W O R L D M E T E O R O L O G I C A L O R G A N I Z A T I O N

###### COMMISSION FOR INSTRUMENTS

###### AND METHODS OF OBSERVATION

**Task Team on Radiation References**

**Teddington, UK**

**15 – 17 November 2017**

**FINAL REPORT**



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**EXECUTIVE SUMMARY**

The First session of the CIMO Task Team on Radiation References (TT-RadRef-1) was held from 15 to 17 November 2017, at the National Physical Laboratory (NPL), in Teddington, UK and focussed on the traceability of terrestrial measurements.

The meeting reviewed the status of the World Infrared Standard Group (WISG), the outcomes of recent instrument intercomparisons, and the characterization and traceability of modern instruments that could be envisaged to compose a future reference.

The meeting recommended that:

* the WISG remains for the moment the reference, as further measurements are required to determine the value of its offset, and further developments are required to enable the establishment of an alternate stable reference,
* a governance framework be established for the WISG,
* any future reference change should follow principles similar to those applied by BIPM, when changing a reference,
* the future reference could possibly be based on a combination of instruments that are currently being tested (IRIS/BB and ACP).

The meeting recommended several activities that need to be performed to better characterize and improve the traceability of terrestrial radiation measurements, in view of a possible future reference change. These include among other further characterization of the WISG below 10 mm integrated water vapour, and further characterization of the modern instruments and of their traceability chain, but also further investigation of the mathematical model and process used for the calibration of field instruments.

The meeting called for development of new/different reference instruments to improve the traceability of infrared measurements.

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**AGENDA**

1. **ORGANIZATION OF THE SESSION**
	1. Opening of the Session
	2. Adoption of the Agenda
	3. Working Arrangements
2. **REPORT OF THE CHAIRPERSON**
3. **review of the current status and issues of infrared radiometrY**
4. **issues with the traceabiliy of field measurements**
5. **Recommendations for the traceability of terrestrial radiation measurements**
6. **OTHER BUSINESS**
7. **CLOSURE OF THE SESSION**

# GENERAL SUMMARY

1. **ORGANIZATION OF THE SESSION**
	1. **Opening of the Session**
		1. The meeting of the Commission for Instruments and Methods of Observation (CIMO) Task Team on Radiation References (TT-RadRef), First Session, was held at the National Physical Laboratory, in Teddington, United Kingdom of Great Britain and Northern Ireland The session was opened on Wednesday, 15 November 2017 at 9:00, by the vice president of CIMO and chairperson of TT-RadRef, Mr Bruce Forgan. He welcomed all the participants to the meeting. The list of participants is given in [Annex I](#Participants).
		2. Mr Forgan indicated that the meeting is a reduced meeting of TT-RadRef that will be focussing on the traceability of terrestrial radiation measurements. It would be conducted in the form of a workshop, together with the support of participants representing the Baseline Surface Radiation Network (BSRN), supported by the USA National Ocean and Atmosphere Administration (NOAA), the USA National Renewable Energy Laboratory (NREL) and the metrology communities.
	2. **Adoption of the Agenda**

 The meeting adopted the Agenda as reproduced at the beginning of this report.

* 1. **Working Arrangements for the Session**

 The working hours and tentative timetable for the meeting were agreed upon.

1. **Report of the Chairperson**
	1. Mr Bruce Forgan briefly explained the reasons for holding the reduced meeting of TT-RadRef. The meeting is expected to critically review the way terrestrial radiation standards are defined and the need for them, identify potential issues and propose solutions to resolve them, and to develop recommendations that should be submitted to the forthcoming session of CIMO that will be held in Amsterdam, The Netherlands, in October 2018. Relevant activities could then be incorporated in the CIMO workplan. Mr Forgan expressed his view that this special reduced TT-RadRef meeting is key for the future of WMO to ensure radiation references are/will be properly maintained/set, and that future terrestrial radiation measurements in the Global Climate Observing System remain a considered reference data set.
	2. Mr Forgan mentioned the plans of WMO to restructure its technical commissions, possibly reducing the number of commissions from 8 to 2. He stressed that it will be vital that the measurement community be clearly involved in the new commissions.
	3. Mr Forgan also noted that the goals of the meeting are very well aligned with the strategies listed in the Vision for the Future of Environmental Measurements that was recently developed by CIMO towards sustaining the knowledge on measurements through the WMO reorganization process.
2. **review of the current status and issues of infrared radiometrY**
	1. The meeting was presented with a series of invited presentations covering the whole traceability chain of terrestrial radiation measurements. The presentations covered:
* The development of the current basic pyrgeometry practices including the evolution of the current equations in field use.
* The practices that were used to set up the World Infrared Standard Group (WISG), the outcomes of relevant measurement campaigns focused on the assessment and traceability to the World Infrared Standard Group (WISG), such as the second International Pyrgeometer Comparison (IPgC-2015) held in 2015 at the Physikalisch-Meteorologisches Observatorium Davos/World Meteorological Centre (PMOD/WRC) in Davos, Switzerland, and the calibration procedures to trace network infrared measurements to the WISG.
* The characterization of modern instruments that could potentially be used as references for the measurement of terrestrial radiation and their traceability to the International System of Units (SI), independently of the WISG. This discussion focused on the PMOD black body, the Absolute Cavity Pyrgeometer (ACP) developed by the National Renewable Energy Laboratory (NREL), and the Infrared Integrating Sphere (IRIS) – a transfer standard instrument developed by PMOD/WRC.
* Preliminary results of recent measurement campaigns.
	1. Throughout the meeting, the participants critically reviewed each step in the traceability chain and ascertained their appropriateness. The meeting developed a list of issues and associated recommendations aimed at clarifying the traceability of terrestrial radiation measurements that are listed in [Annex II](#Annex2_Recomm). Some of them are also explained with additional details in the rest of this report. The meeting invited the Task Team, PMOD/WRC, the developers of modern instruments, BSRN and the metrology community to work collectively in clarifying those issues in the coming years.

***Basic pyrgeometry practices and equations in field use***

* 1. Mr Forgan presented the development of the current basic pyrgeometry practices including the evolution of the equations in field use.
	2. Thirty years ago, infrared measurements had an uncertainty of 30 to 70 W m-2 corresponding to roughly 20% of the signal. At that time the USA established the “Atmospheric Radiation Measurement” (ARM) program. The World Climate Research Programme, established around the same time, the precursor of the Baseline Surface Radiation Network (BSRN) that was aimed at supporting the satellite community. Around 1995 BSRN decided to abandon the use of net radiometers and to use instead pyrgeometers that had a much lower uncertainty.
	3. In the mid-1990s the BSRN community recommended a form of the Albrecht, Peollet and Cox equation for use with pyrgeometers. This required determining 4 coefficients, with 3 determined in a laboratory using a blackbody, and the fourth, the thermopile sensitivity, by comparison with a radiometric reference. In the late 1990s PMOD/WRC developed an absolute sky scanning radiometer (ASR) that was self-referencing to the SI using an internal blackbody. This instrument in a number of campaigns, by 2005, demonstrated that the uncertainty of infrared measurements had been reduced to 5 W m-2. A group of instruments at PMOD/WRC were calibrated using the PMO/WRC blackbody for 3 ‘instrument’ coefficients and the ASR for the thermopile sensitivity. Based on these findings, CIMO recommended establishing a World Infrared Standard Group (WISG) and entrusted PMOD/WRC to establish it. Unfortunately, ASR could no longer be used, and the reference to SI was solely through the WISG. Recently, clear sky measurements with the newly developed ACP and IRIS have shown a discrepancy of approximately 4 W m-2 to the WISG.
	4. Long-term measurements of the downward longwave irradiance suggest an increase of the irradiance over time and in agreement with the IPCC models. It is critical to be able to demonstrate the stability of pyrgeometer measurements in order to ascertain the veracity of such trends in the context of the investigation of climate change and to further extend the record in time.
	5. Mr Forgan showed a number of equations that are used in the field of pyrgeometry and the assumptions linked to each of them. He noted that some of the coefficients retrieved from the black body calibrations during the IPgC-2015 are not compatible with the physical model that is used to derive the recommended BSRN equation and may require further investigation.
	6. He invited the participants to critically examine all the steps of the current traceability of downward longwave terrestrial irradiance measurements that include:
* pyrgeometer equations in use, and their assumptions,
* blackbody calibrations and their processes,
* outdoor calibrations and their processes,
* status of WISG,
* status of IRIS,
* status of ACP,
* accessibility and security of historical meta data.

and propose a future path and investigations for the WMO measurement community.

* 1. Mr Forgan informed the meeting that historical documents describing key decisions of BSRN and WMO relating the the development of the recommended terrestrial irradiance measureand were not readily available on internet, probably because of institutional changes. The meeting recognized the need to ensure such documents remain available to the community in the future.
	2. It was noted that though BSRN had decided to abandon the use of net radiometers 20 years ago, some communities, like the agrometeorology community, are still using them. The meeting recognized the need to better inform users on the limitation of such instruments.

***Traceability of network instruments***

* 1. Mr Gröbner explained the different steps required to ensure the traceability of pyrgeometers to the International System of Units (SI).
	2. The working principles of pyrgeometers are based on energy balance. The coefficient k1, k2 and k3 are considered to be instrument parameters and are retrieved using a black-body, while the instrument’s thermopile sensitivity is derived from comparison to the WISG in order to account for the difference between the spectral distribution of a black body irradiance and that of the atmospheric irradiance. The calibration is carried out in such a way to enable the characterization of the pyrgeometer dome emission and transmission.
	3. Mr Gröbner went through the characterization process used at PMOD, the creation of a new blackbody operation in 2005 after the demise of the sky scanning radiometer, and the long term monitoring of the relationship of the instruments in the WISG. The results showed that there has been no long-term change in the WISG since its formation, and the latest blackbody gave results that closely matched to original blackbody.
	4. Mr Gröbner using the results of the IPgC-2015 showed that the pyrgeometer thermopile sensitivity coefficients obtained using a blackbody or the WISG are different. The observed differences seem to be mainly dependent on the instrument type. Mr Gröbner indicated that these differences are likely due to the spectral transmission of the domes, and the reason why thermopile sensitivities are determined outdoors to ensure consistency of results during regular operation of those instruments.
	5. Some seasonal effects were noticed in the retrieval of the pyrgeometer sensitivity. This led PMOD to decide to perform calibrations only when the integrated water vapour (IWV) is above 10 mm to minimize such effects.
	6. Instruments of the same model but using different dome types showed very different relationships to the WISG as a function of the integrated water vapour (IWV) content of the atmosphere. Exchanging their domes exchanged their behaviour, which suggested that the differences could be due to the dome characteristics. However, investigation of the spectral transmission of their domes up to 50 µm did not show any evidence that could explain this behaviour.
	7. It was recognized that latest models of pyrgeometer (for example, the Kipp & Zonen CGR4) had been improved to reduce the dome-body temperature difference, so that the dome coefficient k3 can be neglected.
	8. The meeting thanked Mr Gröbner for the presentation and then discussed the implications the results presented.
	9. The meeting expressed concern about the fact that manufacturers have only very limited information on the spectral characteristics of the domes used on the instruments. There was also discussion on the potential failure of one or more of the instruments in the WISG and how that could be managed. There was general consensus that other pyrgeometers be considered as potential members of the WISG.
	10. In discussing the results of the IPgC-2015 the meeting noted that of the 39 instruments participating and all with the k1 determined in the PMOD blackbody, half had a positive k1 while the remainder had a negative k1. A negative k1 was inconsistent with the physics and mathematical approximations that indicate k1 can only be positive. It was also noted that the retrieval of the instrument parameters in the PMOD black body are performed at temperatures similar to those encountered outdoors in Davos. In principle, it would be possible to carry out these measurements at higher temperatures, similar to those occurring in other areas of the world where some of the instruments will eventually be used.
	11. Most pyrgeometer include a temperature compensation circuit to account for the temperature dependency of their thermopile. Such instruments have a very small k1. The meeting concluded that the k1 derived by the blackbody process may likely reflect the temperature response of the thermopile, and not the mathematical approximation that results in k1 in the BSRN recommended pyrgeometer equation.

***Characterization of modern instruments***

* 1. Mr Ibrahim Reda gave a detailed presentation on the development of the ACP, and the equations that govern its use. At the time of the meeting there were two ACP in existence, both belonging to NREL. This innovative design uses a focussing cavity and does not have a dome. The cavity is placed on top of an Eppley pyrgeometer with its dome removed and with insulation between the cavity and the pyrgeometer body. The temperature of the cavity is monitored using a number of thermometers, and the standard outputs of the pyrgeometer make up the rest of the measurement set. The focussing cavity has been patented by NREL. As it has no dome the ACP can only be operated outdoors at night to measure downward terrestrial irradiance.
	2. Mr Reda showed that ACP is self-referencing to the SI though temperature and voltage measurements with three coefficients required to reference the ACP: the thermopile sensitivity, the transmission of the focussing cavity and the emissivity of the internal gold-plated walls of the focussing cavity. Measurements of the transmission of the first ACP were conducted at NIST, and models for the emissivity of gold are used that vary the emissivity based on temperature. The sensitivity of the thermopile is derived at the start of a measurement sequence by rapidly cooling the base of the pyrgeometer and then restoring it to ambient. Mr Reda explained that the thermopile sensitivity changed throughout a night of measurements and confirmed a change of 5% was not uncommon in changing terrestrial irradiance conditions.
	3. Mr Reda then showed a number of comparison results with both pyrgeometers calibrated by the WISG and direct comparisons with the IRIS developed by PMOD. The measurements showed a consistent offset of about 4 W m-2 to WISG.
	4. After thanking Mr Reda for his presentation, the meeting commented that the derivation of the equations combined both classical physics and elements of quantum physics, but the use of the gold focussing cavity was innovative and very useful. There was also discussion on the impact of the changing emissivity of gold, and why the derived thermopile sensitivity factors could vary so rapidly during a night of measurements. Mr Forgan noted that two other derivations of the ACP equation were possible, both using a classical physics approach.
	5. The meeting invited Mr Forgan to make a presentation of the different derivations of the equations for operation and calibration of the ACP. The first method used the same physical model of the ACP but included a term due to extra conduction during the cooling and heating process. Using data provided by Mr Reda results were presented showing excellent agreement during the IPgC-2015 but with a reduced change in the thermopile sensitivity. The second approach could only be described in a mathematical model as it required the temperature of the bottom cavity plate in the Eppley pyrgeometer, as it assumed that in the cooling phase there was not radiative equilibrium between the base of the thermopile and the bottom cavity plate. In normal operation of a pyrgeometer the base of thermopile and the bottom cavity plate are in radiative equilibrium.
	6. Mr Gröbner presented the IRIS, the calibration of its detector sensitivity in the PMOD blackbody, and its overall uncertainty budget. The IRIS is an innovative design using a pyroelectric detector, an internal blackbody reference, and a rotating spherical shutter. Like the ACP there is no window on the front aperture, and it can only be operated at night. Several radiation centres have purchased IRIS radiometers that are returned regularly to PMOD for calibration in the PMOD blackbody.
	7. Mr Gröbner indicated that as the IRIS is a relative instrument and does not self-calibrate to the SI, the stability of the sensitivity of the IRIS detector is critical. However, there is an issue with the stability of the current detectors and until an alternate detector can be sourced regular calibrations of the detector against a suitable blackbody are required. To assist in the future there is an EU project in place to develop portable blackbodies for this purpose, as well as comparing reference blackbodies in the EU.

***Outcomes of recent intercomparison campaigns***

* 1. Mr Gröbner presented investigations on the stability of the WISG. The WISG appears to be stable. However, WISG measures between 2 and 5 W m-2 lower than IRIS in clear-sky conditions. Mr Reda confirmed this difference with comparisons to the WISG when the two ACPs participated in the IPgC-2015.
	2. Comparison of the WISG with instruments that had taken part in IPSARC-1 (at which the parameters of the WISG pyrgeometers were set) also points towards the fact that there is an offset between the WISG and these other pyrgeometers of the order of 2.1 %.
	3. Mr Ohkawara presented the preliminary results of an intercomparison performed in Darwin, Australia, 16-27 October 2017. An IRIS was compared to 3 pyrgeometers traceable to the WISG at high integrated water vapour. The preliminary results confirm the offset that was observed between the WISG and IRIS above 10 mm IWV. However, there is a lot of scatter in the value of the offset observed in Australia, covering roughly the range of 28 to 52 mm IWV.
	4. Mr Long, Mr Reda and Mr Gröbner also discussed the current status of the joint comparison between the IRIS, ACP and WISG calibrated instruments as a joint BSRN and CIMO project being sponsored by NOAA, PMOD and the ARM site in Oklahoma, USA. The first phase was completed in late October, and the second phase will begin later in 2017.
	5. The preliminary results from the field intercomparisons performed in Australia, and in the USA seem to support the PMOD evidence of a 4-5 W m-2 offset between the instruments of the WISG that use filtered domes, and new window-less instruments either absolute instruments or calibrated in the PMOD blackbody. Note that in the field comparison at the SGP ARM site in the USA an Atmospheric Emitted Radiance Interferometer (AERI instrument) also confirmed this offset, being in agreement with IRIS/ACP.
1. **issues with the traceabiliy of field measurements**
	1. The meeting reviewed the current practices to ensure the traceability of field measurement to the SI, including the effectiveness of inter-comparisons to support and sustain the global traceability hierarchy of the WISG, and the outputs of the WMO World Radiation Centre.
	2. The meeting recognized that WMO sponsored intercomparisons, like IPgC-2015 organized conjointly with the International Pyrheliometer Comparison (IPC) remain the most effective mechanism to promote traceability in terrestrial and solar radiation measurements.
	3. The meeting recognized that the impact of a scale change to terrestrial radiation databases is not straightforward due to the traceability chain of the instruments to the WISG and the PMOD blackbody particularly for those instruments for which the instrumental characteristics have not been determined in the PMOD blackbody and would require further investigation.
	4. The meeting recalled that BSRN measurements are of primary importance in supporting the validation and confirmation of satellite measurements and computer model estimates, including for use in the context of climate monitoring. The traceability of the BSRN data is therefore crucial to achieve its stated goals. The meeting also recalled the BSRN uncertainty requirements for infrared radiation that are 3 W m2 or 2 %.
	5. The meeting was informed that a significant portion of measurements performed within BSRN have unknown traceability and that only few instruments are traceable to the WISG. The meeting was concerned by the apparent lack of traceability of the BSRN measurements. It felt that BSRN, as a GCOS network, should apply the GCOS principles and that data not complying with the BSRN network criteria should be flagged accordingly, so that users are properly informed of the data quality. The meeting encouraged BSRN to improve that situation by ensuring that BSRN sites meet the BSRN membership criteria.
	6. The meeting was informed that the concept of fiducial reference measurement (FRM, see [Annex III](#Annex3_FiducialRefMeas)) is being increasingly used within the CEOS (Committee on Earth Observation Satellites) community to describe a set of measurements that has scientific traceability and rigor, so that it is suitable for use as ground-based reference for satellite validation. The meeting encouraged BSRN to follow the concepts of FRM.
	7. The meeting recommended that CIMO and BSRN work together in re-examining the pyrgeometer equation recommended for use in BSRN, ensuring that outcomes of pyrgeometer characterizations (k1, k2 and k3) are in agreement with the physical model used as the base for that equation.
	8. The meeting recommended to develop additional guidance material informing users on key pyrgeometer specifications (possibly also including how they can be tested), and on the calibration process for field instruments (as well as its possible limitations) for inclusion into the Guide to Meteorological Instruments and Methods of Observation.
	9. Some smart sensors that have come to the market provide the instrument output directly in W m-2. Such instruments can usually not be calibrated but have to be returned to the manufacturer to insert the new calibration. The meeting noted those limitations and the possibly limited value of such instruments for the meteorological/climatological community.
2. **Recommendations for the traceability of terrestrial radiation measurements**
	1. The meetings commended the developments made in the field of terrestrial radiation over the last 10 years that are essential for maintaining confidence in terrestrial measurements, for ensuring their traceability, and for assessing their absolute uncertainty. These developments include among others:
* the maintenance of the WISG by PMOD/WRC,
* the development of the ACP by NREL and of the IRIS by PMOD/WC,
* the influence that BSRN and ARM have had in continuing the development in the field of terrestrial radiation measurements, and in expanding the network of terrestrial measurements.
	1. The meeting highlighted 20 issues (see [Annex II](#Annex2_Recomm)) related to traceability to SI of the WISG and of network measurements, and related to the characterization of modern instruments that could potentially be used as reference in the future. It recommended that the high-level recommendations provided in [Annex II](#Annex2_Recomm) be brought to the attention of the CIMO Management Group, so that it could take necessary actions and submit appropriate recommendations to the CIMO-17 session.
	2. At the time CIMO adopted the World Radiation Reference (WRR), it entrusted PMOD/WRC to maintain the World Standard Group (WSG) of pyrheliometers. CIMO also established a mechanism to oversee the status of the WSG and the dissemination of the WRR. This lead to the fact that the community has confidence in the established mechanism, which enabled the WRR to be recognized by the International Bureau of Weights and Measures (BIPM) Consultative Committee on Photometry and Radiometry (CCPR).
	3. The situation is somewhat different in the case of terrestrial radiation. The thirteenth session of CIMO entrusted PMOD to establish and maintain a group of at least three of the most stable pyrgeometers from different manufacturers. The fourteenth session of CIMO recommended that the Infrared Radiometry Section of the World Radiation Centre (WRC-IRS) establishes an Interim WMO Pyrgeometer Infrared Reference using the procedures and instrumentation that make up the World Infrared Standard Group, but no specific governance framework was specified. The unexpected demise of the ASR that was providing the traceability of the WISG led to a belief that the traceability of the WISG to SI was tenuous. The meeting recommended that a governance framework be established to ensure the stability of the current interim reference that is the WISG and towards establishing a future sustainable and stable reference for terrestrial irradiance and so, to maintain the trust of the community in the process, similar to that in place for the WRR/WSG. The meeting recommended that PMOD/WRC be invited to propose such a mechanism to the CIMO-MG that should eventually lead to the adoption of a recommendation by CIMO-17 on the governance framework for terrestrial radiation measurement reference and the WISG.
	4. The meeting acknowledged the likely 4 W m-2 offset of the WISG to the ACP in its current mode of operation and to the PMOD blackbody through the IRIS.
	5. The meeting made detailed examinations of the current traceability chain to the WISG, and the potential to establish a replacement of the WISG using blackbodies and absolute instruments. The meeting was of the opinion that while there was significant potential in these new instruments and methods, more work needed to be done over the next few years to ensure a stable and maintainable terrestrial reference can be developed to replace the WISG before any recommendations for a reference change are made to CIMO or the Executive Council.
	6. In order to ensure the homogeneity of radiation data, the meeting recognized that it is critical that a reference change would be based on sound scientific knowledge demonstrating the improvements that would be achieved by the new reference (e.g. lower uncertainty, better stability), that it is carefully planned, and that the maintenance of the new reference can be properly secured in the future. This should avoid repeating the unfortunate experiences that had been made with the solar radiation reference, where several reference changes occurred in the years between 1956 and 1966.
	7. In this context, the meeting noted the practice that is being followed by BIPM in considering a change of reference for the unit of mass where specific requirements (including a number of independent realizations) must be achieved before the change can occur (see the reproduction of the BIPM CCM recommendation in [Annex IV](#Annex4_BIPMCCMRec)).
	8. The meeting was of the opinion, that there is currently not enough confidence in the value of the WISG offset to SI, and on the ability to secure a more stable reference with the current status and number of alternative potential references (Blackbody/IRIS and ACP) to warrant a reference change. The meeting recommended to the CIMO MG to keep the WISG as the current interim reference for terrestrial irradiance. It further recommended that WMO follows a process similar to the one followed by BIPM for the modification of the definition of the mass and that CIMO-17 should adopt a recommendation on the conditions to be met before CIMO recommends to WMO to change the reference for terrestrial radiation measurements.
	9. The meeting discussed the conditions that would be needed to achieve acceptance by the scientific community of a new standard (likely based on ACP and IRIS/BB) providing appropriate traceability to SI. The meeting recommended that at least the following conditions be met prior to recommending a reference change:
* have an unbroken chain of calibration linking outdoor measurements to the SI,
* have at the minimum 2 instruments, operating on different principles/having different traceability path to SI that are metrologically traceable to SI[[1]](#footnote-1),
* that the uncertainty of the new reference be lower than that of the WISG.
	1. The meeting considered whether other international and/or national agencies should be responsible and accountable for radiation references. Taking into consideration the specialized nature of solar and terrestrial radiometry, the meeting recognized that WMO and its World Radiation Centre remain the most effective organizations to be accountable for solar and terrestrial references. This was supported by the national metrology specialists that attended the meeting.
	2. The meeting appealed to the metrology community to consider developing new/different reference instruments to improve the traceability of infrared terrestrial measurements to SI.
	3. The meeting recommended that IPgC should continue to be organized on a regular basis, preferably in conjunction with the IPC to rationalize resources.
	4. In discussion the meeting felt that the current uncertainty estimate for terrestrial irradiance measurement to the SI based on the WISG at 5 W m-2 is underestimated and a more appropriate figure is 10 W m-2 until the ~4 W m-2 offset is resolved.
1. **OTHER BUSINESS**
	1. The International Organization for Standardization (ISO) is in the process of finalizing the revision of the standard ISO 9060 – “Specification and classification of instruments for measuring hemispherical solar and direct solar radiation”. The meeting was informed that some manufacturers and the Association for Hydro-meteorological Equipment Industry (HMEI) have approached WMO to share their concerns as they are of the opinion that some of the proposed modifications may not be in the best interest of the meteorological users community.
	2. The meeting recalled that in the 1990s WMO moved away from having strict instrument classes, but preferred to focus its guidance on the ability to create good instruments. The meeting recommended that the WMO Secretariat approaches ISO to ensure that ISO 9060 and the latest version of the WMO Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8) are not disseminating conflicting guidance, proposing to review the standard, and to comment on it, if necessary, before the standard is finalized.
2. **CLOSURE OF THE SESSION**

The session closed on Friday 17 November 2017 at 17:30 hours

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# LIST OF PARTICIPANTS

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| ***Chairperson TT-RadRef*Bruce FORGAN**Bureau of MeteorologyPO Box 1289MELBOURNE 3001Victoria**Australia**tel.: +61 3 9669 4111fax: +61 3 9669 4736b.forgan@bom.gov.au | ***Vice-Chairperson TT-RadRef*Julian GRÖBNER**PMOD/WRCWorld Radiation CenterDorfstrasse 33 CH-7260 Davos Dorf**Switzerland**tel.: +41 81 417 5157fax: +41 81 417 5100julian.groebner@pmodwrc.ch |
| **Nozomu OHKAWARA** Japan Meteorological Agency (JMA)1-3-4 Otemachi, Chiyoda-kuTokyo 100-8122**Japan**Tel:  +81-3-3287-3439Fax: +81-3-3211-4640ohkawara@met.kishou.go.jp | **Nigel Fox*Representative of BIPM/CCPR*** National Physical LaboratoryHampton Road, Teddington, Middlesex, TW11 0LW **United Kingdom of Great Britain and Northern Ireland**Tel: 020 8943 6825nigel.fox@npl.co.uk |
| **Ibrahim Reda*Invited expert***DOE National Renewable Energy Laboratory15013 Denver West PkwyGolden, Colorado 80401**USA**Tel: +1 303 384 6385Fax: +1 303 384 6391Ibrahim.reda@nrel.gov | **Peter Blattner*Invited expert***Federal Institute of Metrology METASPhysics and Chemistry / Length, Optics and Time / OpticsLindenweg 503003 Bern-Wabern**Switzerland**Tel:  +41 58 387 03 40Fax:  +41 58 387 02 10peter.blattner@metas.ch |
| **Charles Long*Invited expert, Representative of BSRN***Earth Science Research Laboratory /GMDNOAA Office Oceanic and Atmospheric Research325 Broadway StreetBoulder, Colorado 80305**USA**Tel: +1 303 497 6056Fax: +1 303 384 6975chuck.long@noaa.gov | **Allison McComiskey*Invited expert, Representative of BSRN***Earth Science Research Laboratory /GMDNOAA Office Oceanic and Atmospheric Research325 Broadway StreetBoulder, Colorado 80305**USA**Tel: +1 303 497 6183Fax: +1 303 384 6975allison.mccomiskey@noaa.gov |
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| --- | --- |
| **WMO SECRETARIAT** 7 bis, avenue de la Paix Case postale 2300 CH 1211 Geneva 2 Switzerland  | **IMOP website**[<http://www.wmo.int/pages/prog/www/IMOP/IMOP-home.html>](http://www.wmo.int/web/www/www.html) |
| **Isabelle RÜEDI***Head, Instruments and Methods of Observation Unit**WMO Observing Systems Division* | Tel.: +41 22 730 8278Fax: +41 22 730 8181E-mail: IRuedi@wmo.int  |
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# Annex II

# List of issues related to the traceability of terrestrial radiation measurements and associated recommendations

**High-level issues and related recommendations**

1. **Belief in traceability of the WISG to the SI was lost through the demise of the ASR**
	* Support EMPIR Meteoc-3
	* Encourage research community to develop new methodologies for traceability to SI
	* Develop uncertainty budgets for the traceability methods
	* Continue the evaluation of the ACP and its associated measureand
	* Continue development of IRIS as transfer standard
	* Continue to watch developments in spectral infrared radiometry
	* CIMO: Encourage Members to support above activities.
	* CIMO MG: Invite PMOD to propose a governance framework to the MG for the WISG by March 2018.
2. **Currently, there is only one artifact (PMOD Blackbody) that is used to determine instrument parameters (k1, k2, k3)**

 For comparison to the existing artefact:

* + Use of different black bodies to determine instrument parameters (k1, k2, k3)
	+ Develop alternate methods to determine (k1, k2, k3, and their uncertainties) for comparison
1. **Lack of pyrgeometer specifications in the CIMO Guide**
	* Develop guidance using existing knowledge for incorporation in a future edition of the CIMO Guide:
		+ for Table 1E
		+ Including an instrument specification table in radiation chapter and how they may be tested
2. **Need to improve the traceability of IR measurements to SI**

Additional absolute infrared instruments would be of benefit:

* + Inform metrology community on the need to develop new/different reference instruments that meet various measurement requirements
1. **Is it time to modify the basic endorsed pyrgeometer equation?**

Given the results of IPgC-2 in relation to k1:

* + TT and BSRN to re-examine the pyrgeometer equation used by GCOS/BSRN and develop a recommendation

**Traceability issues and related recommendations**

1. **Why do we have a change of relationship between new CG4s/IRISs/ACP and the WISG at <10 mm IWV?**

The observed offset between IRIS/ACP/AERI and WISG traceable pyrgeometers is not constant over time and throughout the year; the best correlation is found with the dryness of the atmosphere, quantified through the integrated water vapour.

There is a significant volume of evidence on the difference between some pyrgeometers and IRISs against WISG at 10 mm IWV. It appears to be related to the spectral transmission of the interference filter domes of the pyrgeometers in the WISG and old models of CG4s and all examined PIRs.

* + Produce more pyrgeometers with domes having no interference filters
	+ Request PMOD to establish an alternate WISG set that has the characteristics of no changing relationship to IRIS/ACP across 0-40 mm IWV
	+ Examine the transmission of a sample of PIR domes and model the total atmospheric irradiance from atmospheric models and available hyperspectral irradiance measurements
	+ CIMO: That in relation to dome spectral transmission continuation of the work on the performance of the WISG below 10 mm IWV be requested of PMOD.
1. **The change of sensitivity of the thermopile with temperature and its impact on the calibration of the pyrgeometer**
	* Investigate the relationship between k1 and the pyrgeometer thermopile temperature sensitivity by running the blackbody characterization process across normal temperature range and then extend it to higher temperatures (at least +10 K) to quantitatively determine if a significant change in k1/k2/k3 is evident.
2. **How well does the indicated temperature reflect the actual internal case temperature at the base of the thermopile**
	* In selected pyrgeometers, take additional temperature measurements using calibrated thermometers at several locations inside the case including in PIRs the black plate beneath the thermopile, both in controlled laboratory and outside ambient conditions
3. **Examine existing pyrgeometer equations in detail to assess their impact on calibration methods, network measurements and pyrgeometer development**
	* Re-examine the pyrgeometer equation in use.
	* Do a sensitivity analysis on the key parameters from field calibrations or blackbody calibrations to be used in network measurements.
	* Investigate the impact of change in calibration procedures before implementing the change
4. **Calibration values provided in calibration report may not reflect the conditions in which the instrument is used**
	* Develop guidance to make clear to the users what are the potential limitations for using the values outside of the range of calibration and guidance on how to apply them outside that range.
	* Collaborate with metrology community on how to express the uncertainty of the extremes for the range of calibrations in the natural environment.
5. **Review ACP physical model, including its throughput**
	* Examine alternate ACP equations and alternate temperature monitoring within the body
	* Examine the apparent change of gold emissivity in the concentrator vs temperature and wavelength
	* Encourage other agencies to acquire and use an ACP
	* Develop finite element model of the ACP
	* Ask NREL to develop a report on the early work of the ACP gold cavity emissivity
	* Examine the temperature field in the body of a PIR during the transient cooling process

While NIST has examined some optical characteristics of the concentrator:

* + Examine additional optical characteristics of the ACP by using a laser source
1. **Improve the uncertainty of pyrgeometer night-time calibrations**
	* Consider the development of non-solar blind\* reference pyrgeometers for use in night-time calibrations
	* Examine the potential for using the non-solar-blind\* reference pyrgeometers over a wider range of acceptance criteria during night-time calibrations.

 \* non-solar blind = domes that do not have interference filter coatings.

1. **Regarding the influence of solar radiation on the pyrgeometer signal do we have sufficient knowledge to develop daytime characterizations of pyrgeometers?**
	* Identify sources and relative magnitude of uncertainties for shaded and un-shaded operation
	* Examine methods to reduce the contribution of the higher magnitude components of the uncertainty
2. **For traceability there is a continuing need to validate the equivalence of the results of multiple laboratories and instruments through intercomparisons**
	* Continue to support and promote future intercomparisons, covering a range of operation conditions, and the publication of their outcomes
3. **Is it time for another round-robin, including NMIs?**
	* CIMO to invite BSRN and the TT to organize another round-robin intercomparison (in the form of a set of pyrgeometers to be sent to several calibration institutions operating network pyrgeometer calibration procedures, as per the 1993-1996 round-robin) using a framework based on existing NMI intercomparisons.

**Characterization issues and related recommendations**

1. **Lack of information from manufacturers on dome characteristics**

Given that spectral transmission of the dome has a significant impact on the sensitivity factor and concern about the quality and reproducibility of the dome transmission characteristics including deposited interference filter:

* + Request manufacturers to make available the transmission & emissivity of the dome (curves or the pyrgeometer dome prior to assembly for external characterization); ideally for individual domes, but at least for batches.

NPL could measure a few sample domes.

* + Investigate solar transmission of pyrgeometer domes.
1. **Test the effect of the thermopile circuitry compensation on determining k1 for PYR**
	* Investigate dependency of k1 on the pyrgeometer body temperature to check whether a change in k1/k2/k3 is a significant contributor to the uncertainty; run the calibration across normal temperature range and then extend it to higher temperatures , at least +10 K offset from normal conditions.
	* Remove temperature compensation from a selected number of pyrgeometers and then repeat procedure above
	* Repeat two procedures above using domes with no solar-blind\* filter
2. **Could k3 be determined in another manner compared to the PMOD Blackbody?**

Using different calibration methods:

* + Derive alternate k3 values using:
		- other black bodies
		- outdoor methods
			* k3 single-value regression (method used by C. Long)
			* Solar heating of the dome (method used by B. Forgan)
	+ Developers of these methods provide documentation to TT or to open literature
1. **Can the thermopile responsivity of the ACP be determined in a different manner?**
	* Investigate alternate methods for determining the thermopile responsivity, for example:
		+ using direct solar irradiance
		+ using appropriate wavelength(s) laser power source
2. **Proliferation of smart sensors, including pyrgeometers (outputting only W m-2)**
	* Investigate new developments of smart sensors and assess and report back to the community on their suitability for providing traceable terrestrial infrared measurements
	* Promote access to the signals and metadata of the smart sensors used to produce the digitally-provided irradiance value

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# Annex III

# Fiducial reference measurements (FRM)

The suite of independent ground measurements that provide the maximum return on investment for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission (Sentinel-3 Validation Team)

A FRM must:

* Have documented evidence of its degree of consistency for its traceability to SI through the results of round robin inter-comparisons and calibrations using formal metrology standards.
* Be independent from the satellite geophysical retrieval process.
* Have a detailed uncertainty budget for the instrumentation and measurement process for the range of conditions it is used over.
* Adhere to community agreed measurement protocols, and management practices and have UC levels fit for the application they are used for.

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# Annex IV

# Reproduction of the Recommendation from BIPM CCM on a new definition of the kilogram

**RECOMMENDATION OF THE CONSULTATIVE COMMITTEE FOR MASS AND RELATED QUANTITIES SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES**

**RECOMMENDATION G 1 (2013)**

**On a new definition of the kilogram**

The Consultative Committee for Mass and Related Quantities (CCM)

***recalling*** its previous Recommendations to the CIPM on the “Conditions for a new definition of the kilogram”, CCM G 1 (2005), and “Considerations on a new definition of the kilogram”, CCM G 1 (2010),

***welcoming*** Resolution 1 (2011) of the CGPM “On the possible future revision of the International System of Units, the SI” which, when accomplished, will link the unit of mass to the Planck constant,

***recognizing*** the need to confirm and clarify Recommendation CCM G 1 (2010) in the light of that Resolution,

***considering***

* recent statements of stakeholders and user communities such as the OIML, the International Organization of Legal Metrology, and CECIP, the European weighing industry association, on the envisaged revision of the International System of Units, the SI, and specific activities of the CCM and its working groups in response to Resolution 1 (2011) of the CGPM,
* continued progress at several National Metrology Institutes and the BIPM with watt balance and X-ray Crystal Density (XRCD) experiments, two distinct and highly-accurate routes to determining the Planck constant, with new and significantly improved data available now, and additional results anticipated before the end of the year 2015,
* progress towards the *mise en pratique* for the realization of the new definition of the kilogram and its future dissemination,
* significant progress at the BIPM to establish an ensemble of reference mass standards,

***foreseeing*** the necessity to develop or improve methods and operate facilities so that, after redefinition, 1 kg can be realized and disseminated with a standard uncertainty not larger than 20 μg,

***recommends*** that the following conditions be met before the CIPM asks CODATA to adjust the values of the fundamental physical constants from which a fixed numerical value of the Planck constant will be adopted,

1. at least three independent experiments, including work from watt balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties1 not larger than 5 parts in 108,

2. at least one of these results should have a relative standard uncertainty[[2]](#footnote-2) not larger than 2 parts in 108,

3. the BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the watt balance and XRCD experiments have been compared as directly as possible with the international prototype of the kilogram,

4. the procedures for the future realization and dissemination of the kilogram, as described in the *mise en pratique*, have been validated in accordance with the principles of the CIPM-MRA[[3]](#footnote-3).

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1. According to ILAC, metrological traceability requires:

	* Unbroken chain of comparisons
	* Uncertainty of measurements
	* Documentation
	* Competence
	* Reference to SI units
	* Calibration intervals [↑](#footnote-ref-1)
2. supportive arguments for these requirements, which aim at a sound experimental basis for the CODATA adjustment of *h* before the redefinition, are given in *Metrologia*, 2010, **47**, 419-428 [↑](#footnote-ref-2)
3. as stated in the document CIPM MRA-D-05 “Measurement comparisons in the CIPM MRA [↑](#footnote-ref-3)