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# RADIATION SCALES AND THE SOLAR CONSTANT

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## RADIATION SCALES

Several radiation scales are used in radiometry at the present time. These are of two basic types: one type is derived from thermodynamic theory and the other type is derived from pyrheliometers which are always used with the sun as the source of radiant energy. The former are referred to as Thermodynamic Scales and the latter as Pyrheliometric Scales. It is impossible, at the present time, to convert measurements made relative to the thermodynamic scales to the pyrheliometric scales on an absolute basis. This situation results from the fact that pyrheliometric scales are established with the sun used as the source of radiant energy which means that contributions of radiant energy from circumsolar sky radiation are always incident upon the detectors. The detectors cannot be exposed to a blackbody in exactly the same manned as they are exposed to the sun since it is impossible to duplicate the circumsolar sky radiation with a blackbody.

Thermodynamic theory establishes the Thermodynamic Kelvin Scale (TKS). This is an absolute scale based on the temperature of the gold freezing point. International agreement on a new value to be used for the gold point can result in small changes to this scale. A practical or laboratory scale is derived from the TKS and is known as an International Practical Temperature Scale (IPTS) with the year of international adoption always referenced. Such scales were adopted in 1927, 1948, and 1968.

The pyrheliometric scale most used in the United States prior to 1956 was established by the Smithsonian Institution of Washington, D.C. in 1913 and revised in 1932 and 1954. In Europe the scale most used, prior to 1956, was the Original Ångström Scale. In 1956, the World Meteorological Organization accepted a new pyrheliometric scale, which was effective 1 January 1957, to be used in reporting of all solar measurements. The new scale was the International Pyrheliometric Scale of 1956 [IPS (1956)]. This scale was established prior to the International Geophysical Year of 1958 (IGY) in order to compare solar data from the different countries involved in IGY more easily and to reduce the chance of errors. The scale was established in terms of the pyrheliometric scales in use prior to 1956 as follows:[1]

"To express pyrheliometric observations in the IPS (1956):

(a) Measurements made according to the original uncorrected Ångström Scale are to be increased by 1.5 percent;

(b) Measurements made according to the Smithsonian Scale 1913 are to be decreased by 2.0 percent."

The Ångström scale is based on the compensation pyrheliometer introduced by K. Angstrom, which was recommended in 1905 by the International Meteorological Organization for meteorological radiation measurements.[2]

The Smithsonian scale is based on Abbot's silver disk pyrheliometer[3,4] which was used to establish the "Smithsonian revised pyrheliometric scale of 1913."[5] The pyrheliometers used to maintain this scale are designated S.I. 5 and A.P.O. $8_{bis}$ by the Smithsonian Institution. Before 1932, these pyrheliometers were calibrated with an absolute calorimeter developed by the Smithsonian Institution in which the temperature of the water, temperature rise of the water, flow rate, and aperture size through which solar energy was incident were measured. An improved calorimeter was built in 1932 which was simplier to use and more accurate than the original one. This calorimeter employed Ångström's electrical compensation method so that electrical energy could be compared to solar energy directly. This resulted in the Smithsonian Scale change of 1932 which changed the 1913 scale by minus 2.4%. However, the original arbitrary scale adopted by the Smithsonian to report all measurements was 1.8% below the standard scale of 1913.[6] In 1954, the Smithsonian announced that the mean of all comparisons between pyrheliometers S.I. 5, A.P.O. $8_{bis}$ and the Smithsonian calorimeter indicated that the scale of 1913 was 2.5% too high.[7] This means that all Smithsonian data should be reduced by 0.7% in order to be expressed in the Smithsonian 1954 scale and reduced by 0.6% to be expressed in the 1932 scale.

More recently (1969), JPL has introduced the Active Cavity Radiometric Scale (ACRS)[8] which is preserved by the cone radiometer developed at JPL by Kendall.[9] This scale has been compared to IPS (1956) at Table Mountain, California by means of the primary group of pyrheliometers maintained by the Eppley Laboratory of Newport, Rhode Island which are compared frequently with WMO standard pyrheliometers maintained in Davos, Switzerland.[10] To convert values of total irradiance in terms of IPS (1956) to ACRS, the IPS (1956) values are multiplied by 1.022.[8] The ACRS yields results which are 2.2% higher than those obtained by IPS (1956).

It is of interest to compare this conversion factor to the conversion factors necessary to convert the other pyrheliometric scales to IPS (1956). The multiplication factors necessary to convert values from the above scales to IPS (1956) are:

| SCALE | FACTOR |
|---|---|
| Original Angstrom Scale | 1.015 |
| Smithsonian Original Arbitrary Scale | 1.002 |
| Smithsonian 1954 Scale | .995 |
| Smithsonian 1932 Scale | .994 |
| Smithsonian 1913 Scale | .980 |
| Active Cavity Radiometric Scale | .978 |

The uncertainty of the JPL cone radiometer based on thermodynamic theory is stated to be ± 0.4% which indicates a systematic error in the IPS (1956) ranging from - 1.8% to - 2.6%.[8] This seems to indicate that the JPL cone radiometer reproduces the 1913 Smithsonian Scale more nearly than any of the other pyrheliometric scales listed above.

## SOLAR SIMULATION RADIOMETRY PROBLEMS

Published data, until very recently, of the values of the solar constant were given in terms of one or the other of the pyrheliometric scales discussed above. No international agreement exists at present as to the correctness of any of the pyrheliometric scales in terms of the absolute accuracy of these scales in relation to thermodynamic theory. The advent of solar simulators, which have to be set to an irradiance level equal to the solar constant by use of detectors calibrated in terms of thermodynamic and/or pyrheliometric scales, have introduced several radiometric problems and not a little confusion. The two types of scales, the impossibility of converting absolutely from one type of scale to the other, the use of detectors calibrated in terms of the thermodynamic scale used to set the level of irradiance of solar simulators, and the conflicting values of the solar constant on the several pyrheliometric scales have all contributed to the present radiometric problems associated with solar simulator calibration. Two examples will illustrate this: one; if a detector calibrated in terms of the Thermodynamic Scale is used to set the irradiance level of a solar simulator, the value of the solar constant to be simulated in terms of this detector's calibration is uncertain; two; if a detector calibrated in terms of one of the pyrheliometric scales is used, then the value of the solar constant to be simulated must be in terms of the same pyrheliometric scale. Most pyrheliometric scale calibrated detectors in use in the United States at present, are calibrated in terms of the IPS (1956) and the most commonly accepted value for the solar constant[11] is given on the Smithsonian 1932 Scale. The difference between these two scales is small (0.4%); but, the difference can be much larger as shown on the next page:

| Pyrheliometric Scale | Johnson's Value of Solar Constant |
|---|---|
| Original Ångström | 138.0 mw cm$^{-2}$ |
| Smithsonian 1954 | 139.5 |
| Smithsonian 1932 | 139.6 |
| IPS (1956) | 140.1 |
| Original Arbitrary Smithsonian | 140.4 |
| Smithsonian 1913 | 142.9 |
| JPS ACRS | 143.2 |

## RECENT MEASUREMENTS OF THE SOLAR CONSTANT

Recent measurements of the solar constant have been made by workers at GSFC,[12] ARC,[13] JPL[14] and The Eppley Laboratory[15] in this country. All except ARC used both total and spectral data to determine the solar constant. ARC used spectral data only. In Germany, Labs and Neckel[16] have published a value for the solar constant based on spectral data obtained at European Observatories and, in Russia, Makarova and Kharitonov[17] have published a value for the solar constant averaged from thirty independent series of spectral measurements obtained by different investigators. Stair and Ellis[18] have published a new value for the solar constant based upon new spectral irradiance measurements from 310 nm to 530 nm made at Mauna Loa, Hawaii.

JPL and GSFC have both developed an absolute radiometer which has been used to obtain a value for the solar constant. The GSFC cone radiometer was flown aboard the NASA ARC Convair 990 in August 1967 and obtained a value for the solar constant of $135.8 \pm 2.4$ mw cm$^{-2}$.[12] The JPL cone radiometer has been flown on both Mariner 6 and 7 in 1969 and has obtained a value for the solar constant of $135.3 \pm 2.0$ mw cm$^{-2}$.[19] These two values compare very favorably with each other, a difference of 0.5 mw cm$^{-2}$ having been obtained between the two published values.

GSFC and JPL-Eppley Laboratory have each used detectors calibrated in terms of IPS (1956) to obtain a value for the solar constant. GSFC used two Ångström Pyrheliometers manufactured by the Eppley Laboratory aboard the 1967 Convair 990 flights. These obtained values of $134.3 \pm 2.6$ mw cm$^{-2}$ and $134.9 \pm 4.0$ mw cm$^{-2}$.[12] The JPL-Eppley Laboratory have flown Eppley manufactured pyrheliometers aboard the NASA ARC Convair 990, a B-57B, and a X-15 during 1966-1968. The value of the solar constant obtained from these flights is $136.0 \pm 0.2$ mw cm$^{-2}$.[15] The difference between the Eppley-JPL value and the average of the GSFC values is 1.4 mw cm$^{-2}$. The GSFC average value of 134.6 mw cm$^{-2}$ compares favorably with the average obtained by the GSFC and the JPL cone radiometers which is 135.55 mw cm$^{-2}$.

The Eppley-JPL value of 136.0 mw cm$^{-2}$ compares very favorably to the cone values also. All these values are within the absolute accuracies claimed for the GSFC and JPL cone radiometers and the IPS (1956). GSFC estimates an accuracy of ±1.4% for the cone radiometer,[12] JPL estimates an accuracy of ±0.4% for the cone radiometer,[8] and the uncertainty claimed for the IPS (1956) is ±1%.[2]

It is of interest to note that the result of all solar constant determinations made by the Smithsonian Institution for the thirty year period between 1924 and 1954 yielded a mean value for the solar constant of 135.2 mw cm$^{-2}$ expressed in the 1954 Smithsonian Scale. This value is 134.5 on the IPS (1956) which is between the values obtained by GSFC on the IPS (1956) and is 1.5 mw cm$^{-2}$ below the value obtained by JPL and Eppley.

The ARC obtained spectral data aboard the Convair 990 in 1967 for the spectral range 300 nm to 2500 nm.[13] The instrumentation was calibrated using a standard of spectral irradiance.[20] The standard of spectral irradiance is derived from the standard of spectral radiance established by the NBS in 1960.[21] The standard of spectral radiance was established by reference to a blackbody. The temperature of the blackbody was established by means of an optical pyrometer calibrated by the NBS. The temperature scale used at NBS, until very recently (1969), to calibrate temperature-measuring instruments was the IPTS (1948).[22] The uncertainty associated with the standard of spectral irradiance ranges from 8% at 250 nm to 3% at 2500 nm.[20] Preliminary results from the current work with spectral radiance and irradiance standard-lamps at the NBS indicate that the new values of spectral energy are lower in all wavelength regions with about a 6% difference at 250 nm, a 2.5% difference at 650 nm, and a 3.5% difference at 850 nm.[23] This seems to indicate that a reduction of at least 2.5% would be required for data on the value of the solar constant obtained with the 1963 standard of spectral irradiance. The ARC value for the solar constant was 139.0 ± 2.8 mw cm$^{-2}$ based on an integration of the data recorded and assuming radiant energy from the sun beyond 2500 nm to be similar to a 5800 K blackbody. If this value is reduced by 2.5% on the basis of the above, then this value of the solar constant would reduce by 3.5 mw cm$^{-2}$ to a value of 135.5 mw cm$^{-2}$ which is the average value of the solar constant obtained by the GSFC and JPL absolute cone radiometers.

The GSFC also obtained spectral data aboard the Convair 990 in 1967. Measurements were made by several instruments over the wavelength region 300 nm to 15000 nm. A blackbody temperature for the sun of 5000 K at 15000 nm decreasing to 4950 K at 20000 nm was assumed for energy beyond the measurement range. The GSFC curve obtained from the data of all the instruments, both total and spectral, yielded a value of 135.1 ± 2.8 mw cm$^{-2}$ based on the IPS (1956). This result also compares favorably with the other results discussed above.

Stair and Ellis[18] in 1968 proposed a value of 136.0 ± 6.8 mw $cm^{-2}$ based on new spectral irradiance data obtained at Mauna Loa, Hawaii. The new data covered the range 310 nm to 530 nm with the data for solar spectral irradiance beyond this range obtained from Johnson's tabulation of the Smithsonian data. It is also noted in this paper[18] that the standard employed by Dunkelman and Scolnik[24] to obtain data which was later used by Johnson[11] yielded values about 4.5% above the present standard of spectral irradiance. This latter lamp is at least 2.5% higher than the standard lamps now being established at NBS which indicates that Dunkelman and Scolnik's data as used by Johnson may have been 16% too high (4.5% + 2.5% + 9.0% increase by Johnson to match the Smithsonian data). This would lower Johnson's value of the solar constant somewhat.

Johnson used the data of Dunkelman and Scolnik for the wavelength region from 318 nm to 600 nm. This interval contains 35.0% of the total irradiance as obtained by Johnson or 49.0 mw $cm^{-2}$. Moon's data[25] was used for the interval 600 nm to 1200 nm, a 6000 K gray-body was assumed to represent solar energy from 1200 nm to 14000 nm. This data was used to construct a relative solar spectral irradiance curve from 220 nm to 3000 nm. The absolute energy scale was assigned to the curve following the method of the Smithsonian Institution. This consists of an ultra-violet and infrared spectrobologram correction. The Smithsonian obtained spectrobolograms for the wavelength interval 346 nm to 2400 nm in conjunction with measurements of total irradiance. The value of the solar energy below 346 nm is called the ultra-violet spectrobologram correction and is expressed as a percentage of the total solar irradiance at the ground for the spectral range 346 nm to 704 nm. The infrared spectrobologram correction is expressed as a percentage of the total solar irradiance at the ground for the spectral range 704 nm to 2400 nm and yields the value of the total solar energy beyond 2400 nm. The ultra-violet corrections are obtained for several air masses and extrapolated to zero air mass to obtain the ultra-violet zero air mass correction. The infrared corrections are obtained for several values of centimeters of precipitable water and extrapolated to 0 cm which is the infrared zero air mass correction.

Johnson calculated the ultra-violet and infrared spectrobologram corrections, than he normalized his spectral curve in the spectral range 346 nm to 2400 nm on the basis of these corrections. The infrared correction was not changed but the ultraviolet correction indicated that the energy in this region (346 nm - 2400 nm) should be increased by 0.4 mw $cm^{-2}$ over the Smithsonian value. Johnson thus obtained an absolute energy scale for his curve with 128.4 mw $cm^{-2}$ in the spectral range 346 nm to 2400 nm, 5.9 mw $cm^{-2}$ below 346 nm, and 5.3 mw $cm^{-2}$ beyond 2400 nm to yield a value of 139.6 mw $cm^{-2}$ for the solar constant.

Labs and Neckel have published values of the solar spectral irradiance and the solar constant for the spectral range from 200 nm to 100 microns.[16] These values are based primarily on their data, obtained at the Jungfraujoch Scientific Station, for the spectral range 330 nm to 1250 nm and on the data of several other investigators for the remainder of the spectral range. The spectral irradiance values are given in terms of the TKS based on a gold point temperature of 1337.58 K. The value of the solar constant derived from their spectral irradiance curve is 136.5 mw $cm^{-2}$ in terms of the TKS scale and is called the spectrophotometric solar constant. The value for the spectral region 346 nm to 2400 nm derived from this spectral curve is 126.3 mw $cm^{-2}$ with 4.98 mw $cm^{-2}$ below 346 nm and 5.20 mw $cm^{-2}$ beyond 2400 nm. These are known as the ultra-violet and infrared corrections respectively.

Labs and Neckel also obtain a pyrheliometric scale value for the solar constant using the unweighted average of their spectrophotometric value along with the value obtained by Drummond, et al[14] (136.1 mw $cm^{-2}$) and the value of Johnson[11] as modified by them. (Reduction of ultra-violet and infrared corrections by 0.8 mw $cm^{-2}$ to yield a value for the solar constant equal to 138.8 mw $cm^{-2}$.) This value is given as $137.1 \pm 0.84$ mw $cm^{-2}$. This corresponds to an effective temperature of the sun equal to $5780 \pm 10$ K. They also use an effective temperature of 5140 K for the sun at 10 microns which compares favorably with the value used by GSFC.

Makarova and Kharitonov[17] have published values for the solar spectral irradiance and the solar constant based on an average of thirty independent series of measurements which were reported in the literature prior to 1967. They made no attempt to convert each of these series into one standard radiation scale. Many of their data were based on early standards of spectral radiance which are now believed to have given results which were too high as discussed above. The value for the solar constant obtained by these workers is $141.8 \pm 3.5$ mw $cm^{-2}$. The value for the energy contained in the spectral range 340 nm to 2300 nm is given as 131.8 mw $cm^{-2}$ and is referred to as the meteorological solar constant. The effective temperature of sun is given as $5829 \pm 35$ K which is higher than the value of Labs and Neckel by approximately 50 K. They also report a brightness temperature of 5180 K for the sun at 10 microns which compares favorably to the values reported by Labs and Neckel and GSFC.

The values obtained by the above workers for the solar constant (expressed in mw $cm^{-2}$) in the spectral range from 346 nm to 2400 nm as well as the ultra-violet and infra-red values are:

| Δλ(nm) | Russian | ARC | Johnson | Smithsonian | German | GSFC |
|---|---|---|---|---|---|---|
| 346 - 2400 | 131.8 | 128.6 | 128.4 | 128.1 | 126.3 | 123.90 |
| 0 - 346 | 10.0 | 5.3 | 5.9 | 4.4 | 5.0 | 5.54 |
| 2400 - ∞ | — | 5.1 | 5.3 | 2.7 | 5.2 | 5.61 |
| TOTAL | 141.8 | 139.0 | 139.6 | 135.2 | 136.5 | 135.05 |

These have been listed in decreasing amounts of energy obtained for the spectral range from 346 nm to 2400 nm. The Russian value is substantially greater than any of the others in this range. The values obtained by Johnson, Smithsonian, and ARC are fairly close together. The German and GSFC values are lower than any of the others. When the ultra-violet and infra-red corrections are added, Johnson and GSFC obtained essentially the same value, 11.2 mw cm$^{-2}$ and 11.15 mw cm$^{-2}$ respectively. The Russian, German, and ARC value averages 10.2 mw cm$^{-2}$, individual values are 10.0. 10.2, and 10.4 mw cm$^{-2}$ respectively. The Smithsonian value is substantially lower than any of the others with a value of 7.1 mw cm$^{-2}$. This poses the question as to which of these represents the true solar irradiance beyond 2400 nm and below 346 nm. Only the Smithsonian value differs from the others by more than 1.2 mw cm$^{-2}$ which indicates that this value may not be the correct one. The average of the other five gives 10.59 or 10.6 mw cm$^{-2}$. The average value for the spectral range from 346 nm to 2400 nm for the German and GSFC data is 125.1 mw cm$^{-2}$. If one then adds the average of the ultra-violet and infra-red corrections, excluding the Smithsonian data, obtained above, a value for the solar constant of 135.7 mw cm$^{-2}$ is obtained. If one adds the average of the ARC, Smithsonian, and Johnson values in the same manner, a value for the solar constant of 139.0 mw cm is obtained. If one reduces the ARC and Johnson data in the spectral range 346 nm to 2400 nm by 2.5% as discussed above, then a value for the solar constant of 135.9 mw cm$^{-2}$ is obtained. This value is only 0.2 mw cm$^{-2}$ greater than the average of the GSFC and German values. One might argue on the above basis that the value that should be accepted for the solar constant should be an average of the above values, as modified, which is 135.8 mw cm$^{-2}$.

However, this is not a valid argument for the following reasons:

1. Different radiation scales were used by the observers and no valid comparisons among the data can be made unless all are converted to a common scale;

2. Even if this is accomplished, the reduction of the ARC and Johnson data, based on the above discussions relative to the standard lamps used, also results in a correction to the ultraviolet and infrared corrections to be used which yields a slightly different value for the solar constant;

3. The relatively close agreement among all the observers except Smithsonian for the values of the infrared and ultraviolet corrections is more likely fortuitous rather than an indication of the correct amount of energy in these regions;

4. Some of the observers assumed gray body radiators of various temperatures for the infrared while others measured these regions, all of these data have to be reduced to a common basis before valid comparisons can be made;

5. All of the observers, except Smithsonian, used NRL rocket data[26,11] for the ultraviolet portion of the curve yet the values vary from a high of 5.9 mw $cm^{-2}$ obtained by Johnson to a low of 5.0 mw $cm^{-2}$ obtained by Labs and Neckel, these scale changes have to be accounted for on some basis;

6. All of the observers changed the scale of some of the data which were used to establish the solar spectral irradiance data, unless a total radiation measurement was made at the same time as the spectral measurements, such scale changes can result in errors; and,

7. The corrections applied to the data of each observer to convert to air mass zero are not the same.

The values obtained by the total radiation detectors for the value of the solar constant are:

| Detector | Scale | Value (mw $cm^{-2}$) | Value on IPS (1956) |
|---|---|---|---|
| JPL cone | ACRS | 135.3 ± 2.0 | 132.3 ± 1.96 |
| GSFC cone | TKS | 135.8 ± 2.4 | ? |
| GSFC Angstrom | IPS (1956) | 134.6 ± 3.0 | 134.6 ± 3.0 |
| JPL-Eppley Angstrom | IPS (1956) | 136.0 ± 0.2 | 136.0 ± 0.2 |

The average value obtained for the two cone radiometers is 135.55 mw $cm^{-2}$ on the thermodynamic scale. These values agree very closely. The average value for the solar constant for all three on IPS (1956) is 134.3 mw $cm^{-2}$, but the difference between the extreme values is 3.7 mw $cm^{-2}$.

The difference between the extreme values for the solar constant based on spectral data, excluding the Russian value, is 4.4 mw $cm^{-2}$; with the Russian data the difference is 6.7 mw $cm^{-2}$. This is comparable to the difference obtained with the total detectors based on IPS (1956) if the Russian data is excluded.

All of the spectral values discussed above which can be converted to the IPS (1956) are summarized below:

| Observer | Value |
|---|---|
| Johnson | 140.1 |
| Smithsonian | 134.5 |
| GSFC | 135.1 |

Therefore, based on the IPS (1956), values for the solar constant range from a high of 140.1 to a low of 132.2 or a difference of 7.8 mw $cm^{-2}$. However, the recent results only range from 132.3 to 136.0 or a difference of 3.7 mw $cm^{-2}$. Both the Smithsonian and GSFC spectral values are within the limits recently observed by the total radiation detectors.

In conclusion, all of the recent measurements of the solar constant with total radiation detectors indicate that the current accepted value for the solar constant is too high. The recent measurements with spectral instrumentation, with the exception of the ARC and Russian work, also indicate that the current value is too high. The ARC value is probably too high because the standard lamp used to calibrate the instrumentation seems to yield too high values.[23] The Russian work, which is based on thirty independent series of spectral measurements made prior to 1967, did not take into account the various radiation scales upon which each series of measurements were based which may account for the resulting high value obtained for the solar constant.

The best value for the IPS (1956) solar constant based upon an unweighted average of all the recent measurements which can be converted to this scale is 134.5 mw $cm^{-2}$ (JPL cone, GSFC Angstrom, JPL-Eppley Ångström, GSFC spectral).

The best value for the TKS solar constant based upon an unweighted average of all the recent measurements which can be converted to this scale is 135.9 mw $cm^{-2}$ (German spectral, GSFC cone, JPL cone).

Until a more definitive comparison among the recent data is performed, a reasonable value to assume for the solar constant to establish the total irradiance level of solar simulators is the average of the TKS and IPS (1956) values which is 135.2 mw $cm^{-2}$. This value is more likely closer to the true value of the solar constant than the presently accepted value of 139.0 mw $cm^{-2}$.

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