M.O. 254a.

FOR OFFICIAL USE.

AIR MINISTRY.

METEOROLOGICAL OFFICE.

GEOPHYSICAL MEMOIRS, No. 21.

(*First Number of Volume III.*)

PYRHELIOMETER COMPARISONS

AT KEW OBSERVATORY, RICHMOND

AND THEIR BEARING
ON DATA PUBLISHED IN

THE GEOPHYSICAL JOURNAL

BY

R. E. WATSON, B.Sc.

Published by the Authority of the Meteorological Committee.

LONDON:
PRINTED & PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
To be purchased through any Bookseller or directly from H.M. STATIONERY OFFICE
at the following addresses: Imperial House, Kingsway, London, W.C.2, and
28 Abingdon Street, London, S.W.1; York Street, Manchester;
1 St. Andrew's Crescent, Cardiff; or 120 George Street,
Edinburgh.

1923.

Price 2*s*. 0*d*. *Net*.

Table of Contents.

Blue Cloth

Kettering on back :

Meteorological Offiee ,

Geophysical Memoirs Vol.111 ,

1923 - 1926

To be returned to :

Meteorological Office,

Royal Air Force,

Cranwell.

Sleaford.

Lincs.

PYRHELIOMETER COMPARISONS AT KEW OBSERVATORY, RICHMOND,

AND THEIR BEARING ON DATA PUBLISHED IN THE

GEOPHYSICAL JOURNAL.

---

§ 1. INTRODUCTORY.

IN 1905 the International Meteorological Congress at Innsbruck adopted the Ångström instrument as the standard pyrheliometer for direct observation of the intensity of solar radiation, as did also the International Union for Co-operation in Solar Research at Oxford in the same year. Among the resolutions of the latter body is one, "that it is desirable to obtain accurate comparisons between the records of Ångström's pyrheliometer and other standard instruments." In accordance with the ruling of the above-mentioned bodies, measurements of the intensity of solar radiation have formed a part of the regular routine at Kew Observatory since 1907, the pyrheliometer employed being the Ångström electrical compensated type. Observations have been taken within half an hour of noon on all fine days, the results being published in the *Geophysical Journal*, Part III., Section 2, of the *British Meteorological and Magnetic Year Book*. The conditions of the several instruments used have varied with age, and the published results of intensity of solar radiation have been affected to a corresponding degree.

In the following paper an attempt has been made to determine corrections to the published results to make them comparable with results from a standard Angström instrument. The corrections have been arrived at mainly by comparing the Ångström instruments, used in the normal observations, with an Abbot "Silver Disk" pyrheliometer, which, as the results will show, has behaved consistently since its reception in 1916. As the two types of pyrheliometer differ essentially in construction and methods of use, it seems desirable to give a brief description of the principles involved and the uncertainties which may be expected before proceeding to the discussion of the comparisons.

§ 2. THE ÅNGSTRÖM PYRHELIOMETER.

Description.—In the Ångström instrument* the radiation from the sun is received on a thin metal strip, coated on the receiving surface with dead black paint, to give as great an absorbing power as possible. The thermal capacity is small, so that the strip soon assumes a temperature at which it is radiating as quickly as it is absorbing heat. A second and similar strip is shielded from the sun, and raised

* Pyrheliometer, by Knut Ångström, *Astrophysical Journal*, Vol. IX, 1899, pp. 332–346, and *Actes de a Société royale des Sciences d'Upsala*, 1886.

(9745) Wt. 2159/8731 (P.F. 844) 130 625 8/23 Harrow G.69 A 2 to the same temperature as the first by the heating effect of an electric current passed through it. The two strips are placed side by side on a metal frame and it is assumed that their radiating properties are the same; also, that when their temperatures are equal, the rate of supply of energy to the two strips is the same. The rate at which electrical energy is expended in heating the second strip is given by ri^2 watts, where r is the electrical resistance in ohms, and i the current in ampères. Thus, the area of the exposed strip being known, we get the solar radiation per unit area from the formula,

$$S = Ki^2.$$

The constant K, depending on the area and electrical resistance of the strips, is determined before the instrument is sent out by the makers. As a delicate means of determining when the two strips have been raised to the same temperature, attached to the backs of the strips by means of zinc-white paint are thermo-couples of copper-constantan, the electro-motive-forces of which act in opposition in the same circuit as a reflecting galvanometer. When the temperature is the same in each strip there is no resultant electro-motive-force, and consequently no movement of the galvanometer needle. A sensitive milliammeter serves to measure the current in the second strip. When using the instrument each strip is exposed in turn and the mean current, for the time of exposure, is taken as $\frac{(A+2B+C)}{4}$ where A, B and C are three consecutive readings of the current. The time between successive readings is that required to direct the strip towards the sun, to cover one strip and expose the other, and adjust the current through the covered strip, until there is no deflection of the galvanometer needle. This time is shorter the more expert the observer, and is generally about half a minute.

Errors.—Although the Ångström instrument has been found to be generally satisfactory, there are possibilities of error by which the results may be affected, although these errors, according to the inventor, do not amount to more than 1·8 per cent. in a standard instrument. The blacking of the strips may be affected by age, resulting in a decreased absorbing power of the strips, and it is not probable that the two strips will be affected to the same extent. The thermal contacts of the thermo-couples may deteriorate with time and the deterioration is not likely to be the same for each strip. The method of observation attempts to allow for this by exposing the strips alternately. If the thermal contacts were the same, other circumstances being equal, we should, theoretically, get the same current i whichever strip was exposed. In practice, however, there is usually a difference; but, provided the difference in the currents is due solely to difference in thermal contacts a simple calculation shows that if the ratio of the currents for the two strips lies between 0·8 and 1·2, the resulting error is not more than 1 per cent. The accuracy of the milliammeter may vary with time, but frequent standardization of the instrument will supply any necessary corrections to its scale readings.

Further uncertainties arise owing to the practical difficulties of determining accurately the constants of the strips. Paschen found that slight errors occur from lack of uniformity in the thickness of the metal. Then the theoretical question presents itself as to whether a strip heated internally by an electric current is under the same radiation conditions as one heated by external radiation. If not, then the amount of electrical energy required to maintain it at the same temperature as the exposed strip would not be equal to the solar radiation energy received by the latter.

This question has been exhaustively treated by Kurlbaum,* and the order of magnitude of the error introduced is stated as not greater than ½ per cent. W. Marten† has recently found that the readings of the Ångström pyrheliometer which he used were systematically too low by 2·8 per cent., owing to the method of exposing the strips to the sun. The error arises from the fact that small portions of the ends of

* cf. A. K. Ångström, *Astrophysical Journal*, Vol. XL, 1914, p. 275.

† W. Marten, " Zur Frage der absoluten pyrheliometrischen Skala," *Meteorologische Zeitschrift*, November 1922.

the strip which is exposed to the sun are shaded from direct radiation, whilst the unexposed strip is heated throughout its whole length by the electric current. If, then, all Ångström instruments are constructed identically with the one examined, all will be subject to this systematic error. The errors arising from a deterioration of the blacking and the thermal contacts of the thermo-couples are the most important, since they are not constant. The other uncertainties mentioned above, while probably giving rise to slight errors in the absolute values of the solar radiation, would still leave observations with the same instrument strictly comparable among themselves, whereas an error which may change with time, if it is serious, will affect the utility of the pyrheliometer even for purposes of studying secular change in the solar radiation. Thus, it is of great advantage to be able to compare such an instrument from time to time with one like the Abbot " Silver Disk " pyrheliometer, which is presumed to be free from variable errors.

§ 3. The Abbot Pyrheliometer.

Description.—In the Abbot " Silver Disk " pyrheliometer,* a small silver disc is exposed to the solar radiation and the intensity of the radiation is measured by observing directly the temperature changes produced in the disc. The disc is covered with dead black paint and is fitted near the opening of a containing chamber whose interior is also painted dead black. The instrument is so devised that no irregular temperature changes affect the disc. The temperature of the disc is read by means of a mercury thermometer whose bulb is inserted in a hole bored radially in the disc, thermal contact being maintained by mercury between the bulb and the disc. The thermometer is graduated in tenths of a degree Centigrade, and the temperature can be read to one-hundredth of a degree. The thermometer stem is carefully calibrated, and the corrections for different parts of the stem are given as percentage corrections to be applied to the measured rise or fall in temperature. Theoretically, a knowledge of the thermal capacity of the disc and attachments would enable us to deduce the rate at which solar radiation is received. In practice, however, the computation of this quantity would be difficult. The bulb of the thermometer, along with the glass, the mercury and other substances which are fixed to the disc for various purposes form a considerable portion of the heated body, so that it is practically impossible to measure accurately the thermal capacity of the heated bodies *in situ.* The really important point is that this quantity should remain constant, so that the instrument, although unsuitable for direct absolute measurements, should provide a reliable method of making observations which are comparable amongst themselves.

Standardization.—An absolute pyrheliometer has been constructed at the Smithsonian Institution by comparison with which all " Silver Disk " pyrheliometers are standardized, these latter instruments being known as secondary standards. The standardization renders unnecessary the knowledge of the thermal capacity of the disc, as a constant factor is obtained for each instrument, which, when applied to the final corrected rise in temperature over a specified time, gives the intensity of solar radiation in milli-watts per square centimetre.

Method of Use.—In using the Abbot instrument a definite interval of time is laid down for exposing and covering the disc, for which interval the constant factor supplied with the instrument applies. The total time taken for a single determination of the intensity of solar radiation is six minutes, as is shown in the following brief description of the operation :—

The instrument being directed to the sun, the disc is covered and the change in temperature for a 100-seconds interval is observed. The disc is then exposed to the sun and the rise in temperature for a 100-seconds interval is noted, when the disc is again covered. These operations are continued alternately as long as is desired, two shaded intervals and the intervening exposed interval being necessary for the determination of the solar radiation, as illustrated below.

* *Smithsonian Miscellaneous Collections,* 1911, Vol. LVI, No. 19.

TABLE I. REDUCTION OF ABBOT OBSERVATIONS.

Date, July 12, 1921. Air Temperature 27·3° C.

	Disc Shaded.		Disc Exposed.		Disc Shaded.	
Reading number	1	2	3	4	5	6
Time	h m s 11 46 20	h m s 11 48 00	h m s 11 48 20	h m s 11 50 00	h m s 11 50 20	h m s 11 52 00
Temperature	41°·25 C.	40°·05 C.	40°·30 C.	41°·72 C.	41°·50 C.	40°·32C.
Differences	1°·20 C.		1°·42 C.		1°·18 C.	
Cooling Correction	—		1°·19 C.		—	
R. (Real Rise in Temperature) ..	—		2°·610 C.		—	
Mean Temperature during exposure	—		41°·0 C.		—	
Corrections	—		+ 0°·049 C.		—	
R′ (Rise in Temperature corrected to Standard Conditions).	—		2°·659 C.		—	
Intensity of Radiation≡R′×35·38 (Constant Factor)=67·49 milliwatts/cm².						

The corrections which go to form the resultant correction +0°·049 C. are a calibration scale correction, a correction for the difference from a standard bulb temperature of 30° C., and a correction for the difference of the air temperature from a standard stem temperature of 20° C.

Errors.—Accidental errors in the measurement of the intensity of solar radiation with an Abbot pyrheliometer would be liable to arise from errors in timing the 100–seconds interval during which the disc is exposed or shaded. An error of ± 1 second at the beginning and end of the exposed period would result in an error of ± 2 per cent. in the final value. With a skilled observer, however, and using the " eye and ear " method with a chronometer for timing, errors of this magnitude are extremely unlikely. Moreover, for a long comparison of instruments, from which the mean of the intensity of solar radiation is computed for that period, the total error from this source should be negligible. Experiments made by the Smithsonian Institution have shown that the accidental error of observation, with experienced observers, is not greater than 0·3 per cent.

It will be noted that during a comparison of these two types of pyrheliometer, while the Ångström observer takes readings with the strips exposed alternately, at intervals depending on circumstances, the Abbot observer has his times very definitely scheduled, and as the two observers are obliged to work more or less independently, it is not easy to obtain readings on the two instruments for exactly the same period. The result is that the mean Ångström value over the interval during which the Abbot disc is exposed is to some extent a compromise, the computer using his judgment as to what readings give the best mean for the interval. During a long comparison, however, the final means for the period of comparison should fairly represent the mean intensities of solar radiation as measured by the two instruments. There is no obvious point in the construction of the Abbot pyrheliometer which would lead us to suspect probable changes in its constant factor, such as we have in the thermo-couple attachment of the Ångström instrument. The only likelihood of such a change occurring is in the possible deterioration of the blacking on the receiving surface of the disc. This question has been investigated at the Smithsonian Institution, and it is claimed that defects in the blacking over a period of five years have an effect of less than 1 per cent. on the results. If, then, we accept the conclusion reached by the Smithsonian Institution that over a long period there is no sensible change in the constant factor of the Abbot secondary pyrheliometer, comparisons with other pyrheliometers at intervals should determine the changes in the constants of these instruments.

§ 4. The Ångström Instruments used at Kew Observatory.

For routine work three Ångström pyrheliometers have been in use at Kew Observatory, No. 24, No. 100 and No. 157, and the following gives a brief history of the instruments:

No. 24.—In use from May–Sept. 1907, Sept. 1911–Sept. 1912, May 1916–June 1921; used when observations first commenced and intermittently up to the present time without alteration to any of its parts.

No. 100.—In use from Oct. 1907–Aug. 1911, April 1914–April 1916, July 1921 onwards; considered to be a better instrument than No. 24, it was in use from October 1907 until August 1911 when one of the strips was found to be damaged. After repair by the maker it was re-introduced in April 1914. It was again damaged in April 1916 and was sent for repair. It was brought into use again in July 1921 and is the instrument used at present.

No. 157.—In use from Oct. 1912–April 1914; received on loan from Upsala to replace No. 100 while the latter was being repaired in 1912. It was used until April 1914 when, on the receipt of No. 100, it was returned to Upsala.

No. 24 is of the older type of instrument, in which the strips are made of platinum, the electrical resistance of which changes sensibly with variations in temperature. No. 100 and No. 157 are later, improved instruments, whose strips are of manganin, this metal being adopted owing to its small temperature coefficient of resistance. As No. 24 has been in use at the Observatory for the whole period under survey, if we had known how its constant had varied, if at all, we could have determined, by comparison with the other pyrheliometers in use, the true relation between the values of the solar radiation obtained at various times. On its arrival No. 157 was regarded as a superior type of instrument to No. 24, and a comparison between the two showed that No. 24 was reading $4\frac{1}{2}$ per cent. lower than No. 157. Assuming No. 157 to be a standard instrument of its type, a correction of $+ 4\frac{1}{2}$ per cent. was made to the values of solar radiation observed in August and September 1912, when No. 24 was in use. This correction should be extended to the whole remaining period when No. 24 was employed in 1911 and 1912.

No systematic comparison was carried out, however, until the Abbot "Silver Disk" secondary pyrheliometer No. 28 was received from the Smithsonian Institution in 1916. In the absence of systematic comparison prior to that date, as a test of constancy, or otherwise, of the Ångström instruments, an examination has been made of the readings taken during each period when a particular instrument was in use. As already mentioned, the two factors most likely to introduce a change in the constant of the instrument are the thermo-couple attachments and the blackening of the strips, and it is extremely unlikely that both strips will be affected to the same extent by a deterioration in these factors. Consequently, if either or both these effects be active, as the instrument ages we should expect to find a difference in the ratio of the electric currents when the strips are exposed in turn.

§ 5. Tests of the Constancy of the Instruments.

At Kew the observations are recorded for each strip, the strips being distinguished as "left-hand" (L), and "right-hand" (R). In Table II the mean ratio of the currents, measured with the right-hand strip exposed and the left-hand strip exposed, has been obtained for each month since the Ångström instrument was introduced in 1907. The constancy, or otherwise, of this ratio provides a rough guide to the constancy of the instrument. In those months marked with an asterisk the number of observations was five or less, so that much reliance cannot be placed on the results.

TABLE II.—MEAN MONTHLY RATIO OF CURRENT MEASURED WHEN "R" EXPOSED TO CURRENT MEASURED WHEN "L" EXPOSED FOR ÅNGSTRÖM INSTRUMENTS NOS. 24, 100 AND 157.

Instrument.	Year.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
No. 24 ..	1907	—	—	—	—	1·00	0·93	1·08	1·09	1·09	—	—	—
	1911	—	—	—	—	—	—	—	—	0·98	1·03	1·02	0·89*
	1912	0·95*	0·94*	0·92*	0·94	0·93	0·92	0·96	0·93*	0·94	—	—	—
	1916	—	—	—	—	1·01	0·99*	1·00	1·00	1·00	1·01	0·97	0·98*
	1917	0·95	0·94	0·94	0·93	0·95	0·98	1·00	1·00	0·99	0·96	0·94	0·89
	1918	0·83	0·87	0·89	0·92	0·96	0·97	1·00	1·00	0·99	0·98	0·96	0·99
	1919	1·01	0·86	—	1·00	—	—	0·98	1·09	1·00	0·96	0·93	0·97
	1920	0·96	0·95	0·98	0·99*	1·00	1·01	1·03*	1·01	1·02	0·98	0·95	0·94
	1921	0·95	0·94	0·95	0·96	0·99	0·97	—	—	—	—	—	—
No. 100 ..	1907	—	—	—	—	—	—	—	—	—	1·02	1·02	1·02
	1908	1·04	1·02	1·03	1·02	1·02	1·02	1·02	1·01	1·02	1·02	1·02	1·02
	1909	1·02	1·03	1·00*	1·01	1·02	1·01	1·01	1·01	1·02	1·01	1·02	1·02
	1910	1·02	1·02	1·01	1·01	1·01	1·00	1·01	1·01	1·01	1·01	1·01	1·01
	1911	—	1·01	1·01	1·01	1·01	1·01	1·01	1·00	—	—	—	—
	1914	—	—	—	0·99	0·98	0·99	0·96	0·98	0·98	0·98	0·98	0·98
	1915	0·99	0·99	1·00	1·00	0·98	0·99	0·99	0·99	0·99	0·99	1·00	0·99*
	1916	1·00	1·00	0·98*	0·99	—	—	—	—	—	—	—	—
	1921	—	—	—	0·99	—	1·00	1·05	1·08	1·10	1·10	1·05*	1·11
	1922	1·08	1·10	—	—	—	—	—	—	—	—	—	—
No. 157 ..	1912	—	—	—	—	—	—	—	—	—	0·98	0·96*	0·98*
	1913	0·97	0·98*	0·96*	0·96	0·96	0·97	—	—	—	—	—	—
	1914	—	0·95*	0·98	0·98	—	—	—	—	—	—	—	—

* Five Observations, or less, available for the compilation of the monthly mean.

The table shows that prior to 1914, during the periods when instruments No. 100 and No. 157 were in use, the relative readings given by the two strips showed practically no change, and in the absence of further evidence to the contrary, it will be assumed that the results obtained with these two instruments prior to 1914 were such as would have been obtained with standard instruments, and that no corrections are needed. It will be noticed that the strips of No. 100 gave practically equal readings immediately after its return from the makers in April 1921, but that in July of that year a change appeared, the right-hand strip giving higher readings than the left. No obvious cause for this change was detected by an examination of the strips, nor do the values of the intensity of solar radiation seem to be affected by this change, so far as can be judged from a comparison of this instrument with the Abbot pyrheliometer before and after the change. The ratio of the currents remains fairly constant after July, so that we may take it that any relative change in the strips ceased at the end of that month.

No. 24 shows large variations, and in the years 1917–1920 the figures would lead one to suspect a regular seasonal change in the instrument, as the ratio of the currents shows a steady rise towards midsummer, and from then a fall towards midwinter. However, an examination of the observations failed to detect any connection between the above ratio and the intensity of solar radiation in any particular month, otherwise it might naturally be supposed that the connections between the strips and the thermo-couples were affected by temperature. If the difference is due to defects in the blacking with consequent loss of absorbing power, the decreased absorption of one strip is not compensated by any higher absorption in the other strip, and we get a value for the intensity of solar radiation which is too low, whether one or both strips are affected. It is evident that the separate observations with individual strips give no indication of the extent or even the presence of an error due to this cause, hence the importance, from this point of view, of periodic comparisons with an independent instrument.

§ 6. Comparison between the Pyrheliometers Ångström No. 100 and Abbot No. 28.

The first comparisons of this nature carried out at Kew were between Ångström pyrheliometer No. 100 and the Abbot "Silver Disk" pyrheliometer No. 28, in April and May 1916. Thereafter, owing to an accident to the strips of No. 100, Ångström No. 24 was compared from time to time with Abbot No. 28, until Ångström No. 100 was finally repaired in April 1921. After this date intercomparisons were made between the Ångström instruments No. 24 and No. 100 and Abbot No. 28. The results are therefore given in separate tables. As Ångström No. 24 has been used for comparisons since 1916, the results obtained, assuming Abbot No. 28 unchanged, may be used for standardizing the values of the intensity of solar radiation since published.

The results of comparisons between Ångström No. 100 and Abbot No. 28 are given in the following tables:

Table IIIA. Comparisons of Pyrheliometers. Abbot No. 28 and Ångström No. 100.

Comparison Number.	Observers.	Date.	Number of Readings.	Air Temperature.	Mean Ratio :— Abbot 28 / Ångström 100.
		1916—			
1	E. G. Bilham	April 11	3	—	1·09
2	and	May 19	5	22° C.	1·07
3	E. H. Nichols	May 20	4	22° C.	1·44
4		May 24	4	21° C.	1·01
5		June 17	3	12° C.	1·17
6		Sept. 7	3	20° C.	1·24
7	C. D. Stewart and N. Tunstall.	1917, April 26	3	8° C.	1·14

Table III B. Comparison of Pyrheliometers. Abbot No. 28 and Ångström No. 100.

Comparison Number.	Observers.	Date.	Number of Readings.	Air Temperature.	Mean Ratio :— Abbot 28 / Ångström 100.
		1921—			
1	R. E. Watson,	April 8.	32	7·7° C.	1·031
2	E. Taylor	April 12.	15	18·9° C.	1·025
3	and	April 13, a.m.	8	19·5° C.	1·018
4	C. H. Kellett.	April 13, p.m.	2	21·2° C.	1·030
5		June 2.	3	20·4° C.	1·046
6		June 17.	6	23·8° C.	1·047
7		July 12, a.m.	10	27·3° C.	1·040
8		July 12, p.m.	10	28·9° C.	1·058
Final Mean Ratio (weighted according to number of observations)					= $1{\cdot}035_6$

Table III A is of interest principally as showing the considerable variation introduced into the values of solar radiation as measured by the Ångström pyrheliometer, by the varying conditions of the strips. Only comparison No. 1 on April 11 has any bearing on the published values of the intensity of solar radiation, the remaining comparisons having been made after an undoubted deterioration of the Ångström instrument. In the interval between comparisons Nos. 1 and 2 the blacking of one of the strips of the instrument had been damaged. The strips were reblacked and comparison No. 2 shows that after this operation the instrument was reading much as before. Almost immediately, however, the blacking was again found to be seriously defective, as shown by comparison No. 3 made the following day, when the instrument was reading very low. The comparisons Nos. 4, 5, 6 and 7 were made after the instrument had been repaired by an instrument maker and they seem to show a steady deterioration in it. It is uncertain, however, what the exact condition of the instrument was at this period, as there is some reason to think that the blacking was renewed at least once. Thus, corrections to the published values for 1916 have been based on the comparisons made with Ångström No. 24.

Table III B gives the results of 86 observations of the ratio of Abbot 28 to Ångström 100, immediately after the latter had been returned from the makers after overhauling and repair. Before despatch to Kew the instrument was compared with the standard Ångström pyrheliometer No. 70 at Upsala, and the constant factor used was that obtained from this comparison. Thus, the results should be regarded as those obtainable from a freshly standardized instrument. Assuming Ångström No. 100 at this time to be such an instrument, the ratio $1\cdot035_6$ obtained from the comparison of Ångström No. 100 and Abbot No. 28 indicates that the Abbot pyrheliometer was normal. W. Marten* found from observations with five Ångström instruments that the ratio Abbot/Ångström varied from $1\cdot035$ to $1\cdot053$, while in 1913, Kimball, at the United States Weather Bureau found the ratio to be $1\cdot047$. In 1919, Dr. Anders Ångström at the Meteorological Bureau, Stockholm, gave the ratio as $1\cdot032$. As the final mean value for this ratio given in Table III B agrees closely with the ratio obtained for standard Ångström and Abbot instruments, it will be assumed, in the absence of evidence to the contrary, that Ångström No. 100 and Abbot No. 28, at this time, were both standards of their types. Thus, no corrections will be applied to results published for 1921, after the introduction of Ångström No. 100 for regular observations.

There is no reason to suppose that any appreciable change took place in the Abbot instrument, as it had never been dismantled, nor had the disc been removed from its normal position. It has already been remarked that under these circumstances the Smithsonian Institution failed to detect any sensible deterioration of the disc in an interval of five years.

Thus, taking the Abbot pyrheliometer as unchanged and the ratio for the standard instruments Abbot/Ångström $= 1\cdot035_6$, the comparison No. 1, Table III A would give for No. 100 in terms of the normal Ångström scale in April 1916, prior to its injury, a value $\frac{1\cdot035_6}{1\cdot09}=0\cdot950$. This shows that at the time No. 100 was reading 5 per cent. too low and consequently the published results need a $+5$ per cent. correction. The result of comparison No. 1, Table III A, in April 1916, has also a direct bearing on the values of the intensity of solar radiation obtained from April 1914, when Ångström No. 100 was re-introduced for routine work. On five days in September 1914, comparisons were made at Kew between Ångström No. 100 and Ångström No. 116, which was the pyrheliometer normally employed at Eskdalemuir Observatory. The results showed that No. 100 was reading from 5 to 6 per cent. lower than No. 116. Now, although there is no evidence to indicate that No. 116 was a standard instrument, it was newer than No. 100 and had not been damaged, whereas No. 100 had been repaired and suffered a journey from Upsala to America and back just prior to the comparison. Hence, this comparison certainly provides indirect evidence that No. 100 was reading too low on its re-introduction in 1914, and, in the absence of more conclusive evidence, to cover the period when No. 100 was in use, we are justified in extending to April 1914, the $+5$ per cent. correction given as a result of the comparison with Abbot No. 28 in April 1916.

§ 7. Tests of Ångström Pyrheliometer No. 24.

The following table gives the results of direct comparison made in 1921 between Ångström No. 24 and the freshly standardized No. 100.

---

* *Ergebnisse der meteorologische Beobachtungen in Potsdam*, 1911, p. 11.

TABLE IV.—COMPARISON BETWEEN PYRHELIOMETERS ÅNGSTRÖM NOS. 24 AND 100.

Comparison Number.	Observers.	Date.	Number of Observations.	Air Temperature.	Mean Ratio :— Ångström 24 / Ångström 100.
		1921—			
1	R. E. Watson,	April 5.	4	11°·6 C.	0·863
2	E. Taylor	April 8.	5	12°·4 C.	0·849
3	and	April 12.	15	18°·9 C.	0·864
4	C. H. Kellett.	April 13.	2	21°·2 C.	0·856
5		June 2.	3	20°·4 C.	0·879
6		June 17.	5	23°·8 C.	0·887
7		July 12, a.m.	8	27°·3 C.	0·869
8		July 12, p.m.	10	28°·9 C.	0·901
Final Mean Ratio (weighted according to number of observations)					= 0·873

The final mean from the above table shows that Ångström No. 24 was reading 12·7 per cent. lower than Ångström No. 100 at the time stated, so that the published values for the intensity of solar radiation for 1921, up to the end of June, when observations with No. 24 ceased, need a correction of +13 per cent.

Table V. below covers the period from 1916 to 1921 when Ångström No. 24 was employed, and provides data for obtaining the necessary corrections for the years in question.

TABLE V.—COMPARISON OF PYRHELIOMETERS ÅNGSTRÖM NO. 24 AND ABBOT NO. 28.

Comparison Number.	Observers.	Date.	Number of Observations.	Air Temperature.	Mean Ratio : Ångström 24 / Abbot 28.	Mean for Year.*
		1916—				
I.	E. G. Bilham	May 19.	3	22° C.	0·854	
	and	May 20.	4	22° C.	0·847	0·850
	E. H. Nichols.	Sept. 7.	2	20° C.	0·848	
		1917—				
II.	C. D. Stewart	April 24.	12	11° C.	0·887	0·889
	and N. Tunstall.	April 26.	1	8° C.	0·908	
		1918—				
III.	R. E. Watson	May 9.	10	17° C.	0·883	
	and	May 10.	4	11° C.	0·916	
	A. C. Lloyd.	May 17.	6	24° C.	0·880	
		May 18.	10	21° C.	0·927	0·900
		May 21.	4	26° C.	0·920	
		May 22.	4	27° C.	0·866	
		1920—				
IV.	R. E. Watson,	Sept. 20.	16	16° C.	0·890	
	C. H. Kellett	Oct. 20.	13	14° C.	0·894	
	and	Oct. 30.	14	11° C.	0·889	0·881
	F. J. Scrase.	Nov. 2.	5	7° C.	0·852	
		Nov. 17.	15	10° C.	0·873	
		Nov. 19.	15	13° C.	0·871	
		1921—				
V.	R. E. Watson,	Feb. 2.	5	13° C.	0·849	
	C. H. Kellett	April 12.	15	19° C.	0·844	
	and	April 13.	1	21° C.	0·848	
	E. Taylor.	June 2.	3	20° C.	0·848	0·843
		June 17.	6	24° C.	0·822	
		July 12, a.m.	8	27° C.	0·835	
		July 12, p.m.	11	29° C.	0·855	

* Weighted according to number of observations.

From a study of the above table we are led to the conclusion that at first the change in the Ångström No. 24 instrument was in the direction of improvement up to the middle of 1918 when deterioration commenced.

As stated previously, it is proposed to assume that Abbot No. 28 and Ångström No. 100, as they were in 1921, were standards of their types. The comparison shown in Table III B indicates that the ratio between the pyrheliometric scales of these two instruments is $1 \cdot 035_6 : 1$. The mean of the ratio of the scale values of Ångström No. 24 and Abbot No. 28, given for each of several years in Table V, is transcribed in Table VI and multiplied by $1 \cdot 035_6$ to give yearly means for the ratio of the scale of Ångström No. 24 to the standard Ångström scale. The corresponding corrections to be applied to the readings published in the *Geophysical Journal* are also shown.

TABLE VI.—CORRECTIONS TO THE OBSERVATIONS TAKEN WITH ÅNGSTRÖM NO. 24.

Year.	Observed Mean Ratio Ångström $_{24}$/Abbot $_{28}$	Computed Mean Ratio Ångström $_{24}$/Ångström $_{100}$	Corrections to published values.
1916	0·850	0·880	+12 per cent.
1917	0·889	0·921	+ 8 per cent.
1918	0·900	0·932	+ 7 per cent.
1920	0·881	0·912	+ 9 per cent.
1921	0·843	0·873	+13 per cent.

In 1919 no comparisons were made between the Abbot and Ångström pyrheliometers, but it is obvious from the above table that some correction should be assigned to the values published for 1919, for Ångström No. 24 was then in use. Taking the view that the improvement in No. 24 had reached a maximum in the middle of 1918, and that then a steady deterioration set in, the correction for 1919 should be +8 per cent., a mean of the corrections for the adjacent years.

§ 8. SUMMARY OF CORRECTIONS TO BE APPLIED TO PUBLISHED DATA.

Finally, the corrections arrived at may be summarised in chronological order from the commencement of the observations in 1907, as follows :—

TABLE VII.—CORRECTIONS TO THE PUBLISHED VALUES OF THE INTENSITY OF SOLAR RADIATION MEASURED AT KEW OBSERVATORY.

Ångström Instrument.	Period.	Corrections.
No. 24	1907—May–Sept.	Nil.
„ 100	1907—Oct.–Dec.	Nil.
„ 100	1908—All months.	Nil.
„ 100	1909—All months.	Nil.
„ 100	1910—All months.	Nil.
„ 100	1911—Jan.–Aug.	Nil.
„ 24	1911—Sept.–Dec.	+ 4·5 per cent.
„ 24	*1912—Jan.–July.	+ 4·5 per cent.
„ 157	1912—Oct.–Dec.	Nil.
„ 157	1913—All months.	Nil.
„ 157	1914—Jan.–April.	Nil.
„ 100	1914—May–Dec.	+ 5 per cent.
„ 100	1915—All months.	+ 5 per cent.
„ 100	1916—Jan.–April.	+ 5 per cent.
„ 24	1916—May–Dec.	+ 12 per cent.
„ 24	1917—All months.	+ 8 per cent.
„ 24	1918—All months.	+ 7 per cent.
„ 24	1919—All months.	+ 8 per cent.
„ 24	1920—All months.	+ 9 per cent.
„ 24	1921—Jan.–June.	+ 13 per cent.
„ 100	1921—July–Dec.	Nil.

* Published values for August and September, 1912, already corrected.

The Geophysical Journal was first published in 1911, in the *British Meteorological and Magnetic Year Book*, Part III, Section 2. Previous to that year mean monthly values of the solar radiation were published in the Annual Report of the Observatory Department of the National Physical Laboratory, but these values will not be considered here as no corrections are needed prior to 1911.

The following table gives the revised values, from 1911 to 1921, of the intensity of solar radiation measured at Kew Observatory, after the application of the corrections shown in Table VII, to the values already published in the *Geophysical Journal*.

For details of the state of the sky prevailing on the dates enumerated reference should be made to the appropriate number of the *Geophysical Journal*. Some idea of the consistency of the results obtained by the application of the corrections may be gathered from the following figures which are the means of the intensity of solar radiation for the nine days of highest value in each year. Nine days have been taken because an examination of the observations seemed to indicate that nine was the best average number of really exceptional days for observation of solar radiation in the years under review. The corrected means in mw/cm^2 from 1911 to 1921 inclusive are 88, 87, 79, 85, 85, 89, 85, 85, 82, 86, 87 respectively. The low values for 1913 and 1919 are probably due to the limited number of observations in those years, no observations having been made from July to December, 1913, and none in March, May and June of 1919.

TABLE VIII.—REVISED VALUES OF THE INTENSITY OF SOLAR RADIATION AT NOON BY THE ÅNGSTRÖM PYRHELIOMETER.

Richmond, Kew Observatory.

1911. Date.		mw/cm²
Jan.	—	No obs.
Feb.	24	63
March	1	72
	2	85
	9	87
	21	37
	24	44
	25	72
	28	51
April	3	83
	10	61
	12	67
	13	72
	20	80
	22	79
	24	88
	26	87
	28	83
	29	91
May	4	90
	8	47
	10	51
	11	53
	13	62
	22	60
	23	59
	24	69
	29	59
	30	61
	31	46
June	1	62
	2	68
	3	64
	6	46
	7	63
	8	81
	9	68
	13	87
	15	61
	27	70
	28	83
July	3	82
	5	82
	6	70
	7	59
	8	64
	10	65
	12	78
	13	78
	14	76
	18	88

1911. Date.		mw/cm²
July	19	86
	21	84
	24	61
	25	61
	27	87
	28	58
Aug.	1	82
	4	88
	8	83
	9	74
Sept.	6	58
	7	69
	8	66
	18	69
	21	76
	22	53
	23	53
	25	78
	26	73
	27	71
	29	66
	30	74
Oct.	6	25
	7	32
	11	43
	12	27
	22	54
	25	71
Nov.	6	74
	7	65
	9	63
	29	38
Dec.	4	48
	5	40
	8	52
	11	60
	13	39
	19	31
1912.		
Jan.	2	27
	5	62
	8	51
	29	28
Feb.	10	65
	17	41

1912. Date.		mw/cm²
Mar.	21	71
	26	78
	27	72
	29	84
	30	82
April	3	64
	10	88
	12	46
	13	56
	16	70
	18	76
	19	79
	20	69
	22	68
	23	74
	24	65
	25	79
	26	42
	30	78
May	1	67
	2	75
	9	61
	10	44
	11	61
	13	71
	14	67
	16	94
	25	72
	28	87
	29	67
	30	59
June	4	91
	5	83
	6	67
	10	90
	19	78
	21	73
	22	87
	26	69
	28	75
	29	67
July	12	61
	15	49
	16	47
	17	50
Aug.	20	56
	22	60
Sept.	4	67
	9	49
	18	21
	21	53

1912. Date.		mw/cm²
Sept.	27	59
	28	32
Oct.	3	61
	4	51
	5	46
	7	52
	17	53
	18	58
	19	57
	25	35
Nov.	1	50
	2	45
	22	42
Dec.	17	39
	29	33
1913.		
Jan.	2	26
	6	50
	9	38
	12	41
	15	40
	16	46
	27	26
	31	48
Feb.	8	53
	11	32
	22	51
	27	60
Mar.	5	70
	15	62
	18	61
	21	69
April	3	43
	13	68
	17	78
	19	80
	20	77
	23	32
	24	49
	29	57
May	11	72
	13	63
	15	58
	16	62
	17	65

1913. Date.		mw/cm²
May	18	82
	23	70
	24	80
	25	78
	26	68
	28	74
	30	78
June	2	77
	15	69
	16	59
	18	66
	25	48
	28	80
	29	75
July	1	61
Aug.	—	No obs.
Sept.	—	No obs.
Oct.	—	No obs.
Nov.	—	No obs.
Dec.	—	No obs.
1914.		
Jan.	—	No obs.
Feb.	16	34
	24	26
	25	31
	28	60
March	10	75
	11	73
	12	73
	17	65
	27	37
	31	82
April	6	79
	8	81
	14	83
	15	51
	16	54
	17	73
	18	73
	20	37
	21	32
	26	40
	28	69

Table VIII (*continued*).

Richmond, Kew Observatory.

1914.		
Month	Date.	mw/cm²
May	2	83
	12	85
	18	83
	19	41
	20	46
	21	83
	22	69
June	3	90
	4	58
	8	80
	10	82
	11	75
	15	79
	18	53
	24	89
	25	83
	27	70
	29	79
	30	90
July	4	88
	9	81
	10	69
	11	26
	13	84
	14	79
	17	85
	18	82
Aug.	11	78
	12	78
	17	79
	18	68
	19	26
	21	27
	22	77
	27	75
	29	78
Sept.	1	71
	2	78
	4	38
	6	32
	7	26
	8	72
	9	82
	18	66
	19	71
	21	75
	22	53
	23	83
	24	76
Oct.	1	74
	3	45
	7	53
	8	57
	24	57

1914.		
Month	Date.	mw/cm²
Oct.	26	77
	27	62
	28	68
Nov.	3	72
	5	67
	7	45
	14	65
	17	47
	20	37
	25	59
	26	50
Dec.	3	59
	21	53
	24	23
1915.		
Jan.	2	44
	11	50
	17	55
	18	50
	29	57
Feb.	1	32
	5	55
	9	63
	10	71
	16	67
	25	71
	26	70
Mar.	8	71
	19	77
	20	84
	21	67
	27	68
April	8	84
	9	87
	10	85
	11	45
	14	80
	16	81
	17	68
	19	82
	21	75
	28	53
	29	57
	30	58
May	3	75
	6	80
	7	72
	8	60
	9	59
	10	61

1915.		
Month	Date.	mw/cm²
May	11	40
	15	43
	19	56
	23	67
	25	64
	26	61
	27	77
	31	79
June	4	68
	7	67
	8	77
	13	23
	14	64
	15	54
	17	53
	19	70
	20	77
	21	59
July	6	55
	9	79
	15	87
	20	84
	27	85
	28	82
	29	78
	30	85
Aug.	16	68
	17	69
	19	68
	24	57
	25	59
	26	19
	27	45
	28	47
	30	77
Sept.	3	66
	5	63
	8	69
	9	50
	10	76
	11	62
	15	70
	17	80
	18	46
	19	68
	20	75
	21	56
	22	62
	29	63
Oct.	1	77
	4	45
	13	58
	19	55
	29	44

1915.		
Month	Date.	mw/cm²
Nov.	3	51
	11	35
	15	59
	16	55
	17	43
	26	42
	30	57
Dec.	8	60
	13	33
1916.		
Jan.	3	59
	10	61
	11	35
	14	57
	22	40
	23	50
	24	69
	25	43
Feb.	5	68
	7	71
	8	45
	9	54
	10	61
	12	59
	15	61
	16	78
	17	78
	24	35
Mar.	27	53
	29	72
April	1	45
	2	60
	8	54
	10	77
May	19	73
	20	90
	26	90
	27	64
	29	85
	31	59
June	6	84
	7	73
	8	91
	30	86
July	4	82
	7	88
	10	94
	20	32

1916.		
Month	Date.	mw/cm²
July	28	36
	29	74
	31	74
Aug.	1	66
	3	72
	5	84
	7	62
	9	48
	10	29
	12	80
	14	78
	19	48
	21	82
	22	29
	26	88
Sept.	7	45
	13	80
	14	77
	15	81
	16	64
	18	86
	21	53
	28	16
Oct.	1	49
	7	73
	16	69
	19	58
	21	67
	23	69
	26	71
	27	72
	30	57
Nov.	8	73
	9	68
	15	53
	16	41
	17	67
	21	49
	22	52
	27	39
	28	28
Dec.	22	49
	24	46
	30	41
1917.		
Jan.	4	68
	5	54
	10	44
	12	51
	13	35

TABLE VIII (*continued*).

Richmond, Kew Observatory.

1917.		
Date.		mw/cm²
Feb.	6	33
	8	22
	9	19
	17	37
	26	68
	27	40
March	1	12
	4	41
	17	36
	20	68
	24	67
	27	84
	30	83
April	5	80
	6	57
	9	63
	12	60
	13	73
	15	73
	19	78
	23	52
	24	75
	26	65
May	2	30
	3	57
	4	67
	7	65
	8	64
	9	49
	13	83
	14	82
	23	80
	26	62
	28	71
	29	62
	30	65
June	4	85
	5	44
	7	80
	9	49
	12	59
	14	83
	15	83
	16	57
	25	84
	26	77
July	3	62
	7	63
	11	30
	13	44
	20	51
	23	59
	27	72

1917.		
Date.		mw/cm²
Aug.	5	44
	7	52
	10	85
	11	86
	13	85
	18	87
	20	77
	24	77
	31	77
Sept.	4	72
	6	57
	8	46
	12	78
	15	78
	16	83
	17	83
	24	71
	25	66
	26	48
	27	70
Oct.	1	38
	2	51
	3	77
	5	82
	6	73
	11	65
	15	58
	18	78
	19	67
	22	69
	23	71
	25	72
	27	58
	29	52
	31	58
Nov.	6	72
	7	67
Dec.	1	62
	3	53
	5	46
	6	36
	14	54
	15	46
	17	44
	18	26
	25	44
1918.		
Jan.	3	33
	4	30
	7	57

1918.		
Date.		mw/cm²
Jan.	8	57
	10	25
	13	61
	16	54
	24	60
	29	57
Feb.	6	47
	8	52
	16	77
	18	39
	21	61
	25	73
	27	67
	28	68
Mar.	2	68
	6	33
	9	14
	11	58
	12	60
	13	29
	14	46
	15	50
	18	58
	20	67
	21	58
	22	68
	23	65
	25	60
	26	80
April	8	62
	22	56
	25	61
	27	61
May	4	78
	8	62
	9	74
	11	57
	17	58
	20	67
	21	72
	22	63
	27	65
	29	68
	30	63
	31	50
June	1	58
	6	71
	8	61
	11	57
	12	55
	21	86
	22	74
	27	83

1918.		
Date.		mw/cm²
July	1	62
	3	76
	4	57
	24	88
	29	57
Aug.	1	54
	10	62
	13	78
	14	80
	15	81
	19	64
	21	79
	29	61
Sept.	6	74
	10	88
	12	83
	19	88
	20	79
	25	76
	27	82
	28	83
Oct.	4	80
	7	72
	13	67
	17	33
	23	30
	30	59
Nov.	7	29
	9	56
	14	43
	21	42
	22	55
	23	43
	27	42
	30	43
Dec.	16	56
	17	49
	19	45
	24	40
1919.		
Jan.	2	25
	10	41
	16	51
	17	57
Feb.	8	59
	9	51
	10	55
	11	10

1919.		
Date.		mw/cm²
Mar.	—	No obs.
April	3	65
	7	64
	18	65
	23	44
May	—	No obs.
June	—	No obs.
July	9	54
	16	72
	21	81
	22	68
	26	59
Aug.	8	78
	9	81
	11	70
	13	83
	14	80
	15	76
	16	62
	18	81
	21	83
	26	70
	27	77
Sept.	8	60
	9	77
	10	81
	11	81
	12	76
	17	51
	18	57
	20	84
	24	76
	27	49
Oct.	3	66
	4	36
	7	35
	8	69
	9	78
	15	57
	17	63
	20	17
	21	49
	22	60
	23	65
	26	58
	27	50
Nov.	13	29
	18	14
	20	66
	21	60
	24	58

TABLE VIII (*continued*).

Richmond, Kew Observatory.

Date.		mw/cm²
1919.		
Nov.	25	65
	26	48
Dec.	2	65
	24	36
	25	59
1920.		
Jan.	2	36
	7	24
	8	48
	9	56
	14	65
	22	39
	25	58
	29	61
	30	65
Feb.	1	49
	3	55
	6	32
	7	52
	11	50
	17	65
	18	16
	19	61
	26	40
March	1	65
	3	63
	4	66
	7	82
	8	61
	9	61
	11	66
	12	61
	16	46
	18	76
	19	73
	20	68
	21	74
	22	19
	23	51
	31	81
April	13	85
	16	86
	28	86
	30	85

Date.		mw/cm²
1920.		
May	3	87
	4	86
	7	80
	12	80
	13	66
	15	68
	19	70
	23	57
	24	74
	27	71
June	2	81
	7	76
	9	75
	21	80
	22	80
	24	68
	28	77
	30	81
July	18	83
	19	84
	29	74
Aug.	1	83
	3	87
	4	88
	11	57
	14	82
	19	82
	24	57
	27	50
Sept.	3	65
	10	84
	12	70
	16	36
	20	73
	27	55
	28	26
	29	47
	30	19
Oct.	2	82
	5	27
	6	75
	7	37
	8	43
	9	27
	10	43

Date.		mw/cm²
1920.		
Oct.	11	33
	12	61
	18	49
	19	39
	20	59
	21	46
	25	29
	26	34
	28	60
	29	37
	30	64
Nov.	6	23
	8	32
	11	16
	16	60
	17	58
	19	44
	23	13
	24	22
Dec.	1	58
	16	48
	20	34
	22	58
	23	25
	26	40
	30	24
1921.		
Jan.	3	21
	8	18
	11	23
	14	43
	16	32
	19	42
Feb.	4	50
	5	18
	14	37
	20	27
	21	26
	22	60
	24	50
	26	59
	27	38

Date.		mw/cm²
1921.		
March	2	84
	7	71
	10	85
	14	84
	15	85
	17	72
	24	85
April	1	31
	4	77
	5	67
	12	45
	13	72
	14	88
	16	88
	20	50
	30	75
May	2	71
	9	85
	13	61
	16	73
	17	80
	18	51
	20	85
	21	76
	22	68
	24	72
	25	32
June	2	81
	7	79
	10	84
	15	62
	16	52
	17	60
	21	72
	23	76
	24	57
	25	69
	29	80
July	2	79
	3	37
	5	68
	9	59
	10	80
	11	80
	13	57
	15	50
	18	69

Date.		mw/cm²
1921.		
July	20	77
	21	80
	28	46
Aug.	8	89
	9	90
	10	78
	16	82
	18	68
	19	64
	26	85
	29	83
	31	67
Sept.	3	82
	5	76
	7	53
	8	64
	9	67
	12	88
	16	79
	23	76
	26	75
	28	48
	29	39
	30	46
Oct.	1	37
	3	75
	4	73
	5	71
	7	77
	8	79
	10	67
	13	48
	14	70
	15	55
	17	44
	18	70
	21	59
	24	71
	29	52
Nov.	7	65
	24	11
Dec.	13	35
	17	66
	20	62
	24	54
	29	51
	31	43

§ 9. CONCLUSION.

In conclusion I should like to thank Dr. C. Chree, F.R.S., for his guidance, and Mr. C. H. Kellett, B.Sc., Kew Observatory, for his assistance with the arduous arithmetical work during the preparation of this memoir. I am also indebted to Mr. C. D. Stewart, B.Sc., of Valencia Observatory, for the historical notes of the instruments which he extracted whilst at Kew Observatory.