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Fiducial Reference Measurements for Sea Surface Temperature (FRM4SST)

D90 - Result from CEOS International Thermal Infrared Radiometer Inter-comparison (CRIC)
Part 1 of 3: Laboratory Comparison of Blackbodies

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DOCUMENT APPROVAL

Contractor Approval

Name	Role in Project	Signature & Date (dd/mm/yyyy)
Y Yamada	Metrology lead and comparison pilot	Y.Y. 30/03/2023
N Fox	Metrology lead and CEOS WGCV rep	Nigel Fox 30/03/2023

CUSTOMER APPROVAL

Name	Role in Project	Signature	Date (dd/mm/yyyy)
C Donlon	ESA Technical Officer		

APPLICABLE DOCUMENTS

AD Ref.	Ver. /Iss.	Title
AD-1	Issue – 1	Fiducial Reference Measurements for Sea Surface Temperature (FRM4SST): Protocol for FRM4SST CRIC Laboratory Comparison of Radiometers and Blackbodies
AD-2	Issue – 1	Fiducial Reference Measurements for Sea Surface Temperature (FRM4SST): Protocol for FRM4SST CRIC Field Comparison of Radiometers
AD-3	Issue – 2	Fiducial Reference Measurements for Sea Surface Temperature (FRM4SST): D80 - Implementation plan for Laboratory and Field Comparisons of Radiometers and Blackbodies
AD-4	Issue – 1	Fiducial Reference Measurements for Sea Surface Temperature (FRM4SST): D90 – Results from CEOS International Thermal Infrared Radiometer Inter-comparison (CRIC) Part 2 of 3: Laboratory Comparison of Radiometers
AD-5	Issue – 1	Fiducial Reference Measurements for Sea Surface Temperature (FRM4SST): D90 – Results from CEOS International Thermal Infrared Radiometer Inter-comparison (CRIC) Part 3 of 3: Field Comparison of Radiometers

CONTENTS

ACRONYMS AND ABBREVIATIONS

BB	Blackbody
CEOS	Committee on Earth Observation Satellites
IR	Infra-Red
ITS-90	International Temperature Standards of 1990
NPL	National Physical Laboratory
PTB	Physikalisch-Technische Bundesanstalt
RSS	Root Sum Square
SI	International System of Units
SPRT	Standard Platinum Resistance Thermometer
SSE	Size-of-Source Effect
SST	Sea Surface Temperature
WGCV	Working Group for Calibration and Validation

1 INTRODUCTION

The measurement of the Earth's surface temperature is a critical product for meteorology and an essential parameter/indicator for climate monitoring. Satellites have been monitoring global surface temperature for some time, and have established sufficient consistency and accuracy between in-flight sensors to claim that the measurement is of "climate quality". However, it is essential that such measurements are fully anchored to International System of Units (SI) and that there is a direct regular correlation with "true" surface/in-situ based measurements.

The most accurate of these surface-based measurements (used for validation) are derived from field-deployed IR radiometers. These are in principle calibrated traceably to SI, generally through a reference radiance blackbody (BB). Such instrumentation is of varying design, operated by different teams in different parts of the globe. It is essential for the integrity of their use, to provide validation data for satellites in-flight and to provide the link to future sensors, that any differences in the results obtained between them are understood. This knowledge will allow any potential biases to be removed and not transferred to satellite sensors. This knowledge can only be determined through formal comparison of the instrumentation, both in terms of its measurement capabilities in relation to primary "laboratory based" calibration facilities, and its use in the field. The provision of a fully traceable link to SI as part of this process ensures that the data are evidentially robust and can claim their status as a "climate data record".

The "satellite IR Cal/Val community" is well versed in the need and value of such comparisons having held highly successful exercises in Miami in 2001 [1, 2], and at the National Physical Laboratory (NPL), Teddington UK, in 2009 [3, 4] and in 2016 [5, 6, 7, 8], all carried out under the auspices of CEOS. However, six years had passed since the last comparison and it was considered timely to repeat/update the process, and so a similar comparison was repeated in 2022. The 2022 comparison included:

a. Comparison of the BB reference standards used for calibrating the radiometers (laboratory based).
b. Comparison of the radiometer response to a common SI-traceable BB target (laboratory based).
c. Evaluation of differences in radiometer response when viewing sea surface targets in particular the effects of external environmental conditions such as sky brightness (field-based).

The comparison took place during two weeks in June of 2022. The first week involved the laboratory-based comparisons (a. b.) at NPL. The second week was devoted to the field-based comparison (c.), at the tip of Boscombe Pier in Bournemouth, UK. Unlike the previous comparison in 2016, land surface temperature measurement was not a part of the 2022 comparison. Details of all the comparisons including the comparison scheme can be found in the protocols of the comparisons [AD-1, AD-2] and the implementation plan [AD-3].

This is Part 1 of a three-part report, and covers the result of the laboratory comparison of the BBs of the participants against the temperature scale realised on the NPL reference radiometer. Reports on the laboratory comparison of participant radiometers carried out at NPL can be found in Part 2 [AD-4], and the field comparison of radiometers at Boscombe Pier in Part 3 [AD-5].

2 ORGANISATION OF THE COMPARISON

2.1 PILOT

As in the recent previous comparisons, NPL, the UK National Metrology Institute (NMI), served as pilot for the 2022 comparison. NPL, as the pilot, was responsible for inviting participants, for preparing the protocols that the participants had agreed, for providing the implementation plan to enable participants to prepare for the comparison, for providing the reference scale traceable to the SI for comparison, for the analysis of data following appropriate processing by individual participants and for the compilation of a report that is agreed by all participants.

2.2 PARTICIPANTS

A call was made inviting potential participants in the related scientific community to express their interest to participate in December 2021. The list of participants that actually participated is shown in Table 1. As can be seen, six participants including the pilot took part. This is a reduction from the previous 2016 comparison where eleven institutes, including the pilot, were present. Although there was a certain number of expressed interests, no institute could participate from the USA and China, primarily due to travel restrictions imposed due to the COVID-19 pandemic.

Table 1. Comparison participants

Contact person	Short version	Institute
Yoshiro Yamada (pilot)	NPL	National Physical Laboratory Hampton Road, Teddington, Middlesex, TW11 0LW United Kingdom
Werenfrid Wimmer	UoS	University of Southampton, European Way, Southampton, SO19 9TX, United Kingdom
Tim Nightingale	RAL	STFC Rutherford Appleton Laboratory Harwell Campus, Didcot,Oxon OX11 0QX United Kingdom
Nicole Morgan	CSIRO	CSIRO / Australian Bureau of Meteorology CSIRO, 3-4 Castray Esplanade, Battery Point, TAS 7150 Australia
Frank-M. Göttsche	KIT	IMK-ASF / Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen Germany
Raquel Niclòs	UoV	Dept. of Earth Physics and Thermodynamics, University of Valencia. 50 Dr. Moliner. ES-46100, Burjassot (Valencia), Spain

3 TIMELINE

The preparation for the comparison, the comparison measurements, and the analysis and report writing were conducted according to the timeline shown in Table 2. The laboratory comparison was undertaken in the week 13 – 17 June 2022, before the week of the field comparison at Boscombe Pier.

Table 2. Comparison activity timeline

Invitation to participate	December 2021
Formal agreement of protocol	May 2022
Participants send preliminary report of measurement system and uncertainty to pilot	May 2022
Laboratory measurement of participants' radiometers against reference BBs. Laboratory measurement of participants' BBs by reference thermometer.	13 – 17 June 2022
SST measurement comparison of participants' radiometers.	20 – 24 June 2022
Participants send all data and reports to pilot	~ August 2022
Pre-Draft A result communication with individual participants for comments, corrections and confirmation	~ November 2022
Draft A report circulation among participants	March 2023
Draft B report submission to CEOS WG (tentative)	March 2023

4 COMPARISON SCHEME

4.1 OVERVIEW OF THE COMPARISON

The laboratory comparison exercise was conducted by having the participants' artifacts gathered in a laboratory at NPL and one by one compared with an SI-traceable reference standard of NPL. The measurand to be compared was the brightness temperature of the BBs at approximately 10 µm, in the range from 10 °C to 50 °C. For this, a laboratory large enough to accommodate all participant radiometers and BBs, as well as the NPL reference radiometer and BBs, was prepared.

The BB comparison consisted of measurement of the participants' BBs with the NPL radiometer. The radiometer measured the participants' BBs set by the participants at the pre-agreed set of temperatures above the dew point. The radiometer, operated by the pilot, was a transfer standard calibrated against the NPL reference standard traceable to the International Temperature Scale of 1990 (ITS-90) [9].

4.2 REFERENCE STANDARDS

The reference standard for the BB comparison is the NPL's reference standard radiometer Absolute Measurements of BB Emitted Radiance (AMBER) [10].

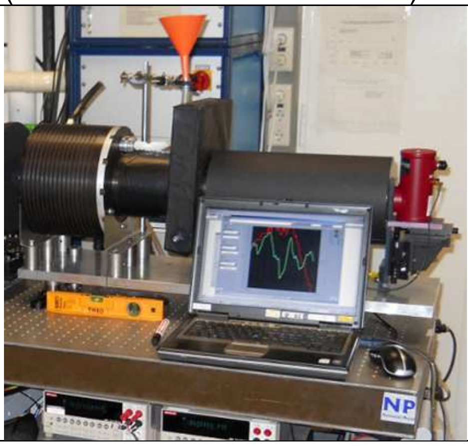
In previous comparisons the temperature scale was realised radiometrically on the AMBER through a calibration at the gallium (Ga) melting point (29.7646 °C) via an NPL reference fixed-point BB [11], and extending the scale to other temperatures using the knowledge of the relative spectral responsivity of the instrument, in a similar way as in the definition of the ITS-90 above the silver point [9], although at a much lower temperature. The scale had previously been verified through comparison with Physikalisch-Technische Bundesanstalt (PTB) [12]. For the current comparison exercise, a new scale realisation scheme was applied employing a second reference temperature at around −30 °C through measurement of an ammonia heatpipe BB equipped with an SPRT calibrated traceable to the ITS-90, and extrapolating down to determine the zero-radiance signal, thus rendering the problematic realisation of the zero-radiance source unnecessary. Detailed description of this two-point interpolation scale realization is presented in a separate article [13].

A transfer standard radiometer was introduced for the first time in this comparison, which was the NPL TRT-IV.82 manufactured by Heitronics (hereinafter referred to as 'Heitronics'). This transfer standard was introduced following the positive contribution to the previous comparison by a radiometer of a similar model belonging to PTB [12]. The Heitronics transfer standard radiometer was calibrated by comparison against the AMBER reference standard utilising as comparator sources the same NPL variable temperature BBs of ammonia heatpipe and the stirred liquid bath that were employed as reference sources for the radiometer comparison [AD-4]. Then the Heitronics transfer standard was used to measure the temperature of the participant BBs.

The AMBER has a relatively small but not insignificant size-of-source effect (SSE). Therefore, correction was made for the AMBER SSE to account for the difference in the size of the two sources used for scale realisation (30 mm diameter for the Ga-point BB and 75 mm diameter for the ammonia heatpipe BB). For the Heitronics, correction was made for the effect of the difference in the source size of the ammonia heatpipe BB used to calibrate the Heitronics against by comparison with the AMBER, and the participants' BB sizes. For this a new SSE correction scheme was established, enabling correction up to large source sizes at all measurement temperatures. The established scheme is described in a separate article [14]. The stability of the Heitronics was monitored by measurement of the Ga-point BB a few times a day before and during the comparison period. An abrupt shift of approximately 70 mK was detected after the calibration just before the comparison, and a correction was applied to the measurements made of the participants' BBs to account for this. Uncertainty in this correction was also included in the uncertainty of the reference temperature.

The specifications of the AMBER and Heitronics relevant to the comparison measurements are given in Table 3.

Table 3 Radiometer specifications

	AMBER (reference standard radiometer)	Heitronics TRT-IV.82 (transfer standard radiometer)
		
Wavelength	10.1 µm (9 µm – 11 µm)	8 µm - 14 µm
Target size	ϕ 5 mm	ϕ 8.7 mm
Measurement distance	70 mm	503 mm
Effective window/lens diameter	ϕ 13 mm	ϕ 57 mm
Scale realization	Through relative spectral response measurement, and BB measurement at the Ga melting point and at a second reference temperature at -30 °C.	By comparison with AMBER

A view of the laboratory is shown in Fig. 1. On the left, the NPL transfer radiometer (Heitronics) is shown viewing the compact Ga-point BB placed on the optical bench. On the left of the Ga-point BB a red CASOTS-I BB is seen, together with two blue CASOTS-II BBs to its left. At the far end of the row of BBs a Landcal P80P BB is seen. A second Landcal P80P was present but is not shown in the photograph. (See Section 5 for more information on the BBs.)

Figure 1 Radiometers measuring the reference BBs

4.3 MEASUREMENT TEMPERATURES

The participants' BBs were set at the nominal temperatures covering the range from 10 °C to 50 °C as shown in Table 4. Temperature points of 40 °C and 45 °C were not in the protocol but were added for voluntary based participation. 0 °C was in the protocol but was not attempted since the dew point was higher than this and none of the BBs had purge systems that allow them to be used without dew and frost forming. All BBs participated at all temperature points up to 35 °C, above which only the two P80P BBs, of UoV and KIT, participated. Measurements at 55 °C and 60 °C were also made by KIT, but these are not considered a part of the comparison since the reference scale on AMBER and Heitronics was not realised up to these temperatures and uncertainties at these temperatures are not available. However, the measurement results are shown for information purpose in Section 5.

Table 4 Measurement temperature points

	Nominal temperature / °C
BB comparison	10, 15, 20, 25, 30, 35, 40, 45, 50, (55, 60)*

*: Outside the scope of comparison

4.4 MEASURAND

The principle measurand in the comparison is brightness temperature at 10 μm. Temperature here refers to that of the ITS-90.

5 PARTICIPANTS' BBS AND MEASUREMENTS

In the following sections, descriptions are given of the comparison artifacts, namely the participants' BBs that are used to calibrate the participants' radiometers, as reported by each participant. In the Figures the reference values, i.e., the BB brightness temperatures measured by the transfer standard radiometer, are shown together with the reported brightness temperature recorded by each participant. The error bars are the standard uncertainties of, respectively, the calibration of the transfer standard and as claimed by each participant for their BB. Each measurement with the Heitronics was conducted for approximately 30 s to evaluate repeatability by taking the standard error of the mean over this period, and this was combined with the calibration uncertainty of the Heitronics. This did not lead to any noticeable increase in the uncertainty. At each temperature, a set of measurements consisted of three measurements with the Heitronics, while re-alignment was done in between to enable evaluation of the reproducibility. All time values are given in British Summer Time (BST).

5.1 MEASUREMENT OF UoV BB

5.1.1 Description of BB, route of traceability and uncertainty contributions

Make and type of the BB: Land Infrared Landcal BB Source P80P.

Outline Technical description of the BB: Material: Aluminium with black, high temperature refractory coating. Design: 50 mm (diameter) × 155 mm (length), 120º cone at closed end. Emissivity>0.995. Thermometers: Internal PRT connected to digital display with 0.01 K resolution. External PRT-100 traceable to National Standards (UKAS calibration certificate).

Establishment or traceability route for primary calibration including date of last realisation and breakdown of uncertainty: The BB temperature given by the internal PRT was calibrated in our laboratory against the external PRT calibrated to 0.1 K (UKAS calibration certificate) with 0.01 K resolution in May, 2022. Based on the measurements performed, the following uncertainty analysis is presented, which is summarised in Table 5:

Type A

- Repeatability: 0.017 K or 0.006% at 300 K (typical value of standard deviation of external PRT readings at a fixed BB temperature during 15 min.).
- Reproducibility: 0.016 K or 0.005% at 300 K (typical value of difference between external PRT readings at the same temperature for two different runs).

Total Type A uncertainty (RSS): 0.023 K or 0.008 % at 300 K.

Type B

- Emissivity: Assuming uncertainty in emissivity <0.005 (according to manufacturer), which translates in a temperature uncertainty of 0.13 K at 8-13 μm.
- BB thermometer calibration: 0.1 K (external PRT calibration), the differences between the internal and external PRT readings being always lower than 0.1 K.
- BB cavity temperature non-uniformity: 0.3 K (standard deviation of the BB cavity temperatures as measured by a high resolution thermal infrared camera with apparent resolution of 0.1 K).
- Stability of source: 0.03 K (maximum value of standard deviation of external PRT readings at a fixed BB temperature during 90 min).
- Reflected ambient radiation: 0.005 K (assuming variations of 1 K in ambient (laboratory) temperature).

Total Type B uncertainty (RSS): 0.34 K.

Type A + Type B uncertainty (RSS): 0.34 K.

Operational methodology during measurement campaign: The BB was set to each one of six fixed temperature values (from 0 to 50ºC), and temperature measurements were performed with the external PRT during more than 90 minutes for each temperature. This procedure was repeated one more time for all temperatures to assess reproducibility. The BB temperatures measured by the external PRT must be corrected for emissivity effects (including the reflection of ambient radiation) in order to be compared with radiation thermometer measurements. Thus, the corrected (radiative) BB temperature, T_R, is given by

$B(T_R)=\varepsilon B(T_{BB})+(1-\varepsilon)L(amb)$

where B is Planck function for the appropriate wavelength or spectral band, ε is emissivity (0.995), T_{BB} is the PRT BB temperature, and L(amb) is the ambient radiance, which can be approximated as $L(amb)=B(T_a)$ with T_a being the ambient (laboratory) temperature when a radiometer operating at ambient temperature is placed in front of the BB cavity to take radiance measurements, or as $L(amb)=(1-f)B(T_a)+fB(T_{int})$, f being the fractional solid angle subtended by the BB aperture respect to the aperture of a cooled radiometer operating at sub-ambient temperature T_{int} (e.g., T_{int}=77 K for AMBER radiometer). The influence of the radiometer operating temperature can be minimized by placing the radiometer at enough distance from the BB. For instance, when the radiometer aperture (diameter of 50 mm) is at 80 mm from the BB aperture, the subtended solid angle is 0.31 sr, which yields $f = 0.31/2\pi = 0.05$.

BB usage (deployment), previous use of instrument and planned applications. The primary usage of the BB is laboratory calibration of thermal infrared radiometers used for in situ measurements of land surface temperature, and sea or inland water surface temperatures, with the aim of validating satellite-derived surface temperatures.

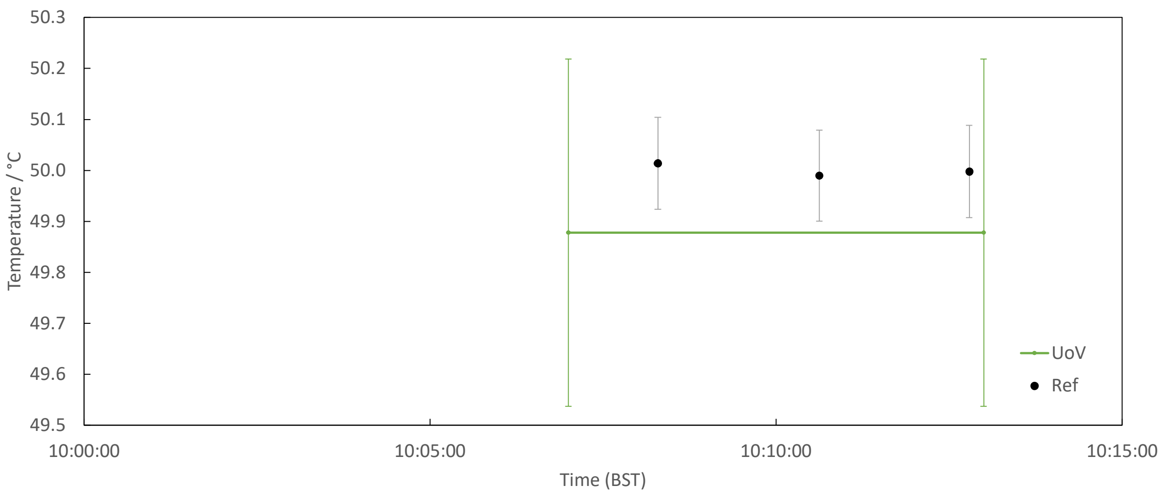
Table 5 Uncertainty Contributions associated with UoV Landcal P80P BB

Parameter	**Type A uncertainty in Value / K / % (1)**	**Type B uncertainty in Value / K**	**Standard uncertainty in Brightness temperature / K**
Repeatability of measurement	0.017 K / 0.006 %		0.017
Reproducibility of measurement	0.016 K / 0.005 %		0.016
Blackbody emissivity		0.13 (2)	0.13
BB Thermometer Calibration		0.1	0.1
BB cavity temperature non-uniformity		0.3	0.3
BB temperature stability		0.03	0.03
Reflected ambient radiation		0.005 (3)	0.005
Radiant heat/loss gain			
Convective heat/loss gain			

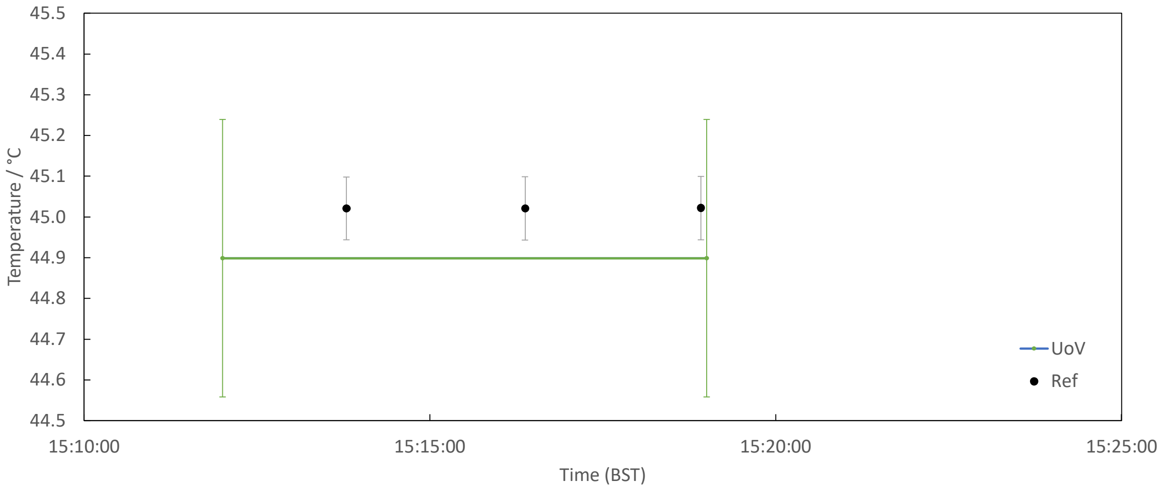
Primary Source		-	-
Combined uncertainty (RSS)	0.023 K / 0.008 %	0.34	0.34

5.1.2 Measured data

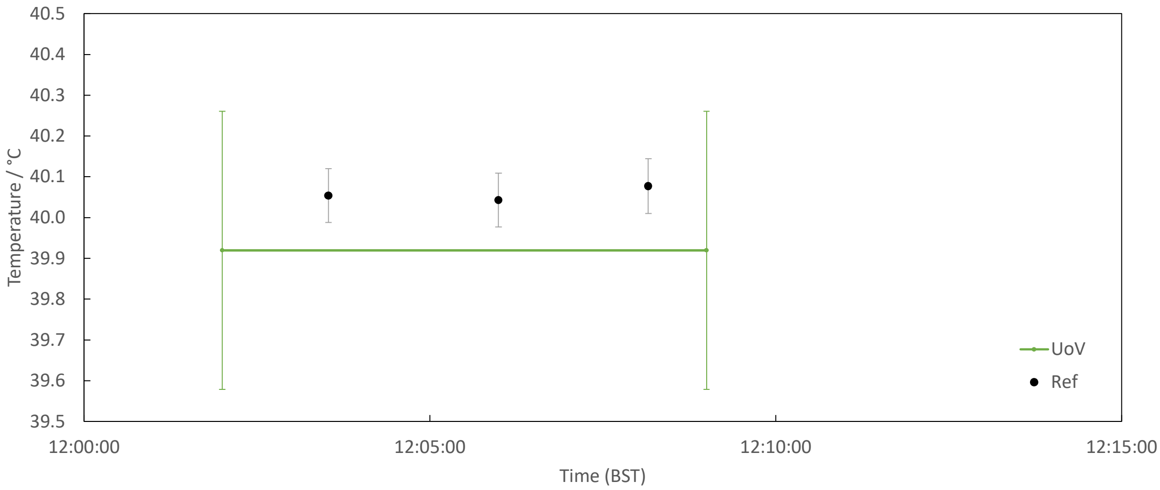
Figure 2 shows the brightness temperature measured with the reference Heitronics and that reported by the participant for the UoV BB. Error bars denote standard uncertainties. The combined standard uncertainty reported for the UoV BB (0.34 K) is mainly due to the cavity temperature non-uniformity estimated using a thermal infrared camera as explained in section 5.1.1. However, this uncertainty is likely overestimated as concluded from results of the blackbody intercalibration in 2016 [5].



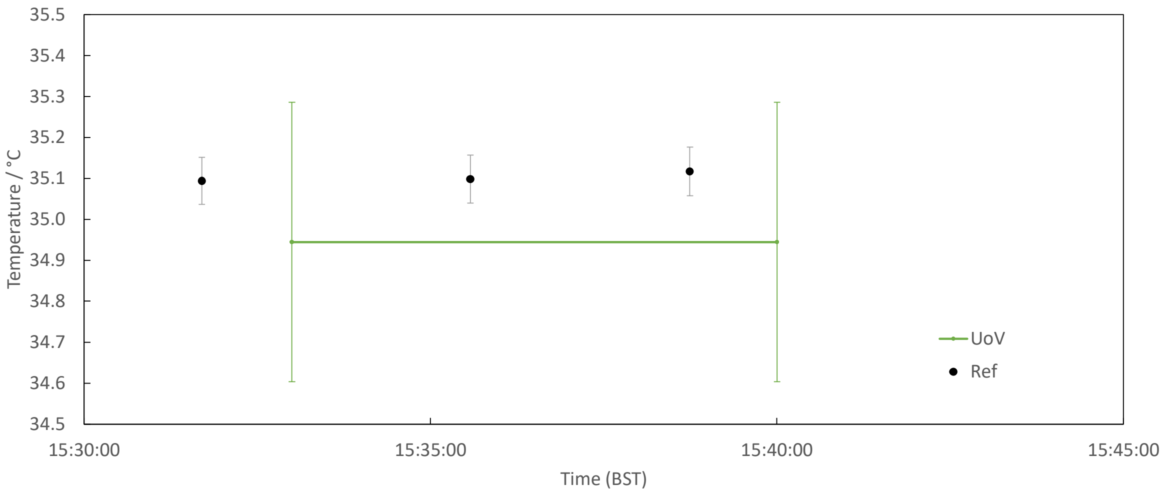
a) 50 °C (16 June 2022)
Figure 2 Measurement of UoV BB (Error bars denote standard uncertainty) (continued on next page)



b) 45 °C (16 June 2022)

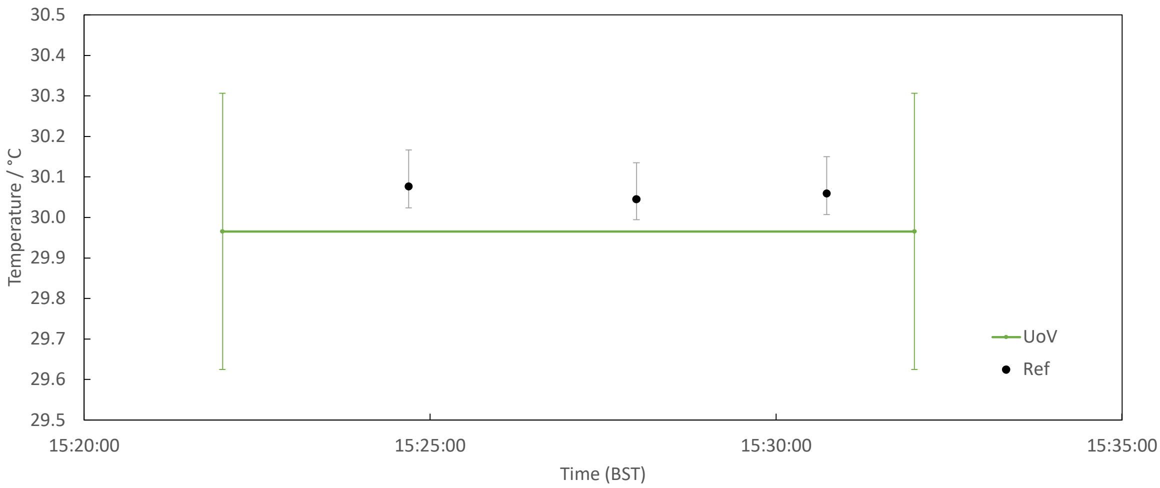


c) 40 °C (16 June 2022)

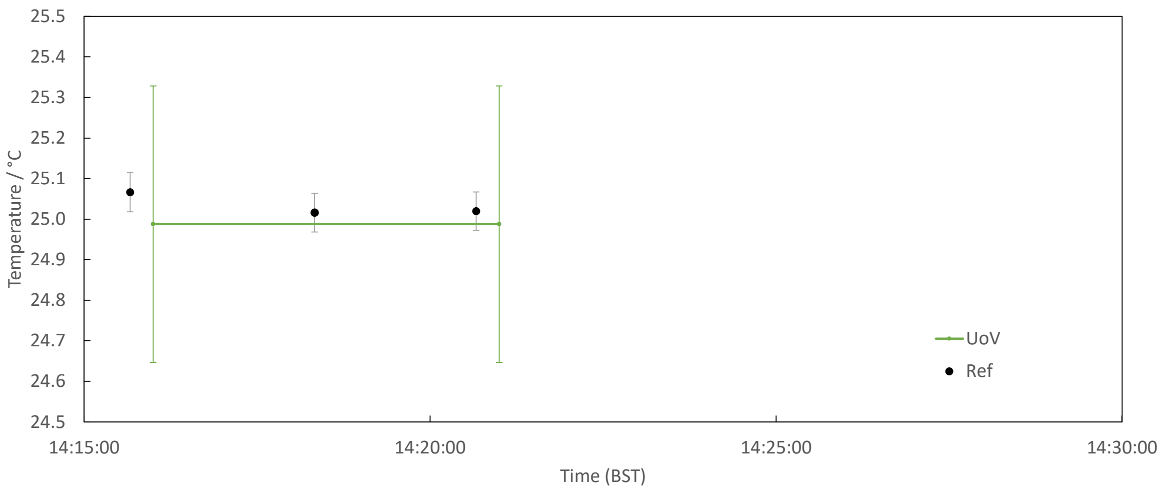


d) 35 °C (13 June 2022)

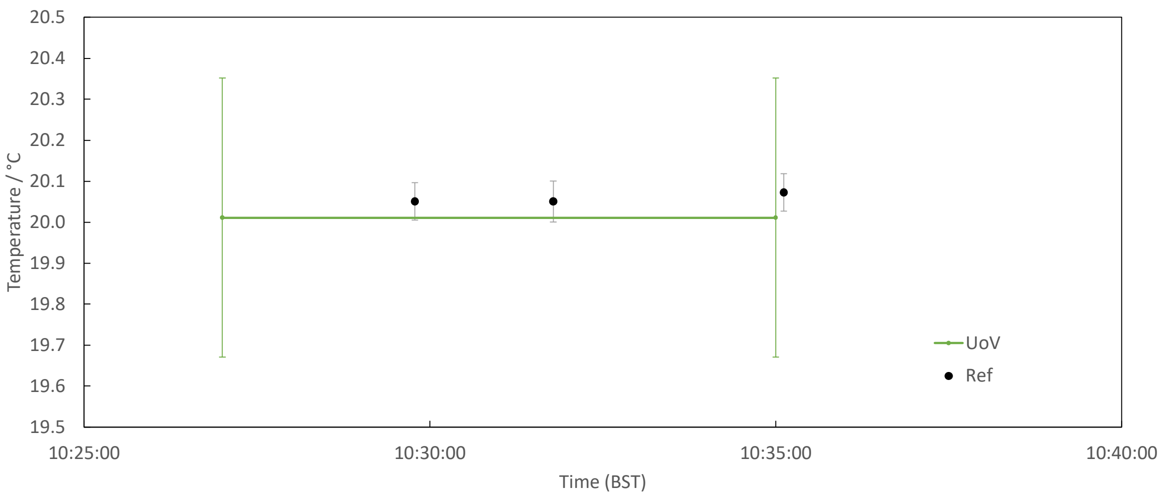
Figure 2 Measurement of UoV BB (Error bars denote standard uncertainty) (continued on next page)



e) 30 °C (15 June 2022)

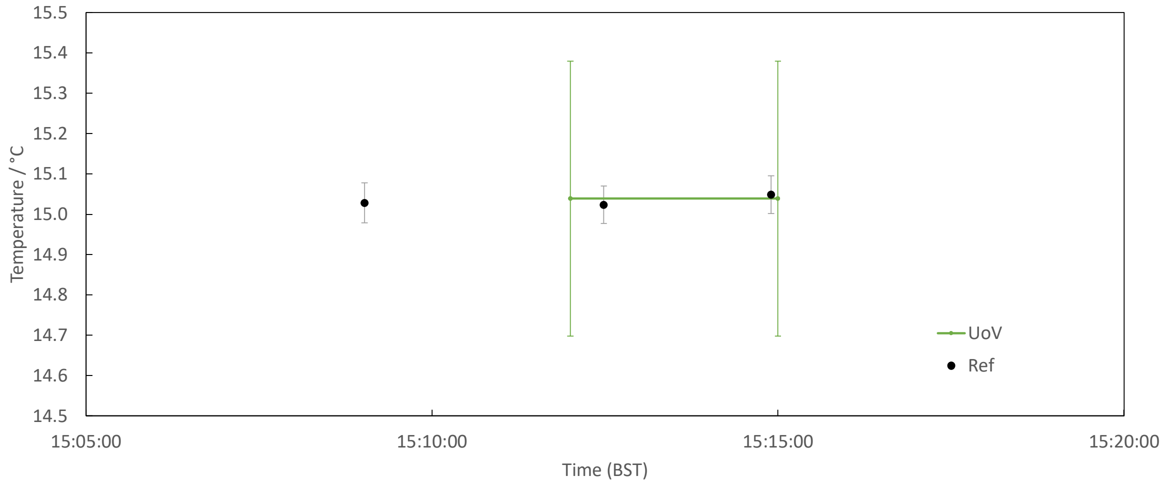


f) 25 °C (15 June 2022)

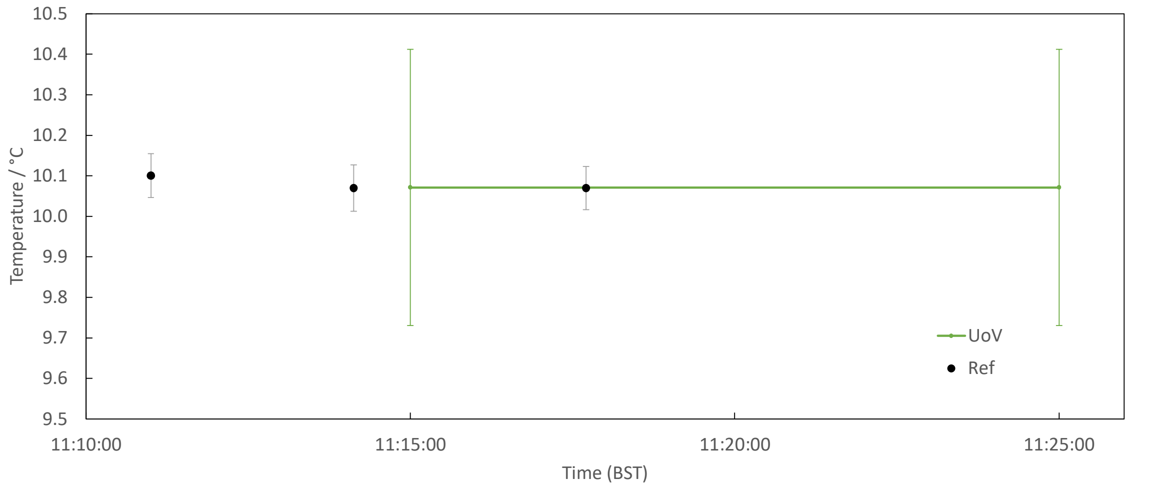


g) 20 °C (15 June 2022)

Figure 2 Measurement of UoV BB (Error bars denote standard uncertainty) (continued on next page)



h) 15 °C (15 June 2022)



i) 10 °C (14 June 2022)

Figure 2 Measurement of UoV BB (Error bars denote standard uncertainty) (cont.)

5.2 MEASUREMENT OF KIT BB

5.2.1 Description of BB, route of traceability and uncertainty contributions

Make and type of the BB: Land, Infrared BB Source Landcal P80P

Outline Technical description of the BB: The Landcal P80P (serial #321388-1) is a variable temperature, portable standard BB radiation source for high precision calibration between -10 °C and +80 °C. The cavity is a 120° cone with an internal length of 150 mm and an aperture of 50 mm diameter. The cone is made of aluminium and has a high temperature refractive coating, giving the BB an emissivity greater than 0.995. Resistance thermometers control the temperature of the Landcal P80P (display: 0.01 K resolution). An optional platinum resistance thermometer can be inserted at the front of the BB: the junction of the thermometer then lies in the plane of the cone point, but is 40 mm below. Its temperature agrees with the cone point radiance temperature to within ±0.5K. KIT integrated two external PRT-100 sensors (traceable to National Standards) into a rod: these continuously measure the P80P's cone temperature.

Establishment or traceability route for primary calibration: The BB temperature given by the internal PRT (display) and two external PRTs was calibrated at the "Physikalisch Technische Bundesanstalt" (PTB) against a reference radiometer to 0.1 K (PTB calibration certificate) with 0.01 K resolution on 2020-12-07. Based on producer specifications and additional measurements, the Landcal P80P's uncertainty components are estimated as (see Table 6 for detail):

Type A

- Repeatability: 0.011 K or 0.004% at 300 K (standard deviation of external PRT readings at a fixed BB temperature during a 15 minute period).
- Reproducibility: 0.035 K or 0.012% at 300 K (difference between external PRT readings at the same temperature for two different runs).

Total Type A uncertainty (RSS): 0.037 K at 300 K.

Type B

- Emissivity uncertainty is estimated as less than 0.005 (manufacturer specification). This translates to a temperature uncertainty of 0.13 K in the 8 to 13 μm region.
- External thermometer (PRT) calibration: 0.1 K, i.e. the difference between the two external PRTs is always less than 0.1 K.
- BB cavity temperature non-uniformity: 0.2 K (manufacturer specifications).
- Stability of source: 0.02 K (maximum standard deviation of external PRT readings at a fixed BB temperature over 90 min).
- Reflected ambient radiation: 0.005 K (assuming ambient temperature variations of 1 K).

Total Type B uncertainty (RSS): 0.259 K.

Operational methodology during measurement campaign:
The P80P was set to eleven temperatures from 10 to 60 ºC at steps of 5 ºC. Measurements were performed after the displayed temperature had stabilised (usually after 40 minutes). For later analysis, the two external PRT measurements were recorded by a data logger once per minute. The reported BB brightness temperatures for a radiation thermometer at 10 μm are averages of the two external PRT readings corrected for emissivity effects; the correction uses a calibration relationship determined at an ambient temperature of 22°.

BB usage (deployment), previous use of instrument and planned applications.
The primary usage of the Landcal P80P BB is the re-calibration of thermal infrared radiometers, which KIT uses for in-situ land surface temperature (LST) determination.

Table 6 Uncertainty Contributions associated with BBs:

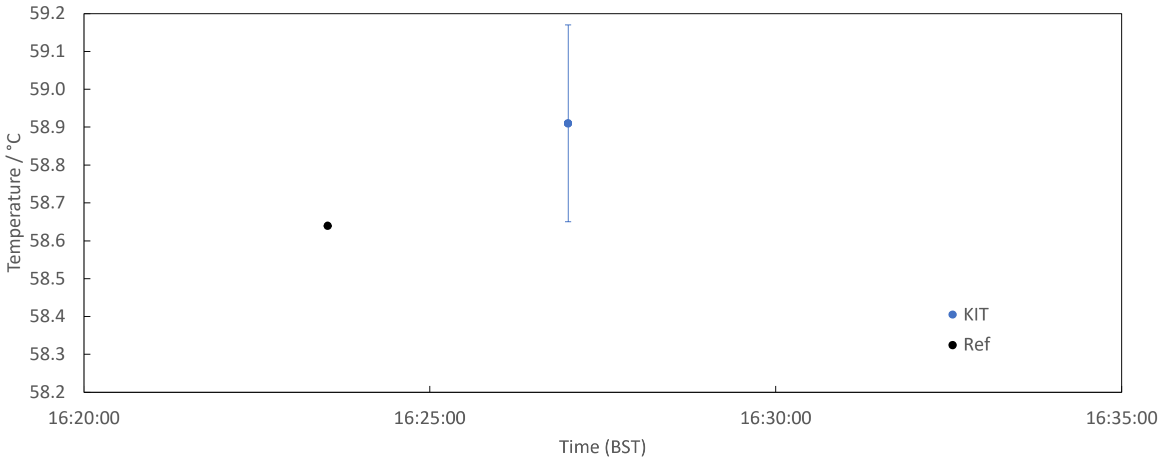
Instrument: Landcal P80P
Temperature: 20 °C

Parameter	**Type A uncertainty in Value / (appropriate units)**	**Type B uncertainty in Value / (appropriate units)**	**Standard uncertainty in Brightness temperature / °C**
Repeatability of measurement	0.004 %		0.011
Reproducibility of measurement	0.012 %		0.035
BB emissivity		0.5 %	0.130
BB Thermometer Calibration		0.1 °C	0.100
BB cavity temperature non-uniformity		0.2 °C	0.200
BB temperature stability		0.02 °C	0.020
Reflected ambient radiation		1 °C in ambient temperature	0.005
Radiant heat/loss gain		-	-
Convective heat/loss gain		-	-
Primary Source		-	-
Combined uncertainty	0.012 %		0.262

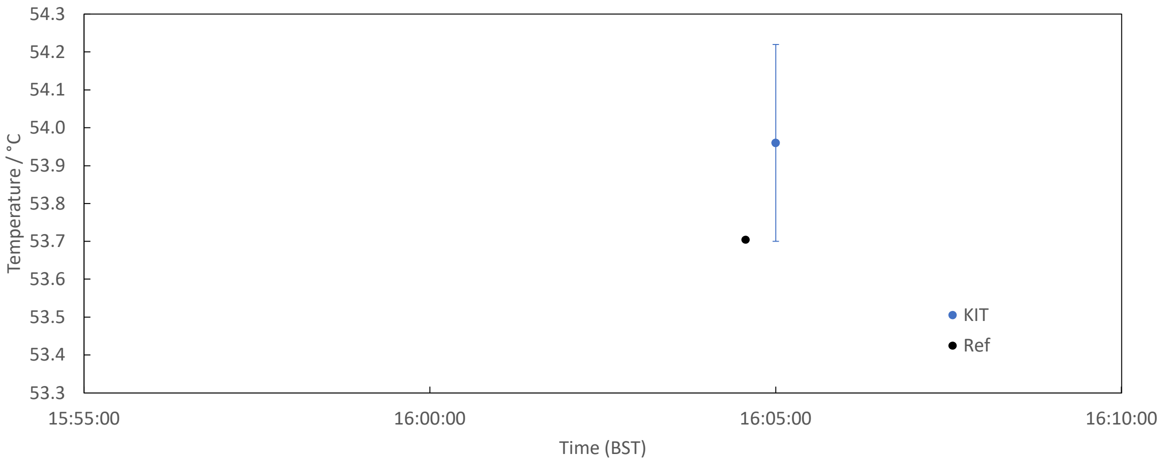
Note: All uncertainty values are in standard uncertainties (i.e. *k* = 1)

5.2.2 Measured data

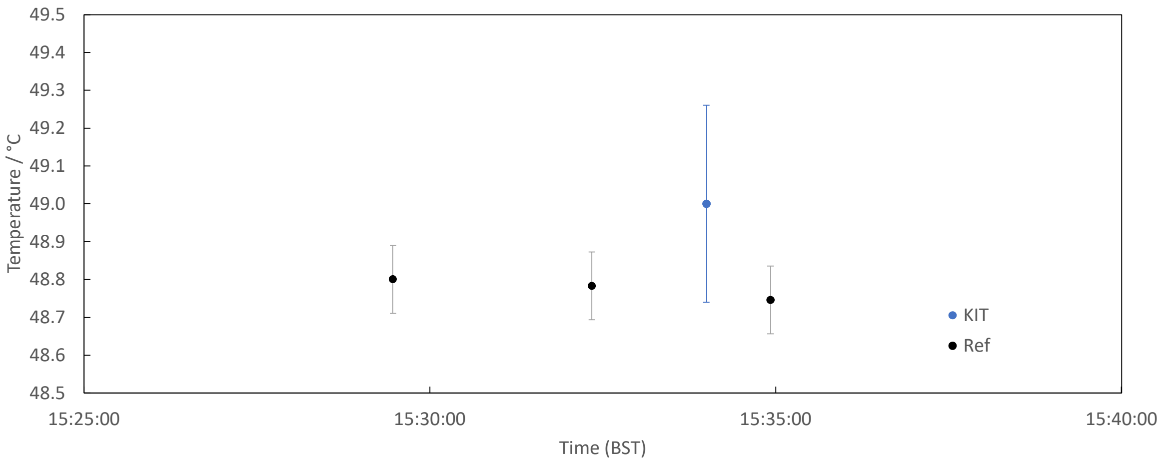
Figure 3 shows the brightness temperature measured with the reference Heitronics and that reported by the participant for the KIT BB. Error bars denote standard uncertainties. No uncertainties are available for the reference value in Figs. 3 a) and b), and this is outside the scope of the comparison.



a) 60 °C (16 June 2022)

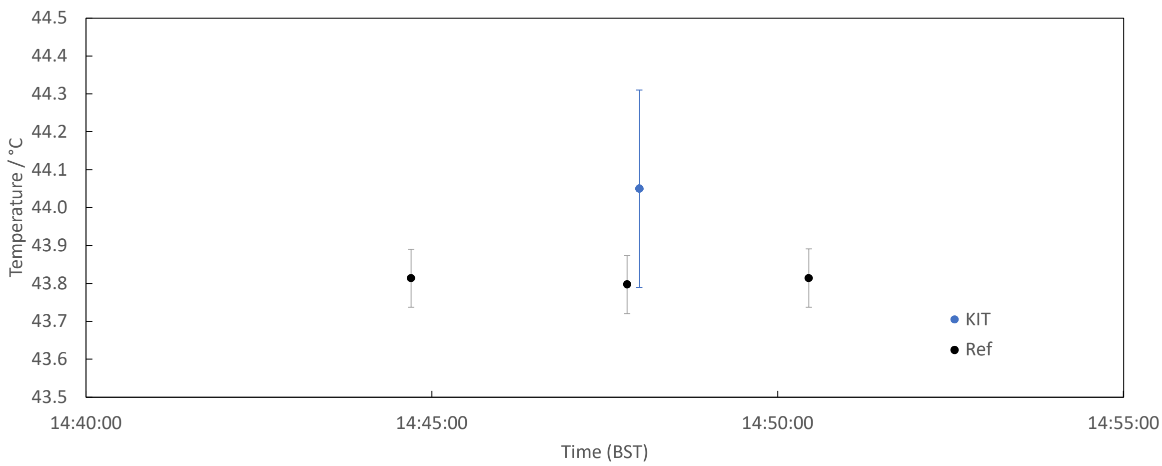


b) 55 °C (16 June 2022)

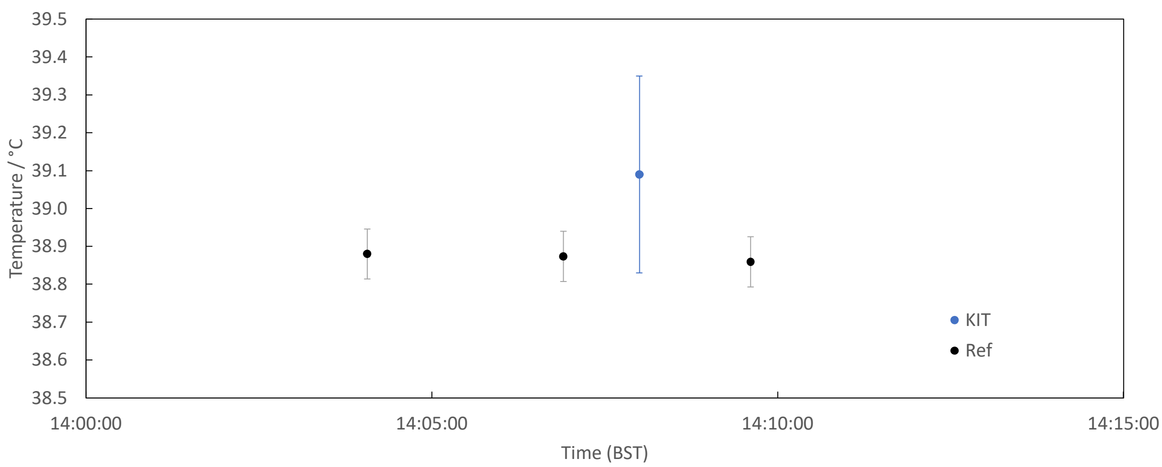


c) 50 °C (16 June 2022)

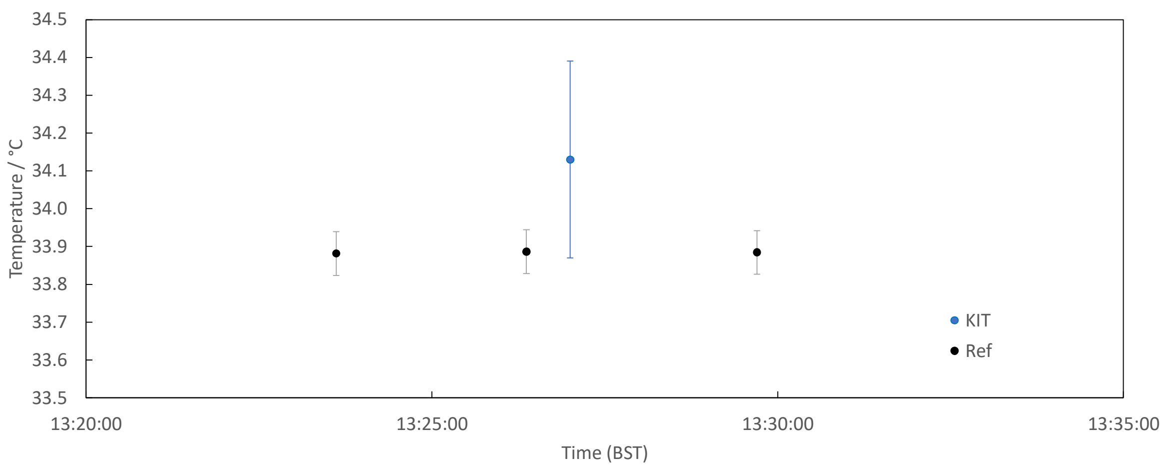
Figure 3 Measurement of KIT BB (Error bars denote standard uncertainty) (continued on next page)



d) 45 °C (16 June 2022)

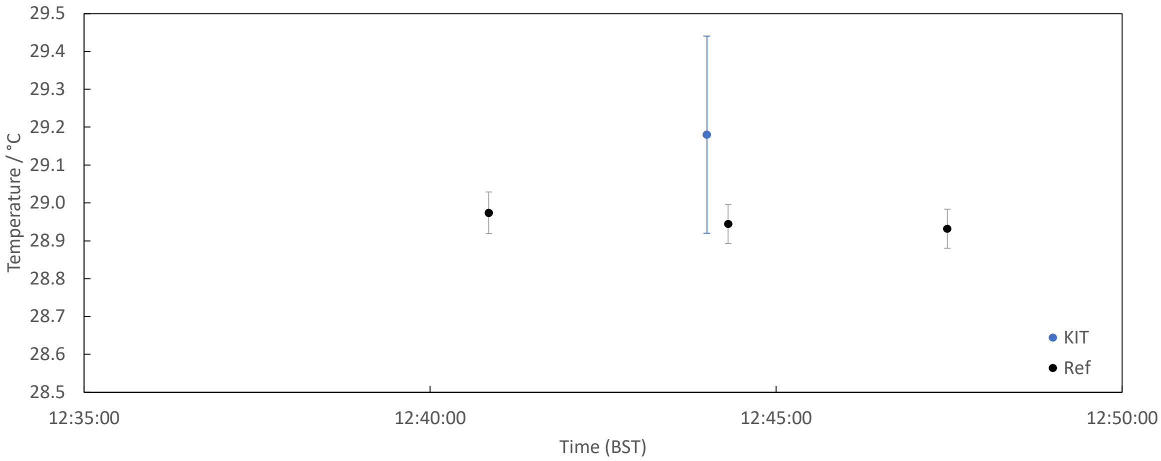


e) 40 °C (16 June 2022)

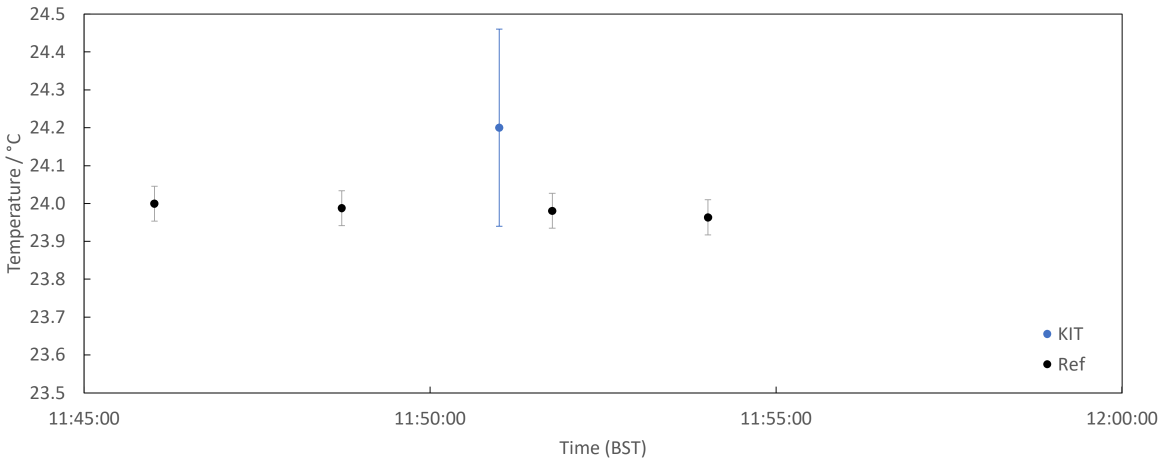


f) 35 °C (16 June 2022)

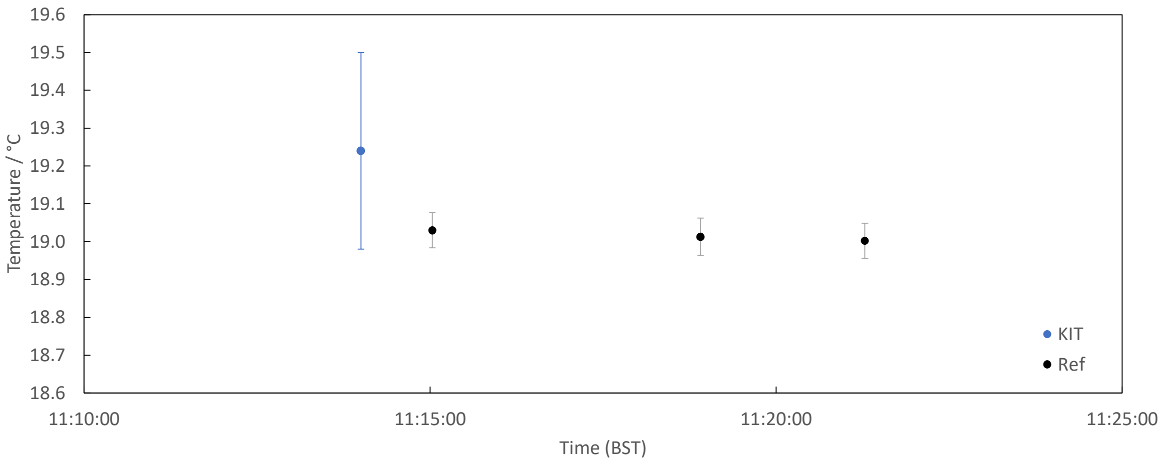
Figure 3 Measurement of KIT BB (Error bars denote standard uncertainty) (continued on next page)



g) 30 °C (16 June 2022)

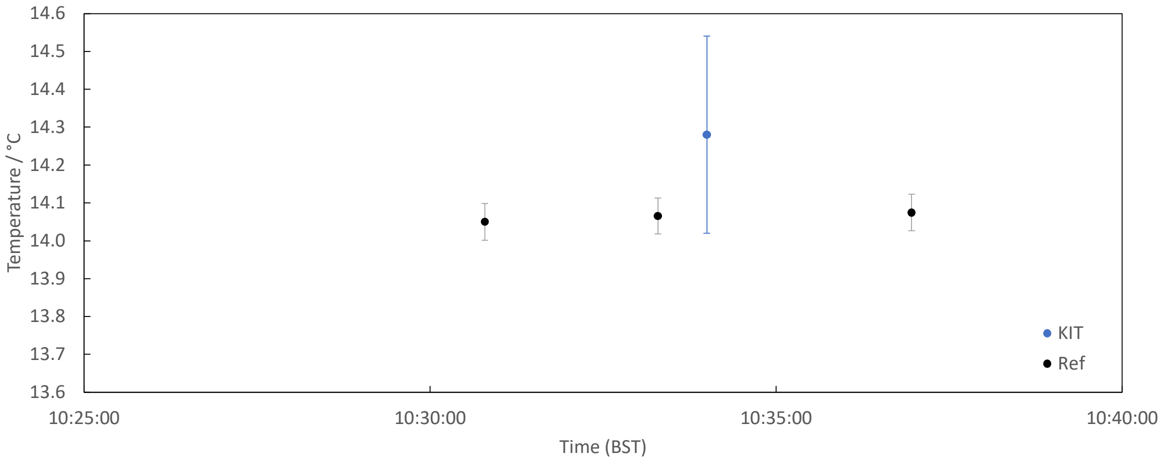


h) 25 °C (16 June 2022)

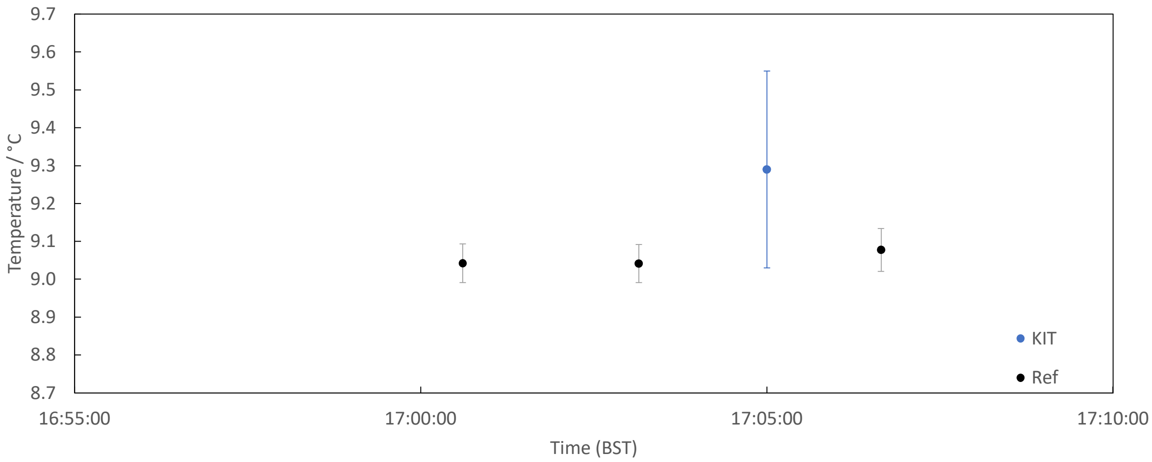


i) 20 °C (16 June 2022)

Figure 3 Measurement of KIT BB (Error bars denote standard uncertainty) (continued on next page)



j) 15 °C (16 June 2022)



k) 10 °C (15 June 2022)

Figure 3 Measurement of KIT BB (Error bars denote standard uncertainty) (cont.)

5.3 MEASUREMENT OF CSIRO BB

5.3.1 Description of BB, route of traceability and uncertainty contributions

Make and type of the BB: CASOTS-II

Outline Technical description of the BB:
The CSIRO BB is a CASOTS-II type BB. This BB had a user selectable exit aperture and can operate from the dewpoint to 20 K above. Full information on this type of BB can be found in [15].
This BB is used with a Fluke 1524 with a single PRT which were calibrated together as a matched pair.

Establishment or traceability route for primary calibration including date of last realisation and breakdown of uncertainty:

Table 7 shown below shows the uncertainty budget for the CSIRO CASOTS-II BB. The total combined uncertainty was 0.02°C. Full information on the uncertainty budget of CASOTS-II BB can be found in the paper ([15]), highlighted above.

Table 7 CSIRO uncertainty table

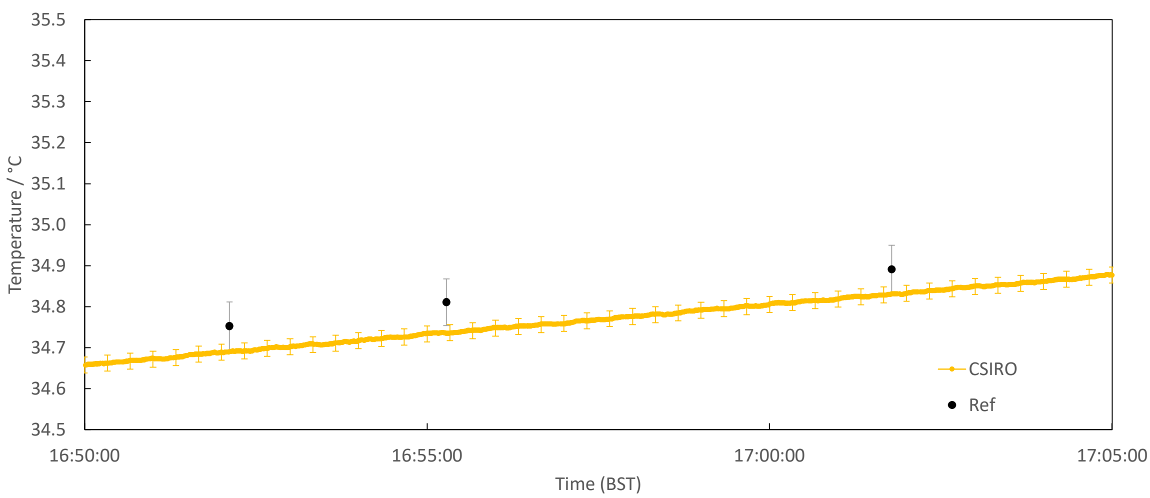
NEXTEL paint emissivity	0.012
Stray radiance error	0.008
Thermometry system	0.0042
Heating rate error	0.0076
Water bath thermal gradients	0.0096
Cavity wall–paint thermal gradient	0.0025
Combined uncertainty	**0.019549**

Operational methodology during measurement campaign:
The height will be adjusted to the required measurement height using spacers, and when not being measured, the BB opening will remain covered. The Fluke temperature probe will be polled by operator's laptop at 1Hz sampling rate and the temperature data logged. A time comparison between operator's laptop and radiometer will be done at the start and completion of each temperature of the BB comparison. The CASOTS-II temperature is not settable but can be adjusted with addition and subtraction of hot/cold water. The pump must be running continuously which in turn heats up water. After comparison is completed the start and stop times will be examined and the data adjusted as required to match radiometer times.

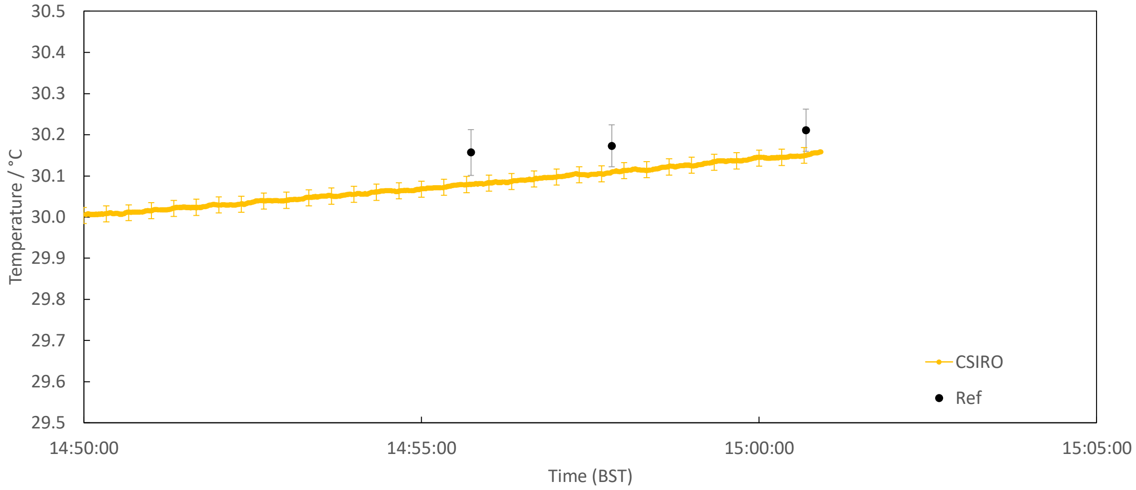
BB usage (deployment), previous use of instrument and planned applications. The CASOTS-II BB is currently used for the calibration of the CSIRO ISAR. It has previously participated in the FRM4SST intercomparison in 2016 and may be used for the calibration of the Australia Antarctic Division (AAD) ISAR in the future.

5.3.2 Measured data

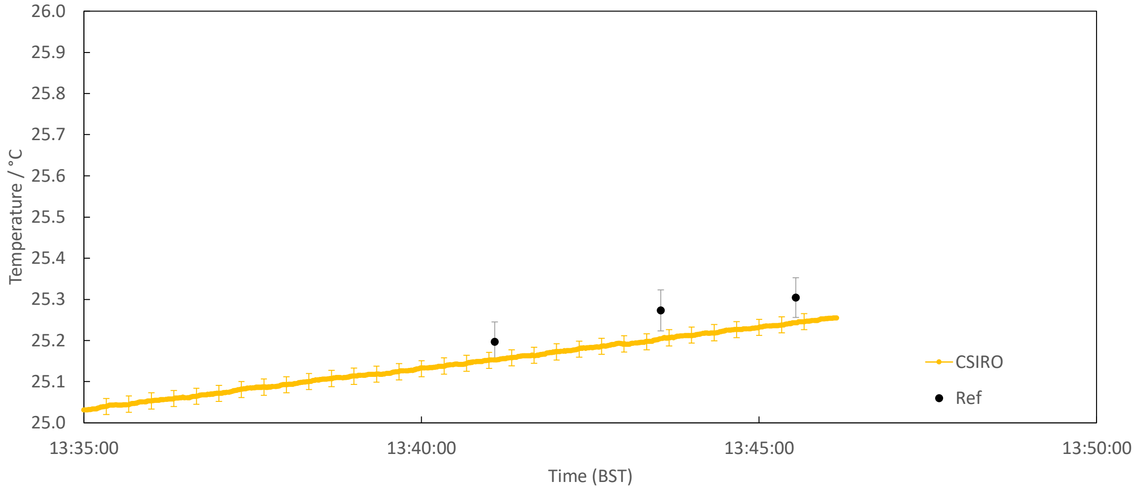
Figure 4 shows the brightness temperature measured with the reference Heitronics and that reported by the participant for the CSIRO BB. Error bars denote standard uncertainties.



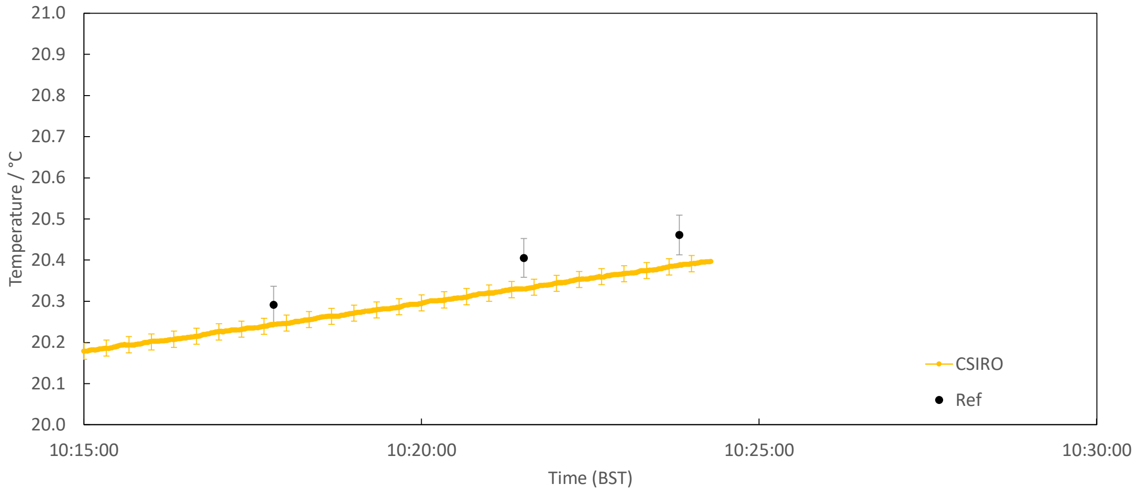
a) 35 °C (13 June 2022)
Figure 4 Measurement of CSIRO BB (Error bars denote standard uncertainty) (continued on next page)



b) 30 °C (15 June 2022)

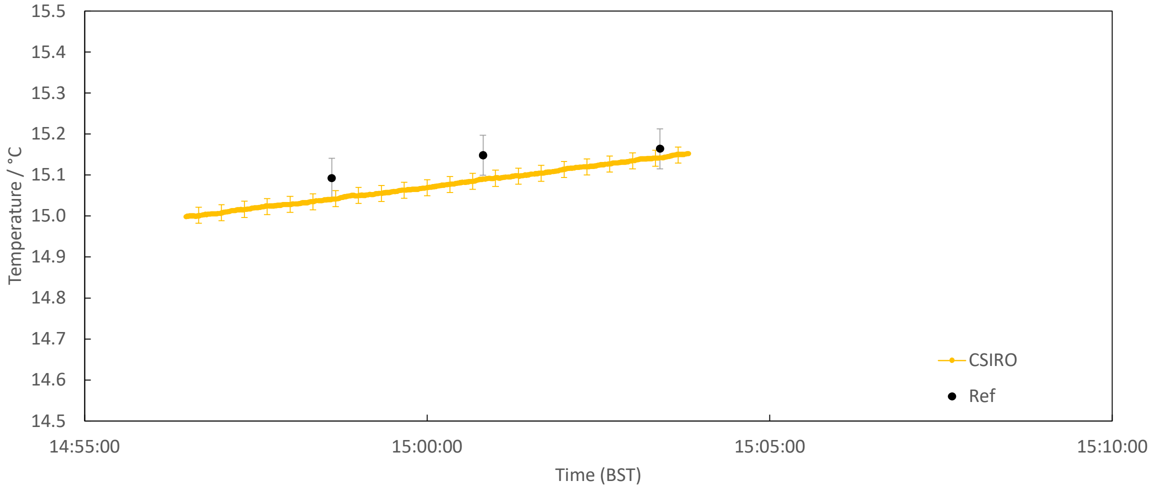


c) 25 °C (15 June 2022)

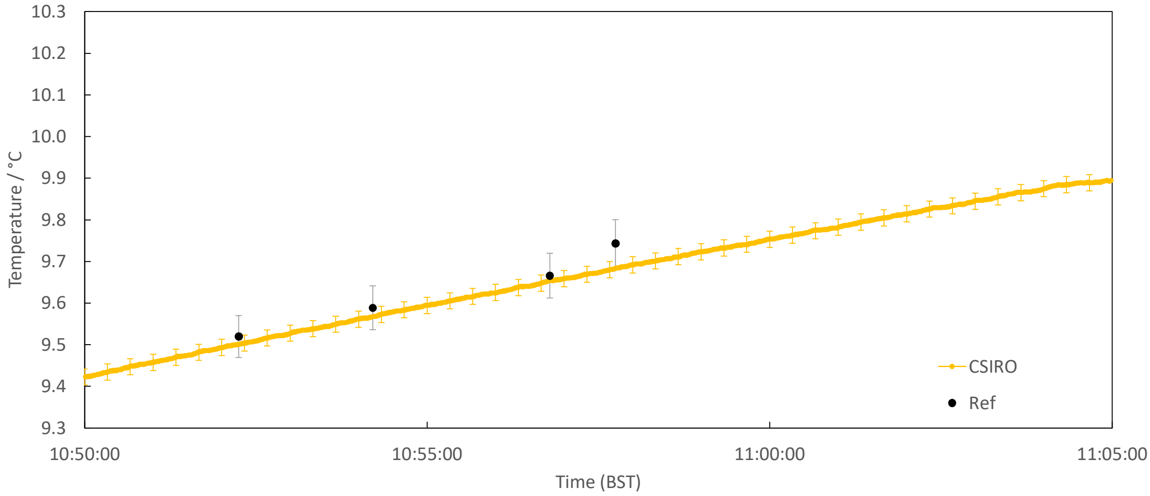


d) 20 °C (15 June 2022)

Figure 4 Measurement of CSIRO BB (Error bars denote standard uncertainty) (continued on next page)



e) 15 °C (14 June 2022)



f) 10 °C (14 June 2022)

Figure 4 Measurement of CSIRO BB (Error bars denote standard uncertainty) (cont.)

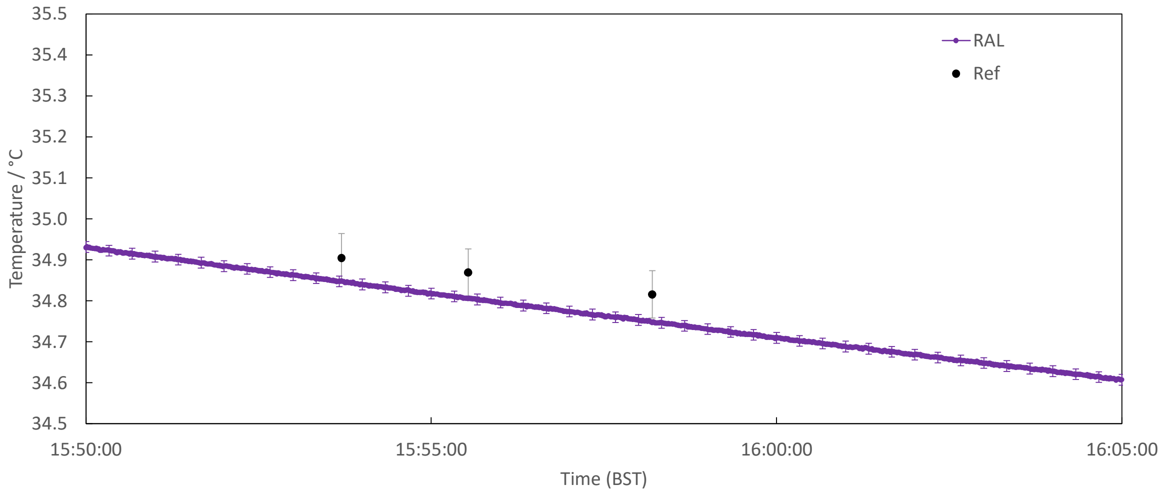
5.4 MEASUREMENT OF RAL BB

5.4.1 Description of BB, route of traceability and uncertainty contributions

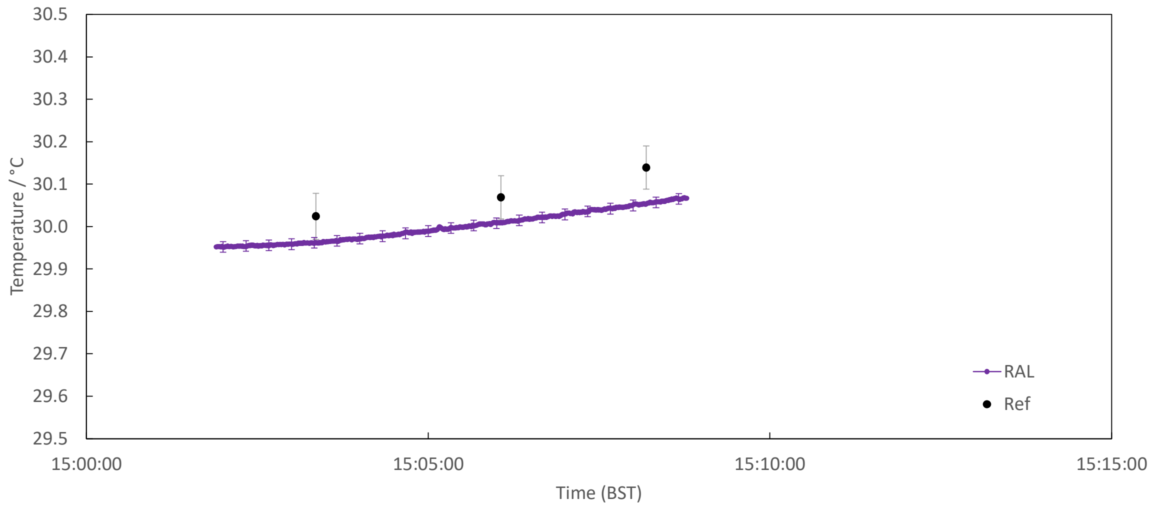
The BB provided by the RAL Space of the STFC Rutherford Appleton Laboratory was a CASOTS-I BB [16]. The cavity of this BB was not actively controlled but was allowed to drift as heat was dumped into the water bath by the stirring pump. The RAL BB had a 10 cm diameter exit aperture and could cover the temperature range from the Dew point (with ice cooling) to approximately 32°C. The combined uncertainty of the RAL BB ranged from 24 mK to 30 mK over the range of temperatures measured during the 2016 comparison, with a minimum when the cavity was at the estimated room temperature of 21 °C.

5.4.2 Measured data

Figure 5 shows the brightness temperature measured with the reference Heitronics and that reported by the participant for the RAL BB. Error bars denote standard uncertainties.

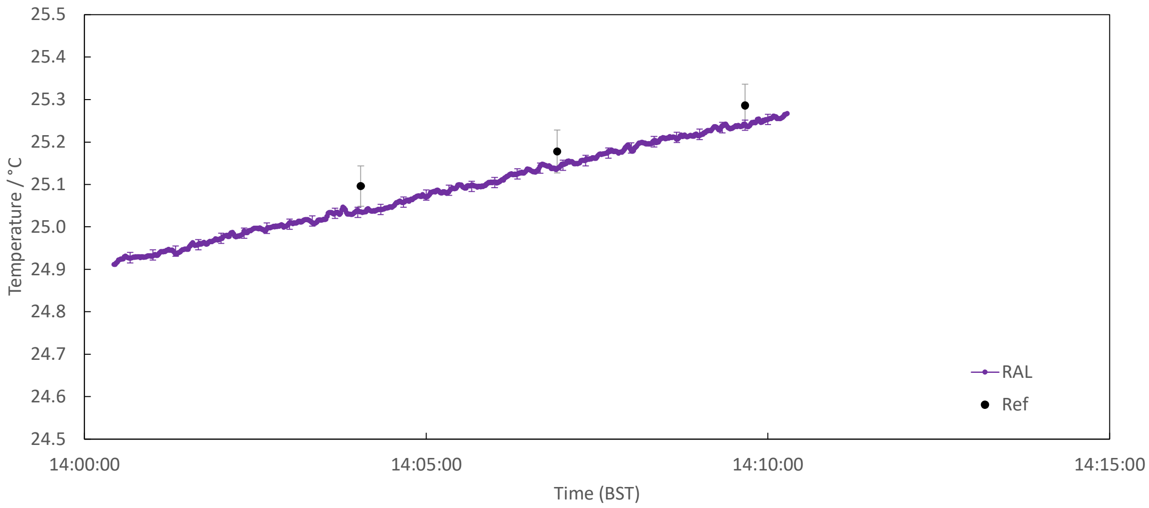


a) 35 °C (13 June 2022)

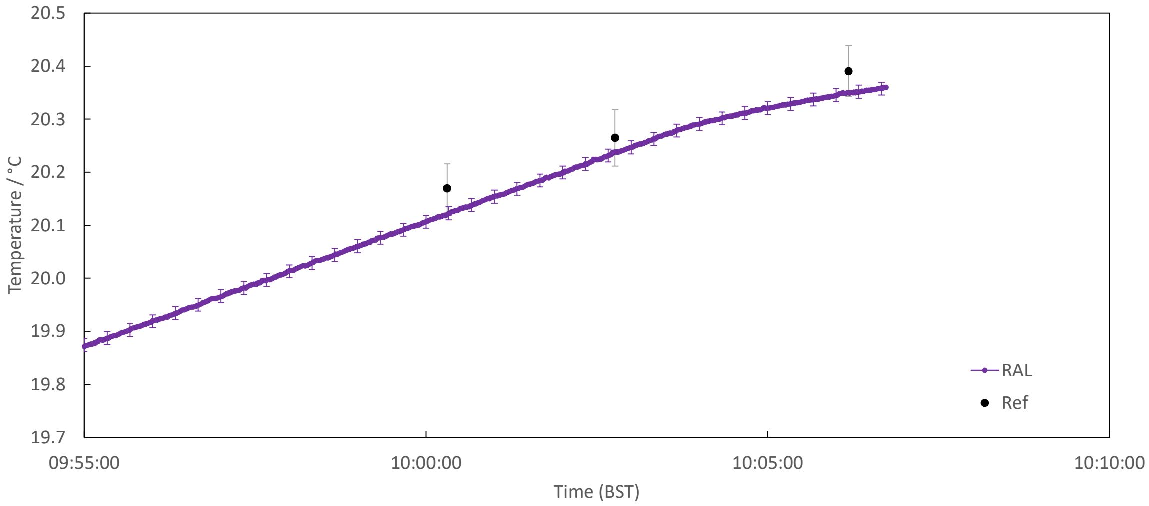


b) 30 °C (15 June 2022)

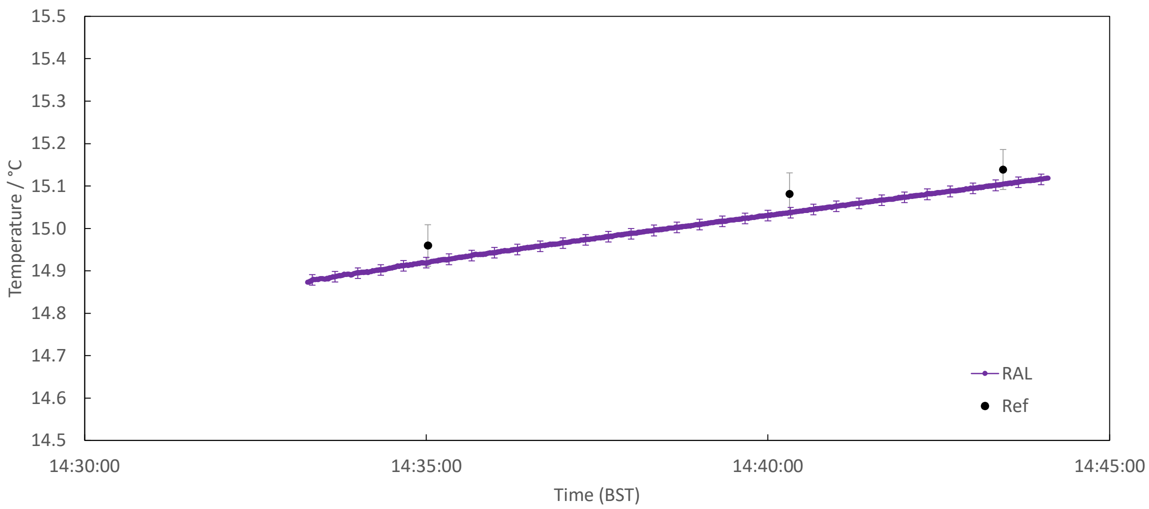
Figure 5 Measurement of RAL BB (Error bars denote standard uncertainty) (continued on next page)



c) 25 °C (15 June 2022)

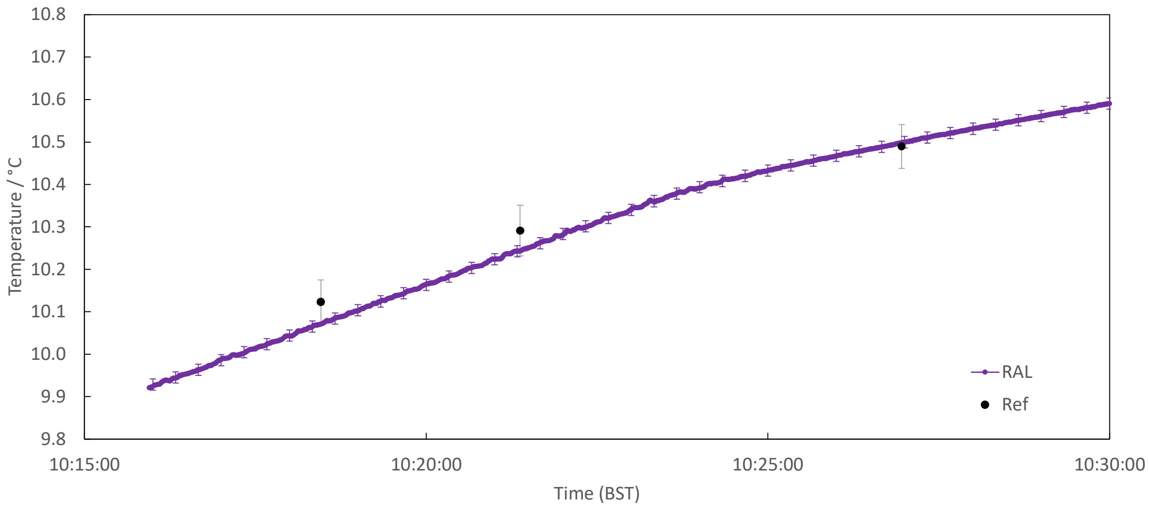


d) 20 °C (15 June 2022)



e) 15 °C (14 June 2022)

Figure 5 Measurement of RAL BB (Error bars denote standard uncertainty) (continued on next page)



f) 10 °C (14 June 2022)

Figure 5 Measurement of RAL BB (Errors bar denote standard uncertainty) (cont.)

5.5 MEASUREMENT OF UoS BB

5.5.1 Description of BB, route of traceability and uncertainty contributions

Make and type of the BB

The UoS BB is a CASOTS-II type BB. This BB had a user selectable exit aperture and can operate from the dewpoint to approximately 40 °C, where the upper temperature is set by the water pump maximum temperature. Full information on this type of BB can be found in: [15] This BB is used with a Hart 1504 with a Thermometrics 225 probe which were calibrated together as a matched pair.

Establishment or traceability route for primary calibration including date of last realisation and breakdown of uncertainty:
Table 8 shown below shows the uncertainty budget for the CSIRO CASOTS-II BB. The total combined uncertainty was 0.02K, estimated from [15] for an aperture plate of 50 mm. Full information on the uncertainty budget of CASOTS-II BB can be found in the paper ([15]), highlighted above

Table 8 UoS uncertainty table

NEXTEL paint emissivity	0.012
Stray radiance error	0.008
Thermometry system	0.0067
Heating rate error	0.0076
Water bath thermal gradients	0.0096
Cavity wall–paint thermal gradient	0.0025
Combined uncertainty	**0.02023 K**

The calibration of the HART 1504 and the Thermometrics probe is checked annually with a secondary standard.

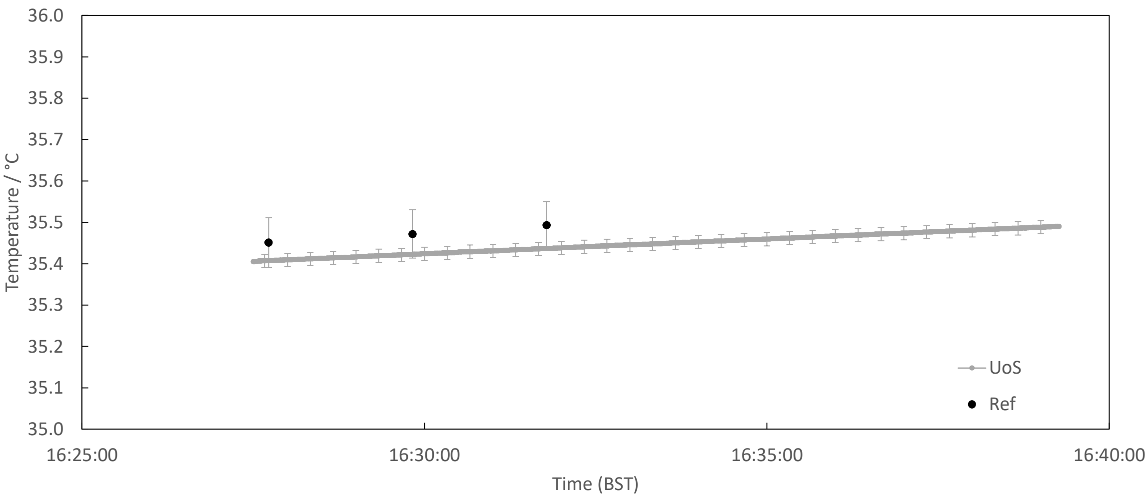
Operational methodology during measurement campaign:

The height will be adjusted to the required measurement height using spacers, and when not being measured the BB opening will remain covered. The Fluke temperature probe will be polled by operator's laptop at 1Hz sampling rate and the temperature data logged. A time comparison between operators' laptop and radiometer will be done at the start and completion of each temperature of the BB comparison. The CASOTS-II temperature is not settable, but the starting point can be adjusted with addition and subtraction of hot/cold water. The pump must be running continuously which in turn heats up the water and therefore the temperature of the waterbath will rise during the comparison with a heating rate of approximately 0.6 K h-1 [15]. After comparison is completed the start and stop times will be examined and the data adjusted as required to match radiometer times.

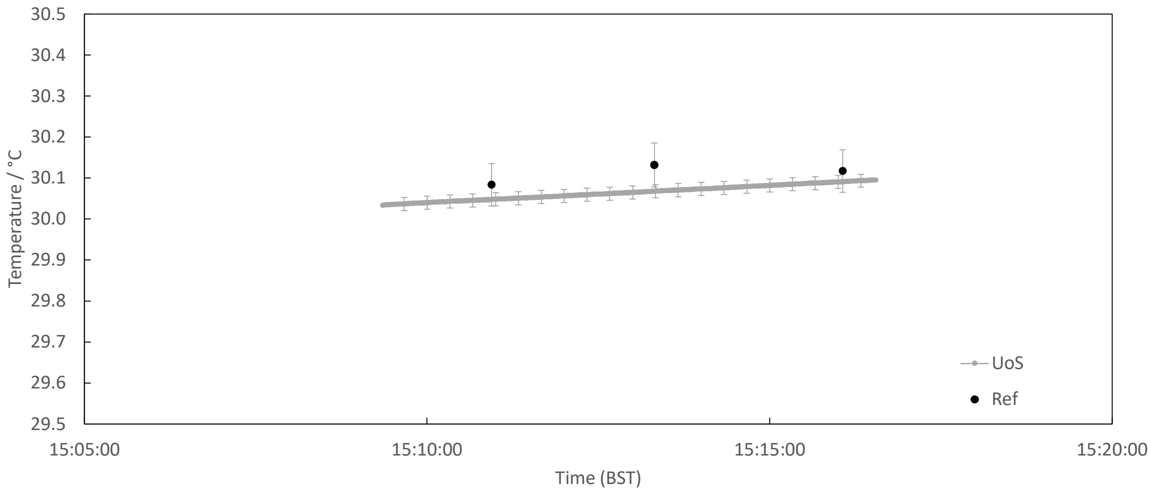
BB usage (deployment), previous use of instrument and planned applications.
The CASOTS-II BB is currently used for the calibration of the UoS ISARs and for all ISAR after completed assembly before shipping to the customers. It has previously participated in the FRM4SST intercomparison in 2009 and 2016 and was used for the pre- and post- deployment calibration of ISAR used in the SST, ICE and Land temperature comparisons in 2016.

5.5.2 Measured data

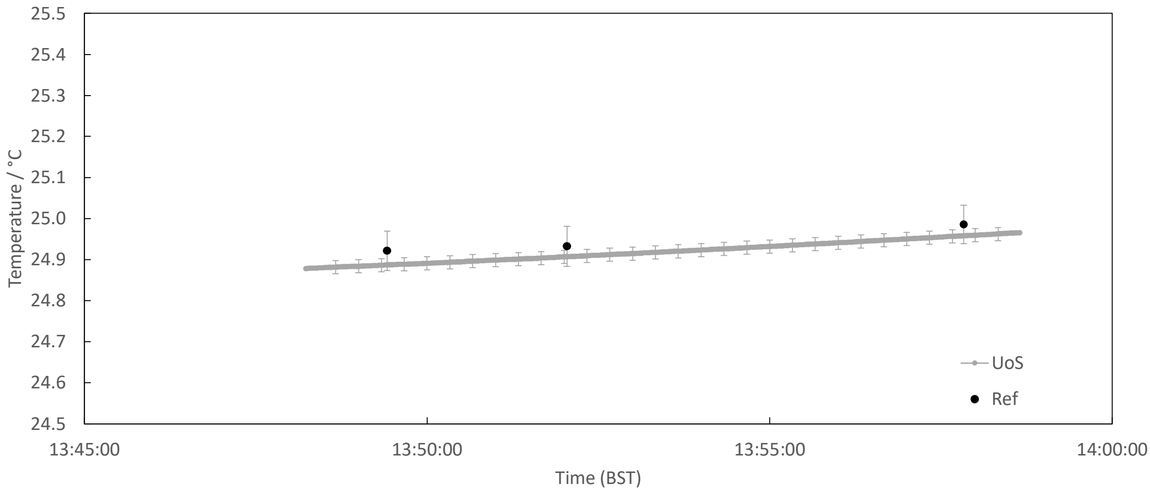
Figure 6 shows the brightness temperature measured with the reference Heitronics and that reported by the participant for the UoS BB. Error bars denote standard uncertainties.



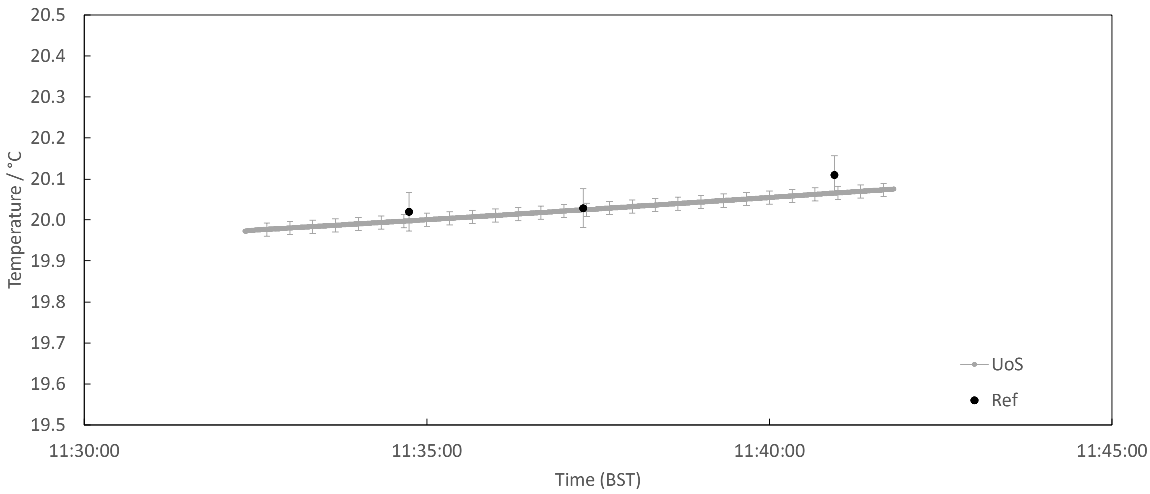
a) 35 °C (13 June 2022)
Figure 6 Measurement of UoS BB (Error bars denote standard uncertainty)
(continued on next page)



b) 30 °C (16 June 2022)

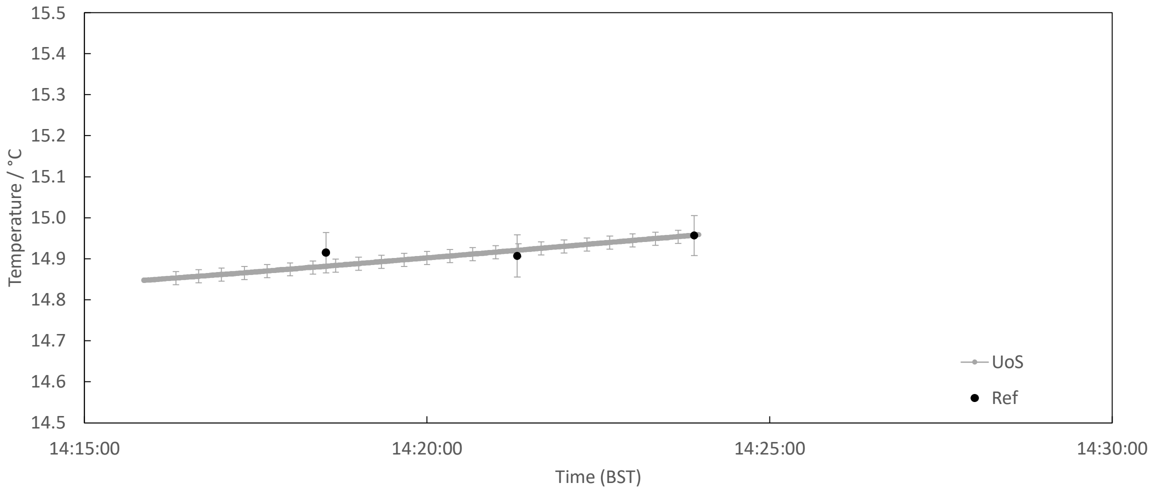


c) 25°C (15 June 2022)

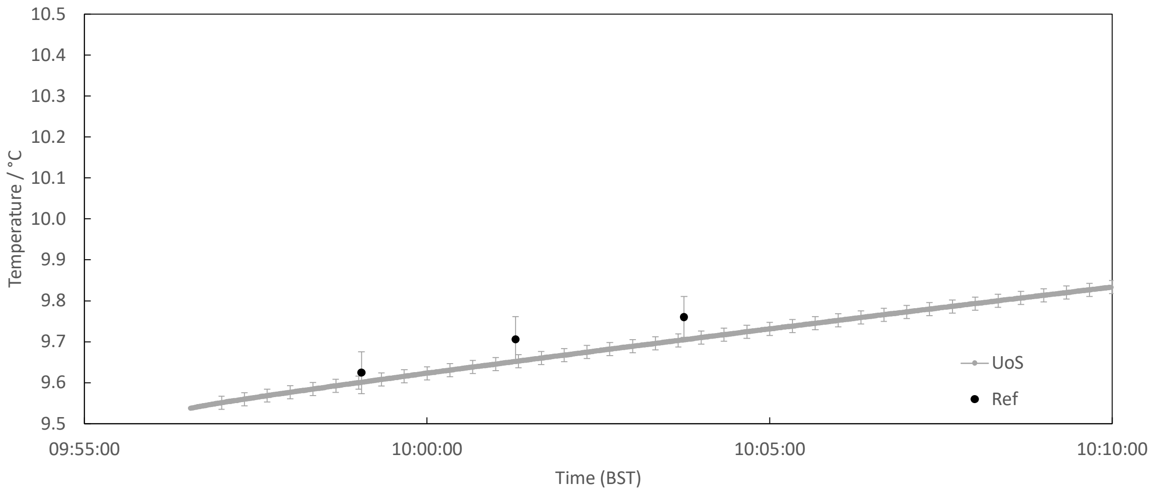


d) 20 °C (15 June 2022)

Figure 6 Measurement of UoS BB (Error bars denote standard uncertainty)
(continued on next page)



e) 15 °C (14 June 2022)



f) 10 °C (14 June 2022)

Figure 6 Measurement of UoS BB (Error bars denote standard uncertainty) (cont.)

6 OVERALL COMPARISON RESULT

6.1 TEMPERATURE DIFFERENCE FROM THE REFERENCE

From the reported brightness temperature temporal data shown in Figs. 2 to 6, the values at the times matching the three reference measurements are evaluated and the differences from the reference are calculated, from which the mean of the differences is obtained. When the participant reports a single value instead of temporal data the difference of this value from the simple mean of the reference measurements is used. The difference from the reference thus evaluated is plotted in Fig. 7.

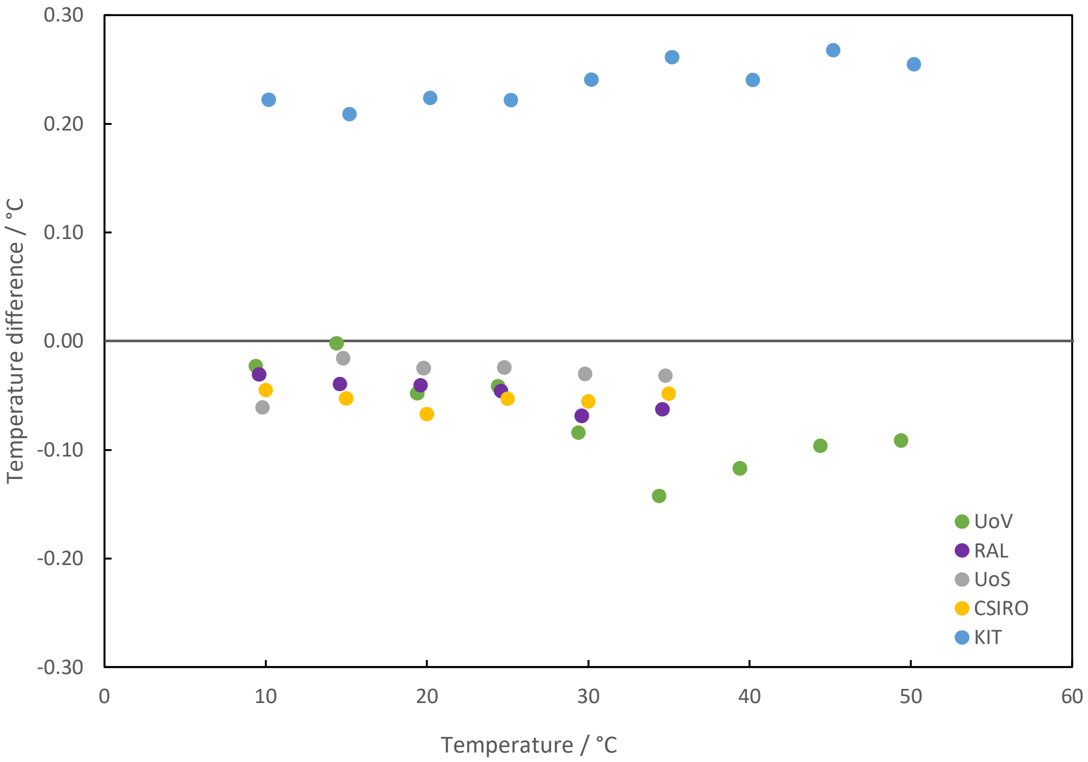
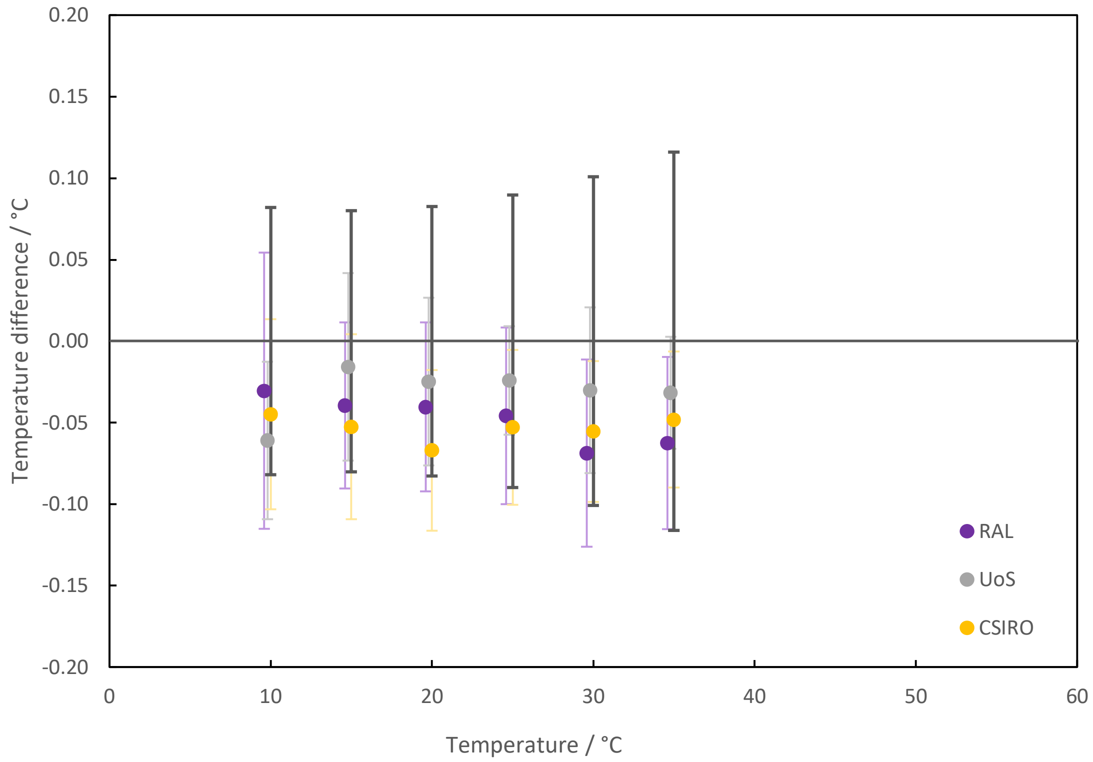


Figure 7 Temperature difference from the reference value

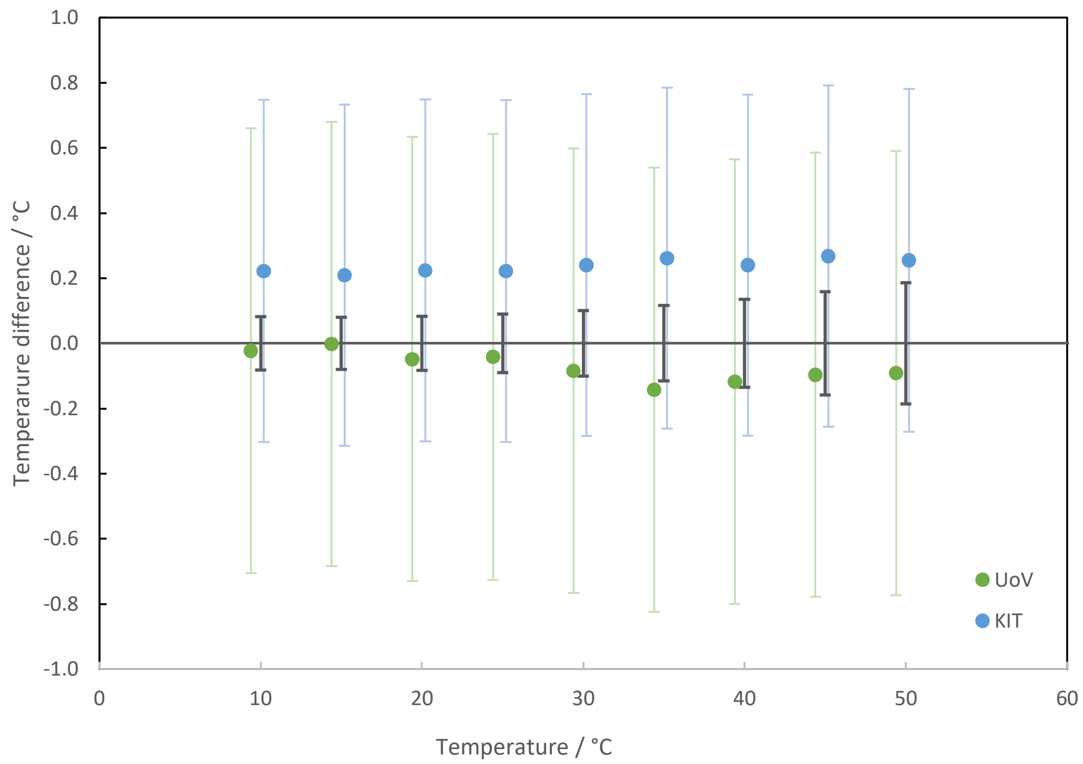
6.2 AGREEMENT WITH THE REFERENCE

Agreement with the reference value is evaluated by plotting the data of Fig. 7 with error bars added to both the measured values and the reference values, as shown in Figs. 8 a) and b). The error bars are the expanded uncertainties (*k* = 2). When there was a time stamped temporal data report from the participants, the standard deviation of the three temperature differences from the reference was evaluated for each set of measurements, and this was combined with the participant reported uncertainty.

Since the CASOTS-I and CASOTS-II BBs have significantly smaller reported uncertainties, Fig. 8 a) show results for these BBs, while Fig. 8 b) shows those for the others. Note the difference in the vertical scales.



a) CASOTS-I and CASOTS-II BBs



b) Landcal P80P BBs

Figure 8 Agreement with the reference value

Error bars are the expanded uncertainties (*k* = 2) for the participant reported values and for the reference value (black bars). Plots are shifted slightly to make them distinguishable.

7 DISCUSSIONS

Figures 4 to 6 show the results with the CASOTS-I and CASOTS-II BBs, which are the types with the BB cavity immersed in a stirred bath. The figures show that, although the BB temperatures are slowly fluctuating, the Heitronics reading follows the temporal fluctuation of the monitored BB temperature. The figures also verify that the stabilities of the participant CASOTS-I and CASOTS-II BBs are sufficient as long as the timings of the temperature readings are matched with the timings of the radiometric measurements, as is done in the current comparison. The other BB type, with the cavity in a temperature-controlled metal block (the Landcal P80P), is believed to have stable enough temperature control to assume its temperature to be constant, although this was not verified from the data since no temporal data were provided by the participants (Figs. 2 & 3). In the case of the UoV BB, the stability was studied, before the intercalibration, using external PRT readings at fixed BB temperatures (10, 20, 40 and 50 ºC) during 90 minutes (see section 5.1.1), obtaining a maximum standard deviation value of 0.03 K.

The standard measurement uncertainty with the Heitronics, including the scale realisation on the AMBER, was approximately 45 mK at 20 °C, which is comparable to or slightly smaller than the 53 mK reported for AMBER in the previous comparison [5]. This is due mainly to the employment of the novel two-point interpolation scale realisation on the AMBER, and the improved short-term stability and reproducibility achieved by the use of the Heitronics as the transfer standard for the comparison measurement. The short-term repeatability of the Heitronics was good and including this uncertainty term did not increase the calibration uncertainty.

Figure 7 shows that the deviations of the temperature realised for the CASOTS-I and CASOTS-II BBs (belonging to RAL, UoS and CSIRO) from the reference value are relatively small and are all less than 50 mK. The Landcal P80P BBs (of UoV and KIT) show larger deviations exceeding 0.1 K. No apparent dependence of the deviations on BB temperature is observed. The Landcal P80P BBs have emissivity of 0.995 (c.f. section 5.1.1), and may be affected by reflection of objects that are at different temperatures from the ambient.

In Fig. 8, the error bars, corresponding to the expanded uncertainty (k=2), overlap with each other, confirming the agreement with the reference value within the uncertainties for all BBs at all temperatures. The uncertainty of the reference is larger than the claimed uncertainties for the CASOTS-I and CASOTS-II BBs, but the former is sufficiently small to claim the comparison supports the reliability of the compared artefacts.

The temperature range of comparison for the CASOTS-I and CASOTS-II BBs was from 10 °C to 35 °C, and good agreement with the reference value was confirmed in this range. This range is sufficient for the intended application, namely sea surface temperature measurement. If similar accuracy is to be required for ice or land surface temperature measurements, the BB operation temperature range needs to be expanded. Formation of dew and frost will not be an issue if the ambient temperature can also be lowered together with the set point so that it corresponds better to the actual condition in the field, for by doing so the dew point will also be lowered.

Figure 9 Comparison participants

8 CONCLUSIONS

Five BBs used for calibrating radiometers for sea surface temperature measurement were gathered at NPL and their realised brightness temperatures were compared against the NPL reference standard radiometer scale as a part of the CEOS International Thermal Infrared Radiometer Inter-comparison (CRIC). During the comparison which took place during five days in June 2022, the BBs were measured with the transfer standard radiometer calibrated against the reference standard radiometer, AMBER, on which the scale was realised radiometrically traceable to the ITS-90 primary standards of NPL. The temperature range of comparison covered from 10 °C to 35 °C for all participants, and to 50 °C for two of the participants. The brightness temperature reported by the participants agreed with the reference value measured by the NPL transfer standard radiometer within the uncertainties for all temperatures and for all BBs.

Two new features were introduced in the current comparison compared to the previous comparison in 2016. The first is the introduction of the transfer standard radiometer to perform the actual measurement of the BBs. This overcomes the issue of the short-term stability of the AMBER, eliminates the thermal interaction of the cryogenically cooled AMBER with the BB, and reduces the problem with its poor operability encountered for practical measurements. The second is the employment of a novel scale realisation on the AMBER utilising two reference temperatures, which resulted in reduced uncertainty and made the realisation of a zero-radiance source unnecessary.

A group photograph of participants is shown in Fig.9. It was unfortunate that the number of participants was smaller than the last comparison primarily due to travel restrictions imposed by the COVID-19 pandemic. In recent years, new improved radiometers for SST measurements are being developed, and more radiometers are being deployed at the sea. A future repeat of the current exercise will be needed, possibly with a reduced interval between comparisons than the current six to eight years, when the new radiometers are being used in the field.

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