AN ABSTRACT OF THE THESIS OF

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(Major Professor)

Since 1890 the Astrophysical Observatory of the Smithsonian Institution has been studying the radiation of the sun in an endeavor to find some correlation between the variation of solar energy and meteorological changes. Of the stations established only two are at present in operation, one in the Andes Mountains of South America, the other on Table Mountain, L.A. county in California. Cost limits the number of stations so that the locations at which data are available is limited. It was thought that some sort of semi-portable spectrobolometer, embodying the principles of the instrument as invented by Langley, could be devised and used not only for weather studies, but also for a study of radiation in green houses, in forests, etc. If successful, the instrument may be of importance in investigations on plant growth.

In designing a semi-portable instrument size, weight, and stability of adjustment must be considered. Compactness was obtained by using a Wadsworth mirror mounting, with two dispersions through a rock salt prism. The spectrometer and a bolometer are housed in a vacuum chamber to limit temperature disturbances. The lead screw turning the spectrometer arm will be driven by a governor-controlled falling weight.

Recording must of necessity be photographic on account of the use of a high sensitivity galvanometer. Photostat paper was selected because of its high sensitivity and comparatively low cost. Daylight loading is essential and special cassettes for the paper were designed. In the paper-drive is incorporated a scheme for perforating the angle-coordinate so that the record will not be spoiled by shrinkage or expansion of the paper by processing.

The instrument has been completed to the point beyond which special design for portability is no longer needed.

A SEMI-PORTABLE, INFRA-RED, VACUUM SPECTROMETER

by

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INTRODUCTION

The analysis of the spectrum, particularly that of the sun, has engaged the attention of many well known men of science. Sir Isaac Newton demonstrated by means of the prism that white light or sunlight may be dispersed into a blending band of colors, which may not be further dispersed into apparently different colors but may be recombined to give a white light. Sir William Herschel (5) in 1800 observed that a thermometer, placed in the solor spectrum beyond the visible red, continued to rise in temperature, and that the rise in temperature was greater at the red end of the spectrum than at the violet end, with no observed heating effect beyond the visible violet. He found that these invisible rays were reflected and refracted according to the ordinary laws, but believed that heat and light were separate constituents of the solar spectrum.

Leslie in 1804 found that different substances, possessed different powers of radiating and absorbing heat, with glass strongly absorbing the invisible radiations. This further strengthened the erroneous belief in the separate entities of light and heat.

In 1843 Melloni stated that light and heat are "merely a series of calorific indications sensible to the organ of sight and that vice versa the radiations of obscure heat are veritable invisible radiations of light". This now completely accepted theory was then almost as completely rejected. Melloni and Seebeck showed that the disposition of heat in the prismatic spectrum is dependent upon the prism material.

In 1840 Sir John Herschel (6) first published a thermograph showing the unequal absorbtion in the infra-red. In 1842 Dr. J. W. Draper observed by phosphorescence, three wide absorption bands. However, as he, with other earlier experimenters, accepted Canchy's dispersion formula for wave length determinations, he supposed that these bands marked the limit of the spectrum. Müller (13) in 1859 limited the spectrum to 1.8μ and assigned two-thirds of the energy to the invisible part of the spectrum. Lemansky (8) in 1871 used the thermopile to map the energy in the solar prismatic spectrum, showing three gaps in the infra-red radiations.

In 1883 H. Becquerel (4) using the quenching effect of infra red on phosphorescent materials, mapped out the spectrum roughly to 1.4μ, and noticed the variation of the absorption bands with varying atmospheric conditions. Abney (2) in 1880 photographed the solar spectrum to 1.0μ and in 1886 (3), using a Rowland concave grating, obtained values of the absorption lines from the extreme red to 1.0μ. Lommel (13), in 1890, using the method of Becquerel, published a good spectral chart.

All these earlier experimenters were handicapped by the inadequate radiation measuring instruments then at hand, the poor sensitivity of the thermometer, the unreliability of the early thermopile, and the inadaptability of the radiometer. Present day research in the field owes much to Langley's (9) invention of the bolometer in 1881, an instrument using two platinum strips in a Wheatstone bridge circuit. Light, falling on one strip, raises the temperature of the platinum, and the consequent lowering of resistance allows a current to flow through a sensitive galvanometer.

Applying the bolometer to the distribution of energy in the solar spectrum, Langley (10) was able to obtain both normal energy and prismatic curves to 2.8μ, and to show that the maximum ordinate of the glass prismatic curve is at about 1.0μ while the normal energy curve has a maximum in the orange. By taking bolometric indications with varying air mass, he was able to show that the absorption in the normal energy curve increased rapidly with decreasing wavelength. This work introduced the spectrobolometer, a spectrometer with a "minimum deviation" or Wadsworth mirror and arms arranged for the bolometer and collimating apparatus.

In 1884 Langley, (11) using the spectrobolometer on Mt. Whitney at an elevation of 12,000 feet, discovered a new region beyond the then known 2.8μ limit, and in 1886, (12) using a rock salt prism and a carbon arc as a light source, mapped the spectrum to 5.3μ. In 1895, Keeler (7) published a résumé of the several investigations of Rubens, Snow, Paschen, and other in obtaining tables for the dispersion of rock salt to 10μ. In 1897 Rubens and Trowbridge (15) published tables for rock salt spectra to 22.3μ.

Langley's work at Mr. Whitney (11) was instrumental in the founding of the Astrophysical Observatory of the Smithsonian Institution in 1890 and it is in this report that he states the vision of the observatory as follows: "If the observation of the amount of heat the sun sends the earth is among the most important and difficult in astronomical physics, it may also be termed the fundamental problem of meteorology, nearly all whose phenomena would become predictable, if we knew both the original quantity and kind of this heat; how it affects the constituents of the atmosphere on its passage earthward; how much of it reaches the soil; how, through the aid of the atmosphere, it maintains the surface temperature of this planet; and how, in diminished quantity and altered kind, it is finally returned to outer space." That this was a statement of a man of unusual forewight is borne out by ensuing work of the Astrophysical Observatory. Volume I of the Annals of the Astrophysical Observatory (16) consists of a description of the instruments then used in the accurate mapping of the lines of solar and terrestrial absorption in the infra-red solar spectrum, with determinations of wave lengths and indices of refraction for spectra produced by prisms of rock salt and fluorite. This work is still considered authoritative in spectrobolometric research and has been used freely in the preparation of this thesis.

Since then new and improved apparatus has been developed and used in the investigation of the general question of the dependence of terrestrial affairs on radiation. Stations have been established at far corners of the world in order that suitable data might be taken, from which some correlation to meteorological observations could be used as the basis of long range weather forecasting.

But solar radiation has been shown to have an important direct effect on biological reactions. Abbot (1) in his book "The Sun and the Welfare of Man" summarizes the effects of solar radiation on the growth of plants and animals, including the treatment of certain human diseases. Research in this phase of bio-physics has much to offer, for it constitutes a field in which far too little is definitely known and in which valuable contributions to human welfare undoubtedly lie. It is with this in mind that the construction of the following apparatus is undertaken.

DESIGN AND CONSTRUCTION

All of the apparatus used heretofore has been of such a nature that a somewhat permanent set-up has been required, and consequently the number of locations at which data have been and is being taken is limited. For instance, there are no data available for the west coast excepting at Table Mountain, Mt. Whitney, and Mt. Wilson, all in California. With a semi-portable apparatus for solar spectrum analysis, data taken at other locations could be correlated with those from the permanent station on Table Mountain to give an insight to Oregon weather.

The limitations on design include "semi-portable", which means that the apparatus is to be of such size and weight that it may be moved by one or two men and transported in any type of automobile. It must be of such construction that it may be moved and reassembled to take data without prolonged adjusting and testing. The choice of locations may be such as to avoid the use of desired electrical power so that mechanical means of operation are to be preferred.

A wavelength of 20μ was selected as the extreme boundary of the region to be studied as indications beyond this are of such feeble intensity that present instruments of the type used cannot successfully record them. Since rock salt has less absorption to infra-red than other possible materials, such as fluorite, quartz, and glass, and is transparent to 20μ, the design was based upon the use of this material. An examination of the rock salt crystals available limited the size of the prism to one of approximately 2-inch square faces, with prisms of somewhat larger size but of other materials also available. From this it was decided to use 2 1/2 inches as the basic dimension.

The Wadsworth mirror type of mounting, as used in the spectrometer of Langley, was selected, but the light was sent through the prism twice at the minimum deviation angle. This gives a dispersion equivalent to that of a much larger prism. There are several possible arrangements of mounting as is shown diagramatically in Fig. 1. Arrangement (a) was chosen because it gives the most compact mounting. Light focused on a slit S diverges to a stationary concave mirror C, which collimates the rays. These parallel rays are reflected by a plane mirror to the rock salt prism, through which they pass at minimum deviation. A second plane mirror, this one stationary, reflects the light back to the prism, through which it again passes at minimum deviation. It is once more reflected by the first plane mirror to the concave mirror which focuses the light on a bolometer strip mounted directly below the slit.

POSSIBLE LIGHT PATHS USING A WADSWORTH MIRROR

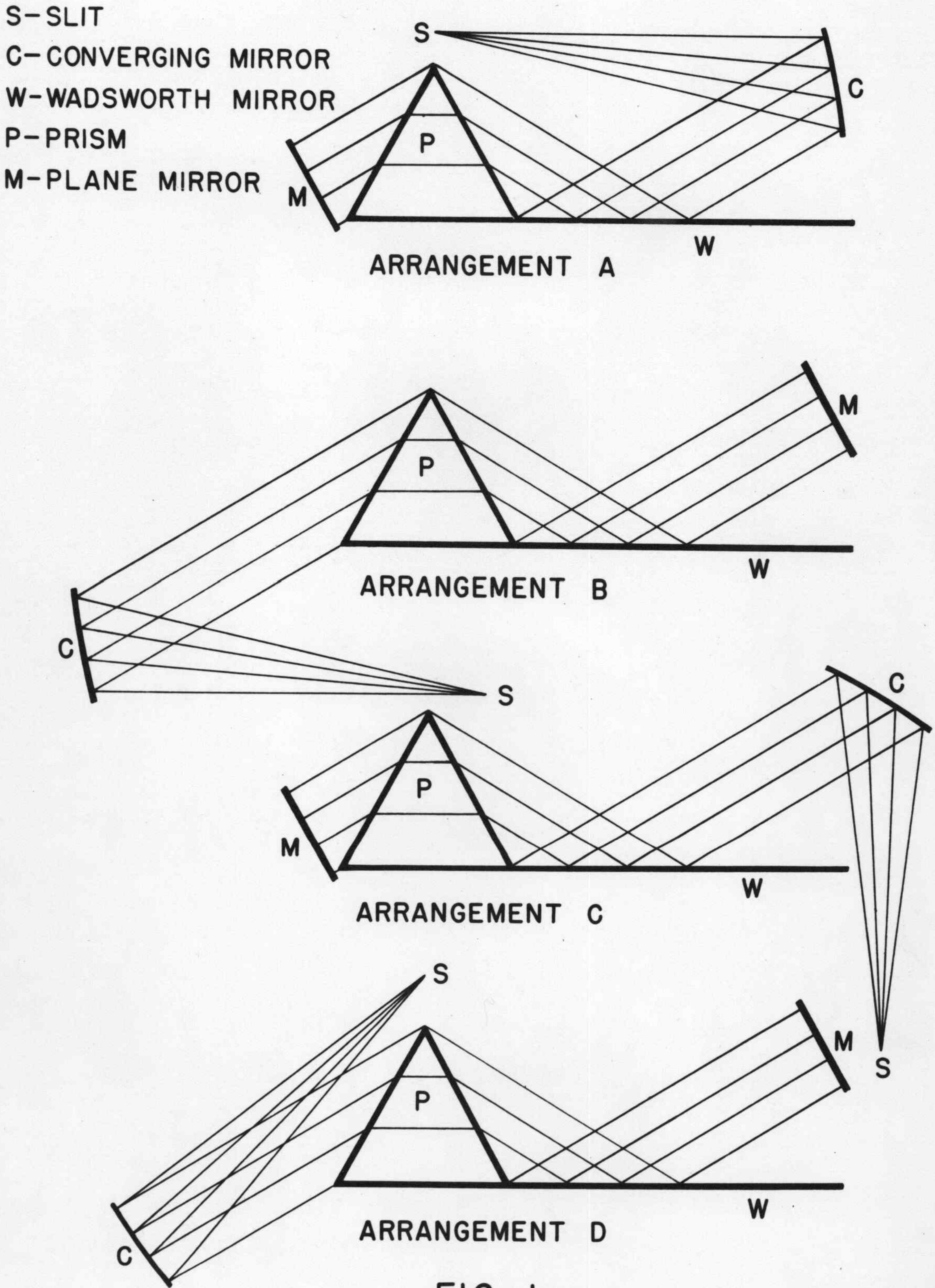


FIG. I

Given the size of the prism, the arrangement of the optical apparatus, and the limiting wavelength of 20μ, the dimensions of the mirrors may be determined. In Fig. 2 when a ray of light OP enters a prism AEF, it is bent in the direction PQ, and on emerging, is again bent in the direction QR. Thus the ray OP is bent out of its original course to BR. The total change of direction is measured by the angle of deviation, D. The angle A of the prism is the refracting angle. It may be proved experimentally and mathematically that the angle of deviation has its minimum value when the light passes through the prism symmetrically, that is, when the beam PQ is perpendicular to the bisector of the refracting angle. In this case the angle of incidence i at P equals the angle of emergence i' at Q. A simple method of measuring the index of refraction is to measure the refracting angle A and the angle of minimum deviation D, and to calculate the index of refraction from the formula

$$n = \frac{\sin\left(\frac{A + D}{2}\right)}{\sin \frac{A}{2}}$$

Our calculations are to be made using a rock salt prism, with wavelengths of 0.5μ to 20μ. From tables (16) (Vol. I, p. 263) the value of the index of refraction of rock salt for wavelengths of 0.5μ and 22.3μ were taken as 1.55 and 1.34 respectively. The refracting angle was taken as 60° and the minimum deviation angle and the angle of

REFRACTION OF LIGHT BY A PRISM TO GIVE MINIMUM DEVIATION

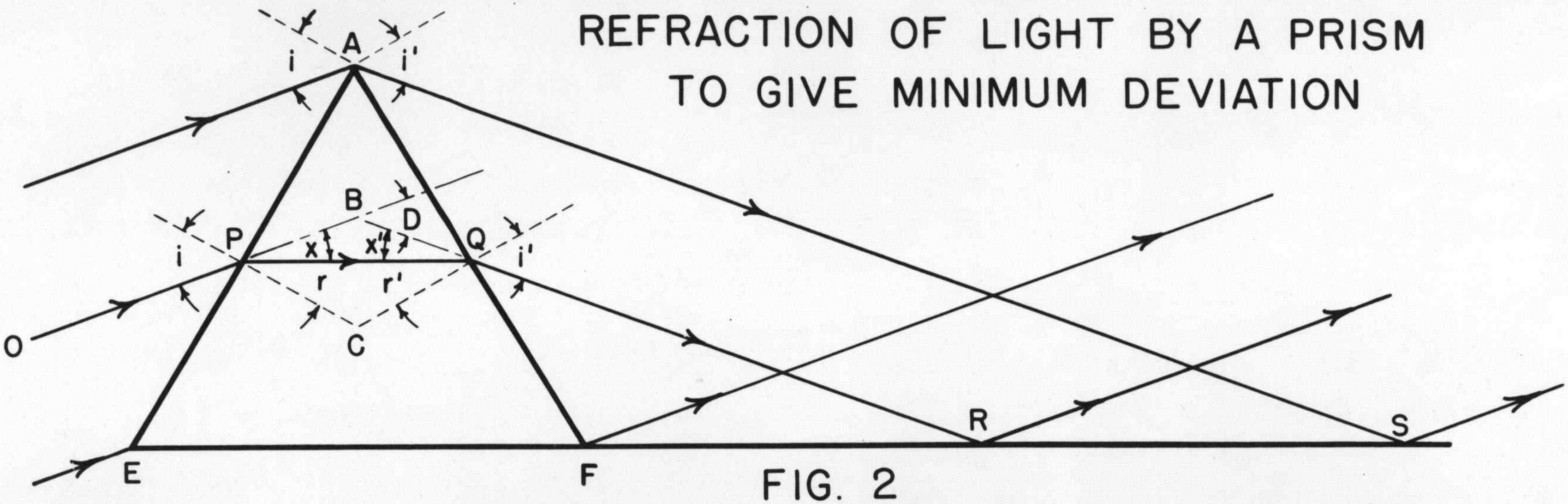


FIG. 2

SPECTROMETER LIGHT PATHS—.5μ AND 22.3μ

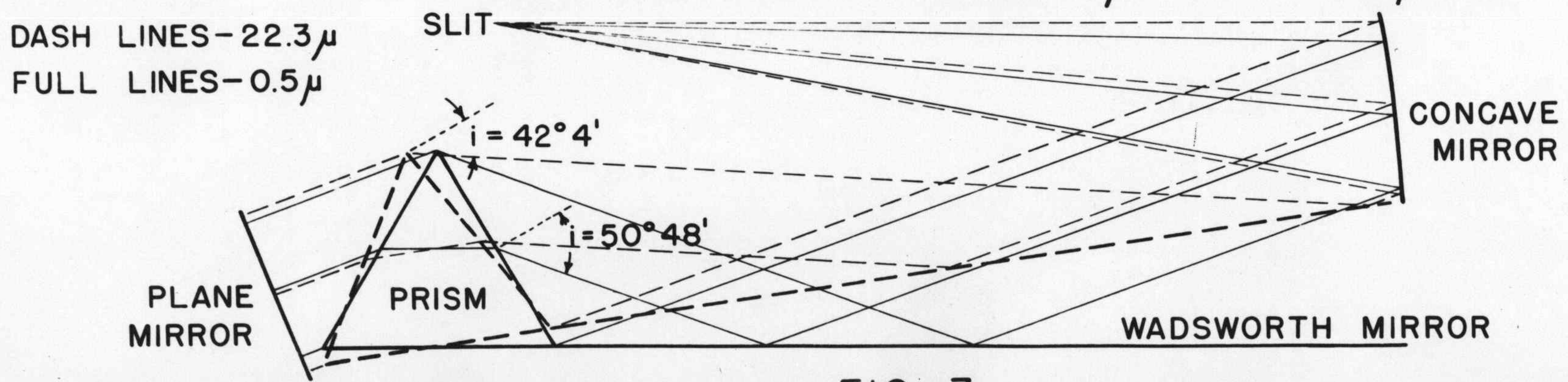


FIG. 3

incidence calculated and tabulated.

Wavelength	Refractive Index	Refracting Angle	Minimum Deviation Angle	Angle of Incidence
μ	n	A	D	i
0.5	1.55	60°	41°36'	50°48'
22.3	1.34	60°	24°8'	42°4'

From these calculations the maximum angle through which the rock salt prism will turn is the difference of the respective angles of incidence for 0.5μ and 22.3μ or 8°44'. The length of the Wadsworth mirror FS (Fig. 2) is determined by the minimum angle of incidence, in this case 42°4'. The trigonometric solution shows the Wadsworth mirror must be 8 3/4 inches long for a 2 1/2 inch prism face turning through an angle of 8°45'. Using these dimensions, the limiting positions were drawn as in Fig. 3, using the full aperture of the prism. In the drawing the broken lines represent the prism at 22.3μ and the full lines at 0.5μ. The plane and collimating mirror were positioned from this drawing and the maximum width of the band of light found to be 1.85 inches for both mirrors. This distance, together with the height of the prism, 2 inches, determines the size of the mirrors, or 1.85 inches by 2 inches for the plane mirror and 2 3/4 inches diameter for the concave mirror.

The design of the Wadsworth mirror and prism mounting must be such as to allow the horizontal adjustment of the prism, the vertical adjustment of the mirror, and the leveling of the entire mounting. The design is shown in Fig. 4. A triangular brass plate 2 1/2 inches on each side was made and mounted so as to allow 1/16 inch adjustment in any direction. The prism is attached to this plate with wax and final adjustment secured by the adjusting screws shown. Vertical adjustment of the Wadsworth mirror is accomplished by means of three bent wire clamps, holding the mirror in place through constant spring compression. Two of these placed below the mirror and one above, give three point support. Leveling is accomplished as usual by three screws resting in hole, slot, and plane plate.

The design of the spectrometer arm is shown in Fig. 5. The hole and slot are secured to the spectrometer arm as accurately as possible, critical adjustment of the prism being secured by the adjusting screws at the prism base. The vertical axis of rotation of the spectrometer arm must lie exactly on the bisector of the prism refracting angle, and further, the axis of rotation must remain perpendicular to the plane of motion. The arrangement chosen consists of two C-clamps, one fastened rigidly to the spectrometer arm, the other fastened rigidly to the supporting base (Fig. 6). Holes were drilled in the top of each C-clamp,

PRISM AND WADSWORTH MIRROR MOUNTING

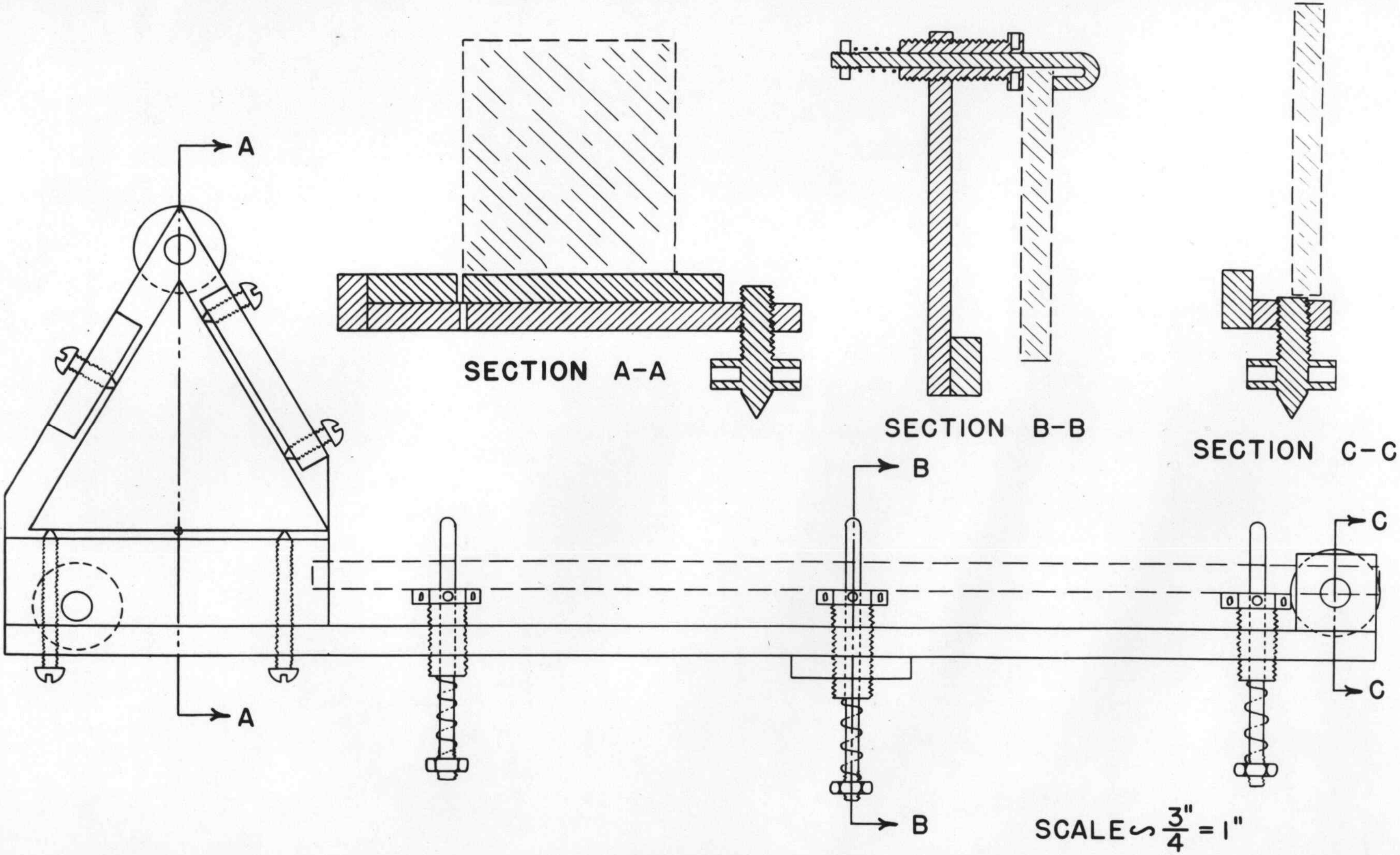


FIG. 4

SPECTROMETER ARM
WITH
ADJUSTABLE BALANCE

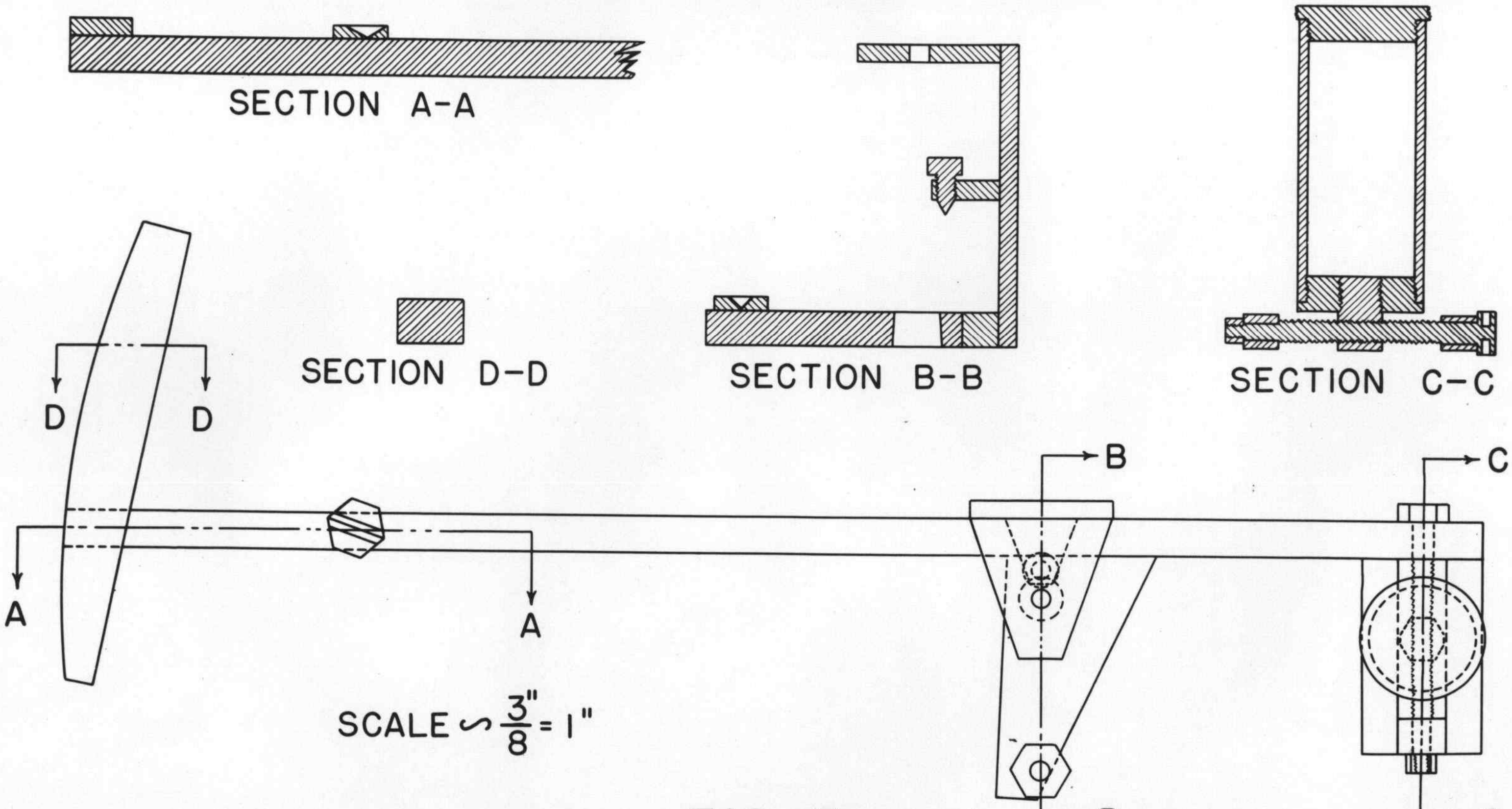


FIG. 5

SUPPORT FOR SPECTROMETER ARM AND STATIONARY MIRRORS

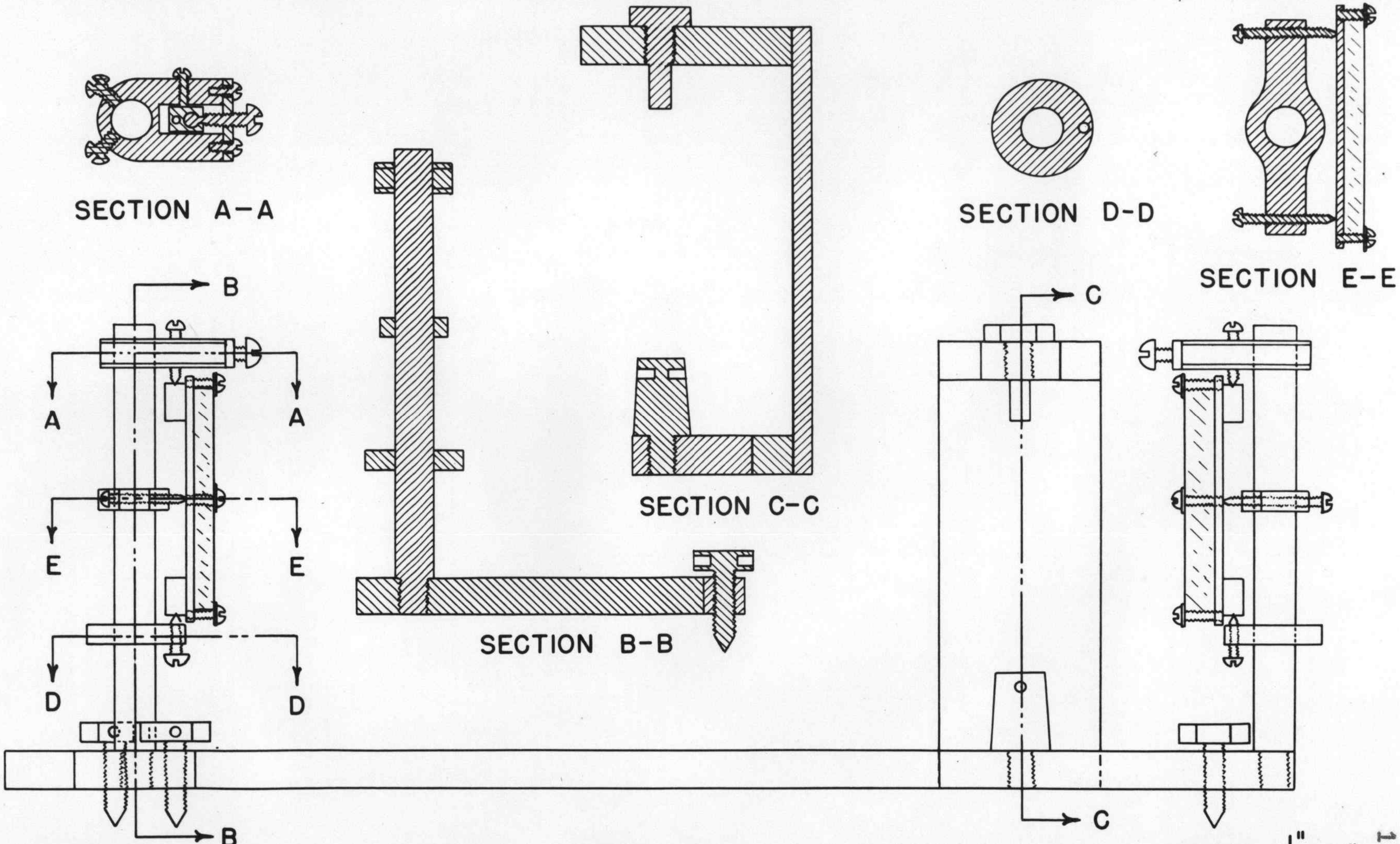


FIG. 6

SCALE ∽ $\frac{1}{2}$" = 1"

and an accurately turned center placed in each hole. The base was carefully leveled and by means of a transit telescope, two points lying in the vertical plane were located on the base. The base was rotated through 90° and two more such points located. The intersection of the lines joining these points determined the intersection of the vertical axis with the base. The support selected is a cone bearing approximately 1/2 inch in diameter, having a taper of 1 1/2 inches per foot. Both cone and cone bearing were turned out with the same setting of the taper attachment. The bearing was lapped in with pumice, first on the lathe and finally by hand. This could be considered sufficient support, but it was felt that a guide pin through the tops of the clamps would increase rigidity and would help to prevent strain due to possible unbalanced loading. A small adjusting screw was mounted in the C-clamp of the spectrometer arm to permit a loose clamping of the prism base and thus prevent movement during transportation of the apparatus. The spectrometer arm and all the apparatus which it carries counterbalanced by means of shot placed in a hollow cylinder so mounted as to allow adjustment in a direction perpendicular to the spectrometer arm.

The means selected for rotating the spectrometer arm consist of a flexible tape with one end fastened to the arm and the other to a lead screw nut. Naturally, the end of the spectrometer arm must be an arc about the axis of rotation. This arc was made in a lathe, but since the length of the spectrometer arm was considerably greater than the swing radius of the lathe machine turning was out of the question. The first attempt was made by swinging the spectrometer arm through the arc by hand. It was found that this method was not sufficiently accurate on account of the elastic deformation of the arm. The problem was solved by using a tool post grinder while rotating the head stock by hand through the proper angle.

The support for the spectrometer arm and the stationary mirrors is shown in Fig. 6. This support is carried by three leveling screws and the customary hole, slot, and plane plates. The location of the fixed mirrors was determined as shown in Fig. 3. Half inch brass posts were screwed into the supporting base at the proper points.

The mounting of the plane and concave mirrors must allow for a slight tilt of the axis as well as for limited rotation about that axis. The mirror holder is swung between centers and tilt is secured by providing for a motion of one of these as shown in section AA of Fig. 6. Fine adjustment of rotation and clamping is secured by screws in a horizontal plane as shown in section EE of Fig. 6.

From the beginning, one factor controlling the design was the requirement of portability. The apparatus may possibly be well in the open, with little protection from temperature changes. As all energy measuring devices are highly sensitive to extraneous temperature changes, it is extremely desirable to use a vacuum chamber. It was decided to mount both bolometer and spectrometer in the same vacuum. It seemed that the best and cheapest form of vacuum chamber is a steel pipe with flanged ends. To decrease bulk and weight of the instrument, the lead screw was mounted in a tube that was screwed and soldered into the pipe. Thus the lead screw is within the vacuum chamber and is connected to the driving mechanism through a packed joint, the design of which is shown in section D-D of Fig. 10. Two lock nuts limit longitudinal motion of the lead screw.

Recording must perforce be photographic. Photostat paper is sufficiently sensitive and much cheaper than film. Some scheme for daylight loading must be devised. The familiar cassette of the miniature camera provided the fundamental idea. Fig. 7 shows the design adopted, in section. The cassette consists of three "spools". The inner, or true spool, will hold about 75 feet of 5 3/4 inch photostat paper (half of an 11 1/2 inch roll). The other two "spools" are really hollow cylinders provided with necessary slots. The inner spool turns freely within the middle spool, and this fits the outer spool somewhat

DAYLIGHT LOADING PHOTOGRAPHIC PAPER HOLDER

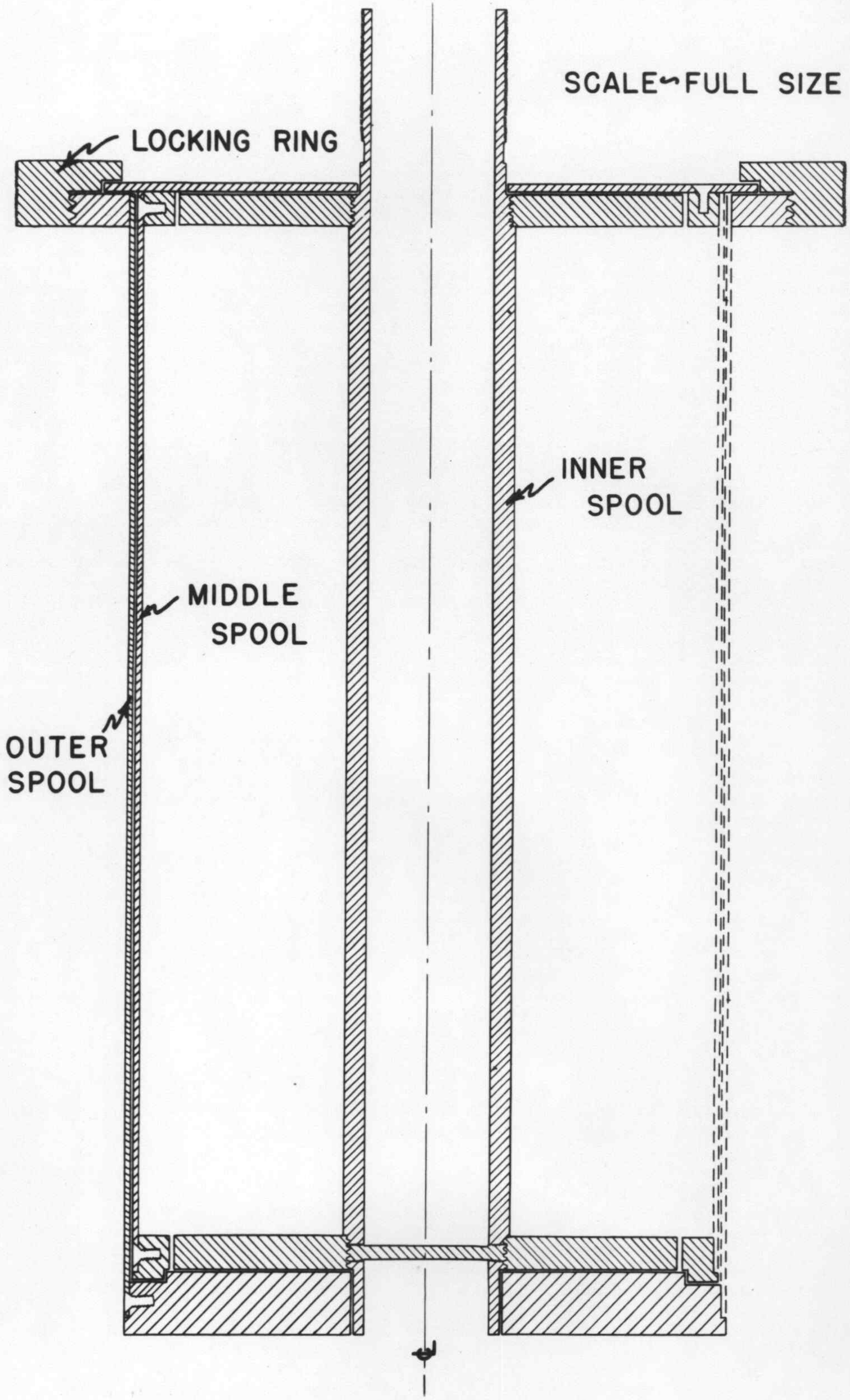


FIG. 7

more closely. Both of the other spools are made of sheet brass fastened to guide rings or plates. Each has a 1 1/2 inch slot across its face. Matching the two slots allows the paper to be freely unwound from the inner spool; rotating the two outer spools until the slots are 180° apart provides a light-tight chamber for the paper. A lock ring holds the three spools together.

The schematic assembly of the photostat paper recorder is shown in Fig. 8. Two cassettes are used, one for the unexposed and the other for the exposed paper. In processing photostat paper there is expansion followed by shrinkage. Hence, in order to have a proper coordinate scale, marks must be provided along the two edges of the paper. These marks are put on by the paper-drive. This drive consists of a true cylinder provided with equally spaced phonograph needles 5 1/2 inches apart. The needles in each row are 5/8 of an inch from each other. Each needle can be adjusted by means of a set screw. These needles puncture the paper and then pull it from the supply roll as the drive cylinder is rotated. Referring to Fig. 8, it is seen that the paper coming from the loaded cassette passes over a stationary guide and thence over the paper drive cylinder. The paper then passes around another stationary guide to the take-up cassette. The spool in this cassette is driven and overruns the paper drive cylinder so that

SCHEMATIC ASSEMBLY FOR PHOTOGRAPHIC PAPER RECORDER

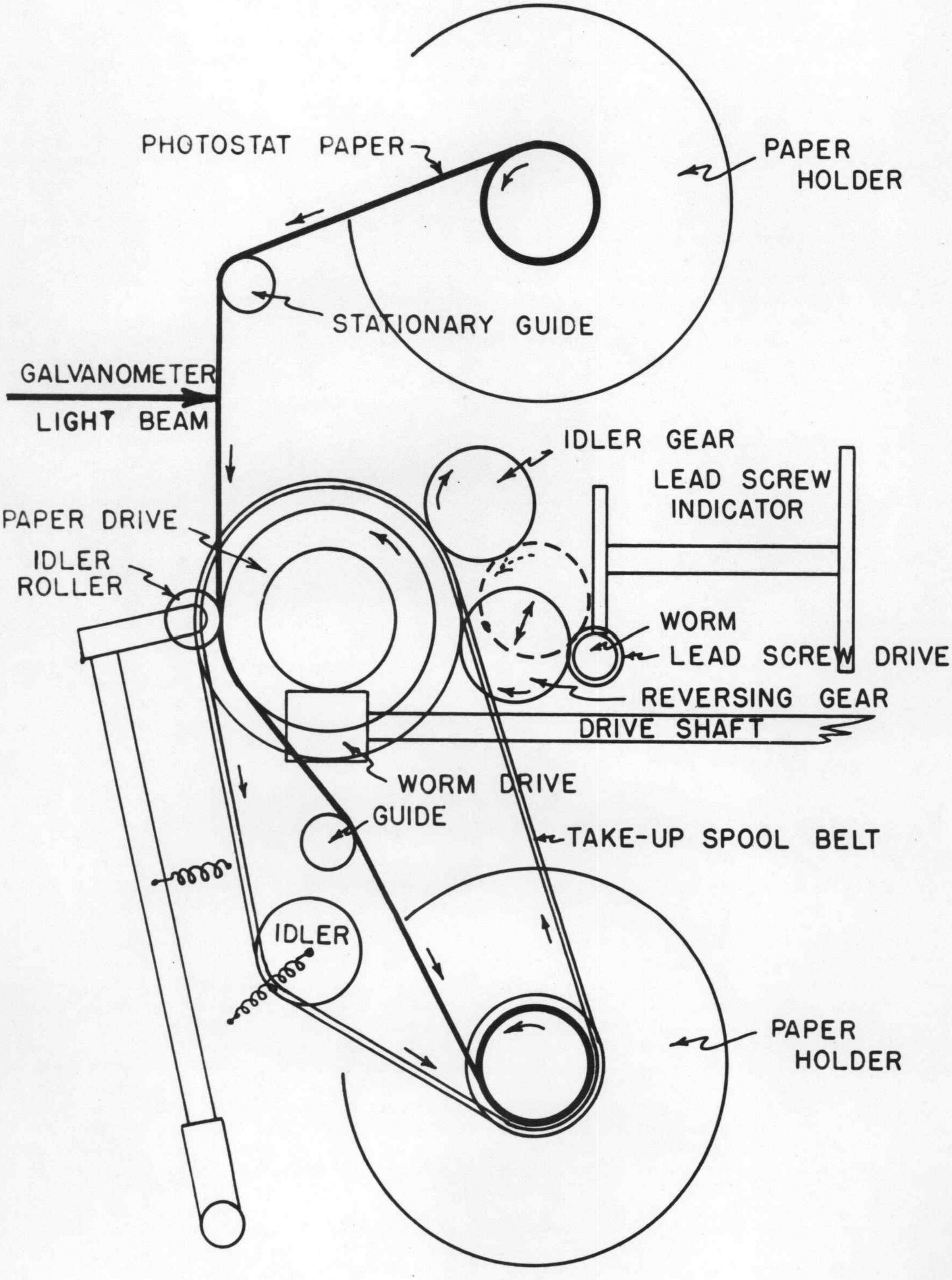


FIG. 8

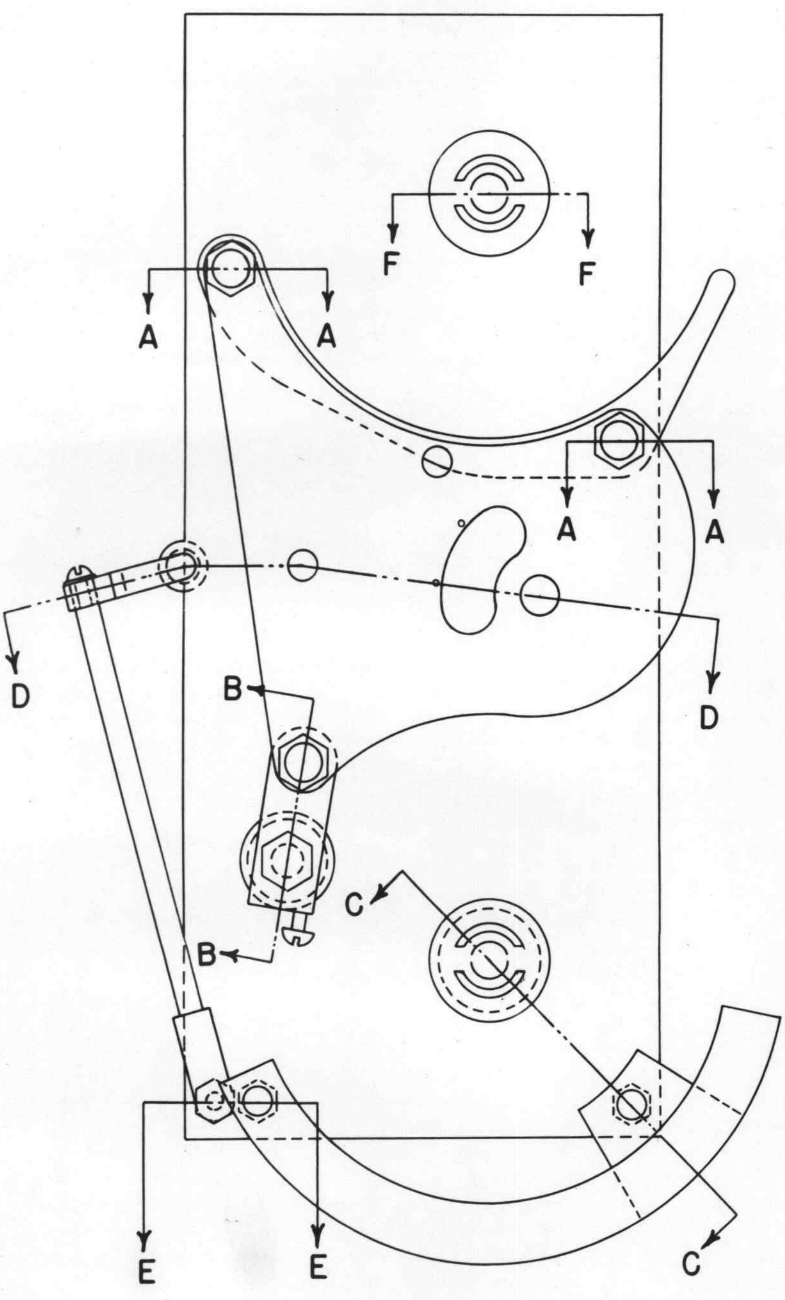
the photostat paper is under continuous tension.

Since the spools are mounted horizontally, the paper moves in a vertical plane between the drive cylinder and the stationary guide. A horizontal slit placed in this region permits exposure by the galvanometer beam, which of course swings horizontally. An idler roller presses against the paper drive cylinder and assures that the needle points will pierce the paper. Fig. 9 shows the supporting framework for the recorder; Fig. 10, given sections through the principal parts of the mechanism.

The necessary travel of the lead screw nut is somewhat more than 2 inches (a change of 8°45' on a 14 inch radius). Since the lead screw has 20 threads per inch, 40 or more turns are necessary for recording one spectrum. Each rotation of the paper drive cylinder advances the paper 6 1/4 inches. Since roughly 4 feet of paper are ample for recording one spectrum, the spectrometer and the paper drives must be in the ratio of 5:1 (actually 80 and 16 teeth, 32 pitch).

The paper must necessarily be driven in the same direction at all times, whereas the lead screw must be reversed at each end of its travel. Records may be taken with the lead screw moving in either direction. Hence the gear train must provide forward, neutral, and reverse drive positions. An idler gear of 32 teeth is in constant

SUPPORTING FRAMEWORK FOR PHOTOGRAPHIC PAPER RECORDER



SCALE ∽ $\frac{1''}{2} = 1''$

FIG. 9

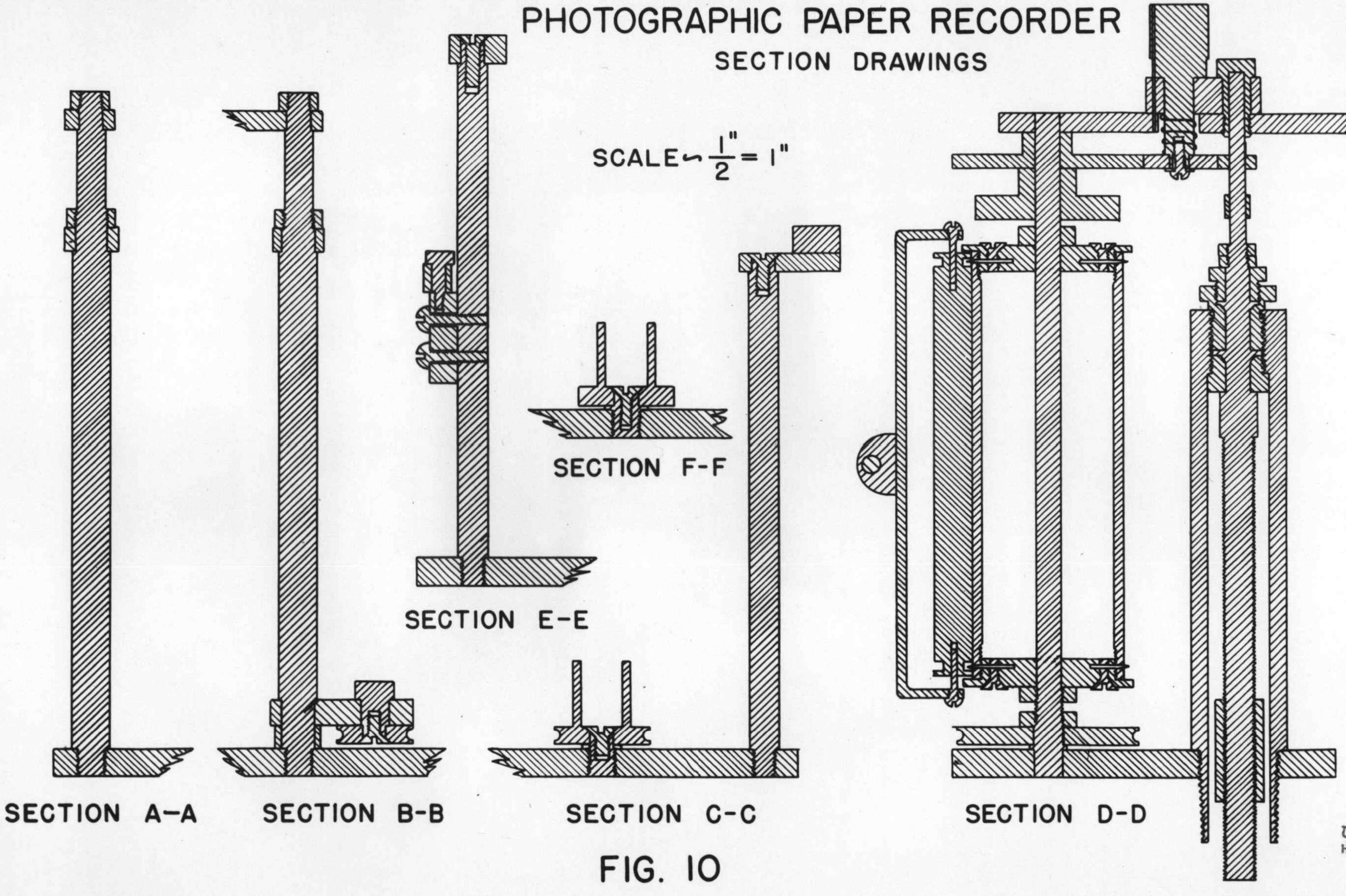

PHOTOGRAPHIC PAPER RECORDER
SECTION DRAWINGS
SCALE ~ 1"/2 = 1"
SECTION A-A
SECTION B-B
SECTION E-E
SECTION F-F
SECTION C-C
SECTION D-D

FIG. 10

mesh with the paper-drive gear. The lead screw drive gear is in constant mesh with another 32 tooth gear. The latter can be moved in an arc about the axis of the lead screw so as to mesh either with the paper drive gear or with the idler gear, or with neither. The position of the movable gear is fixed in any one of its three positions by a locking pin and spring.

To show the region of the spectrum being recorded at any instant, a worm and worm gear having a ratio of 60:1 is driven off the lead screw shaft; the worm gear is provided with a pointer moving over a calibrated scale.

The vacuum chamber consists of a 24 inch length of 12 inch steel pipe provided with flanged ends. Blind flanges cushioned on rubber gaskets are bolted to each end. A rock salt window is properly placed in one blind flange. Two electrical connections for the bolometer are provided. Hole, slot, and plane plates are rigidly fastened to the inside of the vacuum chamber to allow the insertion of the spectrometer without changing its calibration.

CONCLUSION

The points of design and construction peculiar to the problem of making a recording infra-red vacuum spectrobolometer semi-portable have been overcome as indicated. That which remains to be done before the instrument can be calibrated is to silver the mirrors, polish the rock salt prism, provide a weight drive, construct the bolometer and provide a galvanometer and its illumination system. If sunlight is to be studied, some sort of heliostat is necessary.

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