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We described the pyranometer in an earlier paper.[1] Its purpose is to measure the radiation, originally a part of the solar beam, which reaches a horizontal surface by scattering from all parts of the sunlit sky; or to measure at night the loss of heat of a blackened horizontal surface by reason of its long-wave radiation toward the whole sky. The pyranometer may be used also to measure solar radiation. We published in our earlier paper a comparison between observations of solar radiation with the pyranometer and the pyrheliometer, and these showed almost exact agreement. As these measurements were made at various altitudes of the sun from about 10° upward, they indicated strongly the probable accuracy of the pyranometer for sky radiation, which comes from all angles.

Further use of the instrument has not diminished our confidence in its accuracy, but we have found it necessary to alter the method of reading with it. As stated in our earlier paper, the pyranometer is developed from the plan of the Ångström electrical compensation pyrheliometer. A thermo-electric couple connected to a moving coil galvanometer indicates differences of temperature between the two blackened metallic strips which form the receiving surfaces for radiation; and a heating current of electricity furnishes to these strips a quantity of energy whose measured intensity is the index of the intensity of the absorbed radiation. In our first observations we found that nearly 30 seconds must elapse after throwing on a heating current before a new state of temperature equilibrium becomes completely established, as shown by a steady state of the galvanometer. Accordingly we adopted the custom of waiting 30 seconds after each exposure to radiation, in order that the steady state might be reached, before recording the galvanometer deflection. At Mount Wilson our attention was drawn to a phenomenon unnoticed at Washington. When exposing the instrument to sunlit sky, through the glass hemisphere used to cut off long-wave rays, the deflection of the galvanometer came to a maximum within 5 seconds, and then con-

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[1] Smithsonian Misc. Coll., Vol. 66, No. 7.

tinually decreased for as much as a minute thereafter. The decrease in 30 seconds was a very considerable part of the whole sky-deflection. Our original method of reading thus proved quite arbitrary, for there was no reason to suppose the reading at 30 seconds after exposure was better than at 20 or 40 seconds. A similar drift of the galvanometer but very small relatively to the whole deflection, was observed after the lapse of about 20 seconds after exposure to the sun through the glass hemisphere. Whenever the glass hemisphere was removed, whether observing the sky by day or by night, or the sun, the deflection increased gradually for about 20 or 30 seconds, as with the heating current.

A clue was soon found. Generally if the sky is observed by day in Washington, with glass removed, almost no deflection occurs. The gain of heat to the blackened strips from scattered sun rays at Washington is almost equal to the loss of heat by emission of long-wave rays toward the sky. But if the observation is made on Mount Wilson, a large negative deflection occurs. At summer temperatures of observation the scattered sun rays at Mount Wilson are by no means equal in energy to the long-wave rays emitted toward the sky. Now it is well known that glass is a nearly perfect absorber of these long-wave rays, and hence is a nearly perfect radiator of them as well. But, on the other hand, the brightly polished metal cover, used as a shutter to the pyranometer, radiates almost nothing, being a nearly perfect reflector for long-wave rays. But the nickel plated cover absorbs about 30 per cent of the shorter-wave solar rays which meet it, and thereby is warmed, and warms the glass close below it by air convection. Now when the cover is removed the glass can cool rapidly by radiation, and as it is almost completely transparent to solar rays, it is hardly warmed at all by them. Hence the glass after exposure grows cooler than before, and as it subtends a full hemisphere, it tends strongly to reduce the temperature of the blackened strips below, thus causing the gradual decrease of the galvanometer deflection.

Having discovered the cause of error, the remedy was seen to lie in shortening the period of exposure so much that there would not be time for the glass to become appreciably cooled on the inside. We therefore began to investigate the behavior of the galvanometer with a view to observing the first swing instead of the permanent deflection.

As is well known to many readers, the time of swing of a moving coil galvanometer is shortest on open circuit, and increases as the external resistance in closed circuit diminishes, until at length no second swing occurs. Of two galvanometers tried by us both gave about 2 seconds' time of single swing on open circuit, but when closed on the pyranometer alone, one gave no second swing at all, the other a second swing of about 1/20 the magnitude of the first. By inserting 75 ohms or more resistance in series with the first galvanometer, it also gave a second swing, and the time of single swing of each galvanometer, when just giving a second swing, was about 4 seconds. Even with 75 ohms in series, the first-tried galvanometer gave about twice as much deflection as the other, but for several reasons we at length preferred the second one. This was a galvanometer by Rose, of Upsala, Sweden, made for use with the Ångström pyrheliometer. Its resistance is about 15 ohms. The resistance of the pyranometer is 30 ohms. When used with the pyranometer, whether with or without additional resistance of 200 ohms or less in series, the Rose galvanometer completes its first swing in about 4 seconds.

We next made tests with the heating current and with radiation at night to see if the first swing is proportional to the final deflection. We found this to be the case. We also found that both with the heating current and with nocturnal radiation, not only the first swing but the deflections, attained after 10, 15, 20, 25, and 30 seconds, maintained certain definite proportions to the final deflection, no matter what the strength of the current, or the intensity of the observed radiation. We also found that when proper allowance was made for the non-uniformity of sensitiveness of the galvanometer for large and small deflections, the deflections observed due to heating currents were exactly proportional to the square of the heating current employed.

These facts ascertained, the way seemed clear to avoid the source of error mentioned above, and at the same time to greatly increase the rapidity of reading the instrument, and also to avoid drifting of zero, so apt to occur in long exposures. In short for all daylight observations we adopted the plan of reading first swings, and of omitting exact adjustments of the energy of the heating currents to equal that of the observed radiation. Our present procedure in day work is as follows:

(1) On exposure to radiation, read the first swing of the galvanometer, and immediately close the shutter.

(2) After 30 seconds or more throw on a heating current sufficient to cause a deflection approximately equal to that from the radiation, and again note the first swing, and the exact strength of the heating current.

(3) Let D_R be the deflection due to radiation, D_C the deflection due to heating current, C the strength of current, and K the constant of the pyranometer. (For our pyranometer, A. P. O. No. 6, $K=2.54$.) Then the intensity of radiation $R=K\frac{D_R}{D_C}C^2$.

For the observation of nocturnal radiation we sometimes use the same method, but generally we effect an exact compensation of the nocturnal radiation by adjusting the heating current to reduce the galvanometer deflection to zero. In this way the temperature of the strips is brought back to the temperature of the air, and experience shows that even on windy nights the galvanometer is steady under these conditions. When the glass hemisphere is removed for night work, the constant of the pyranometer is decreased from 2.54 to 2.41. (See our earlier paper.)

When in the use of the pyranometer deflections are observed too large for convenient reading, a suitable resistance is used in series with the galvanometer. In new instruments a little switch is provided for this purpose and marked G. It provides three degrees of sensitiveness according as open or closed on one side or the other.

SAMPLE OBSERVATIONS MADE ON MOUNT WILSON

On the proportion borne by the deflections observed after fixed intervals to the final deflections due to different heating currents. Glass hemisphere on.

A. With German galvanometer. Resistance 58 ohms.

1. Current strength, 0.200 amperes. No extra resistance in circuit, and no definite first swing.

Time in seconds....	5	10	15	20	25	30	40	50	60	75
Deflection in cm ...	7.34	8.93	9 24	9.32	9.35	9.36	9.37	9.38	9.39	9.40
Proportion of final.	.781	.950	.983	.991	.993	.996	.997	.998	.999	1.000

2. Current 0.400 amp. Extra resistance 60 ohms. Deflections 20 to 23 cm.

Proportion of final.	.869	.967	.987	.994	.998	.999	.999	.999	1.000	1.000

3. Current 0.605 amp. Extra resistance 260 ohms. Deflections 20 to 23 cm.

Proportion of final.	.870	.966	.987	.993	.995	.999	.998	.999	.999	1.000

4. Current 0.802 amp. Extra resistance 560 ohms. Deflections 18 to 22 cm.

Proportion of final.	.820	.956	.987	.995	.997	.999	1.000	1.000	1.000	.999

B. With Swedish galvanometer.[1] Resistance 15 ohms.

1. Current 0.300. No extra resistance. Deflections 2.8 to 3.0 cm.

Time in seconds....	4	10	15	20	25	30	40	50	60	75
Proportion of final.	.915	.965	.984	.994	.994	.997	1.000	1.000	1.000	1.000

2. Current 0.385. No extra resistance. Deflections 4.6 to 5.0 cm.

Proportion of final.	.915	.965	.985	.995	.996	.998	1.000	1.000	1.000	1.000

From these experiments we see that the deflection attained after the first swing, or after any specified interval, is closely proportional to the final deflection whatever the strength of the heating employed. The final deflection is approximately attained in 20 seconds.

On the proportion borne by the deflection observed after fixed intervals to the final deflection, due to emission of nocturnal radiation. Glass hemisphere off.

A. German galvanometer. No extra resistance.

Time in seconds..............	5	10	15	20	25	Final
Deflection in cm......	9.28	11.40	11.84	11.90	11.79	11.89
Proportion of final............	.781	.959	.996	1.001	.992	1.000
Previous result with current...	.835	.960	.986	.993	.996	1.000

B. Swedish galvanometer.[1] No extra resistance.

Time in seconds..............	4	10	15	20	25	Final
Deflection in cm..............	1.90	2.00	2.02	2.06	2.05	2.09
Proportion of final...........	.910	.957	.967	.985	.981	1.000
Previous result with current...	.915	.965	.984	.995	.996	1.000

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[1] We here read the first swing, which occurred in approximately 4 seconds.

From these experiments we see that after definite intervals the deflection due to emission of nocturnal radiation reaches sensibly the same proportions of its final value that occur when heating currents are observed. Hence we may conclude that the true deflection due to the radiation of the sun or the sunlit sky, if such deflections could be observed apart from the secondary cooling effects described above, would follow the same law of increase with lapse of time as does the deflection due to current. Thus if the one is observed when the first swing is complete, the other should also be so observed to yield comparable results.

On the degree of uniformity of the scale of the Swedish galvanometer.

A constant source of electromotive force having been provided, deflections of the galvanometer were observed when the following values formed the total resistances in the galvanometer circuit.

Resistance in ohms R	10014	6014	3514	2514	1614	1214
First swing D	2.32	3.99	6.96	9.81	15.42	20.70
Final deflection D_1	1.92	3.31	5.80	8.16	12.88	17.20
Ratio $\frac{D}{D_1}$	1.208	1.206	1.200	1.202	1.197	1.203
Product $D \times R$	23230	23970	24430	24630	24910	25150

From these experiments it appears that the first swing is closely proportional to the final deflection for all parts of the scale. But the scale is evidently far from uniform, and gives greater sensitiveness for large deflections.

On the proportionality between deflection and the square of the heating current applied to the pyranometer.

Test made with Swedish galvanometer, reading first swings.

Current square C^2	.0395	.1580	.3472	.6292
Deflection D	1.175	4.835	10.93	20.00
Ratio $\frac{C^2}{D}$	.3361	.3268	.3176	.3146
Sensitiveness factor from scale test S	(234)	241	247	251
Product $\frac{C^2S}{D}$	(788)	788	787	788

From these experiments it appears that when proper allowance is made for non-uniformity of the sensitiveness of the galvanometer scale, the deflection observed is exactly proportional to the square of the strength of the heating current applied to the pyranometer. Hence it follows that if a certain current C_1 produces a deflection D_1, and a certain radiation R produces a slightly different deflection D_2, the radiation R would be exactly compensated by a current C_2 such that $\frac{C_1^2}{C_2^2} = \frac{D_1}{D_2}$. This valuable result enables us to dispense with the tedious process of producing exact compensations.

On the method of observing in daytime with the pyranometer as illustrated by sample observations on Mount Wilson.

AUGUST 7, 1916

Time	Zero	First swing	Defl. D	Object	Current (C) amperes	C^2	$\frac{C^2}{Dc}$	Calories
$2^h28^m0^s$	11.00	14.26	3.26	Sky........	......	......	......	0.137
	10.88	13.78	2.90	Current.......	.223	.0497	.0171	......
30 30	11.15	14.47	3.32	Sky..........	......	......	......	0.140
	11.28	14.48	3.20	Current.......	.231	.0534	.0167	......
33 30	14.98	21.96	6.98	Sun and sky...	......	......	......	1.240
	14.99	20.18	5.19	Current.......	.607	.368	.0709	......
35 30	14.99	21.86	6.87	Sun and sky...	......	......	......	1.220
	14.92	20.30	5.38	Current.......	.610	.372	.0691	......

On the method of observing at night with the pyranometer as illustrated by sample observations on Mount Wilson.

AUGUST 7, 1916

Time	Compensating current C amperes	C^2	Calories
$7^h55^m0^s$	.285	.0810	.195
57 20	.280	.0782	.188
8 0 0	.281	.0789	.190

NOTE.—Quite windy, but the galvanometer remained steady when balance was reached.

On the comparison of solar readings by the pyranometer and pyrheliometer as observed on Mount Wilson.

Observations made with pyranometer A. P. O. No. 6 and secondary pyrheliometer A. P. O. No. IV. Results in calories per cm.^{2} per min.

August 6, 1916. Hour Angles 1^h52^m to 1^h37^m

Secant *Z*.	1.160	1.148	1.137	1.132
Pyranometer × secant *Z*.	1.462	1.464	1.471	1.451
Pyrheliometer	1.477	1.469	1.467	1.460
Difference	+ .017	+ .005	— .004	+ .009

August 7, 1916. Hour Angles 5^h35^m to 5^h23^m

Secant *Z*.	4.017	3.808	3.620	3.448
Pyranometer × secant *Z*.	1.064	1.079	1.104	1.109
Pyrheliometer	1.067	1.077	1.087	1.118
Difference	+ .003	— .002	— .017	+ .009

From these experiments it appears that the pyranometer gives values of solar radiation comparable in accuracy with those observed with the pyrheliometer. As the results are of satisfactory accuracy at both great and small zenith distances, the pyranometer may be supposed to give accurate results on the sky, which involves all zenith distances.

DIRECTIONS FOR OBSERVING AND REDUCING OBSERVATIONS

Employ a galvanometer of not more than 60 ohms resistance giving a first swing within 5 seconds. If too sensitive diminish its deflection by a suitable resistance in series. Employ a heating current adjustable from zero to 0.8 amperes. If a storage battery is available it will be found the most satisfactory source to furnish the current, but dry cells may be used. A simple slide wire rheostat is required for nocturnal work. Employ an accurate ammeter for reading the current strength.

Daylight work.—Place the pyranometer on a level surface in the place where the intensity of radiation is to be measured. If the sun is sometimes to be shaded off, adjust the flat arc (which is the sunshade support) to lie north and south, set the arc to the latitude of the place, and set the shade to cast its shadow centrally on the pyranometer. The shade is to be turned forward as the sun goes westward. Employ the glass hemisphere in measurements of direct or scattered sun light. Remove it for nocturnal measurements. Be sure the glass screen has no dirt or finger marks upon it. (The glass may be cleaned by breathing upon it and while damp wiping with clean cloth or cotton.) When ready to observe, read the position of the galvanometer scale, open the shutter, read the first swing, close the shutter, wait a half minute, read the galvanometer, throw on a current suitable to give about the same swing, read the first swing, and read the current strength.

Let the deflection due to radiation be D_R, that due to current be D_C, the constant of the instrument be K ($=2.54$ for pyranometer A. P. O. No. 6 with glass on). Then the result in calories per cm.^{2} per min. is $K \frac{D_R}{D_C} C^2$. Where there is non-uniformity of the galvanometer scale, as here, it is of course necessary that D_C shall not differ greatly from D_R. We generally form the quotient $\frac{C^2}{D_C}$ and take the mean of several values of it to use for neighboring values of radiation.

Night work.—The glass hemisphere is removed. When ready to read note the zero of the galvanometer. On opening the shutter a negative deflection occurs. The zero of the galvanometer is then to be restored by throwing on a suitable current, and adjusting its strength by means of the slide wire rheostat until exact compensation is reached. This should occupy not less than 30 seconds to enable the apparatus to reach a steady state. Read the current, C. The intensity of radiation is given by KC^2, where K is the constant of the pyranometer with glass removed. (For pyranometer A. P. O. No. 6, K is then 2.41.)

SUMMARY

Test experiments tend to verify the accuracy of the pyranometer. A new method of observing is described which conduces to more accurate results and to quicker operation. Sample observations are given, as made with the two-strip pyranometer No. 6 on Mount Wilson. The new method of observing is applicable, however, to the one-strip form of pyranometer described in our former publication,[1] and if used in the new way it is possible that this simpler form of pyranometer will prove equally accurate as well as more sensitive than the two-strip form.

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[1] Smithsonian Misc. Coll., Vol. 66, No. 7.