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Copy of submitted paper: 'The 2016 CEOS infrared radiometer comparison: Part 2: Laboratory comparison of radiation thermometers'

The 2016 CEOS infrared radiometer comparison: Part 2: Laboratory comparison of radiation thermometers.

by

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ABSTRACT

To ensure confidence, measurements carried out by imaging radiometers mounted on satellites require robust validation using 'fiducial quality' measurements of the same 'in-situ' parameter. For surface temperature measurements this is optimally carried out by radiometers measuring radiation emitted in

the infrared region of the spectrum, co-located to that of a satellite overpass. For ocean surface temperatures the radiometers are usually on-board ships to sample large areas but for Land and Ice they are typically deployed at defined geographical sites. It is of course critical that the validation measurements and associated instrumentation are internationally consistent and traceable to international standards. The Committee on Earth Observation Satellites (CEOS) facilitates this process and over the last two decades has organised a series of comparisons, initially to develop and share best practise, but now to assess metrological uncertainties and degree of consistency of all the participants. The fourth CEOS comparison of validation instrumentation: blackbodies and infrared radiometers, was held at NPL during June and July 2016 sponsored by the European Space Agency (ESA). The 2016 campaign was completed over a period of three weeks and included not only laboratory based measurements but also representative measurements carried out in field conditions, over land and water. This paper is one of a series and reports the results obtained when radiometers participating in this comparison were used to measure the radiance temperature of the NPL ammonia heat-pipe blackbody during the 2016 comparison activities i.e. an assessment of radiometer performance compared to international standards.

INTRODUCTION

The measurement of the Earth's surface temperature and, more fundamentally, its temporal and spatial variation, is a critical operational product for meteorology and an essential parameter for climate monitoring. Satellites have been monitoring global surface temperature for some time. However, it is essential for long-term records that such measurements are fully anchored to international physical standards as represented by the Systeme International (SI) units. Field-deployed infrared radiometers[1] currently provide the most accurate surface-based measurements which are used for calibration and validation of Earth observation radiometers. These radiometers are in principle calibrated traceably to SI units, generally through a blackbody radiator. However, they are of varying design and are operated

1 This report describes the comparison of instruments which are referred to by participants as "radiometers". However, radiometers generally measure and report radiometric parameters in radiometric units (W, Wm^{-2}, etc.). The instruments dealt with here measure temperature (in units of degrees C or K) so they are thermometers or "radiation thermometers". However, in view of the common usage of the terminology for this application, this report will continue to use the term "radiometer".

by different teams in different parts of the globe, and the quality of the blackbody radiator can be variable. It is essential for the integrity of their use, that any differences in their measurements are understood, so that any potential biases are removed and are not transferred to satellite sensors. One way of ensuring this is for the radiometers to be calibrated against a common high quality SI traceable blackbody and be tested alongside each other under field conditions. As part of this process, it is also essential that each radiometer and its procedure for use is well-documented and a detailed uncertainty budget related to the traceability of its measurements to SI units is created. To recognise this rigour and distinguish such measurements from other 'in-situ' measurements the term 'fiducial reference measurements' (FRM) has been established (https://earth.esa.int/web/sppa/activities/frm) and is being used for similar measurements of other Earth Observation parameters e.g. Ocean colour, Sea height etc. Previous CEOS comparisons of terrestrial based infrared (IR) radiometric instrumentation used to support calibration and validation of satellite borne sensors, with emphasis on sea/water surface temperature, were completed in Miami in 2001 (Barton et al., 2004) (Rice et al., 2004) and at NPL and Miami in 2009 (Theocharous and Fox, 2010) (Theocharous et al., 2010). However, seven years had passed, and many of the satellite sensors originally underpinned were at best nearing the end of their life. Under the auspices of CEOS, ESA established a new comparison of terrestrial based infrared (IR) radiometric instrumentation, in this case with their use expanded to support calibration and validation of satellite borne sensors for sea/water/land/ice surface temperature, this was completed at NPL during June and July 2016. The expansion of applications reflected the capabilities of new sensors such as SLSTR on the Copernicus Sentinel 3 satellite and the increasing importance of Land and Ice temperature measurements, particularly for climate monitoring. The objectives of the 2016 comparison were to establish the "degree of equivalence" between terrestrially based IR Cal/Val measurements made in support of satellite observations of the Earth's surface temperature and to ensure their traceability to SI units through the participation of National Metrology Institutes (NMIs). The comparison was organised through an ESA project called Fiducial Reference Measurements for Surface Temperatures derived by Satellite (FRM4STS) which also carried out a critical review of community measurement practises, details can be found at http://www.FRM4STS.org.

During the 2016 comparison, NPL acted as the pilot laboratory and provided traceability to SI units during laboratory comparisons. Stage 1 consisted of Lab comparisons, and took place at NPL during the week starting on 20th June 2016. This Stage involved laboratory measurements of participants' blackbodies calibrated using the NPL reference transfer radiometer (AMBER) (Theocharous et al., 1998) and the PTB infrared radiometer. In another exercise run concurrently, participants' radiometers were calibrated using the NPL ammonia heat-pipe reference blackbody. Stage 2 took place at Wraysbury reservoir during the week starting on 27th June 2016 and involved field measurements of the temperature of the surface of the water. Stage 2 included the testing of the same radiometers alongside each other, completing direct daytime and night-time measurements of the surface temperature of the water. Stage 3 took place in the grounds of NPL during the week starting on 4th July 2016 and involved field measurements of the temperature of the surface of a number of solid targets. Stage 3 included the testing of the same radiometers alongside each other, completing direct daytime and night-time measurements of the surface temperature of: short grass, clover, soil, sand, gravel and tarmac/asphalt.

This paper provides the results of the comparison of the participants' radiometers while they were viewing the NPL ammonia heat-pipe reference blackbody. During the 2016 comparison, all participants were encouraged to develop full uncertainty budgets for all measurements they reported. All measurements reported by the participants, along with their associated uncertainties, were analysed by the pilot laboratory and are presented in this report.

1 ORGANISATION OF THE COMPARISON

Recognising the increasing reliance of satellite operators and their customers/users on the quality of the data that comes from the satellite sensors it is essential that measurements used for their validation can be relied upon over a wide range of operational environments. Investments in projects which support the long term delivery of data for decades to come, such as the EU Copernicus program, have encouraged the community to subject such measurements to the scrutiny and practises common to other sectors of commerce i.e. comparison and/or audit by independent experts. The international metrology community has a responsibility to support such initiatives and therefore undertake regular comparisons between themselves of key quantities and report the results in open literature to ensure global consistency and transparency to the SI (https://kcdb.bipm.org/). To support this process, they have established procedures and guidance on how to optimally carry out such comparisons and analyse the results. The EO community is taking advantage of this knowledge and adopting the guidance to meet its needs. The Quality Assurance Framework for Earth Observation (QA4EO) [http://qa4eo.org/} developed by CEOS is the embodiment of this, and the comparison described below was organised following these metrology-based guidelines and practises.

This meant that before the comparison took place, a formal protocol describing the nature of the comparison, timelines, measurements to be undertaken, reporting format and, in particular, guidance on the content and presentation of an uncertainty budget was developed and agreed by all participants. Such protocols can then be subsequently used, with minor modifications, for similar comparisons in the future and will ensure a degree of consistency in how to interpret results.

During the 2016 comparison, NPL acted as the pilot laboratory and, with the aid of PTB, provided formal traceability to SI units during the laboratory comparisons at NPL. NPL was supported with specialist application advice from University of Southampton, RAL and KIT during the development of the necessary protocols. The 2016 series of comparisons consisted of three stages. Stage 1 took place at NPL in June 2016 and involved laboratory measurements of participants' blackbodies calibrated using the NPL reference transfer radiometer (AMBER) (Theocharous et al., 1998) and the PTB infrared radiometer, while the performance of the participants' radiometers was compared using the NPL ammonia heat-pipe reference blackbody. The performance of 8 blackbodies and 18 radiometers operating in 23 measurement channels was compared during Stage 1 at a range of different observation temperatures. Stage 2 took place on the platform which is located in the middle of Wraysbury reservoir in June/July 2016. The performance of 9 radiometers operating in 14 measurement channels was compared during Stage 2. Stage 2 included the testing of the participating radiometers alongside each other, completing direct daytime and night-time measurements of the skin temperature of the reservoir water. Stage 3 took place in the grounds of NPL during the week starting on 4th July 2016 and involved field measurements of the temperature of the surface of a number of solid targets. Stage 3 included the testing of the five radiometers alongside each other, completing direct daytime and night-time measurements of the surface temperature of targets, including short grass, clover, soil, sand, gravel and tarmac/asphalt.

This report provides the results, together with uncertainties as provided by the participants, of the radiometer measurements of the NPL ammonia heat-pipe blackbody operating at seven fixed temperatures as performed in one of NPL's temperature-controlled laboratories during the week beginning 20th June 2016. The laboratory comparison of the participants' blackbodies, as measured by the NPL AMBER radiometer and the PTB infrared radiometer, as well as the Water Surface Temperature (WST) comparison at Wraysbury reservoir and the LST comparison that took place in the NPL grounds are being presented elsewhere.

During the 2016 comparison, all participants were encouraged to develop uncertainty budgets for all measurements they reported. In order to achieve optimum comparability, tables containing the principal influence parameters for the measurements were provided to all participants. All measurements reported by the participants, along with their associated uncertainties, were analysed by the pilot laboratory, blind to all participants, and are presented in this report.

2 MEASUREMENT PROCEDURE FOR THE RADIOMETER LAB COMPARISON

The NPL ammonia heat-pipe reference blackbody (Chu and Machin, 1999) was used in the comparison of the participating radiometers. This blackbody uses a heat-pipe to control the blackbody cavity temperature. This results in negligible temperature gradients along the length of the cavity. The length of the ammonia heat-pipe blackbody cavity is 300 mm, and it has a 75 mm internal diameter with a 120^{o} cone angle at the end wall. The blackbody cavity is coated with a high-emissivity Nextel black paint. The emissivity of the blackbody cavity has been calculated using the series integral method (Berry, 1981). The effective emissivity of the cavity was estimated to be 0.9993, assuming an emissivity of 0.96 for the Nextel black coating (Betts, *et al.,* 1985).

The temperature of the blackbody cavity was obtained from an ITS-90 calibrated platinum resistance thermometer (PRT) which was inserted into a well of 150 mm depth in the rear of the cavity. The front of the blackbody contained a circular support which allowed aperture plates with different diameters to be positioned in front of the blackbody cavity. The blackbody had a 75 mm diameter aperture mounted on the blackbody casing. There was a total distance of approximately 75 mm from the front of this aperture to the actual blackbody cavity. This, in turn, meant that if radiometers with a large field of view were measuring the reference blackbody, then there was a possibility that they could be seeing parts which were outside of the blackbody cavity, even when they are placed right up against the front of the blackbody casing. While participants were free to position and align their blackbodies in front of the reference blackbody, most of the participants placed their radiometers right up against the reference blackbody, in order to ensure that blackbody cavity overfilled the entire Field of View of their radiometers.

The temperature of the blackbody cavity was controlled by a cylindrical heat exchanger which fitted closely around the blackbody cavity. Heat transfer fluid was circulated through a continuous 6 mm wide helical groove which was machined in the surface of the internal cylinder. Full information on the ammonia heat-pipe blackbody can be found elsewhere (Chu and Machin, 1999).

At sub-ambient temperatures i.e. at temperatures below the Dew point, the blackbody cavity was purged with dry nitrogen, in order to prevent water from condensing on the internal surfaces of the cavity which could damage the internal black coating and change the effective emissivity. The dry nitrogen gas was fed into the blackbody cavity from the rear. Its temperature was iso-thermalised within the feed tube which was embedded within the wall of the heat pipe. The gas was introduced into the front of the blackbody cavity via a gas distribution ring consisting of 12 holes of 1.5 mm diameter. In order to reduce the effect of convection currents from the surroundings, the aperture of the blackbody cavity was open whilst measurements were being made but was blocked at all other times with an insulation plug.

For each comparison point, the reference blackbody was set at a nominal temperature known only to NPL and enough time was allowed for its cavity temperature to stabilise to the new setting. Once the operating temperature had been selected, the system required just 30 minutes to reach temperatures greater than 0 ^{o}C, but as much as 3 hours to reach temperatures on the region of −30 ^{o}C. Once the set-point had been reached, the blackbody required another 0.5 to 1 hour to stabilize at the new temperature. Once the temperature of the reference blackbody was stabilised at a particular temperature, each participant was allowed a maximum period of 30 minutes to position their radiometer, align it to the aperture of the blackbody and take measurements at that particular temperature setting. The order with which radiometers completed the measurements at the beginning of the comparison depended on the readiness of the radiometers of the different participants to do measurements at that particular time. Towards the end of the comparison, participants were allocated 30 minute periods, according to timetables which were circulated to all participants. Participants with more than one radiometer were asked to arrange for the 30 minute measurement period to be shared between all their measuring radiometers. Figure 1 shows the RASMAS M-AERI radiometer viewing the ammonia heat-pipe blackbody during the comparison.

The temperature of the reference blackbody was continuously logged referenced to UTC and the participants were asked to use the same time reference. This allowed the direct comparison of the measurements of each participant with the corresponding measurements of the reference blackbody.

Participants were asked to provide their measurements in pre-defined spreadsheets. The top of each spreadsheet indicated the date on which the measurements shown in the spreadsheet were performed. Each spreadsheet consisted of a minimum of three columns. The first column indicated the time of the measurement, in a UTC format. The second column gave the brightness temperature of the reference blackbody, as measured by the participant, at the time indicated in the first column. The third column provided the combined (total) uncertainty of the measurement of the brightness temperature measured by the participant corresponding to the measurement indicated in the second column.

Participants were encouraged to develop and provide full uncertainty budgets for their measurements. In order to help participants to do this, tables were provided listing the parameters which were likely to contribute to the uncertainty of the measurement. Some participants provided completed tables, providing extensive information on each uncertainty contribution, while other participants provided considerably less information on their uncertainty budgets, and this is recognised by the community as an area where more work is needed.

3 PARTICIPANTS' RADIOMETERS AND MEASUREMENTS

A total of 19 radiometers operating on 24 different measurement channels took part in the 2016 radiometer lab comparison. This section gives brief descriptions of the participating radiometers.

THE UNIVERSITY OF VALENCIA CIMEL ELECTRONIQUE CE312-2 RADIOMETERS

Two radiometers were provided by the Dept. of Earth Physics and Thermodynamics of the University of Valencia, Spain. Both radiometers were of the CIMEL Electronique CE312-2 type and operated in six spectral bands, 8.0 µm to13.3 µm, 10.9 µm to11.7 µm, 10.2 µm to 11.0 µm, 9.0 µm to 9.3 µm, 8.5 µm to 8.9 µm, and 8.3µm to 8.6 µm. Both radiometers employed germanium windows and used narrow band filters with zinc sulphide substrates to select the different wavelength bands. Both instruments had a 10 degree Field of View and included a built-in radiance reference made of a concealable gold-coated mirror which enabled comparison between the target radiance and the reference radiation from inside the detector cavity. The temperature of the detector was measured with a calibrated PRT, thus allowing compensation for the cavity radiation. The relevant outputs of the radiometer were the detector temperature and the difference in digital counts between the signals from the target and the detector cavity. Further information on these radiometers can be found in Sicard et al., (1999) and in Legrand et al., (2000).

THE KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT) HEITRONICS KT15.85 IIP RADIOMETER

The radiometer provided by the IMK-ASF, Karlsruhe Institute of Technology (KIT), Germany was a Heitronics KT15.85 IIP radiometer with L6 lens. This was a single channel radiometer based on a pyroelectric infrared detector. This type of sensor links radiance measurements via beam-chopping to internal reference temperature measurements and thermal drift can practically be eliminated. The KT15.85 IIP responds in the 9.6 µm to 11.5 µm spectral range, has an uncertainty of approximately 0.3 K over the temperature range relevant to land surfaces and claims good long-term stability.

THE ONERA RADIOMETERS

Four radiometers were provided by the ONERA, France. The first three radiometers were Heitronics KT19.85 II having a 95 mm target diameter at a distance of 2 m. These radiometers operated in the 9.6

µm to 11.5 µm spectral band and offer a 60 mK temperature resolution. Their measurement uncertainty was ±0.5 °C+0.7% of the difference between target and housing temperature. The fourth ONERA radiometer was a BOMEM MR304SC Spectroradiometer covering the 3 µm to 13 µm wavelength range with two detectors, one InSb and one MCT detector with a 4 cm^{-1} resolution. This radiometer has a 20° (full angle) FoV. The measured radiance spectrum was converted into brightness temperature and averaged over the 9.6 µm to 11.5 µm wavelength range of the Heitronics radiometers. The temperature uncertainty was assessed for each measurement and ranges from 0.2 K to 0.4 K, depending on the blackbody set temperature.

THE CSIRO ISAR RADIOMETER

The radiometer provided by the Marine National Facility, CSIRO, Australia was an ISAR 5D radiometer. Full information on this type of radiometer is given by Donlon et al., (2008) and Wimmer et al., (2016).

THE STFC RAL SISTER RADIOMETER

The radiometer provided by the Science and Technology Facilities Council Rutherford Appleton Laboratory, UK, was the Scanning Infrared Sea Surface Temperature Radiometer (SISTeR). SISTeR was a chopped, self-calibrating filter radiometer manufactured by RAL Space. It had a single-element DLaTGS pyroelectric detector, a filter wheel containing up to six band-defining filters and two internal reference blackbodies, one operating at ambient temperature and the other heated to approximately 17 K above ambient. During operation, the radiometer selects, with a scan mirror, successive views to each of the blackbodies and to the external scene in a repeated sequence. For Sea Surface Temperature (SST) measurements, the external measurements include views to the sea surface, and to the sky at the complementary angle. The instrument field of view is approximately 13°. During this comparison, a filter centred at 10.8 µm was used. Further information on the SISTeR radiometer can be found in http://www.stfc.ac.uk/research/environment/sister/

THE SOUTHAMPTON UNIVERSITY ISAR RADIOMETER

The radiometer provided by the National Oceanography Centre of Southampton University, UK, was an ISAR with a Field of View of 3.5 degrees (half angle). The radiometer responded to wavelengths in the 9.6 µm to 11.5 µm spectral band. This radiometer offers a 10 mK temperature resolution. Full information on the ISAR radiometer can be found in the papers by Donlon et al., (2008) and Wimmer et al., (2016).

THE DANISH METEOROLOGICAL INSTITUTE (DMI) RADIOMETERS

Two radiometers were provided by the DMI, Denmark. The first radiometer was an ISAR-5D. Full information on this radiometer can be found in the paper by Donlon et al., (2008). The second radiometer was a Campbell Scientific IR120. This was a broadband radiometer measuring over the 8 µm to 14 µm wavelength range. This radiometer offers a 10 mK temperature resolution and a ±0.2 °C measurement uncertainty. For further information on the Campbell Scientific IR120 radiometer see:

https://s.campbellsci.com/documents/eu/manuals/ir100_ir120.pdf

THE OCEAN UNIVERSITY OF CHINA (OUC), QINGDAO RADIOMETERS

Two radiometers were provided by the OUC, Qingdao, China. The first radiometer was an ISAR 5C radiometer. Full information on this radiometer can be found in Donlon et al., (2008) and in Wimmer and Robinson, (2016).

The second radiometer provided by the OUC was an Ocean University of China First Infrared Radiometer (OUCFIRST) developed for measurements of the sea surface temperature. The OUCFIRST radiometer was similar to the ISAR radiometer and was based on the Heitronics KT15.85 IIP detector which responds in the 9.6 µm to 11.5µm wavelength range. The OUCFIRST radiometer also included two internal reference blackbody sources.

THE GOTA CIMEL ELECTRONIQUE CE312-2 RADIOMETER

The radiometer provided by Grupo de Observacion de la Tierra y la Atmosfera (GOTA) Universidad de La Laguna, Spain was a CIMEL Electronique CE312-2 radiometer. This radiometer incorporates a thermopile detector and can operate over six wavelength bands spread over the 8 µm to 13 µm wavelength range. Further information on this radiometer can be found in Legrand et al., (2000).

THE RSMAS M-AERI RADIOMETER

The radiometer provided by the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, USA was a Marine-Atmospheric Emitted Radiance Interferometer (M-AERI). This radiometer is based on a Fourier-Transform Infrared Spectro-radiometer, has a field of view of 22.5 mrad (half angle) and responds over the 3 µm to 19 µm wavelength range. It had a 25 mm diameter entrance aperture and a spectral resolution of 0.5 cm^{-1}. Its temperature resolution was 5 mK. Full information on this radiometer can be found in Minnett et al., (2001).

RESULTS AND DISCUSSION

Figure 2 plots, as an example, the measurements provided by the STFC RAL SISTeR radiometer (orange circles) when viewing the NPL blackbody maintained at about 10 °C and the corresponding measurements of the cavity temperature made by the NPL (blue dashes). Also plotted in the same figure are the combined uncertainty values of the measurements made by SISTeR and those of the NPL blackbody measurements. Figure 2 shows that at this blackbody temperature the difference between the average of the measurements made by the SISTeR radiometer over this time period and the average of the corresponding NPL measurements of the blackbody temperature was 60 mK.

Figures 3 to 9 show the plots of the mean of the differences between the radiometer readings and the corresponding NPL measurements of the temperature of the ammonia heat-pipe reference blackbody, for all the blackbody temperatures at which the radiometers were compared. The uncertainty bars shown in these Figures represent the combined uncertainty (k = 1) of the measurements provided by the participants.

Figures 3 to 9 show that when the blackbody was operating at temperatures above 0 °C, the differences between the participants' radiometer readings and the corresponding temperature of the NPL reference blackbody, were (with few exceptions), within the uncertainty of the measurements. However, these differences became progressively larger as the reference blackbody temperature decreased to -15 °C and -30 °C. This observation is not altogether surprising because measurements were made in a lab, with the measuring radiometers operating at ambient temperatures. This meant that the internal blackbodies within the participating radiometers which provided the reference against which the radiometers were basing their measurements were also operating at near ambient temperatures; hence for low temperatures of the ammonia heat-pipe blackbody, the difference between the temperature of the test blackbody and the internal reference blackbodies increased, probably leading to the observed discrepancies. The discrepancies are likely to arise due to the large extrapolation ranges (up to 50 °C) and may be enhanced by other effects. If, for example, the out-of-band response of the radiometer was measured incorrectly or had a small undetected spectral leak, then discrepancies are likely to arise. It is estimated that the output of a radiometer responding in the 10 µm to 11 µm region, which is calibrated at 30 °C and extrapolated to -30 °C, will be 0.26 % different from the output obtained if the radiometer had an out-of-band response in the 5 µm to 6 µm region which was just 1 % of the response in the 10 µm to 11 µm band.

It is important to point out that if the radiometers were used to measure low temperature targets, such as the surface temperature of ice in the arctic, then the radiometers (as well as the internal blackbodies) will also be at low temperatures so the extrapolation will not be over a significant temperature range. This means that the discrepancies between the radiometer measurement of the ice and the true surface temperature of ice are likely to be much smaller. For future comparisons where such low temperatures are important, consideration should be given to how the ambient temperature of the radiometers can be reduced to be more representative of the operational environment.

Moreover, as the temperature of the reference blackbody decreases, the signal detected by the photodetectors within the radiometers also decreases, resulting in poorer signal-to-noise ratios and thus more unreliable measurements.

It is important to note that the NPL AMBER radiometer was used in the past to measure the temperature of the same ammonia heat-pipe reference blackbody used in this comparison and the agreement between the NPL AMBER measurements and the blackbody measurements was good, indicating its reliability. In fact the difference between the NPL AMBER measurements and the reference blackbody measurements are included in the Figures for blackbody temperatures of -30 ^{o}C, 0 ^{o}C, 10 ^{o}C, 20 ^{o}C and 30 ^{o}C. The agreement between the AMBER and the reference blackbody measurements indicates that the discrepancies observed in the measurements of some radiometers (which can be as large as 2 K for blackbody temperatures around -30 ^{o}C) do not arise due to issues with the blackbody but are likely to be associated with the participants' measurements. Furthermore, NPL AMBER was used to measure the temperature of the ammonia heat-pipe blackbody of PTB, the German national standards lab, and that comparison also showed good agreement between the measurements provided by NPL AMBER and those provided by the PTB reference blackbody. Full information on that comparison can be found in the paper by Gutschwager (Gutschwager et al., 2013).

The NPL reference blackbody had an aperture of 75 mm in diameter which could be decreased by adding apertures with diameters smaller than 75 mm on the blackbody casing. The distance between the front of the blackbody cavity and the aperture formed/mounted on the blackbody casing was also 75 mm, meaning that the Field of View (FoV) of a radiometer placed against the casing would be overfilled by the blackbody cavity, provided its half angle was less than 26.5° (53° full angle). Although the 75 mm diameter of the blackbody and its position were defined and open for review in the protocol before the measurements took place, this was a source of error for radiometers with a large angle field of view which could not be positioned close to the blackbody casing aperture. For these radiometers, the measurements taken would likely capture the edges of the blackbody cavity, as well as radiation emitted by blackbody cavity, thus introducing biases to the measurements. To avoid this problem, some participants made their measurements with their radiometers as close to the blackbody front aperture as possible. Other than increasing potential of interactions between the blackbody and the radiometer this was in general considered to be a satisfactory compromise.

For the temperatures below 0 °C, ice began to form near the aperture of the reference blackbody cavity. While the ice only formed near the entrance to the cavity (the cavity was continuously purged with dry nitrogen gas), the presence of the ice may have affected the effective emissivity of the areas on which ice was deposited and thus alter the effective emissivity of the reference blackbody for radiometers with very large FoVs. This may also have impacted some of the results associated with the measurement of the temperature of blackbody cavity. However, the same measurements were made using the NPL AMBER radiometer and no discrepancies were observed for blackbody temperatures as low as -45 ^{o}C, indicating that no ice was formed inside the reference blackbody cavity.

For the majority of radiometers being compared, their intended use was for sea surface temperature measurements. This would mean their calibration range is for temperatures above 0 °C. This, in turn, means that some measurements taken during this laboratory comparison were outside the range of calibrated temperatures for these instruments. Any consideration of irregularities with the values for measurements and their associated uncertainties made below 0 °C should take this into account.

During the 2016 radiometer comparison, a 30 minute period was allocated to each participant to allow for the alignment of the radiometer to the reference blackbody aperture and the making of the measurements at a particular blackbody temperature. Some participants reported that 30 minutes was not enough. However, because of the number of radiometers participating in the 2016 comparison and the number of temperatures which had to be completed over the week-long comparison, the 30 minute period could not be extended. It is recommended that in future comparisons, participants should be asked to state how long they would ideally require in order to align and complete a measurement (at a particular blackbody temperature). If the total duration of the comparison could not be extended, or the number of participating radiometers could not be reduced, then the number of reference blackbody temperatures at which measurements are done should be reduced to allow participants the extra time periods they require to complete their measurements.

REFERENCES

Barton, I. J., Minnett, P. J., Maillet K. A., Donlon, C. J., Hook, S. J., Jessup, A. T. and Nightingale, T.J., 2004, ”The Miami 2001 infrared radiometer calibration and intercomparison: Part II Shipboard results”, *Journal of Atmospheric and Oceanic Technology*, **21**, 268-283.

Berry, K., 1981, “Emissivity of a cylindrical black-body cavity with a re-entrant cone end face”, *J. Phys. E: Scientific Instruments,* **4,** 629–632.

Betts D B *et al.,* 1985, “Infrared reflection properties of five types of black coating for radiometric detectors”, *J. Phys. E:Sci. Instrum.,* **18,** 689–696.

Chu, B and Machin, G., 1999, “A low-temperature blackbody reference source to -40 °C”, Measurement Science and Technology, **10**, 1–6

Donlon, C., Robinson, I. S., Wimmer, W., Fisher, G., Reynolds, M., Edwards, R., & Nightingale, T. J. (2008). “An infrared sea surface temperature autonomous radiometer (ISAR) for deployment aboard volunteer observing ships (VOS)”. *Journal of Atmospheric and Oceanic Technology*, ***25***, 93-113.

Gutschwager, B, Theocharous, E., Monte, C., Adibekyan, A., Reiniger, M., Fox, N.P. and Hollandt, J., ”Comparison of the radiation temperature scales of the PTB and the NPL in the temperature range from -57 °C to 50 °C”, Measurement Science and Technology, 24, Article No 095002, 2013

Legrand, M., Pietras, C., Brogniez, G., Haeffelin, M., Abuhassan, N.K. and Sicard, M., (2000). “A high-accuracy multiwavelength radiometer for in situ measurements in the thermal infrared. Part I: characterization of the instrument”, J. *Atmos. Ocean Techn.,* ***17***, 1203-1214.

Minnett, P. J., Knuteson, R.O., Best, F. A., Osborne, B.J., Hanafin, J.A. and Brown, O.B., 2001 “The Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), a high accuracy, sea-going infrared spectroradiometer”, *J. Atmos. Oceanic. Technol.,* **18**, 994-1013.

Rice, J. P., Butler, J. I., Johnson, B. C., Minnett, P. J., Maillet K. A., Nightingale, T. J, Hook, S. J., Abtahi, A., Donlon, and. Barton, I. J., 2004, ”The Miami 2001 infrared radiometer calibration and intercomparison. Part I: Laboratory characterisation of blackbody targets”, *Journal of Atmospheric and Oceanic Technology*, 21, 258-267.

Sicard, M., Spyak, P. R., Brogniez, G., Legrand, M., Abuhassan, N. K., Pietras, C., and Buis, J. P. (1999). “Thermal infrared field radiometer for vicarious cross-calibration: characterization and comparisons with other field instruments”, *Optical Engineering*, **38**, 345-356.

Theocharous, E., Fox, N. P., Sapritsky, V. I., Mekhontsev, S. N. and Morozova, S. P., 1998, “Absolute measurements of black-body emitted radiance”, *Metrologia*, **35**, 549-554.

Theocharous, E., Usadi, E. and Fox, N. P., **2010, “CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part I: Laboratory and ocean surface temperature comparison of radiation thermometers”,** NPL Report COM OP3.

Theocharous, E. and Fox, N. P., **2010, “CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part II: Laboratory comparison of the brightness temperature of blackbodies”,** NPL Report COM OP4.

Wimmer, W., and Robinson, I., (2016) “The ISAR instrument uncertainty model”. *J. Atmos. Oceanic Technol*. doi:10.1175/JTECH-D-16-0096.1, in press.

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APPENDIX: FIGURE CAPTIONS:

Figure 0: Confirmation of submission

Figure 1: The RASMAS M-AERI radiometer viewing the ammonia heat-pipe blackbody during the 2016 radiometer comparison.

Figure 2: Measurements of the STFC RAL SISTeR radiometer viewing the NPL reference blackbody maintained at approximately 10 °C (in orange) and the corresponding measurements made by NPL of the blackbody temperature (in blue).

Figure 3: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of -30 °C.

Figure 4: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of -15 °C.

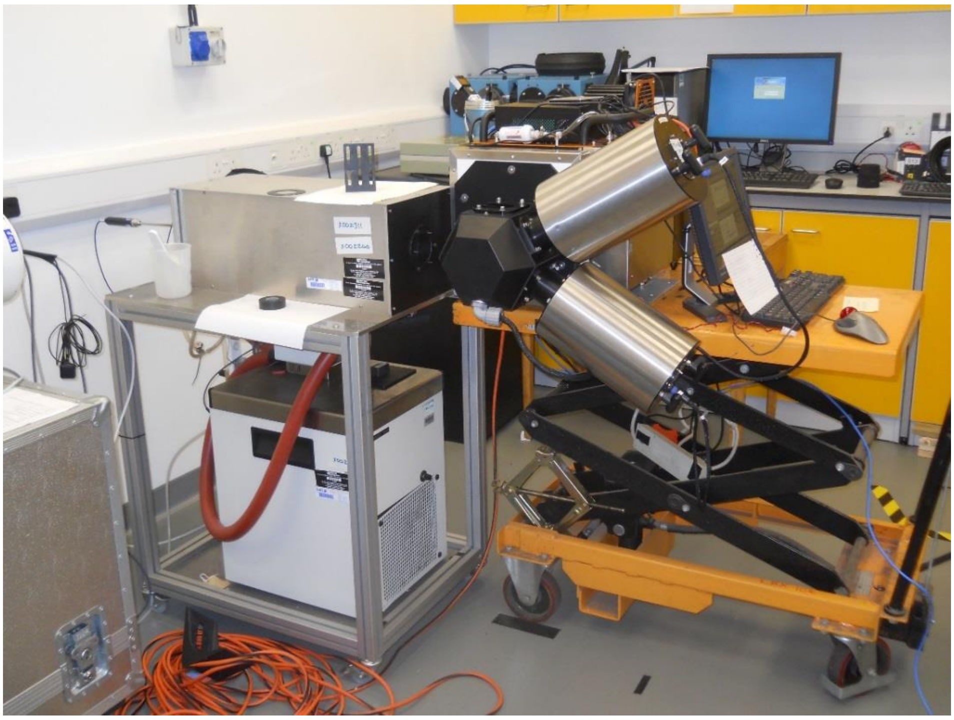
Figure 5: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 0 °C.

Figure 6: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 10 °C.

Figure 7: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 20 °C.

Figure 8: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 30 °C.

Figure 9: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 45 °C.



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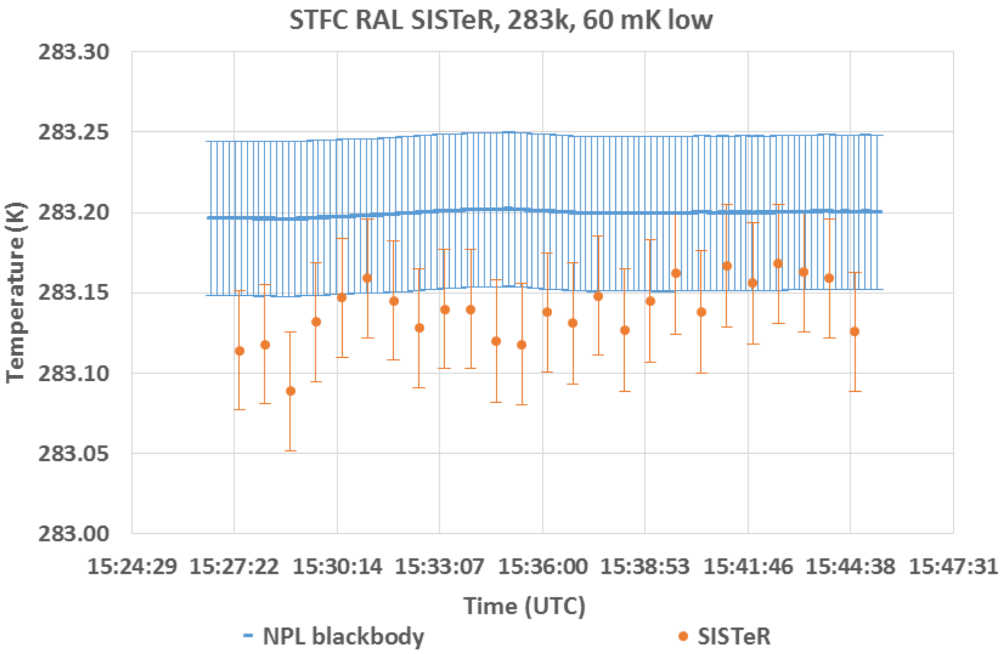

Figure 2: Measurements of the STFC RAL SISTeR radiometer viewing the NPL reference blackbody maintained at approximately 10 °C (in orange) and the corresponding measurements made by NPL of the blackbody temperature (in blue).

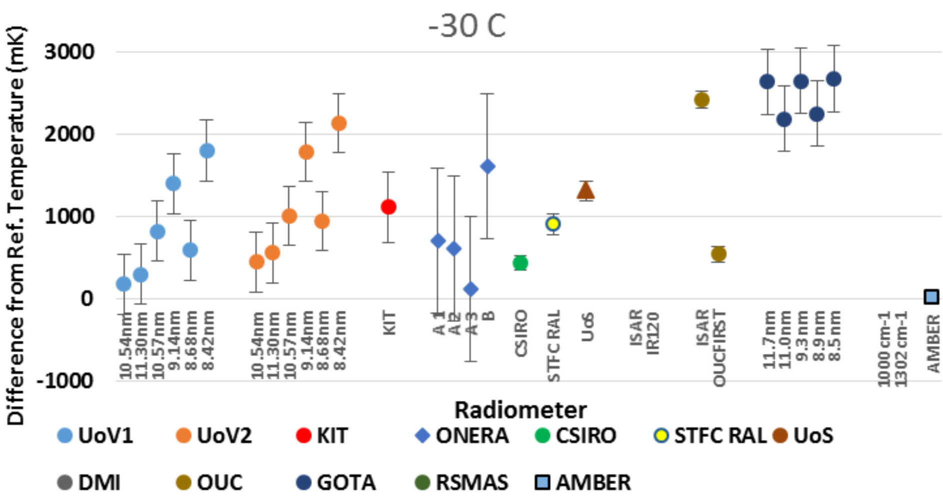

Figure 3: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of -30 °C.

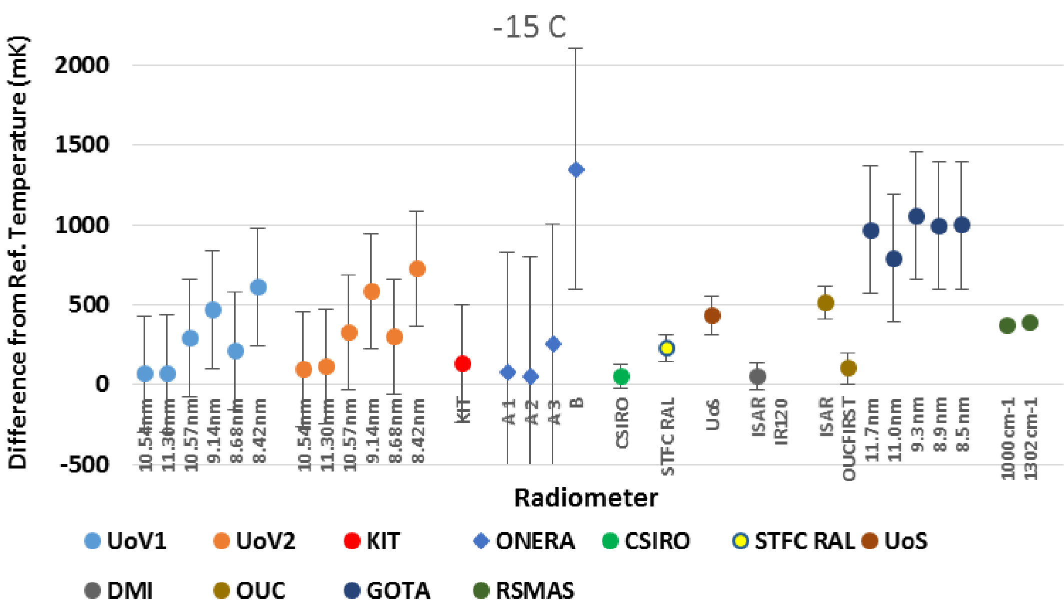

Figure 4: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of -15 °C.

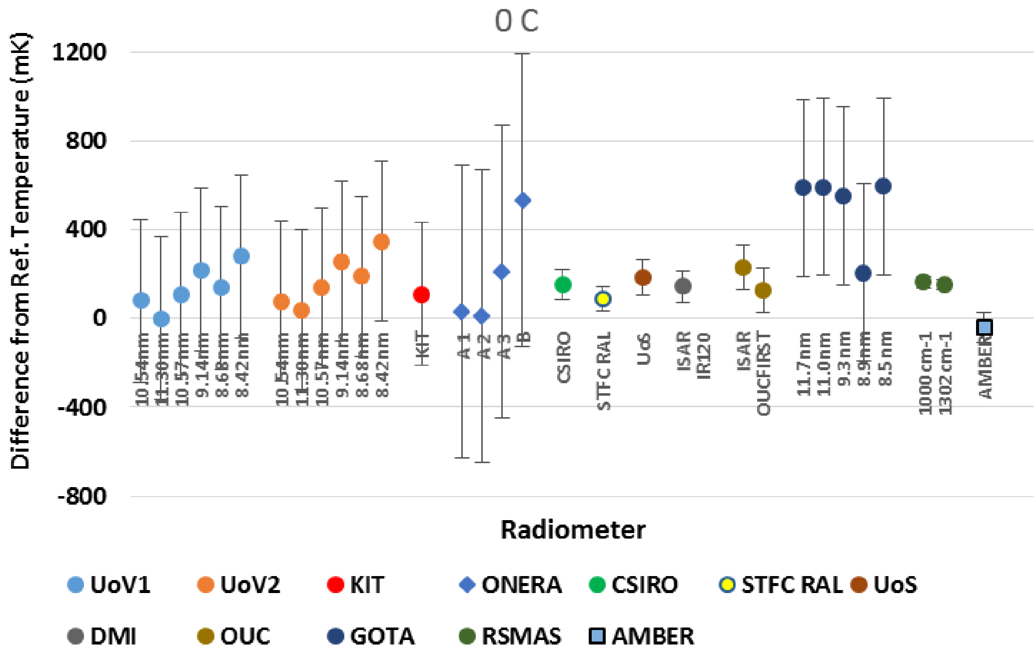

Figure 5: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 0 °C.

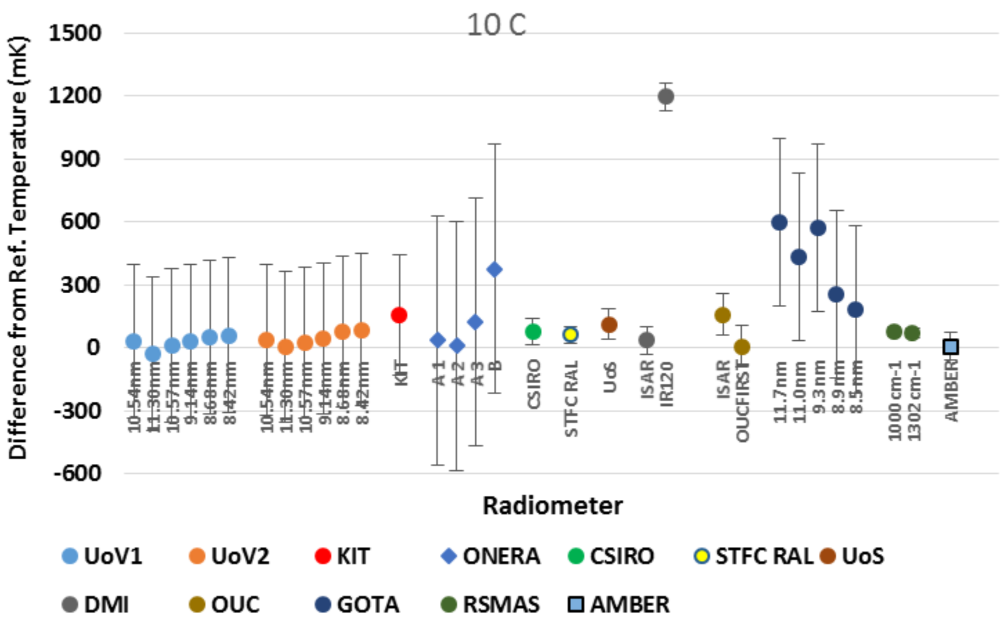

Figure 6: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 10 °C.

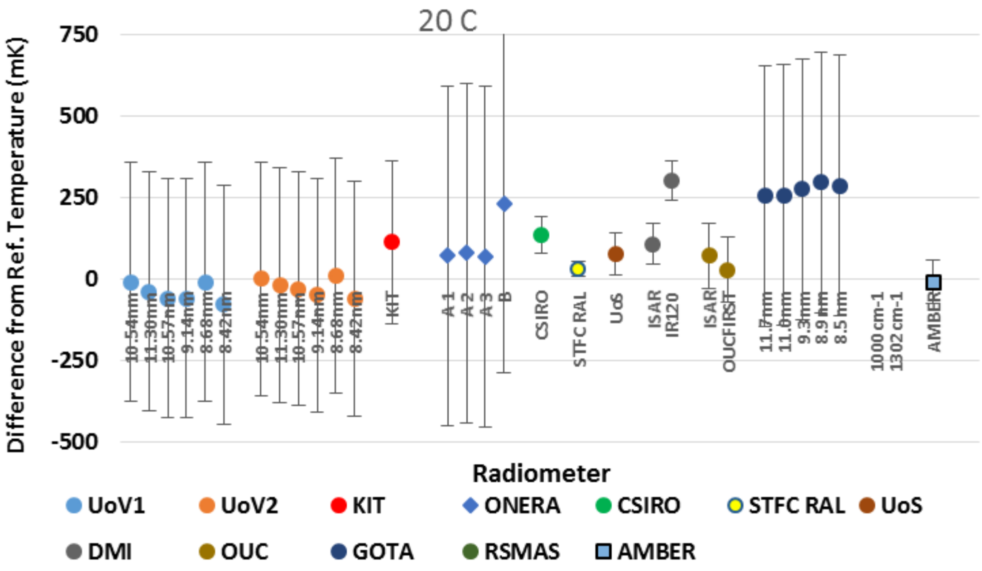

Figure 7: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 20 °C.

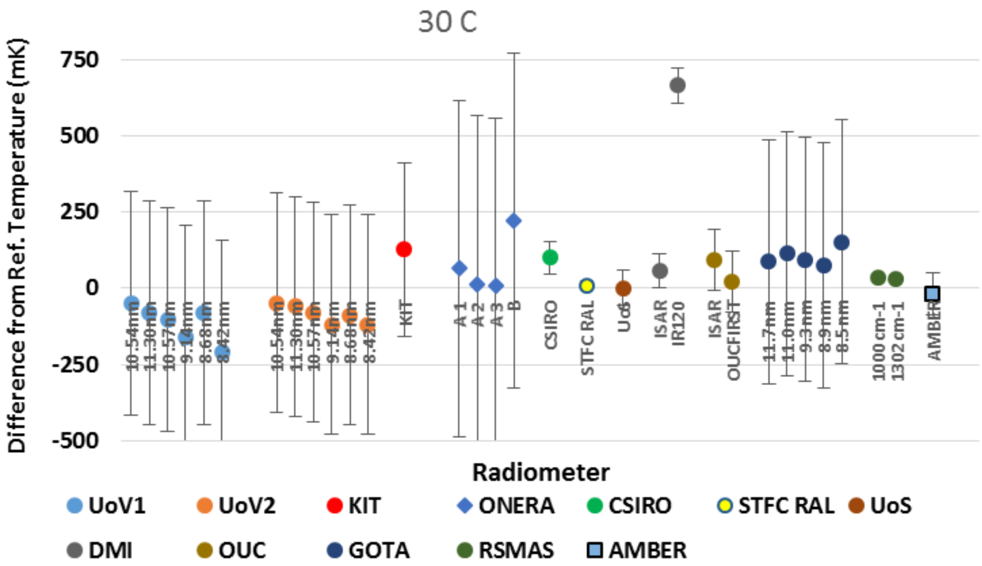

Figure 8: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 30 °C.

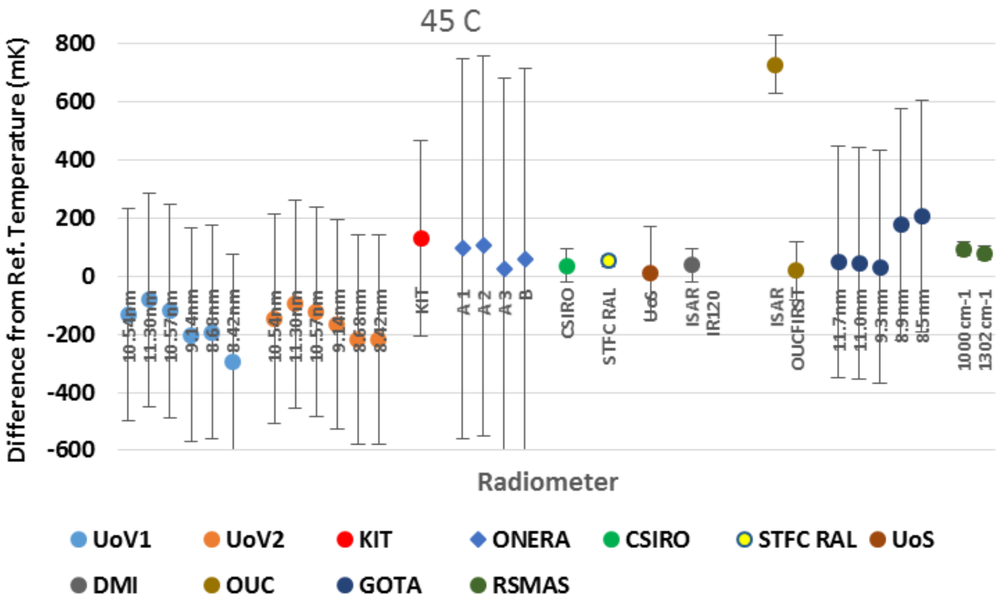

Figure 9: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 45 °C.