A study of the compensation principle and the Ångström Pyrheliometric Scale

By BERTIL RODHE, *Swedish Meteorological and Hydrological Institute, Norrköping, Sweden*

(Manuscript received October 28, 1974; in final form February 11, 1975)

ABSTRACT

The International Pyrheliometric Scale of 1956 (IPS 1956) is based upon the original standards of the Ångström and Smithsonian scales by suitable corrections (+1.5 and −2.0%, respectively). The old standards will soon be replaced by new kinds of absolute actinometers, and a revision of the international scale is at hand. The present paper reviews the Compensation Principle with special regard to absolute pyrheliometry and the increased demands of accuracy since the principle was formulated by Knut Ångström in 1893. The Swedish manufacturers have maintained a practice of measuring the characteristics of self-calibration of newly-made pyrheliometers so as to provide a check of the maintenance of the Ångström Scale.

1. Introduction

A new era in the science of absolute pyrheliometry has begun. New actinometers (Crommelynck, Fröhlich, Geist, Kendall, Wilson) will soon replace the old ones in a revision of the absolute pyrheliometric scale. The Ångström Pyrheliometric Scale of 1905 was once embodied in a particular pyrheliometer (No. 70) on the principles of electric compensation presented by Knut Ångström (1893), and the scale was verified in many series of newly-made pyrheliometers (Bäcklin, 1925). In the years 1920 to 1913, the Astrophysical Observatory of the Smithsonian Institution conducted an intensive campaign to produce a standard pyrheliometer and established the Smithsonian Pyrheliometric Scale of 1913. The water-flow and the water-stir standard pyrheliometers, both designed by C. G. Abbot, were the basic absolute pyrheliometers of this scale. The two scales differed from each other, and the International Pyrheliometric Scale of 1956 seemed on good reasons to be an acceptable compromise between the original scales, but it was not itself embodied in an absolute actinometer.

The modern design of the compensation pyrheliometer is a handy instrument for use as a secondary standard at calibrations of actinometers at meteorological stations. On the condition that its characteristics of self-calibration are known, any compensation pyrheliometer may in principle be used as a primary standard for verification of the original Ångström Pyrheliometric Scale.

The "compensation" is generally understood as a procedure in which the absorption of radiation by one of the sensor strips is counterbalanced by a supply of an equivalent amount of electric heat to the other. K. Ångström (1893) identified the point of equivalence of the heat gain of both strips with the equivalence of their temperatures. A. Ångström (1914) drew attention to two shortcomings, namely the "edge effect" and the difference between the types of heat flow in the case that heating is alternatively effected by irradiance and by electricity. Kyle (1967) commented on this last matter and estimated, as even Ångström did, that the measured value of the sun's irradiance could quite reasonably be 0.5% too low because of the thermal resistance of the soot coating of the strips. A. Ångström (1968) replied that a difference of 5.0% between the Smithsonian and Ångström scales might be covered by the edge effect (2.0%), the effect of the soot layer (0.5%) and the correction (2.5%) of the Smithsonian Scale of 1913 announced by Abbot & Aldrich (1948). The scale comparison is however influenced by atmospheric turbidity if the scales are re-

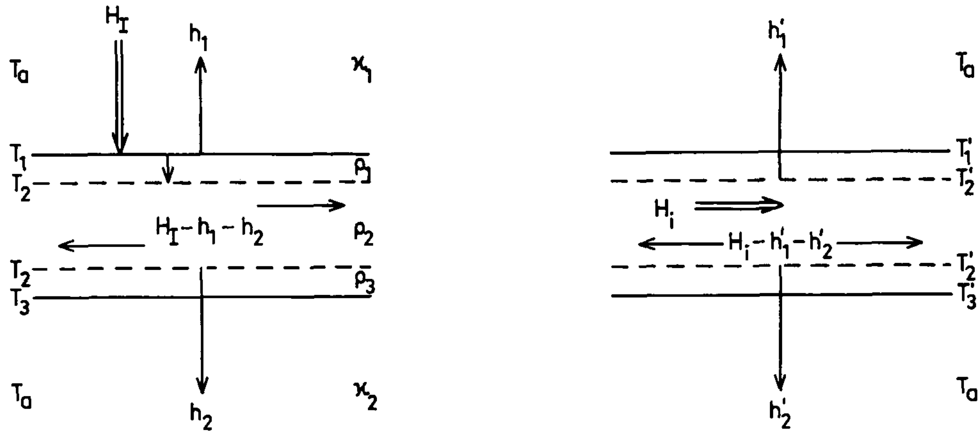

Fig. 1. A diagrammatic scheme of the heat fluxes at a strip of the compensation pyrheliometer. Left: The strip is heated by irradiation. Right: The heating is effected by means of electric energy.

presented by actinometers having different apertures. Under such conditions, the difference between the scales appeared to be about 3.5% (Ångström & Rodhe, 1966).

The difference between the Smithsonian and Ångström scales has lead to many discussions, and Courvoisier (1963), Crommelynck (1973) and Wierzejewski (1973) have studied in detail the conditions of heat exchange between the strip and their surroundings within the pyrheliometer tube. It is obviously not perfectly correct to identify the equivalence of the heat gain of both strips with the equivalence of their temperatures if there is not complete symmetry between the characteristic parameters.

Alternatively, the concept of "compensation" may be understood in the way that the screened strip is compensated with electric heating for its loss of the sun's irradiation, i.e. the irradiation is replaced by electric heat. The mathematical treatment of the compensation principle is in this case simpler than in the preceding alternative since we do not juxtapose in the same equation the parameters of different strips.

The difference between these alternatives, which in the following will be discussed under the concepts of the "cold" and the "warm" zero-points, is sometimes felt to be of minor importance. K. Ångström's demand on accuracy was no greater than what he could achieve with the techniques of his time. He (K. Ångström, 1899) was aware of the fact that the coefficient attributed by him to the absorption power of the black coating of the strip, might be in error by 0.5%. He did not go further and meet the problems raised by Courvoisier, Crommelynck and Wierzejewski in their above-mentioned papers. He initiated the application of the "warm" zero-point. Following his interpretation of the concept of "compensation", Fröhlich and Wierzejewski (1972), however, recommended the "cold" zero-point as a logical consequence of the condition that the equivalence of temperature should be settled between the strips.

2. The heat balance at the strip of a pyrheliometer

The sensible receiver of the sun's irradiation in the pyrheliometer tube consists of two manganin strips, each of which is 2 cm long, 0.2 cm wide and 0.002 cm thick. As far as the manufacture permits, the strips are made equal to each other in dimension and electric resistance. They are blackened firstly by platinizing, secondly with soot from a candle. A thermojunction of copper-constantan is attached to the backside of each strip so that the temperature difference between the strips can be observed with a sensitive galvanometer.

Without intending to give a correct presentation of the relative thickness of the platinum and soot layers, Fig. 1 shows a diagrammatic scheme of the heat fluxes in a part of the strip. There are two alternatives; either the strip is heated by the sun's irradiance H_I or by the effect H of an electric heating current. Each of these effects are balanced, partly by the conduction of heat to the ends of the manganin strip, and partly by the losses due to convection in the ambient air and to infrared radiation. The latter are assumed to be proportional to the difference between the temperatures,

$$h_1 = \varkappa_1(T_1 - T_a),\ h_1' = \varkappa_1(T_1' - T_a) \tag{2.1}$$

at the frontside, and

$$h_2 = \varkappa_2(T_3 - T_a),\ h_2' = \varkappa_2(T_3' - T_a) \tag{2.2}$$

at the backside.

In Fig. 1 are also found the temperatures T_2 and T_2' which refer to the platinized surfaces of the manganin. Since the thermal conduction in manganin is good, the temperature is assumed to be constant within the cross section between the platinized surfaces. The thermal connection between the manganin and the thermojunction is assumed to be good so that the latter yields a thermoelectric current which responds well to the temperature T_2 (or T_2'). Under steady conditions, there is no accumulation of heat within the manganin strip, and the heat flux $H_I - h_1 - h_2$ (or $H_i - h_1' - h_2'$) to the sinks at the ends of the strip and at the thermojunction is proportional to the difference between T_2 (or T_2') and the temperature T_a of the environment.

The temperature profile through the whole cross section of the strip, inclusive of the layers of platinum and soot, is determined by the transverse heat flux and the resistances of thermal conduction (ϱ_1 and ϱ_3) within the layers. Taking into consideration that the absorbed amount H_I is transferred through the frontal soot layer, we get for the first alternative the equation

$$T_1 = T_3 + \varrho_3 h_2 + \varrho_1(H_I - h_1) \tag{2.3}$$

In the alternative of electric heating, the equation reads simply

$$T_1' = T_3' + \varrho_3 h_2' - \varrho_1 h_1' \tag{2.4}$$

By introduction of (2.1) and (2.2) we arrive at the following equation of the upper and lower surface temperatures in the two alternatives,

$$(T_1' - T_1)(1 + \varrho_1\varkappa_1) = (T_3' - T_3)(1 + \varrho_3\varkappa_2) - \varrho_1 H_I \tag{2.5}$$

The electric heating current is assumed to have such an intensity that the temperature of the thermojunction is the same in both alternatives, i.e. $T_2 = T_2'$. In consequence,

$$T_3 = T_3',\ h_2 = h_2',\ H_I - h_1 - h_2 = H_i - h_1' - h_2'$$

and

$$H_I = H_i - (h_1' - h_1) = (1 + \varrho_1\varkappa_1)H_i \tag{2.6}$$

under the conditions of equations (2.1) and (2.5).

Accepting the values of $\varkappa_1$ and ϱ_1 given by Kyle (1967),

$\varkappa_1 = 12$ watt/(m^2 °C)

$\varrho_1 = 32\ d_1$ (m^2 °C)/watt

where d_1 is the thickness of the soot layer, we get the relation

$$H_I = H_i(1 + 400 d_1) \tag{2.7}$$

In the Stockholm version of the Ångström Compensation Pyrheliometer, d_1 is about 10^{-5} m. The difference between the alternatives H_I and H_i is therefore about half a percent, the electric heating being smaller than that of irradiation.

3. The "warm" zero-point

The procedure of measuring is started by facing both strips to the sun by means of the diopter along the pyrheliometer tube. The screen is put in such a position that it does not shade any of the strips, and the electric current is interrupted.

Let us assume that the sun's irradiance is I watt/m^2, and that there may be a slight variation between the measured values I', I'' etc. during the run of the measuring procedure. If the length of the irradiated part of the left-hand strip for instance is L_l, its width b_l and the absorption coefficient of its blackened surface a_l, then the heat amount absorbed by the strip is

$$H_l = I_l a_l b_l L_l \text{ watt} \tag{3.1}$$

The same formula is applicable to the right-hand strip

$$H_r = I_r a_r b_r L_r \text{ watt} \tag{3.2}$$

Under steady conditions, the absorption is balanced by the heat losses of conduction, convection and radiation. The temperature difference obtained between the thermojunctions when the strips are simultaneously irradiated, determines the galvanometer's indication of the "warm" zero-point.

It is not possible to make the strips and the locations of the thermojunctions so similar that their characteristics of heat balance do not differ at all. Therefore we have to take into consideration that even under the conditions of simultaneous irradiation, there may be a small temperature difference between the thermojunctions. The difference remains constant even when the sun's irradiance varies within the small normal range (I', I'' etc.) during the few minutes of the measuring procedure. The "warm" zero-point is in fact under undisturbed ambient conditions a constant reference point.

In its reciprocal form, the definition of the "warm" zero-point constitutes the basis of the compensation theory: *The "warm" zero-point verifies that* I_l *and* I_r *in (3.1) and (3.2) are equal.*

When the zero-point of the galvanometer has been determined, the first of three measurements begins. The left-hand strip is shaded by the screen, and it is, in the way shown by the equation (2.6), compensated for the loss of I_l' with an equivalent amount of electric heat,

$$I_l' a_l b_l L_l = i_l'^2 R_l(1 + \varrho_l \varkappa_l) \tag{3.3}$$

where R_l is the electric resistance of the strip in ohms. The current i_l' is regulated so that the galvanometer's indication moves back to the "warm" zero-point. According to the statement above, the amount I_l' in equation (3.3) is then equal to the I_r', which for the moment is the radiation falling upon the right-hand strip and therefore, I_l' is identical with I',

$$I' = k_l i_l'^2 \quad \text{where} \quad k_l = R_l(1 + \varrho_l \varkappa_l)/(a_l b_l L_l) \tag{3.4}$$

The second measurement is started by changing the position of the screen so that the left-hand strip now gets exposed to the sun's irradiation (I_l'' gets identical with I'') and the right-hand strip is shaded. The right-hand strip is compensated for the loss of I_r'' with an electric heat effect,

$$I_r'' a_r b_r L_r = i_r''^2 R_r(1 + \varrho_r \varkappa_r) \tag{3.5}$$

The current i_r'' is by the condition of the "warm" zero-point adjusted so that the equivalence $I_r'' = I_l''$ is ascertained, and consequently also the equivalence $I_r'' = I''$,

$$I'' = k_r i_r''^2 \quad \text{where} \quad k_r = R_r(1 + \varrho_r \varkappa_r)/(a_r b_r L_r \tag{3.6}$$

For the third measurement, the left-hand strip is again shaded and the procedure of the first one is repeated. Finally, the position of the zero-point is checked by exposing both strips to the sun's irradiation.

The sun's irradiance is overcompensated for in the measurement at one strip and is equally undercompensated for in the next measurement at the other, when a zero-point other than the "warm" is referred to, that means

$$I' + E = k_l i_l'^2 \quad \text{at the first measurement} \tag{3.7}$$

$$I'' - E = k_r i_r''^2 \quad \text{at the second measurement} \tag{3.8}$$

and

$$I''' + E = k_l i_l'''^2 \quad \text{at the third measurement} \tag{3.9}$$

Introducing the weighted means

$$i^2 = (i_l'^2 + 2i_r''^2 + i_l'''^2)/4 \tag{3.10}$$

and

$$I = (I' + 2I'' + I''')/4 \tag{3.11}$$

we get

$$I = Ki^2 + [E + (I' - 2I'' + I''')/4](k_l - k_r)/(k_l + k_r) \tag{3.12}$$

The pyrheliometer's factor K of self-calibration is related to k_l and k_r by the equation

$$2/K = 1/k_l + 1/k_r \tag{3.13}$$

Complete symmetry between the strips is difficult to achieve in the manufacture of the pyrheliometer so that $(k_l - k_r)$ is mostly not zero, but nevertheless the well-known pyrheliometer formula

$$I = Ki^2 \tag{3.14}$$

is valid for the following reasons.

A. The irradiance is in most cases either constant ($I' = I'' = I'''$) or subject to an almost constant variation ($I''' = I'' + \varepsilon = I' + 2\varepsilon$) during the short run of the three measurements. The term

$$(I' - 2I'' + I''')/4 = (I' - I'')/4 + (I''' - I'')/4 \tag{3.15}$$

is in both alternatives zero. Otherwise, the variations are accidental, and the term disappears from the average of many measurements.

B. The part E, which is due to deviations from a strict application of the "warm" zero-point, is accidental and dissappears from the average values of (3.12). Its variance is mostly of the same order of magnitude as that of (3.15).

C. The factor $(k_l - k_r)/(k_l + k_r)$ is small.

4. The "cold" zero-point

The eq. (2.6) for the quantities H_I and H_i is valid on the condition that the strips are identical. The condition is evidently fulfilled when only one strip is involved as for instance in (3.3) or (3.5). But if H_I and H_i refer to heat fluxes which go to different strips, then we have to find a criterium for the equivalence of the temperatures T_2 and T_2' (Fig. 1), and we have to put mean values of ϱ and $\varkappa$ into the formulae,

$$Ia_r b_r L_r = i_l^2 R_l(1 + \varrho\varkappa) \text{—the left-hand strip is shaded} \tag{4.1}$$

$$Ia_l b_l L_l = i_r^2 R_r(1 + \varrho\varkappa) \text{—the right-hand strip is shaded} \tag{4.2}$$

Or,

$$I = k_{l/r} i_l^2 = k_{r/l} i_r^2 \tag{4.3}$$

where

$$k_{l/r} = R_l(1 + \varrho\varkappa)/(a_r b_r L_r) \quad \text{and} \tag{4.4}$$

$$k_{r/l} = R_r(1 + \varrho\varkappa)/(a_l b_l L_l)$$

differ from k_l and k_r in (3.4) and (3.6).

The "cold" zero-point arose from the demand for a criterium of the equivalence of the temperatures T_2 and T_2' in different strips. It was put in practice by the Davos Physical-Meteorological Observatory in the 1960's. It was used earlier almost exclusively when windy weather made it difficult to find the equilibrium of the heatings of the strips under exposed conditions. The reason for occasional deviations from the application of the "warm" zero-point was under such conditions a practical one, but the Davos Observatory based their deviation upon the generally accepted interpretation of the concept of "compensation".

The galvanometer's indication of the "cold" zero-point is obtained when neither the sun's irradiation is falling upon the strip nor the electric heating is effected. Under this condition, both strips have the same temperature as the surroundings inside the pyrheliometer tube, and the temperature is constant along each strip.

But the temperature is not constant along a strip when it is heated. The heat sinks at the ends of the strip and at the location of the thermojunction determines a particular temperature profile (Ångström, 1974; Major et al., 1974). An important condition so that equal temperatures might exist at the thermojunctions is the symmetry between their locations on the backsides of the strips. However, such a degree of symmetry is not feasible, and it is therefore not realistic to presume that the "cold" zero-point under "warm" conditions constitutes a verification of the equivalence of the heat income of both strips.

Indeed, the "warm" and the "cold" zero-points differ from each other not only in theory but even in practice. If the points do not coincide and the "cold" zero-point is referred to, then E in (3.12) includes a constant part which, in contrast to the accidental part, does not vanish in the average of a lot of measurements. Then, it depends on the degree of symmetry between the strips, which is expressed in terms of the factor $(k_l - k_r)/(k_l + k_r)$, whether the pyrheliometer formula (3.14) is valid or not. The question should be settled for each instrument separately on the basis of the required accuracy and the possible advantage of the "cold" zero-point over the "warm".

5. The maintenance of the Ångström Pyrheliometric Scale

The Ångström Compensation Pyrheliometer is an absolute actinometer, but nevertheless each

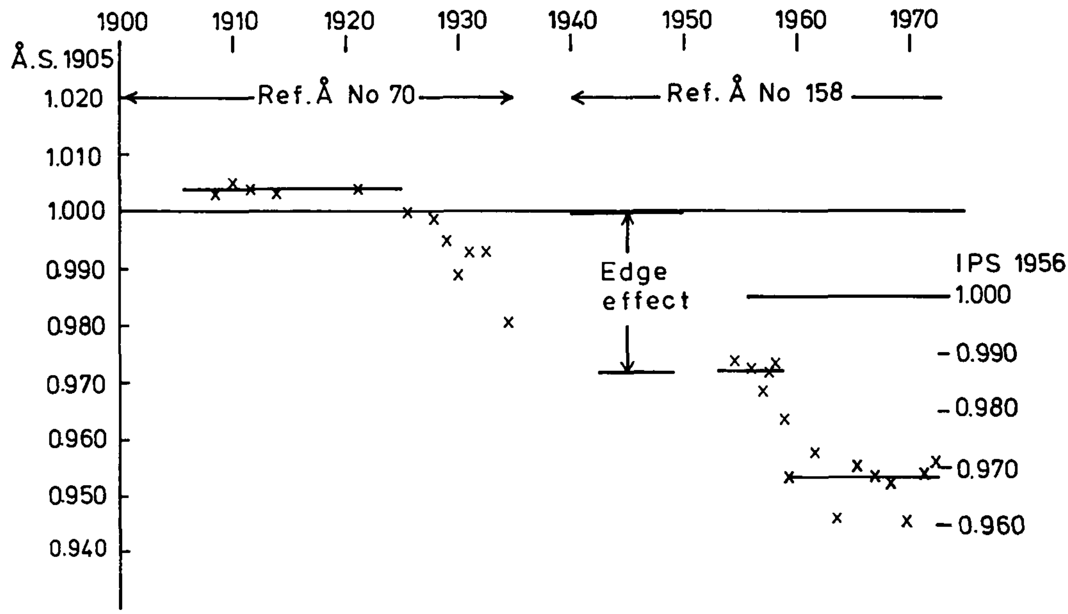

Fig. 2. The annual variation of the ratio K_{obs}/K_{calc} within the series of pyrheliometers manufactured at Uppsala and Stockholm, Sweden.

pyrheliometer is calibrated with reference to a standard actinometer. The ratio K_{obs}/K_{calc} between the instrument factors, which are obtained by calibration with reference to a standard and by calculation in terms of the instrument's own characteristics, is a tool for the control of the manufacture of the instrument and provides a check of the materialization of the pyrheliometric scale by the standard actinometer which the calibration has been referred to.

However, since the formula (3.13) was not known from the beginning, the instrument factor has been calculated in a good approximation by means of the formula

$$K_{calc} = 1/2[R_l/(b_l L_l) + R_r/(b_r L_r)]/0.98 \qquad (5.1)$$

where the value 0.98 stands for the absorption coefficient. The effect of the thermal resistance (ϱ) of the soot layer was not considered.

When the International Meteorological Conference in 1905 adopted the Ångström Compensation Pyrheliometer as an actinometer for absolute measurements of the sun's irradiance, pyrheliometer No. 70 became the standard to which new pyrheliometers were referred during several years of manufacture at Uppsala. In the series of 55 pyrheliometers manufactured between 1905 and 1912, the average of the ratio K_{obs}/K_{calc} was 1.0026 ± 0.0009 (Granqvist, 1912). In this way it was confirmed that the Ångström Pyrheliometric Scale was correctly based upon the Compensation Principle and not arbitrarily represented by No. 70.

With some exceptions, the ratio K_{obs}/K_{calc} has been determined from the beginning at Uppsala and later at Stockholm for new pyrheliometers up to the present time. The instruments are subject to "aging and death" but the abovementioned ratio at the "birth" of new instruments makes it possible to keep the scale under control and "alive". The ultimate reference of the scale should in fact be neither the old No. 70 nor any other particular pyrheliometer—but the "generations" of newly-made pyrheliometers.

The run of the annual averages of K_{obs}/K_{calc} in the series of pyrheliometers manufactured since the beginning has been studied earlier by Granqvist (1912), Bäcklin (1925), Courvoisier (1957) and Lindholm (1958*b*). An extended diagram up to the present time is shown in Fig. 2.

Before 1925, the ratio was almost constant and equal to 1.004, but later there have been some breaks. In 1928, damage was discovered in the black coating of the right-hand strip of the reference pyrheliometer No. 70. The strip was repaired before the next calibrations in 1929. By careful comparison with other instruments before and after the repair, the effect of the damage was proved to have been 1.0%. The calibrations in 1928 were accordingly corrected (Bäcklin & Kellström, 1930).

But the ratio remained a bit too low in the following years. Perhaps, it was due to a decrease of the absorption coefficient of the strips of No. 70.

The manufacture of new pyrheliometers ceased at Uppsala in 1935 and was resumed at Stockholm in 1940. The calibrations were then performed at the laboratory of the Swedish Meteorological and Hydrological Institute with reference to another standard, pyrheliometer No. 158. Unfortunately, the K_{calc} was not computed for the series manufactured in the years from 1940 to 1953.

The Uppsala standard No. 70 was in 1951 transferred to Stockholm. After repair by renewed blackening, it was compared with No. 158 as well as another old pyrheliometer of the same design, No. 153. The repair seemed to have been successful (Lindholm, 1958*a*).

A new design of the Ångström Compensation Pyrheliometer was introduced in 1954 (Ångström, 1958). The edge effect, which the pyrheliometers of the previous design suffered from, was now eliminated.

In the series of manufacture from 1954 to 1958, the ratio K_{obs}/K_{calc} decreased to 0.972. Lindholm (1958*b*) attributed the decrease to the elimination of the edge effect.

Fig. 2 indicates that in 1959, just before the IPC-I at Davos, there was another decrease of the ratio by 1.8% down to 0.954. This value has been maintained in the 1960's to present time.

A change of the ratio K_{obs}/K_{calc} may be explained in any of the following three ways.

A. There may have been one or more constant errors in the calibration procedure for the determination of K_{obs}. The milliammeters which were used at the calibrations in the 1960's, suffered from some errors which now have been corrected (Rodhe, 1974).

B. The possibility of constant errors in the determination of K_{calc} must also be considered. As a proof of the techniques of measuring the width and the electric resistance of a strip, new methods were recently introduced. In fact, the ratio K_{obs}/K_{calc} retained its low value. An unintentional change of the procedure of blackening the surface of the strips may cause a variation of the absorption coefficient. The coefficient has been assumed to be 0.98 but may surely vary within at least 0.5%.

C. Perhaps the absorption power of the strips of the old reference pyrheliometer No. 158 has become less effective because of aging. Unfortunately, all old pyrheliometers of this type may possibly suffer from the same shortcoming, and a consistent verification of the maintenance or a change of the No. 158 has not been obtained by comparisons.

The increased difference between the Ångström Pyrheliometric Scale and the Smithsonian Scale, which Fröhlich (1974) and Latimer (1973) have drawn attention to, is probably related to the decrease of the ratio K_{obs}/K_{calc} shown in Fig. 2. It is perhaps caused by a deterioration of the absorption coefficient of the sensors of the old Ångström standards. The final judgment is not yet pronounced.

Acknowledgement

The author is much indebted to Dr Anders Ångström for valuable discussions.

REFERENCES

Aldrich, L. B. & Abbot, C. G. 1948. Smithsonian pyrheliometry and the standard scale of solar radiation. *Smithsonian Miscellaneous Collections 110*, 5.

Ångström, A. 1914. The Ångström Compensation Pyrheliometer and the pyrheliometric scale. *Astrophys. Journ. 40*, 274–281.

Ångström, A. 1958. On pyrheliometric measurements. *Tellus 10*, 342–354.

Ångström, A. & Rodhe, B. 1966. Pyrheliometric measurements with special regard to the circumsolar sky radiation. *Tellus 18*, 25–33.

Ångström, A. 1968. Note regarding the article by T. G. Kyle "An error in the Ångström Pyrheliometric Scale". *Tellus 20*, 198–199.

Ångström, A. 1974. The temperature distribution within pyrheliometric receivers. *Symposium on Solar Radiation Measurements and Instrumentation, Smithsonian Inst. & Eppley Research Found. 1973.*

Ångström, K. 1893. Eine elektrische Kompensationsmethode zur quantitativen Bestimmung strahlender Wärme. *Nova Acta Reg. Soc. Sc. Upsal. 3*, 1–8 (Transl. *Phys. Rev. 1*, 365).

Ångström, K. 1899. Über absolute Bestimmungen der Wärmestrahlung mit dem elektrischen Compensationspyrheliometer, nebst einigen Beispielen der Anwendung dieses Instrumentes. *Ann. Phys. Chem. 67*, 633–648 (Transl. *Astroph. Journ. 9*, 339).

Bäcklin, E. 1925. Über die Konstanz der Ångströmschen Pyrheliometerskala. *Arkiv för matem. astron. och fys. 19A*, 18, 1–8.

Bäcklin, E. & Kellström, G. 1930. Die Ångströmsche Pyrheliometerskala. *Meteor. Zscht. 47*, 52–56.

Courvoisier, P. 1957. Contributions to standard pyrheliometry. *Swed. Meteor. Hydrol. Inst. Communications B13*, 1–51.

Courvoisier, P. 1963. On the Compensation Pyrheliometer. *Archiv für Meteor. Geophys. Bioklim. B12*, 422–441.

Crommelynck, D. 1973. Théorie instrumentale en radiométrie absolue. *Inst. Roy. Météor. Belg. A81*, 1–50.

Fröhlich, C. & Wierzejewski, H. 1972. Die verschiedenen Messverfahren zur Bestimmung der Strahlungsintensität mit dem Kompensationspyrheliometer und die Entwicklung eines verbesserten Modells. *Swiss Meteor. Inst. Publ. 25*, 1–31.

Fröhlich, C. 1974. The relation between the IPS now in use and the Smithsonian Scale 1913, Ångström Scale and Absolute Scale. *Symposium on Solar Radiation Measurements and Instrumentation, Smithsonian Inst. & Eppley Research Found. 1973.*

Kendall, J. M., Sr & Berdahl, C. M. 1970. Two blackbody radiometers of high accuracy. *Applied Optics 9*, 1082–1091.

Granqvist, G. 1912. Bericht über aktinometrische Arbeiten am Observatorium der Physikalischen Institution in Uppsala. *Tagungsber. Int. Strahl. Komm. in Rapperswyl.*

Kyle, T. G. 1967. An error in the Ångström Pyrheliometric Scale. *Tellus 19*, 240–242.

Latimer, J. R. 1973. On the Ångström and Smithsonian absolute pyrheliometric scales and the International Pyrheliometric Scale 1956. *Tellus 25*, 586–592.

Lindholm, F. 1958. On the Ångström Pyrheliometric Scale. *Tellus 10*, 249–255.

Lindholm, F. 1958. The Ångström Compensation Pyrheliometer and the absolute pyrheliometric scale. *Geof. Pura e applicata 41*, 177–182.

Major, G., Mersich, I. & Miskolci, F. 1974. Sensitivity distribution along the strips of the compensation pyrheliometers. *Tellus 26*, 691–693.

Rodhe, B. 1973. The Ångström Compensation Pyrheliometer Instruction Manual. *Swed. Meteor. Hydrolo. Inst. Stockholm.*

Rodhe, B. 1974. The Stockholm representation of the IPS 1956. *Symposium on Solar Radiation Measurements and Instrumentation, Smithsonian Inst. & Eppley Research Found. 1973.*

Wierzejewski, H. 1973. Das Kompensations- und Substitutionsverfahren und ihre Varianten für die Messung der Strahlungsintensität mit dem Kompensationspyrheliometer. *World Radiation Center Davos Techn. Note 2*, 1–66.

ИССЛЕДОВАНИЕ ПРИНЦИПА КОМПЕНСАЦИИ И ПИРГЕЛИОМЕТРИЧЕСКАЯ ШКАЛА АНГСТРЁМА

Международная пиргелиометрическая шкала 1956 г. (МПШ 1956) основывается на первоначальных стандартах шкалы Ангстрёма и смитсонианской шкале с соответствующими поправками (+1,5 и −2,0 %, соответственно). Старые стандарты будут вскоре заменены новыми вариантами абсолютных пиргелиометров и будет произведена ревизия международной шкалы. В настоящей статье дается обзор принципа компенсации с уделением специального внимания абсолютной пиргелиометрии и растущим требованиям к точности, поскольку этот принцип был сформулирован Кнутом Ангстрёмом в 1893 г. Шведские промышленники с давних пор поддерживали практику измерений характеристик самокалибровок изготовляемых пиргелиометров для того, чтобы обеспечить проверку соответствия шкале Ангстрёма.