UNCLASSIFIED

AD 274 298

Reproduced
by the

UNCLASSIFIED

SOLAR RADIATION MEASUREMENT INSTRUMENTATION

by

Reinhold M. Marchgraber

and

Ralph W. Armstrong

January 1962

ASTIA

APR 20 1962

TiSiA

A

U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

January 1962

USASRDL Technical Report 2251 has been prepared under the supervision of the Director, Surveillance Department, and is published for the information and guidance of all concerned. Suggestions or criticisms relative to the form, contents, purpose, or use of this publication should be referred to the Commanding Officer, U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, Attn: Chief, Atmospheric Physics Branch, Meteorological Division.

J. M. KIMBROUGH, JR.
Colonel, Signal Corps
Commanding

OFFICIAL:
H. W. KILLAM
Major, SigC
Adjutant

DISTRIBUTION:
Special

<u>ASTIA Availability Notice</u>

Qualified requestors may obtain copies of this report from ASTIA.

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C., for sale to the general public.

SOLAR RADIATION MEASUREMENT INSTRUMENTATION

Reinhold M. Marchgraber
and
Ralph W. Armstrong

Abstract

A pyranometer for measuring sun and sky radiation on a hori-
zontal surface in selected broad spectral ba .ds has been developed
by The Eppley Laboratory and the Signal Corps along lines suggested
by, but differing materially from, an equipment for this purpose fur-
nished some years ago by the Smithsonian Astrophysical Observatory
to the Quartermaster Corps at Fort Lee, Virginia. The Eppley
Laboratory substantially modified its thermoelectric-type sensor to
permit use of hemispheric glass filters of practical size.

Desired spectral bands can be selected by using two or more units
with differing sharp cut-offs on the ultraviolet side of their pass bands,
but nearly identical transmission limits on the infrared side; and sub-
tracting the output of the narrower bands from the longer.

The new equipment is described and its design philosophy and per-
formance are discussed. A mount providing for altitude and azimuth
adjustments, and provision for as many as three different hemispheric
filters on each sensing unit, make the equipment suitable for a variety
of applications.

CONTENTS

CONTENTS (contd)

Figures

SOLAR RADIATION MEASUREMENT INSTRUMENTATION

INTRODUCTION

Quantitative knowledge of the radiation arriving from sun and sky is of great value for many areas of interest to the Army. Besides the dominant role solar and sky radiation and reradiation from the earth's surface play in the heat budget of the planet Earth, the comfort, health, and combat efficiency of the soldier depend directly and indirectly (heat load and indirect influences such as Schlieren effects and glare) to a large extent on the amount and spectral nature of solar and sky radiation. The trafficability of roads, air-strips, and terrain; the design of proper clothing, shelters, and weapons; protection against spoilage of rations; and many more imponderables of a modern army depend heavily on the presence of solar and sky radiation and its effects; for example, the useful life span of deployed chemical and biological agents is known to be influenced by the presence of radiation of the solar spectrum or, more specifically, of parts of this spectrum.

Since progress in understanding these various relations parallels the progress of measuring-techniques and instruments, a task was undertaken to improve the state of the science of measurement of solar and sky radiation. This undertaking was based on requests received from different Technical Services of the U. S. Army, including the Quartermaster Corps, the Corps of Engineers, the Transportation Corps, the Chemical Corps, and also from USAEPG, which was approached by various Technical Services looking for more precise data on solar and sky radiation from the special weather teams of its Meteorological Department.

Depending on the intended use of radiation data, the requirements of the Technical Services varied considerably. Needs were expressed for relatively simple global (pyranometric) sensors with analog read-out, as well as for far more sophisticated instrumentation for simultaneous and continuous sensing, recording, integrating, and integral print-out of radiation within various bands of the solar spectrum.

A survey of the field and discussions with scientists and engineers of potential user installations made it obvious that successful meeting of the requirements within a reasonable time and economic effort would be possible only if the various and specific requirements could be brought to a common denominator, and the assistance of a competent contractor could be secured to support the internal effort in obtaining sensors as well as recorders and integrating equipment capable of meeting all specific requirements by proper combination and exchange of components such as, for example, filters.

Two different instruments and instrumentations already existing helped considerably in finding a starting point for the planned task. They are the

well-known Eppley pyrheliometer bulb (now Eppley pyranometer) (Fig. 1), used all over the world and considered at the time of the task planning to be a very reliable product; and an instrumentation (Figs. 2, 3, and 3A) designed and constructed by the Smithsonian Institute (Dr. Aldrich and Dr. Hoover) in 1946 for Quartermaster Corps experiments at Fort Lee, Virginia, on the influence of solar and sky radiation on paints and fabrics.

The behavior of the Eppley pyranometer bulb has been studied by many authors and its characteristics are well established. The calibration stability of the Eppley cell supported from the beginning the planned use of thermopiles as transducing means, though nonlinearity characteristics of the sensitivity of thermoelectric junctions and dependency of the output of the radiation sensor on environmental conditions other than the radiation environment made it clear that difficulties in meeting the integration accuracy requirements could be expected. Further, the Eppley cell did not lend itself directly to the application of filters, especially when ease of exchangeability of filters is a requirement of importance.

The Fort Lee instrumentation, on the other hand, facilitates the providing of filters for three bands, and it was obvious that the astrophysical observatory personnel of the Smithsonian Institute had put much thought and acceptable design features into this instrumentation. Shortcomings are mainly the mechanically intricate recording--sensitive to mechanical influences and hence useful only in a fixed installation--and lack of means for obtaining integral values for the radiation required for most applications by the Technical Services of the Army.

The requirements for measuring solar and sky radiation in different spectral bands necessitated further coordination with the users, since it was felt that the different requirements set forth could be combined and a minimum number of filters could be selected to realistically cover the needs of the users.

The Radiation Commission of the World Meteorological Organization (WMO) had, fortunately, completed careful studies on determining spectral bands of interest as well as on finding suitable stable and weather-fast filters which were to be used during the International Geophysical Year.[1]

With this background available, the areas of needed improvement became clear, and a specification was written (Appendix I), based on the existing, however integrated, requirements of the Technical Services of the Army and the knowledge obtained in analyzing existing equipment. An attempt was made to keep the specifications as realistic as possible in order to obtain improved solar and sky radiation instrumentation within a reasonable and foreseeable time. Invitations to bid were sent to eight companies, including The Eppley Laboratories, the manufacturer of the Eppley cell. On the basis of estimates on the cost of the commercially available Eppley cell and the
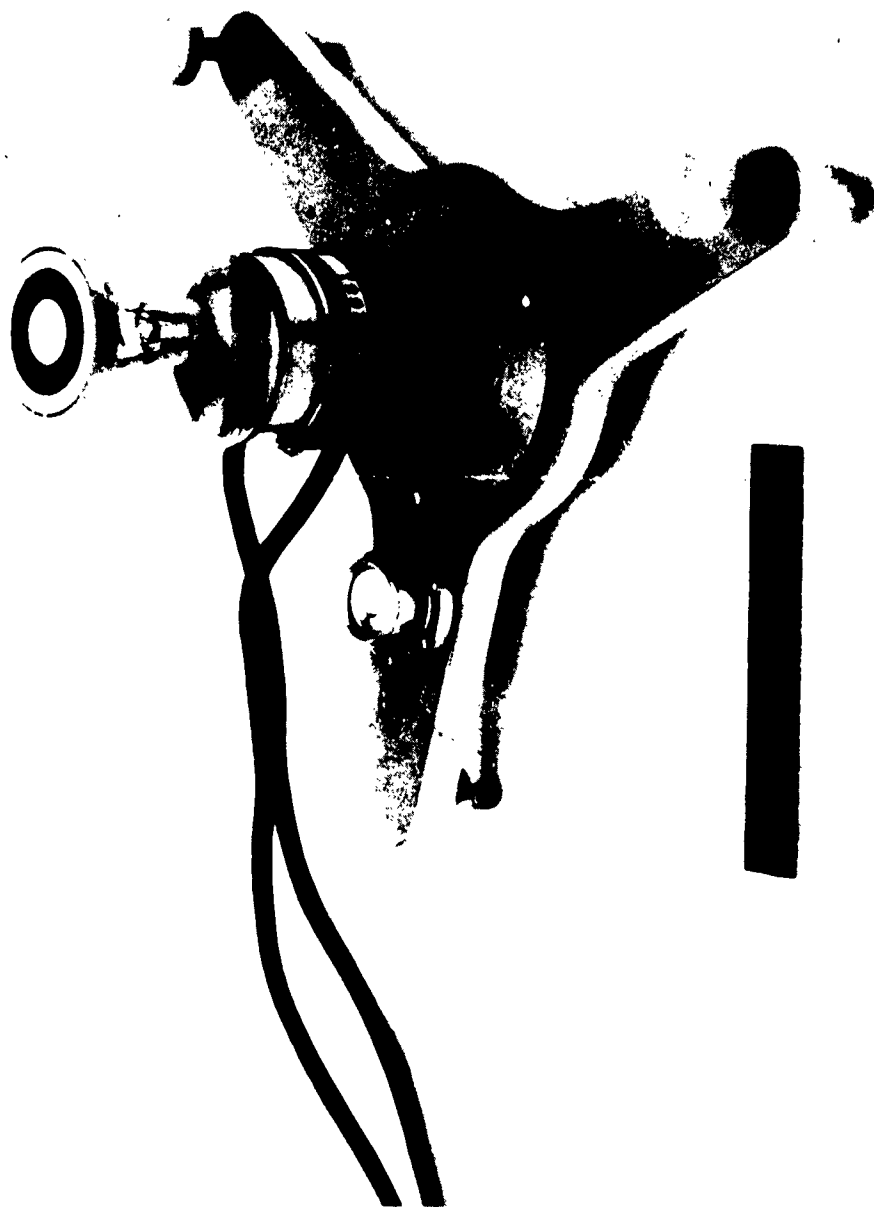
Fig. 1. Eppley Pyrheliometer
(Old type, now classed as a pyranometer)
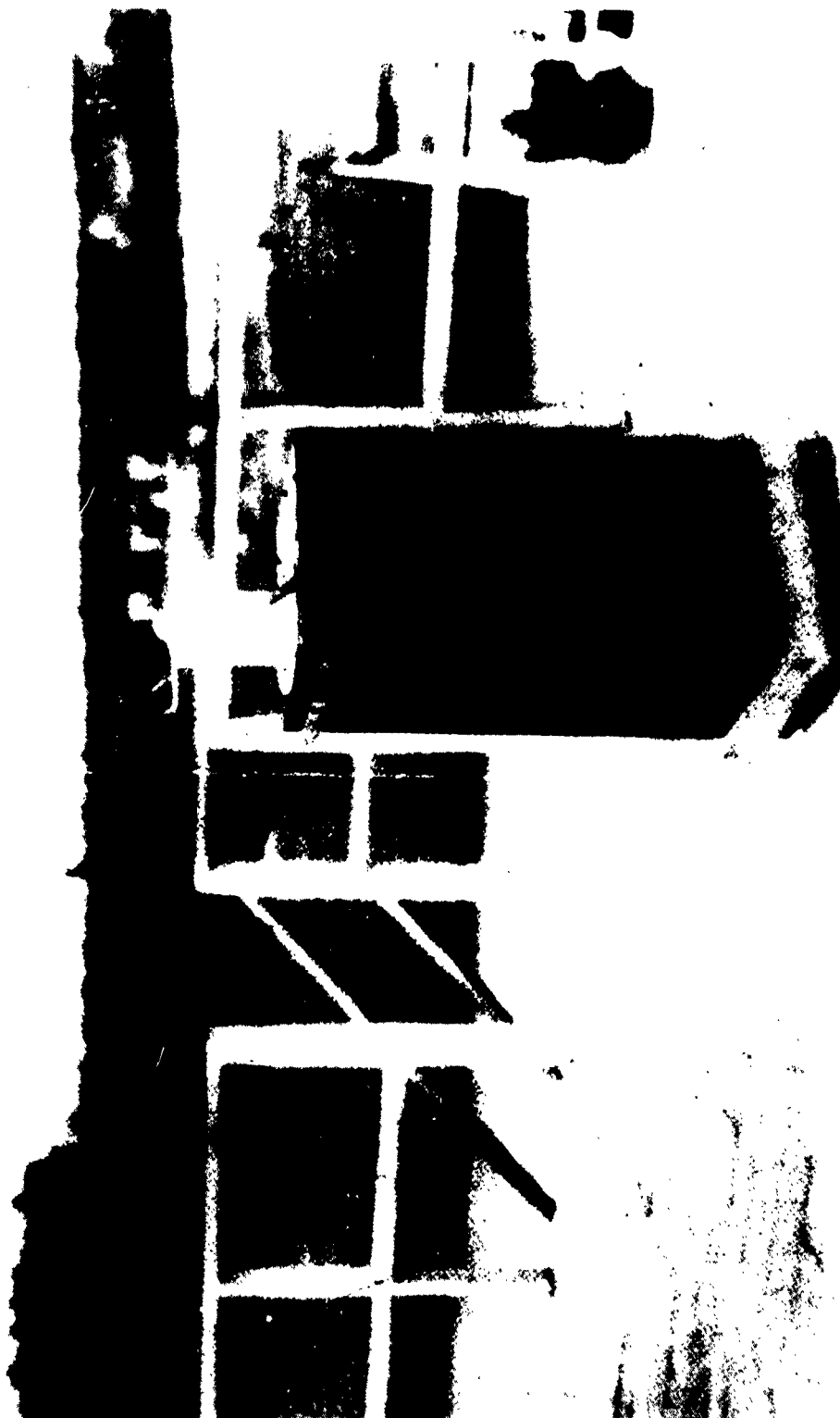
FIG. 2 SMITHSONIAN RADIOMETER WITH REMOTELY OPERATED COVER

FT. LEE, VIRGINIA

M-61-1044

4

FIG. 3 RADIOMETERS MOUNTED 45° EAST

FT. LEE, VIRGINIA

M-61-1045
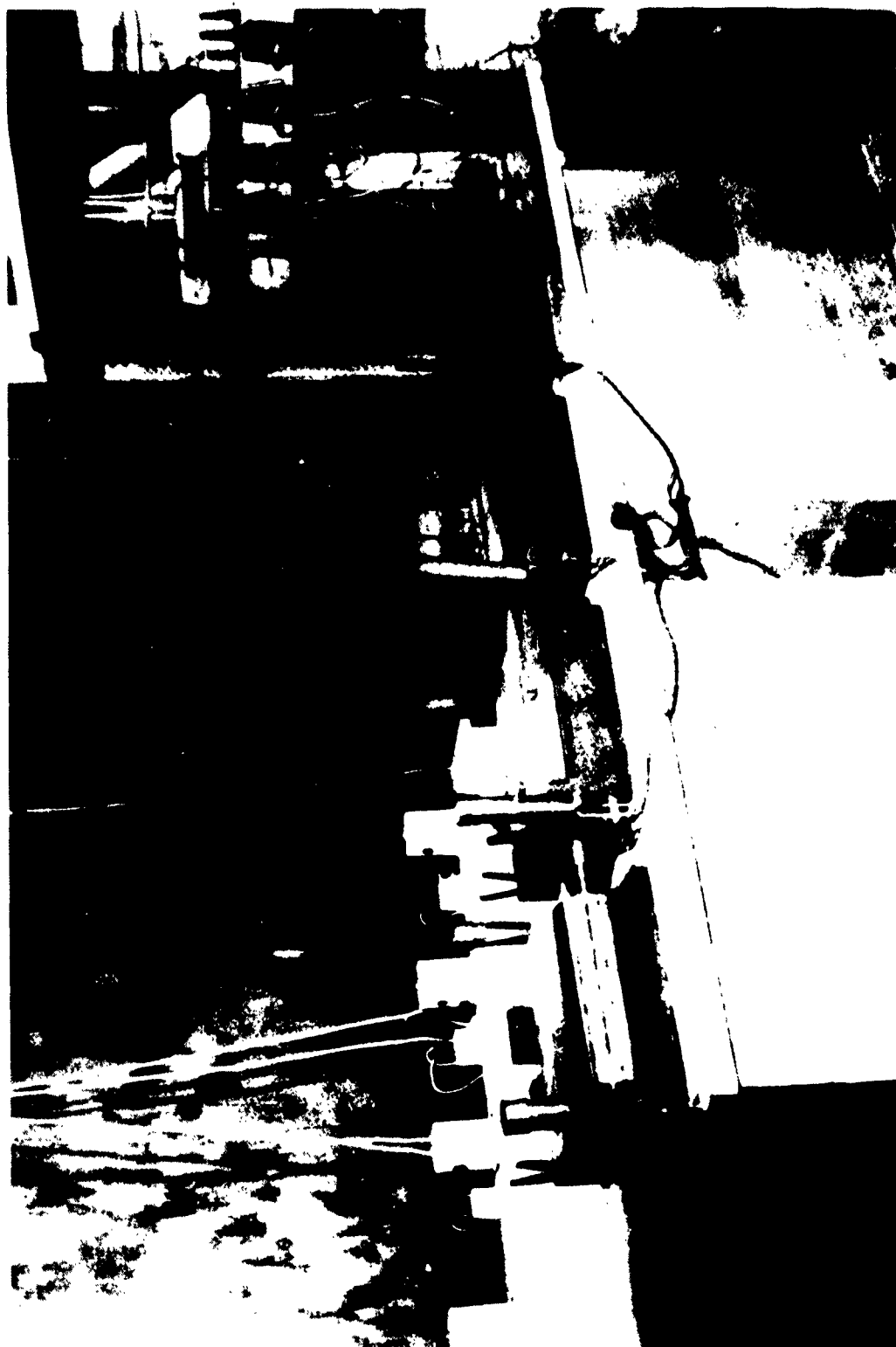
FIG 3A IMPROVED PHOTOGRAPHIC TYPE RECORDERS

FT. LEE, VIRGINIA

M-61-1046

6

cost of recording and integrating components available, it was hoped to improve these components and to combine them with an equipment in accordance with the specifications, for the funded amount.

Negotiations with The Eppley Laboratory resulted in combining this development work with that of a related instrumentation, resulting in savings in cost.

During the first technical discussions with The Eppley Laboratory, some slight modifications to the specifications were proposed by Eppley as well as USASRDL and agreed on. These modifications were of minor nature, the most significant one being that, instead of hourly integral values, 30-minute integral values would be fed to the print-out to make use of existing and thoroughly tested General Electric Demandmeter as an integral print-out device. Also agreed on was that the daily integral values for the equipment expected from this contract would be obtained either by taking two time-spaced readings of a continuous counter built into the equipment, for test and control purposes, or by adding the half-hourly printed integral values.

It was further agreed in these early discussions that Eppley would try to redesign its sensor for the specified use set forth in the technical requirements. The design of a smaller sensor accommodating the various exchangeable filters was considered advantageous since it was anticipated that the desired high degree of precision in hemispherical filters would necessitate the use of grinding rather than hot-forming tecnniques and hence the costs would increase drastically with increase of the hemisphere radius.

It was decided early during the contract that, in accordance with the IGY recommendation, filter material manufactured by Jenaer Glaswerk, Schott and Genossen, would be used. This decision to give a foreign product preference was justified by thus obtaining filters that are internationally used in solar radiometry. Figure 4 shows the typical transmission characteristics of the selected Schott filters as well as the spectral bands which may be obtained by subtraction.

During the course of the contract with Eppley another modification (not of the original requirements, but of the planned instrumentation) had to be made; namely, the addition of a temperature-compensating circuit forming an
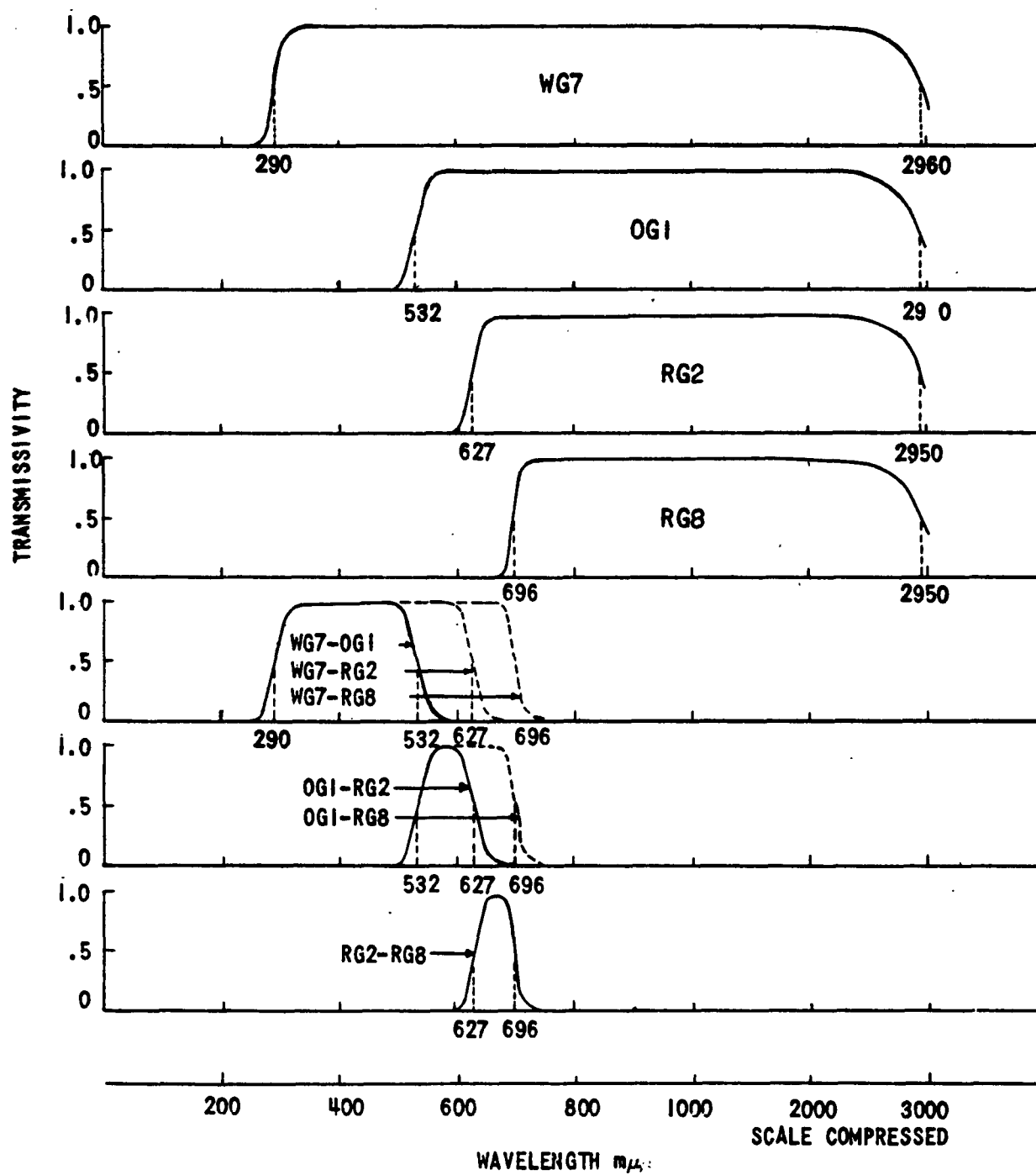
FIG. 4 SPECTRAL BANDS OBTAINED THROUGH FILTERS
RECOMMENDED BY WORLD METEOROLOGICAL ORGANIZATION

8

integral part of the radiation sensor, since early models of the new sensor could not eliminate the influence of environmental temperature on the read-out,* a fact which devalued the precision of the integration to be performed.

The modified design included a thermistor-compensation, originated and developed at USASRDL and now standard in all precision radiometers (pyranometers and pyrheliometers) manufactured by The Eppley Laboratory. The equipment consists, in accordance with the specification, of the following major parts:

1. The sensor with filter hemisphere(s) and compensation for the temperature environment.

2. The mount with means for aligning the sensor in any desired orientation.

3. The potentiometric analog recorder.

4. The integrator forming part of the analog recorder.

5. The integrator print-out with built-in clocking device.

6. Accessories such as connecting cables, etc.

DISCUSSION

The Sensor

The intended universal use of the radiometer sensor necessitates its use in other than horizontal orientation. This holds in any case for an instrument sensing the radiation as received directly from the sun in normal incidence (pyrheliometer), but was an additional requirement for the global sensor (pyranometer) since, for example, the Quartermaster Corps intended to measure the total radiation received on surfaces oriented other than horizontal in order to study influence of radiation on the weathering properties of paints, canvas, etc. This requirement is not necessarily met by mounting the sensor on a universal mount; a sensor readout independent of its position is also needed.

The requirement that the pyranometer shall be capable of being used in universal orientation without loss of the specified accuracy imposes further tight accuracy requirements on the "cosine behavior" of the sensor, since the sun may be seen in certain orientations under extremely small angles.

*The old Eppley cell also had a temperature coefficient which, though 50 percent smaller than the temperature coefficient of the new sensor, was prohibitively large for the specified over-all system accuracy.

9

The requirement of a precise cosine behavior is also necessary if arctic or antarctic use in normal horizontal orientation (or any other) is intended. Even for low elevation angles of the sun, it is normally assumed that the actual cosine error has a relatively small effect on the total sensed radiation, since the energy can no longer be regarded as a predominately direct beam because the contribution of diffuse sky radiation to the total radiation increases rapidly. In the very transparent air of the Arctic and Antarctica, however, there has to be strong concern about the cosine errors of the sensor even for solar elevations of less than, for instance, 30 degrees. Therefore an attempt had to be made to reduce the cosine error as much as possible as well as the "positional error" of the sensor.

To reduce the cosine error, two major properties of the sensor have to be considered carefully: the absorbing surface and the transient behavior due to changes in environmental temperature.

The choice of the blackening, absorbing coating of the sensor has to meet the requirement of a flat absorption characteristic (constant absorption coefficient) over the whole spectral band of interest as well as to show a uniform absorption characteristic for all angles of incidence.

Practically all black coatings which have been employed in solar radiometry (mostly carbon blacks, sometimes platinum black) are flat in response* (gray) in the spectral band from 0.3 to 3 μ. It was felt, however, that a new design of a sensor should attempt to make the sensing surface equally adaptable for the exposure to solar ultraviolet (a task forming the substance of another procurement) and also to long-wave terrestrial infrared radiation if the same sensor were to be useful in a later-to-be-designed model of a net radiometer.

Parson's black, manufactured in England, was excellent in uniformity of absorption over the spectral range of concern extending from UV through the visible to at least 40 μ infrared, and showed no detectable change of the absorbing properties with the angle of incidence. Comparison data of the characteristics of Parson's black with the generally accepted gold black taken at The Eppley Laboratory and spot-checked at USASRDL will be presented later in this report.

With the selection of Parson's black for the absorbing receiver surface, the requirement for flat (gray) response over the widened spectral range was solved as satisfactorily as could be expected. The excellent cosine characteristic of Parson's black, applied to a geometrically flat surface, pinpointed the refractive and reflective properties of the filter hemispheres as the cause of any cosine trouble still present. A means to minimize this

*Gold black, generally accepted to be a nonselective, flat absorber from UV out to a wave length of at least 40 μ, shows a strong dependency on the angle of incidence, being flat black only for normal and near normal incidence.

influence was given by Mr. Drummond, Chief Scientist of The Eppley Laboratory, who conceived the idea of correcting for deviations of Lambert's cosine law by adjusting the inner hemispherical filter in such a way that this filter represents a trifle less than a total hemisphere. By adjusting the halving plane of the inner hemispherical filter in respect to the receiver surface, the cosine error could be kept within the specification and is, after this correction, indeed small, as the data given later in this report indicate.

The influence of the environmental temperature on the radiation-sensor performance is two-fold and will be discussed here only briefly since a satisfying quantitative theoretical analysis, especially of the transient behavior, has so far evaded formulation.* This environmental temperature influence depends on the fundamentals of operation of the sensor, and its discussion can well start with a review of those fundamentals.

Thermopile radiation receivers are thermoelectric transducers that provide an emf related to the temperature difference experienced by the two (two sets of) junctions connected in the well-known manner such that equal temperatures of the junctions (set of junctions) generate equal and opposite emf's and therefore provide a zero emf on the output.

A temperature difference being present, the resulting output of the thermopile will depend on the actual temperatures of the two groups of junctions as well as on the temperature difference experienced by them since the functional relation of emf versus temperature is not strictly linear, but essentially described by a quadratic equation (see Appendix II). There is, therefore, a distinct dependence of the radiation output emf (representing a certain radiation flux) on the temperature level at which a certain temperature difference is experienced. This is one cause for the dependency of the output of thermoelectric radiation detectors on the environmental temperatures.

A second and equally important cause is more complicated and is basically of transient character. It shows only if the environmental temperature has a time derivative and both junctions (or set of junctions) do not follow the changes in environmental temperatures in exactly the same manner. (While this report was in preparation, an analytical model was found which describes the influence of environmental temperatures, including transient errors. The result will be published in another report.) Thus, the requirement that a temperature transient not occur in the sensor when the environmental temperature changes quickly is that the black disk and copper rings, to which the two thermojunctions (or sets of junctions) are attached, follow the environmental temperature change in the same way. This requirement was met very closely in the old Eppley Cell, since the black

---

*It is not a requirement that both junction groups follow changes in environmental temperature with the smallest possible lag. The requirement is only that both follow in exactly the same manner so that, with no radiation present, both junctions (groups) have the same temperature at all times.

sensor as well as the white reference sink are both of nearly the same mass and thermodynamic properties, are exposed to the same environment, and have as nearly as possible the same symmetry, size, and location, which determine heat transfer by convection and conduction. Only fast transient changes caused sensor outputs not entirely due to radiation.

The requirement for exchangeable filters, however, necessitated deviation from this original design, since a vacuum-tight seal could not be obtained over the nonoperating and operating environments specified and no "white" paint for the reference (flat in response to all wavelengths of concern and resistant to small changes in water vapor leaking under the filter) could be found.

An alternate solution, the use of a heat sink having the temperature of the environment of the blackened sensor, was chosen. This approach, however, imposes design criteria hard to meet; i.e., the blackened sensing surface has to follow changes in environmental temperature (heating or cooling rates) in exactly the same manner as the sink, so that sensing surface and sensing thermoelectric junctions are at all times precisely (to at least $\pm 0.1^{\circ}C$)* at the same temperature as the sink, with no radiation present; and so that in the presence of radiation the temperature difference between sensing and sink junctions shows no larger environment-caused transients than approximately said $\pm 0.1^{\circ}C$.

It can be seen that at best this requirement for exchangeable filters can be met perfectly for one and only one physical design and that the change of filters, absorbing part of the arriving energy and assuming thus a temperature higher than the environment, will upset the intricate thermal balance, necessitating a compromise in universal instruments with exchangeable filters. The $\pm 0.1^{\circ}C$ requirement has to be supplemented. Any transient behavior depends on the transfer function of the system involved and hence the $\pm 0.1^{\circ}C$ requirement has to be implemented by a statement as to the input change (in this case the rate of change in the environmental temperature) causing the $\pm 0.1^{\circ}C$ transient, and, if the integral values are to be obtained, the integral of the transient has to be sufficiently small to insure the specified integration accuracy, a condition which is not necessarily identical to, or met by, the $\pm 0.1^{\circ}C$ requirement. The supplementary condition is best chosen by stating that no larger transient amplitude than said $\pm 0.1^{\circ}C$ shall show under all possible environmental conditions, and with sufficient adequacy, for any rate of change in environmental temperature of $3^{\circ}/min$ and a span of 20 degrees anywhere within the temperature band from $-40^{\circ}C$ to $+40^{\circ}C$. (See Para. 3.3.10.2 in Technical Requirements SCL-5814, Appendix III.)

---

*The value $\pm 0.1^{\circ}C$ is based on the actual final design where a radiation of about 1.8 cal/cm^2/min causes a temperature rise of the sensing junctions of about $20^{\circ}C$. The accuracy requirement of $\pm 0.5 \times 10^{-2}$ leads, then, to the $\pm 0.1^{\circ}C$ admissible transient.

12

The model evolved during the contract with The Eppley Laboratory did not meet this transient condition for all filters, especially the strongly absorbing ones. However, the time-constant (the duration of transient amplitudes caused by large rates of environmental temperature changes) is not excessive, as will be shown later; and the transient influence on the time integral of the radiation falls within the admissible error band of the integral values.

Experiments with simulated environmental conditions yielded valuable insight, and design changes are presently being made in a follow-up procurement which will result in an improved transient response.

The influence of the environmental temperature described above is essentially of a transient nature. Another effect of the environmental temperature level is more serious, since it is of steady-state nature and limits the accuracy of integration even under very slowly changing environmental temperatures. This influence is reflected in a dependency of the output emf for any specific radiant flux on the temperature environment.

The reasons for the temperature transient effect, as previously mentioned, are twofold: a) The emf/$^{\circ}$C of the used thermojunctions (bismuth silver) varies with the temperature level, and b) the assumption that the temperature rise of the sensing surface (the sensing junctions) is equally proportional to the radiation received at all environmental temperature levels is true only in first approximation. This is due principally to small nonlinearities in the thermodynamic behavior of the sensor caused by energy exchange between sensor surface and the air volume under the filter enclosure and the dependency of conduction and convection coefficients on temperature (especially of the air inclosed in the radiometer). So far, a satisfactory quantitative analysis has not been obtained, * but the lumped steady-state influence of the temperature environment can be measured accurately and compensated for by means of a passive network with a temperature-dependent transfer function. Using a thermistor as the temperature-sensitive resistive component, a simple arrangement allows the compensation of the temperature environment over a wide span (-50°C to +40°C) to a large degree, with a residual maximum error of about ±0.4% over the whole range.

From the foregoing it is obvious that the properties of the radiometer discussed are determined not only by the sensing surface, the thermoelectric junctions, the sink, and the radiation-permeable filters, but also, though to a lesser degree, by the entire design of the enclosure. The arrangement of the components in this enclosure, the materials used, and the mounting of the radiometer through the thermal fluxes through these components will determine the transient behavior of sensing surface and sink and will, in

*Due mostly to the mathematical difficulties inherent in three-dimensional heat-flow problems.

13

steady state, determine the transfer function which relates radiation input to the emf of the output.

The following paragraphs give typical design data as verified by experiments performed at The Eppley Laboratory and at USASRDL (Figs. 5 and 6). It should be realized that the data presented were obtained by analyzing the final product. Many more tests yielding unsatisfactory data, but indicating the direction of improvement, were made before a radiometer performance reflected in the presented data was obtained (Fig. 7).

Technical Details of USASRDL Pyranometer

1. Enclosure. Figure 8 shows a cross section of the finalized radiometer, and Fig. 9 the actual instrument. Figure 8 shows provisions for three filters. The instrument described in this report, however, uses only two filtering hemispheres, as indicated in the detail at the upper left corner of the figure. A three-filter arrangement provides an additional instrument capability whenever very narrow bands necessitating filter combinations are needed for spectral measurements. The figure is self-explanatory. The material used is brass, with the exceptions of the sensing disk made from pure silver and the heat-sink ring manufactured from electrolytic copper to insure a high degree of temperature uniformity of the reference junctions. The temperature-compensating device is housed partially in the heat sink (No. SR 17) (the temperature-sensitive thermistor) and partially in compartment No. SR 16 (the resistor network part).

Position No. SR 13 (shown clearly in Fig. 9) holds a desiccant to absorb any water vapor inclosed during manufacture and entering from the surrounding atmosphere through small unavoidable leaks, with temperature and pressure gradients between environment and instrument interior as driving forces.

2. Sensing Surface. The receiving part of the sensor consists of a thin (0.38 mm in thickness) silver disk of 9-mm diameter, which is coated on the side exposed to the radiation with Parson's optical black lacquer to form the radiation-absorbing surface. Cemented in close thermal contact to the back side of the disk are the hot junctions of the silver bismuth thermocouples, equally spaced around the circumference. These junctions are insulated from the silver metal, since 15 junctions connected in series (to increase the emf output of the sensor) are used.

The use of Parson's black as absorbing coating was met with considerable difficulty when the first coating attempts were made. The drying of the highly volatile lacquer base causes surface tensions that tend to warp the very thin silver disk. It was learned, however, that applying Parson's black with an airbrush in consecutive thin layers resulted in maintaining a geometrically flat sensor surface.

14

Fig. 5. Test Setup of Eppley Special Radiometer No. 3449. For
measuring calibration stability, positional errors,
environmental errors, and transient behavior.

1 May 58

15

Fig. 6. Instrumentation for Thermopile Calibration, USASRDL Test Chamber
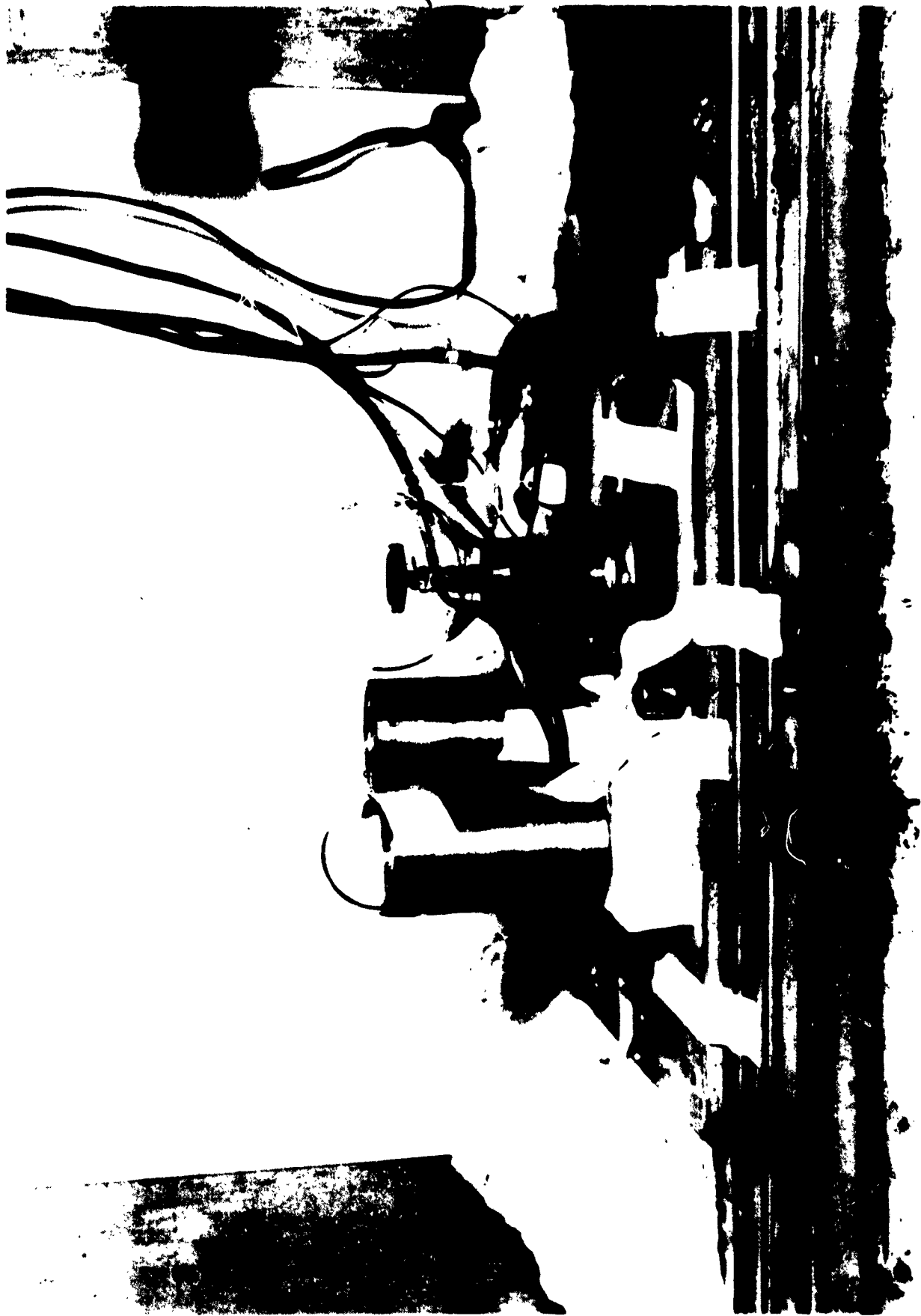
Fig. 7. Early Model of Thermopile Receiver. With and without clear (WG7) hemisphere, in USASRDL test chamber. Eppley cell (old type) at right for comparison measurements.

17

DETAIL FOR 2 HEMISPHERES

SR-26
SR-25

-6-32 ALLEN HEADLESS SCREW

1/2", 4-36 F.H.

1/2, 8-32 FIL. H
SR-15

THERMISTOR CIRCUIT INCORPORATED IN
LEADS FOR ELECTRICAL COMPENSATION
OF RADIOMETER RESPONSE WITH
TEMPERATURE.

DRYER SR-13

3/4", 10-32, F.H.

SR-23

SR-17
SR-16
SR 7

PYR-T-29

SR-22

SR-16

SR-9
SR-10
SR-11

SR-27

O-RING, VICTOR
73011

SR-12

SR-8

SR-20

SR-3

3/4", 1/4"-20
KNURLED HEAD
SCREWS

SR-1

SR-20

3/4", 10-32, F.H.

FIG. 8 CROSS - SECTION OF NEW EPPLEY PYRANOMETER

-18-

Fig. 9

EPPLEY SPECIAL RADIOMETER #3449 . (Exper. Model)

Overall View .

The sensing disk with the black coating on the upper surface and the hot junctions on the lower surface is supported and held in position by means of five equally spaced fine quartz fibers cemented with glyptol* in grooves around a 10-mm diameter circular opening in the upper surface of a 1-mm thick disk of phenolite (Fig. 10).

The reference junctions corresponding to the hot junctions in number and design are in thermal contact with and cemented onto the heat sink formed by the short copper tube forming the body of the mounted thermopile.

3. <u>Thermojunction Bi-Ag</u>. Bismuth-silver thermojunctions were chosen for three reasons: 1) the large emf/$^{\text{o}}$C of this combination, 2) the smaller β value (as compared to other suggested thermojunctions such as Fe/Cu, Cu/constantan, and Fe/Ag), and 3) the good long-time stability of the well-made junctions.

To establish background for analytical effort, the α and β values of the thermojunction were established in careful laboratory measurements, and the emf/$^{\text{o}}$C values were computed on the Burroughs 620 for 0.1$^{\text{o}}$ steps and over the range from -50$^{\text{o}}$C to +50$^{\text{o}}$C, using the well-established quadratic relation,

$$emf = \alpha t + \beta t^2 ** . \qquad (1)$$

The tabulated results for $t_r = 0$ (t_r = temperature of reference junction) are presented in Appendix II.

It should be mentioned that the manufacture of highly stable thermojunctions is an art rather than a science and depends strongly on human performance, once the choice of material and dimensions is made. The thermojunctions used in subject pyranometer are formed by electric welding of 0.025-mm-diameter wires of silver (fine) to 0.065-mm-diameter wires of bismuth (c.p.). Aging by means of thermal cycling removes incidental stress and structure changes caused during manufacture to the extent that no performance-influencing deviations occur with time. (Test on the overall calibration characteristics of four models after two years of use shows that the calibration constant did not change more than approximately $\pm 1\%$.) This observed change, however, is too close to the inherent inaccuracy of the calibration procedure to be broken down with reasonable probability into contributing components. These changes are due to slight changes of various origins such as solarization of the inner (and outer, if WG7 glass is used for the latter) hemisphere, changes in the absorbing properties of the sensor by aging of its lacquer base, etc., and certainly not due entirely to changes in the thermopile characteristic.

* Glyptol is used throughout the radiometer as the cementing compound, either in air-dried or polymerized form.
**See, for example, <u>Handbook of Chemistry and Physics</u>, Chemical Rubber Publishing Co., Cleveland, Ohio.

Fig. 10. Thermopile of New Eppley Pyranometer

Tests on the stability of the Bi-Ag junction itself were not performed beyond measurements before and after aging through thermal cycling. Only small changes, negligible for radiometric application, were revealed. Even these changes may vary from junction to junction, depending on the manipulation during manufacture. It should be pointed out here that variation in the α and β values of the junctions between different thermopiles made from material originating from different sources is irrelevant, since of most concern is the long-time stability rather than absolute characteristics, with the latter varying only so slightly that the design of the compensation for the environmental temperatures is not influenced at all. This holds especially since the compensation in secondary standard radiometers calling for extreme precision is done on an individual instrument basis.

4. Environmental Temperature Compensation. As mentioned before, the environmental temperature changes the sensor readout obtained for a constant radiation flux. The main reasons were discussed and it was mentioned that a stringent analytical treatment has not yet been made. The large amount of change in readout with changes in environmental temperature necessitated, however, a fast solution of this unwanted feature. It so strongly limits the accuracy of the integral values of radiant flux to be determined that an engineering approach to this problem was chosen, not waiting for a detailed analysis of the causing processes.* With the linearity of the readout in respect to the sensed levels of radiation established (within the specified limits) at various environmental temperatures, the compensation sought for could be limited to an adjustment of the readout characteristic slopes to a normalized slope at various environmental temperatures.

With the function of readout for constant radiation input versus environmental temperature under steady-state conditions established, and the decision made that compensation rather than elimination should be accomplished, the solution was obvious: a temperature-sensitive voltage divider was the means to be used. (A detailed description of the implementation of this principle may be obtained from a technical report, "Compensation of Environmental Temperature Influence on Precision Radiometers," now being prepared by the Meteorological Division, USASRDL. Only the basic principle is described here.)

Assume the noncompensated transfer function to be known by measurement. Then the problem is that of insuring that a constant flux input to the radiometer causes a constant output no matter what the environmental temperature may be. If use of an amplifier is to be avoided, the compensated output for any sensed flux has to be smaller than the smallest possible

---

*The writers of this report consider the process of "compensating" instead of "eliminating" as superior, especially if the errors do not exceed, for example, ±10%. Elimination needs perfect understanding of the causing occurrences and tedious repetitive redesign, while compensation can be obtained frequently if only the unwanted behavior of the over-all transfer function is known. 22

noncompensated output, thus, $K = f(t_{environment})_{min}$. The amount that K must be below $f(t_{environment})_{min}$ will depend on the characteristic of the temperature-sensitive component used in the voltage-dividing circuitry.

Since the environmental characteristic (shown in Fig. 11 in the form of a normalized error) shows an increase of the output with decreasing temperature, a voltage divider of the sketched type (Fig. 12) necessitates a temperature sensitive resistor R_T having a negative temperature coefficient (decrease of resistance) with increase of temperature.

The input $emf_{(in)}(t)$ to the compensating network being given as the emf of the sensor which varies with the temperature of the environment for any constant radiant input, the condition for compensation is obtained with R_i, the internal resistance of the source (thermopile of the sensor).

$$R_S \left[\frac{emf_{in}(t)}{emf_{(out)}} - \frac{R_i}{R_S} - 1 \right] = R_T. \tag{2}$$

Because of the linearity* between flux and sensor emf, the ratio $emf_{(in)}/emf_{(out)}$ is constant for all flux levels and varies only with the environmental temperature.

The above relation allows many solutions. The output emf (emf_{out}) is limited only by the requirement of equation (2), and the choice of R_S is still free.**

Additional requirements imposed by properties of associated circuitry as well as the availability of components with temperature-depending characteristics, however, limit considerably the multifariousness of equally suited solutions. The basic difficulty, however, that of finding a "best solution" by trial and error methods, is not eliminated. In the present case the limiting requirements are about as follows:

1) The output should be as high as possible.

---

* The measuring techniques used did not reveal any nonlinearity of the flux-emf relation. Though certain nonlinearities may be expected because of the radiant energy exchange sensor-surface environment, these effects are much less than the inherent and admissible inaccuracies of the sensor.

**The presence of an infinite number of correct solutions is typical for compensation problems; other requirements such as ease of instrumentation and economic circuitry, however, usually limit the multiple choice to certain areas. The fact that only in extreme cases the compensating component (here, R_T) can be built to match the mathematical requirement, as well as the availability of only a limited number of temperature-sensitive components, narrows the choice of the variables further.

READ OUT FOR INPUT = 1 LANGLEY·MIN⁻¹
—— UNCOMPENSATED PYRANOMETER
-- COMPENSATED PYRANOMETER

ERROR OF READ OUT FOR INPUT = 1 CAL. CM^{-2} MIN^{-1} IN PERCENT OF INPUT
—— UNCOMPENSATED PYRANOMETER
-- COMPENSATED PYRANOMETER

TEMP °C	-40	-30	-20	-10	0	+10	+20	+30	+40	+50
ERROR RED	+11.8	+9.5	+5.7	+2.9	0	-2.9	-5.7	-8.5	-11.3	-14.0
ERROR BLUE	+1.3	+0.8	+0.4	+0.1	0	-0.1	-0	+0.2	+0.6	+1.1

COMPENSATING NETWORK

THERMOPILE

THERMISTOR
$R_t = f(t)$
R_p
R_s
OUTPUT

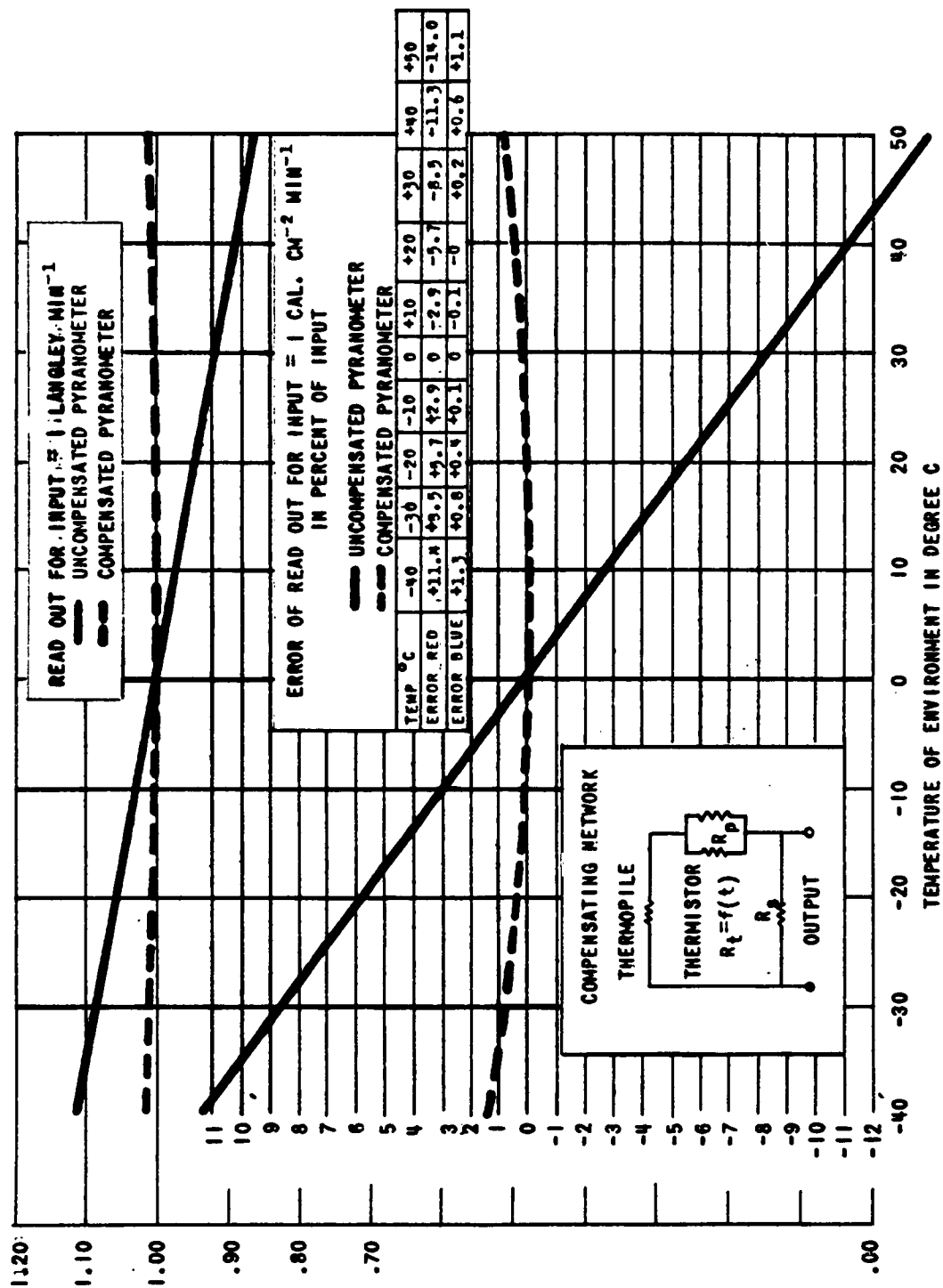TEMPERATURE OF ENVIRONMENT IN DEGREE C

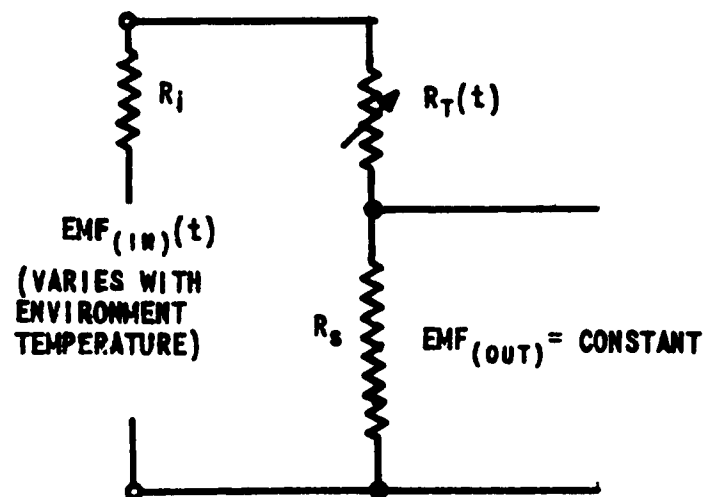FIG. 11   INFLUENCE OF ENVIRONMENTAL TEMPERATURE ON EPPLEY PYRANOMETER

24

Fig. 12. Circuit to Compensate for Different Environmental Temperatures

2) The impedance as seen from the output terminals of the combination sensor and compensating circuitry have to be kept low to avoid loading errors caused by the recording instrument used.

The first requirement depends on the R_T characteristic available (thermistor characteristic) and the normalized (percentage) difference between emf $(t_{env})_{max}$ and emf $(t_{env})_{min}$.

The second requirement depends strongly on the characteristics of associated circuitry, and the available temperature-sensitive resistors.

Since considerable work was done at this Laboratory on temperature-sensitive resistors with negative temperature coefficients (thermistors), the choice of a "first try" thermistor was easily made and its curve was matched to the required transfer characteristic by means of a suitable parallel resistor and subsequent variation of the ratio $emf_{(in)}(t)/emf_{(out)}$ by proper adjustment of R_S. (t, as before, is the temperature of the environment.)

It was further decided to keep the impedance of the compensated radio-meter below 1000 ohms to avoid excessive loading error by the servo-type potentiometric recorder used for analog recording of the radiant flux.

Experimental test permitted keeping the amount of trial and error computations small. The insert of Fig. 11 shows the circuit finally used, which has a transfer function that may be computed from equation (2). The same figure shows the improvement obtained.

A more rapid method, demonstrating the superiority of the use of analog computing techniques for the compensating circuitry design, is described in detail in the above-referenced report on radiometer compensation.

From equation (2) and the resistance $R_T(t)$, the combination thermistor $R_{TH}(t)$ and a parallel resistor R_p,

$$R_T = \frac{R_{TH} \cdot R_p}{R_{TH} + R_p} ,$$

one obtains

$$R_{TH}(t) = \frac{R_S \left[\dfrac{emf_{(in)}}{emf_{(out)}} - \dfrac{R_i}{R_S} - 1 \right]}{1 - \dfrac{R_S}{R_p} \left[\dfrac{emf_{(in)}}{emf_{(out)}} - \dfrac{R_i}{R_S} - 1 \right]} \tag{3}$$

26

This equation may be used to determine R_p and R_S for two known values of $R_{TH}(t)$ and $\dfrac{emf_{(in)}}{emf_{(out)}}$, properly selected.

Figure 11 shows the results obtained with the described simple circuitry and the reduction of environmental temperature influence obtained. Further reduction is possible by using more than one temperature-sensitive resistor and a somewhat more sophisticated passive network. However, optimal design of such a network necessitates the use of analog computer techniques if the time spent on the design is to be in an economic ratio to the improvement possible.

The physical location of the compensator is such that the thermistor is exposed to the same temperature as the heat sink and is assured (by imbedding the thermistor bead in the heat sink) of having the same transient response (or nearly the same, since the thermistor is glass coated) as the sink.

Table 1 shows a typical result of the compensation used and the errors, expressed in percents of the arbitrarily chosen value at $0^{\circ}C$. In more recent models, careful selection and "trimming" of components result in further reduction of the residual errors to the mentioned ± 0.9 percent.

Table 1. Percent Deviation of Radiometer Output from Output Value of $0^{\circ}C$

Temperature $^{\circ}C$	Sensor Without Compensation	Sensor With Compensation
-40	+11.4	+1.4
-30	+8.5	+0.8
-20	+5.7	+0.4
-10	+2.9	+0.1
0	0	0
+10	-2.9	-0.1
+20	-5.7	0
+30	-8.5	+0.2
+40	-11.3	+0.6
+50	-14.0	+0.9

Notice the nearly linear characteristic. It is somewhat unexpected, knowing the thermocouple characteristic which is slightly curved because of the square law behavior of emf/$^{\circ}C$ versus temperature. The β value of the bismuth-silver thermojunction, however, is very small; and the conductivity and convection in air change opposite in nonlinear manner with temperature, causing a linear (within measuring accuracy of the experiment performed) dependency on the environmental temperature.

Referring to the insert of **Fig. 11**, the values of the network components are approximately 1500 ohms for R_S and 1000 ohms for R_p, varying according to the variations between samples of the thermistor used, which, in the described instrument, is a glass-coated bead of the 14B type. For its characteristics, see references 2 and 3.

Response Characteristic, Radiant Energy Versus EMF Output

It was mentioned before that the input-output characteristic of the assembled radiometer is highly linear for any environmental temperature kept constant. The linearity test was performed at The Eppley Laboratory and accepted as valid since at that time The Eppley Laboratory had facilities more adequate than those available at USASRDL as well as a secondary standard radiometer, the linearity of which was established by careful calibrations (Eppley Secondary Thermopile Standard No. 2427). The measurements were made using instrument No. 2427 as linearity standard. Table 2 shows the findings.

Table 2. Input (Radiant Energy) Versus Output (EMF) Characteristic of Radiometer No. 2427

Distance from Source (cm)	Radiation Input In cal cm^{-2}min^{-1}	Thermopile No. 2427	Radiometer	Ratio $\dfrac{\text{No. 2427}}{\text{Radiometer}}$
246.8	0.099	0.80	0.72	1.11
200.8	0.143	1.15	1.04	1.11
167.8	0.206	1.66	1.50	1.11
123.3	0.389	3.11	2.83	1.10
90.0	0.708	5.60	5.15	1.10
79.0	0.901	7.18	6.55	1.10
66.2	1.323	10.63	9.62	1.105

The measurement was performed on a three-meter optical bench, using a tungsten lamp as light source and monitoring this light source for constant output by observing volt and ampere meters as well as the output of a photovoltaic cell kept at fixed distance from the light source.

The deviation from linearity of less than ± 0.5 percent is within the specified limits and is considered excellent. Here, again, a slightly larger deviation from ideal linearity could be expected if only the emf/°C behavior of the thermopile used were considered. As mentioned before, however, the fraction of heat exchange between sensing disk and environment which takes place through the gas (air) inside the radiometer by means of conduction and convection is slightly nonlinear by nature. This behavior tends to straighten the slightly curved temperature-versus-emf characteristic of the bismuth-silver thermoelectric junctions.

28

Selectivity of Receiver

The importance of a "gray" response of the sensor over the total spectral range was stressed before, and the selection of Parson's black was mentioned. Table 3 shows the results of significant tests. The grayness

Table 3. Comparison of Parson's Black and Gold Black

Source	Mercury Arc*	Tungsten Lamp	Carbon Filament	High-Temperature Black Body			Low-Temperature Black Body	
Temperature of Source C^O	?	2800	1700	1000	800	500	100	50
Maximum radiation at a wavelength in microns	0.35	0.95	1.5	2.3	2.7	3.7	7.7	9.0
Ratio: Parson's black / gold black	0.93	0.91	0.91	0.905	0.91	0.91	0.92	0.915

*With filter restricting the output to the .27 to .38 μ band of the spectrum.

was evaluated by a relative technique using a gold black coated surface as comparison. The excellent absorbing properties of gold black surfaces for incidences normal or close to normal are sufficiently well established to permit their use as reference. To measure the absorption in respect to gold black and in various spectral bands, different radiant energy sources were used. The selection is straightforward. The presented data are mean values of repeated measurements at the contractor's plant. The ratio values show an estimated 3σ band of about ± 0.005, with a probable higher value for the mercury lamp.

Filter Inclosures

As mentioned before, and reflected in SCL Technical Requirements 5814 (Appendix III), Schott filters WG7, OG1, and RG8 were used in accordance with the recommendations of the WMO for use during IGY. (The other glass, RG2, of the series recommended by WMO, could have been included on another sensing unit at additional cost.) The filters serve a double purpose: 1) to surround the sensing surface with a steady atmosphere in order to insure stability of performance, prevent damage of the sensor and its absorbing surface, and to insure as much as possible independence from environmental conditions; and 2) to select proper spectral bands in accordance with user requirements.

The hemispheres were manufactured by a grinding and polishing technique which had to be used to avoid changes of the optical filter properties connected with warm forming processes and to insure the required uniformity of transmissivity. The filter materials selected had been tested at The Eppley Laboratory during manufacture. The transmission characteristics shown in Appendix III were obtained at USASRDL on a Perkin-Elmer Spectrochord and duplicate the transmission properties given by Eppley.

Azimuth Error

The azimuth error, defined as the deviations of the readout of the horizontally oriented pyranometer from the true value* for all azimuth positions, was not specified in the technical requirements forming the basis for the pyranometer development, since the "over-all" performance requirements prohibit an excessive azimuth per se. In discussions with Eppley, however, it was found that its determination gives a valuable figure of merit on the performance of pyranometers. Therefore, effort was made to design an adequate testing procedure. Because of the relaxed accuracy requirements for the cosine behavior of the pyranometer at low-radiation-source elevations, it was found adequate to test the azimuth errors with a beam of 15° elevation (light source, for example, a 1000-watt tungsten lamp at a distance producing a sensor output approximately equal to a radiant flux of 1 cal cm^{-2} min^{-1})** taking output readings for varying azimuth orientations of the pyranometer (with the inner filter in place).

The deviations of these readings from the mean value represent the azimuth errors after the evaluation of the pyranometer in the horizontal plane is so adjusted that the errors observed represent a minimum. The same method is used to orient the bubble-level used for horizontal positioning in practical use of the instrument. Measurements of the described nature were taken with the satisfying result that the deviations from the observed mean were less than one percent in all observations; that is, taken with and without the outer filter hemisphere. An azimuth test for the purpose of checking the correct orientation of a pyranometer can and should be made in the field from time to time by choosing a clear day and a sun elevation of about 15° to 25° to check the constancy of readout with azimuth orientation. If work is done fast and the day is clear, the setting of the sun during the test will cause a negligible change of elevation angle, which may be corrected for if a second radiometer is available for a lock-in reference. This test allows checking the position of the bubble level normally used for instrument orientation.

---

*The "true value" is replaced practically by the mean value of at least ten readings obtained at equally spaced azimuth intervals over the whole 360-degree scale.
**Of the order of magnitude of the sun's radiation near midday.

Cosine Law Performance

As previously pointed out, cosine law performance is a requirement for any instrument measuring the intensity of radiation as received on a horizontal surface to weight properly the radiation fluxes coming from different angles of elevation. The cosine law states that the response of the sensing surface to radiant flux from any direction should be proportional to the flux received on a surface normal to that direction times the cosine of the angle of incidence on the receiving surface.

The cosine law will be met by a sensor having a perfectly flat surface with absorbing properties that are independent of the angle of incidence and constant over the spectral band of concern.* Any medium, however, with optical properties which reflect, refract, or absorb the radiant flux by an amount dependent on its direction of arrival (or penetration) placed within the path of the radiant flux to be measured, will cause deviations from the ideal case. The optical enclosure(s) of the pyranometer discussed forms such a medium. The "grey" and flat properties of the sensor established, the cosine law performance depends on the size, shape, and optical properties of the filter hemispheres.

During early tests, deviations from cosine-law behavior were observed which empirically were correlated to the refractive properties of the inner hemisphere. Mr. Drummond of Eppley Laboratory suggested attempting correction by lowering the inner hemisphere, thus forming an enclosure slightly less than a full hemisphere. Considerable improvement was obtained by this method. The still-remaining error pattern could be further reduced by increasing the diameter of the inner hemisphere, a procedure too expensive and unhandy to be implemented, especially since it was believed that the errors still present are within the allowable error margin.

The testing of cosine-law performance is straightforward. A beam of parallel light of constant intensity, whose angle with respect to the sensing surface is variable in steps from grazing incidence (90° to the sensing surface-normal) upward through the perpendicular plane bisects the surface to grazing incidence in the opposite sense. Rotating the sensor in its own plane allows testing for azimuthal constancy of the cosine-law performance.

In carrying out this test, the main problem was getting a constant, controllable light source of suitable intensity. The two sources used were a powerful tungsten lamp and natural sunlight as available on bright clear days at noon. The use of the tungsten lamp was abandoned since the use of artificial sources necessitates special experimental gear that could not be

---

*Since the sensor discussed in this report is a "secondary" standard, 100 percent absorption of the radiant flux on the sensing surface is not required. "Constant grey" response is sufficient.

obtained within the time available. Sunlight, under the environmental conditions mentioned, is a constant source parallel to within about $\pm 0.5^o$ and of suitable intensity. The drawback to its use, in the absence of a heliostat, is the difficulty in controlling its direction. This difficulty was handled by a compromise. The pyranometer was mounted on a tilting platform with a large elevation-angle dial, and the angle of incidence was changed by tilting the pyranometer. This technique introduces the possibility of an error in case the angle of tilt affects the pyranometer output. Since the output of the old Eppley cell showed this effect to some extent, preliminary tests were made, with the satisfactory result that the new pyranometer showed no observable positional influence* on its calibration.

Figure 13 shows the experimental setup for the cosine law test. An aluminum tube 5 inches in diameter and 48 inches in length, blackened with optical black on the inside, was fastened to an automatic sun-following mount (equitorial mount) standing on a platform outside the laboratory. Fixed irises of four-inch diameter mounted on both ends of the tube prevented reflections of sunlight on the internal black surface of the tube in case the tube was not aligned exactly parallel to the sun's rays or it deviated from perfect alignment during the run of the experiment. The parallel beam of sunlight brought into the room was directed onto the pyranometer tilt-table. The centering of the beam was checked frequently and the pyranometer output was recorded on a Leeds and Northrup potentiometric recorder identical with the one forming part of the integrated sun and sky instrumentation. The constance of the sun's brightness was monitored on another recorder which recorded the output of a pyranometer mounted horizontally on a close-by 30-foot-tower platform.

Figure 14 shows a typical result obtained on pyranometer No. 3488 with both outer and inner clear (WG7) filters in place. The curve represents the mean of five observation runs, which agreed very closely (to about one percent). Figure 14a shows the average of two curves (very similar) for pyranometer No. 3491, taken for azimuths 90 degrees apart. The curves show a somewhat peculiar deviation from the cosine law. When normalized to have the value unity at perpendicular incidence, the pyranometer output curve shows a decrease below the cosine curve at angles in the neighborhood of 30 degrees off the vertical, and an increase above the cosine for angles in the neighborhood of 60 degrees from the vertical. These deviations can perhaps be qualitatively explained as refractive and reflective errors--as preliminary ray tracing shows--for normal and near normal incidence, an increase of the effective sensor area;** and at angles of incidence around

---

*See paragraphs under "Influence of Orientation on the Calibration Constant," page 37.

**The parallel rays are made slightly convergent, causing an increase of average flux density in the beam arriving on the sensor as compared to an equal cross section of the parallel beam before passing the hemispherical filters.

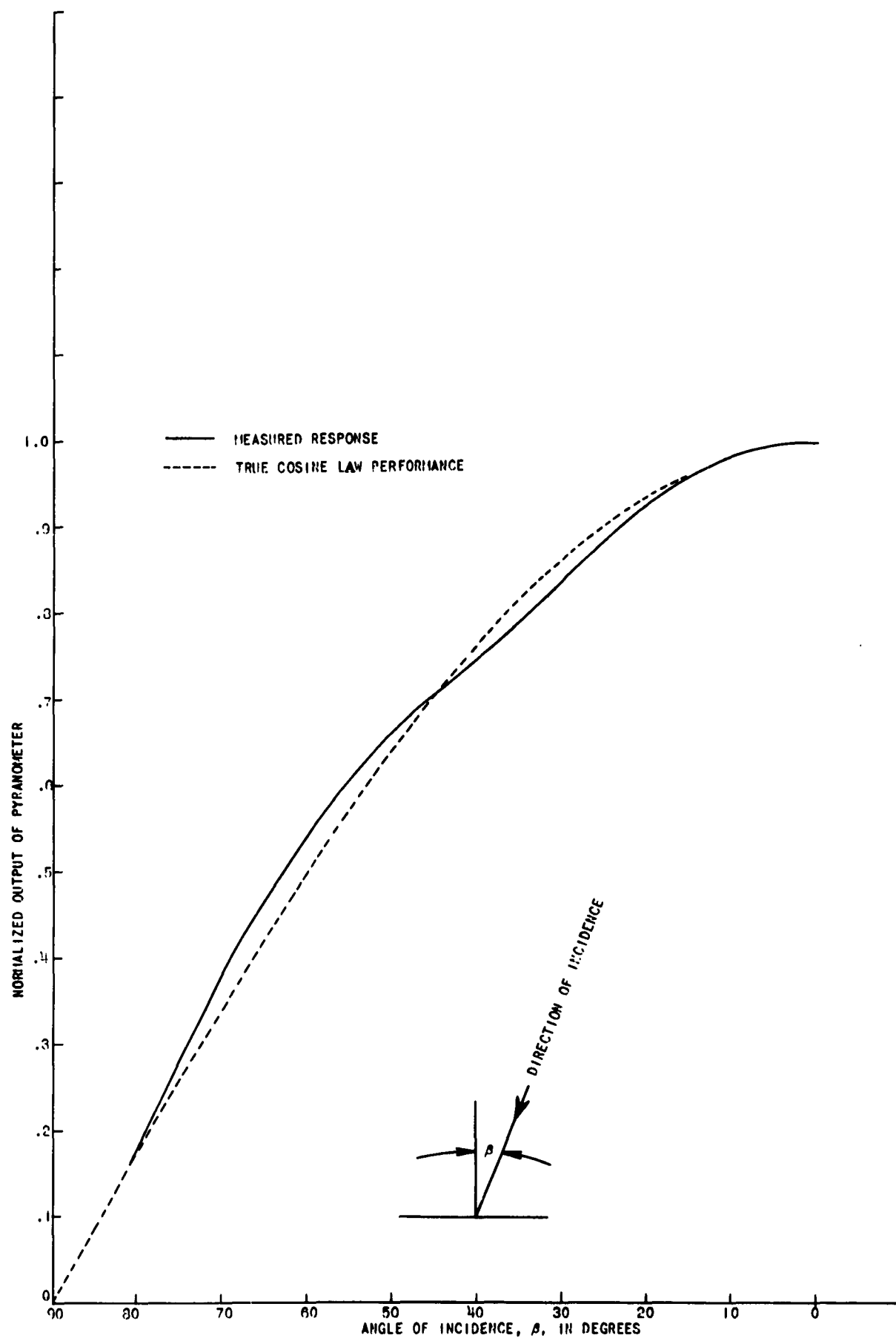Fig. 13. Solar Tracking Tube and Pyranometer Tilt-Table for Cosine-Law Test

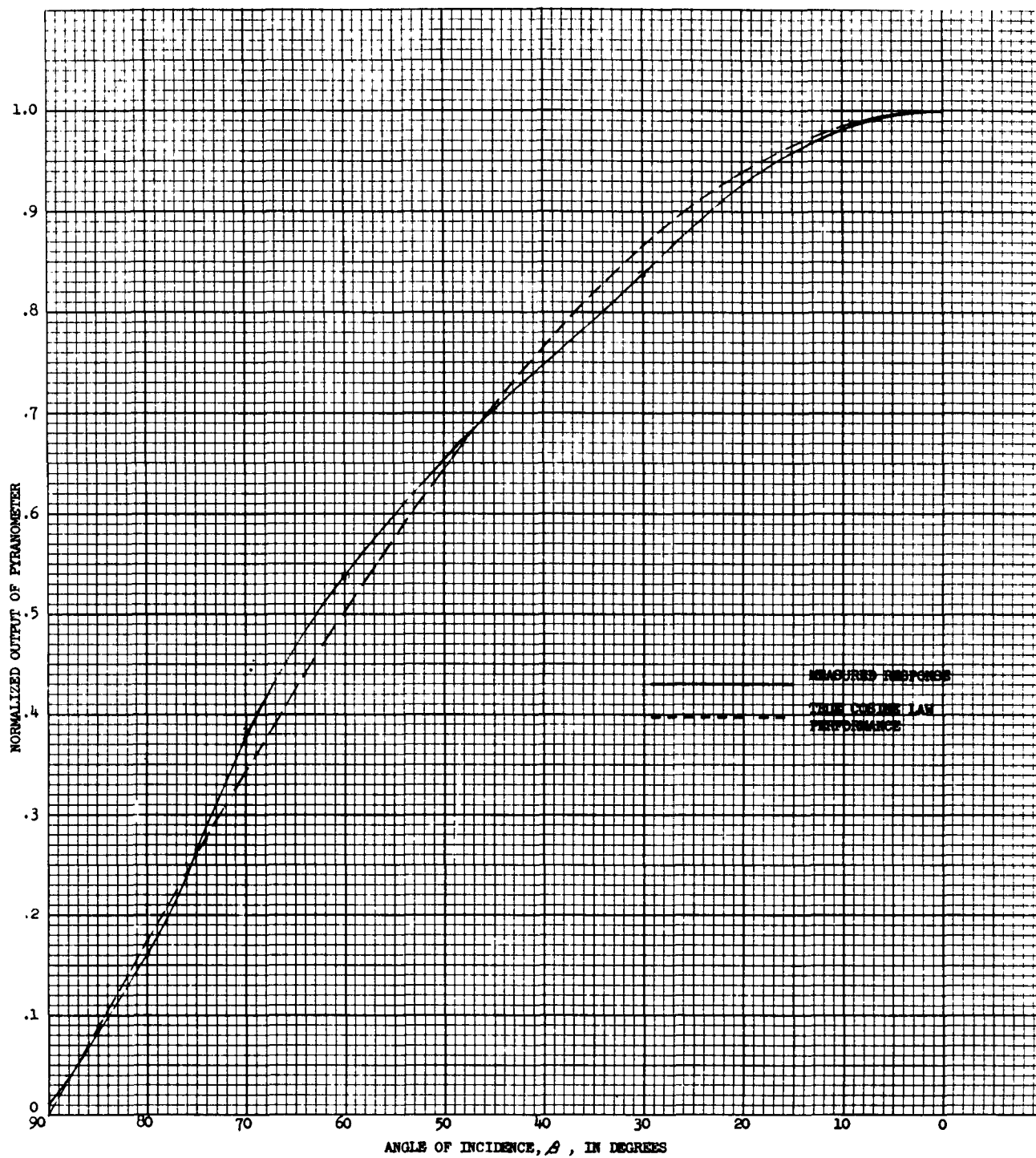FIG. 14   COSINE LAW PERFORMANCE OF EPPLEY PYRANOMETER, NEW TYPE (SER. NR. 3488)

34

FIG. 14a.   AVERAGE OF TWO CURVES FOR PYRANOMETER NO. 3493

-35-

60 to 70 degrees, the gain in the sensed flux may be due to multiple reflections. This statement, however, needs verification through numerical analysis.

A detailed analysis of the cosine behavior will be presented in a later report. The observed deviations from the cosine-law behavior are not serious since they stay within the over-all instrumental accuracy, especially when it is considered that the deviations shown hold only for parallel light beams. In actual use a large part of the received radiation comes from many directions, and direct sun rays form only part of the flux measured with a pyranometer-type instrument. For use of the pyranometer under extreme (arctic or tropic) conditions, however, the deviations from the cosine law may have to be considered.

The Eppley Laboratory tests the cosine-law performance indoors, using a tungsten lamp as the radiation source as well as following the classical procedure* of determining the instrument-constant by observing the output of the pyranometer under test at various elevations of the sun and using simultaneously taken pyrheliometric measurements made with angstrom or silver-disk pyrheliometers.

As an example of the results obtained by this latter method, Table 4 shows the results of one calibration made by The Eppley Laboratory. The mean value of the observation tabulated is used as calibration-constant for the instrument, and the use of this mean obtained from solar elevations typical for the geographical area of use tends to reduce the influence of slight anomalies in the cosine-law response.

Table 4. Check of Cosine Response by Measurements at Various Solar Elevations

Place	Date	Local Apparent Time	Elevation (degrees)	Radiation Constant per cal $\cdot$ cm^{-2} min^{-1}
Newport	10 Aug 58	11.10	60	7.20
		12.59	59	7.17
		14.34	46	7.27
		15.50	33	7.40
		16.58	20	7.34
		17.50	10	7.22
				Mean 7.27

*Described in IGY Instruction Manual, Part VI.

36

Shock and Vibration Test

The most sensitive part of the pyranometer to shock and vibration exposure is the thermopile unit. Though no military field use for the radiometer was planned, it was believed useful to test shock and vibration resistance of the thermopile sensor as well as of the assembled pyranometer to the extent of insuring that no changes of calibration or mechanical breakdowns would occur during shipping and handling under adverse geophysical conditions.

The tests were limited to accelerations of 15 g, generated by a mechanical vibrator with an amplitude of about 3 mm (1/10 inch) and a frequency of about 45 cps. The tests were made over a five-minute period and resulted in no visible mechanical damage or change of spot-checked performance (calibration constant, cosine law) characteristics.

Influence of Orientation on the Calibration Constant

The old Eppley cell showed an expressed dependency of its calibration constant (about $\pm 5\%$) on the orientation of the receiving surface with respect to the horizon. This is of no concern as long as the instrument is used in a horizontal position as is the case in normal radiometry. The requirement for using the instrument in any angular position in respect to the horizon, as needed in experiments planned by the Quartermaster Corps and the Medical Corps, necessitates positional independence of the calibration constant if mistakes or repeated readjustment of the calibration of recording and integrating instrumentation at every change in orientation is to be avoided.

The reason for this dependency of the calibration constant from the orientation was found to be due mostly to convection currents within the envelope of the pyranometer changing the thermodynamic equilibrium of the receiver-reference combination. Since this effect has been studied extensively, especially by Buettner and coworkers,[4,5] the redesign of the pyranometer sensor could provide means of reducing the positional influences. It was expected, and confirmed by tests performed at USASRDL in close cooperation with The Eppley Laboratory, that a heat sink for the reference junction would be superior in this respect to the white-painted reference ring of the old Eppley cell.

Table 5 shows the result of one test of positional influence on the calibration constant as a demonstrating example.

Calibration Procedure and Calibration Constant

With the linearity, the spectral flat response, the cosine law performance, and the independence of performance from position and environmental

Table 5. Position Test

Environmental temperature: 25°C

Radiation	Radiometer Position		
cal cm^{-2} min^{-1}	Horizontal	45°	Vertical
	(output in mv)*		
0.190	1.375	1.380	1.380
0.149	8.39	8.35	8.37

*Values are mean values over a two-hour observation period.

influences established, a single calibration constant can be given for each instrument which sufficiently describes the radiometer. The radiometer calibration constant is best described by stating the emf (in millivolts) obtained for a received radiant flux of one Langley (1 cal cm^{-2} min^{-1}):

$$K = \frac{(mV)}{(cal \cdot cm^{-2} \, min^{-1})}.$$

Two methods may be employed to obtain this calibration constant.

1. Direct standardization against a primary or, more customarily, a secondary standard normal incidence radiometer (pyrheliometer), or

2. Comparison with a standardized horizontal surface radiometer (pyranometer) of either the same or a different* type under natural conditions of exposure.

The first of these methods** compares the computed vertical component I_H of the direct solar intensity as measured by a pyrheliometer (I_N)*** with that measured by the radiometer under test.

In practice, occasions are selected with clear skies, at least within a half-angle of 20 degrees around the sun and steady total sun plus sky radiation (as judged from a simultaneously taken pyranometer record). The direct solar component is eliminated from the test-record by shading the

*When using a different type radiometer, even more care must be taken than in the case in which a comparison instrument of the same type is used in order to insure that "steady state" response is reached before a reading is taken.
**Partially quoted from IGY Handbook, Part VI, Radiation Instruments and Measurements.
***Subscripts H for horizontal surface receiver, and N for receiver for normal incidence only.

radiometer for a short time (10 to 20 minutes) with a disk of 10-cm diameter mounted on the end of a slender support and held at least one meter from the radiometer under test. Special care must be taken to insure that the refractive parts of the pyranometer under test (inner and outer hemispheres) are perfectly shaded. Then,

$$I_N \sin h = \frac{(T_H - D_H)}{K}, * \tag{4}$$

wherein

I_N = solar radiation intensity in cal cm^{-2} min^{-1} observed with standard pyrheliometer,

h = the elevation angle of the sun at the moment of observation,

T_H = the output (in mV) of the instrument under test receiving sun and sky radiation,

D_H = the output (in mV) of the instrument under test receiving only sky radiation (sun-shaded), and

K = the instrument constant in (mV)/(cal cm^{-2} min^{-1}).

The second method is straightforward and involves only correlating the outputs of the instrument under test and the comparison instrument.

The rules for selecting proper occasions for testing are less critical, but the occasions should preferably be clear days with steady total radiation, as mentioned above. It may, however, be advantageous to extend the calibration tests to cloudy sky (steady, however) conditions to obtain assurance of an instrument behavior independent of the spectral distribution of the radiant energy sensed.

The use of filters of different absorbing properties leads one to suspect an influence on the calibration constant of the pyranometer, since the glass filters used absorb radiant energy according to their spectral characteristics and the absorbed energy causes an increase of the filter temperature above the temperature of the environment. This temperature rise has two consequences:

1. The absorbing filter acts as a frequency transformer, reradiating part of the absorbed energy at lower frequencies, and

2. The temperature of the air inclosed under the filter envelope is changed (raised).

*Sometimes in literature one finds another calibration constant defined by

$h = \frac{1}{K}$ with the dimension $\frac{(cal\ cm^{-2}\ min^{-1})}{(mV)}$.

The first phenomenon has no significant influence on the radiometer calibration so long as an inner hemisphere is used that has a low transmissivity for long-wave radiation. In the absence of such an inner enclosure of the sensing surface, however, the reradiated energy may significantly influence the invariance of the calibration constant.

The second effect has no influence on an instrument of the type of the old Eppley cell, which uses a white-painted surface exposed to the received radiant flux as reference junction sink. The instrument described in this report, however, utilizing a heat sink for the reference junctions of the thermopile, is subject to calibration variations when an absorbing filter is used and the calibration (and also the compensation) is made with clear enclosures.

The presence of the inner envelope is again of advantage, reducing the temperature difference between the air volume above the sensor (inside the inner hemisphere and the heat sink).

Although a thorough investigation is yet to be made, preliminary tests have proved the change in calibration to be small (about one percent for the red filter which absorbs the largest percentage of radiation). Experiments will be continued when a new model of the radiometer, with slight improvements based on the present findings, becomes available. It will be of interest to prove an expected slight nonlinearity of response due to different temperature gradients between air above the sensor and heat sink caused by the different levels of radiation absorbed in the filter(s).

Performing radiometer calibration in the laboratory, using artificial sources of radiant energy, is per se a secondary (indirect) method, depending on means of knowing or of measuring precisely the radiant flux originating in an artificial radiation source. Two methods can be used: First, comparison of the instrument under test with a suitable reference standard on the optical bench, using an artificial source (lamp) to replace the sun at either normal incidence or any specific azimuths and/or elevations; second, comparison, in an integrating sphere, simulating direct as well as diffuse radiation.

In using artificial sources, care must be taken to eliminate the radiant energy beyond a wave length of, for example, 3μ from the instrument under test. This can be done by inserting a ventilated glass screen between source and receiver. To obtain high values of radiant flux, rather large lamps such as a 5000-watt tungsten lamp must be used which produce a large amount of long-wave-length radiation. Although the use of the sun itself for calibration purposes is usually given preference, the laboratory method may be quite satisfactory for calibrating radiometers for field use. Repeats of calibrations made with the laboratory method yield a calibration

constant identical to approximately one percent to the constant obtained outdoors.

As expected, variations in the calibration constants of individual instruments were found. Since thermopiles may be slightly different, the thermodynamic properties of the measuring instrument vary; and, finally, the compensating circuitry is adjusted in accordance with the behavior of the individual instruments. With the provisions for variable recorder (and integrator) adjustment, these variations are of no concern; especially since use of individual calibration constants allows setting a recorder input potentiometer to adjust for the over-all instrument performance characteristics. Table 6 shows a listing of the calibration constants of the set of sensors obtained on the discussed development effort.

Table 6. Calibration Constant

No. of Sensor	Calibration Constant in $mV/cal\ cm^{-2}\ min^{-1}$
3488	6.80
3489	7.30
3490	6.15
3491	6.45
3492	7.20
3493	6.45
3494	6.75
3495	6.80

Response Characteristic of the Pyranometer

Because of the heat capacities and the heat-conduction characteristics of the various components forming the radiometer sensor, mount, and housing, some time will pass before equilibrium of the thermodynamic system sensing disk and instrument components is reached. The time of transient behavior will be longer the larger the mass of the receiver and the longer the resistance path of heat transfer between the absorbing surface of the receiving disk and sink.

Mechanical considerations--mostly the surface section of the base of the receiver block--*put a lower limit to the dimensions of the receiving surface. Since, however, the absorption of radiant energy takes place immediately and it is only the transformation of this absorbed energy into a temperature rise and emf, respectively, which shows a lag time, integral values of the integration of the radiant energy measurement will not be

*There is a certain area needed to mount the thermojunctions, and the application of Parson's black requires a minimum stiffness of the silver disk.

41

affected* even if the instantaneous value of radiant flux indicated on the analog plot is incorrect (see Appendix IV).

Since at the time the specifications were written some doubts existed regarding the radiometer to be developed as to whether it would have a "first order" response characteristic, the original specifications provided that the required lag be defined by the 1/e time of the instrument and required a performance characteristic more independent of the instrument and that a 99-percent indication of a step-function input should be available within at least 60 seconds after the step is applied.

Meanwhile, tests have indicated that the dynamic behavior of the sensor is sufficiently described by specifying a 1/e lag. Theoretical analysis, supported by experimental results, suggests, however, a transfer function of higher order which may be approximately modeled by a series of first-order lags presented by heat conductivity and heat capacity of the main sandwiched components of the sensor; viz., Parson's black, silver disk, and insulation of glyptol glue, and measuring thermo junctions with the proper losses through conduction, convection, and radiation.

The measured lag time varies about ± 15 percent between instruments of the same type. This variation is insignificant in actual use of the instrument and is explained mainly by variation in the thickness of the components with low heat conductivity (Parson's black, insulating glyptol, and the length of the thermopile leads to the sink).

Figure 15 shows an example of a time-lag measured. It is self-explanatory and shows a 1/e (63 percent)**time of about ten seconds, so a 99-percent value is reached in about one minute. No dependency on environmental temperatures of the response to a step-function radiant input could be observed in agreement with the theoretical expectation.

Transient Behavior Caused by Changes in Environmental Temperature

While the transient characteristic of the sensor in response to changes in radiant flux can be readily understood, the response to changes in environmental temperature is much more complicated in its mechanism and the errors caused by this behavior during the environmental temperature transient period are more complicated than those due to the radiant flux transient. A passive temperature-sensitive thermistor network solves (previously described) quite successfully the steady-state error problems. Differences in response characteristic of measuring and reference thermojunction

---

*This statement assumes that the integration time is reasonably long as compared to the 1/e time of the sensor, and neglects second-order errors caused by nonlinear sensor characteristics.
**The response, though very close to a first-order type, is essentially of higher order. See dotted line indicating exponential response.
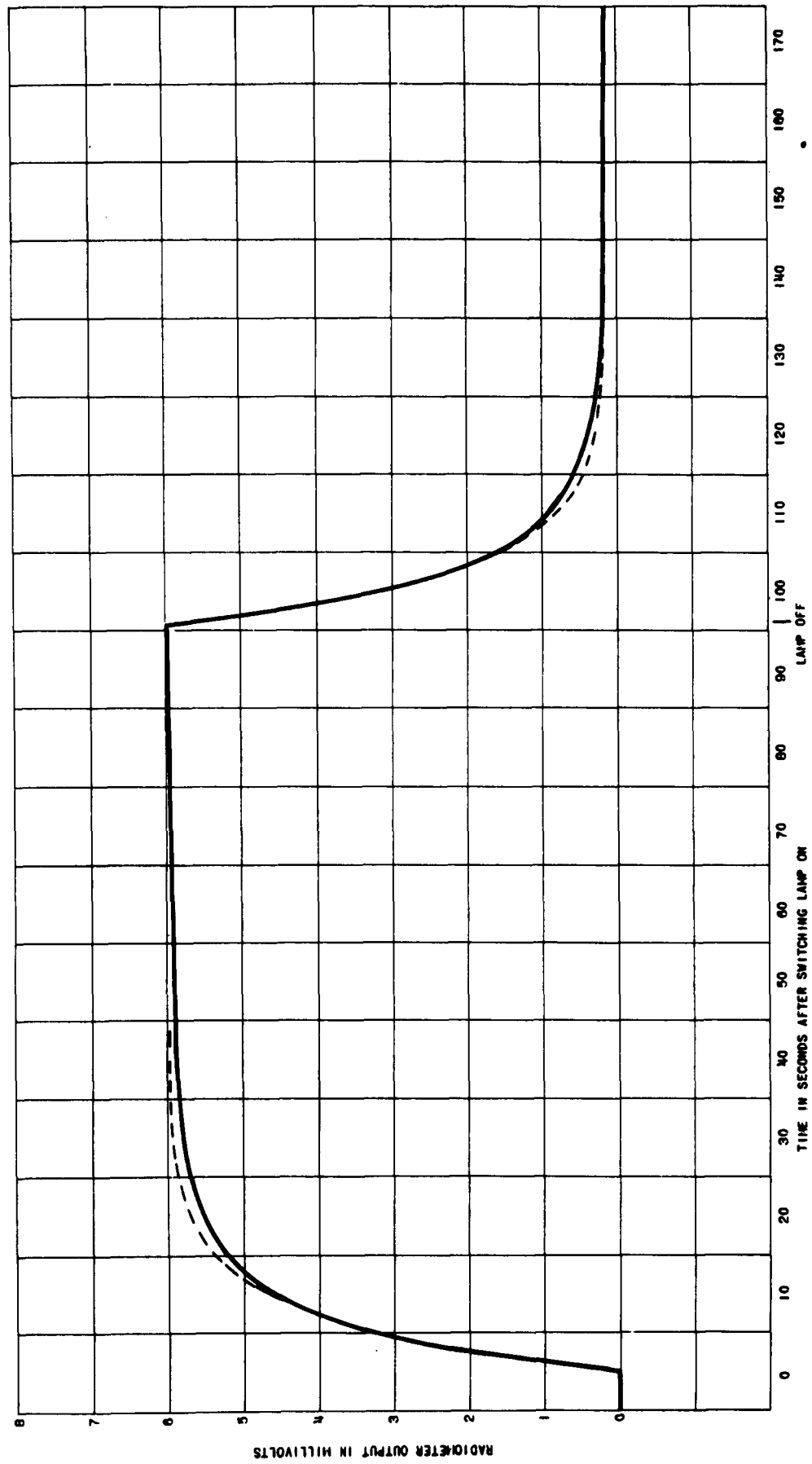
42

FIG. 15 MEASURED LAG TIME OF NEW EPPLEY PYRANOMETER

(and the components in close heat-conducting contact with them) and, to a less extent, of the compensating thermistor, cause transient periods where the compensation lags or leads, and the read-out of the radiometer is then in error.' This error occurs--and was actually observed on records--even when no significant radiation is present whenever sudden changes in the temperature environment occur. Figures 16 and 17 show on a much enlarged scale this error as observed in a test chamber, with the radiometer having no radiation input and with the temperature of the environment changing in a ramp-like step.*

The experimental picture supports the assumption of a transient temperature difference between sensor and sink caused by the different cooling or heating rates of the sensor and sink aggregate. Figures 16 and 17 show two typical results obtained during the study of the radiometer-transient behavior. In both cases the temperature of the environment was changed 17°C (from +3°C to +20°C) within two minutes, and the output with and without compensating network as well as the temperature difference between the air above the sensor (inside the inner filter) and the temperature of the casing close to the coppering of the sink was recorded. As expected, the transient is of higher amplitude and shorter duration with the outer filter removed, and of smaller amplitude and longer duration with the outer filter in place.

The reduction in amplitude observed with the compensation network in place is only imaginary, since the output of the sensor is lowered by the network's voltage-dividing characteristic, the same percentage for all inputs.

The observed transient may be simulated by two first-order lags (with different coefficients in the exponent) approaching the same steady-state value at a different rate. A reversal of the sign in the transient during the decaying period, observed in some experiments (those with very small amplitude), suggests the existence of higher than first-order lags.

The "transient" experiments, though of exploratory character, established two valuable results: 1) that the transient error is (as far as can be judged from the observation technique used) independent of the level at which the temperature step occurs and linearly related with the amplitude of the temperature step, and 2) that thermodynamic timing through careful design will allow minimizing of the error when only one or only both hemispheres are used on one instrument. Error elimination for both cases at the same time is not possible since the presence or absence of the outer filter changes the heating or cooling of the air above the sensor.

---

*Temperature step-functions could not be simulated. To eliminate this difficulty, the new specifications specify a ramp-forcing function which can be obtained with inexpensive test facilities.
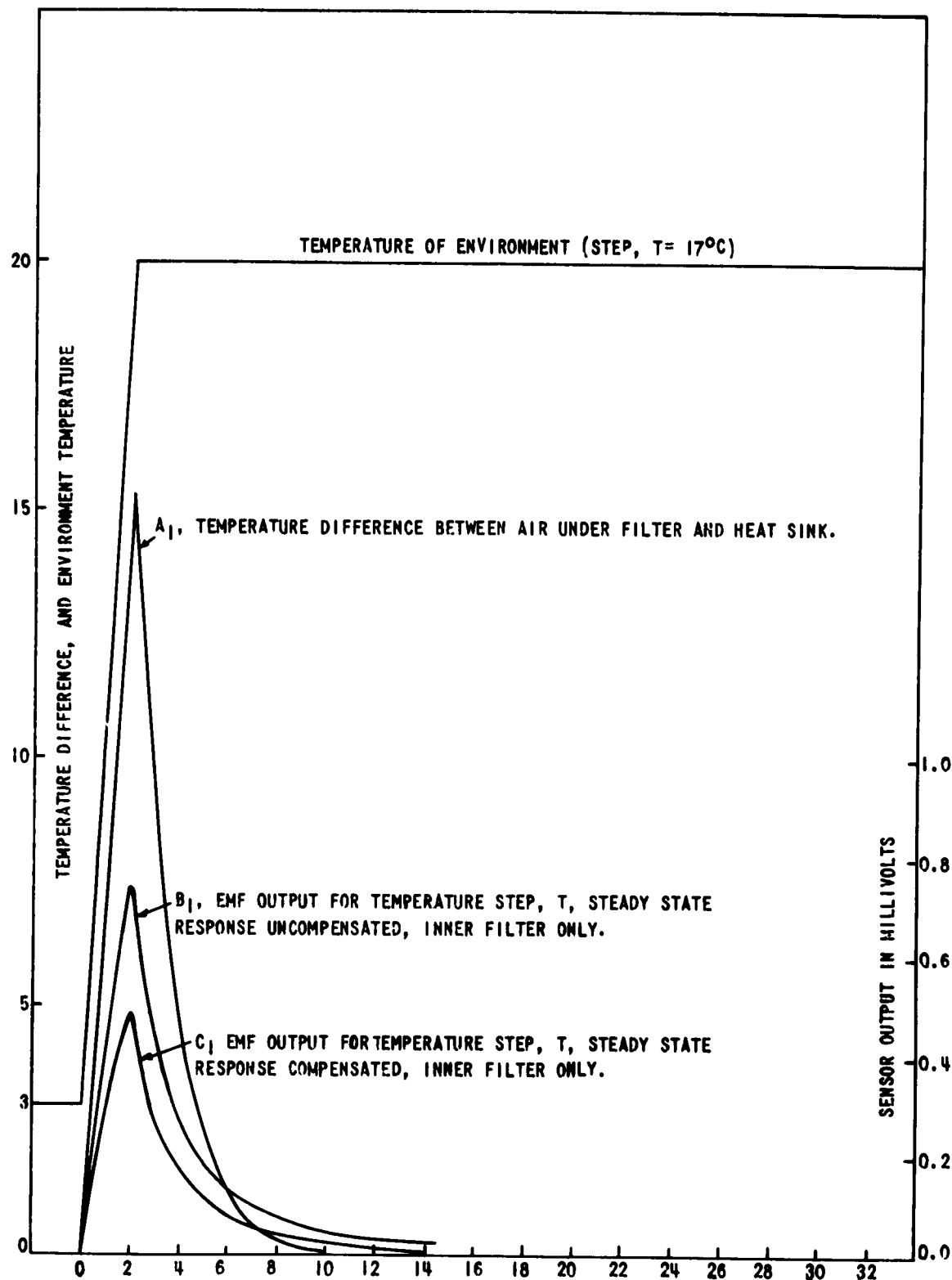
FIG. 16 TRANSIENT RESPONSE OF THE SIGNAL CORPS-EPPLEY PYRANOMETER TO CHANGES IN THE ENVIRONMENT TEMPERATURE (17°C STEP FROM 3°C TO 20°C) INNER FILTER ONLY.
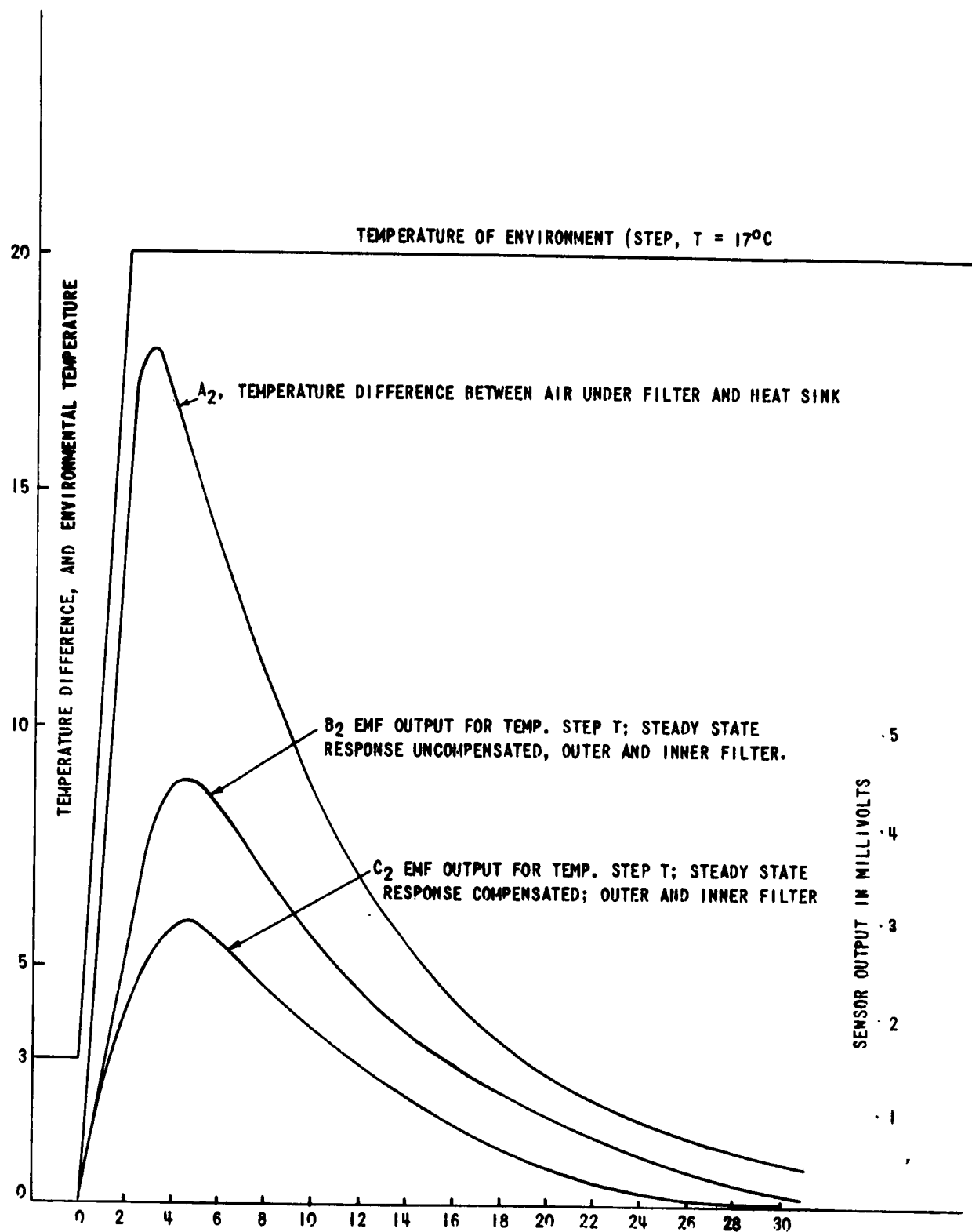
45

FIG. 17   TRANSIENT RESPONSE OF THE SIGNAL CORPS-EPPLEY PYRANOMETER TO CHANGES IN THE
ENVIRONMENT TEMPERATURE.   (17° STEP FROM 3°C TO 20°C) INNER AND OUTER FILTERS

46

The Pyranometer Mount

The pyranometer is generally used mounted on an adjustable support which allows any orientation of the sensor in the upper hemisphere. The features of this mount are described in the specifications (Appendix III). Figures 9 and 18 show the layout of the mechanical parts of the mount and the final model. A weather-resistant aluminum alloy is used throughout as construction material and the screws are made of rust-resistant steel.

The design provides ease of aligning and handling and is adequate for its purpose. Small modifications consisting of an increased clamping area for the azimuth and elevation adjustments were made on a later model manufactured for the Meteorological Teams of Fort Huachuca. In the future the clamps will be tightened by wing nuts to make the use of tools unnecessary when changing towards another sensor attitude.

Connectors and Cables

Connectors and cables used are in compliance with military specifications and have performed without failure over a one-year test period. The use of a shielded cable for the connection of the sensor with recording instrumentation is a necessity, and care should be taken to avoid swinging of this cable in the wind since this may cause erroneous readout fluctuations caused by earth magnetic induction currents. The presence of this effect was observed during laboratory tests with dark filters on radiometers producing small outputs, but shows equally on the models described in this report. In the installation at USASRDL, the leads are inclosed in an iron conduit to insure freedom of induction currents (see Figs. 19, 20, and 21).

The Recorder

The recorder used with the pyranometer is a standard type G, Leeds and Northrup servo-potentiometric recorder, modified by incorporating an integrator and adjustments for the calibration constant. Figure 22 shows the recorder group in the USASRDL installation, with the General Electric Demandmeters used for integral print out. Figure 23 shows the location of the span adjustment, the visual integral read-out, and the switch which actuates the Demandmeter accumulator.

The adjustment for the individual calibration constants of the sensors used is accomplished by means of a calibrated variable precision resistor to change the span (the sensitivity) of the recorder. The dial of this resistor is calibrated in units of the sensor's calibration constant, which simplifies the change of sensors. With the dial set to the constant of the individual sensor, the calibrations of the analog trace on the strip chart and the integrator read-out, described below, are maintained and need no further adjustment. The
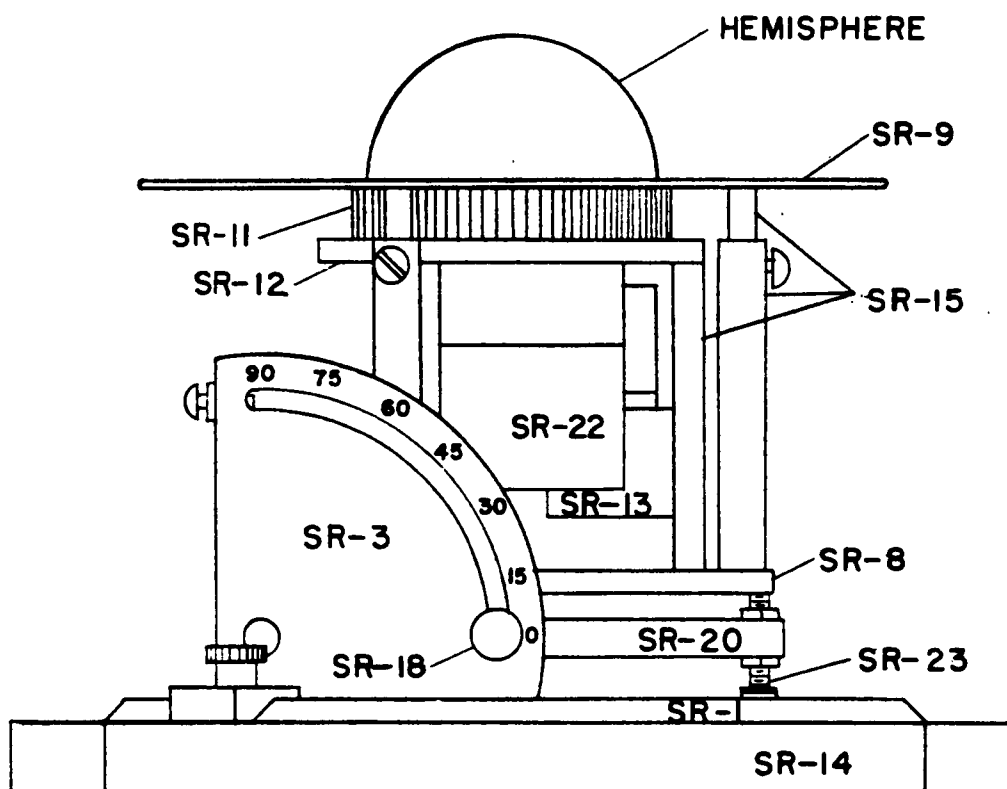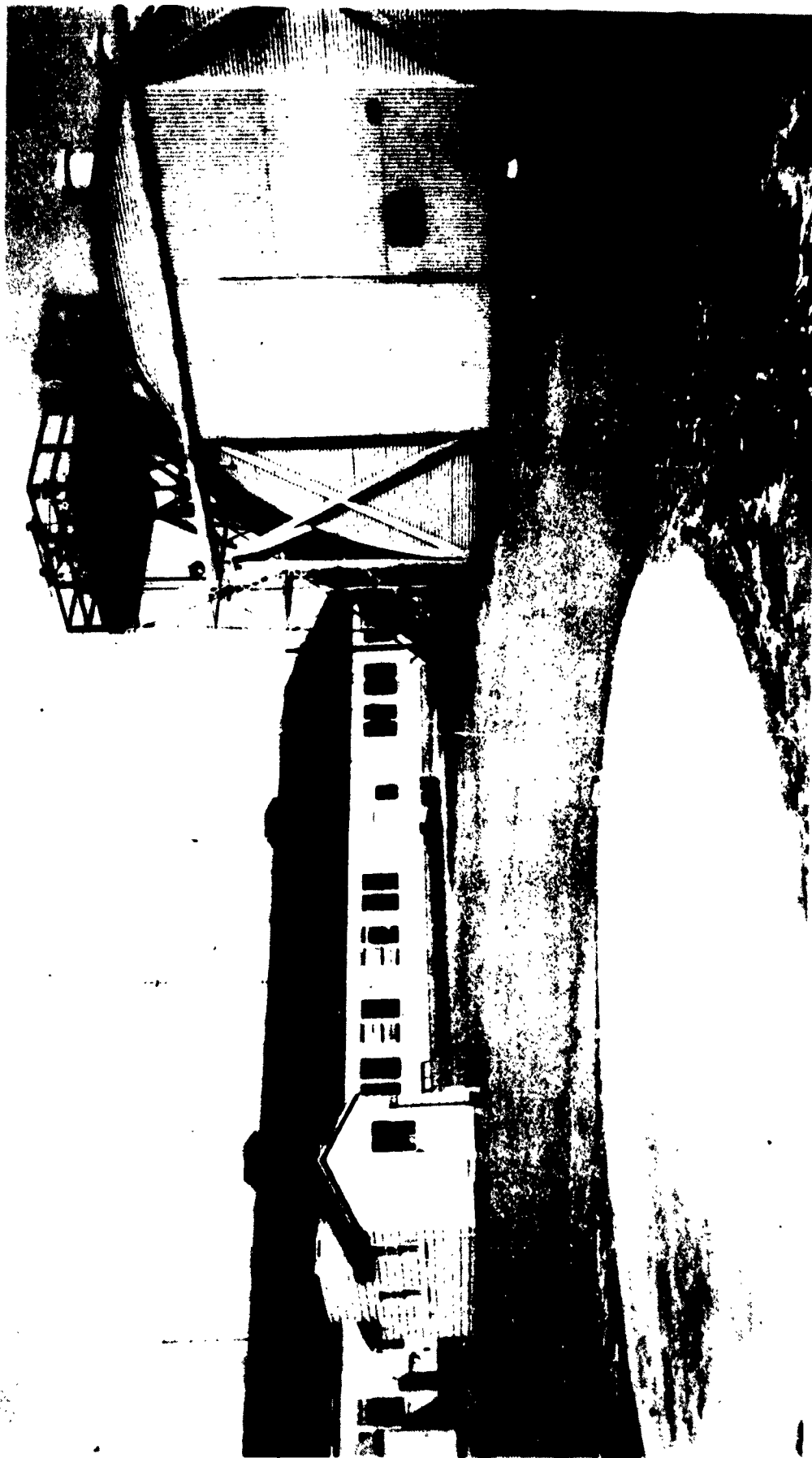
47

Fig. 18. Eppley Pyranometer Mount

48

SIGFM/EL 59-103

Fig. 19

SOLAR RADIATION INSTALLATION at USASRDL. (Devel.)
Mfr. Eppley Laboratories Inc.
Overall View. Showing Sensing Units Installed on Tower,
Integrating and Recording Instruments Located in Building
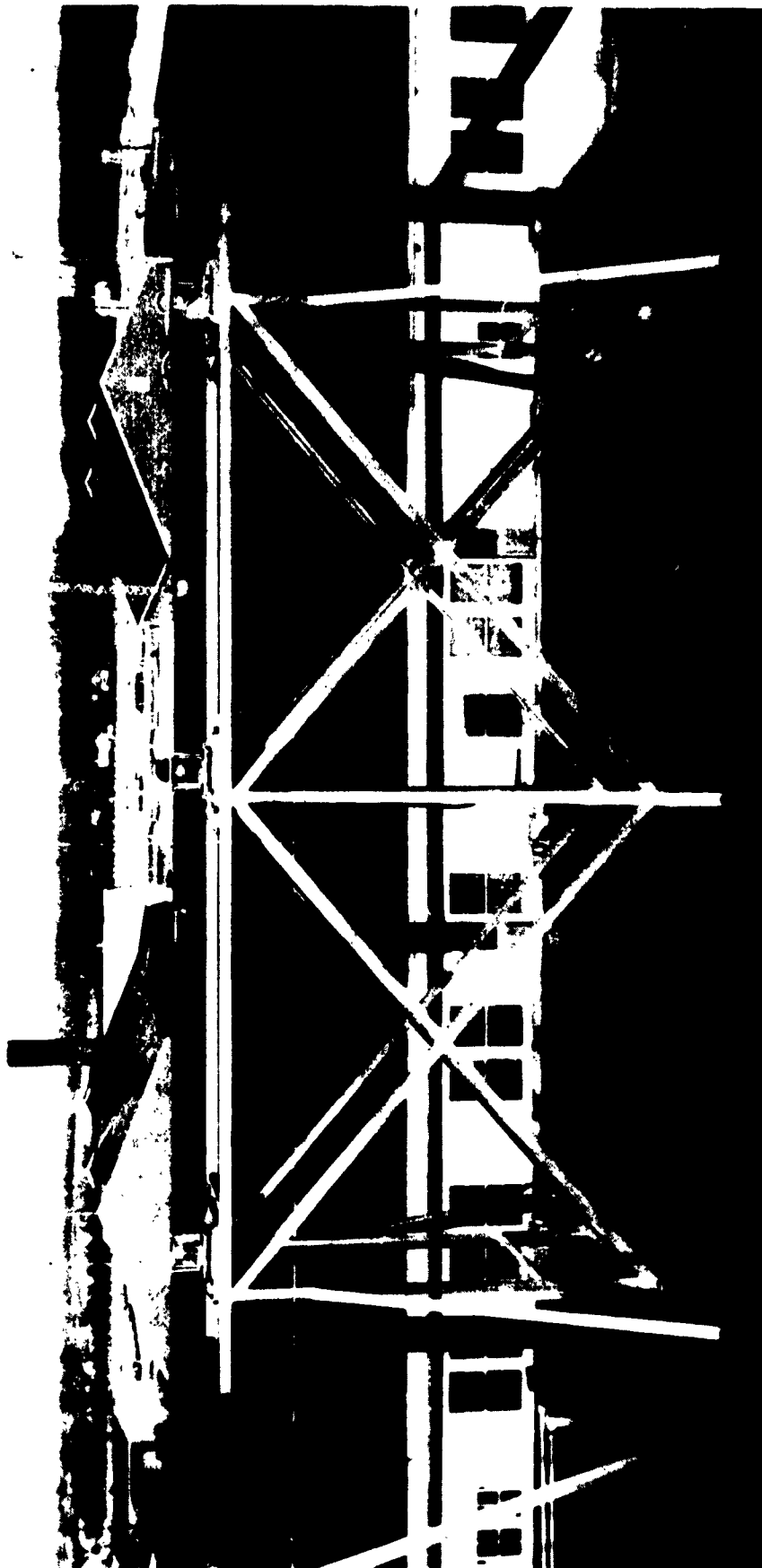21 Jan 59

FORT MONMOUTH, N. J.

U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY

-49-

Fig. 20

PYRANOMETERS, with GLASS FILTERS . (Devel.) .
Clear TYPE WG7, Very Dark Red RG8, and Yellow Orange OG1
Mfr. Eppley Laboratory, Inc.
Overall View . Showing Equipment Mounted on Tower . 21 Jan 59

SIGFM/EL-59-106

Fig. 21

FORT MONMOUTH, N. J.

PYRANOMETER, with CLEAR GLASS FILTER, TYPE W67 . (Devel.)
Mfr. Eppley Laboratories Inc.
Overall View . Showing Equipment Mounted on Tower
21 Jan 59
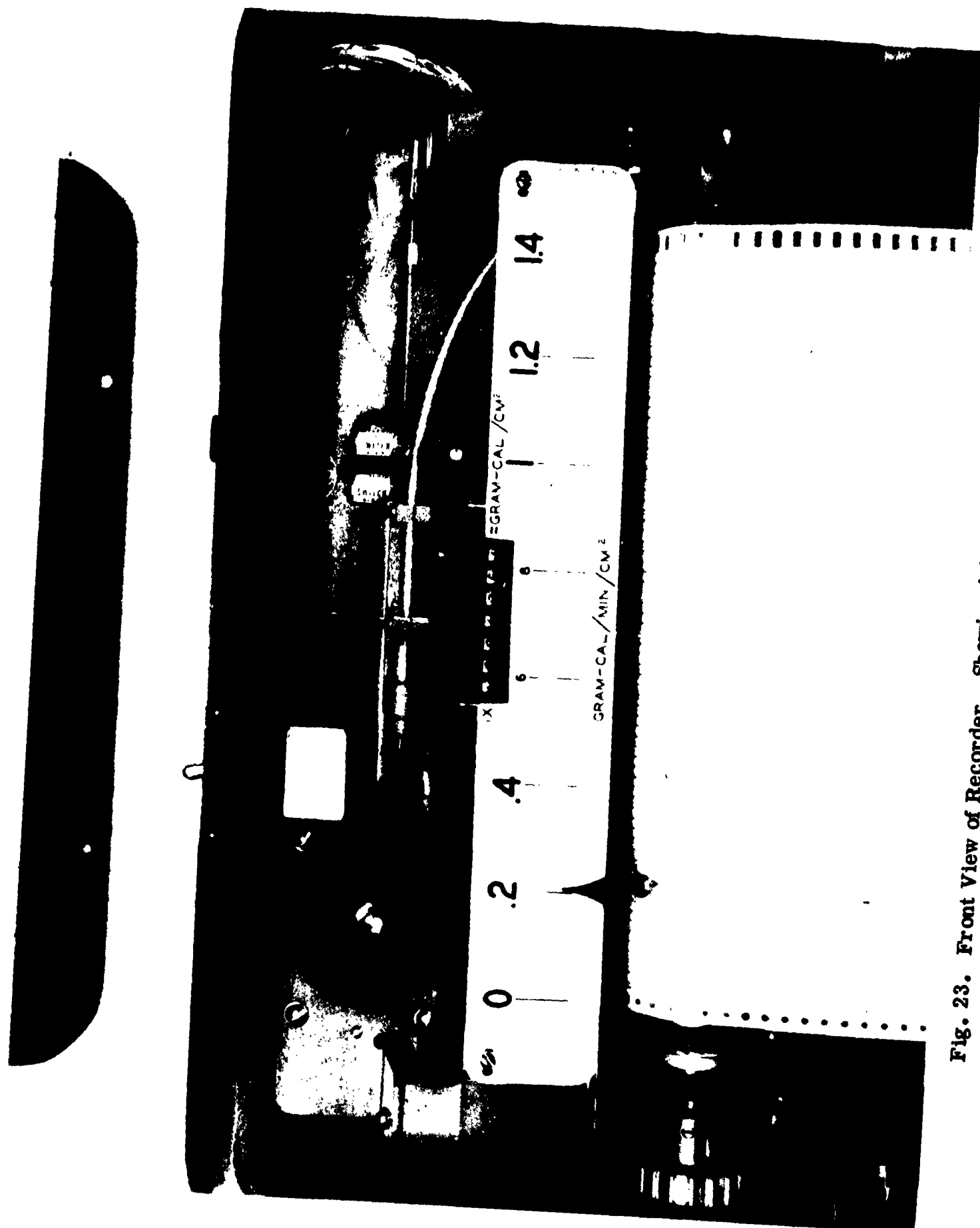
U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
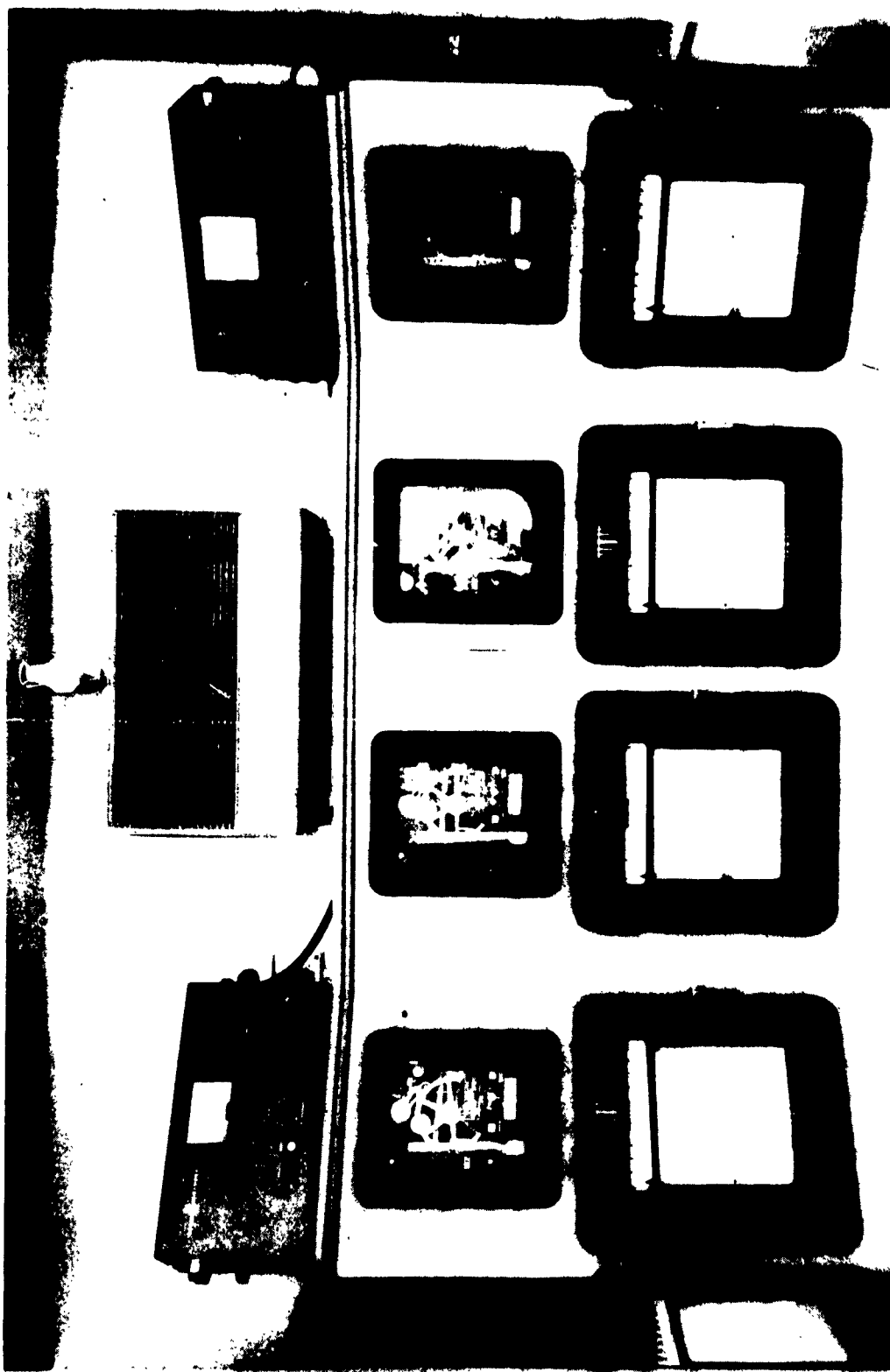
SIGFM/EL- 59-104

Fig. 22

FORT MONMOUTH. N. J.

SOLAR and SKY RADIATION RECORDING and INTEGRATING EQUIPMENT . (Devel.)

Mfr. Eppley Laboratories Inc.

Overall View . Showing Equipment

21 Jan 59

U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY

52

Fig. 23. Front View of Recorder. Showing integrated radiation counter and dial.

calibration dial covers for all recorders a "calibration constant" range from 5.0 to 10.0 millivolt per cal cm^{-2} min^{-1}, corresponding to a full-span sensitivity of the recorder of 10 to 20 millivolt on the recorders used in combination with the clear filter sensors, thus making a recording from zero to two Langleys possible.

If permanent use of a recorder in combination with a radiometer with a spectral range limited by means of filters is planned, the readout scale of the recorder may be changed to obtain maximum readability of the analog chart by expanding the scale to an appropriate value (approximately 1.8 cal cm^{-2} min^{-1} for use with the yellow filter and 1.4 cal cm^{-2} min^{-1} for use with the red filter, corresponding to a full-scale sensitivity of 9 to 18 and 7 to 14 millivolts, respectively).

The paper speed, though variable, is standard at one inch per hour.

The resolution on the chart is more than adequate for the sensor accuracy and in obtaining an easily readable chart. The inch marks printed on the 100-line strip chart thus become hour marks, which may be aligned to the time-schedule of the integrator print-out. With the one-inch-per-hour recording speed, one chart lasts about two months.

Operation, maintenance, and repair are described in the Leeds and Northrup Instruction Manual 77-10-5-1, which is supplied with every instrument. The recorder has built-in automatic standardization (against a built-in standard cell) once every 48 minutes. During standardization the integration is interrupted only shortly so the error caused does not even approach the specified allowable limit.

The recorders were fitted with ballpoint pens, allowing an uninterrupted operation over the length of one roll of recording chart. However, small impurities in the paper surface and probably dust particles in the instrument environment make pen-cleaning a necessity at shorter intervals. The pen seems to be the weakest part of the whole system. Other pen types (capillary pens) were tried, but they did not increase the reliability of the writing device. All wet processes seem to have a high amount of susceptibility to small amounts of always-present dirt; and the only means of long-time trouble-free operation is preventive maintenance (frequent cleaning) or the use of pressure-sensitive paper or similar techniques rather than a wet inking method.

Integration and Integrator

Automatic integration of the sensed radiant flux is obtained by a combination of two components: a mechanical integrator connected to the shaft of the servo potentiometer of the recorder, and a General Electric Demand-meter as a timed print-out device. The integrator used is essentially an amplitude-measuring device which presents periodically (once every second)

54

as a shaft rotation the instantaneous values of radiant flux, the amount of which is proportional to the measured amplitude, and accumulative. Since the mechanical analog to the instantaneous radiation values is formed in precise time-intervals, integration is performed through summation, with each amplitude representing the area given by the amplitude times the time-interval between two consecutive measurements.

The integrating mechanism,* Figs. 23, 24, 25a and b, and 26, is all mechanical and its inherent accuracy corresponds to the accuracy of the potentiometric device to which it is attached. The summation process is accomplished by a unidirectional clutch of the ratchet type which moves the integrator shaft in one direction.**

The shaft rotation is properly geared down, and a switching device produces an electrical impulse which at its occurrence represents a defined integral area. This conversion from the analog shaft rotation to the digital pulse seems at first to reduce the accuracy of the integration inherent in the original sampling, since in any fixed integration time-interval the pulse will have an uncertainty of plus or minus one area unit as represented by one pulse. Since, however, the integration interval is 1800 seconds (30 minutes), a $\pm 1\%$ accuracy for the integration (as specified for a continuous radiation input to the sensor of one Langley) would require only one count every 18 seconds.

The General Electric Demandmeter, chosen because of its availability, low cost, and well-proved reliability, allows 300 counts per 30-minute integration period, and is hence well suited for use as an integrator print-out device. Further, since both the mechanical integrator and the clocking mechanism of the Demandmeter are timed by the same 60 cps power source, no timing error through difference in times scales of integrator and printer is expected. To insure coordination of the two components, the printing-time instant closes a contact in the Demandmeter, and this closure is used to mark the end of any integration period on the analog strip chart. This mark is preferably adjusted to coincide with the inch marks of the recording paper.

The performance of the integrator was tested in the loop by simulating the output of the radiation sensor with a precision voltage source and a precision voltage divider, and integrating known inputs over 30-minute periods. These tests were repeated after the equipment had been in operation for approximately one year. There was no indication of performance deterioration. The only maintenance required was lubrication of the moving parts and the adjustment of one ratchet in one of the four recorders in the installation.

---

*See description of integrator in Appendix III.
**Herein lies a limitation of the integration process, since a reversal in the sign as occurs in net radiometers would not be indicated. The integrator is therefore limited in its use to the integration of incoming radiation only.
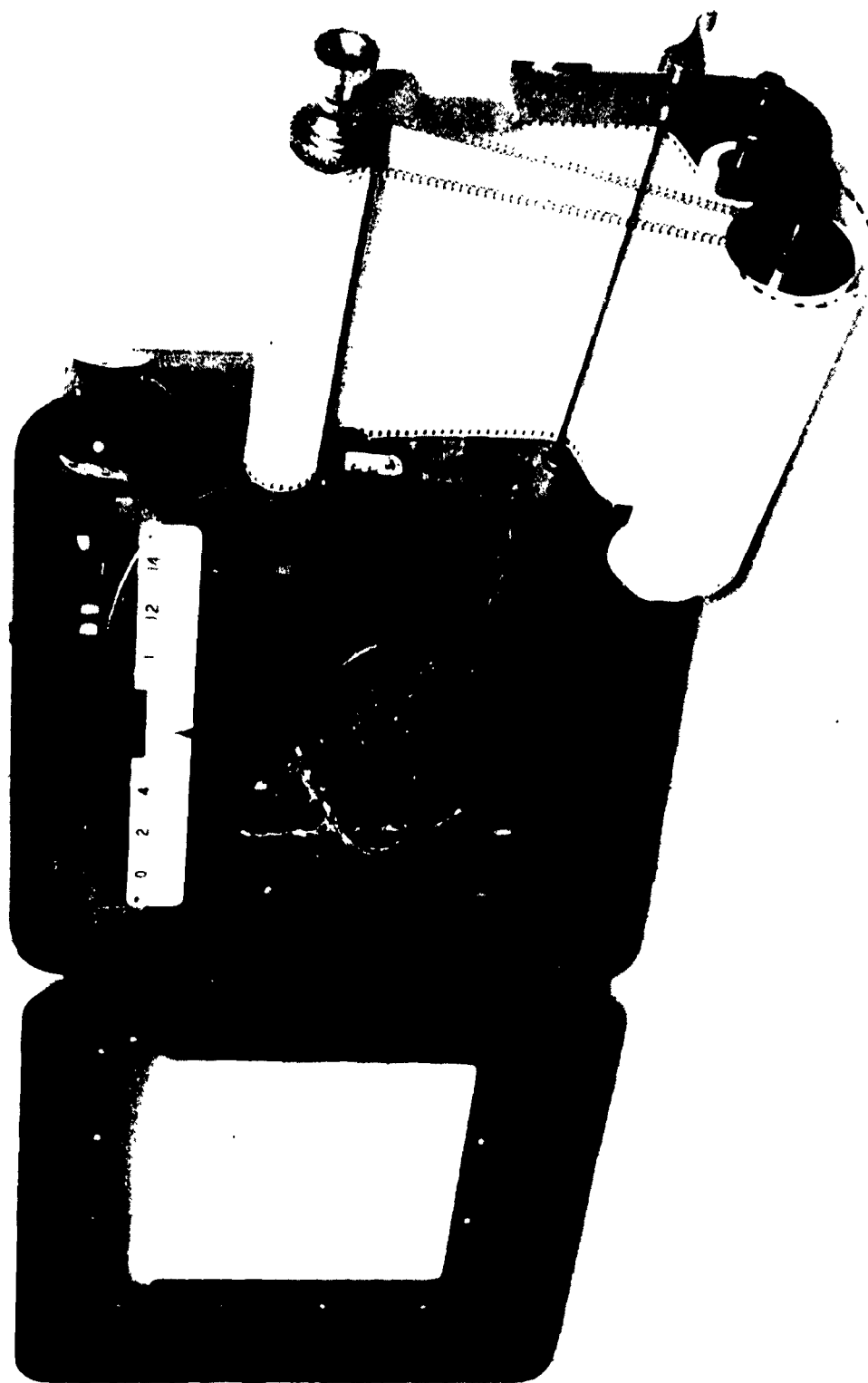
Fig. 24. Solar Radiation Recorder. Front view, with chart-drive mechanism swung out to show location of mechanical integrator.

Fig. 25a. Solar Radiation Recorder. Bottom view, showing roller of cam-operated flipper of mechanical integrator.

Fig. 25b.   Solar Radiation Recorder.   Bottom view, showing ratchet drive and
           cam-operated flipper ratchet engager of mechanical integrator.

Fig. 26. Close-up of Integrator.

Failure of the ratchet has led to erroneous integration, which was discovered only by data comparison between the read-outs of two identical sets of instruments. A performance failure of this nature may develop gradually and thus escape notice. To overcome this remote possibility of failure, regular tests of the integrator with a simulated input are advisable, especially since this test can be performed after sunset, thus leaving no gap in the continuity of observation. An improved model presently being built will incorporate convenient means for this test so that its performance will be a matter of routine, necessitating neither special gear nor experience.

Read-Out

The integral values are for half-hour intervals, printed on a paper tape, side by side with the time of day which represents the end of the integrating period. Figures 27 and 28 show an example record of the analog strip chart and the Demandmeter tape.

CONCLUSIONS

The instrumentation described shows considerable improvement over previously used instruments, and insight was obtained in many aspects of radiation-sensor design. Though much of this insight is only qualitative, it contains valuable information as to how to further improve solar-and-sky-radiation equipment. Since the preparation of the draft of this report, the response characteristic of the thermoelectric radiation sensor has yielded to quantitative analysis, and the use of analog techniques indicates a way to minimize transient errors. It is planned to publish these findings at an early date.

The results of work described in this report are reflected in the technical requirements (Appendix III), which presently forms the basis of an instrumentation procurement. Much is still.left to be done. The importance of radiation intelligence for synoptic meteorology (micro-, meso-, and macro) and for various technological aspects of the Armed Forces necessitates more data-gathering with precise and reliable instruments. Only perfect understanding of instrument performance makes proper design and use possible.
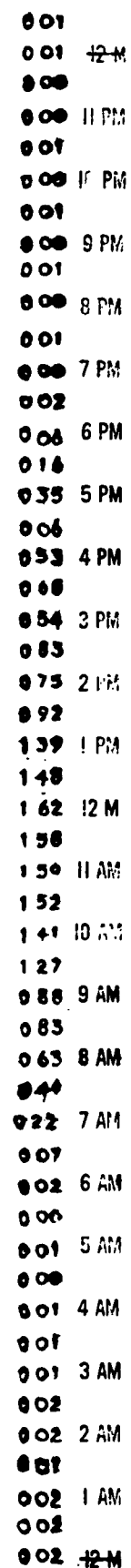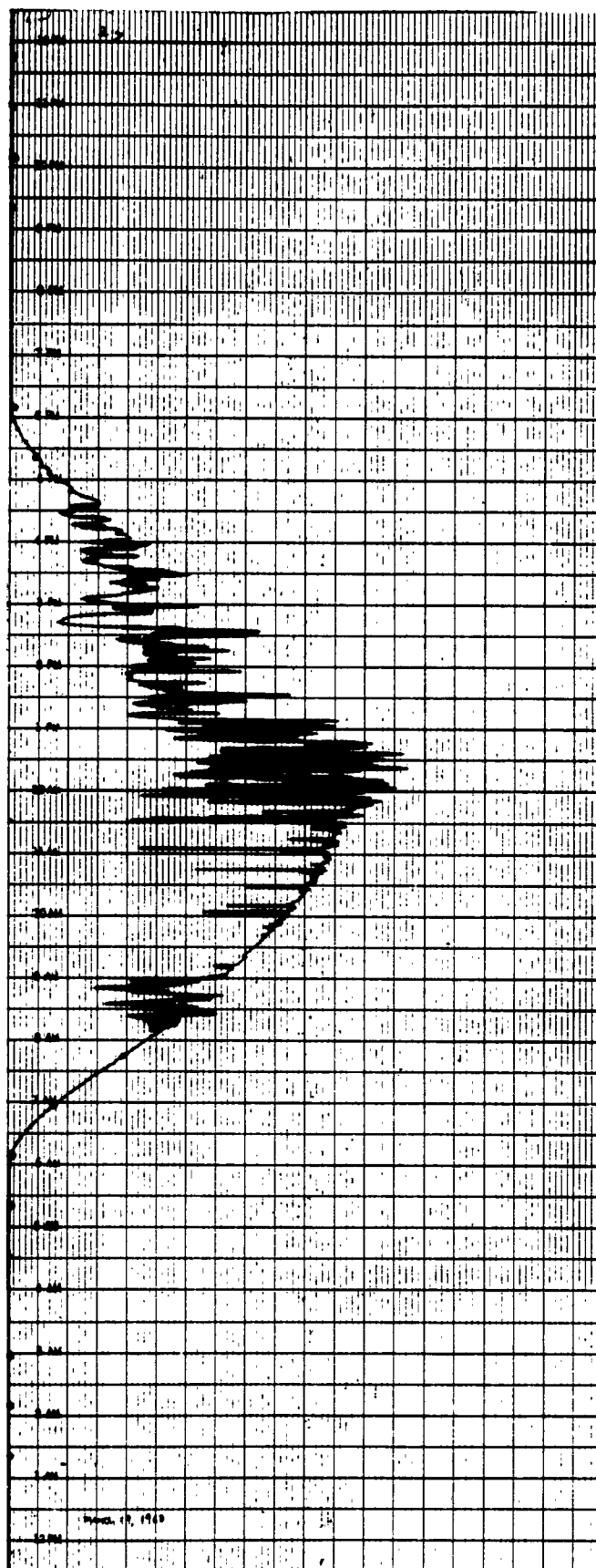
ACKNOWLEDGMENTS

Fig. 27. Sample Strip Chart Record of Solar Radiation

61

Fig. 28. Sample Printed Tape Record

REFERENCES

1. IGY Instruction Manual, Part IV, "Radiation Instruments and Measurements."

2. Clark, Layton E., "Report on the Determination of Exactness of Fit of Western Electric Type 14B Thermistor to the Equations Log R = A + B/(T+θ) and Log R = A + B/(T+θ) + CT, " USASRDL Technical Memorandum M-1951, Feb 58.

3. Clark, Layton E., "Report on the Determination of Exactness of Fit of Thermistors to the Equations Log R = A + B/(T+θ) and Log R = A + B/(T+θ) + CT, " USASRDL Technical Report 2168, Jan 61.

4. Buettner, K., and F. Albrecht, "Fur Theorie von Aktinometern and Pyranometern, " Teil I, Gerlands Betra, Geophys. 22, 13-28, 1929.

5. Fuquay, D., and K. Buettner, "Laboratory Investigations of Some Characteristics of The Eppley Pyrheliometer, " Transactions Am. Met. Soc., Vol 38, No. 1, Feb 1957.

Excerpts from Signal Corps Technical Requirements No. SCL-5336A, dd 1 Nov 56

3.1. **Description, general**. The equipment is to measure and record, at a fixed location, combined sun and sky radiation, using four sensing elements. Three of these sensing elements will measure the radiation on a plane surface at selectable elevation and azimuth angles, in the three spectral ranges of specified clear quartz, yellow glass and black glass sensing element filters, and the other sensing element, on a horizontal surface through a clear quartz envelope. The recorder is to furnish a continuous record of the radiation received by each pyrheliometer, and in addition, printed hourly and daily totals of radiation energy received by each. The equipment is to operate from any nominal 120 volts, 60 cycle per second, single phase a.c. power source. The equipment is intended primarily for use in a temperate humid climate.

3.5 **Detail requirements**

3.5.1 **Sensing units**. The sensing units shall be the standard multi-junction Eppley Laboratory pyrheliometer element, or equal, provided with the special envelopes or envelopes and filters required to give the specified spectral ranges, or a substitute therefore equally or more suitable for the purpose described in 3.1 and other paragraphs of this specification. Four separate sensing units are required.

3.5.1.1 **Pyrheliometer envelope**. The envelope (bulb) of each sensing element shall be of such a form and size that (1) there will be no appreciable error due to formation of a caustic, and (2) the combined envelope and sensing element will meet the specified performance. The spectral ranges, determined by the filter characteristics of the sensing element envelopes, or optionally, by quarts or Corning 96% silica ultraviolet transmitting glass, or equal, envelopes plus separate hemispherical filters, shall be defined by Corning glass color filters as follows: two of the four envelopes shall transmit as well and as uniformly as Corning number 9-54 96% silica ultra-violet transmitting glass, or equal, over the range 250 to 3500 millimicrons (2500 to 35,000 Angstroms); one shall transmit as well and as uniformly over the pass band 480 to 3500 millimicrons, and absorb as well below 480 milli-microns as Corning number 3-71 Novial Shade C glass, or equal, and one shall transmit as well and as uniformly over the band 900 to 3500 millimicrons, and absorb as well below 900 millimicrons as Corning No. 7-56 Heat Transmitting Red glass, or equal. In addition, the three different filters shall not dif-fer from each other in transmission in the range 2500 to 4000 millimicrons, more than do the three Corning filters mentioned herein; and each filter shall be as stable in its filter characteristics with respect to radiation exposure as the corresponding Corning filter.

3.5.1.2 The transmission of the envelopes and filters shall be uniform within ±4% over the upper hemisphere of the envelope.

3.5.1.3 The thickness of the yellow and black filters shall be suffici-ent to reduce the desired transmission to 80% or less. (The transmission

range of Corning number 9-54 glass is approximately 2500 to 40,000 Angstroms; and this specified thickness of yellow glass and black glass will make their transmission bands approximately 4800 to 35,000 Angstroms and 9000 to 35,000 Angstroms, respectively.)

3.5.1.5 If required, temperature compensation, either electrical or thermal, shall be employed to give the accuracy over the ambient temperature range specified in 3.5.7.2.

3.5.1.6 Orientation. The orientation of each pyrheliometer sensing disk shall be known within two (2) degrees. Each pyrheliometer shall be adjustable to any angle of elevation of the normal to the sensing surface, from thirty (30) degrees (sensing surface tilted sixty (60) degrees from horizontal) to ninety (90) degrees (sensing surface horizontal) and to any angle of azimuth. Scales with their indices shall be provided and shall be accurate to 0.5 degree, with scales graduated in degrees with every fifth- and fifteenth-degree mark distinguished.

3.5.2 Recording (and integrating) unit. The recording equipment shall furnish a continuous record of the radiant energy received by each pyrheliometer; and the records of the four pyrheliometers shall be clearly distinguishable. A time mark shall be made on the continuous record, at least once an hour, on the hour. The recording equipment shall also print, on tape for each pyrheliometer, hourly and daily integrated totals, for periods ending on the hour, of calories per square centimeter, along with time of the period ending. The printed values of the four pyrheliometers shall be clearly identified with the corresponding continuous record.

3.5.2.1 Periodic zero drift and calibration checks of the recorder shall be provided if necessary, and if so, the break in the continuous record shall not exceed ten seconds.

3.5.2.2 The recording equipment shall be provided with a simple adjustment for each pyrheliometer to make the scale on its continuous record read directly in calories per square centimeter per minute, and the integrating totalizer read and print correctly in calories per square centimeter.

3.5.2.3 The recording and totalizing equipment shall be capable of operating indoors at a distance up to 50 feet from the pyrheliometers.

3.5.3 Mounts. The pyrheliometer assembly shall be capable of being installed outdoors on a platform above ground.

3.5.3.1 The pyrheliometer mounts shall conform to the requirements of 3.5.1.6.

3.5.3.2 Each pyrheliometer unit shall be mounted so that the scales specified in 3.5.1.6 will indicate the orientation of the pyrheliometer to within one (1) degree in both elevation and azimuth.

3.5.3.3 The design and spacing of the mounts shall be such as to avoid shadows on any of the pyrheliometer envelopes or filters.

3.5.4 Cables. The necessary cables, cable assemblies and terminations shall be provided by the contractor for complete installation. The length of the cables shall be consistent with the requirement of 3.5.2.3.

3.5.5 Power requirements. The equipment shall be capable of operating from any nominal 120 volt, 60 cycle per second a.c. power source.

3.5.7 Over-all performance. The equipment shall operate for eight days without attention except for the cleaning of the pyrheliometer bulbs and filters.

3.5.7.1 Readings of each pyrheliometer and its recording channel shall be repeatable under constant ambient temperature and radiation conditions to within ±2% in any one-hour period over the temperature range -40°C to +40°C when oriented in any of the adjustable positions specified in 3.5.1.6.

3.5.7.2 The over-all absolute accuracy of each pyrheliometer and its recording channel, over the radiation intensity range 0.2 to 2.0 calories per square centimeter per minute, shall be within ±5% over the temperature range -40°C to +40°C when oriented in any of the adjustable positions specified in 3.5.1.6. If calibration of sensing elements varies with the angle of elevation, up to 3 calibrations for 3 regions of elevation angle may be furnished to meet the ±5% accuracy requirement.

3.5.7.3 The over-all response time shall be nc more than one minute.

Appendix II

Thermoelectric Properties of the Bismuth-Silver Thermojunction
(Reference Junction at 0°C)

$$a = -77.367 \ \mu V/°C$$
$$b = 0.02522 \ \mu V/°C^2$$
$$x = at + bt^2$$

Temperature °C	Microvolts	Temperature °C	Microvolts
-50	+3931	-15	+1166
-49	+3851	-14	+1088
-48	+3772	-13	+1010
-47	+3692	-12	+932
-46	+3612	-11	+854
-45	+3532	-10	+776
-44	+3453	-9	+698
-43	+3373	-8	+621
-42	+3294	-7	+543
-41	+3214	-6	+465
-40	+3135	-5	+387
-39	+3056	-4	+310
-38	+2976	-3	+232
-37	+2897	-2	+155
-36	+2818	-1	+77.4
-35	+2739	0	00.0
-34	+2660	+1	-77.3
-33	+2581	+2	-155
-32	+2502	+3	-232
-31	+2423	+4	-309.1
-30	+2344	+5	-386
-29	+2265	+6	-463
-28	+2186	+7	-540
-27	+2107	+8	-617
-26	+2029	+9	-694
-25	+1950	+10	-771
-24	+1871	+11	-848
-23	+1793	+12	-925
-22	+1714	+13	-1002
-21	+1636	+14	-1078
-20	+1557	+15	-1155
-19	+1479	+16	-1231
-18	+1401	+17	-1308
-17	+1323	+18	-1384
-16	+1244	+19	-1461

Appendix II (Contd.)
Thermoelectric Properties of the Bismuth-Silver Thermojunction

Temperature °C	Microvolts
+20	-1537
+21	-1614
+22	-1690
+23	-1766
+24	-1842
+25	-1918
+26	-1994
+27	-2070
+28	-2147
+29	-2222
+30	-2298
+31	-2374
+32	-2450
+33	-2526
+34	-2601
+35	-2677
+36	-2752
+37	-2828
+38	-2904
+39	-2979
+40	-3054
+41	-3130
+42	-3205
+43	-3280
+44	-3355
+45	-3430
+46	-3506
+47	-3581
+48	-3656
+49	-3730
+50	-3805

Appendix III

Signal Corps Technical Requirements No. SCL-5814, "Solar and Sky Radiation
Measuring and Recording Equipment," dd 18 October 1960

As mentioned in the body of this report, Technical Requirements SCL-
5336A were modified in mutual agreement between USASRDL and The Eppley
Laboratory in some details, mostly of a technical nature. These modifi-
cations as well as findings of careful study of the models obtained under
contract are reflected in Technical Requirements SCL-5814, which presently
forms the basis of another contractual effort. Since this specification
presents the present state of the science, it is included in this report
in toto.

SIGNAL CORPS
TECHNICAL   SCL-5814
REQUIREMENTS   18 October 1960

SOLAR AND SKY RADIATION MEASURING AND RECORDING EQUIPMENT

1. SCOPE

1.1 This specification covers the requirements for a ground based
equipment for sensing, measuring, recording and integrating the radiation
from the sun and the sky in toto and/or in selected spectral bands as
received on a plane surface selectively oriented.

1.2 The equipment covered by this specification consists of the fol-
lowing components:

    (a) A pyranometer as the sensing unit for the radiation received
        on a plane surface. (See 3.3)

    (b) A mount for supporting the pyranometer and having selective
        orientation features. (See 3.4)

    (c) A recording unit with strip chart, integrator, print out
        and related devices. (See 3.5)

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect on date of invi-
tation for bids, form a part of this specification:

SPECIFICATIONS

MILITARY

MIL-F-14072   Finishes for Ground Signal Equipment.

SIGNAL CORPS

SCL-6019   Type "PT" Bayonet Lock, Miniature Connectors
SCL-6200   Parts, Materials, and Processes Used in
               Ground Signal Equipment.

(Copies of the documents required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer. Both the title and identifying number or symbol should be stipulated when requesting copies.)

2.2 Other publications. The following documents form a part of this specification. Unless otherwise indicated, the issue in effect on date of invitation for bid shall apply.

AMERICAN TRUCKING ASSOCIATION

National Motor Freight Classification

(Application for copies should be addressed to the American Trucking Association, 1424 16th Street, N.W., Washington 6, D. C.)

ASSOCIATION OF AMERICAN RAILROADS

Uniform Freight Classification

(Application for copies should be addressed to the Association of American Railroads, 202 Chicago Union Station, Chicago 6, Illinois.)

3. REQUIREMENTS

3.1 Functional description. The equipment covered by this specification shall serve to:

(a) Sense, measure and record the instantaneous values of solar and sky radiation as received on a plane surface, oriented according to needs in toto or in a selected spectral band, in analog form.

(b) Integrate the sensed instantaneous radiation values over sequential equal adjustable time intervals.

(c) Print the integral values.

(d) Provide means for remote registration of analog and integral intelligence if so desired.

3.1.1 The equipment shall operate from a 120 volt, 60 cps voltage source. (See 3.7)

3.1.2 The equipment shall operate for 10 days without any attention other than the cleaning of optical parts of the pyranometer.

3.1.3 The equipment shall operate for 30 days without any maintenance other than indicated in 3.1.2 and the changing of recorder stripchart and ink, if any.

3.1.4 The accuracy requirements shall be maintained over at least 3 months without any adjustment other than indicated by the monthly calibration checks, using the built-in check features.

3.1.5 The equipment shall meet the performance requirements of this specification for at least one year, 50 percent duty cycle operation, or 5000 hours continuous operation with no other attention than indicated in 3.1.2 through 3.1.4 and replacement and maintenance which can be performed on site and which will not interfere with a 50 percent duty cycle.

3.2 Design plan. Prior to fabrication of equipment, the contractor shall submit a design plan, together with all engineering calculations and complete layout drawings, in sufficient detail to permit evaluation of the suitability of design for fabrication and use, to the contracting officer's technical representative for evaluation and approval.

3.3 Pyranometer. The pyranometer shall be of compact construction and shall contain all components necessary to sense the radiation to be measured and shall provide an output which is an electrical analog of the sensed radiation. The pyranometer shall include, but not necessarily be limited to, the following:

    (a) Flat sensing surface.

    (b) Thermopile with sink or reference.

    (c) Circuitry for compensation for the temperature environment influences and if necessary for linearization of the output.

    (d) Housing with provisions for:

        (1) Small inner hemisphere.

        (2) Exchangeable outer filter hemispheres.

        (3) Radiation shield.

    (e) Means for indicating the level position of the sensing surface.

    (f) Means to keep all internal parts of the pyranometer dry.

    (g) Means to connect the pyranometer unit to the adjustable mount.

    (h) Means to level the sensing unit with respect to the mount.

    (i) Means to connect the output of the pyranometer to the recording and integrating unit and test apparatus when needed.

3.3.1 Sensing surface. The pyranometer shall have a flat sensing surface which is uniform "gray," of a high degree, over the spectral range from 2500 Å (Angstroms) to 6 microns. The absorbtion shall not be less than 95 percent over the spectral range and shall not vary more than 1 percent over the whole specified range. Parson's black, or equal, shall be used to obtain the absorbing sensing surface specified.

3.3.2 <u>Spectral range of the pyranometer</u>. The spectral range of the pyranometer shall be determined by:

    (a) The optical properties of the inner hemisphere.

    (b) The optical properties of the combination of inner hemisphere and the exchangeable outer hemispheres.

3.3.2.1 <u>Optical properties of inner hemisphere</u>. The optical properties of the inner hemisphere shall be equal to, or better than, that of clear WG7 glass (thickness of 3 mm with optical surface) as manufactured by Schott und Genossen, Glaswerke, Mainz, Western Germany. The inner hemisphere shall be of such dimensions that the requirements of this specification will be met. The diameter of the inner hemisphere and the diameter of the sensing surface shall be chosen properly to avoid sensing errors through caustic.

3.3.2.2 <u>Optical properties of outer hemisphere</u>. The outer hemisphere, removable and exchangeable without need for demounting the pyranometer, determines the spectral band of the pyranometer. Four (4) spectral ranges shall be provided by properly chosen material for the outer filter hemispheres. The spectral bands shall be equal to the combinations of the following filters with the inner hemisphere:

    (a) Clear glass WG7.

    (b) Yellow orange glass OG1.

    (c) Pure red glass RG2.

    (d) Deep red glass RG8.

All optical qualities shall be identical with the glass melts as manufactured by Schott and Genossen Glaswerke, Mainz, West Germany. The outer filter hemispheres shall be manufactured in quality which warrants optical properties over the whole hemisphere uniform to at least 2 percent. The design of these hemispheres and their fittings shall comply with the requirements of this specification. The design shall avoid errors caused by the effects of caustic. The thickness of the outer hemispheres, and the tolerances allowed, shall be equal to those manufactured by The Eppley Laboratory, Newport, Rhode Island, under the following types:

        S-5803 for WG7 glass
        S-5805 for OG1 glass
        S-5806 for RG2 glass
        S-5807 for RG8 glass

3.3.2.3 <u>Mechanical properties of inner and outer hemispheres</u>. The inner hemisphere shall serve as a protective cover for the sensing surface and shall seal the sensing surface of the pyranometer effectively from the environment. The seal shall be effective over the specified environmental range and the transfer of air between inside and outside shall not exceed one (1) microliter/liter/hour for a pressure differential of 500 millibars between inside and environmental pressure. The outer filter hemisphere

shall be of such design as to insure ease of mounting and exchange. The mounting provisions shall allow use of the pyranometer with the inner hemisphere alone. No duct allowing air exchange shall exist between the air volume formed by the space between inner and outer hemisphere and the interior of the pyranometer. To avoid condensation on the inside of the outer filter, air ducts shall be provided which allow communicative air exchange between the air volume formed by the space between the inner and outer hemispheres and the environment. Complete sealing of the outer hemisphere may be an alternate solution if the contractor finds means to avoid condensation on the inside of the outer filter hemispheres.

3.3.3 <u>Thermopile transducer</u>. The temperature rise of the sensing surface, caused by the received radiation, shall be sensed by a thermopile transducer preferably using bismuth silver junctions used in the thermopile receiver manufactured by the Eppley Laboratory, type No. S-5801, or equal. The contractor shall decide whether to use a heat sink as reference, as in the S-5801, or a white or reflective coated reference.

3.3.4 <u>Environmental influence</u>. The calibration of the pyranometer shall be invariant to changes in the temperature environment as specified in 3.3.10.2. Effects of these temperature environments on the output shall not exceed ±0.5 percent over the entire environmental temperature range under steady state conditions. This may be accomplished by means of a compensating circuit as presently used in type S-5802 pyranometer manufactured by the Eppley Laboratory. This compensating circuit shall consist of a passive network having one or more temperature sensing members, if necessary.

3.3.5 <u>Calibration characteristic</u>. The pyranometer shall provide an electrical output of at least 5 millivolts for a radiation received at the sensing surface of one (1) calorie/cm^2/minute. The output of the pyranometer shall be a true analog proportional to the sensed radiation. The output shall be invariant to changes in temperature environment and to all operational orientations.

3.3.6 <u>Linearity</u>. The output of the pyranometer shall be linear to ±1 percent for the full input range from zero (0) to two (2) cal/cm^2/minute.

3.3.7 <u>Precision</u>. The output of the pyranometer shall repeat itself within ±1 percent if repeated after a three month use, and within ±1.5 percent after a one (1) year use and meeting the linearity requirement of 3.3.6.

3.3.8 <u>Accuracy</u>. The accuracy of the calibration (radiation values obtained by using the calibration constant of the manufacturer) shall be at least ±1.5 percent for normal ±10 degree radiation incidence.

3.3.9 <u>Cosine law</u>. The cosine law shall be followed to the extent that the accuracy requirement stated in 3.3.8 is maintained for all angles of incidence (normal incidence 90°) from 90 to 20 degrees and with a gradual decrease of accuracy for smaller angles; however, not exceeding ±2 percent between 20 and 10 degrees and not exceeding ±4 percent for angles between 10 and 5 degrees.

3.3.10 <u>Transient behavior</u>. The transient behavior of the pyranometer is due to the lag characteristics of the temperature sensitive components of the pyranometer and the finite heat transport through its constructional elements.

This transient behavior will cause erroneous outputs under certain conditions of changing radiation flux to be sensed and/or erroneous outputs due to changes in the temperature environment. These errors may be described by specifying the response time of the pyranometer to. changes in sensed radiation and by specifying the maximum error which may be allowed when sudden changes in the environment occur.

3.3.10.1 <u>Pyranometer response to changes in radiation</u>. Due to the thermometric nature of the radiation sensor and thermopile transducer, the response of the pyranometer to radiation flux changes is sufficiently described by a first order system and hence the response characteristic may be specified by the time constant of such a system. The $1/e$ time of response to a step function change in radiation flux sensed shall not exceed 10 seconds for any conceivable step and at any specified operational environmental temperatures.

3.3.10.2 <u>Pyranometer response to changes in environmental temperature.</u> Since the output of the pyranometer is based on the temperature difference between the sensing surface and reference junctions of the thermopile transducer, both measuring and reference junctions of the thermopile must be at precisely the same temperature at all times with no radiation present or must be influenced in precisely the same manner by environmental temperature changes if no errors are introduced by the existence of a time derivative of the environmental temperature. Based on actual performance data of presently available pyranometers, the detrimental influence of changes in environmental temperature shall not exceed the equivalent of $+0.01$ cal/cm^2/min over-riding tue other specified accuracy requirements at any time and for any temperature rise conceivable. This requirement shall be considered met if a temperature change of $+20^{\circ}$C amplitude at a rate of not less than $+3^{\circ}$C/minute will at no time cause a change in output of the pyranometer exceeding the equivalent of $+0.015$ calories/cm^2/min. This requirement shall be met for the pyranometer with the inner hemisphere alone, as well as all specified outer filter hemispheres, for any radiation flux between zero and 1 cal/cm^2/min.

3.3.11 <u>Sealing</u>. The sensing and compensating elements of the pyranometer shall be housed in a hermetically sealed container (see 3.3.2.3). The efficiency of the sealing shall be such that the leakage measured with the inner hemisphere in place shall not exceed one microliter/liter/hour for a pressure differential between inner and outer environment of 500 millibars. To insure a dry inner atmosphere, means shall be provided to sorb the amount of water vapor which may be present in the atmosphere during the sealing of the pyranometer, and which may penetrate to the inside through the leaks allowed by this specification. This water vapor sorbing means shall consist of a cartridge of dessicant inserted directly into the main body of the pyranometer housing. The cartridge shall be removable without dismantling the pyranometer for "check up" and preventive maintenance.

3.3.12 <u>Output terminals</u>. The output of the pyranometer shall be represented by a female receptacle forming a hermetical seal with the pyranometer housing. The receptacle shall conform with class C, hermetically sealed connectors as specified in SCL-6019 and shall provide electrical connection to the temperature compensated linearized output of the pyranometer, the output of the thermopile directly and to the mass of the pyranometer housing. Provisions shall be made to allow sufficient space under the receptacle to connect the measuring cable without difficulty or without dismantling the pyranometer support or mount.

3.3.13 __Radiation shield.__ The pyranometer shall feature a radiation shield effectively coated with white paint. It shall be adjustable and removable for periodic cleaning and adequately designed to:

(a) Prevent the pyranometer from sensing radiation originated in areas not to be sensed.

(b) Avoid heating of the pyranometer enclosure or parts of the support which can heat the pyranometer by means of heat conduction to a temperature significantly different from the temperature of the air volume under the inner hemisphere.

3.3.14 __Leveling means.__ A bubble level indicator oriented level with the sensing surface of the pyranometer and means of leveling the pyranometer in respect to the mount shall be provided. The sensitivity of the bubble level shall be at least ± 0.25 degree.

3.3.15 __Mounting provisions.__ Means to mount the pyranometer to the azimuth and elevation stand (mount) shall be provided. These means shall allow ease of mounting of the pyranometer, with all its components, in a solid and substantial way to the mount described in 3.4 with only standard tools.

3.4 __The mount (also called azimuth elevation stand).__ The mount shall be of solid construction and shall contain all parts necessary to insure ease of alignment adjustment, and connection of the pyranometer. It shall include means for:

(a) Allowing connection of the pyranometer to its mounting platform.

(b) Orienting the pyranometer in all positions from 0 to 95 degrees in elevation and from 0 to 360 degrees in azimuth.

(c) Clamping elevation and azimuth adjustments in place without the use of tools.

(d) Leveling the mount on its support.

(e) Indicating the level position of the mount.

(f) Initially orienting the mount on its support in the true north position with a simple sighting device aligned with the zero marker of the azimuth scale.

3.4.1 __Orientation of mount.__ The orientation of the mount shall be manually adjustable in azimuth and elevation, without the use of tools, by means of properly designed clamping devices. The clamping devices shall not shift during tightening.

3.4.2 __Scales for azimuth and elevation.__ The mount shall feature engraved scales for azimuth and elevation, accurate and readable to at least ± 0.5 degree, with numerical identifications at least every 10 degrees. The marking for the 5-degree interval shall be larger than the markings for the 1-degree intervals for ease of identification.

3.4.3 <u>Sighting device</u>. Means shall be provided to allow orientation of the azimuth "zero" with an accuracy of not less than ±0.5 degree with respect to a landmark.

3.4.4 <u>Leveling indicator</u>. Means shall be provided to indicate the level position of the azimuth orientation of the mount. This means shall be a bubble level, with a sensitivity of at least ±0.25 degree mounted on the rotating part of the azimuth orientation member.

3.4.5 <u>Mechanical construction of the mount</u>. The mechanical design of the mount shall be similar to the "Azimuth Elevation Stand for Pyranometer," type S-5810, manufactured by the Eppley Laboratory, Newport, Rhode Island, and shall meet the requirements of this specification.

3.5 <u>Recording and integrating unit</u>. The recording and integrating unit shall be of compact design for ease of transport, installation, operation, and maintenance. The unit shall include, but not be limited to, the following:

(a) Case.

(b) Servo-potentiometer for the conversion of the pyranometer output to a movement providing a permanent analog record.

(c) Stripchart assembly.

(d) Integrator.

(e) Means to print the integrator output values in numerical form on the stripchart.

(f) Provisions for adding telemetering circuitry for the analog and the integrator outputs when needed.

(g) Timing device to insure equal integrating intervals.

(h) Built-in Zener reference voltage source for the servo-potentiometer, and for periodic accuracy checks on the potentiometer and integrator.

(i) All power supplies and circuitry to allow continuous and satisfactory operation over extended periods of time in the specified environments.

3.5.1 <u>Recording unit</u>. The recording unit with its operational components shall accomplish the following:

(a) Convert the output of the pyranometer to an analog record.

(b) Convert the output of the pyranometer to time integrals of adjustable integration time, repeat this operation over and over for a selected time span and print the integrals in digital form on the analog record identifying the part of the analog recording corresponding to the integral print-out.

75

(c) Provide shaft positions of sufficient torque capability to add coding devices if data transmission should be required.

(d) Provide means to time the sequential integrations, the print-out and the start and stop of the operation of the equipment.

All components needed to accomplish the functions of the recorder and integrator unit shall be in one single unit, packaged to provide ease of operation, maintenance, adjustment, built in performance checks, and repair. The unit shall utilize the most up to date components, with emphasis on solid state components wherever possible in power supplies, amplifiers, servos, integrators, and supplementary circuits.

3.5.1.1 Recording potentiometer. The recording potentiometer shall form an independent part of the recording and integrating package, sharing with the integrator power supply, Zener reference, timing device and strip-chart.

3.5.1.2 Potentiometer voltage source. The voltage for the potentiometer shall be supplied from a Zener diode circuit with an accuracy and long time stability requiring no additional standardization against any other reference voltage over a period of at least six (6) months and under the specified environmental operating conditions. The accuracy of the Zener reference shall be at least one part in one thousand (10^{-3}). The Zener reference voltage may also be used for supplying the reference voltages needed for the integrating device and for internal calibration checks.

3.5.1.3 Measuring range. The potentiometer shall cover millivolt ranges equivalent to one (1) and two (2) calories/cm^2/minute. The millivolt ranges shall be manually adjustable to at least ± 30 percent of the nominal mv/(cal/cm^2/minute) value to allow "dialing" of the pyranometer constants which vary from sensor to sensor. The adjustment shall have locking features preventing an accidental "slip" of the set value and shall bear a scale accurate to ± 0.3 percent of the nominal value of the pyranometer calibration constant. The scale may read either directly in "calibration constants," mv/(cal/cm^2/min), or in digits coordinated by a chart, unseparably mounted inside the recorder, to the calibration constants.

3.5.1.4 Precision. The precision, defined as the ability of the recording potentiometer to repeat a readout for an unchanged input, shall be at least ± 0.5 percent of the full span over the whole range of operating environments.

3.5.1.5 Sensitivity. The sensitivity of the recording potentiometer, defined as the smallest change in input to cause a notable change on the record, shall be equivalent to ± 0.25 percent of full scale.

3.5.1.6 Accuracy. The accuracy of the recording potentiometer shall, under steady state conditions, be within ± 1 percent of full span value measured with millivolt inputs known to be at least 0.1 percent accurate.

3.5.1.7 Linearity. The linearity of the recording potentiometer shall be such that the accuracy requirement of 3.5.1.6 will be met.

3.5.1.8 <u>Zero drift</u>. The total zero drift, including thermoexpansion and mechanical linkage, shall not be more than ± 0.5 percent of full scale under any operational conditions and at all times.

3.5.1.9 <u>Response characteristics</u>. The recording potentiometer shall have a bandwidth of at least 0 to 0.3 cps with no attenuation at any point within the band exceeding the other accuracy requirements.

3.5.1.10 <u>Record</u>. The record provided shall be of the **strip-chart type** and shall provide the following permanent information on a strip-chart not more than 6 inches in total width and not more than 4.5 inches nor less than 3.5 inches in usable width.

(a) An anlog presentation of the sensed radiation in units of $cal/cm^2/min$ with a total span of two (2) $cal/cm^2/min$ and means to change the full range to 1 $cal/cm^2/min$.

(b) Time marks, indicating the integrating periods on the strip-chart, corresponding to the time axis of the analog record.

(c) A digital print-out of the integral values **unambiguously** coordinated to the interval time marks.

(c) A time mark to denote the time of the day at least once during the daily recording cycle. This mark shall coincide with one of the integrating marks and shall preferably mark the noon hour.

3.5.1.11 <u>Strip-chart speed</u>. The strip-chart speed shall be one inch per hour with provisions to change the recording speed to 0.5 inch per hour and to 2 inches per hour. This change of speed may be accomplished by the changing of gear drives, in which case the gears may be stored, by suitable means, inside the recording unit.

3.5.1.12 <u>Type of recording</u>. The permanent record shall be obtained preferably by a "non-ink" type process. The process chosen shall allow at least a 10 day continuous recording without needs for changing styli, ink, etc. The recording process shall further allow "on-off" operation of the recorder with up to 16 hours "off" time without the need of manual adjustment or maintenance. The recording process used shall be chosen by the contractor pending approval by the contracting officer's technical representative.

3.5.1.13 <u>Recorder measuring circuit and pen drive</u>. The recorder measuring and driving circuit shall be a closed loop servo type potentiometer utilizing transistorized circuitry wherever a solid state device is equal to, or better than, vacuum tubes and its over-all operation, including the analog permanent record on the strip-chart, shall be independent of environmental influences over the whole operational environmental range specified for the recording unit.

3.5.2 <u>Integrator</u>. The integrator shall be of the electro-mechanical closed loop servo type similar to model 328 integrator as manufactured by

77

Computer Sciences, Inc., Westbury, N. Y., a subsidiary of Telecomputing Corporation of Los Angeles, California. The integrator shall continuously integrate the instantaneous output values of the pyranometer over sequential, equal, adjustable periods of time. The integrator shall be placed inside the recorder-integrator package and shall operate independently from the potentiometer circuitry contained in the same package. This independence shall preclude that failure of either integrator or potentiometer will not influence the operational performance of the Zener references, timing devices and built-in operational check features.

3.5.2.1 <u>Integrator input range</u>. The integrator shall be capable of integrating the output of the pyranometer. Provisions shall be made to adjust for the calibration constant of the pyranometer which may vary ±30 percent around a nominal value. The input adjustment shall have a calibrated scale allowing for direct setting of the calibration constant to an accuracy of at least ±0.2 percent and shall have locking features to prevent accidental slip when once set.

3.5.2.2 <u>Integrator time intervals</u>. The integrator shall allow the choice of at least three (3) sequential, equal, selectable time intervals of 15, 30, and 60 minutes. The timing shall be derived from a built-in timing device which serves the whole recorder-integrator package. The time needed for reset shall cause no decrease in the accuracy specified.

3.5.2.3 <u>Accuracy of timing</u>. The accuracy of the timing shall be identical with the accuracy of the 60 cps power source used for the operation of the equipment.

3.5.2.4 <u>Precision of integrator</u>. The integrator shall have a precision of at least ±1 percent for an input equivalent to the calibration constant, $mv/(cal/cm^2/min)$, of the pyranometer, with the range adjustment set to this value and for any integration period exceeding 15 minutes.

3.5.2.5 <u>Accuracy of integrator</u>. The accuracy of the integrator shall be ±1 percent for an input equal to the calibration constant of the pyranometer and an integrating period of one (1) hour. This accuracy requirement shall hold over the operational environmental range during at least one month's operation, with 50 percent duty cycle operation, without need for adjustment. The specified accuracy shall be maintained, with monthly adjustments by means of built-in features, for the period of at least one (1) year, 50 percent duty cycle operation, or 5000 hours of continuous operation without maintenance other than monthly calibration adjustments and replacement of tubes or transistors, charts and inking devices, if any.

3.5.2.6 <u>Linearity of integrator</u>. The integrator shall have a linearity such that the requirements for precision and accuracy are met over the whole operating range.

3.5.2.7 <u>Response characteristic of integrator</u>. The integrator shall be capable of handling data inputs of at least 0 to 0.3 cps bandwidths without exceeding the accuracy requirements of this specification.

3.5.2.8 <u>Output of integrator</u>. The printout of the integrator shall be numerical and shall form, together with time marks indicating the integrating

78

time interval, part of the permanent record on the strip-chart. The printing device shall be of simple design similar, or equal, to the type manufactured by Elmeg Co., Santa Monica, California, with automatic reset after each print-out. The print-out units shall be cal/cm²/min and the number of digital places printed shall be adequate for the accuracy requirements placed on the integrator. The output of the integrator shall provide means to add, if so required, a coding device for telemetering the values of the integrals, together with time marking identifying the integrating time period.

3.5.2.9 <u>Built-in calibration feature</u>. A circuit shall be provided which will allow the placing of a voltage, equivalent to approximately the pyrano-meter calibration constant, on the input of the integrator, as well as the recording potentiometer, to test the analog record as well as the one (1) hour integral. The results of this check shall form part of the strip-chart record-ing. Means, independent of the means for range adjustment, shall allow cor-rection for slight deviations of the equipment calibration. This adjustment shall be of such a nature that no slippage can occur accidentally during nor-mal operation of the equipment.

3.5.2.10 <u>Supporting circuitry of the recording and integrating unit</u>. The recording and integrating package shall contain all circuitry needed to obtain the specified performance. This shall include circuitry for:

       (a) The start and stop of the equipment at preselected times with one start and one stop within each 24-hour period and capable of being set to any full hour.

       (b) Selection of the integrating period.

       (c) Switching circuitry for the built-in check out.

       (d) Activation of the time markers.

       (e) Activation of the integrator print out.

       (f) The power supply.

       (g) The reference sources.

       (h) Test points throughout the recording and integrating units to allow performance testing during maintenance and trouble-shooting periods.

All the supporting circuitry shall be constructed in accordance with the requirements of this specification.

3.6 <u>Cables and accessories</u>.

       (a) The pyranometer with the recording and integrating unit.

       (b) The recording and integrating unit with the power source.

All cables shall have insulation capable of withstanding the storage, flexing and exposure conditions likely to be encountered during specified operating

and non-operating conditions. The cable shall be provided with connectors to fit the pyranometer and the recording and integrating unit. The cable connectors shall be of the hermetically sealed type, class C as specified in Specification SCL-6019. The length of the cable shall be 100 feet and the over-all performance of the equipment shall be measured with the cable in the circuit.

3.6.1.2 **Power cable.** The power cable shall be 10 feet long and equipped with a suitable plug.

3.6.1.3 **Protective caps.** All cable connectors shall be protected by protective caps when not in use.

3.6.2 **Accessories.** The accessories shall serve to allow correct installation, operation, maintenance and repair without the need for parts which must be replaced under operational conditions specified for one year, 50 percent duty cycle operation. The accessories shall consist of, but not be limited to, the following:

(a) Strip-chart supply for one year, 50 percent duty cycle operation.

(b) Ink (if any).

(c) Pens or styli.

(d) Means for cleaning.

(e) Replacement tubes or transistors as necessary for replacement during a one year, 50 percent duty cycle operation.

(f) A case for keeping the outer filter hemispheres safe and protected against mechanical damage.

3.7 **Input power.** The equipment shall meet the performance requirements of this specification when operating from any nominal 120-volt, 60 cps, AC power source. The performance requirements shall be met when the voltage varies from 105 to 125 volts and the frequency varies from 55 to 65 cps.(See 3.5.2.3).

3.8 **Protection electrical.** Power input circuits shall be protected by fuses or circuit breakers connected directly to all input terminals. Where practicable, other circuits shall be protected by the same means to prevent damage from incorrect adjustment of the equipment, short or open circuits, or failure of tubes or other parts. Protective devices shall be conveniently located and arranged for safe and easy renewal or resetting. Fuse posts shall be such that the fuses can be renewed without use of tools, and preferably shall be of the bayonet fuse extractor type.

3.9 **Electrical safety.** With the equipment assembled, installed and operating, personnel shall be protected from contact with potentials in excess of 30 volts to ground, chassis or frame, including potentials on charged capacitors. A notice on the equipment shall give warning of electrical hazards when the equipment is opened.

3.10 _Service conditions._ The equipment shall be capable of meeting the following service conditions.

3.10.1 _Equipment non-operating._ The equipment shall comply with the operational requirements of 3.10.2 after subjection to any of the following non-operating conditions successively or in combinations likely to be encountered during world-wide storage and transit:

(a) _Temperature._ Continuous exposure in the range of +65°C (+149°F) to -50°C (-58°F); however, exposure to temperatures above +45°C (+114°F) not to exceed 4 hours and exposure to temperatures below -40°C (-40°F) not to exceed 24 hours at any one time.

(b) _Relative humidity._ Relative humidity up to 95 percent at a temperature of +35°C (+95°F) for an indefinite period of time.

(c) _Elevation._ Elevation up to 50,000 feet above sea level.

(d) _Orientation._ Indefinite storage in any orientation when packed in proper container.

(e) _Rain._ Two (2) inches of rainfall per hour, with wind at nominal 100 miles per hour. (Sensing unit, cables and mount only.)

(f) _Bounce._ As encountered during shipment and transport.

3.10.2 _Equipment operating._ After a warmup period of one hour, the equipment shall meet the performance requirements of this specification while subjected to any of the following conditions successively or in combinations likely to be encountered during world-wide operations:

(a) _Operation._ Continuous operation for a period of 1 year, at 50 percent duty cycle, with no more than normal maintenance and replacement or parts. (See 3.1.1 through 3.1.5.)

(b) _Temperature._ Ambient temperatures as follows:

(1) Continuous exposure at +40°C (+104°F) to -50°C (58°F) for the pyranometer, mount and cables.

(2) +50°C (+122°F) to -20°C (-4°F) for the recording unit with temperatures above +35°C (+95°F) not exceeding 4 hours at any one time.

(c) _Relative humidity._ Relative humidity up to 95 percent at a temperature of +35°C (+95°F).

(d) _Elevation._ Elevation up to 12,000 feet above sea level.

(e) _Orientation._ Any normal operating orientation.

81 .

3.11 **Ease of installation and maintenance.** The equipment shall be so fabricated that it can be easily installed and maintained. Accessibility and serviceability features which will tend to simplify maintenance shall be a prime consideration.

3.12 **Test points and test facilities.** Test points and test facilities shall be built into the equipment to aid in its installation, maintenance, operation, calibration, and repair.

3.13 **Adjustment and repair.** The equipment shall be so constructed that parts, terminals, wiring, etc., are accessible for circuit checking, adjustment, maintenance, repair, and replacement with minimum disturbance to other parts and wiring and with use of the minimum number and variety of special tools, particularly those needed for tuning and adjustment. When special tools for tuning or adjustment are needed, the component where they are used shall provide convenient means for mounting them.

3.14 **Interchangeability.** Corresponding components, replaceable subassemblies, and replaceable parts on contract shall be physically and functionally interchangeable as units without modification thereof or of other items with which the units are used. When dimensions, ratings, characteristics, etc., are not specified, the manufacturer's design limits shall be used to determine compliance with the foregoing. If the contractor is in doubt as to whether a particular subassembly or part is to be considered replaceable, the contracting officer shall be consulted.

3.15 **Parts, materials, and processes.** Unless otherwise specified, parts, materials and processes, shall conform to Specification SCL-6200.

3.15.1 **Finish, protective.** Unless otherwise specified, the equipment shall be given protective finish in accordance with Specification MIL-F-14072.

3.16 **Instruction manual.** An instruction manual, containing a description of the equipment, identifying drawings, location and measuring values of test points, a parts list and operating, maintenance, replacement, troubleshooting and repair instructions shall be provided.

3.17 **Workmanship.** The equipment shall be manufactured and assembled in accordance with applicable portions of Specification SCL-6200.

4. QUALITY ASSURANCE PROVISIONS

4.1 **Contractor's responsibility.** Unless otherwise specified, the contractor shall be responsible for the performance of all inspection requirements prior to submission of equipment for Government inspection and acceptance. The contractor's inspection shall include such visual, electrical and mechanical examination and testing of materials, subassemblies, parts and accessories (including source items) during the process of manufacture as may be required to assure that the complete equipment will meet all the requirements of this specification. Except as otherwise specified, the contractor may utilize his own facilities or any commercial laboratory acceptable to the Government. Inspection records and examinations and tests shall be kept complete and available to the Government as specified in the contract or order. The Government reserves the right for authorized technical representatives to witness any contractor-performed inspections and tests.

4.1.1 <u>Equipment compliance report</u>. The contractor shall submit an equipment compliance report with any equipment that is submitted for acceptance. The report, complete in detail, shall be submitted regardless of whether the tests to determine compliance with specification requirements are to be conducted at the contractor's facilities, Government facilities or independent facilities. The contractor's report shall indicate to what degree the equipment complies with each individual electrical, mechanical, or other specification requirement. The degree of compliance shall be expressed in the report by the use of the same terms as those used in the specification to express the requirement. The equipment compliance report shall be submitted in quintuplicate.

4.2 <u>Acceptance inspection</u>. Acceptance tests shall be made at a Government laboratory or at the place of manufacture as specified in the contract to determine suitability for military service and verification of test procedures in accordance with specification requirements. Acceptance tests shall consist of all tests necessary to determine compliance with the requirements of this specification.

4.3 <u>Performance</u>. The equipment shall be tested to determine full compliance with specification requirements in accordance with procedures as determined during the course of the contract and agreements reached between the contractor and the authorized Government technical personnel.

5. PREPARATION FOR DELIVERY

5.1 <u>Preservation and packaging</u>. The equipment shall be packaged in accordance with good commercial practice and in a manner that will guarantee adequate protection against corrosion, deterioration and physical damage during direct shipment to the receiving activity.

5.2 <u>Packing</u>. The equipment shall be packed for shipment in a manner conforming to the requirements of Uniform Freight Classification for rail shipment, National Motor Freight Classification for truck shipment or the regulation of other carriers as applicable to the mode of transportation employed.

6. NOTES

6.1 None.

NOTICE: When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

INTEGRAL ACCURACY FOR A FIRST-ORDER SYSTEM

The instantaneous amplitudes of a first-order system are described by

$$g(t) = A(1 - e^{-\frac{t}{T}}),\qquad\qquad (1)$$

with T the time-constant and A the amplitude of a Dirac pulse (unit pulse with duration $1/A \ll T$).

Omitting scaling coefficients, the integrated output of (1) is

$$\int_{0}^{\infty} g(t)\,dt = A \int_{0}^{1/A} (1 - e^{-\frac{t}{T}})\,dt + A(1 - e^{-\frac{1}{AT}}) \int_{1/A}^{\infty} e^{-\frac{At-1}{AT}}\,dt$$

$$= 1 \equiv \int f(t)\,dt,$$

wherein f(t) is the input function of the first-order system, and g(t) its output.

For an infinite integration period, the error made in the integral is zero, even though the instantaneous values of the output side are in error all the time.

For a finite integration period of nT, one finds the error easily:

$$\varepsilon = A(1 - e^{-\frac{1}{AT}}) \int_{nT}^{\infty} e^{-\frac{AT-1}{AT}}\,dt.$$

No. of Copies

Chief Signal Officer, ATTN: SIGRD Department of the Army, Washington 25, D. C.	1
Chief Signal Officer, ATTN: SIGPD-8b1 Department of the Army, Washington 25, D. C.	2
Office of the Assistant Secretary of Defense (Research and Engineering), ATTN: Technical Library Room 3E1065, The Pentagon, Washington 25, D. C.	1
Chief of Research and Development Department of the Army, Washington 25, D. C.	2
Chief, United States Army Security Agency ATTN: ACofS, G4 (Technical Library) Arlington Hall Station, Arlington 12, Virginia	1
Commanding General, U. S. Army Electronic Proving Ground ATTN: Technical Library, Fort Huachuca, Arizona	1
Commanding Officer, ATTN: SIGWS-AJ U. S. Army Signal Missile Support Agency White Sands Missile Range, New Mexico	1
Commanding Officer, ATTN: SIGMS-ADJ U. S. Army Signal Materiel Support Agency Fort Monmouth, New Jersey	1
Directorate of Intelligence, ATTN: AFOIN-1b1 Headquarters, United States Air Force, Washington 25, D. C.	2
Commander, ATTN: RAALD, Rome Air Development Center Griffiss Air Force Base, New York	1
Commanding General, ATTN: ROZMS Hq, Ground Electronics Engineering Installations Agency Griffiss Air Force Base, New York	1
Commander, ATTN: ASAPRL, Aeronautical Systems Division Wright-Patterson Air Force Base, Ohio	1
Commander, U. S. Air Force Security Service ATTN: Directorate of Systems Engineering (ESD) DCS/Communications-Electronics San Antonio, Texas	1
Commander-in-Chief, ATTN: DOCER, Strategic Air Command Offutt Air Force Base, Nebraska	1
Commander, Air Proving Ground Center, ATTN: PGAPI Eglin Air Force Base, Florida	1

Commander, Air Force Cambridge Research Laboratories ATTN: CRO, Laurence G. Hanscom Field Bedford, Massachusetts	2
Commander, Air Force Electronic Systems Division ATTN: CCRR and CCSD, Laurence G. Hanscom Field Bedford, Massachusetts	2
Commander, Air Weather Service (MATS), U. S. Air Force ATTN: AWSSS/TIPD, Scott Air Force Base, Illinois	1
AFSC Liaison Office Naval Air Research and Development Activities Command Johnsville, Pa.	1
Chief of Naval Research, ATTN: Code 427 Department of the Navy, Washington 25, D. C.	1
Bureau of Ships Technical Library, ATTN: Code 312 Main Navy Building, Room 1528, Washington 25, D. C.	1
Chief, Bureau of Ships, ATTN: Code 454 Department of the Navy, Washington 25, D. C.	1
Chief, Bureau of Ships, ATTN: Code 686B Department of the Navy, Washington 25, D. C.	1
Director, ATTN: Code 2027 U. S. Naval Research Laboratory, Washington 25, D. C.	1
Commanding Officer and Director, ATTN: Library U. S. Navy Electronics Laboratory San Diego 52, California	1
Commander, U. S. Naval Ordnance Laboratory White Oak, Silver Spring 19, Maryland	1
Director, ATTN: Technical Documents Center U. S. Army Engineer Research and Development Laboratories Fort Belvoir, Virginia	1
Commanding Officer, ATTN: Technical Library, Building 330 U. S. Army Chemical Warfare Laboratories Army Chemical Center, Maryland	1
Commander, Armed Services Technical Information Agency ATTN: TIPCR, Arlington Hall Station, Arlington 12, Virginia	10
Signal Corps Liaison Officer, Ordnance Tank Automotive Command U. S. Army Ordnance Arsenal, Detroit, Center Line, Michigan	1
Army Liaison Officer, ATTN: Code 1071 Naval Research Laboratory, Washington 25, D. C.	1

Signal Corps Liaison Officer, Massachusetts Institute of Technology
Building 26, Room 131, 77 Massachusetts Avenue   1
Cambridge 39, Massachusetts

U. S. Army Signal Liaison Office, ATTN: ASDL-9   2
Aeronautical Systems Division, Wright-Patterson Air Force Base,
Ohio

Signal Corps Liaison Officer, Lincoln Laboratory   1
P.O. Box 73, Lexington, Massachusetts

Signal Corps Liaison Officer, Rome Air Development Center   1
ATTN: RAOL, Griffiss Air Force Base, New York

Liaison Officer, Los Angeles Area   1
U. S. Army Signal R&D Laboratory
75 South Grand Avenue, Building 13, Pasadena, California

USASRDL Liaison Officer, Hq, U. S. Continental Army Command   1
Fort Monroe, Virginia

USASIMSA Liaison Engineer, Signal Section   1
Eighth U. S. Army, A.P.O. 301, San Francisco, California

Chief Scientist, SIGRA/SL-CS, Hq, USASRDL   1
USASMSA Liaison Office, SIGRA/SL-LNW, USASRDL   1

Corps of Engineers Liaison Officer, SIGRA/SL-LNE, USASRDL   1

Marine Corps Liaison Officer, SIGRA/SL-LNR, USASRDL   1

U. S. CONARC Liaison Officer, SIGRA/SL-LNF, USASRDL   3

Commanding Officer, US Army Signal Research Activity   1
Evans Area

Chief, Technical Information Division, Hq, USASRDL   6

USASRDL Technical Documents Center, Evans Area   1

Mail File and Records, File Unit No. 3, Evans Area   1

U. S. Army Research Office, Research Analysis Division   1
ATTN: Dr. Hoyt Lemons, Arlington Hall Station, Virginia

Commanding General, U. S. Army Electronic Proving Ground   1
ATTN: Meteorological Department, Fort Huachuca, Arizona

Commanding General, U. S. Army Electronic Proving Ground   2
ATTN: SIGPG-DCGM, Fort Huachuca, Arizona

Chairman, U. S. Army Chemical Corps Meteorological Committee   1
Fort Detrick, Frederick, Maryland

Director, U. S. Army Chemical Corps Operations Research Group
Army Chemical Center, Edgewood, Maryland   1

Director, Atmospheric Sciences Programs   1
National Science Foundation, Washington 25, D. C.

Director, Bureau of Research and Development   1
Federal Aviation Agency, Washington 25, D. C.

Director, Bureau of Research and Development   1
Federal Aviation Agency
National Aviation Facilities Experimental Center
ATTN: Technical Library, Bldg. 3, Atlantic City, New Jersey

Chief, Fallout Studies Branch, Division of Biology and Medicine
Atomic Energy Commission, Washington 25, D. C.   1

Chief, Bureau of Naval Weapons (FAME)   1
U. S. Navy Department, Washington 25, D. C.

Officer-in-Charge, Meteorological Curriculum   1
U. S. Naval Post Graduate School, Monterey, California

Chief of Naval Operations (OP07)   1
U. S. Navy Department, Washington 25, D. C.

Office of Naval Research, U. S. Navy Department   1
Washington 25, D. C.

U. S. Naval Research Laboratory, ATTN: Code 7110   1
Washington 25, D. C.

Marshall Space Flight Center, Aeroballistic Division   1
Aerophysics Branch (Aero-G), ATTN: William Vaughn
Huntsville, Alabama

Office of U. S. Naval Weather Service   1
U. S. Naval Air Station, Norfolk, Virginia

U. S. Army Corps of Engineers   1
Snow, Ice, and Permafrost, Research Establishment
1215 Washington Avenue, Wilmette, Illinois

U. S. Army Corps of Engineers, Waterways Experiment Station   1
Vicksburg, Mississippi

Office of the Chief of Ordnance, Department of the Army   1
Washington 25, D. C.

Chief, Aerophysics Branch, Aeroballistics Laboratory   1
Army Ballistic Missile Agency, Redstone Arsenal, Alabama

Commanding Officer, ATTN: Technical Information Section   1
Picatinny Arsenal, Dover, New Jersey

	No. of Copies
Director, Meteorological Division Surveillance Department	1
Chief, Atmospheric Physics Branch, Meteorological Division	25
Chief, Meteorological Systems Branch, Meteorological Division	1
Chief, Meteorological Instrumentation Branch, Meteorological Division	1
Technical Reports Unit, Meteorological Division	1
Commanding Officer, ATTN: Library, Building 92, Room 211 Diamond Ordnance Fuze Laboratories, Washington 25, D. C.	1

continued

Desired spectral bands can be selected by using two or more units with differing sharp cut-offs on the ultraviolet side of their pass bands, but nearly identical transmission limits on the infrared side; and subtracting the output of the narrower bands from longer.

The new equipment is described and its design philosophy and performance are discussed. A mount providing for altitude and azimuth adjustments, and provision for as many as three different hemispheric filters on each sensing unit, make the equipment suitable for a variety of applications.