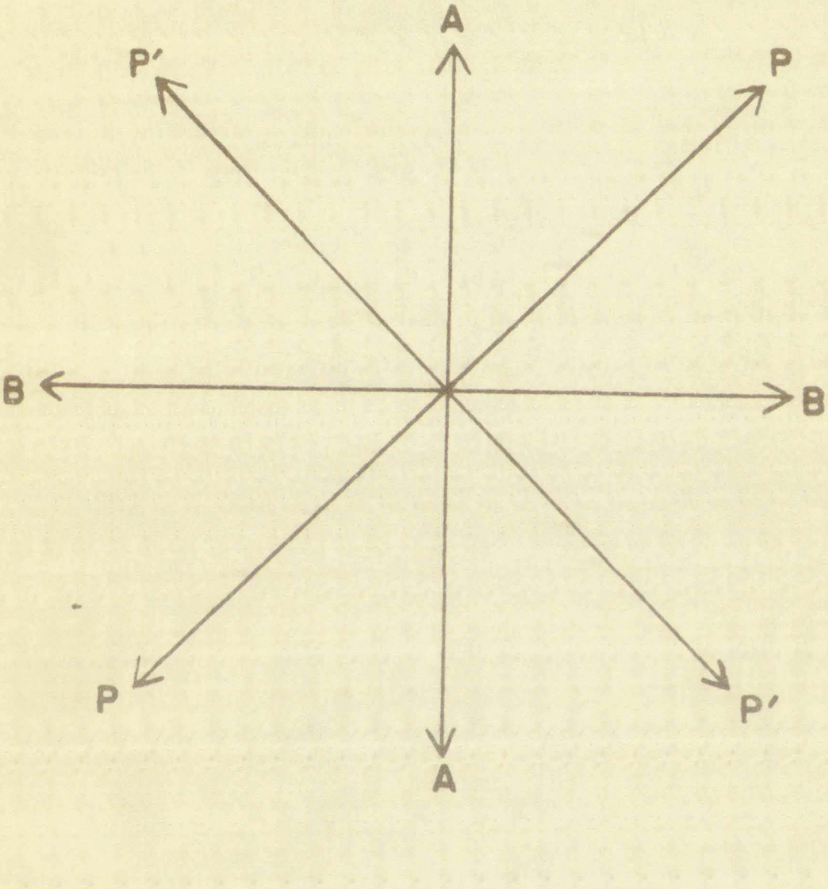

Fig 5

Polarization Diagram

CHAPTER IV

SUMMARY

An instrument has been designed and constructed for the detection of small differences in the intensity of light sources. The design has been made with consideration of compactness of volume and weight so that no essential features need be modified to adapt the instrument for automatic operation on high altitude balloon flights.

In addition to its use as a differential photometer the instrument is readily adaptable for use as a polariscope.

In either use the instrument provides an output for either direct scale reading, recording, or automatic signal transmission.

A high degree of stability in operation is assured through the use of complete degenerative feedback over the entire system, comprising both the optical and electronic components together.

The instrument has been tested successfully for clear detection and reproducibility with changes of less than 0.5% in relative intensity of two sources. This corresponds to an angular precision of approximately 0.1 degrees of arc in the determination of the polarization vector of a light source uniform over a large area.

Acknowledgments

I wish to express my thanks to Dr. Victor H. Regener for suggesting this problem and for his guidance toward its solution. I am also indebted to Mr. John L. Pack for a number of valuable suggestions, and to Mr. Raymond Janness for indispensable assistance in construction of parts of the instrument.