AN ANALYSIS OF THE GATE AIRCRAFT PYRGEOMETER INSTRUMENTATION

B.A. Albrecht **S.K. Cox** **M.A. Prokofyev**

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This contribution is the second in a series of reports on GATE Radiation Subprogramme results which will be published simultaneously as Colorado State University Atmospheric Science Papers in English and in the Transactions of the Main Geophysical Observatory, Leningrad, in Russian.

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by

Bruce A. Albrecht and Stephen K. Cox

Department of Atmospheric Science

Colorado State University

Fort Collins, Colorado

80523

and

M. Prokofyev

Main Geophysical Observatory

Department of Radiation Studies

Leningrad

USSR

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ABSTRACT

Significant differences in US and USSR aircraft measurements of hemispherical infrared irradiance were noted during GATE in-flight intercomparisons. In specific instances the downward irradiance measured by the USSR instrument (a Kozyrev pyrgeometer) was as much as 1.5 times greater than the irradiance measured with the US instrument (an Eppley pyrgeometer). A post-GATE intercomparison at Colorado State University verified these differences; the pyrgeometer measurements were compared with independent measurements obtained with an infrared bolometer and with a radiative transfer calculation. The differences noted during GATE and post-GATE intercomparisons may be attributed to differences in calibration techniques and the accurate determination of the temperature of the instrument's thermopile cold junctions. When corrections based upon this analysis were applied to the USSR data, the maximum intercomparison differences were less than 5%.

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I. INTRODUCTION

During the GATE field phase participating scientists from the USA and the USSR became aware of significant differences between their aircraft measurements of the hemispherical infrared irradiance. Although several in-flight intercomparisons between the US and USSR aircraft were made during the experiment, there was insufficient time to investigate the cause of the observed differences.

At the Informal Planning Meeting for the GATE Radiation Subprogram held in Leningrad, USSR in June 1975, attendees endorsed an effort which would resolve the differences between the two infrared irradiance data sets. In response to this endorsement as well as previous initiatives by scientists from both countries, scientists from both the USA and the USSR met at Colorado State University during October 1975 to investigate the discrepancies noted above.

During the period of their joint investigation, the researchers sought answers to the following questions.

1) How reliable are preliminary aircraft hemispheric radiation data reported from the GATE?
2) What are the physical reasons for the observed discrepancies between the data of the USSR and the USA?
3) What steps may be taken to bring the two data sets into agreement?

The remainder of this report attempts to answer the above questions from the results of the joint research conducted during and after GATE by the authors.

II. THEORY OF OPERATION

The theory of operation of the USSR and USA pyranometers used in GATE is similar and is described by Robinson (1966). Since the pyranometer intercomparison data given in Section IV of this paper did not show large discrepancies, we shall not discuss the characteristics of the pyranometer in detail at this time.

The longwave broadband pyrgeometers used for aircraft measurements during GATE on board the IL-18M aircraft of the Main Geophysical Observatory, Leningrad, are a modification of the well known Kozyrev net radiometers manufactured by the LEEI (Leningrad Electrotechnical Engineering Institute). The detailed description and theory of operation of these radiometers is given by Kozyrev, et al (1966), while the results of the field tests of the first modifications of the instruments were reported by Faraponova and Timanovskaya (1966) and Faraponova (1966).

For the purpose of aircraft measurements, two identical pyrgeometers are used instead of a single net radiometer, each measuring the longwave irradiance coming from a hemisphere.

The pyrgeometers have KRS-5 domes and white receiving surfaces coated with magnesium oxide that reflects the shortwave portion of the incoming radiation. The typical spectral response of these sensors is reproduced in Figure 1. The inner volume of the sensors is filled with dry air at sea level and hermetically sealed.

The longwave radiation flux, L, measured with such a sensor is determined through a relation:

$$L = \delta\sigma T^4 + \frac{V}{\varepsilon(T)} \qquad (1)$$

where $\delta\sigma T^4$ is the detector radiation at the temperature (T) corresponding to its cold junctions, V is the detector output in mv, $\varepsilon(T)$ is the

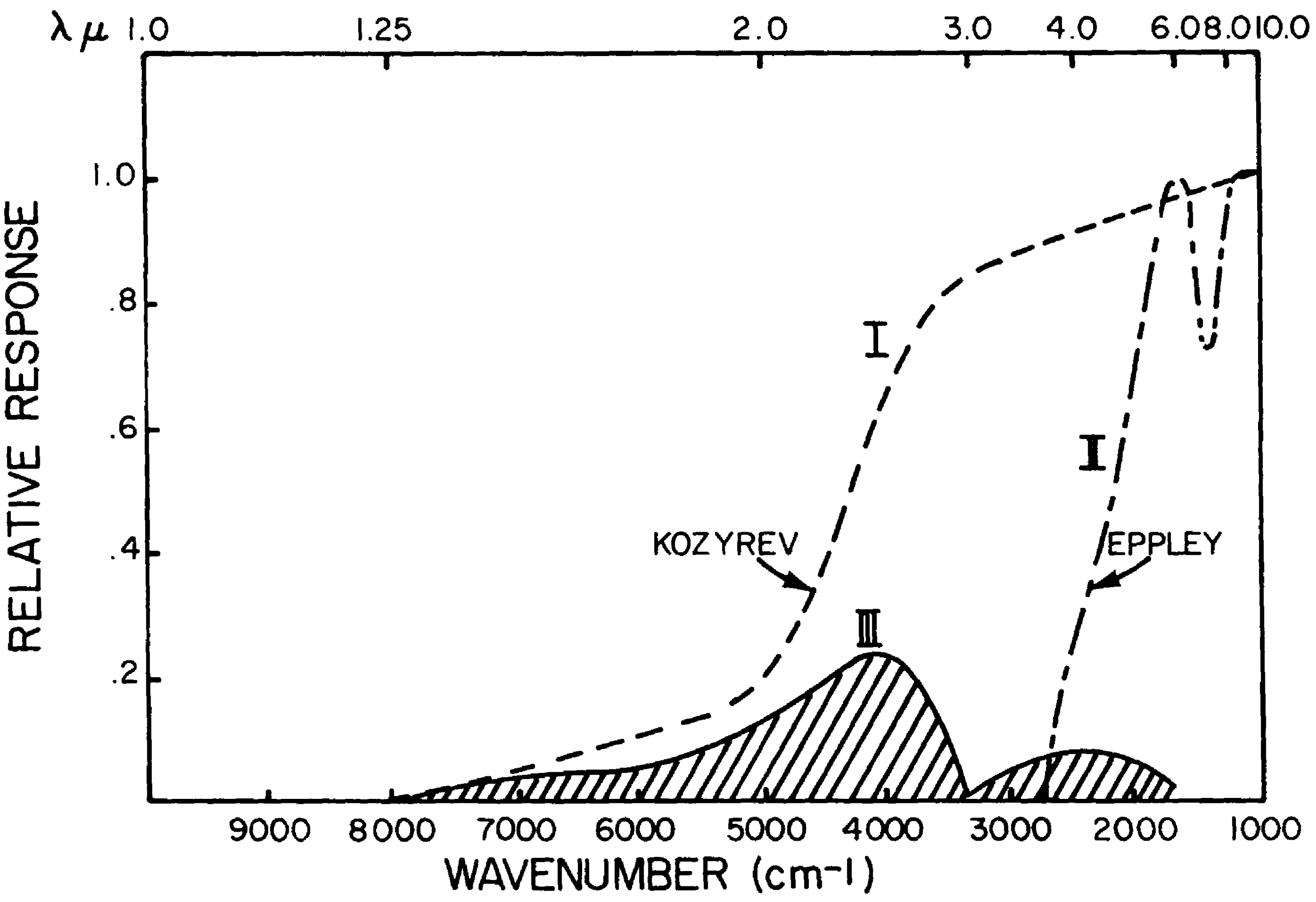


Figure 1. Relative response of the Kozyrev (curve I) and Eppley (curve II) pyrgeometers as a function of wavelength (after Kozyrev, 1966 and Albrecht et al., 1974). The area under curve III represents the relative amount of radiative energy absorbed by the MgO coating of the Kozyrev instruments.

detector sensitivity at a given temperature (T). The thermopile sensors' sensitivity is about .04mv/Wm^{-2} while the response time is about 2 to 3 sec ($\tau_{0.63}$).

The temperature of the instrument is monitored by a copper wire spiral with a resistance of approximately 50 ohms attached to the inner side of the sensor body. The temperature of the KRS-5 dome is not monitored. A photograph and a schematic diagram of the Kozyrev aircraft pyrgeometer are shown in Figures 2 and 3.

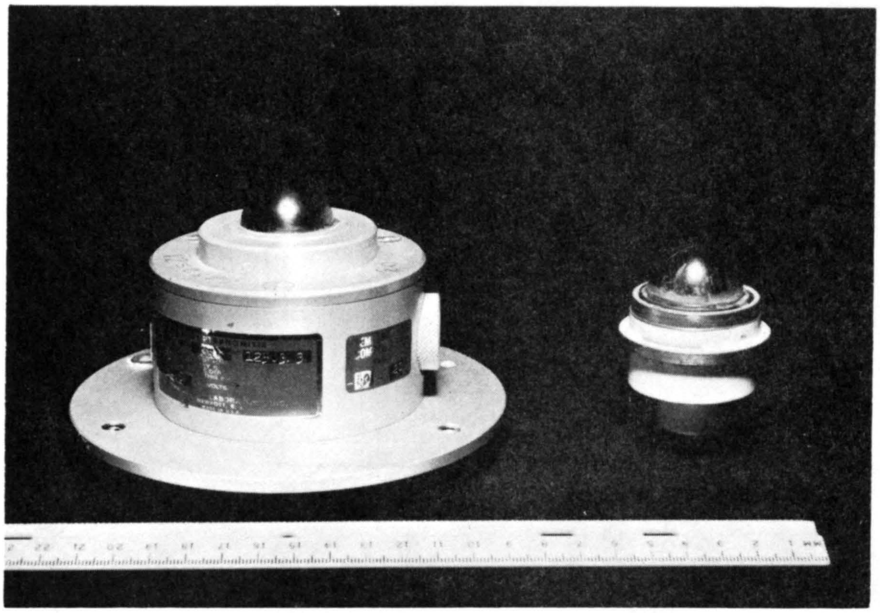
The pyrgeometers used on the U.S. aircraft (C-130, DC-6, Sabreliner, Electra, and Convair 990) are manufactured by Eppley Laboratories. These pyrgeometers were first described by Drummond et al (1970). The theory of their operation and the testing of these instruments from an aircraft platform was described by Albrecht et al (1973).

The Eppley pyrgeometer consists of a thermopile sensor, shielded by a KRS-5 hemisphere. An interference filter is vacuum deposited on the inside of the KRS-5 hemisphere to prevent the transmission of radiation at wavelengths less than 3.5 μm. The spectral response of the Eppley sensor is shown in Figure 1. The thermopile is coated with flat black paint. The sensitivity of the sensor is approximately .005mv/Wm^{-2} with a response time of approximately two seconds.

The longwave radiation, L, is given by the relationship

$$L = \delta\sigma T_s^4 + V/\varepsilon_{(T)} - k\sigma(T_d^4 - T_s^4) \qquad (2)$$

where T_s is the thermopile cold junction or sink temperature and T_d is the temperature of the KRS-5 hemisphere. The sink temperature T_s is measured with a bead thermistor at the point where the cold junctions are connected to the instrument housing. The dome temperatures for instruments used in GATE were measured using a small bead thermistor



EPPLEY KOZYREV

Figure 2. Photograph of the Kozyrev and Eppley pyrgeometers.

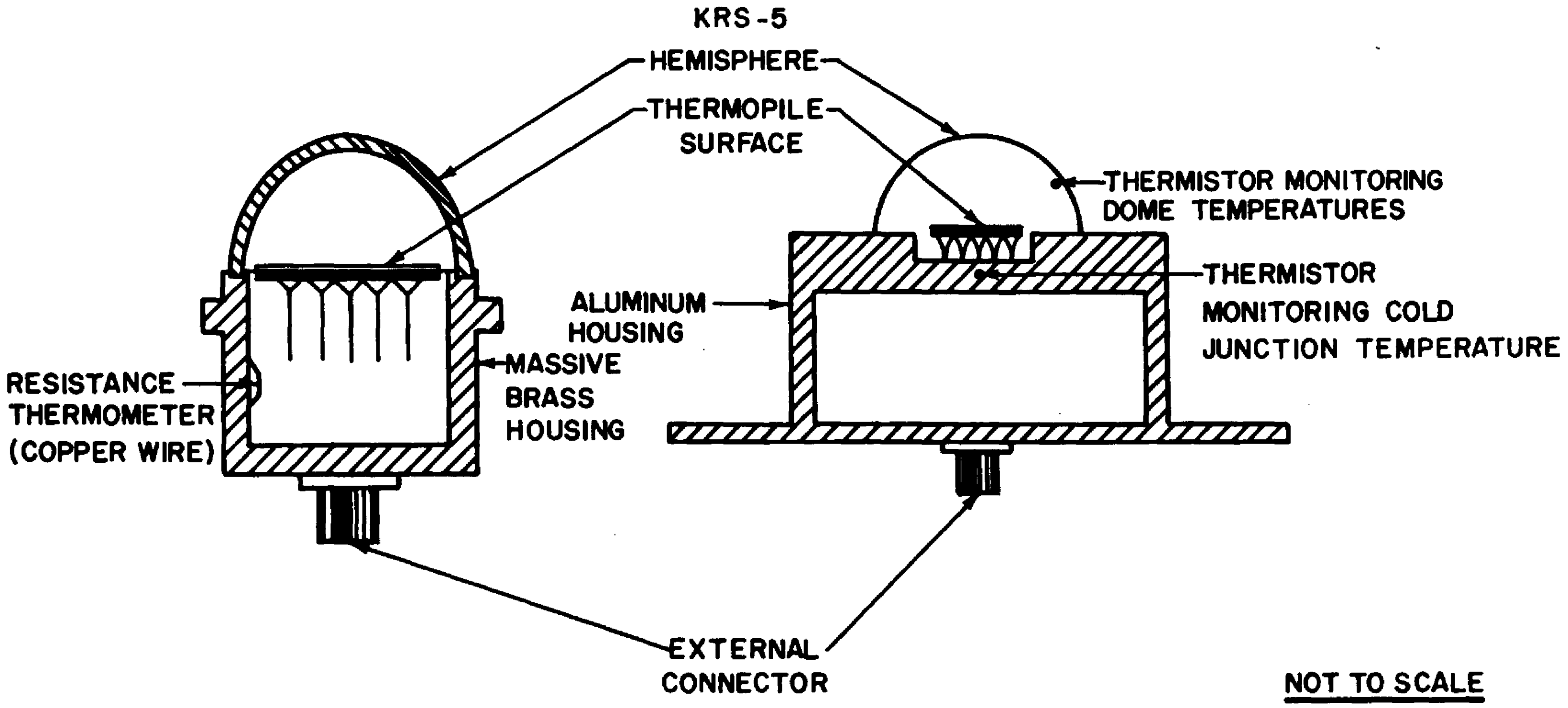


Figure 3. Sketch of the Kozyrev and Eppley pyrgeometers.

attached to the inside of the KRS-5 hemisphere. A photograph of both pyrgeometers and sketches of the instruments are shown in Figures 2 and 3, respectively.

There are two principal differences between the Kozyrev aircraft pyrgeometer and the Eppley pyrgeometers used on board the U.S. aircraft during GATE:

1. A white magnesium oxide coating on the thermopile surface is used in the Kozyrev sensors to block the shortwave radiation; the Eppley instruments have an interference filter deposited on the inner side of the KRS-5 dome serving the same purpose.
2. The thermopile cold junctions of the Kozyrev sensors are suspended in air inside the sensor and are provided with wire "whiskers" for heat dissipation, while the cold junctions of the Eppley instruments are connected to the instrument housing.

III. PYRGEOMETER CALIBRATION PROCEDURE

Both Eppley and Kozyrev pyrgeometers were calibrated using a conical cavity blackbody of large thermal mass. Various target temperatures were obtained by cooling the blackbody to approximately -10°C and allowing the blackbody to warm as the calibrations were performed. Blackbody temperatures were measured at several points on the surface of the conical aperture using thermocouples attached to this surface. Temperature differences between these points were found to be less than .2°C.

To determine the sensitivity of the Eppley thermopile, the instrument is faced into the blackbody cavity and thermopile output, sink temperature and dome temperature are recorded as a function of time for approximately five minutes at each calibration point. An example of instrument output and the dome and sink temperatures as a function of time are shown in Figure 4 for the calibration point. Initially the KRS-5 dome is warmer than the sink, however, when the instrument is faced into the blackbody, the dome cools quickly as it loses energy to the cold blackbody while the thermopile sink cools much more slowly since its thermal mass is much greater. After approximately three minutes the dome and sink cool at approximately the same rate. The instrument output initially decreases rapidly and then stabilizes after approximately three minutes. This behavior is consistent with Eq. (2) which may be written in the form

$$\frac{V}{\varepsilon} = L - \delta\sigma T_s^4 + k\sigma(T_d^4 - T_s^4). \qquad (3)$$

The dominance of the $k\sigma(T_d^4 - T_s^4)$ is apparent in the variation of output as a function of time as shown in Figure 4.

To determine ε in Eq. (3) the instrument output, V, at points where $T_d = T_s$ is plotted against $L - \delta\sigma T_s^4$ where L in this case is determined by the blackbody temperature. In the results given here, the emissivity of both the blackbody and the thermopile are assumed to be 1.0. A plot of these points is shown in Figure 5. The slope of the line connecting these points gives $\frac{1}{\varepsilon} = 178\ \mathrm{Wm^{-2}mv^{-1}}$.

The k value in Eq. (3) may then be determined by plotting $k\sigma(T_d^4 - T_s^4)$ as a function of $L - T_s^4 - \frac{V}{\varepsilon}$ assuming the sensitivity determined in the procedure described above. Plots for three of the runs are shown in Figure 6. The average value of k determined from these plots is k = 4.08.

The same procedure was used for determining the sensitivity of Kozyrev pyrgeometers with the following differences:

1) the dome temperature was not recorded, and

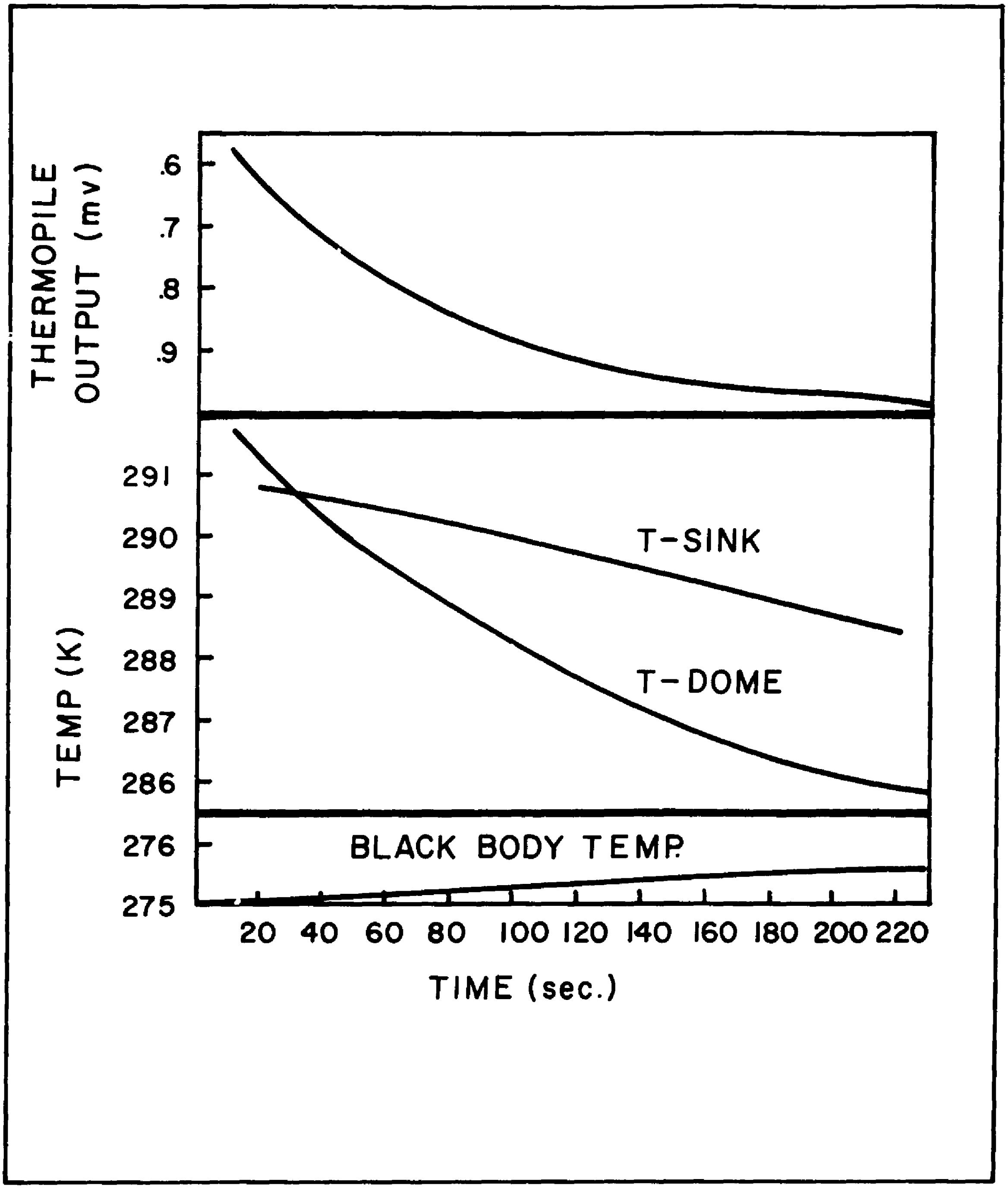


Figure 4. Thermopile output, sink temperature, dome temperature, and blackbody temperature as a function of time for a typical calibration run of the Eppley pyrgeometer.

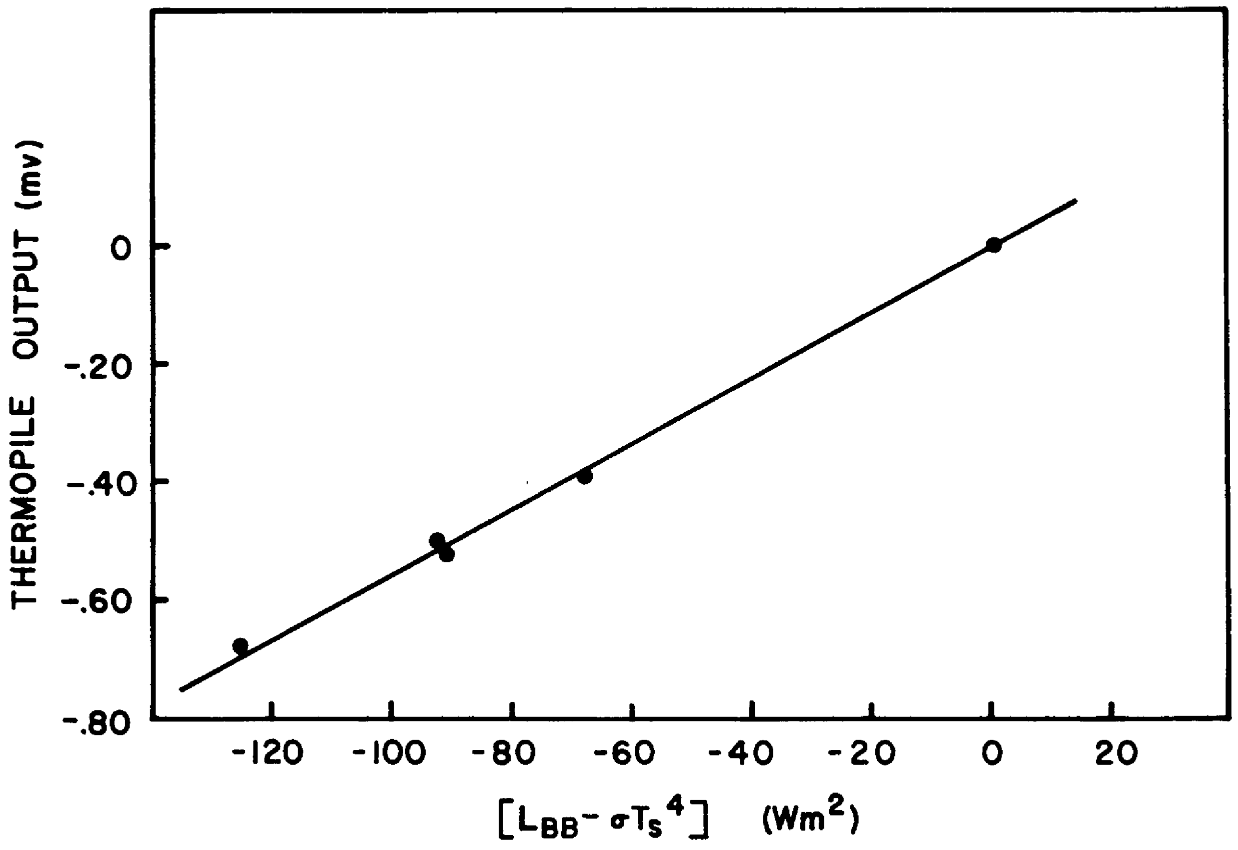


Figure 5. Calibration data for determination of thermopile sensitivity, where $T_s = T_d$ for the Eppley pyrgeometer.

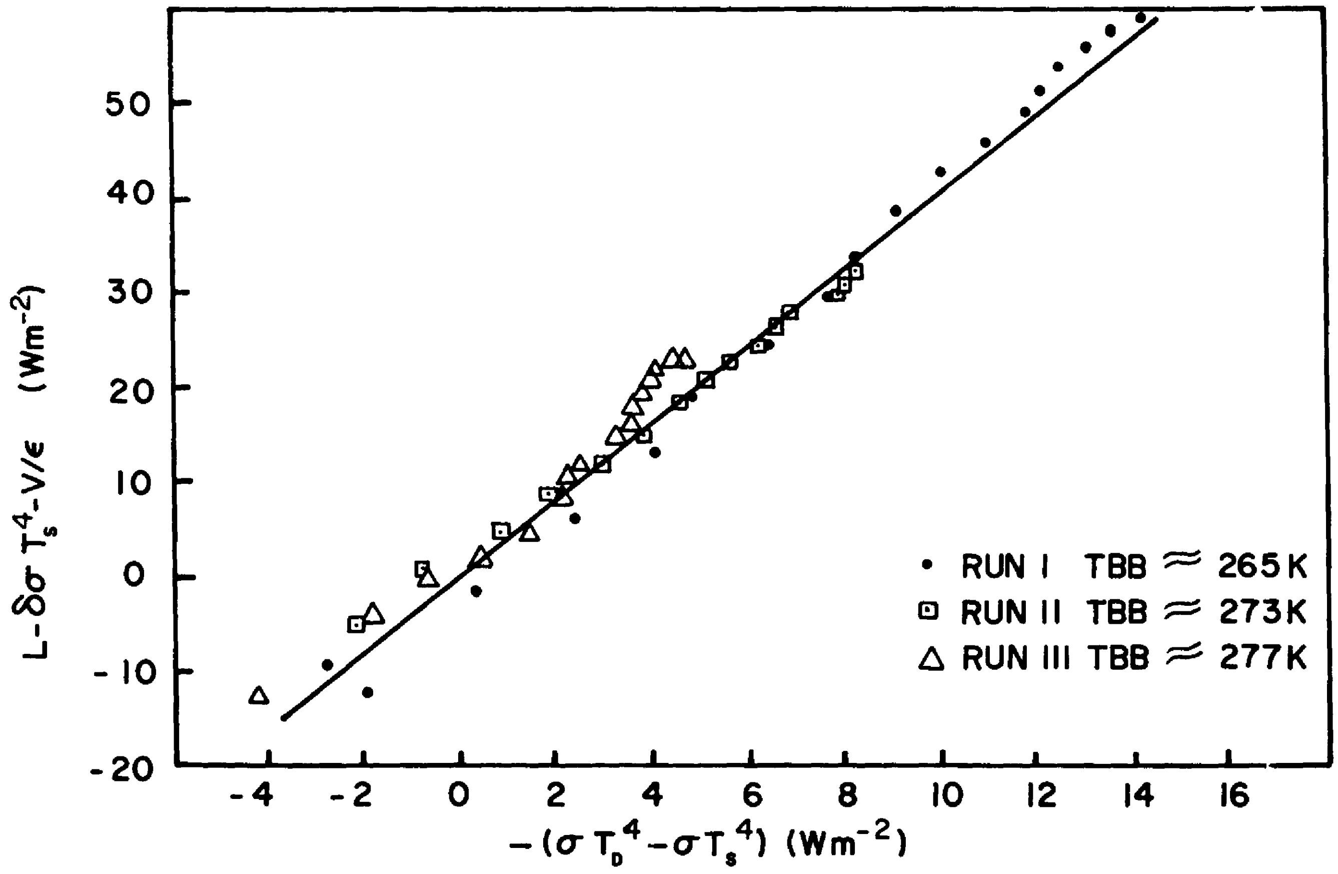


Figure 6. Calibration data for determination of the dome-sink temperature difference coefficient, k, in Eq. 2.

2) the sensitivity was determined by the stabilized output of the instrument. Since T_d was not known, the third term was omitted from Eq. (3).

IV. GATE FIELD PHASE INTERCOMPARISON DATA

A series of prescheduled intercomparisons between various aircraft was conducted during the GATE Field Phase. From these data, given in Tables I and II, generally good agreement between both shortwave irradiance components may be seen. The upward shortwave irradiance data from the IL-18M aircraft tend to be approximately 15% larger than the corresponding U.S. aircraft. It is encouraging that this trait appears to be consistent at all altitudes. Since a discrepancy of the same magnitude does not exist for the K↓ measurements, one is tempted to suggest that the cosine response of the two instruments may be different and would account for the differences in the observations. Such a tentative conclusion is supported by results reported previously by Hanson (1974).

The largest inconsistency noted from the intercomparison data occurs between the measurements of the downward infrared component, LW↓. One readily sees from the data in Tables I and II that the inconsistency is altitude dependent. With these data as a guide, the authors examined the probable physical cause(s) of the observed inconsistency. The possible causes are listed below:

1. differences in spectral characteristics of dome and thermopile coating
2. solar heating of the KRS-5 dome
3. adequacy of ventilation to dissipate solar heating
4. solar heating of the thermopile

Alt.	TIME From	TIME To	L↓ WATT/M² C-130	L↓ WATT/M² IL-18M Before Correction	L↓ WATT/M² IL-18M After Correction	RATIO C-130/IL-18M Before Correction	RATIO C-130/IL-18M After Correction	K↓ WATT/M² C-130	K↓ WATT/M² IL-18M	RATIO C-130/IL-18M	L↑ WATT/M² C-130	L↑ WATT/M² IL-18M Before Correction	L↑ WATT/M² IL-18M After Correction	RATIO C-130/IL-18M Before Correction	RATIO C-130/IL-18M After Correction	K↑ WATT/M² C-130	K↑ WATT/M² IL-18M	RATIO C-130/IL-18M
20K	1058Z	1103Z	175	280	179	.625	.98	984	1014	.970	314	323	296	.972	1.062	161	193	.833
	1112	1115	175	265	170	.660	1.03	946	974	.971	321	322	298	.998	1.078	168	198	.848
	1122	1126	175	265	170	.661	1.03	1009	1042	.968	321	322	298	.998	1.078	161	188	.855
	1133	1135	176	284	181	.619	.97	1037	1064	.974	322	322	298	.998	1.081	158	202	.779
10K	1202	1208	311	379	302	.820	1.03	1012	1032	.981	390	390	394	1.00	.990	140	168	.833
	1214	1218	307	385	312	.799	.98	995	1032	.964	390	392	396	.996	.985	140	162	.862
	1224	1228	307	376	299	.816	1.03	1033	1042	.991	398	394	398	1.01	1.000	136	158	.859
	1235	1239	307	382	309	.804	.99	1047	1064	.984	390	387	391	1.01	.999	133	158	.833
	1243	1248	307	382	308	.804	.997	1061	1071	.990	390	392	396	.998	.985	140	161	.870
	1256	1301	311	381	305	.817	1.02	1082	1072	1.01	399	388	393	1.03	1.016	137	161	.849
	1306	1311	312	384	309	.813	1.005	1082	1078	1.00	396	385	390	1.03	1.016	136	160	.852
	1315	1320	312	385	309	.811	1.005	1082	1071	.977	400	386	391	1.04	1.023	138	153	.904
	1325	1330	311	382	306	.814	1.016	1089	1078	1.01	399	385	390	1.03	1.023	131	153	.858
5K	1341	1349	426	461	407	.924	1.05	907	928	.976	457	437	447	1.05	1.022	92	114	.805
.6K	1401	1409	424	445	387	.953	1.10	883	866	1.02	431	420	427	1.03	1.010	33	38	.855
	1413	1418	420	445	389	.945	1.08	896	884	1.01	431	424	431	1.02	1.000	34	40	.845
	1424	1429	428	441	384	.970	1.11	845	818	1.03	433	422	429	1.03	1.010	34	41	.831
	1434	1439	432	451	398	.957	1.08	817	824	.992	440	427	434	1.03	1.014	34	41	.814

TABLE I: INTERCOMPARISON DATA FROM USSR IL-18M and US C-130 AIRCRAFT, 24 June 1974.

			L↓					K↓			L↑					K↑		
	TIME		WATT/M^2			RATIO		WATT/M^2		RATIO	WATT/M^2			RATIO		WATT/M^2		RATIO
Alt.	From	To	Sabre	IL-18M		Sabre / IL-18M		Sabre	IL-18M	Sabre / IL-18M	Sabre	IL-18M		Sabre / IL-18M		Sabre	IL-18M	Sabre / IL-18M
				Before Correction	After Correction	Before Correction	After Correction					Before Correction	After Correction	Before Correction	After Correction			
20K	1248 1254	30 15	154	224	150	.69	1.027	1202	1155	1.04	367	309	336	1.19	1.093	111	127	.87
10K	1315 1319		279	333	300	.84	.930	1110	1080	1.03	395	378	406	1.04	.974	85	102	.83
5K	1335 1339	15 45	340	378	345	.90	.986	1037	1002	1.03	388	403	381	.96	1.018	60	72	.83
3K	1401 1403	45	352	392	367	.90	.959	1003	960	1.04	387	409	389	.95	.995	44	53	.83

TABLE II: INTERCOMPARISON DATA FROM USSR IL-18M and US SABRELINER AIRCRAFT, 30 July 1974.

5. placement of temperature transducers within instrument
6. calibration procedures.

The measurements summarized in the following sections suggest which of the aforementioned causes are most probable.

V. POST GATE INTERCOMPARISON DATA

Table III summarizes the results of a series of measurements made on 4 November 1975 in Fort Collins, Colorado. This series of intercomparison measurements between the Eppley and the Kozyrev instruments were conducted under varying degrees of solar illumination and ventilation of the instruments. Ventilation was supplied by exposing the appropriate instrument to a stream of compressed air. The instruments were shaded from direct solar illumination using small circular discs.

The sky was virtually cloud free and the data were collected from 1403 LST to 1716 LST. The data were reduced using calibration constants derived as explained in Section III and then applying Eqs. (1) and (2) from Section II.

At 1716 LST an infrared bolometer (2° field of view) with a spectral bandpass of 1.8 to 26μm was used to measure independently the infrared radiance at a few zenith angles. Measurements were made after sunset, thereby eliminating any possible solar contamination. These radiance data are shown in Figure 7. An integration over 2π steradians neglecting any azimuthal variation yields a downward irradiance value of 247 Wm^{-2}.

In addition to the data noted above, the 00Z radiosonde data from Denver, Colorado were used in a computation of LW↓ at the surface. The computation technique described by Cox (1973) yielded an LW↓ value of 263 Wm^{-2}.

VI. ANALYSIS OF INTERCOMPARISON DATA

The easiest item to assess in the list of possible causes given in Section IV is the first one. The possible effects of both instruments' differences in spectral characteristics are shown in Fig. 1. The area under curve III represents the relative amount of radiative

LOCAL TIME	KOZYREV LW↓ Wm^{-2} Before Correction	KOZYREV LW↓ Wm^{-2} After Correction	EPPLEY Assume T_d-T_s=0	LW↓ Wm^{-2} Use $T_d^4 - T_s^4$ in Eq. (2)	INCOMING SOLAR IRRADIANCE Wm^{-2}
1423	409	339 Wm^{-2}	326 Wm^{-2}	230 Wm^{-2}	370-384 Wm^{-2}
1430	340	247 Shaded	263 Shaded	274	370
1436	403	327	264	279	350
1441	349	253 Shaded	322	205	336
1446	378	298	308	225	332
1458	394	321	275 Ventilated	245	285
1505	345	278 Ventilated	310	202	260
1512	349	275 Ventilated and Shaded	309	214	242
1519	399	330	272 Ventilated and Shaded	269	232
1716	349	280	281 Night	264	0

Bolometer observation at 1716 LST (1.8-26μm) LW↓ = 247 Wm^{-2}

Computation using Denver 00Z sounding LW↓ = 263 Wm^{-2}

TABLE III: POST GATE INTERCOMPARISON DATA GATHERED AT FORT COLLINS, COLORADO ON 4 NOVEMBER 1975.

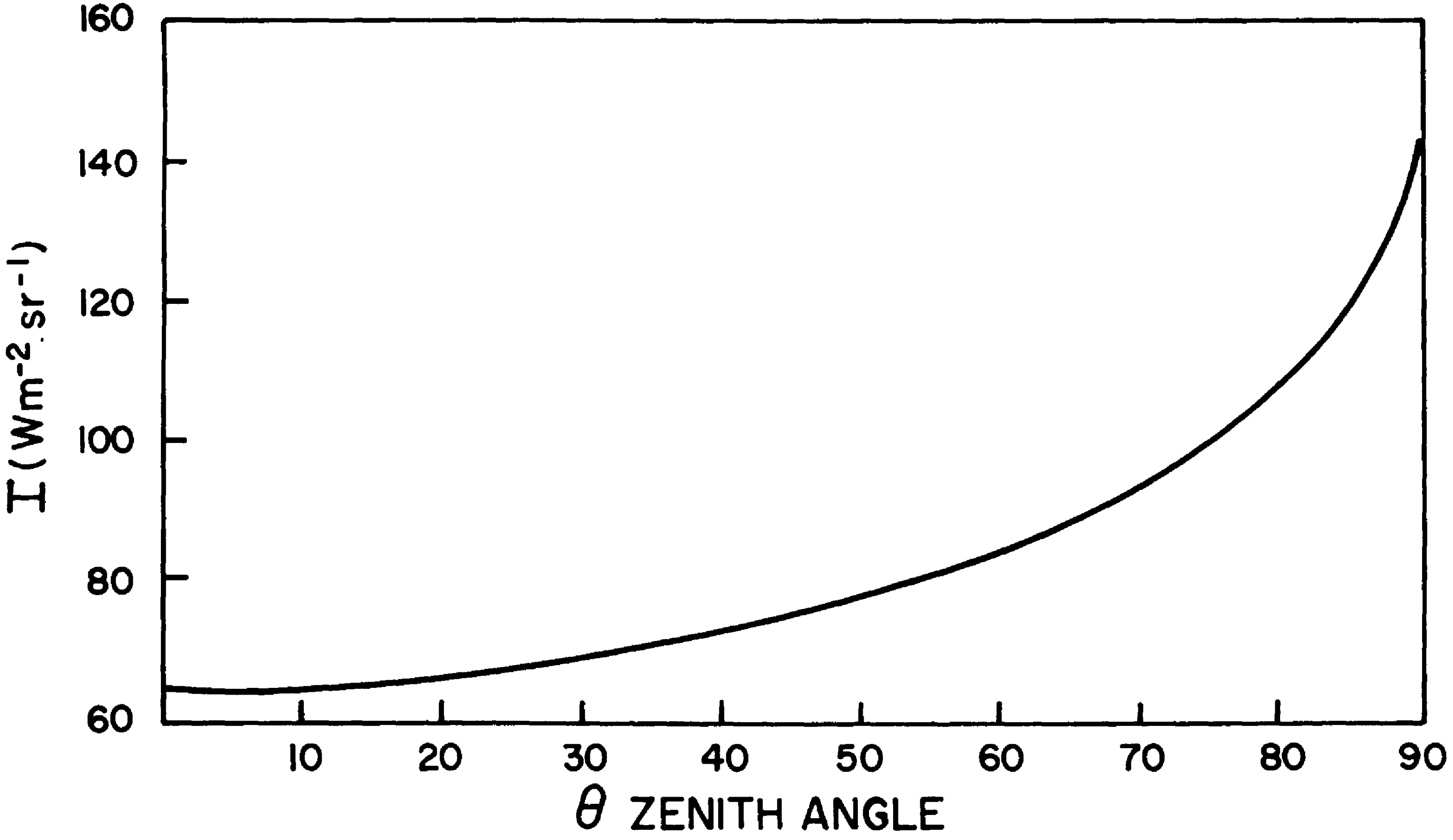


Figure 7. Infrared irradiance as a function of zenith angle.

energy absorbed by the MgO coating of the Kozyrev instrument. It reaches about 23% of the incident flux in the region of 2.5 μm

Using the spectral distribution of direct solar energy (Kondratyev, 1969) one can calculate the possible overestimate of IR flux by the Kozyrev instrument under clear sky conditions as a function of height. For the GATE aircraft measurements, we can assume that $\theta_{\odot} = 0°$. Thus, the maximum overestimate due to differences in spectral characteristics of the filters is as follows:

Height km	Flux overestimate by Kozyrev pyrgeometer, Wm^{-2}
0.5	10
3	13
6	16

Table IV. Possible flux overestimate due to spectral sensitivity differences.

The data in Table III may be used to gain some insight into items 2 to 4 listed as possible causes of the discrepancies in Section IV. Assuming that the actual LW↓ value was constant through the observing period, one notes an obvious dependence upon incident solar energy by comparing shaded and unshaded values of LW↓ from each instrument. Furthermore, in the case of the Eppley instrument, the attempt to correct for this effect by the dome-sink temperature difference resulted in an overcorrection. This may be explained by the fact that the dome temperature is measured at one point on the dome by a thermistor; lacking ventilation, temperature gradients appear on the dome and the single temperature transducer is not representative of the dome temperature.

The Eppley data from 1519 LST (ventilated and shaded) and 1716 LST (night) agree remarkably well with the calculated value (observed 269 and 264 Wm^{-2} vs calculated 263 Wm^{-2}) and with the independent bolometer observation for the spectral bandpass 1.8 to 26μm (247 Wm^{-2}).

Taking the Kozyrev shaded, ventilated and shaded, and ventilated data, one notes that all three cases yield LW↓ values in the interval 340-349 Wm^{-2}; the nighttime value was also 349 Wm^{-2}. The fact that shading the instrument yields nearly the same effect as ventilating the instrument strongly suggests that the solar effect in still air is one of heating the KRS-5 dome rather than solar energy being absorbed by the thermopile itself. It therefore appears that even though solar heating of the dome is important in still air, even moderate ventilation will significantly suppress this effect. With the ventilation offered by the slipstream of an aircraft, this effect should be virtually eliminated.

The differences in the placement of temperature transducers within the instrument may also account partially for the differences in the measurements. When making measurements with the Kozyrev pyrgeometer, it is assumed that the cold junctions are at the same temperature as the instrument housing. This assumption may result in erroneous measurements since the cold junctions and the housing are not in direct thermal contact. In the case of the Eppley Instrument, the cold junctions are attached to the sink of the instrument and the temperature measurement is made at the point where this contact is made.

To illustrate the effect that this difference might have on the measurements, it may be noted that when the pyrgeometer is viewing the downward irradiance the thermopile surface is cooler than the body of the instrument (thermopile output is negative). Consequently, one would assume that the cold junction temperatures would be less than or equal to the instrument temperatures. The more negative the output (the cooler the thermopile surface) the greater the difference that would be expected between the cold junctions and the instrument housing temperature. Hence, if the housing temperature is used to obtain L, the results may be erroneously high when the thermopile output is negative. A temperature difference of 2°C between the cold junction temperature and the housing temperature would cause an error of approximately 10 Wm^{-2}. A similar effect might also be expected when measuring the upward irradiance although in this case the thermopile is warmer than the cold junctions.

Differences in the instrument outputs may also be due to the calibration procedure. When calibrating the Kozyrev pyrgeometer the dome temperature is not monitored. Consequently, this uncertainty may affect the derived sensitivity. For example, if the thermopile output and sink temperature values which stabilize at the end of the calibration run (c.f. Fig. 6) are used, the derived sensitivity would be much larger; in the case of the Eppley instrument using the data given in Figure 4, the sensitivity determined in this way would be 60% greater than the actual sensitivity determined when $T_d = T_s$.

In terms of the measurement of the downward irradiance (thermopile output is negative) the larger sensitivity would result in an erroneously large measured irradiance as shown by Eq. (1). For example, if the measurements made on 4 November with the Eppley instrument were made using the larger sensitivity, the measured value would be increased by approximately 40 Wm^{-2}. Again a similar effect would also occur when measuring the upward irradiance. In this case, however, the thermopile output will be positive so that an overestimate in the sensitivity may result in an erroneously low measurement, particularly when the thermopile output is large. However, when comparing ratios of LW↑ measurements, the differences may not be as significant since the absolute values of LW↑ may be significantly greater than LW↓ at high levels.

Keeping these considerations in mind and assuming that the thermal properties of KRS-5 domes in both Kozyrev and Eppley pyrgeometers are basically the same, an attempt was made to recalculate the Kozyrev pyrgeometer sensitivity using the same approach as that used for the Eppley Instruments' calibration. It was assumed that the equilibrium point $T_d = T_s$ (see Sec. III) is reached by the Kozyrev pyrgeometer with the time lag equal to that of the Eppley one. The instrument sensitivity was then determined according to the technique stated in Section III. It was found out that the sensitivity calculated in this way is 36% lower than obtained originally.

The next attempt was to try to determine the possible error due to temperature differences between the instrument housing and the thermopile cold junctions. For this purpose the Kozyrev pyrgeometer was warmed up or cooled down and then faced into the blackbody cavity, the blackbody itself being at room temperature. The instrument housing temperature and output were recorded till the instrument temperature practically reached the blackbody temperature. Then the IR flux (presumably equal to the blackbody irradiance) was calculated using the new sensitivity value. The results of these calculations are shown in Figure 8.

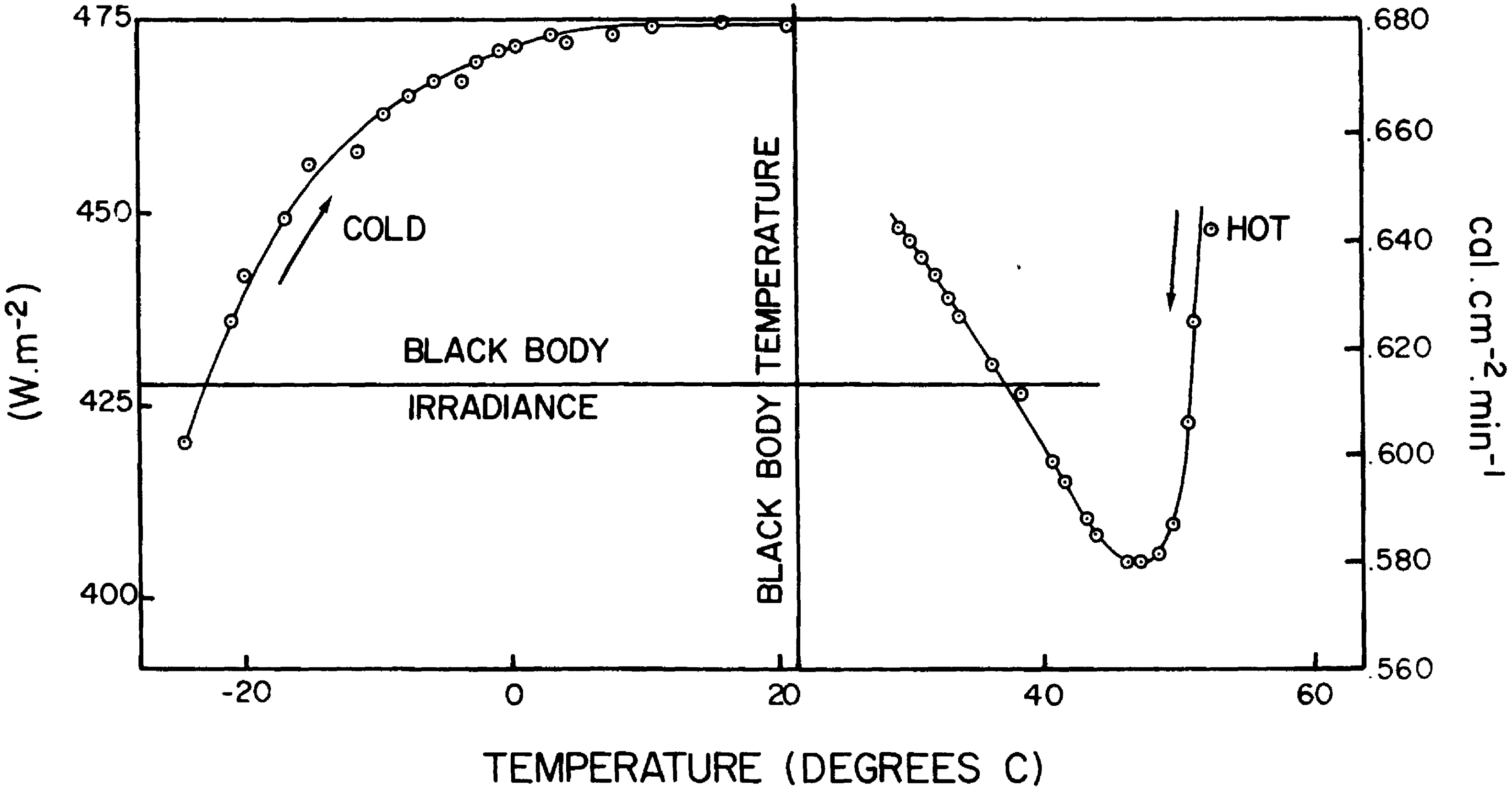


Figure 8. Kozyrev pyrgeometer output as a function of the instrument housing temperature.

It may be seen that the calculated IR flux is significantly higher than that emitted by the blackbody. It is interesting to note the quick drop of calculated flux in case of the warmed-up instrument, which then gradually rises over the level of blackbody irradiance. One can interpret it as the influence of dome, which quickly cools off against the cold blackbody and then gradually comes into thermal equilibrium with the slowly cooling instrument itself.

Assuming that under stable conditions the discrepancy between the calculated flux and the actual blackbody irradiance is merely an instrument offset, the data in Fig. 8 indicate that this offset is 47 Wm^{-2}.

With the new sensitivity data and the offset noted above, the Kozyrev pyrgeometers data were recalculated for both GATE (Dakar) and post-GATE (Fort Collins) intercomparisons. The results of such recalculations are given in Tables I, II, and III under the heading "after correction".

One can readily see from this independent comparison that the proposed correction scheme yields very good agreement for the intercomparisons. Values are within 10% of one another for GATE inflight intercomparisons and to within at least 5% for post-GATE ground intercomparison.

At the same time, the new values for the Kozyrev instruments obtained under the assumption that $T_d = T_s$, are close to those obtained with the Eppley. This suggests that although the data should be corrected for the dome-sink temperature difference, the slipstream of the aircraft does provide (as stated above) sufficient ventilation to neglect such an effect.

VII. CONCLUDING REMARKS

In the introduction, three questions which this report proposed to answer were explicitly stated. In this section we shall restate these questions and offer our best answers to them.

1) How reliable are preliminary aircraft hemispheric radiation data from the GATE?

From the intercomparison data gathered during GATE, K↓ shows very good agreement. In general, K↑ values made by U.S. aircraft are systematically smaller by approximately 15%. This difference is most likely due to the different cosine responses of the instruments.

Most intercomparison data show acceptable agreement between observations of LW↑, however, there are dramatic differences between observations of LW↓. The preliminary data of LW↓ from the USSR aircraft appear too large and we suggest that these data not be used until an appropriate correction is applied.

2) What are the physical reasons for the observed discrepancies between the LW↓ data of the USSR and the USA?

There are apparently three separate reasons which may account for the differences in the observations of LW↓. First, in the USSR instrument, the KRS-5 dome and sink temperatures are assumed equal. Although the laboratory data collected in this study indicates this to be a minor problem, it may still account for some of the observed discrepancy.

Second, the dome-sink temperature difference during calibration may introduce an error into the determination of the sensitivity factor used in the data reduction equation. It is important that the sensitivity factor be resolved from data for which the equivalence of dome and sink temperatures is assured.

Third, in the Kozyrev instrument, the temperature used in the $\delta\sigma T^4$ term in the data reduction is measured on the body of the instrument. In fact, the temperature in the reduction equation is the thermopile cold junction temperature. If these two temperatures are significantly different, as seems likely under conditions of low LW↓ values, significant overestimates of LW↓ would result.

3) What steps may be taken to bring the two data sets into agreement?

On the basis of research presented in this paper, the authors suggest that the values of the IL-18M IR actinometric measurements be reduced according to the following procedure:

1) the sensitivity value be lowered by 36% for both upward and downward looking pyrgeometers;
2) measurement data be reduced according to Eq. (1) using the new sensitivity values;
3) the values obtained in 2) be further reduced by 47 Wm^{-2};
4) the new values of IR fluxes be presented to the RSDC at MGO, Leningrad. However, in agreement with recommendations of Subgroup 3 of the Informal Planning Meeting for the GATE Radiative Subprogram (Leningrad, USSR, June 1975), the original data of the IL-18M actinometric measurements be preserved by the RSDC.

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REFERENCES

Albrecht, B., M. Poellot, and S.K. Cox, 1974: Pyrgeometer Measurements from Aircraft. Rev. Sci. Instrum., 45, No. 1, pp. 33-38.

Cox, S.K., 1973: Infrared Heating Calculations with a Water Vapor Pressure Broadened Continuum. Q.J. Roy. Meteor. Soc., 99, No. 422, pp. 669-679.

Drummond, A.J., W.J. Scholes and J.H. Brown, 1970: A New Approach to the Measurement of Terrestrial Longwave Radiation. WMO Tech. Note, No. 104, pp. 383-387.

Faraponova, G.P., 1971: Tests of Radiation Thermoelements for Radiation Flux Measurements in the Atmosphere. Proceedings of the Sixth International Symposium on Actinometry and Atmospheric Optics, June 1966, Tartu, pp. 193-203.

Faraponova, G.P., and R.G. Timanovskaya, 1971: Field Tests of Radiation Thermoelements. Proceedings of the Sixth International Symposium on Actinometry and Atmospheric Optics, June 1966, Tartu, pp. 204-210.

Hanson, K.J., 1974: Radiation Sensor Comparisons During the GATE International Sea Trials (GIST), Bulletin of the AMS, 55, No. 4, pp. 297-304.

Kozyrev, B.P., 1971: A Compensated Thermoelectric Net Radiometer with Whitened and Bright Detecting Surfaces Protected from Air Currents by KRS-5 Hemispheres. Proceedings of the Sixth International Symposium on Actinometry and Atmospheric Optics, June 1966, Tartu, pp. 168-176.

Robinson, N., 1966: Solar Radiation, Elsevier Publishing Company, 1347 pp.

Radiation Characteristics of the Atmosphere and Underlying Surface. Ed. K.Ya. Kondratyev, L., Hydrometeoizdat, 1969, 564 pp.

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B. Albrecht, S. Cox, and M. Prokofyev

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9. Performing Organization Name and Address

Dept. of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523
U.S.A.

Main Geophysical Observatory
Dept. of Radiation Studies
Leningrad
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16. Abstracts

Significant differences in US and USSR aircraft measurements of hemispherical infrared irradiance were noted during GATE in-flight intercomparisons. In specific instances the downward irradiance measured by the USSR instrument (a Kozyrev pyrgeometer) was as much as 1.5 times greater than the irradiance measured with the US instrument (an Eppley pyrgeometer). A post-GATE intercomparison at Colorado State University verified these differences; the pyrgeometer measurements were compared with independent measurements obtained with an infrared bolometer and with a radiative transfer calculation. The differences noted during GATE and post-GATE intercomparisons may be attributed to differences in calibration techniques and the accurate determination of the temperature of the instruments' thermopile cold junctions. When corrections based upon this analysis were applied to the USSR data, the maximum intercomparison differences were less than 5%.

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