On the Ångström and Smithsonian absolute pyrheliometric scales and the International Pyrheliometric Scale 1956

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ABSTRACT

The generally accepted mean difference between measurements of solar irradiance by means of an Abbot silver-disk pyrheliometer, referenced to the Smithsonian scale of 1913, and by means of an Ångström electric-compensation pyrheliometer, referenced to the Ångström scale of 1905, is 3.5 %, measurements on the Ångström scale being lower. In September of 1956 at Davos the International Radiation Commission of the IUGG recommended the adoption of a new scale to be known as the International Pyrheliometric Scale 1956 (IPS 1956). To express radiation observations on the IPS 1956, measurements made on the Ångström scale of 1905 were increased by 1.5 %, while measurements made on the Smithsonian scale of 1913 were decreased by 2.0 %.

A comparison of the Ångström scale of 1905 with the Smithsonian scale of 1913 at Toronto from 1955 to 1957 yielded a mean difference of 4.6 % between them, which is 1.1 % greater than the original 3.5 % difference upon which the IPS 1956 was based. During the Second International Comparison of Pyrheliometers at Davos in 1964 the mean difference between the Ångström scale of 1905 and the Smithsonian scale of 1913 was found to be 4.85 %, and during the Third International Comparison in 1970 to be 4.4 %. Measurements made with a Kendall cavity-type self-calibrating pyrheliometer during the 1970 comparisons, however, agreed within 0.2 % of the Smithsonian scale of 1913 reduced by 2.0 %.

A new practical scale for use as reference for meteorological radiation measurements is urgently required as a replacement for the IPS 1956. Such a scale can now be realized with high accuracy by means of a radiometer incorporating a cavity-type receiver and an aperture with carefully defined geometry.

1. Introduction

Meteorological radiation measurements have been usually standardized either by the Abbot silver-disk pyrheliometer or the Ångström electric-compensation pyrheliometer.

At the International Meteorological Conference at Innsbruck in 1905, the pyrheliometer of K. Ångström (1899) was adopted as the standard instrument for the measurement of solar irradiance. The Ångström scale of 1905 (ÅS 1905) is based on a group of specimen instruments, No. 70 being the absolute instrument, and No. 158 and several others being the main reference instruments.

The ÅS 1905 was determined later, however, to require a correction because of a so-called marginal effect. The mean marginal correction to pyrheliometer No. 70 was found by Lindholm (1958) to be +2.4%.

The construction of water-stir pyrheliometer No. 4 by C. G. Abbot and co-workers formed the basis of the Smithsonian revised scale of pyrheliometry of 1913 (SS 1913). The introduction of the improved water-flow pyrheliometer No. 5 in 1932 disclosed a correction to the SS 1913 of −2.5% (Abbot & Aldrich, 1932). This correction to the SS 1913 was confirmed again in 1934, 1947 and 1952.

At Davos in September 1956, the International Radiation Commission recommended the adoption of a new scale, to be known as the International Pyrheliometric Scale of 1956 (IPS 1956). The IPS 1956 was based on the best knowledge available at that time of the difference between the ÅS 1905 and the SS 1913 from measurements made at low altitude stations (Courvoisier, 1957). Radiation observations referenced to the two older scales were redefined as follows:

Table 1. *Summary of Toronto comparisons between Abbot silver-disk pyrheliometer SI14 (Smithsonian scale of 1913) and Ångström compensation pyrheliometer no. 149 (Ångström scale of 1905) from 1955 to 1967*

Year	Date	Q. SI14 Å149
1955	June 2	1.049
	3	1.042
	15	1.033
1956	Mar. 19	1.048
	20	1.048
	June 11	1.043
	13	1.045
1958	Feb. 13	1.025
	20	1.036
	Mar. 26	1.054
	Apr. 3	1.029
	9	1.036
	May 2	1.063
	Sep. 11	1.052
	22	1.036
	Oct. 29	1.037
1959	Apr. 24	1.049
	May 1	1.043
	25	1.043
	June 3	1.044
	July 13	1.060
	Aug. 11	1.053
	Sept. 21	1.046
	Dec. 31	1.050
1960	Feb. 2	1.044
	June 20	1.042
	July 6	1.053
	15	1.042
	Aug. 30	1.040
	Sep. 2	1.046
1961	Apr. 20	1.052
	May 11	1.053
1962	May 9	1.040
	11	1.034
	Aug. 2	1.043
1963	Oct. 4	1.042
1967	Apr. 25	1.049
Weighted mean		1.046

Definition A: Measurements made on the SS 1913 were decreased by 2.0%.

Definition B: Measurements made on the ÅS 1905 were increased by 1.5%.

The author uses the terms "Definition A" and "Definition B" to identify separately the two statements. The remainder of this paper is concerned with the comparison of the ÅS 1905 with the SS 1913 and a critical examination of the IPS 1956.

2. Comparison of the Ångström scale of 1905 and the Smithsonian scale of 1913 at Toronto

Comparisons were carried out at Toronto from 1955 to 1967 between Ångström pyrheliometer No. 149 and Abbot silver-disk pyrheliometer No. SI14. The ratio of observations of solar irradiance made simultaneously with the two pyrheliometers, called Q. SI14/Å149, is given in Table 1. The mean value of Q for the 13-year period is 1.046, with the mean error of comparison estimated as $\pm 0.5\%$. The data are weighted according to the number of individual sets of measurements made on each day listed. The larger scatter of the data during the year 1958 was the result of the introduction of a new observer who was unfamiliar with the operation of the silver-disk and Ångström pyrheliometers.

Figure 1 traces the relationship between the ÅS 1905 and the SS 1913 established by the comparisons at Toronto. The definition of the IPS 1956 accounts for a 3.5% difference between the ÅS 1905 and the SS 1913, leaving a residual 1.1% difference not accounted for. A similar series of comparisons made at Davos (a high altitude station) from 1930 to 1946 gave a mean

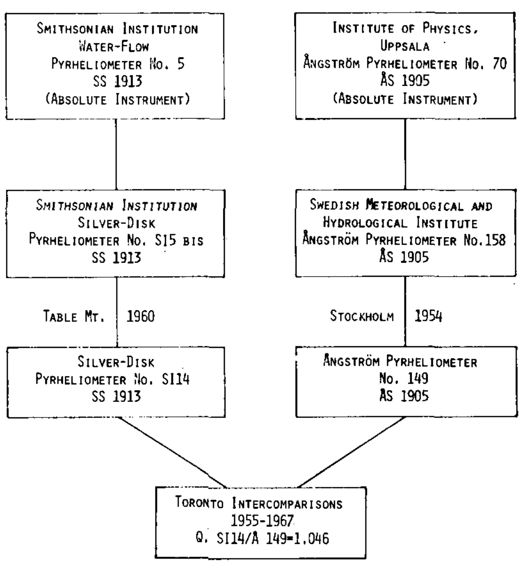

Fig. 1. Intercomparison of Ångström pyrheliometer No. 149 on the Ångström Scale of 1905 with silver-disk pyrheliometer No. SI14 on the Smithsonian Scale of 1913.

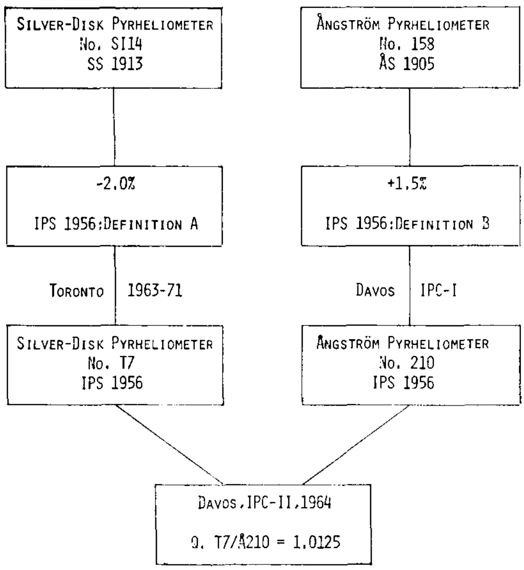

Fig. 2. Intercomparison of silver-disk pyrheliometer No. T7 with Ångström pyrheliometer No. 210 at the Second International Pyrheliometer Comparisons at Davos, 1964.

ratio of 1.0516 (Ångström & Rodhe, 1966). Rodhe (private communication) recorded a single series of ten readings at Stockholm, in the spring of 1973, between Å 158 and Smithsonian *compensation* pyrheliometer SI14 (not to be confused with Smithsonian *silver-disk* pyrheliometer SI14) using new electric equipment. He found the difference between the SS 1913 and the ÅS 1905 to be 4.1%.

3. The Second International Pyrheliometer Comparison at Davos in 1964

The traceability established by the comparison of silver-disk T7 and Ångström pyrheliometer No. 210 at the Second International Pyrheliometer Comparison (IPC-II), held at Davos in 1964, is depicted in Fig. 2. According to the definition of the IPS 1956 the ratio Q. T7/Å210 should be close to unity, whereas a weighted mean difference of 1.25%, with standard deviation ± 0.4%, was measured. The calibration factor used for T7 (0.3694 cal cm^{-2} min^{-1}/°C, IPS A 1956) is derived from a protracted series of calibrations against silver-disk SI14 at Toronto and Mt. Kobau, B. C. (49°07′ N, 119°40′ W, 1864 m a.s.l.) from 1963 to 1971.

4. Comparison of the Newport and Toronto versions of the IPS 1956

An Eppley–Ångström No. 9001 was received from the maker in 1968 and a series of comparisons were made between it and silver-disk T7 in 1968 and 1970. The calibration factor (6.29 cal cm^{-2} min^{-1}/A^2, IPS B 1956) used for E–Å 9001 was the value certified by the manufacturer. The traceability of the comparison data is given in Fig. 3. The value Q. E–Å 9001/T7 given in Table 2 is the ratio of the solar irradiances measured simultaneously by E–Å 9001 and T7.

Again, according to the definition of the IPS 1956, the value of Q given in Table 2 should be unity, instead of being 2.6% too low.

5. The Third International Comparison of Pyrheliometers at Davos and Locarno in 1970

At IPC-III the series of interesting intercomparisons depicted in Fig. 4 were recorded. The comparison data are abstracted from the WMO Preliminary Report (WMO, 1970). The JPL-PACRAD is an absolute radiometer described by Kendall (1969). Another absolute instru-

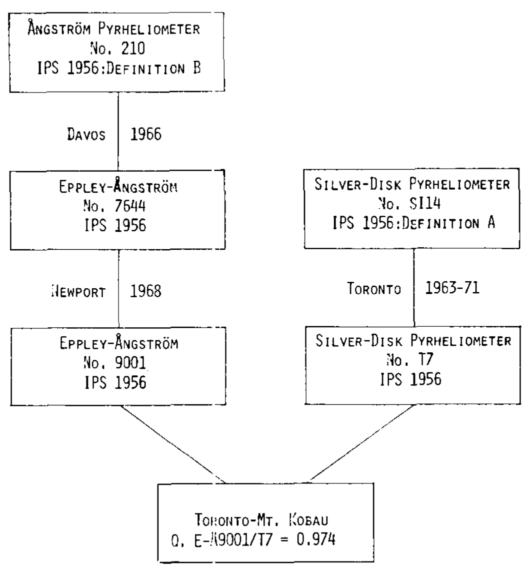

Fig. 3. Intercomparison of Eppley–Ångström No. 9001 with silver-disk pyrheliometer No. T7 at Toronto-Mt. Kobau.

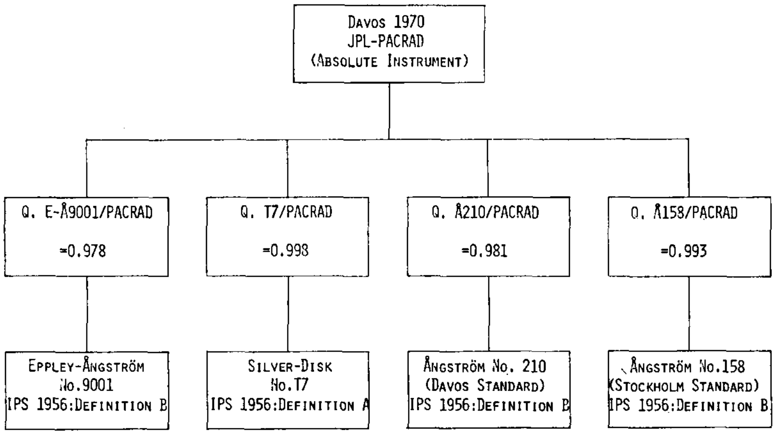

Fig. 4. The relationship between the JPL-PACRAD and Eppley–Ångström No. 9001, silver-disk No. T7, Ångström No. 210 and No. 158 at the Third International Pyrheliometer Comparisons, Davos, 1970.

ment from the U.S. National Bureau of Standards agreed with the JPL-PACRAD to within 0.1 % during observations on two days.

One rather disturbing outcome of IPC-III was the discovery of a 1.2 % difference between the Stockholm standard Å 158 and the Davos standard Å 210. Å 210 was calibrated at IPC-I in 1959 versus Å 158 on the IPS B 1956. Later, at IPC-II in 1964, Å 210 agreed within 0.3 % of Å 158, i.e., close to the generally accepted estimate of error (± 0.25 %) for the comparison of two Ångström pyrheliometers. However, during IPC-III an automatic data recording system (WMO, 1970) was used which eliminated the use of individual current meters with participating electric-compensation pyrheliometers.

Upon his return to Stockholm, Rodhe (1972) made an extensive examination of the several

Table 2. *Summary of comparison of Eppley–Ångström No. 9001 and Abbot silver-disk No. T7 at Toronto and Mt. Kobau, 1968–70 (IPS 1956)*

Date	Location	*Q*. E–Å9001 / T7	m.d.	*N*
24 July 68	Mt. Kobau	.971	.0029	16
27 July 68	Mt. Kobau	.976	.0028	8
28 July 68	Mt. Kobau	.974	.0035	8
17 Mar. 70	Toronto	.975	.0048	20
19 Mar. 70	Toronto	.974	.0020	20
Summary		.974	.0032	72

current meters used over the years with the Stockholm group of Ångström standard pyrheliometers. He found that the milliameter used with Å 158 at IPC-I and IPC-II exhibited scale errors exceeding those specified by the manufacturer for this class of current meter. When appropriate scale corrections were applied to the electric compensation current data recorded during IPC-I and IPC-II with Å 158, Rodhe concluded that the observations of solar irradiance with Å 158 at IPC-I should be increased by 0.62 %, and at IPC-II by 0.65 %. He writes that "it is quite obvious that the change of the calibration factor of the Davos reference No. Å 210 in 1959 should not have been done". He also could not find any indication that the calibration factor of Å 158 had changed after appropriate corrections were applied to the current readings. Since Rodhe's (1972) work has only accounted for a 0.6 to 0.7 % difference between Å 158 and Å 210 there exists another unexplained difference of 0.5 to 0.6 %. This may be due to a real change in the calibration factor of Å 210 between IPC-II and IPC-III, or to scale errors of the current meters used with Å 210 at IPC-I and II.

Following IPC-III, a new Eppley–Kendall absolute radiometer No. 11399 was acquired. A series of 197 comparisons were made during July and August, 1972, at Mt. Kobau. The mean ratio of the solar irradiances measured by silver-disk T7 and E–K 11399 was *Q*. T7/E–K11399 = 1.0013, with a mean deviation of ± 0.0228.

Both instruments have essentially the same aperture. This compares well with the ratio Q. T7/PACRAD = 1.002 found at IPC-III.

6. The effect of aperture geometry on the comparison of pyrheliometers

In any intercomparison involving two types of pyrheliometers consideration must be given to the basic difference in the principle and mode of operation of the two instruments. The silver-disk pyrheliometer has an observation cycle of 6 minutes, only two of which are directly affected by solar radiation, while the Ångström instrument is usually read every minute, or more often. The comparison of readings obtained with an Ångström and silver-disk cannot be, therefore, as accurate as with two instruments of the same type operated simultaneously in the same way.

There is also the effect of differences in aperture shape and size as between the Ångström and silver-disk pyrheliometers (or the PACRAD, and effect of circumsolar sky radiation resulting from the turbidity of the atmosphere (Bossy & Pastiels, 1948). Ångström pyrheliometers No. 149 (Toronto), No. 158 (Stockholm), and No. 210 (Davos) which have essentially the same dimensions, receive a greater amount of circumsolar sky radiation than a silver-disk pyrheliometer which has a smaller aperture. However, the compensating or shaded strips of Ångström-type instruments are also influenced by sky radiation entering the open aperture since no screen separates each half of the pyrheliometer tube. This effect acts to reduce the influence of circumsolar radiation on the comparison of Ångström pyrheliometers with apertures of different shape and size. Rodhe (1972) reports that the effect of turbidity during IPC-III when comparing a Stockholm model Ångström with an Eppley model Ångström as between Davos (low turbidity) and Locarno (high turbidity) amounted to only 0.3%.

IPC-III data show a difference of 2.2% in solar irradiance measurements between the PACRAD and E–Å 9001 (Fig. 4). Both instruments are reported to have equivalent apertures close to 5°. Geist & Kendall (1972) have shown that the effect of atmospheric turbidity on the comparison of PACRAD versus the Eppley–Ångström pyrheliometer should be negligible when compared with the 2.2% difference found between these two pyrheliometers at IPC-III.

7. The relationship of the ÅS 1905 and the SS 1913 to the IPS 1956

The intercomparison data presented in the text above are now assembled together in Fig. 5. An arbitrary reference scale was constructed with the zero mark assigned to silver-disk pyrheliometer SI14 to indicate the SS 1913. Pyrheliometer SI14 was compared with the standards of the Smithsonian Institution in 1937, 1954, 1959 and 1960. The mean standard deviation for the comparison data is 0.45%. It is assumed that the comparison data given in Table 1 for the ratio of the solar irradiance measured by SI14 and Å 149 justifies the assumption that within the limits of measurement error the calibration factors of SI14 and Å 149 did not change between 1955 and 1967.

Silver-disk pyrheliometer T7 has been calibrated repeatedly since 1963 versus silver-disk pyrheliometer SI14, and has its factor reduced by 2.0% in order to represent the IPS 1956 derived through the use of definition A. The position of T7 was marked, therefore, at the left of the reference scale at the −2.0% level to indicate the IPS A 1956 at Toronto. The position of pyrheliometer Å 149 was then marked at the −4.6% level, using the data in Table 1, to indicate the ÅS 1905. The position of Å 149 was again marked 1.5% above this first position to indicate the IPS B 1956 at Toronto.

Finally, Eppley–Ångström pyrheliometer No. 9001 was marked on the reference scale by reducing the scale value of T7 by 2.6% (see Table 2), and Eppley–Kendall radiometer No. 11399 was located by reducing the position of T7 by the 0.13% mentioned in the text above. It seems coincidental that Å149 on the AS 1905 coincides with the position of E–Å9001 on the IPS B 1956.

The comparisons located to the right of the scale in Fig. 5 are positioned using the data presented in Figs 2 and 4. The position of T7, representing the IPS A 1956, is repeated on the right of the scale at the same level as on the left since the pyrheliometers named were compared with T7 at IPC-II and/or IPC-III. However, it should be noted that all the intercomparisons depicted in Fig. 5 are traceable

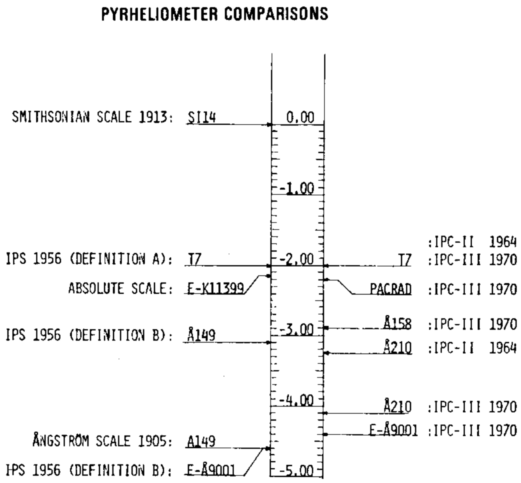

Fig. 5. The relationship of the Smithsonian scale of 1913 and the Ångström scale of 1905 to the IPS 1956, derived from comparisons of pyrheliometers at Davos and Toronto. All positions on the scale are determined with respect to the position of silver-disk pyrheliometer SI14.

to silver-disk pyrheliometer SI14 on the SS 1913 and to Ångström compensation pyrheliometer No. 158 on the ÅS 1905. Also, the positions of Å210 at IPC-II and IPC-III have not been corrected for the errors reported by Rodhe (1972), and mentioned above.

8. Conclusions

The data cited in Table 1 indicate that the SS 1913 and the ÅS 1905 differ by more than 3.5%. Å149 was referenced to Å158 at Stockholm in 1954. Sixteen years later Å149 shows agreement with Å158 within 0.2% when traced through two intermediate pyrheliometers, SI14 and T7 (see Fig. 5). Over this same period comparisons between SI14 and Å149 gave a mean difference of 4.6% between the two scales. More independent measurements between the SS 1913 and the ÅS 1905 are required in order to confirm the difference between the two scales with greater accuracy and precision.

According to Rodhe (1972) the calibration of Å210 at Davos at IPC-I was incorrect by 0.62%, and again by 0.64% at IPC-II. In addition, the difference in scale between Å210 and Å158 had increased to 1.2% at IPC-III. No information is available which would indicate whether this 1.2% difference can be attributed to a real change in Å210, to scale errors of the current meters used with Å210 at IPC-I and IPC-II, or both.

The ratio of the solar irradiance measured by E-Å9001 and T7 at Toronto and Mt. Kobau agree within 0.2% of the same ratio measured at Davos. However, the value of the solar irradiance measured with E-Å9001 using the calibration factor provided by the manufacturer is too low. In fact, it appears that the reference level maintained by the Eppley Laboratory produced a calibration for E-Å9001 which is 1.4% lower than the IPS B 1956 and 2.5% lower than the IPS A 1956.

Of particular interest is the very close agreement, shown in Fig. 5, between the two absolute radiometers, the PACRAD and E-K11399. They differ by less than 0.1%, although the comparison is transferred through silver-disk T7. One series of measurements were made at Davos during IPC-III, while the other was made at Mt. Kobau 2 years later. In addition the absolute radiometers give values of solar irradiance which are within 0.2% of the IPS A 1956 as represented by silver-disk T7.

A more recent intercomparison (Willson, 1972) was held at Table Mountain, California, which included some of the pyrheliometers already mentioned here, as well as others. It is worthwhile noting that E–Å 7644 (see Fig. 3) gave irradiance values about 2.0% lower than the values reported for PACRAD. This compares within the limits of measurement error with the 2.2% difference found between PACRAD and E–Å9001 at Davos (see Fig. 4). The reference instrument used at Table Mountain is called the Active Cavity Radiometer (ACR). Willson's (1972) data show that the ACR gave irradiance values 0.2% higher than the PACRAD which would place the ACR and silver-disk T7 at the same scale position in Fig. 5.

A new practical scale for use as reference for meteorological radiation measurements is urgently required to replace the IPS 1956. Radiometers with cavity-type black-body receivers have been fabricated and have an uncertainty of less than $\pm 0.2\%$ and a precision better than $\pm 0.1\%$ (Kendall, 1969). Therefore, the time seems opportune to replace the IPS 1956 with a revised scale of meteorological radiometry.

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ОБ АБСОЛЮТНЫХ ПИРГЕЛИОМЕТРИЧЕСКИХ ШКАЛАХ АНГСТРЕМА И СМИТСОНОВСКОГО ИНСТИТУТА И МЕЖДУНАРОДНОЙ ПИРГЕЛИОМЕТРИЧЕСКОЙ ШКАЛЕ 1956 г.

Общепринятая средняя разность между результатами измерений солнечной иррадиации с помощью пиргелиометра Аббота с серебряным диском, отнесенными к смитсоновской шкале 1913 г., и с помощью электрически скомпенсированного пиргелиометра Ангстрема, отнесенными к шкале Ангстрема 1905 г., составляет 3,5 %, причем результаты со шкалой Ангстрема ниже. В сентябре 1956 г. в Давосе Международная комиссия по радиации МГГС рекомендовала принять новую шкалу, известную как Международная пиргелиометрическая шкала 1956 г. (МПШ 1956). Чтобы выразить радиационные наблюдения в МПШ 1956 г., результаты измерений, отнесенные к шкале Ангстрема 1905 г. были увеличены на 1,5 %, тогда как результаты измерений, отнесенные к смитсоновской шкале 1913 г. были уменьшены на 2,0 %. Сравнение шкалы Ангстрема 1905 г. со смитсоновской шкалой 1913 г., проведенное в 1955–1957 гг. в Торонто, показало, что средняя разность между двумя шкалами равна 4,6 %, что на 1,1 % больше первоначальных 3,5 %, на которых основывалась МПШ 1956. В течение второго международного сравнения пиргелиометров в Давосе в 1964 г. средняя разница между шкалами Ангстрема и смитсоновской была найдена равной 4,85 %, а в период Третьего международного сравнения в 1970 г. — 4,4 %. Однако измерения с помощью самокалибрующегося пиргелиометра Кендалла с полостью согласуются с точностью 0,2 % со смитсоновской шкалой 1913 г., уменьшенной на 2,0 %. Настоятельно требуется новая практическая шкала вместо МПШ 1956 для использования в качестве отсчетной при производстве метеорологических радиационных измерений. Такая шкала может быть теперь получена с высокой точностью с помощью радиометра, имеющего приемник в виде полости и апертуру с тщательно определенной геометрией.