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## RADIATION REFERENCES

## Report from SC-MINT Expert Team on Radiation References

## Recommendations on conditions to be met for a change in solar and terrestrial radiation references

### Executive summary

New primary references are proposed for solar radiation and terrestrial (infrared) radiation. In both cases, they would result in better traceability to SI and reduced uncertainty. However, also in both cases, they would result in scale changes about the size of the uncertainty of the current references. The scale change is relatively small for solar radiation, but for terrestrial radiation, the size of the scale change is consequential.

The main recommendation of ET-RR is to proceed with the introduction of the new references for solar and terrestrial radiation providing certain conditions are met. For solar radiation, these are that (1) the proposed new primary solar radiation reference should be characterized and its uncertainty budget published in a peer-reviewed publication; (2) it must be compared bilaterally with another cryoradiometer from an NMI with a CMC for spectral sensitivity; (3) a group of ambient temperature cavity radiometers continues to be operated as main transfer standard; and (4) procedures are available for correcting data traceable to the current reference for harmonization to the new reference scale. For terrestrial radiation, these are that (1) the new reference(s) must have a demonstrated traceability to SI, (e.g. established by a CMC), and must be documented in the scientific literature with an uncertainty budget; (2) a group of reference pyrgeometers continues to be operated as main transfer standard; (3) procedures are available for correcting measurement data traceable to the current reference for harmonization to the new reference scale; and (4) pyrgeometer raw data for BSRN stations are recorded in the main BSRN archive.

### Solar radiation

Possible new solar radiation reference

The new proposed reference for solar radiation (CSAR/MITRA) aims at a fully characterized instrument allowing computation of irradiance linked to SI from understanding of the physics of the instrument. The same approach was followed for the instruments composing the World Standard Group (WSG) currently defining the World Radiometric Reference (WRR), but CSAR/MITRA includes major technological improvements and significantly reduced uncertainty. With respect to the ambient temperature cavity radiometers constituting the WSG, the major advance with CSAR/MITRA is the realization of a *cryogenic* cavity radiometer that can be used outside the laboratory. Cryogenic cavity radiometry is a mature technology providing SI-linked references in the laboratory and is formally identified as a primary standard of choice in the CIPM Mise en pratique for radiometry (Consultative Committee for Photometry and Radiometry, 2021). MITRA allows the assessment and determination of uncertainties linked to window transmission, required for cryogenic operation. Comparisons between the current WRR and CSAR indicate that the WRR is about 0.3% higher than the SI-scale. These are consistent with earlier comparisons of radiometric power between cryogenic radiometers and the WRR as well as between recent measurements from instruments deployed in space.

Known issues/limitations linked to the possible new solar radiation reference

Only a single instrument is proposed as new reference for solar radiation, which carries an inherent risk. It is first desirable that a second instrument of the same design (CSAR) is available for ensuring the availability of the primary reference in case of failure. Second, it is also desirable that one (or more) instrument of a different design is available for confirming the measurement of CSAR/MITRA since it is metrological good practice to have more than one independent realization of a reference. To provide a real benefit, such other realization should be truly independent and of comparable uncertainty with a clear definition of the elements of the realization that are tested. Currently, the only technology able to provide a solar radiation reference with uncertainty comparable to CSAR/MITRA is cryogenic cavity radiometry, for which there are limited variations that are practical and have a real impact on uncertainty. The primary ones are anticipated to be window transmittance and aperture area influencing the diffraction and scattering. However, such developments imply multi-year projects for fully characterizing new solar radiation references and establishing their uncertainty. Such a long delay is not acceptable in light of the established need of updating the solar radiation reference. Given the technological maturity in developing field-capable cryogenic absolute cavity radiometers, ET-RR considers as acceptable the risk of proceeding with the solar radiation reference change without waiting for the completion of such projects. In addition, the group of ambient temperature cavity radiometers used as transfer standard would provide a temporary backup in case of failure of the primary reference.

The continuation of a group of ambient cavity radiometers (similar to the current WSG) is desirable for providing an operational main transfer standard between the new proposed solar radiation reference and field radiometers. However, some radiometers constituting the WSG have experienced technical failures in the last years, linked to the decades that most of these instruments have been in operation. If only WSG radiometers with no problem/failures detected in recent years are considered, the current requirement on the number of radiometers constituting the WSG would not anymore be fulfilled. Beside the maintenance already performed on the radiometers currently constituting the WSG, new ambient temperature cavity radiometers should be selected for introduction in the WSG; the selection of such instruments being focused on stability and reproducibility as their traceability would be derived from the new solar radiation reference. Such a group of radiometers should also allow detection of any unforeseen anomalies in the performance of the primary system and thus be an intermediate backup until a second instrument with capabilities similar to CSAR/MITRA is available.

The 0.3% scale shift anticipated to result from the introduction of the new solar radiation reference may have a non-negligible impact on climate research because it should apply to all radiation measurements uniformly. WMO/INFCOM should engage with the BSRN community to evaluate the feasibility of harmonizing historical solar radiation time series from databases most important for climate research (BSRN, GEBA). Such discussions should be conducted at the 2022 BSRN meeting. The harmonization should adapt data traceable to the reference provided by the current WSG to the scale related to the new introduced reference. A final recommendation related to such harmonization should be issued after this evaluation.

Recommendations

The Expert Team on Radiation References (ET-RR) recognizes that:

* the development of the CSAR/MITRA radiometer is mature enough for its introduction as a new reference for solar radiation providing traceability of solar radiation measurements to SI with reduced uncertainty (from about 0.3% to about 0.01%, Walter et al., 2017; Winkler, 2013), resulting in an improved measurement accuracy of the absolute value of solar radiation,
* The understanding of the technology required for the development of CSAR/MITRA is adequate to allow reproducing other instruments of the same radiometer model with similar performance
* The complexity of the operation of cryogenic cavity radiometers such as CSAR/MITRA does not allow their routine operation, and therefore requires the continued use of a group of ambient temperature cavity radiometers (similar to the current WSG) as a main transfer standard
* The introduction of a new solar radiation reference based on CSAR/MITRA and potentially other cryogenic cavity radiometers would introduce a scale shift of about 0.3% (new scale lower than current)
* The potential improvement of the solar radiation reference that would be brought by introducing CSAR/MITRA as the new WRR has been documented since several years (Walter et al., 2017; Winkler, 2013)
* Commercial stakeholders in solar radiation measurements (especially in the solar energy sector) call for the prompt introduction of such a new solar radiation reference

ET-RR therefore recommends to INFCOM that a new solar radiation reference is introduced based on an artefact constituted by CSAR/MITRA, and potentially other cryogenic cavity radiometers, as rapidly as feasible provided that the four following conditions are met:

1. The proposed new reference instrument (CSAR/MITRA) must have been characterized and its uncertainty budget published, preferably in a peer-reviewed publication to demonstrate its operational performances.
2. The proposed new solar radiation reference instrument must have been compared bilaterally with another cryoradiometer from a National Metrology Institute with a CMC for spectral sensitivity and the comparison results published.
3. A standard group of ambient cavity radiometers (similar to the current World Standard Group (WSG)) must continue to be operated as main transfer standard.
4. Procedures must be available for correcting measurement data traceable to the current WRR for harmonization[[1]](#footnote-2) of historical data series to the new reference scale, in particular for major climate time series.

Without precluding the change of solar radiation reference, ET-RR further recommends that WMO/INFCOM urges NMIs, radiation centres and the research community to:

* Develop other independent realizations of the solar radiation reference allowing in-the-field determination of solar radiation with an accuracy comparable to or better than CSAR/MITRA (see first paragraph in section “known issues” above)
* Realize a second instrument of the same model design as CSAR/MITRA to mitigate risks linked with a technical failure of the instrument (see first paragraph in section “known issues” above)
* Continue research on CSAR/MITRA for further improving its accuracy and reliability, for example through inclusion of adaptive diffraction correction, swappable CSAR and MITRA windows and inclusion of dark-current sensor

ET-RR recommends that WMO/INFCOM urges the World Radiation Centre to:

* Do its utmost in enabling the development of a second CSAR/MITRA, including possibly through collaboration with/technology transfer to other institutions
* Ensures that a group of ambient temperature cavity radiometers (similar to the current WSG) is maintained for allowing its continuation as an operational main transfer standard (fulfilling main condition 2 above)
* Manages the process of including new ambient temperature cavity radiometers in the continued WSG (including definition of the process for inclusion of new instruments in the continued WSG as well as definition of the uncertainty/stability requirements)

ET-RR finally recommends that INFCOM:

* Develops and publishes a short document explaining the nature of the solar radiation reference change, the corresponding scale shift and its consequences, as well as guidelines on the necessity and method for correcting field data measured with instrument traceable to the current reference, and advocates for this document to be enclosed with calibration certificates traceable to the new reference.

Other requirement

Following the change of solar radiation reference (update of reference), ET-RR recommends that it is described in calibration certificates traceable to the new reference, including a description on how certificates traceable to the previous reference can be compared to certificates traceable to the new reference (see last bullet point in section “recommendations” above).

### Terrestrial radiation

Possible new terrestrial radiation reference

The approach for the new proposed reference is primarily developing a method allowing linking new infrared radiometers (e.g. IRIS, ACP) to SI. Such new infrared radiometers mainly aim at a windowless design with a uniform spectral response to minimize spectral mismatch errors linked to transposing the calibration using a blackbody source to measurements of an atmospheric longwave spectrum. Such radiometers are typically characterized in blackbodies at radiation calibration centres (at PMOD/WRC, blackbody BB2007). Recent bilateral comparisons within the EMPIR METEOC 3 and 4 projects of the BB2007 and the blackbody of a national metrological institute (PTB) that is linked to the SI radiation temperature scale using different instruments (IRIS, pyrgeometer and a dedicated radiation thermometer) provided an independent path of traceability for the BB2007 and verified its traceability.

Known issues/limitations linked to the possible new terrestrial radiation reference

A scale shift with potential significant consequences on terrestrial irradiance trend analysis and more generally on climate research is expected in case of adoption of the new proposed reference for terrestrial irradiance if the change is not implemented carefully[[2]](#footnote-3). The exact impact on measurements is not yet precisely determined since it depends on the climatology (mainly cloud climatology, see next paragraph) of the measurement location. Even though this shift is estimated to be within the uncertainty of terrestrial irradiance as determined during the Teddington meeting (15–17 November 2017) of the Task Team on Radiation References, the consequences are such that recommendations should address this issue. Such recommendations should allow the adverse consequences of the scale shift to be mitigated. They should be based on the following information:

* Results of the ExTrac project led by PMOD/WRC aimed at (i) better estimating the impact of the proposed terrestrial radiation reference change on pyrgeometer measurements; and (ii) developing methods for the harmonization of historical terrestrial irradiance time series
* Recommendations from the 2022 BSRN meeting (see next paragraph)

The consequence of the scale shift on measurements depends on cloud characteristics, primarily the amount of cloud coverage, and potentially factors such as the amount of atmospheric integrated water vapour. Because of this, it is difficult to determine precisely how much influence the scale shift will have on terrestrial irradiance data measured with commercial pyrgeometers. Likewise, methods for harmonizing historical time series to the new reference scale are not well established, yet. Climate research concerning terrestrial irradiance is mostly based on BSRN data series. Thus, a central reprocessing by the BSRN archive using a uniform reprocessing method would be most optimal. The 2022 BSRN meeting should discuss the feasibility and best method to harmonize BSRN historical terrestrial radiation (to the new reference scale). Thereafter, definitive WMO/INFCOM recommendations should be elaborated concerning the harmonization of historical terrestrial radiation data in the BSRN database.

The harmonization of historical data is likely to be a time-consuming task that can start only after the terrestrial radiation reference change is performed. It is important that the process for this undertaking is defined as quickly as possible.

Recommendations

The Expert Team on Radiation References recognizes that:

* The IRIS infrared radiometers developed by PMOD/WRC measures longwave irradiance with an expanded uncertainty of about ±2 Wm−2 (Gröbner, 2012). They are linked to SI via blackbody characterization using both the main blackbody of the Infrared Radiometry Section at the World Radiation Centre and the PTB hemispherical blackbody, the latter allowing a direct link to the radiation temperature scale of PTB. This methodology is mature enough for its introduction as a new reference for terrestrial radiation.
* The absolute cavity pyrgeometer (ACP) developed by NREL allows determining atmospheric longwave irradiance with an uncertainty of about ±4 Wm-2 (U95) with traceability to SI (Reda et al., 2012). Reda et al. (2012) indicate that the ACP provides an absolute reference for pyrgeometer calibration without requiring the ACP characterization within a blackbody, providing an independent method for SI traceability.
* The new spectrally uniform infrared radiometers (IRIS and ACP) require specific conditions and careful monitoring during operation since they are windowless. Therefore, the continued use of a group of reference pyrgeometers (similar to the current World Infrared Standard Group) is required as a main transfer standard for operational calibrations.
* The introduction of a new terrestrial radiation reference based on the methodologies described above would introduce a scale shift of approximately +5 Wm-2 (with an expanded uncertainty in the new scale of about 2 Wm-2) for clear-sky conditions (new irradiance scale higher than current), decreasing to zero Wm-2 for overcast conditions, (see section “known issues” above).

ET-RR therefore recommends to INFCOM that a new terrestrial radiation reference is introduced based on IRIS (linked to SI via blackbody characterization) and ACP as rapidly as feasible provided that the four following conditions are met:

1. The new reference(s) must have a demonstrated traceability to SI, for instance established by an approved Calibration and Measurement Capabilities (CMC), and must be documented in the scientific literature with performances characterized by an uncertainty budget. In case more than one new reference is eligible, the new references must agree within their stated uncertainties in international comparisons.
2. A standard group of reference pyrgeometers (similar to the current World Infrared Standard Group (WISG)) must continue to be operated as main transfer standard with an updated calibration with respect to the new references following state-of-the-art metrology methods.
3. Procedures must be available for correcting measurement data traceable to the current WISG for harmonization to the new reference scale, in particular for major climate time series.
4. BSRN should make mandatory the recording of pyrgeometer raw data (net IR signal in volts and temperature) using the newly defined logical record LR4000 and BSRN should investigate how many stations are able to provide this record for historical data.

Without precluding the change of terrestrial radiation reference, ET-RR further recommends that WMO/INFCOM urges NMIs, radiation centres and the research community to:

* Further improve and describe the understanding of the two realizations proposed for the terrestrial reference. The knowledge gained in the decade since the production of IRIS and ACP must be published in contributions to peer-reviewed journals, preferably in the metrology domain, particularly concerning improvements in the understanding of the accuracy of these instruments and their traceability to SI. While IRIS and ACP are consistent within the stated uncertainties, the community should conduct further research in order to reduce these uncertainties and better characterize the differences between references.
* Conduct more research to understand the discrepancies observed between different pyrgeometer instruments (even of the same type) during very dry atmospheric conditions (integrated water vapour below approximately 10 mm).

ET-RR recommends that INFCOM urges the World Radiation Centre to:

* Ensure that the current WISG is maintained for allowing its continuation as an operational main transfer standard (fulfilling condition 1 above).
* Manages the process of including additional pyrgeometers in the WISG for ensuring that it always includes a sufficient number of pyrgeometers even if older WISG pyrgeometers fail. Other models than those already in WISG should be considered for inclusion in WISG.

ET-RR finally recommends that INFCOM:

* Engages with BSRN to facilitate BSRN-led efforts for the harmonization of its terrestrial radiation record, especially for ensuring that *adequate resources are available* for such effort at the BSRN World Radiation Monitoring Centre (WRMC) and other international database centres
* Develops and publishes a short document explaining the nature of the terrestrial radiation reference change, the corresponding scale shift and its consequences, as well as guidelines on the necessity and method for correcting field data measured with instrument traceable to the current reference, and advocates for this document to be enclosed with calibration certificates traceable to the new reference

Other requirement

Following the change of terrestrial radiation reference (update of reference), ET-RR recommends that it is described in calibration certificates traceable to the new reference, including a description on how certificates traceable to the previous reference can be compared to certificates traceable to the new reference (see last bullet point in section “recommendations” above).

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1. Harmonization is used instead of homogenization to distinguish the process of applying corrections to historical data for compensating scale changes brought by reference changes from the process of rendering data series homogenous via different means (e.g. statistical homogenization). [↑](#footnote-ref-2)
2. Wild (2020) reviewed the representation of the energy balance in the latest climate model generation (CMIP6) used for the AR6 report of IPCC. In the CMIP6 generation, the multimodel global mean downward longwave radiation agrees with the (BSRN) observational reference best estimate. For all-sky conditions, the CMIP6 multimodel mean is now 2 Wm-2 higher than the best estimate inferred from BSRN data, and 4 Wm-2 higher under clear-sky conditions (Figures 5 and 13, Wild, 2020). The CMIP6 multimodel mean are also higher, and agrees better with observations, than the previous generation CMIP5 multimodel mean (by 4 Wm-2 for all-sky and 3 Wm-2 for clear-sky, the modelling community validating climate models against surface observations for both clear-sky and all-sky fluxes). Hypothesizing that the change in longwave references would result in a shift of the BSRN best estimate by about 2 Wm-2 for all-sky and approximately 5 Wm-2 for clear-sky, the agreement between CMIP6 multimodel mean and the observational reference would be almost perfect, while the CMIP5 multimodel mean would be further from the reference. It is not clear whether it is significant or due to chance since individual models still show an unsatisfactory large spread in both all-sky and clear-sky downward longwave radiation, which exceeds 20 Wm-2 even on a global mean basis (Figure 5, Wild, 2020). The CMIP6 multimodel standard deviation is about 5 Wm-2. Furthermore, the impact of the longwave reference change can also be significant because surface irradiance observations are used for satellite data product validations. For example, Kato et al. (2018) show that the mean bias of monthly mean downward longwave irradiances from a satellite data product is +1.0 Wm-2 over ocean and 0.0 Wm-2 over land. Observations over land used in the study are mostly from BSRN sites. The degree in which the observed downward longwave irradiance will be affected by the longwave reference change depends on sky conditions (e.g. cloud fraction or precipitable water) at each site and how each pyrgeometer was calibrated. Therefore, it is difficult to assess the impact without more information. However, up to 5 Wm-2 is significantly larger than the mean bias of monthly mean downward longwave irradiance from a satellite product. [↑](#footnote-ref-3)