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Fiducial Reference Measurements for validation of Surface Temperature from Satellites (FRM4STS)

ESA Contract No. 4000113848_15I-LG

D100 - Technical Report 2: Results from the 4th CEOS TIR FRM Field Radiometer Laboratory Inter-comparison Exercise

Part 1 of 4: Blackbody laboratory comparison

JUNE 2017

Reference	OFE-D100(Part 1)-V1-Iss-1-Ver-1-Draft
Issue	1
Revision	1
Date of Issue	23 June 2017
Document Type	TR-2

Approval/Acceptance			
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NPL REPORT ENV 12

2016 comparison of IR brightness temperature measurements in support of satellite validation. Part 1: Blackbody Laboratory comparison

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June 2017

2016 comparison of IR brightness temperature measurements in support of satellite validation. Part 1: Blackbody laboratory comparison.

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Abstract

A comparison of terrestrial based infrared (IR) radiometric instrumentation used to support calibration and validation of satellite borne sensors with emphasis on sea/water/land surface temperature was completed at NPL during June and July 2016. The objectives of the 2016 comparison were to establish the "degree of equivalence" between terrestrially based IR Calibration/Validation measurements made in support of satellite observations of the Earth's surface temperature and to establish their traceability to SI units through the participation of National Metrology Institutes (NMIs). 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) and the PTB infrared radiometer, while 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 gardens of NPL during the week beginning on 4th July 2016 and involved field measurements of the temperature of the surface of a number of solid targets which included direct daytime and night-time measurements of the surface temperature of short grass, clover, soil, sand, gravel and tarmac/asphalt. This report provides the results of the blackbody laboratory comparison, together with uncertainties as provided by the participants, for the comparison of the participants' blackbodies. During the 2016 comparison, all participants were encouraged to develop 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.

ISSN: 2059-6030

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1. 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 SI units.

Field-deployed infrared radiometers (see footnote 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, blackbodies used to calibrate these radiometers are of varying design and are operated by different teams in different parts of the globe. 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.

A comparison of terrestrial based infrared (IR) radiometric instrumentation (both blackbodies and radiometers) used to support calibration and validation of satellite borne sensors with emphasis on sea/water surface temperature was completed in Miami in 2001 (Barton et al., 2004) (Rice et al., 2004) and at NPL and Miami in 2009 (Theocharous et al. 2010), (Theocharous and Fox, 2010). However, seven years had passed, and as many of the satellite sensors originally supported were nearing the end of their life, a similar comparison was repeated in 2016. 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 establish their traceability to SI units through the participation of NMIs.

2. ORGANISATION OF THE COMPARISON

During the 2016 comparison, NPL acted as the pilot laboratory and, with the aid of PTB, provided traceability to SI units during the laboratory comparisons at NPL. NPL was supported with specialist application advice from University of Southampton, RAL and KIT. The 2016 comparison 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 19 radiometers operating in 24 measurement channels was compared during Stage 1. Stage 2 took place on the platform which was 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 gardens 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-

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".

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 measurement of the radiance temperature of blackbodies acquired at NPL during the week beginning 20th June 2016. The NPL AMBER radiometer and the PTB infrared radiometer were used in the 2016 laboratory comparison of the participants' blackbodies. Figure 2.1 shows the eight blackbodies which participated in the 2016 blackbody comparison lined up on an optical bench. The PTB radiometer, shown on the extreme left hand side and the AMBER radiometer shown on the right hand side were moved along the bench so they could sequentially measure the radiance temperature of the participating blackbodies. From the left hand side, the eight blackbodies of ONERA, University of Valencia, University of Miami, University of Southampton, Qingdao, RAL, CSIRO and KIT can be seen.

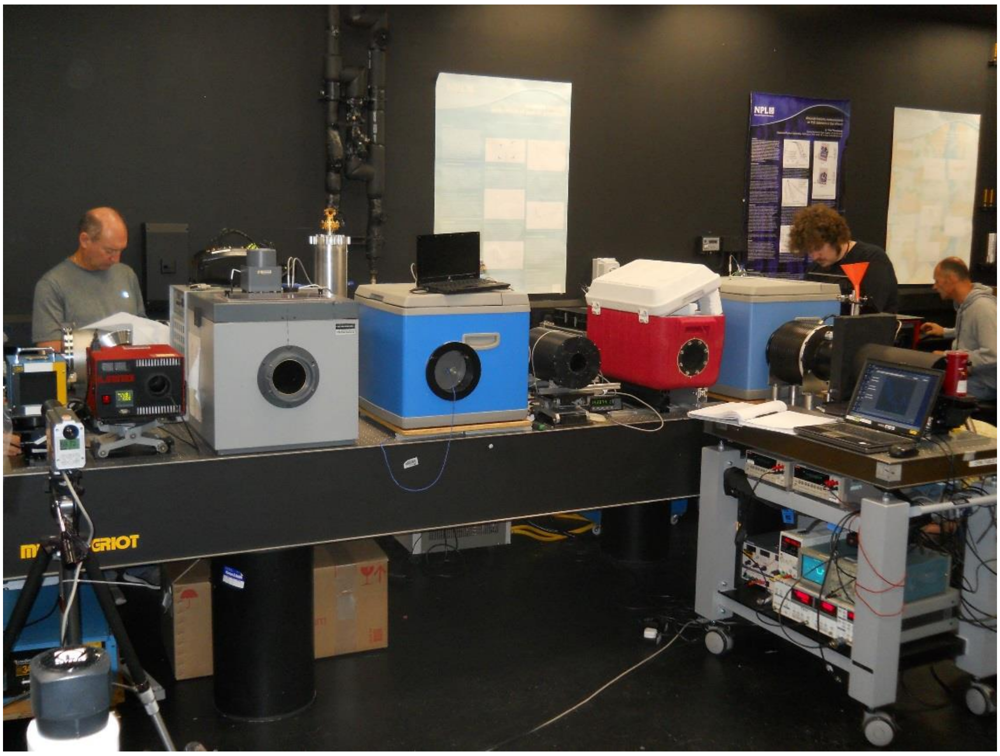

Figure 2.1: Photo of the eight blackbodies which participated in the 2016 blackbody comparison lined up on an optical bench. The PTB radiometer, shown on the extreme left hand side and the NPL AMBER radiometer shown on the right hand side were moved along the bench so they could sequentially measure the radiance temperature of the blackbodies.

The laboratory radiometer comparison as well as the Water Surface Temperature (WST) comparison at Wraysbury reservoir and the Land Surface Temperature (LST) comparison at NPL will be presented in other reports which will be issued shortly (Barker Snook et al., 2017, Barker Snook et al, 2017a, Theocharous et al. 2017).

During the 2016 comparison, all participants were encouraged to develop uncertainty budgets for all measurements they reported. In order to achieve optimum comparability, lists 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 and are presented in this report.

3. PARTICIPANTS' BLACKBODIES AND MEASUREMENTS

Section 3 gives brief descriptions of the blackbodies which participated in the 2016 blackbody laboratory comparison at NPL and gives the measurements which were completed by the NPL AMBER and PTB infrared radiometer during these comparisons, along with the corresponding measurements and combined uncertainty values which were provided by the participants. Section 3 also provides the uncertainty budgets of the measurements completed by the participating radiometers, as provided by the participants. In some cases the level of detail provided by participants in the uncertainty budgets of their measurements is fairly limited and not ideal. However, whatever was provided by the participants is included in this report, along with a summary of the results for each participant for each stage of the comparison.

3.1 VALENCIA UNIVERSITY BLACKBODY

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3.1.1 Description of the Blackbody

Make and type of the Blackbody. Land Infrared Landcal Blackbody Source P80P.

Outline Technical description of the blackbody. Cavity material: Aluminium with black, high temperature refractory coating. Cavity design: 50 mm (diameter) × 155 mm (length), 120º cone at closed end. Emissivity greater than 0.995. Thermometers: Internal Platinum Resistance Thermometer (PRT) connected to digital display with 0.01 K resolution. External PRT-100 traceable to National Standards (UKAS calibration certificate).

3.1.2 Route of Traceability

Establishment or traceability route for primary calibration including date of last realisation and breakdown of uncertainty. The blackbody temperature given by the internal PRT was calibrated at Valencia University against the external PRT calibrated to 0.1 K (UKAS calibration certificate) with 0.01 K resolution in May 13-18, 2016. Based on the measurements performed, the following uncertainty analysis is presented:

Type A

- Repeatability: 0.011 K or 0.004% at 300 K (standard deviation of external PRT readings at a fixed blackbody 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 or 0.012 % at 300 K.

Type B

- Emissivity: Uncertainty in emissivity is less than 0.005 (according to manufacturer), which translates in a temperature uncertainty of 0.13 K in the 8 to 13 μm region.

- 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 blackbody cavity temperatures as measured by a high resolution thermal infrared camera with apparent resolution of 0.1 K).

- Stability of source: 0.02 K (maximum value of standard deviation of external PRT readings at a fixed blackbody 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 blackbody was set to each one of six fixed temperature values (from 0 ºC to 50 ºC), 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 blackbody 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. The influence of the radiometer operating temperature can be minimized by placing the radiometer far enough from the blackbody.

Blackbody usage (deployment), previous use of instrument and planned applications. The primary usage of the blackbody is laboratory calibration of thermal infrared radiometers used for in situ land surface temperature (LST) measurements with the aim of validating satellite-derived LSTs.

UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH BLACKBODY

Parameter	**Type A**	**Type B**	
	Uncertainty in Value / %	**Uncertainty in Value / (appropriate units)**	**Uncertainty in brightness temperature/K**
Repeatability of measurement	0.004		0.011
Reproducibility of measurement	0.012		0.035
Blackbody emissivity		0.005 in emissivity	0.13
BB Thermometer Calibration		0.1 K	0.1
BB cavity temperature non-uniformity		0.3 K	0.3
BB temperature stability		0.02 K	0.02
Reflected ambient radiation		1 K in ambient temperature	0.005
Radiant heat/loss gain		URadiant	
Convective heat/loss gain		UConvect	
Primary Source		-	-
RMS total	**0.037 K 0.012 %**	**0.34 K**	**0.34**

3.1.3 Valencia University Blackbody Measured by NPL AMBER

Figures 3.1.3.1 to 3.1.3.13, show the measurements reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by NPL AMBER as a function of time, at different temperatures in the 0 °C to 50 °C temperature range. The blackbody measurements are shown in red, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the Valencia University blackbody, shown in yellow (340 mK). The uncertainty of the AMBER radiometer during these measurements was 53 mK and is shown in light blue.

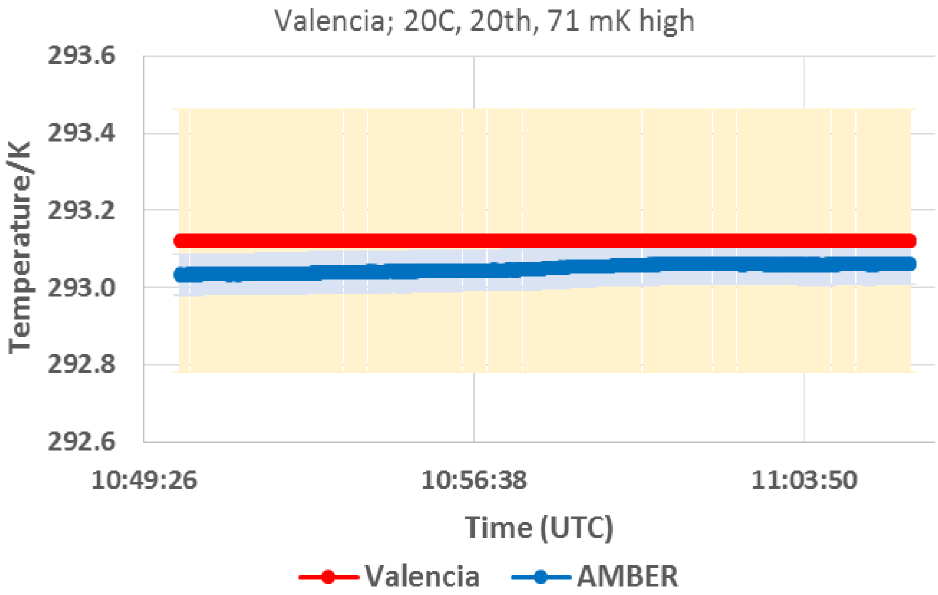

Figure 3.1.3.1: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by NPL AMBER on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 71 mK higher than the corresponding value measured by NPL AMBER.

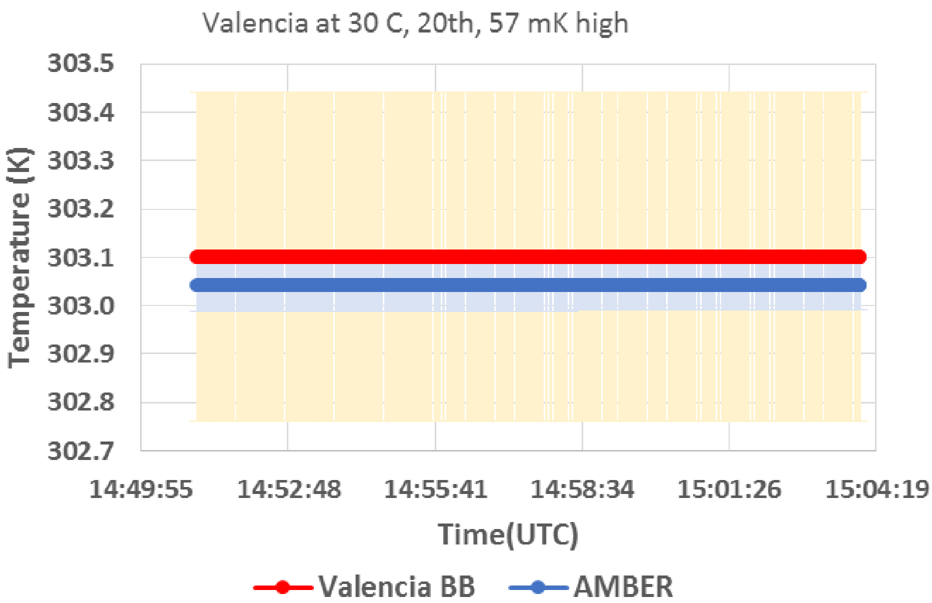

Figure 3.1.3.2: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by NPL AMBER on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 57 mK higher than the value corresponding measured by NPL AMBER.

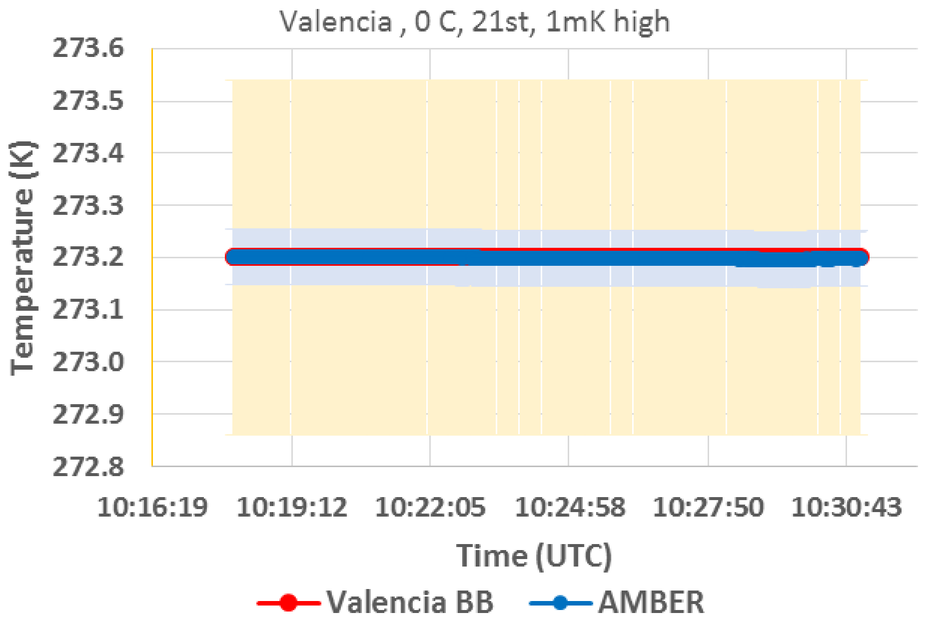

Figure 3.1.3.3: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 21st June, while the blackbody was operating at about 0 °C. The average measurement of the blackbody was 1 mK higher than the value corresponding measured by AMBER.

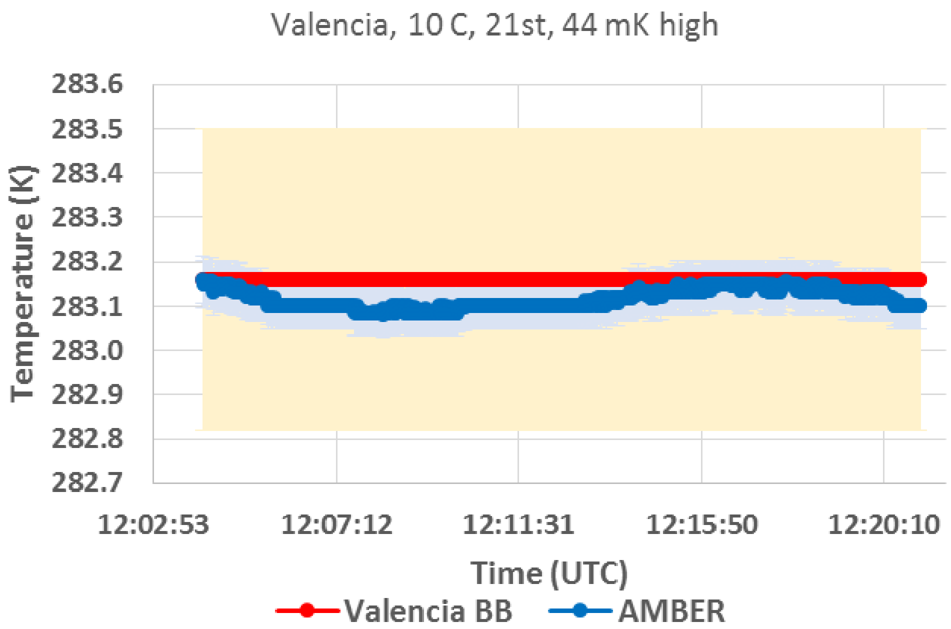

Figure 3.1.3.4: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 21st June, while the blackbody was operating at about 10 °C. The average measurement of the blackbody was 44mK higher than the corresponding value measured by AMBER.

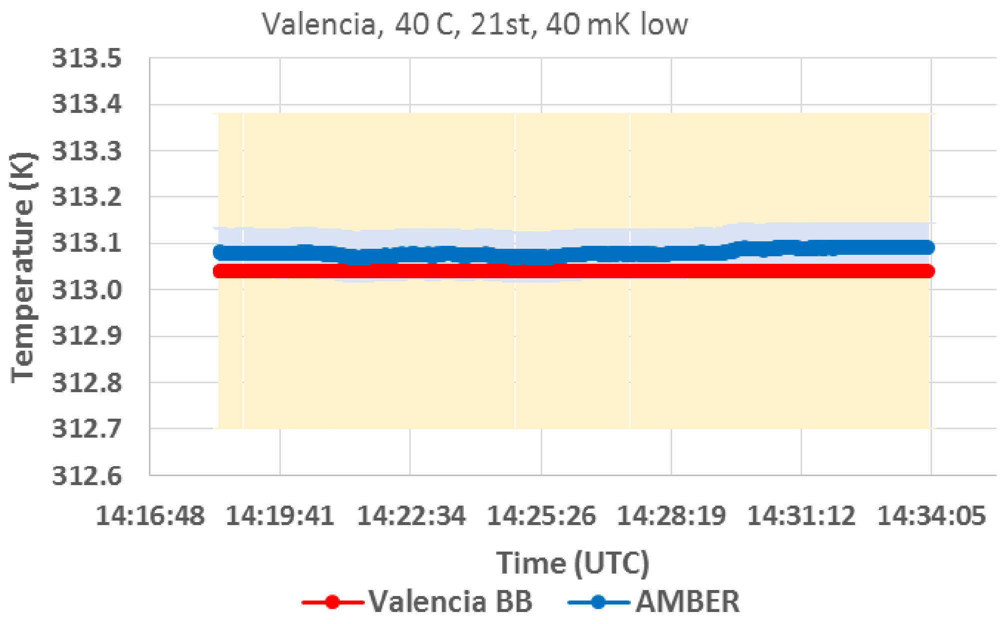

Figure 3.1.3.5: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 21st June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 40 mK lower than the corresponding value measured by AMBER.

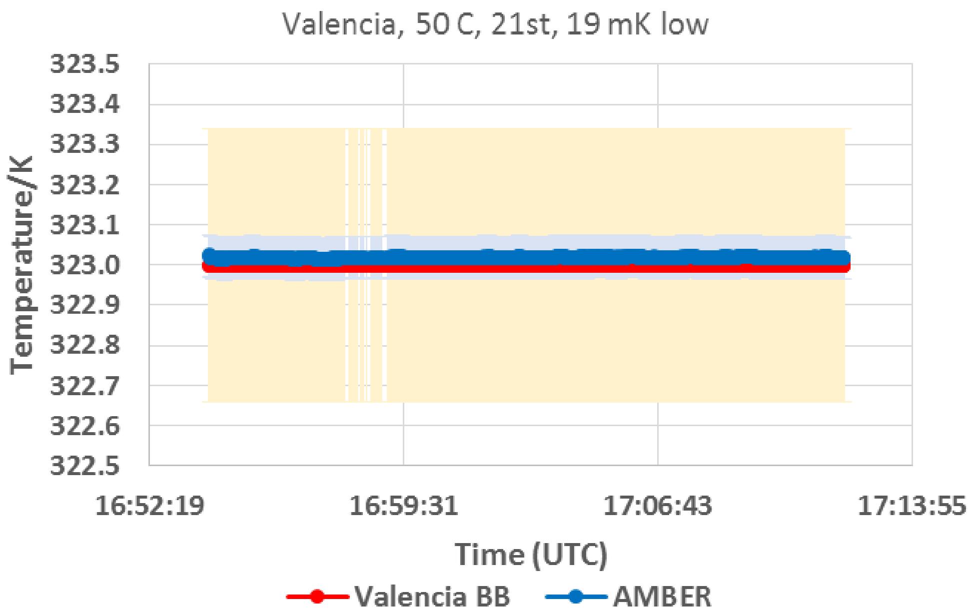

Figure 3.1.3.6: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 21st June, while the blackbody was operating at about 50 °C. The average measurement of the blackbody was 19 mK lower than the corresponding value measured by AMBER.

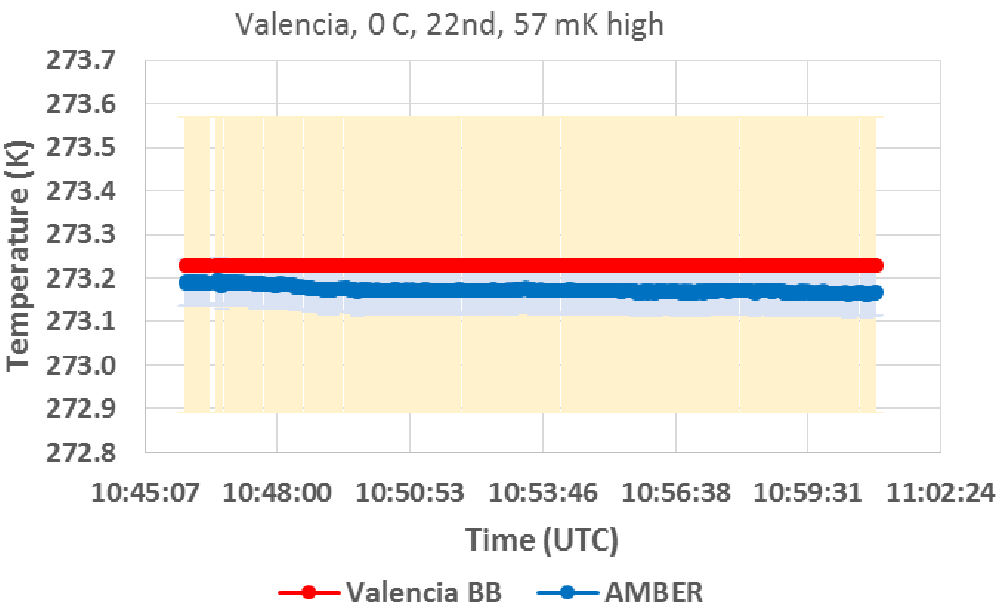

Figure 3.1.3.7: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 22nd June, while the blackbody was operating at about 0 °C. The average measurement of the blackbody was 57 mK higher than the corresponding value measured by AMBER.

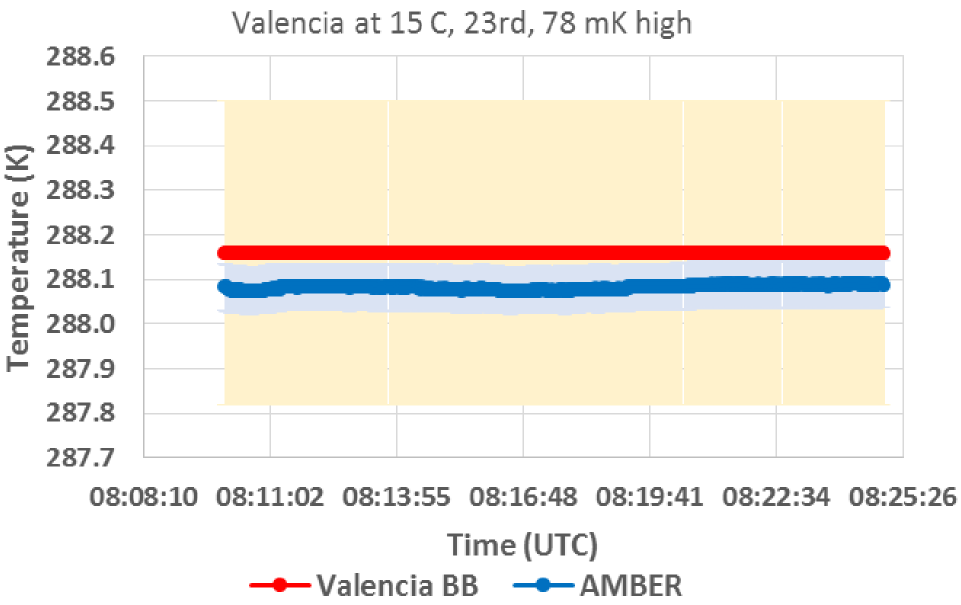

Figure 3.1.3.8: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 23rd June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 78 mK higher than the corresponding value measured by AMBER.

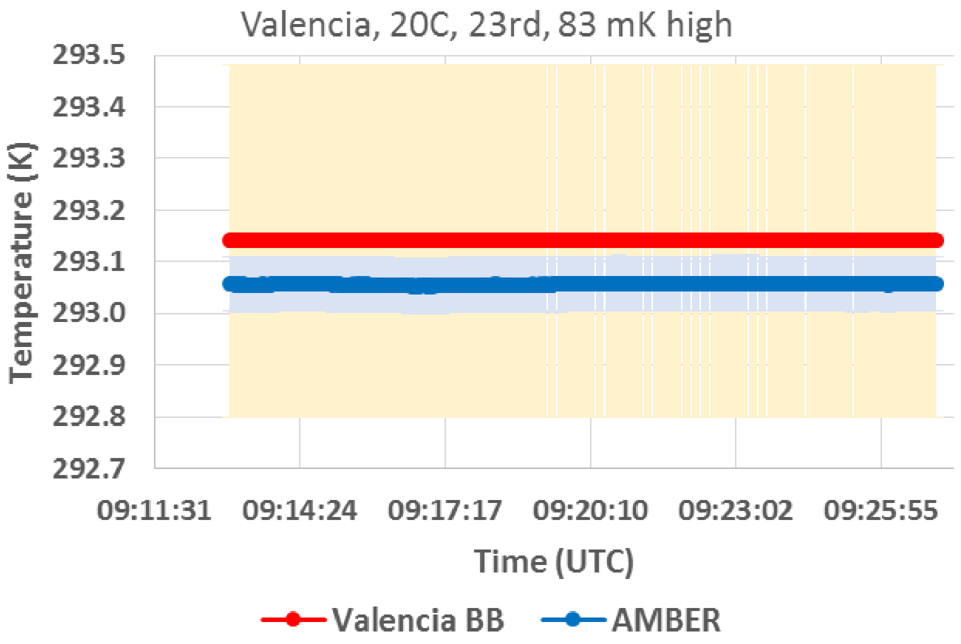

Figure 3.1.3.9: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 23rd June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 83 mK higher than the corresponding value measured by AMBER.

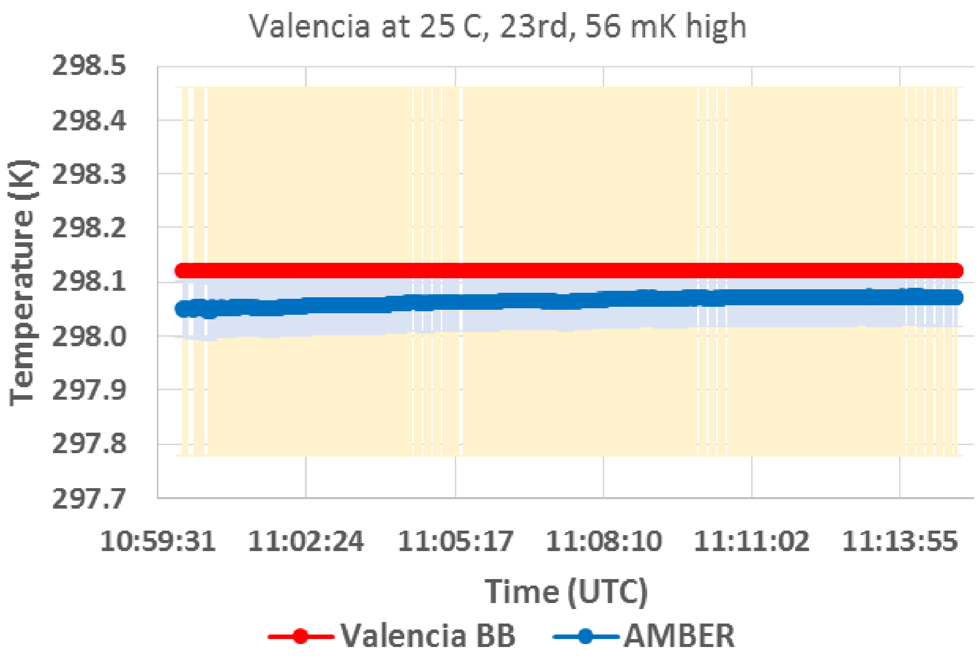

Figure 3.1.3.10: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 23rd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 56 mK higher than the corresponding value measured by AMBER.

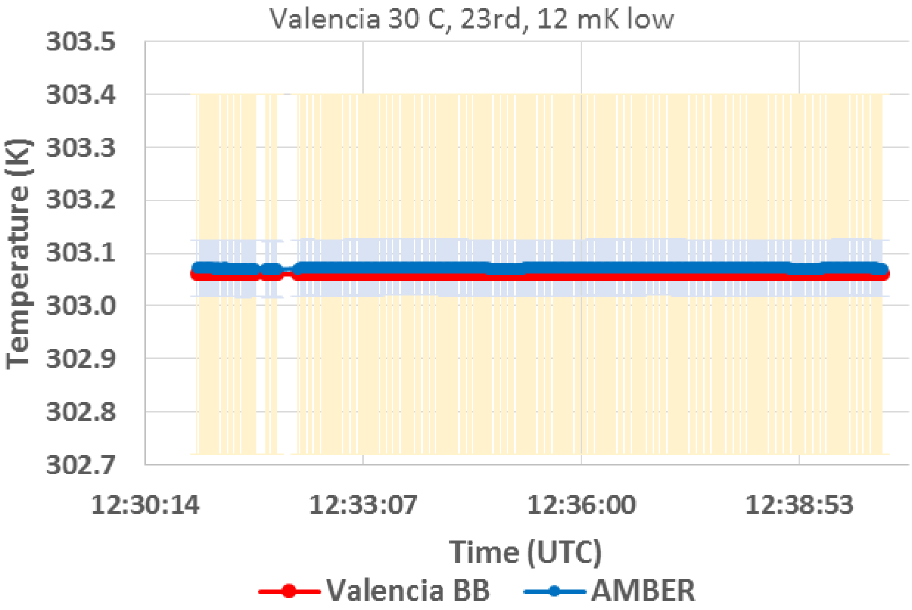

Figure 3.1.3.11: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 23rd June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 12 mK lower than the corresponding value measured by AMBER.

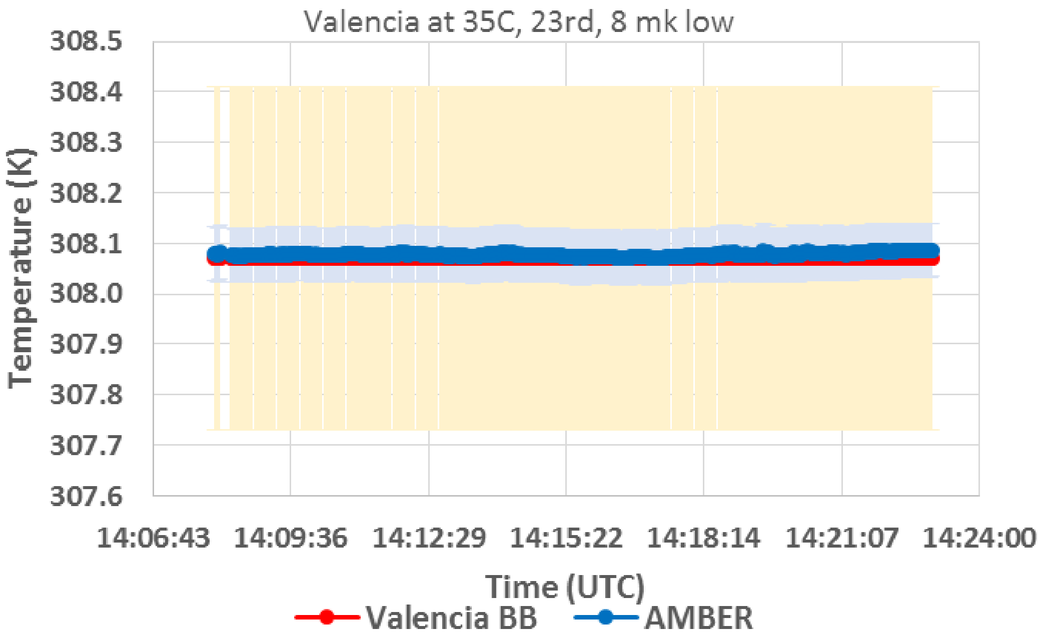

Figure 3.1.3.12: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 23rd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 8 mK lower than the corresponding value measured by AMBER.

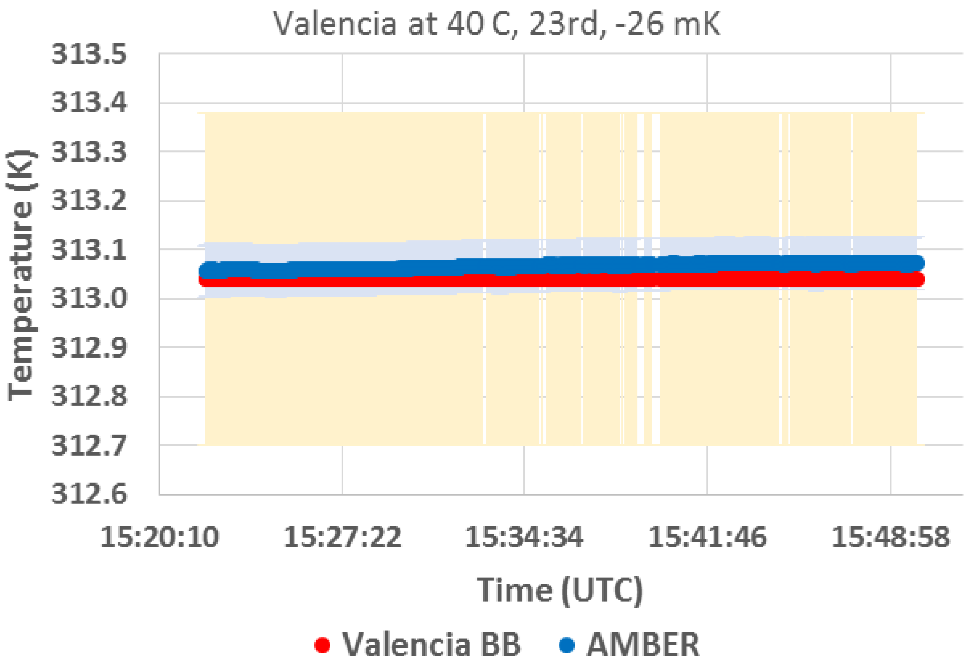

Figure 3.1.3.13: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by AMBER on the 23rd June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 26 mK lower than the corresponding value measured by AMBER.

3.1.4 Valencia University Blackbody Measured by the PTB Radiometer

Figures 3.1.4.1 to 3.1.4.15 show the measurements reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 0 °C to 50 °C temperature range. The blackbody measurements reported by Valencia University are shown in orange/red, while the PTB radiometer measurements are shown in blue. Also shown as black error bars in these Figures is the uncertainty of the Valencia University blackbody (as reported by Valencia University), as well as the uncertainty of the PTB radiometer during these measurements.

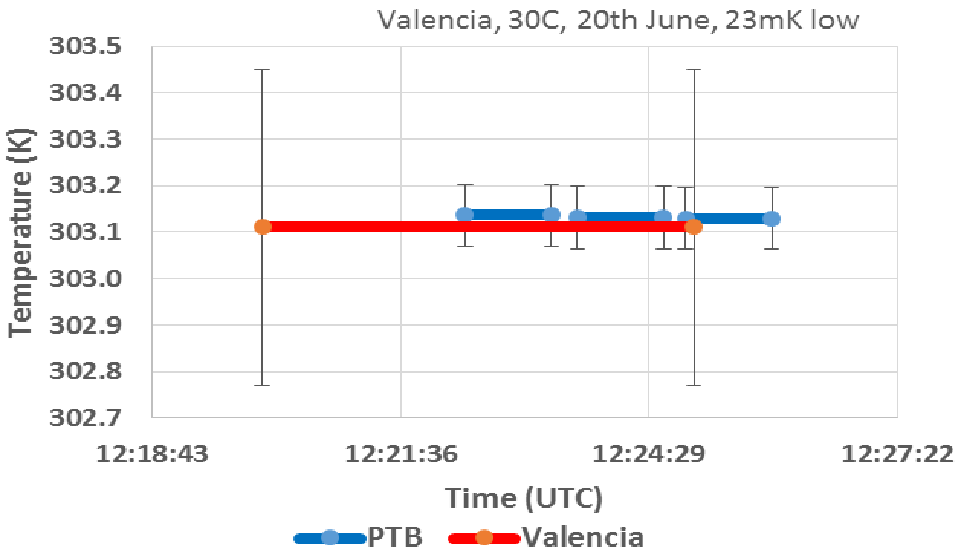

Figure 3.1.4.1: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 23 mK lower than the corresponding value measured by the PTB radiometer.

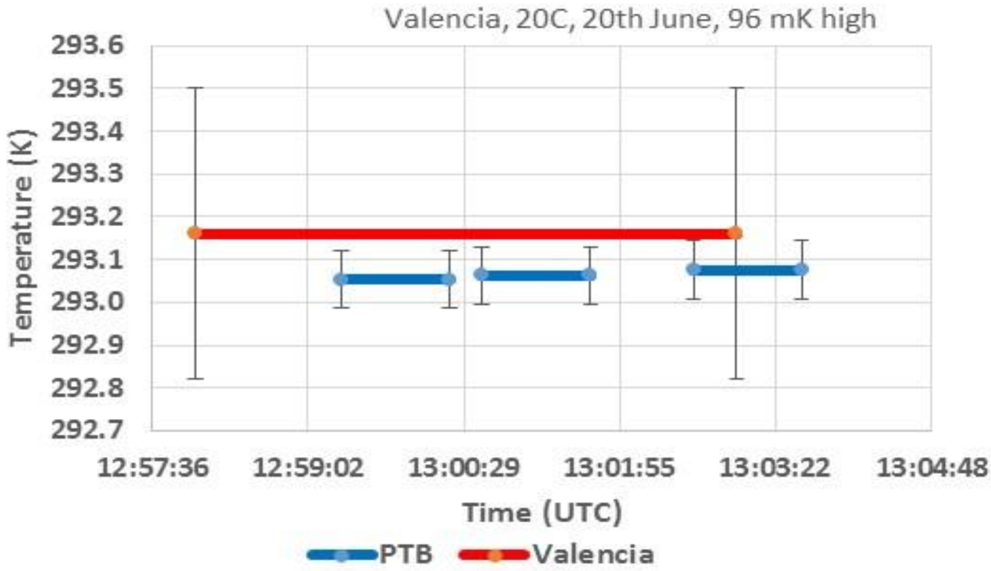

Figure 3.1.4.2: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 96 mK higher than the corresponding value measured by the PTB radiometer.

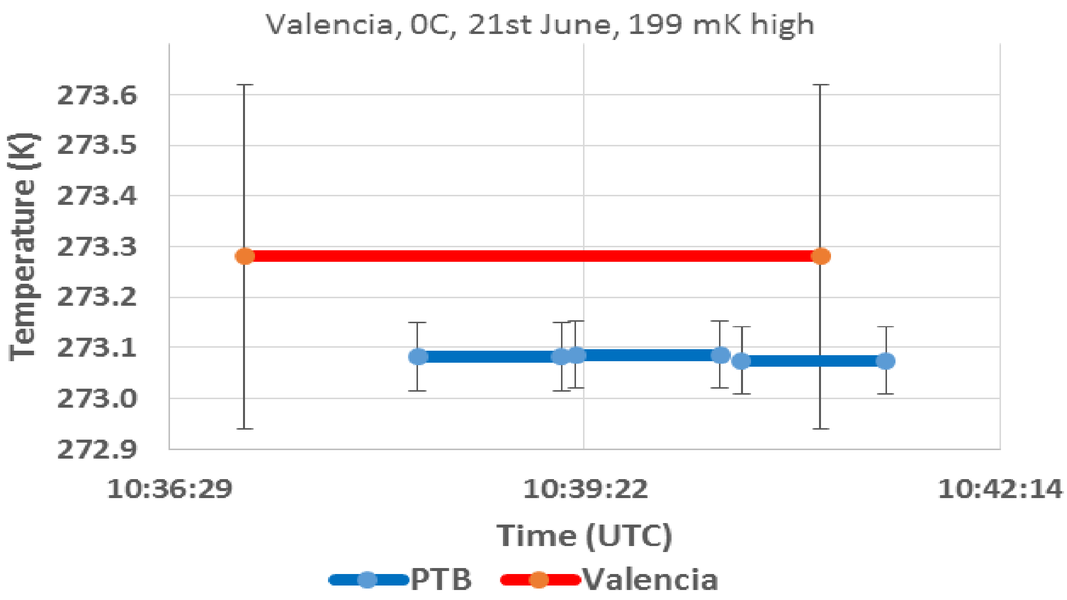

Figure 3.1.4.3: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 0 °C. The average measurement of the blackbody was 199 mK higher than the corresponding value measured by the PTB radiometer.

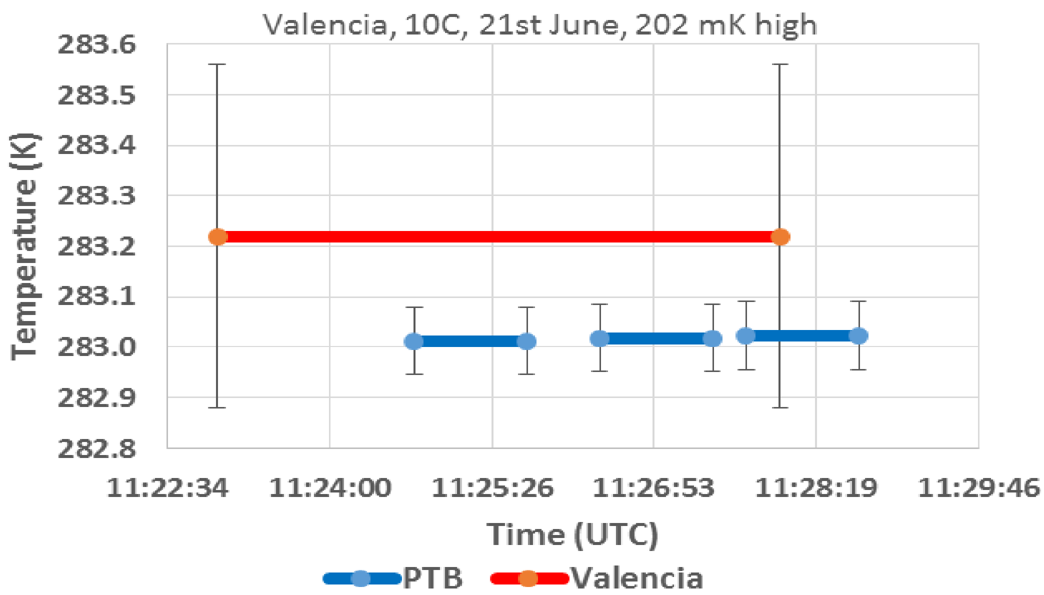

Figure 3.1.4.4: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 10 °C. The average measurement of the blackbody was 202 mK higher than the corresponding value measured by the PTB radiometer.

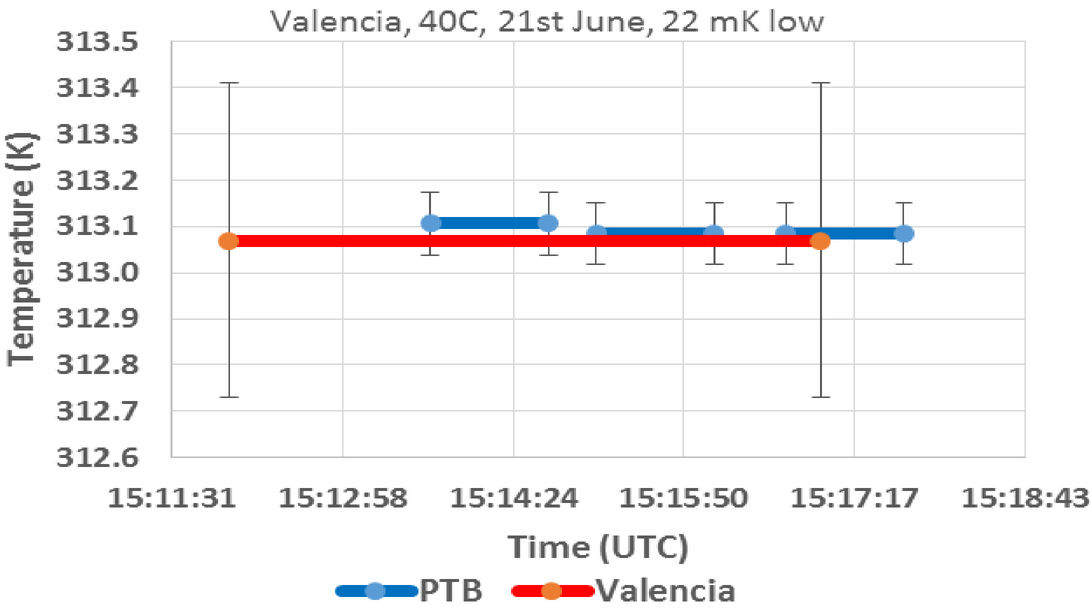

Figure 3.1.4.5: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 22 mK lower than the corresponding value measured by the PTB radiometer.

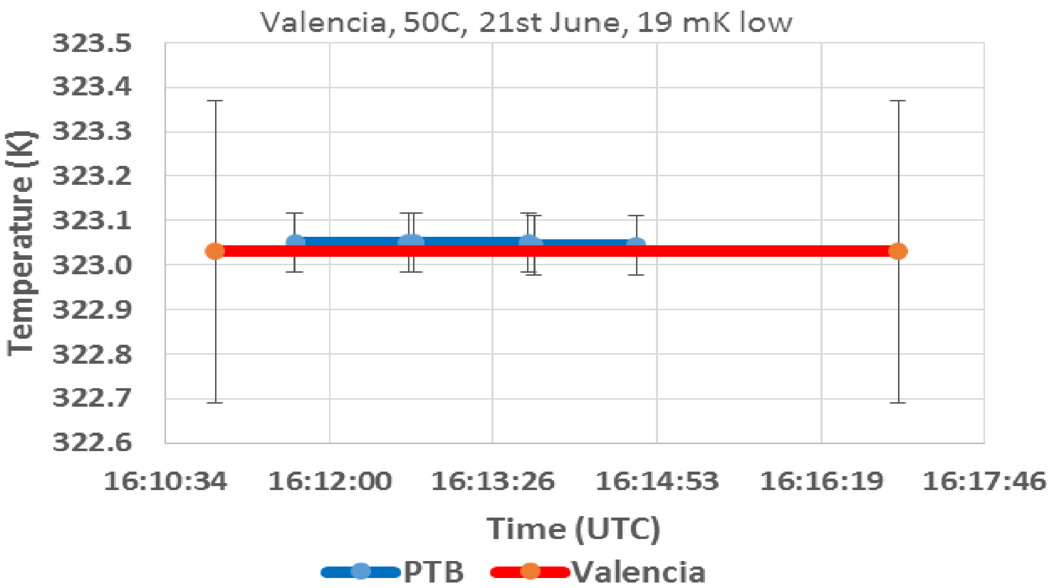

Figure 3.1.4.6: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 50 °C. The average measurement of the blackbody was 19 mK lower than the corresponding value measured by the PTB radiometer.

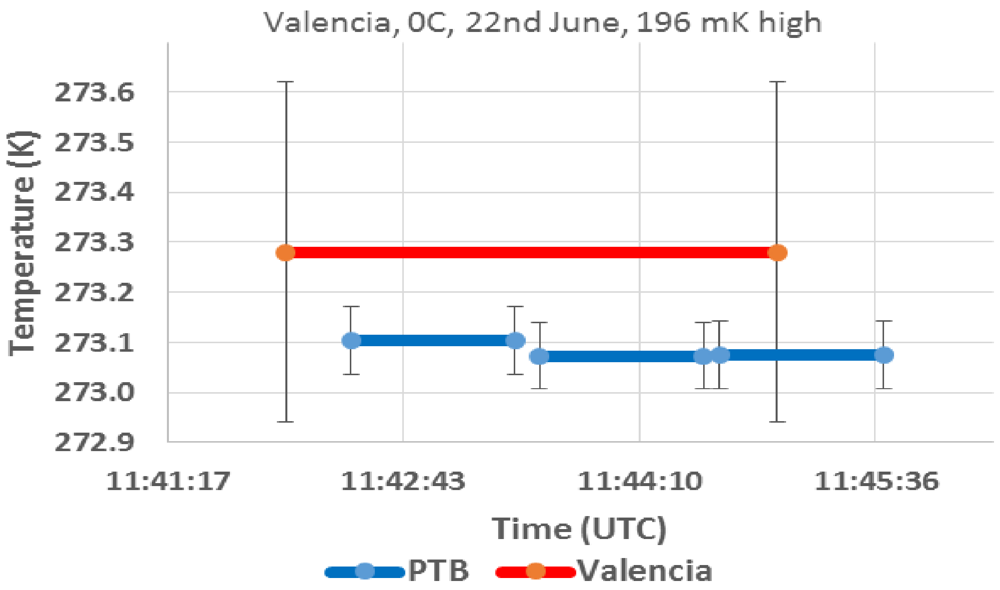

Figure 3.1.4.7: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 0 °C. The average measurement of the blackbody was 196 mK lower than the corresponding value measured by the PTB radiometer.

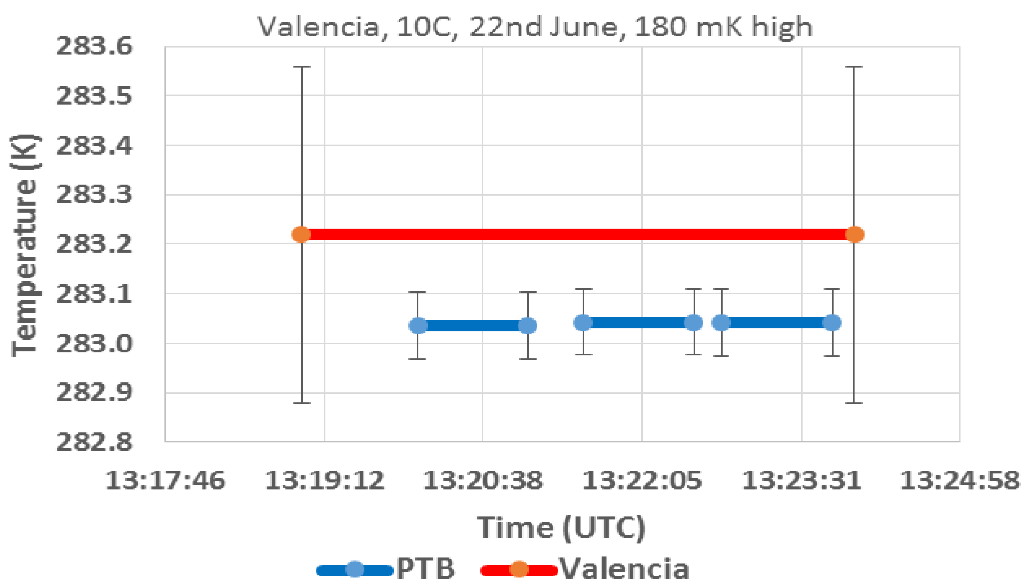

Figure 3.1.4.8: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 10 °C. The average measurement of the blackbody was 180 mK higher than the corresponding value measured by the PTB radiometer.

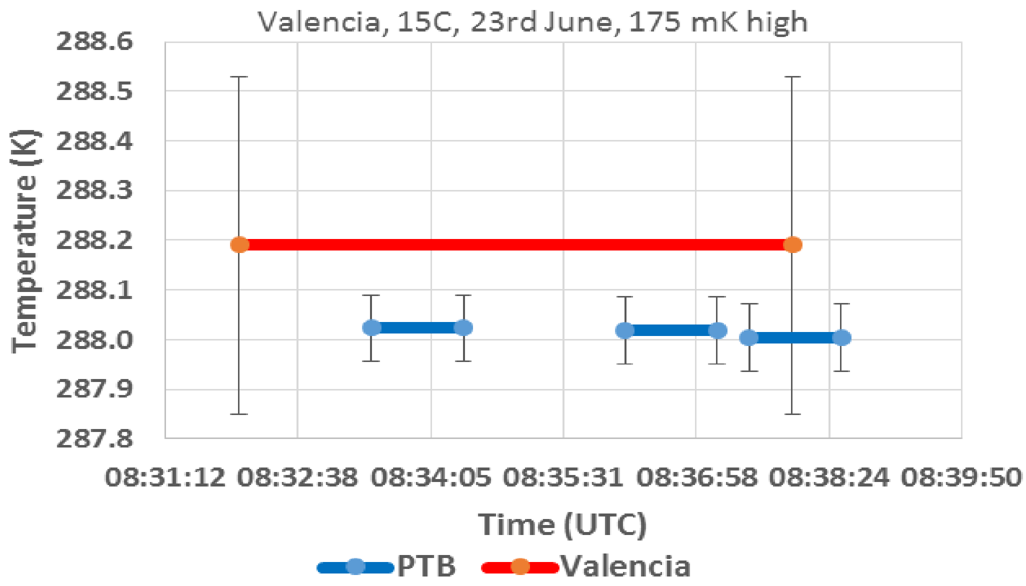

Figure 3.1.4.9: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 175 mK higher than the corresponding value measured by the PTB radiometer.

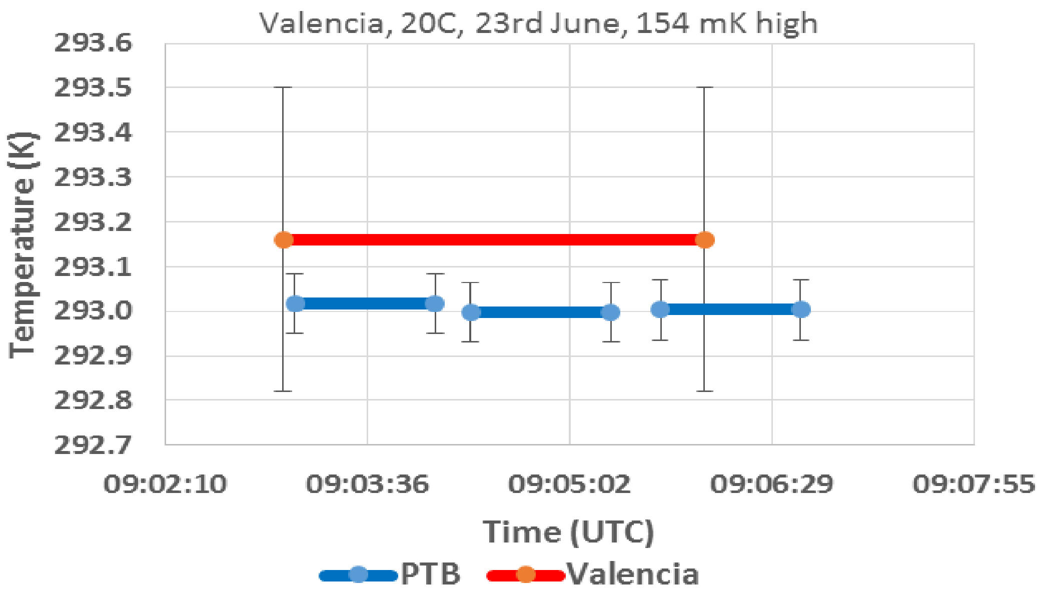

Figure 3.1.4.10: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 154 mK higher than the corresponding value measured by the PTB radiometer.

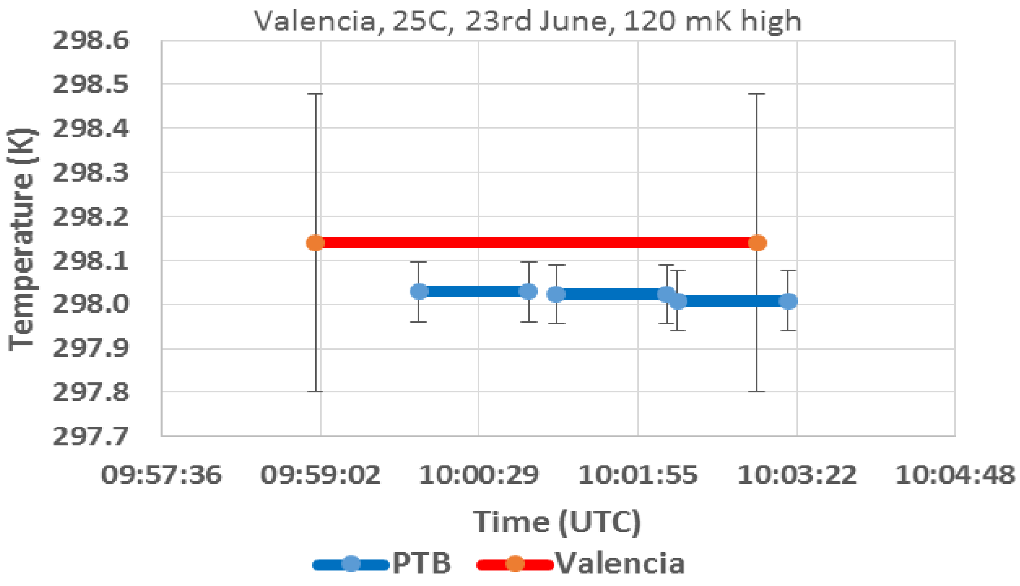

Figure 3.1.4.11: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 120 mK higher than the corresponding value measured by the PTB radiometer.

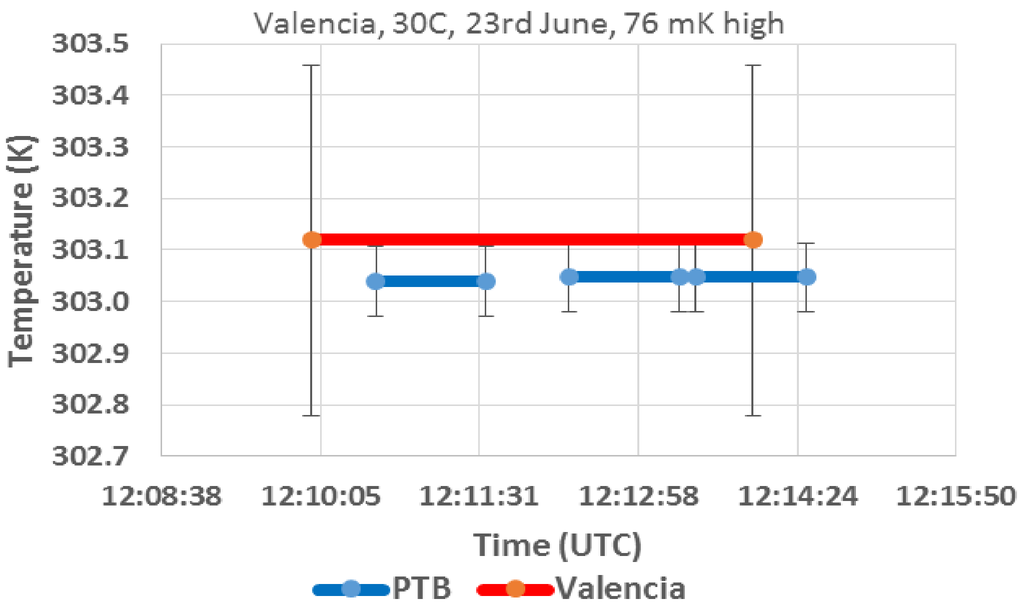

Figure 3.1.4.12: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 76 mK higher than the corresponding value measured by the PTB radiometer.

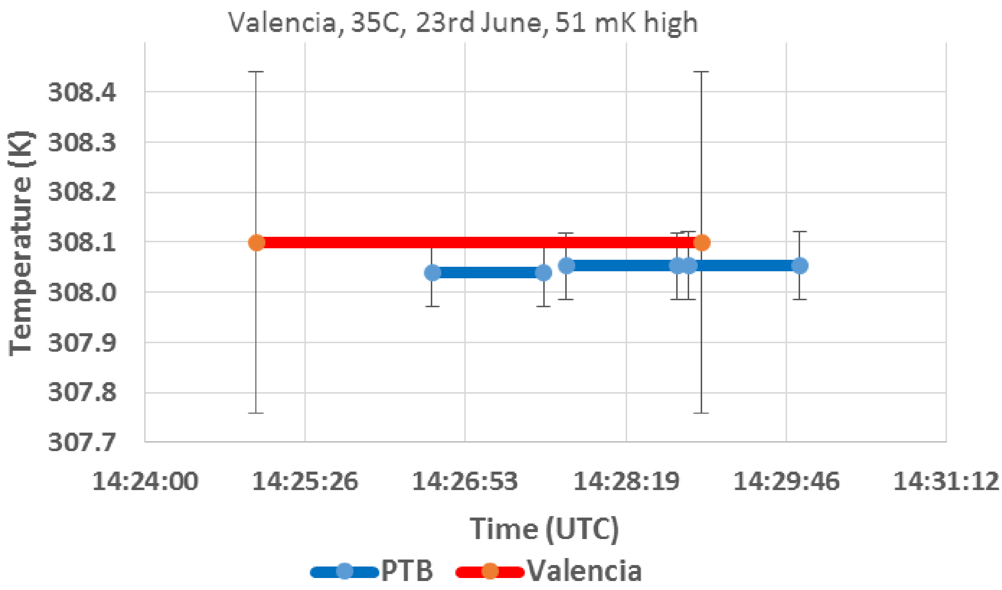

Figure 3.1.4.13: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 51 mK higher than the corresponding value measured by the PTB radiometer.

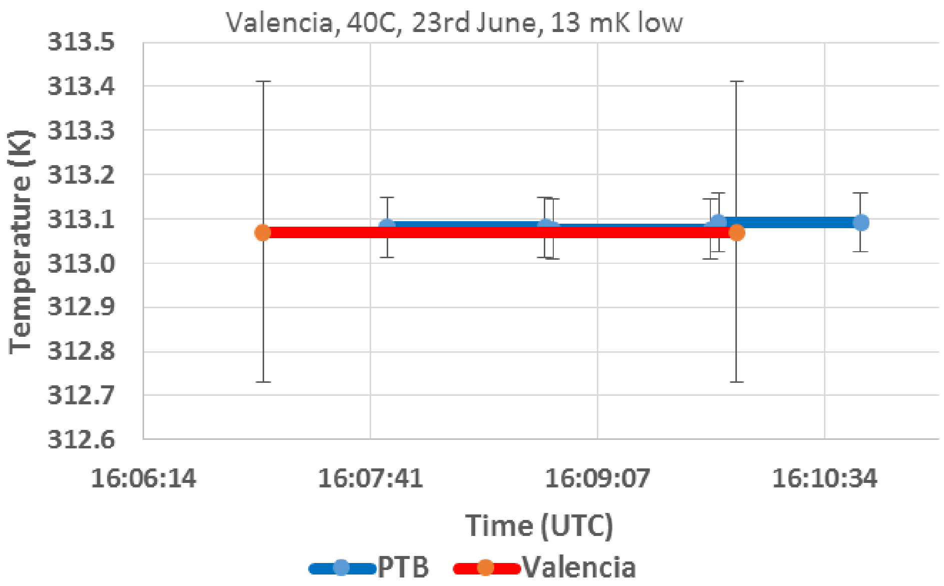

Figure 3.1.4.14: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 13 mK lower than the corresponding value measured by the PTB radiometer.

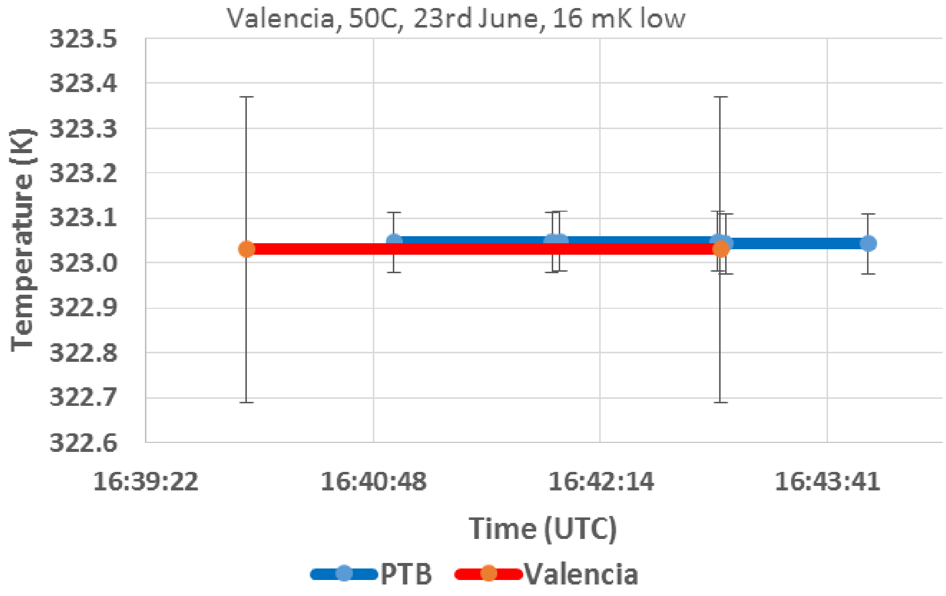

Figure 3.1.4.15: Measurements (as a function of time) reported by the Valencia University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 50 °C. The average measurement of the blackbody was 16 mK lower than the corresponding value measured by the PTB radiometer.

3.2 CSIRO BLACKBODY

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Email: Nicole.Morgan@csiro.au

3.2.1 Description of the CSIRO Blackbody

The CSIRO blackbody is a CASOTS-II blackbody. Information of the CASOTS-II blackbody can be found in the publication: C. J. Donlon, W. Wimmer, I. Robinson, G Fisher, M. Ferlet, T. Nightingale and B. Bras, “A Second-Generation Blackbody System for the Calibration and Verification of Seagoing Infrared Radiometers”, Journal of Atmospheric and Oceanic Technology, **31**, 1104-1127, 2014.

3.2.2 Uncertainty of the measurements of the CSIRO Blackbody

Table 3.2.1 shows the uncertainty budget of the CSIRO CASOTS II blackbody, as reported by CSIRO.

Table 3.2.1: Uncertainty contributions of the CSIRO CASOTS II blackbody reported by CSIRO

Uncertainty contribution	Uncertainty value mK
Uncertainty in NEXEL paint emissivity	7.75
Stray radiance error	5
Thermometry System	0
Heating rate error	7.6
Worst-case water bath thermal gradients	9.6
Cavity Wall-paint thermal gradients	1
Fluke 1524	1
Stabililty	1
Total (mK)	15.4

3.2.3 CSIRO Blackbody Measured by NPL AMBER

Figures 3.2.3.1 to 3.2.3.9 show the measurements reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 8 °C to 35 °C temperature range. The blackbody measurements are shown in orange, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK) and is shown in light blue. The uncertainty of the CSIRO blackbody during these measurements was 15 mK and is shown in light orange.

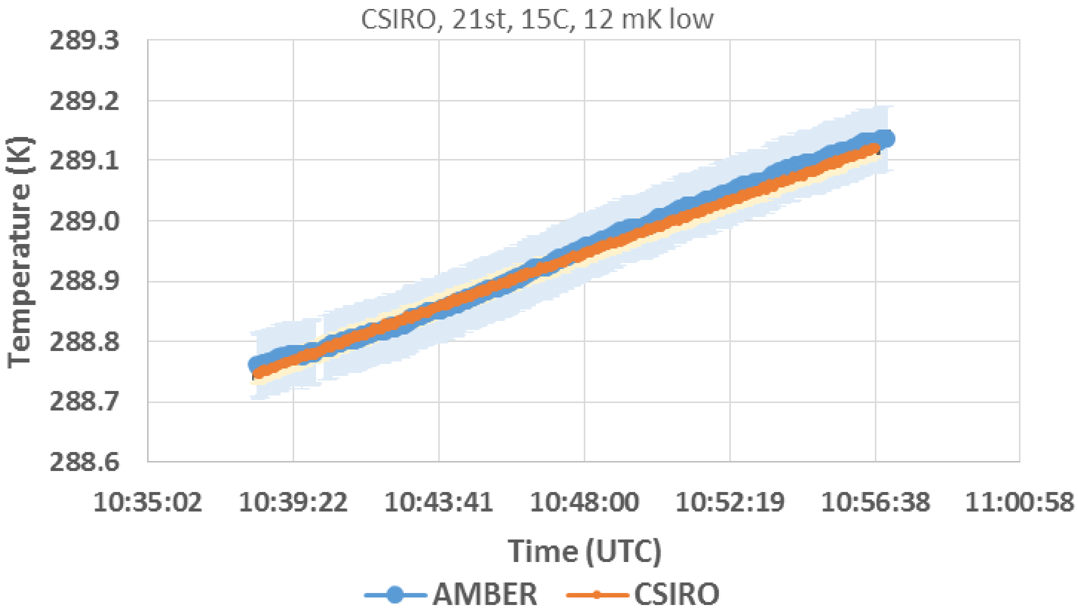

Figure 3.2.3.1: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 12 mK lower than the corresponding value measured by AMBER.

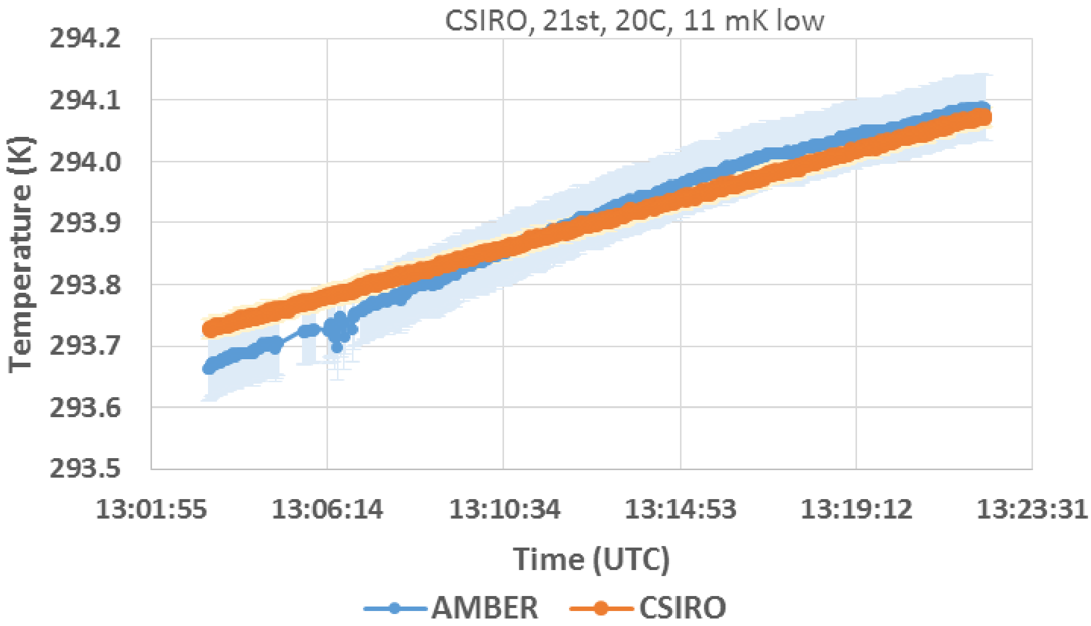

Figure 3.2.3.2: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 11 mK lower than the corresponding value measured by AMBER.

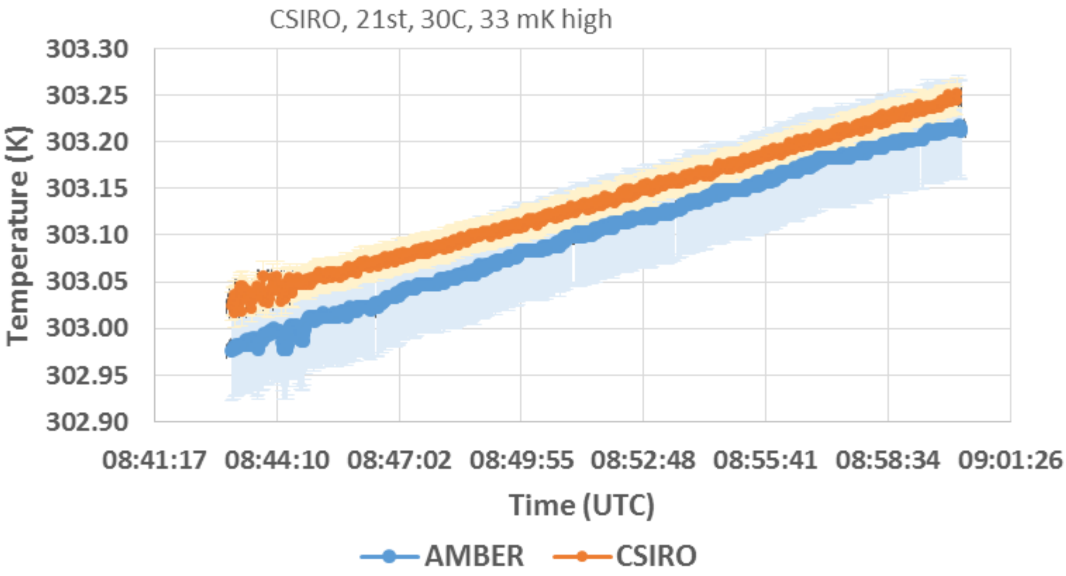

Figure 3.2.3.3: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 33 mK higher than the corresponding value measured by AMBER.

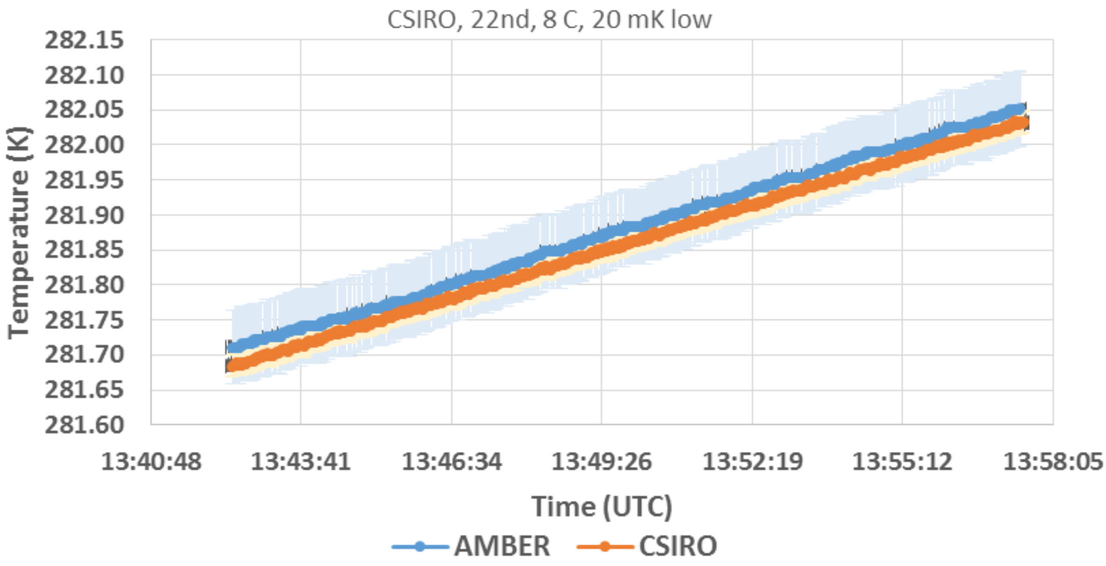

Figure 3.2.3.4: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 8 °C. The average measurement of the blackbody was 20 mK lower than the corresponding value measured by AMBER.

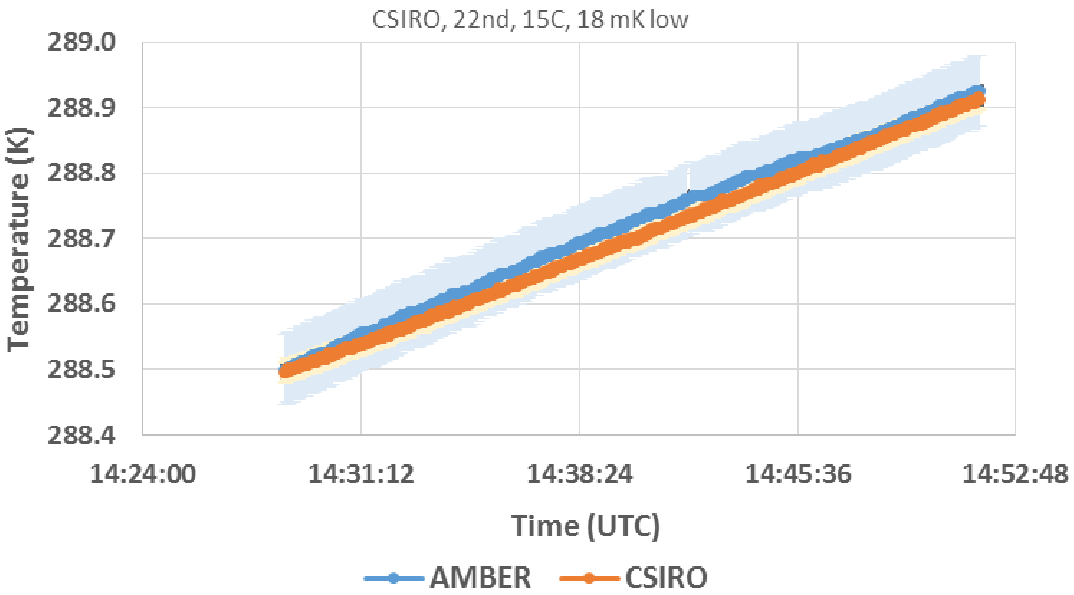

Figure 3.2.3.5: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 18 mK lower than the corresponding value measured by AMBER.

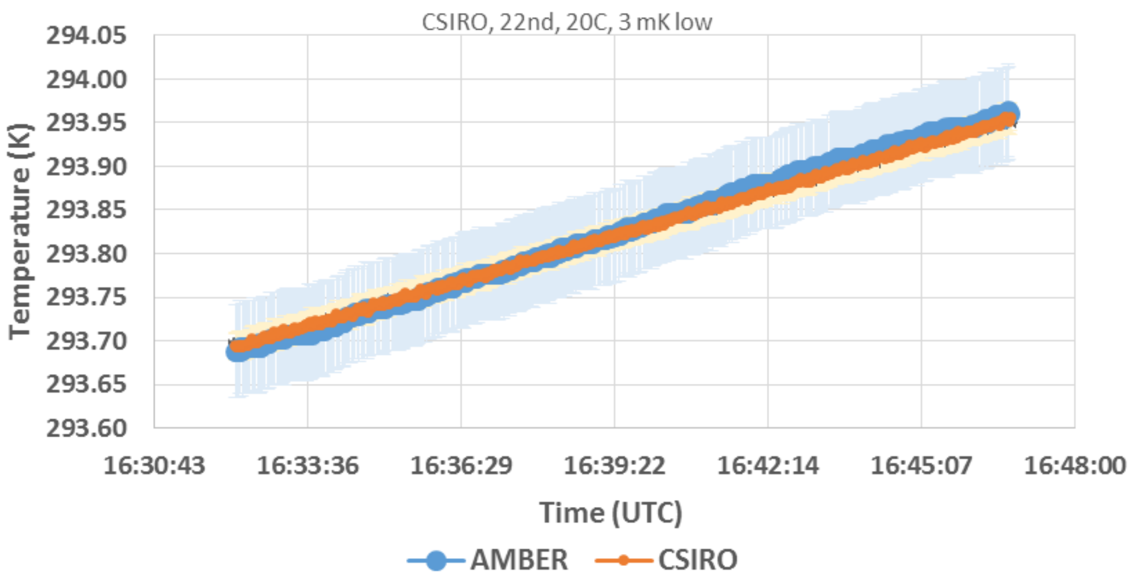

Figure 3.2.3.6: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 3 mK lower than the corresponding value measured by AMBER.

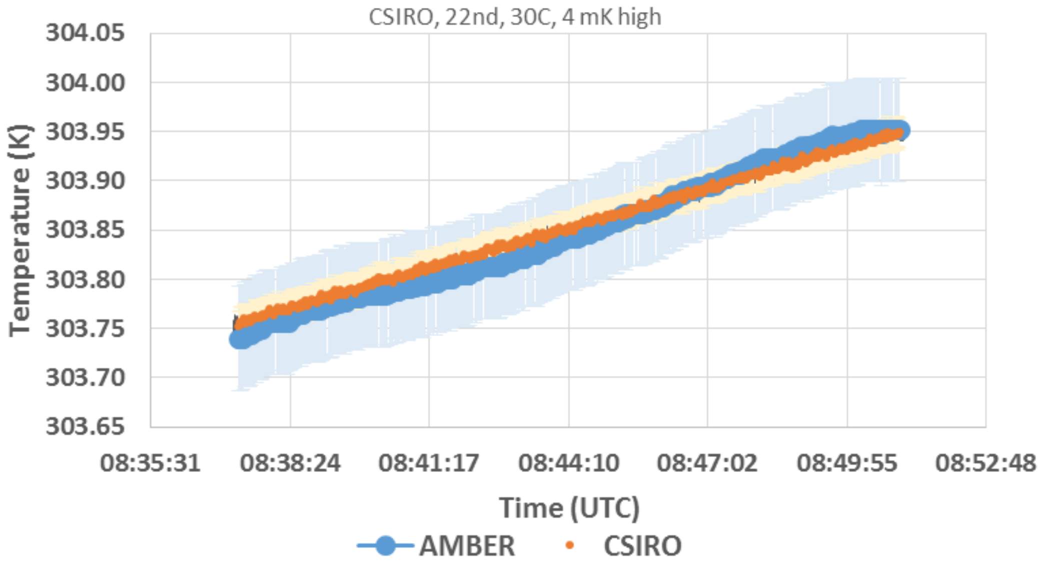

Figure 3.2.3.7: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 4 mK higher than the corresponding value measured by AMBER.

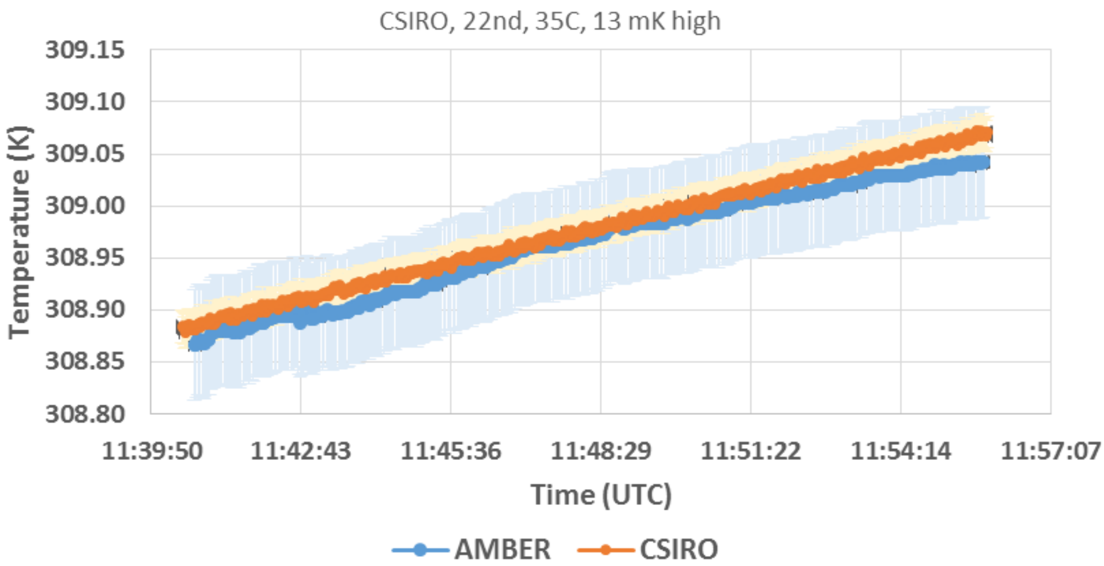

Figure 3.2.3.8: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 13mK higher than the corresponding value measured by AMBER.

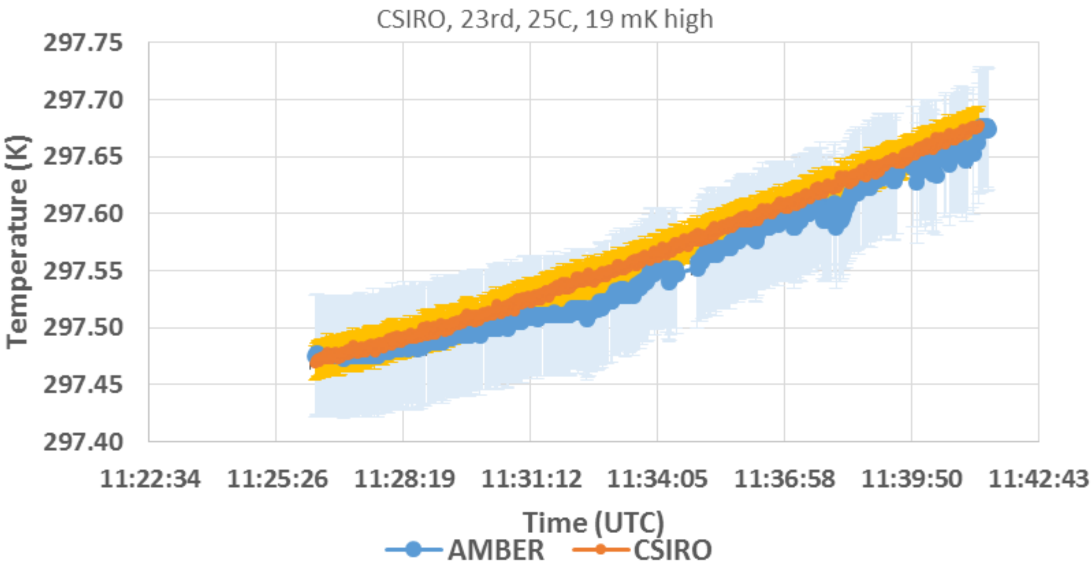

Figure 3.2.3.9: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 19mK higher than the corresponding value measured by AMBER.

3.2.4 CSIRO Blackbody Measured by the PTB Radiometer

Figures 3.2.4.1 to 3.2.4.10 show the measurements reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 8 °C to 35 °C temperature range. The blackbody measurements are shown in orange, while the PTB radiometer measurements are shown in blue. Also shown in these Figures is the uncertainty of the PTB radiometer during these measurements and is shown in black. The uncertainty of the CSIRO blackbody during these measurements was 15 mK and is shown in light orange.

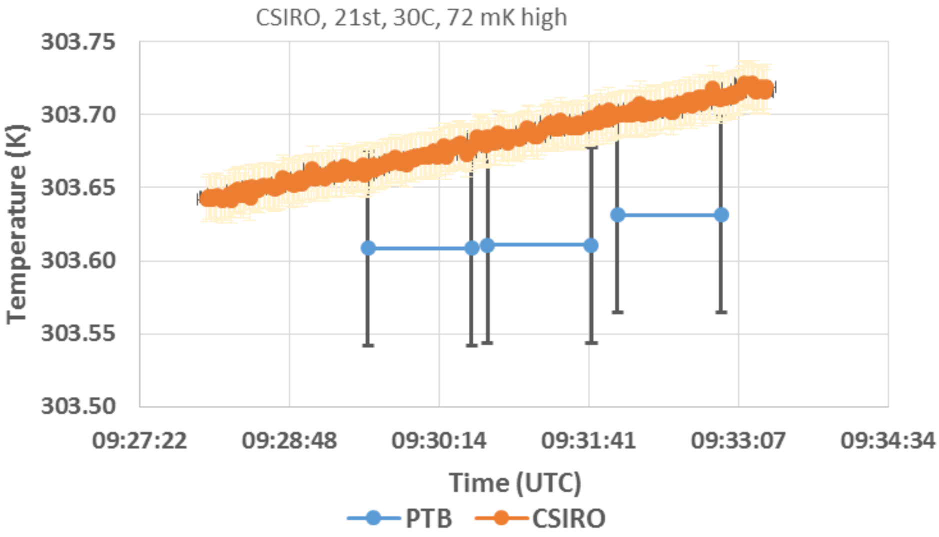

Figure 3.2.4.1: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 72 mK higher than the corresponding value measured by the PTB radiometer.

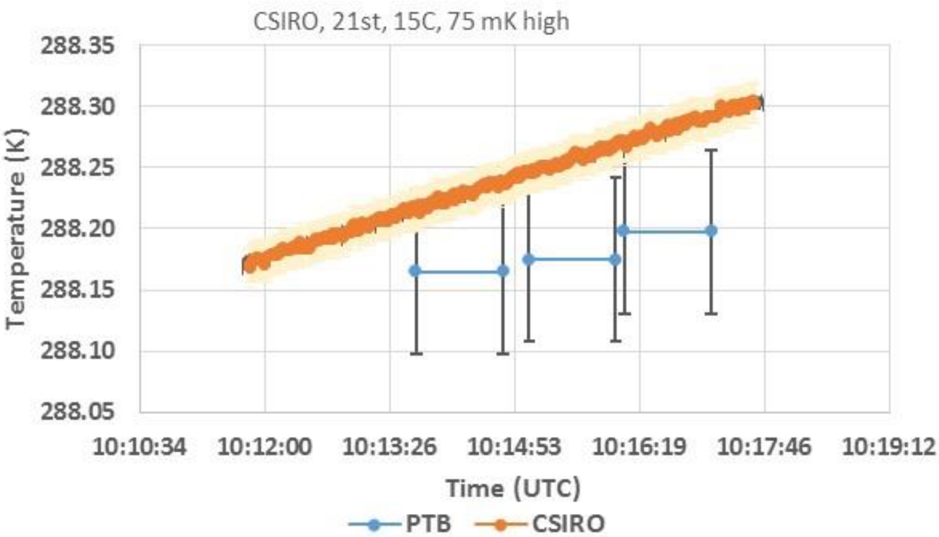

Figure 3.2.4.2: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 75 mK higher than the corresponding value measured by the PTB radiometer.

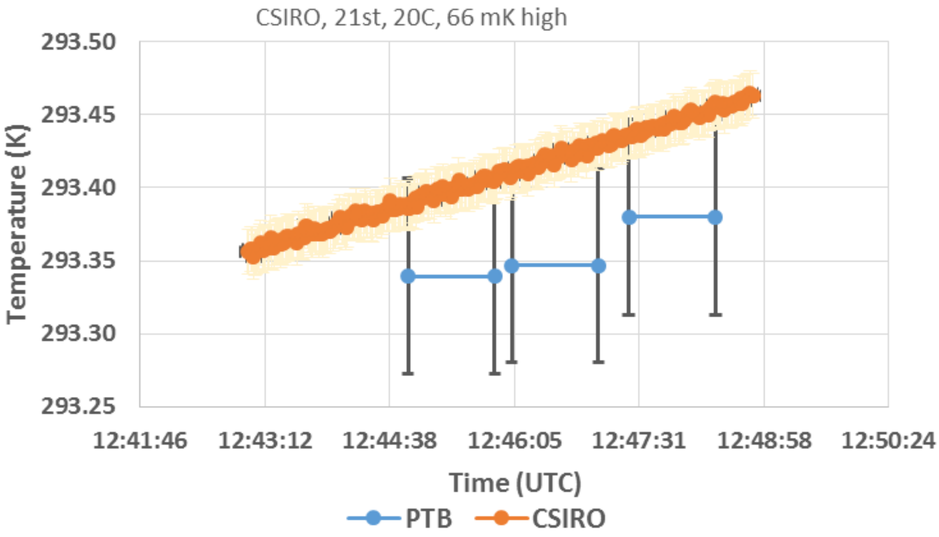

Figure 3.2.4.3: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 66 mK higher than the corresponding value measured by the PTB radiometer.

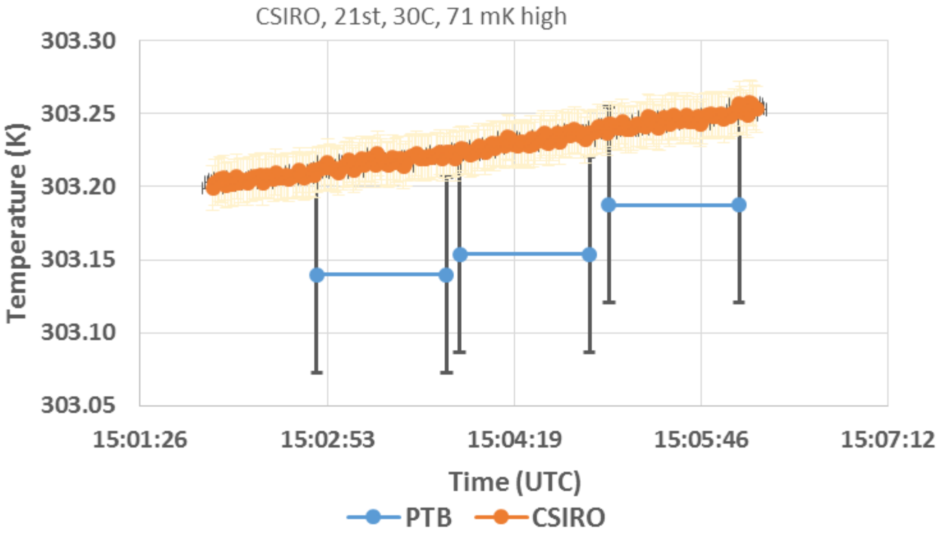

Figure 3.2.4.4: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 71 mK higher than the corresponding value measured by the PTB radiometer.

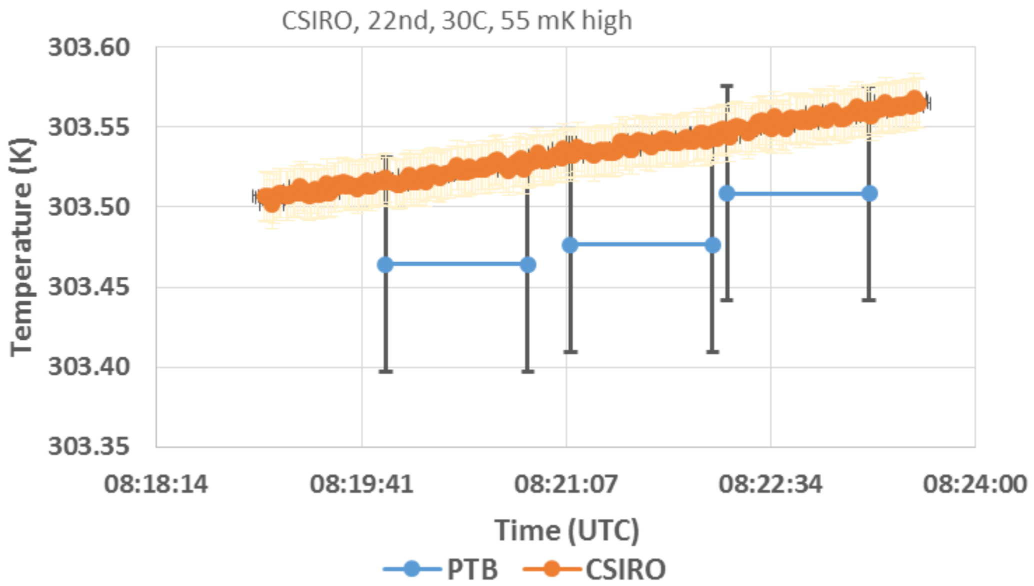

Figure 3.2.4.5: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 55 mK higher than the corresponding value measured by the PTB radiometer.

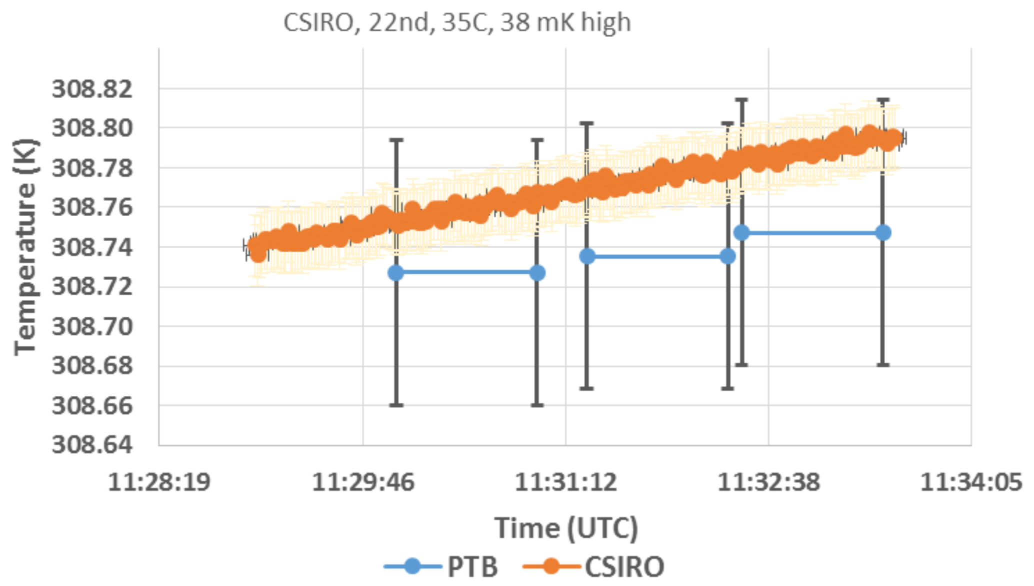

Figure 3.2.4.6: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 38 mK higher than the corresponding value measured by the PTB radiometer.

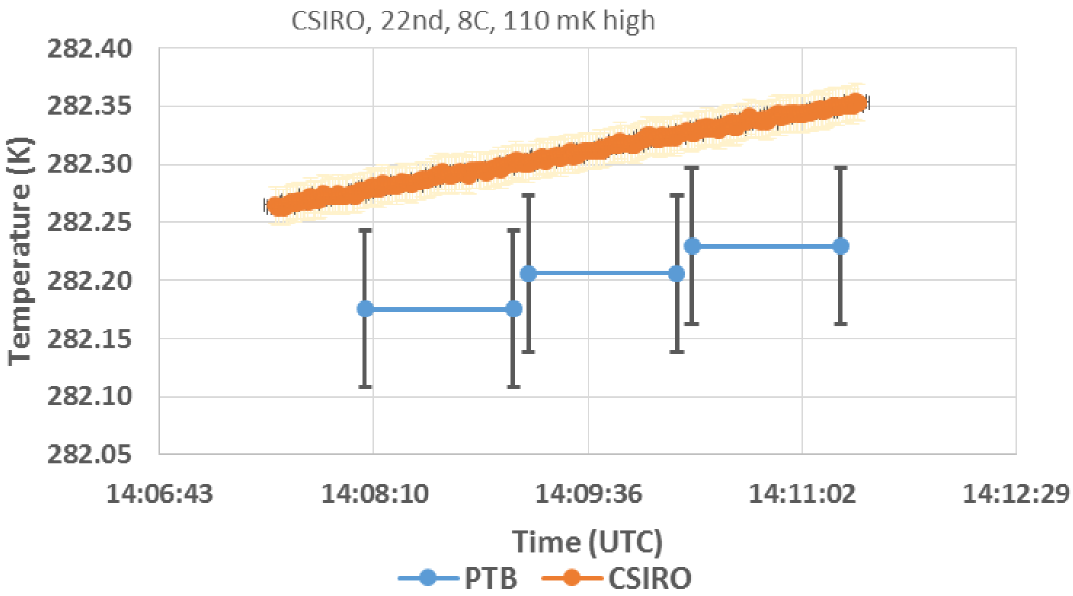

Figure 3.2.4.7: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 8 °C. The average measurement of the blackbody was 110 mK higher than the value measured by the PTB radiometer.

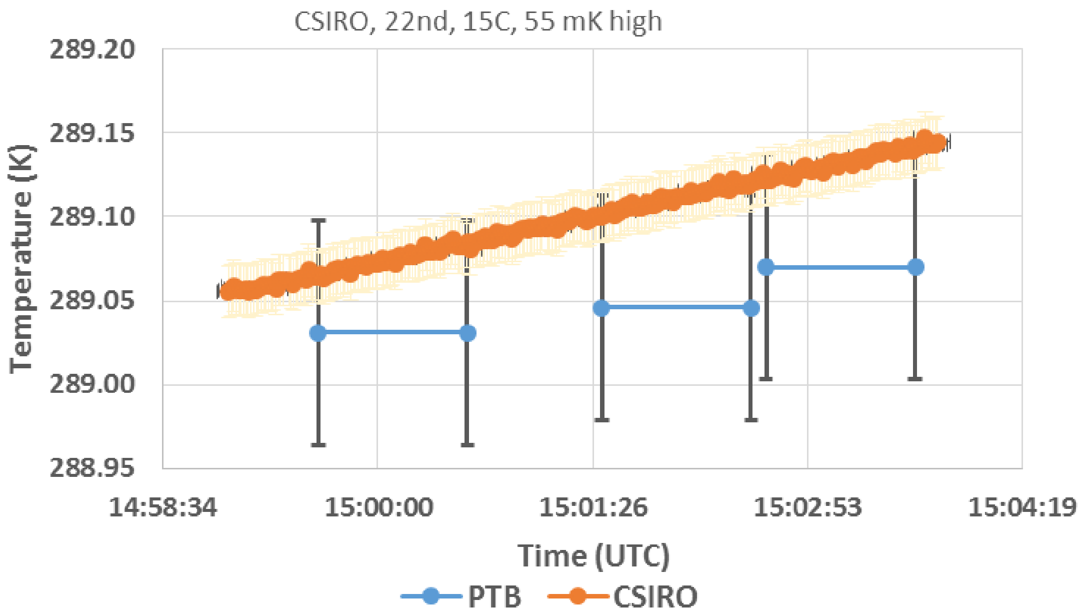

Figure 3.2.4.8: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 55 mK higher than the corresponding value measured by the PTB radiometer.

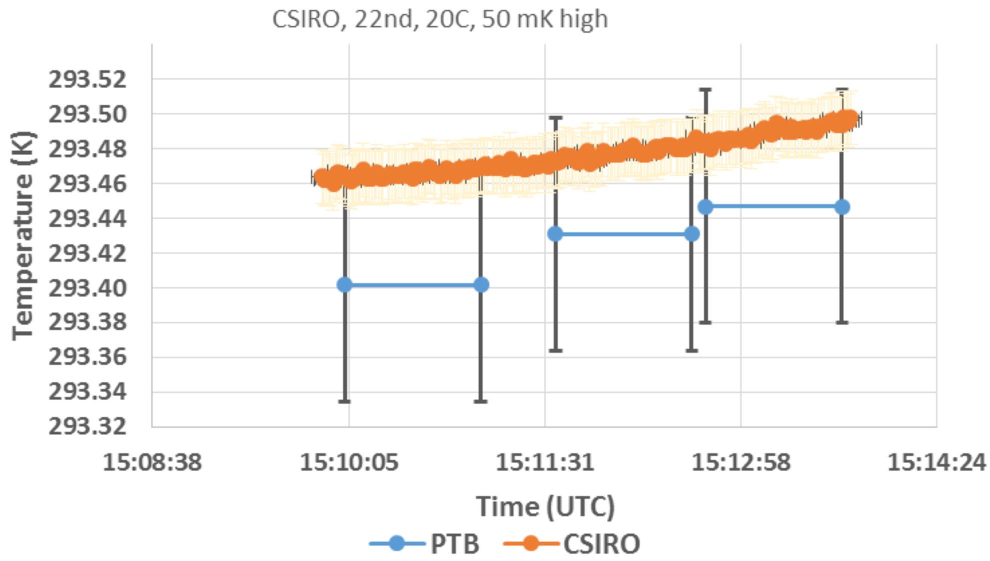

Figure 3.2.4.9: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 50 mK higher than the corresponding value measured by the PTB radiometer.

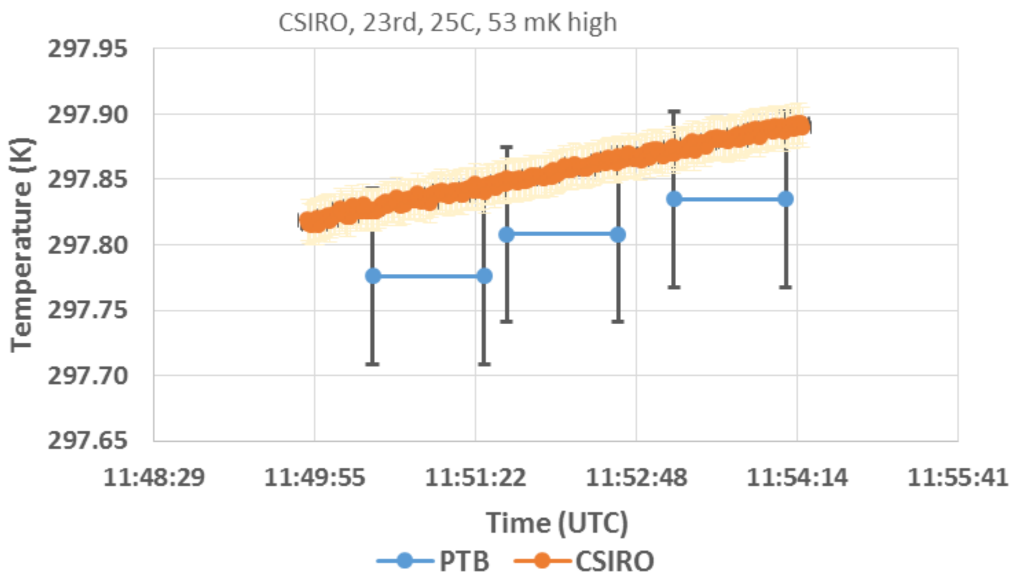

Figure 3.2.4.10: Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 53 mK higher than the corresponding value measured by the PTB radiometer.

3.3 KIT BLACKBODY

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3.3.1 Description of KIT's Blackbody

Make and type of the Blackbody: Land Instruments International, Landcal P80P

Outline Technical description of the blackbody:

The Landcal P80P (serial #321388-1) is a variable temperature, portable standard blackbody 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 blackbody an emissivity greater than 0.995. Resistance thermometers control the temperature of the Landcal P80P but are not suitable for calibration. An optional platinum resistance thermometer (traceable to national standards) can be inserted at the front of the blackbody: the junction of the thermometer then lies in the plane of the cone point, but is 40 mm below. The temperature of the source measured by a platinum resistance thermometer agrees with the cone point radiance temperature to within ±0.5K. More accurate temperature measurements of the source are achieved with calibrated radiation thermometers (calibration by comparison).

Reference: Landcal P80P Calibration Source User Guide, Issue E: April 2010, Publication No 198.031, Land Instruments International.

3.3.2 Establishment of traceability route for primary calibration

It was planned to use the laboratory measurements as an opportunity to calibrate the Landcal P80P blackbody with an additional platinum resistance thermometer. Unfortunately, on the first day of the laboratory comparison at NPL, the data logger used for the experiments was electrically destroyed. The blackbody has not yet been calibrated.

Operational methodology during measurement campaign
The radiometers were mounted on a tripod, placed directly in front of the blackbody aperture and aligned manually. The Landcal P80P's radiance temperature was determined with a calibrated KT15.85 IIP radiometer which had to be read directly from its display (resolution 0.1K). These temperatures are compared to those determined with transfer radiation thermometers from NPL and PTB. Since the two radiometers could not observe the blackbody aperture simultaneously so the radiometers had to measure sequentially. This increased the uncertainty due to temperature fluctuations. Each blackbody temperature was measured 10 times at 10-15 sec intervals and uncertainties were estimated based on the radiometer's (Heitronics KT15.85 IIP) specifications.

Blackbody usage (deployment), previous use of instrument and planned applications.
Previously the P80P blackbody has been used in the laboratory for inter-calibrating radiometers. It is planned to perform a primary calibration of the blackbody using the platinum resistance thermometer.

3.3.3 KIT Blackbody Measured by NPL AMBER

Unfortunately, KIT's data logger broke at the very beginning of the laboratory blackbody comparison. This meant that KIT could not measure the temperature of their blackbody with the internal PT100 contact probe, as planned. Instead, as an emergency solution, KIT measured the blackbody temperature with one of their KT15 radiometers just after the measurements with AMBER and the PTB transfer radiometers. This was necessary because two radiometers could not observe the blackbody cavity (and therefore measure its temperature) of KIT's blackbody simultaneously.

Figures 3.3.3.1 to 3.3.3.3 show the measurements reported by the KIT blackbody as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 20 °C to 33 °C temperature range. The KIT measurements are shown in orange, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK) and is shown in light blue. The uncertainty of the KIT blackbody during these measurements was 270 mK for the measurements at 20 °C and 25 °C and 298 mK for measurements at 33 °C. The uncertainties of the KIT blackbody are shown as error bars in orange.

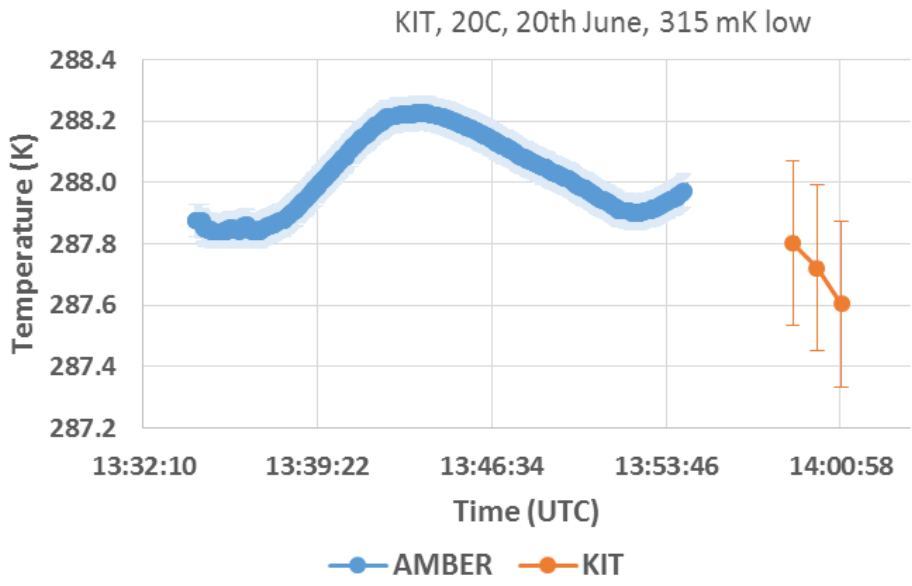


Figure 3.3.3.1: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 315 mK lower than the corresponding value measured by the AMBER radiometer.

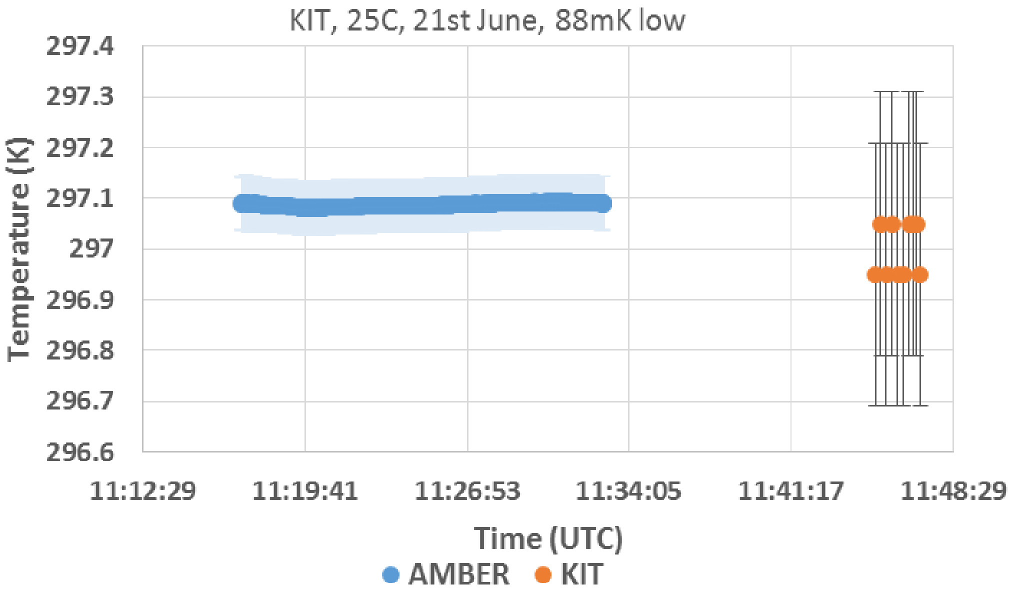


Figure 3.3.3.2: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 88 mK lower than the corresponding value measured by the AMBER radiometer.

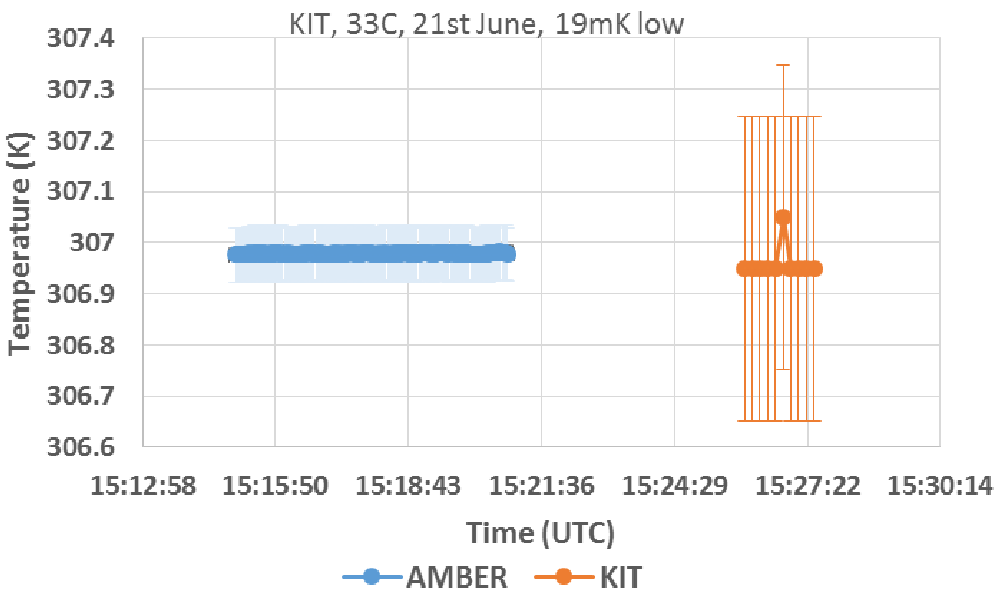
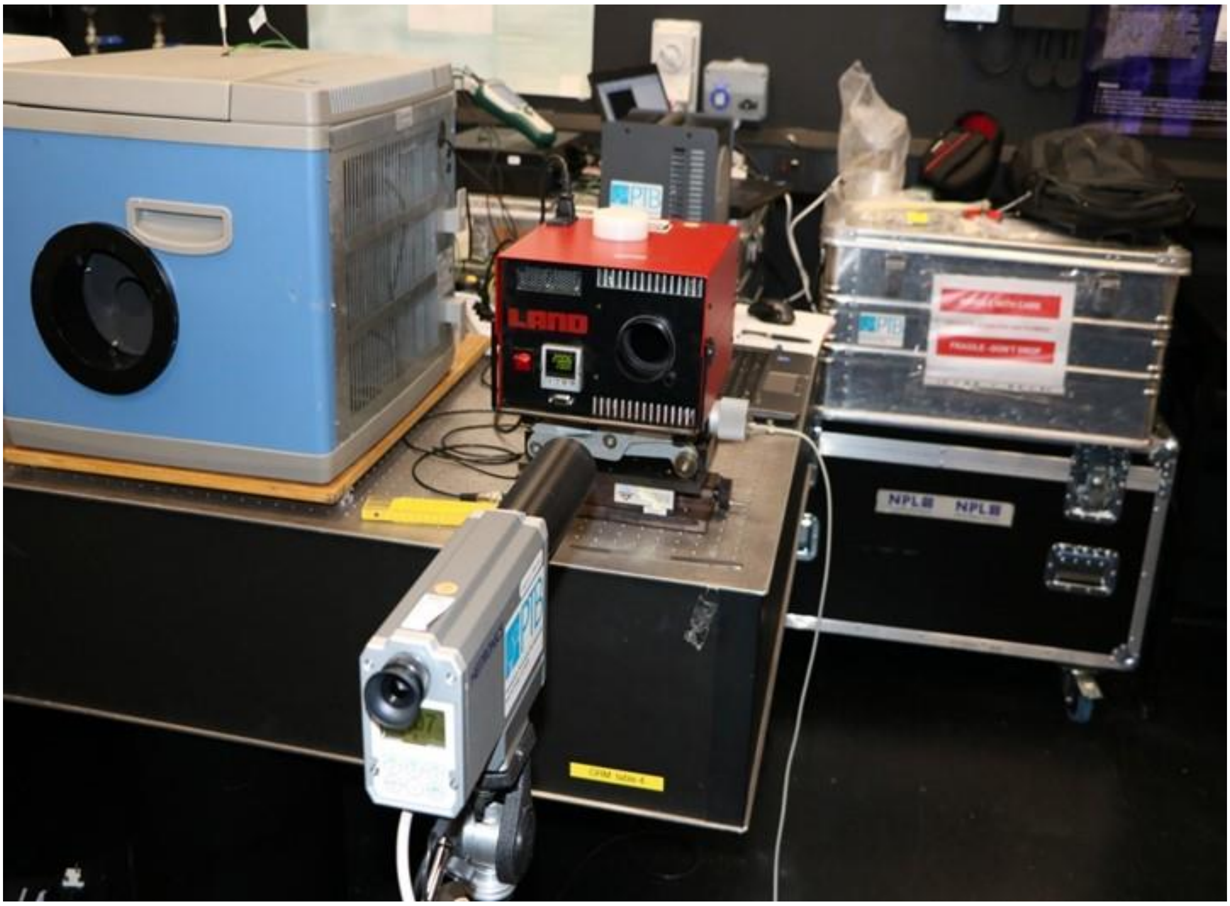


Figure 3.3.3.3: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 33 °C. The average measurement of the blackbody was 19 mK lower than the value measured by the AMBER radiometer.

3.3.4 KIT Blackbody Measured by the PTB Radiometer

The photo below shows the KIT blackbody being measured by the PTB radiometer.



The KIT blackbody being measured by the PTB radiometer

Figures 3.4.4.1 to 3.4.4.10 show the measurements reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 5 °C to 65 °C temperature range. The blackbody measurements reported by KIT are shown in orange/red, while the PTB radiometer measurements are shown in blue. Also shown as black error bars in these Figures is the uncertainty of the KIT blackbody (as reported by KIT), as well as the uncertainty of the PTB radiometer during these measurements.

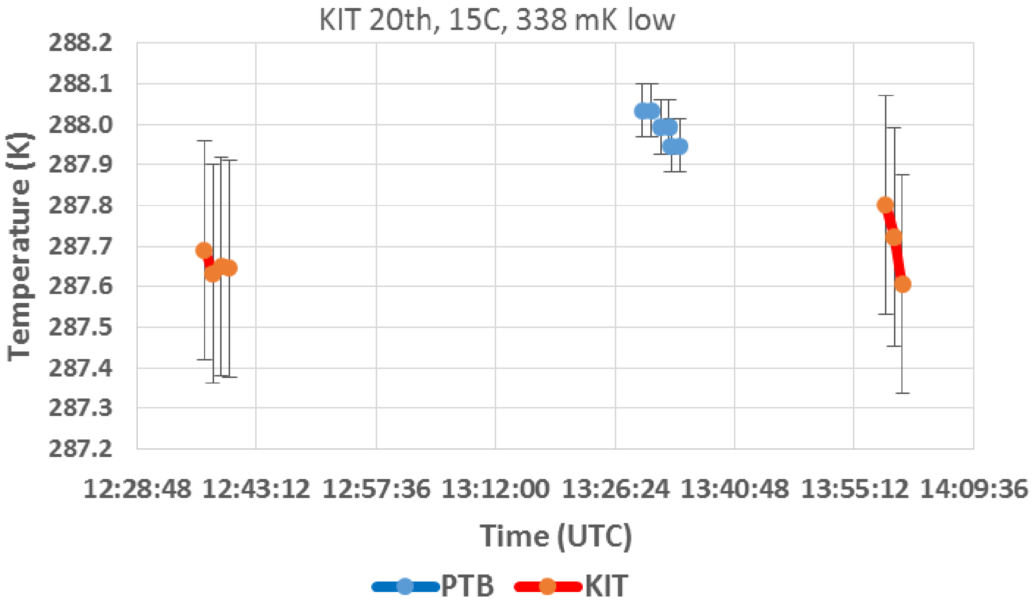


Figure 3.3.4.1: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 338 mK lower than the corresponding value measured by the PTB radiometer.

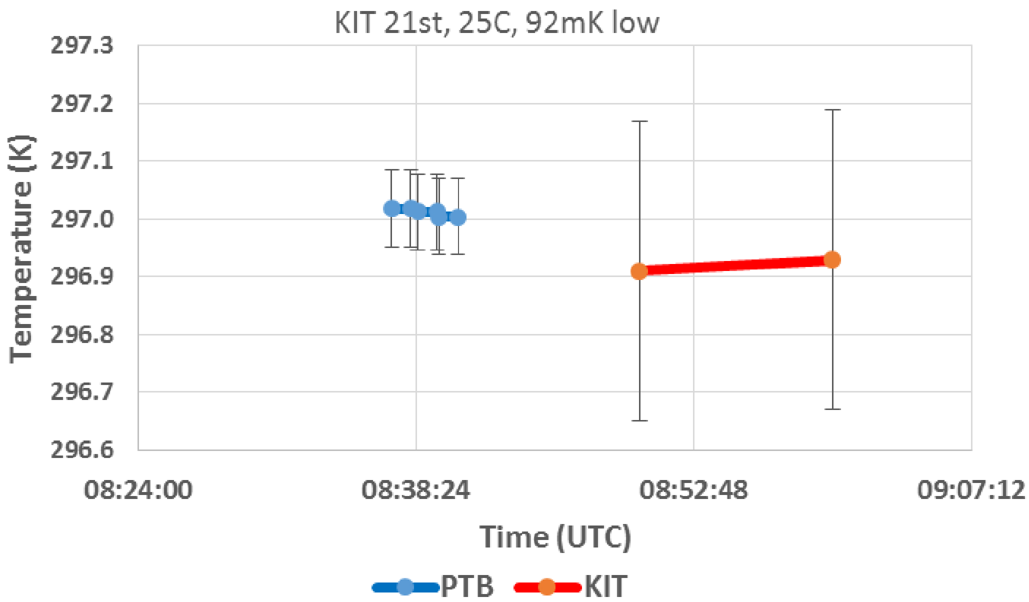


Figure 3.3.4.2: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 92 mK lower than the corresponding value measured by the PTB radiometer.

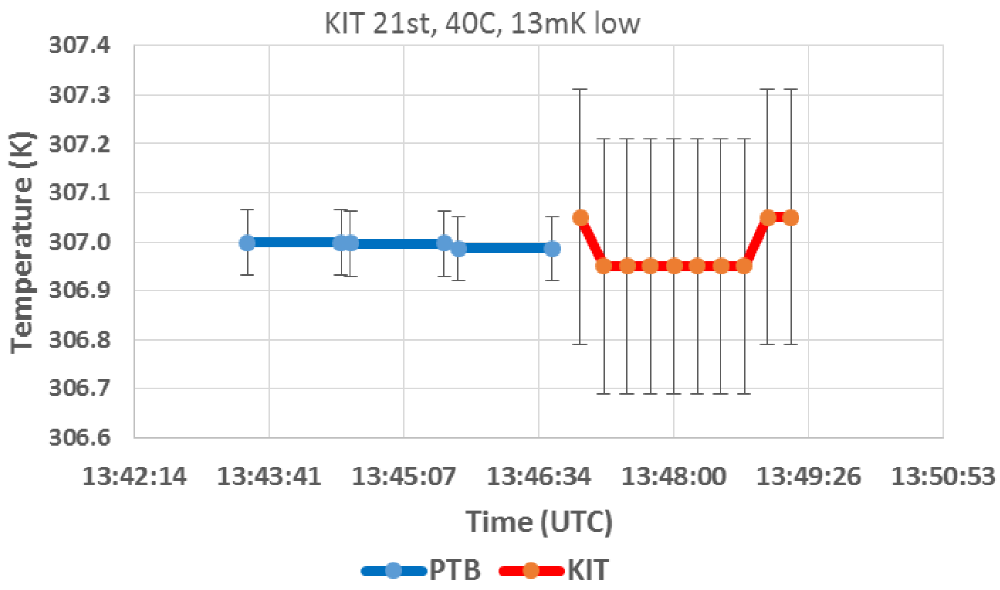


Figure 3.3.4.3: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 13 mK lower than the corresponding value measured by the PTB radiometer.

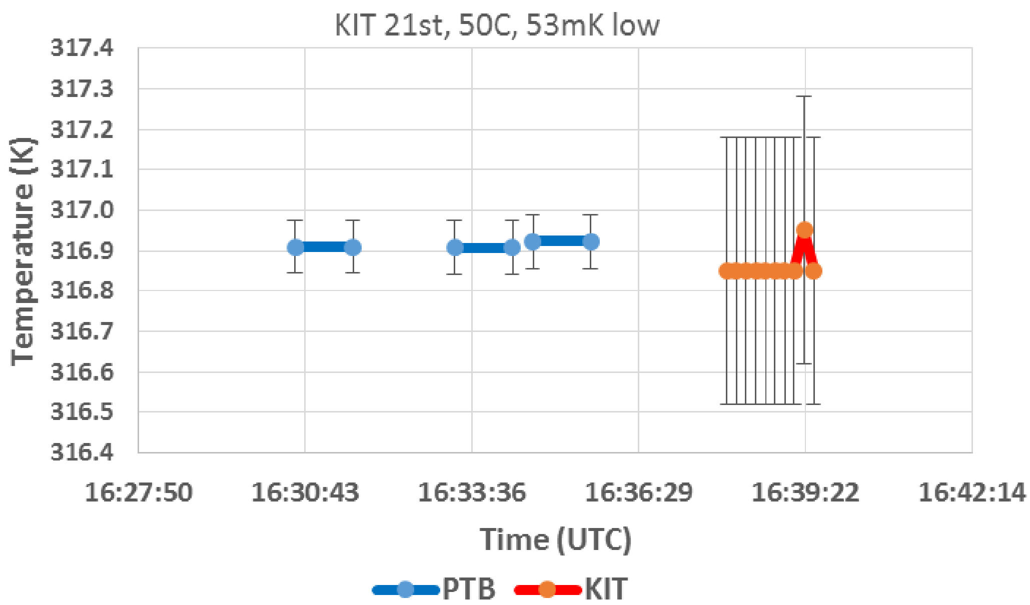


Figure 3.3.4.4: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 50 °C. The average measurement of the blackbody was 53 mK lower than the corresponding value measured by the PTB radiometer.

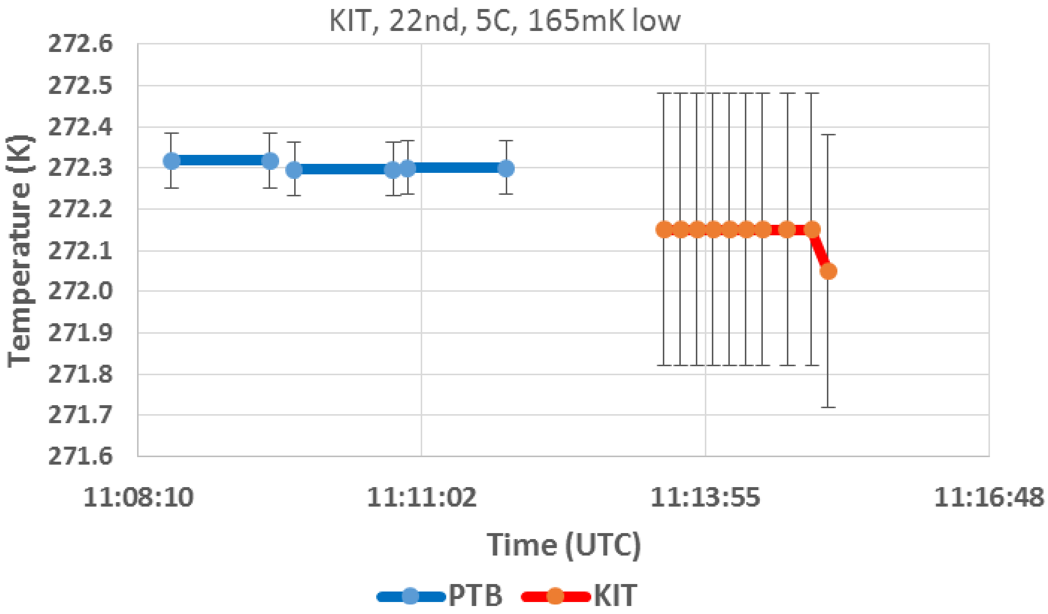


Figure 3.3.4.5: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 5 °C. The average measurement of the blackbody was 165 mK lower than the corresponding value measured by the PTB radiometer.

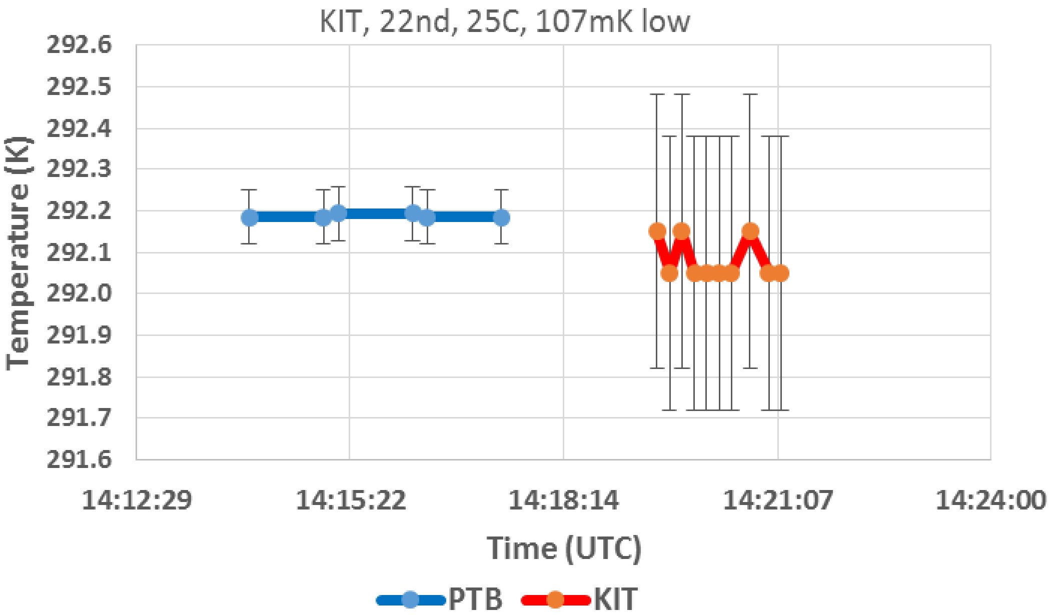


Figure 3.3.4.6: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 107 mK lower than the corresponding value measured by the PTB radiometer.

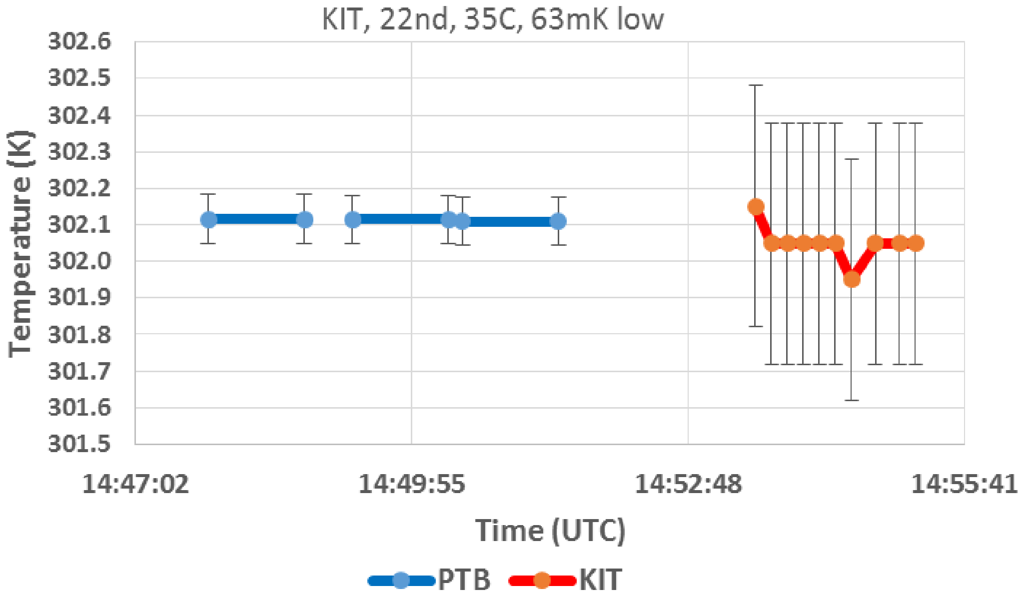


Figure 3.3.4.7: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 63 mK lower than the corresponding value measured by the PTB radiometer.

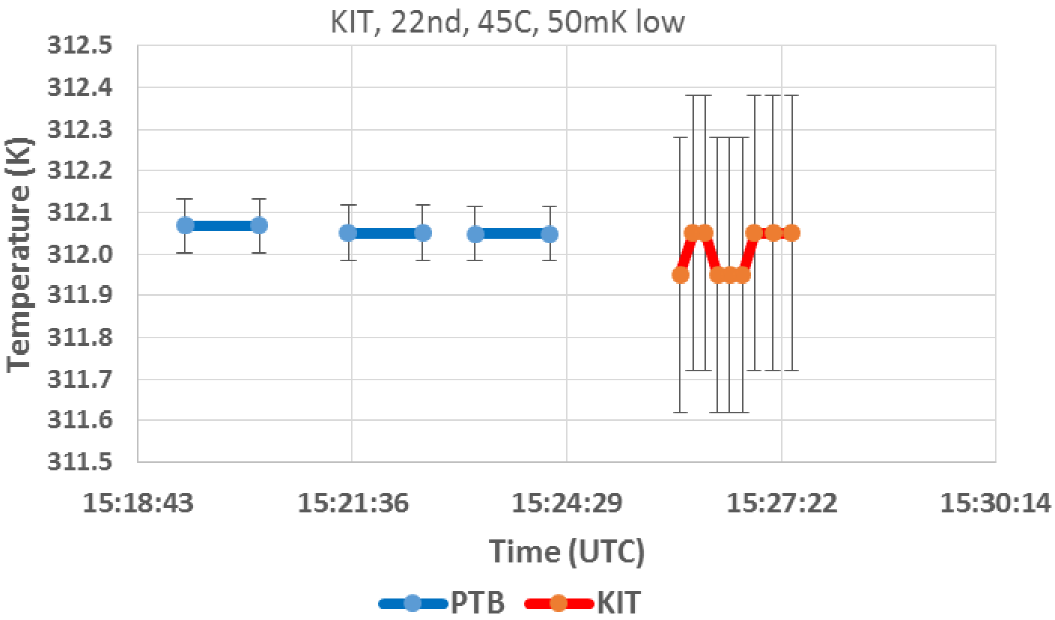


Figure 3.3.4.8: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 50 mK lower than the corresponding value measured by the PTB radiometer.

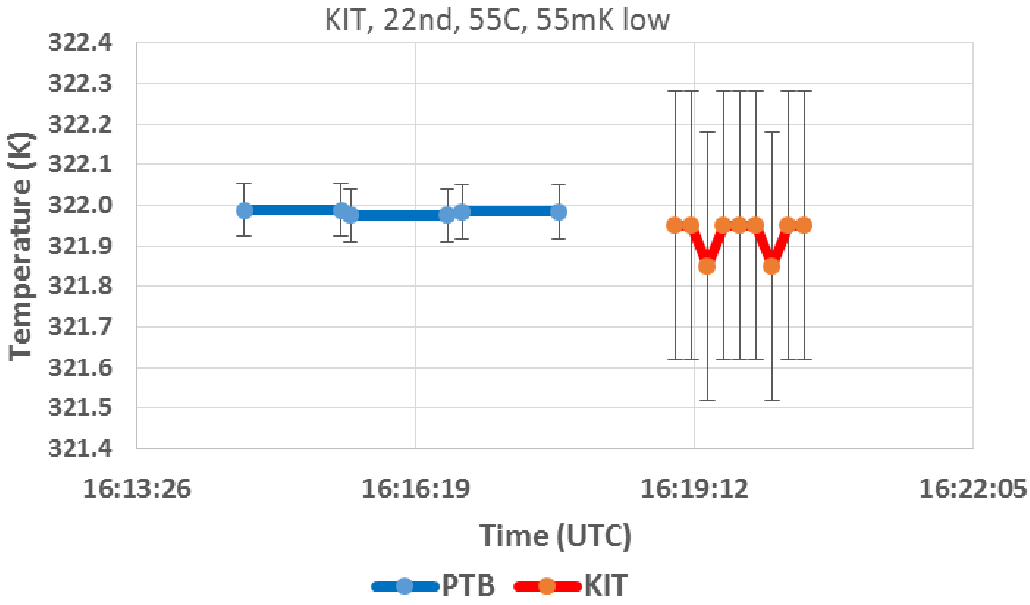


Figure 3.3.4.9: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 55 °C. The average measurement of the blackbody was 55 mK lower than the corresponding value measured by the PTB radiometer.

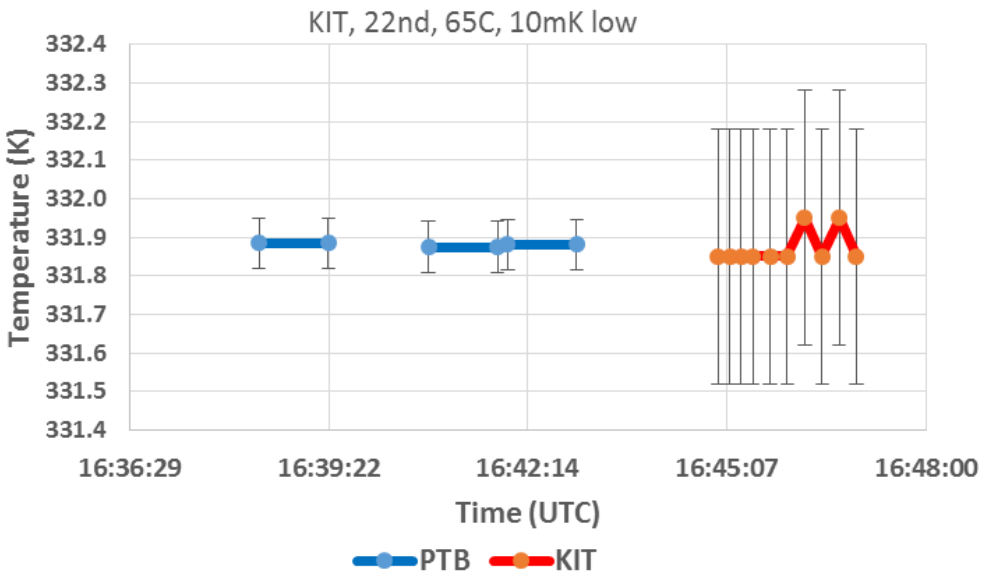


Figure 3.3.4.10: Measurements (as a function of time) reported by the KIT blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 65 °C. The average measurement of the blackbody was 10 mK lower than the corresponding value measured by the PTB radiometer.

3.4 ONERA BLACKBODY

ONERA
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3.4.1 Type of blackbody

The ONERA blackbody was a MIKRON M345 blackbody. This blackbody was a surface emitting blackbody and had an active area of 100 mm by 100 mm and can cover the temperatures in the -10 °C and 150 °C range. The blackbody surface is coated with an Infrablack4 coating. The spectral emissivity of the coating was measured both by NIST and by ONERA on two different samples from which the Mikron blackbody emissivity of 0.975 was estimated. The uncertainty in the nominal emissivity of the Mikron blackbody was ±0.01.

3.4.2 Uncertainty of the ONERA Blackbody

The blackbody temperature is monitored by a platinum RTD probe. The uncertainty is considered to be the sum of an offset of ±0.1K representing the accuracy and a short term repeatability error of 0.04K. This repeatability error was neglected in the measurements of the blackbody by AMBER and the PTB radiometer, because the radiometric measurement is averaged over a long enough period. Table 3.4.1 shows the values of the temperature of the Mikron blackbody at different temperature settings, when it was viewed by the AMBER radiometer. Also given in the same Table is the corresponding combined uncertainty values of the temperatures reported by ONERA.

Table 3.4.1: The values of the temperature of the Mikron blackbody at different temperature settings, when it was viewed by the AMBER radiometer. Also shown are the corresponding combined uncertainty values at the different temperatures.

Mikron set temperature (°C)	Estimated BB brightness temperature (°C)	Uncertainty (°C)
10	9.967	0.087
15	14.9	0.092
20	19.836	0.1
25	24.775	0.113
30	29.716	0.125
35	34.66	0.14
40	39.606	0.153
45	44.553	0.17
50	49.501	0.186
55	54.451	0.198
60	59.402	0.209
65	64.353	0.229
70	69.306	0.247

Table 3.4.2 shows the values of the temperature of the Mikron blackbody at different temperature settings, when it was viewed by the PTB radiometer. Also given in the same Table is the corresponding combined uncertainty values of the different temperatures.

Table 3.4.2: The values of the temperature of the Mikron blackbody at different temperature settings, when it was viewed by the PTB radiometer. Also given in the same Table is the corresponding combined uncertainty values at the different temperatures.

Mikron set temperature (°C)	Estimated BB brightness temperature (°C)	Uncertainty (°C)
10.000	10.231	0.120
11.000	11.212	0.116
12.000	12.193	0.113
13.000	13.174	0.109
14.000	14.155	0.106
15.000	15.137	0.103
20.000	20.048	0.093
25.000	24.964	0.091
30.000	29.882	0.098
35.000	34.805	0.109
40.000	39.730	0.125
45.000	44.657	0.141
50.000	49.587	0.162
55.000	54.519	0.178
60.000	59.453	0.198
65.000	64.388	0.218
70.000	69.325	0.236
75.000	74.263	0.256
80.000	79.214	0.279

3.4.3 ONERA Blackbody Measured by NPL AMBER

Figures 3.4.3.1 to 3.4.3.4 show the measurements reported by the ONERA blackbody as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 15 °C to 50 °C temperature range. The ONERA measurements were based on direct measurements of the blackbody temperature using contact thermometers. The blackbody measurements provided by ONERA are shown in red, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK) and is shown in light blue. The uncertainty of the ONERA blackbody is shown as black error bars at the beginning and end of each run.

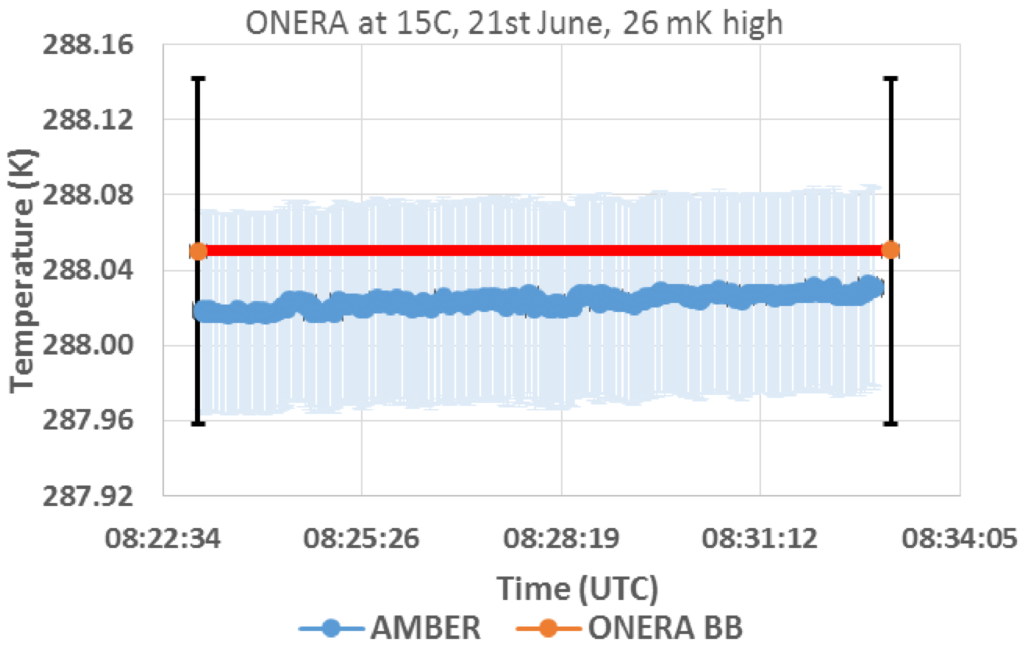

Figure 3.4.3.1: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 26 mK higher than the corresponding value measured by the AMBER radiometer.

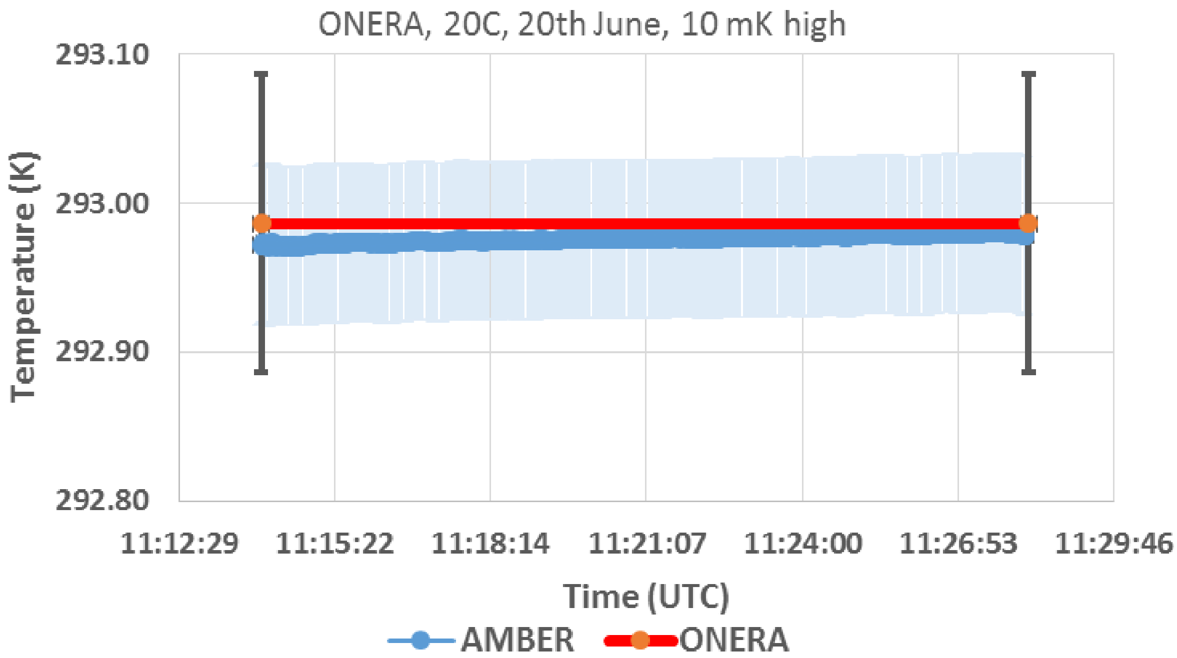

Figure 3.4.3.2: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 10 mK higher than the value measured by the AMBER radiometer.

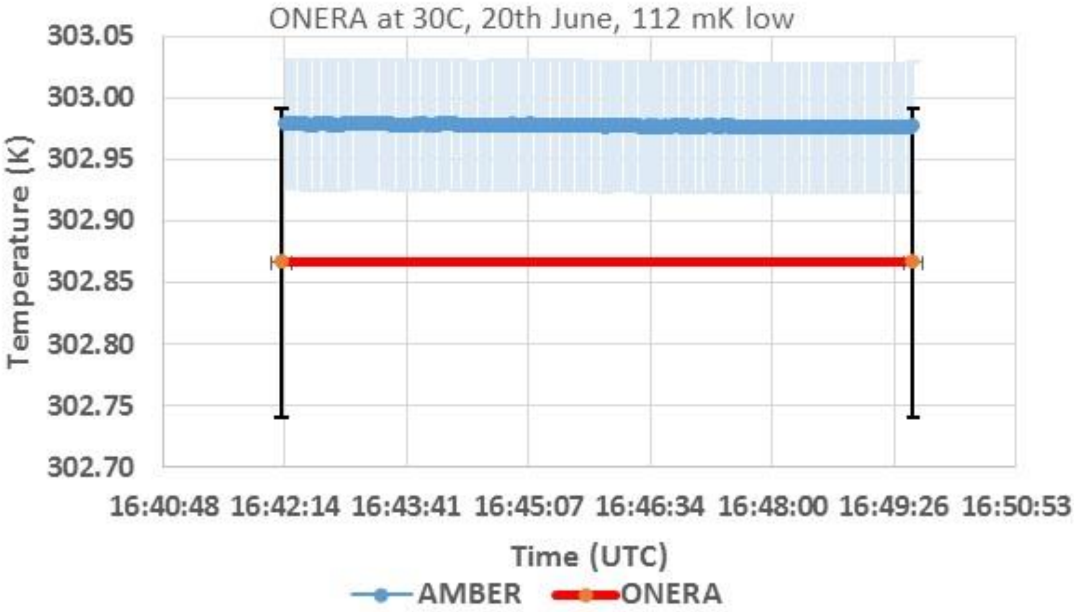

Figure 3.4.3.3: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 112 mK lower than the value measured by the AMBER radiometer.

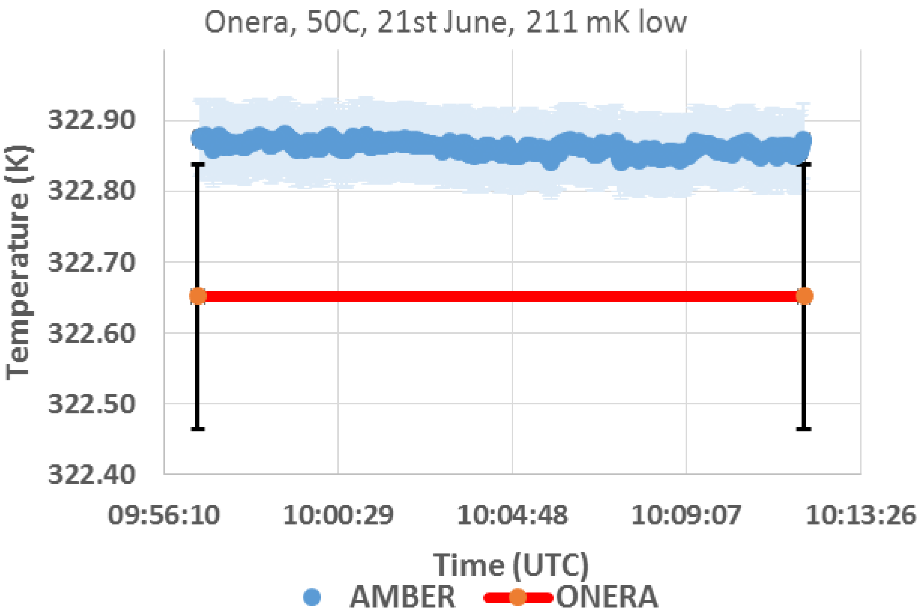

Figure 3.4.3.4: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 50 °C. The average measurement of the blackbody was 211 mK lower than the value measured by the AMBER radiometer.

3.4.4 ONERA Blackbody Measured by the PTB Radiometer

Figures 3.4.4.1 to 3.4.4.16 show the measurements reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 11 °C to 75 °C temperature range. The blackbody measurements reported by ONERA are shown in orange/red, while the PTB radiometer measurements are shown in blue. Also shown as error bars in these Figures is the uncertainty of the ONERA blackbody (as reported by ONERA), as well as the uncertainty of the PTB radiometer during these measurements.

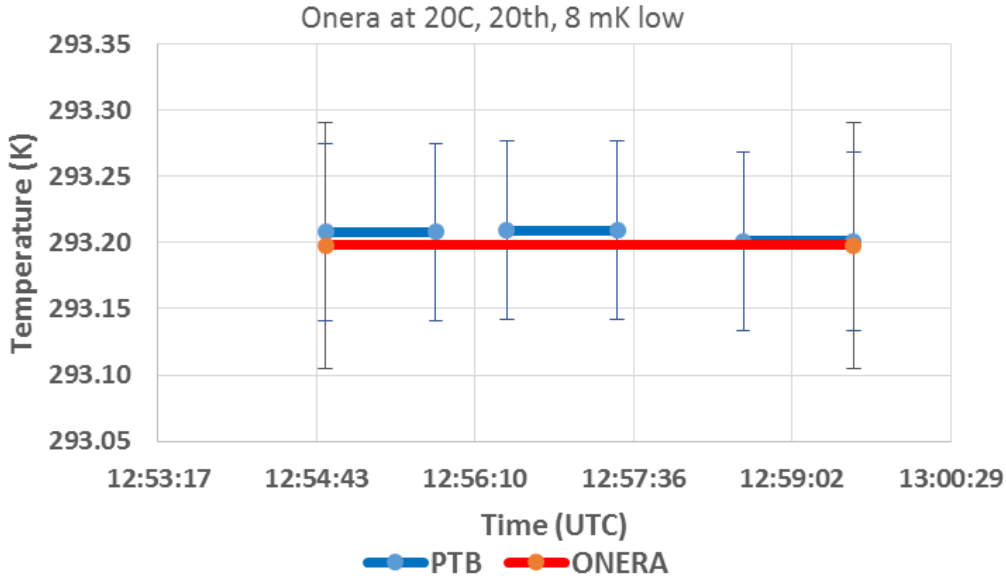

Figure 3.4.4.1: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 8 mK lower than the corresponding value measured by the PTB radiometer.

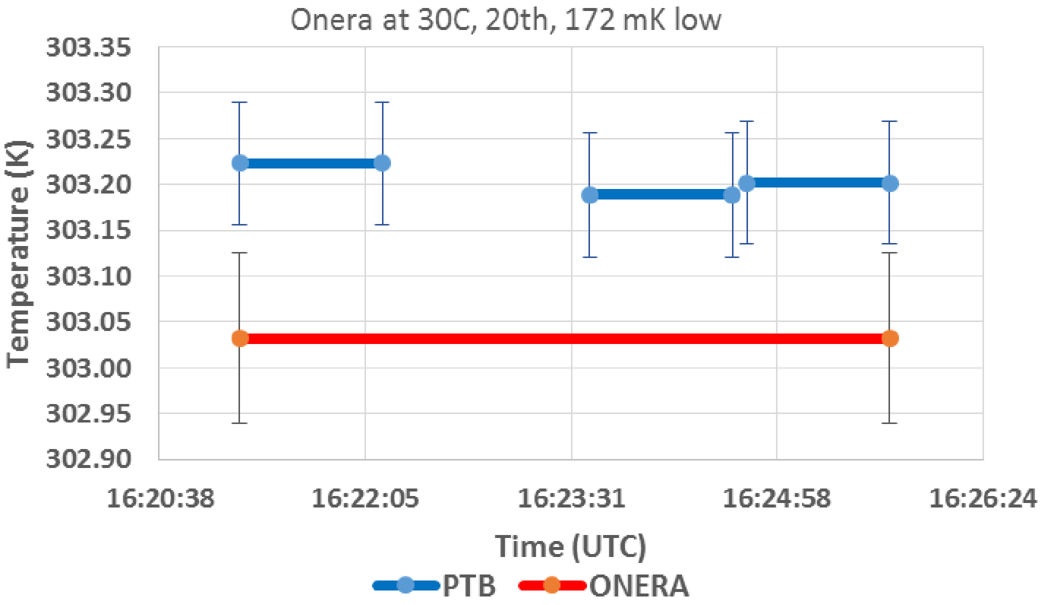

Figure 3.4.4.2: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 172 mK lower than the corresponding value measured by the PTB radiometer.

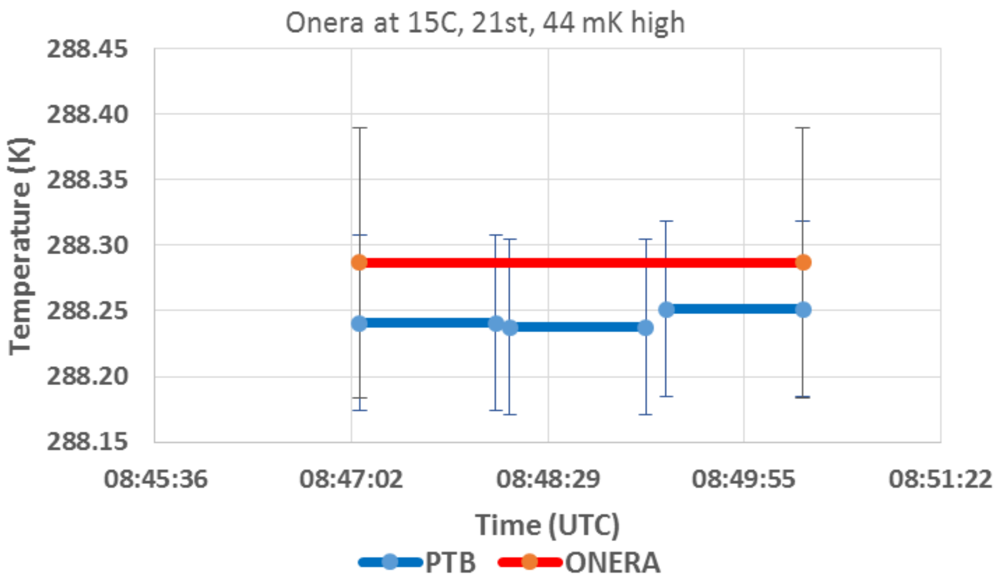

Figure 3.4.4.3: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 44 mK higher than the corresponding value measured by the PTB radiometer.

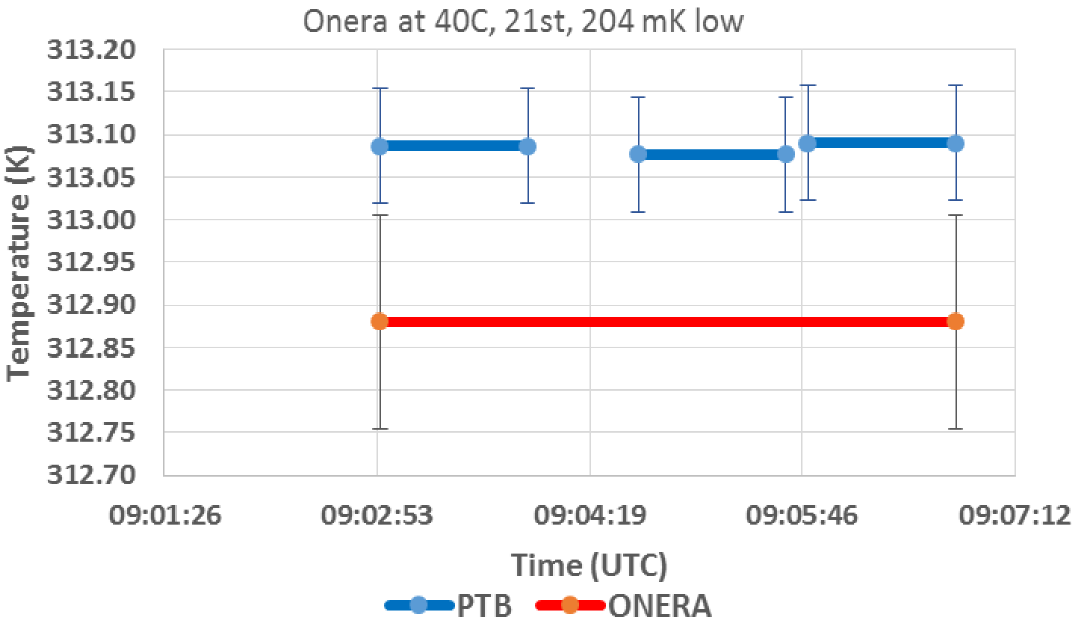

Figure 3.4.4.4: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 204 mK lower than the corresponding value measured by the PTB radiometer.

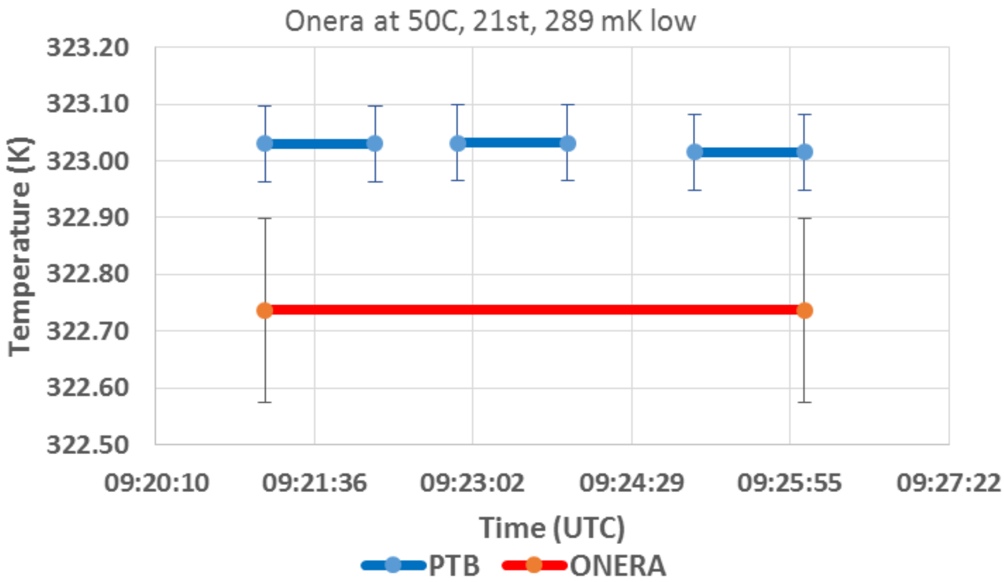

Figure 3.4.4.5: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 50 °C. The average measurement of the blackbody was 289 mK lower than the corresponding value measured by the PTB radiometer.

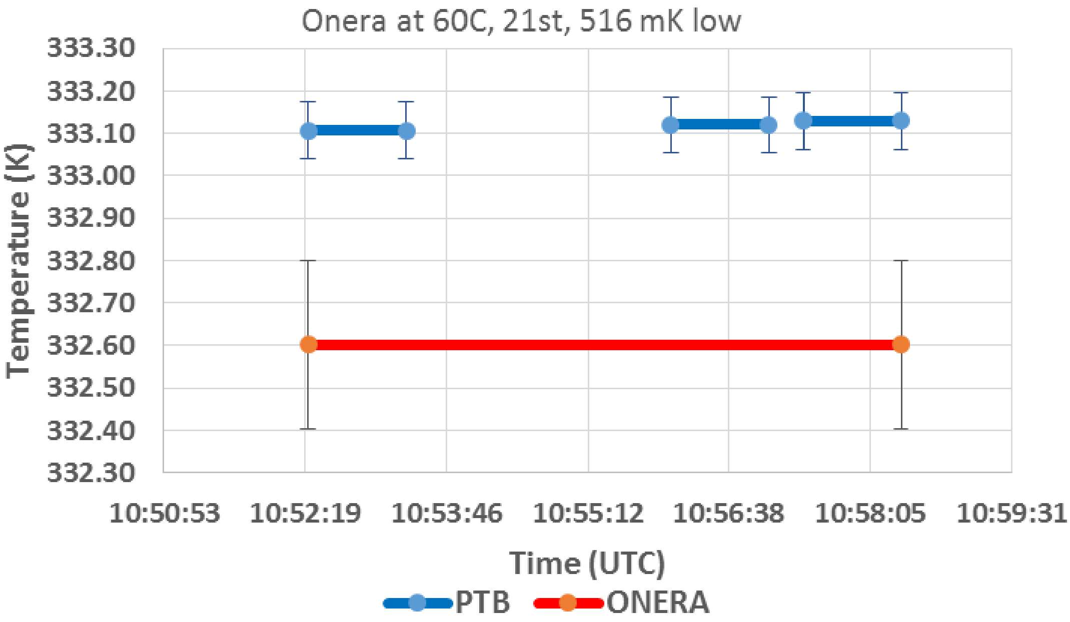

Figure 3.4.4.6: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 60 °C. The average measurement of the blackbody was 516 mK lower than the corresponding value measured by the PTB radiometer.

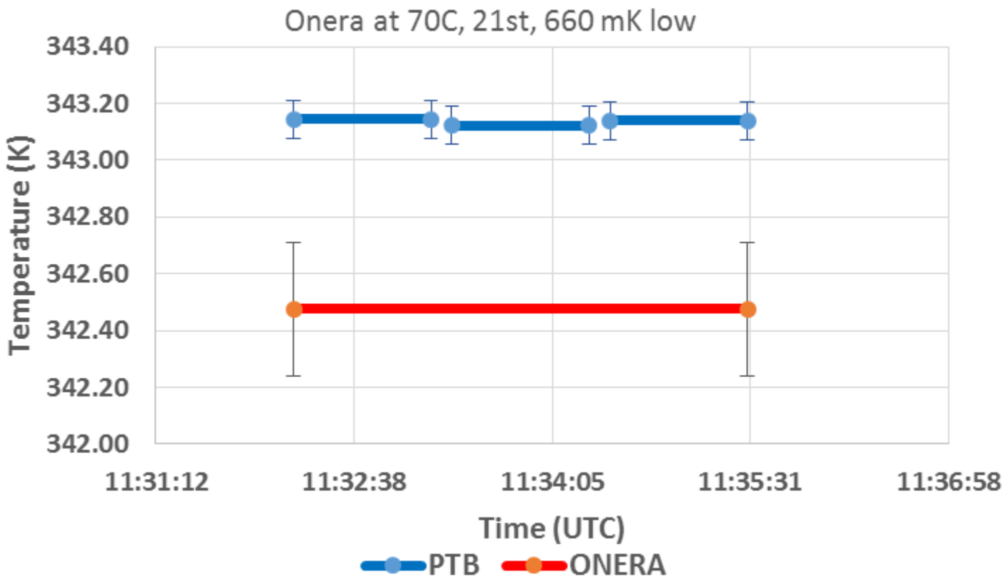

Figure 3.4.4.7: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 70 °C. The average measurement of the blackbody was 660 mK lower than the corresponding value measured by the PTB radiometer.

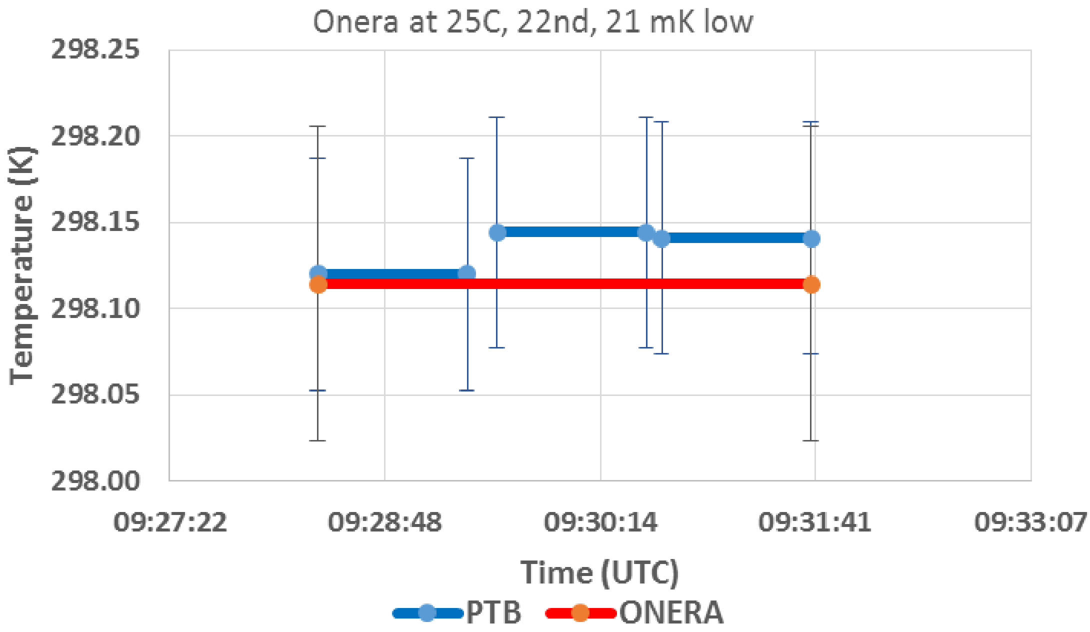

Figure 3.4.4.8: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 21 mK lower than the corresponding value measured by the PTB radiometer.

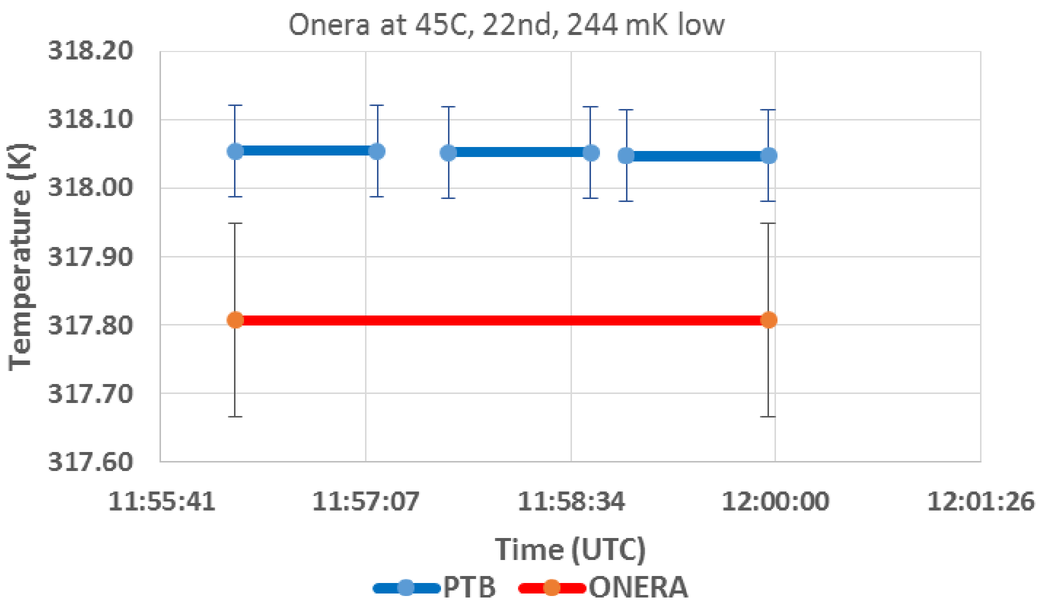

Figure 3.4.4.9: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 244 mK lower than the corresponding value measured by the PTB radiometer.

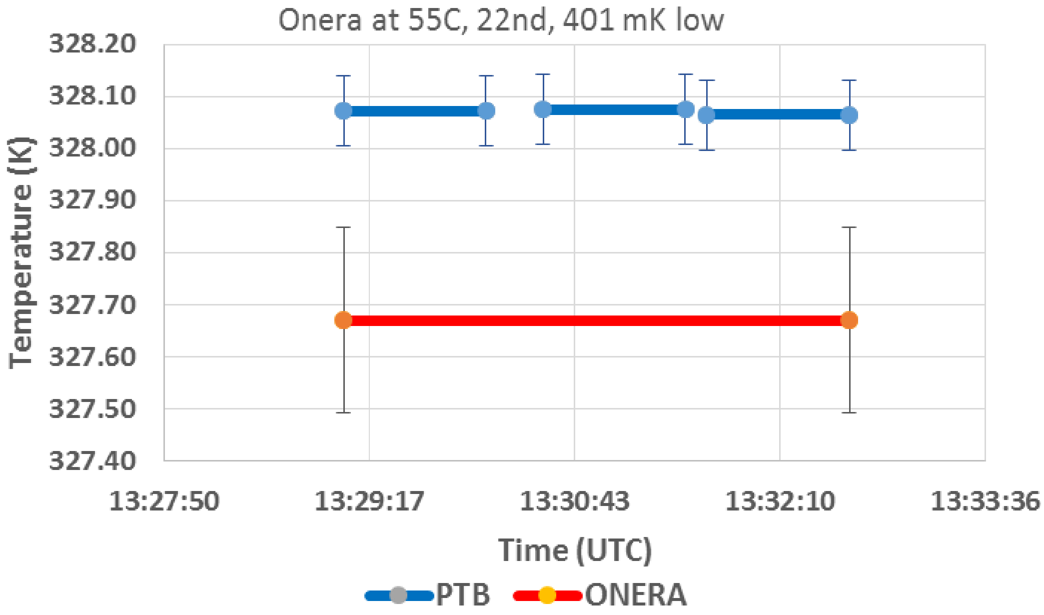

Figure 3.4.4.10: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 55 °C. The average measurement of the blackbody was 401 mK lower than the corresponding value measured by the PTB radiometer.

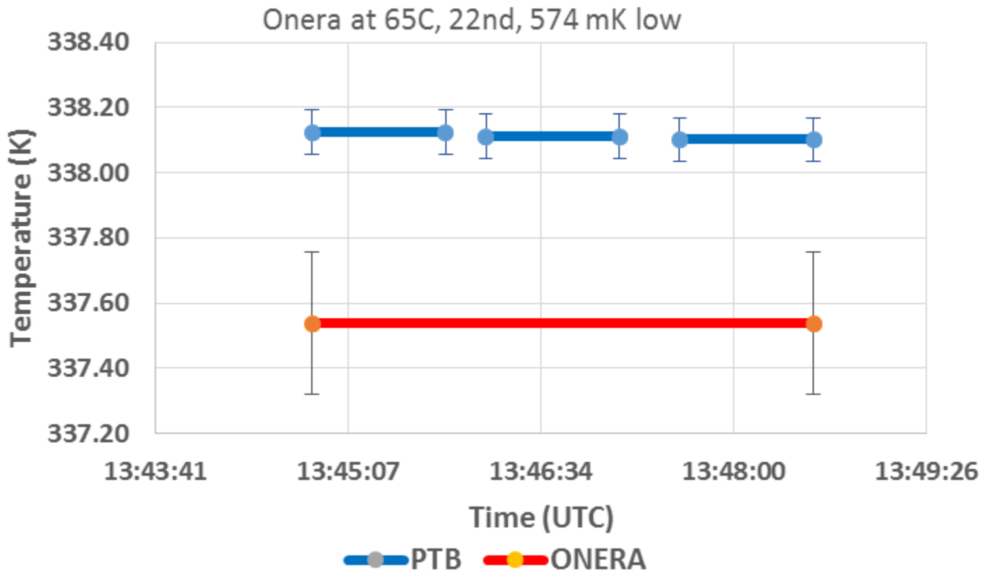

Figure 3.4.4.11: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 65 °C. The average measurement of the blackbody was 574 mK lower than the corresponding value measured by the PTB radiometer.

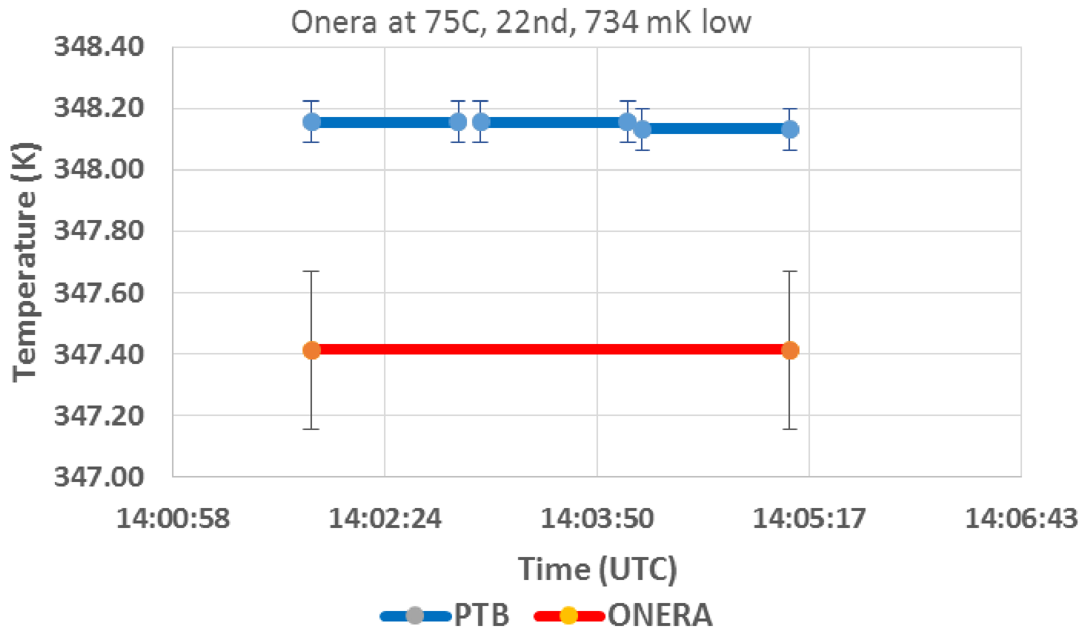

Figure 3.4.4.12: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 75 °C. The average measurement of the blackbody was 734 mK lower than the corresponding value measured by the PTB radiometer.

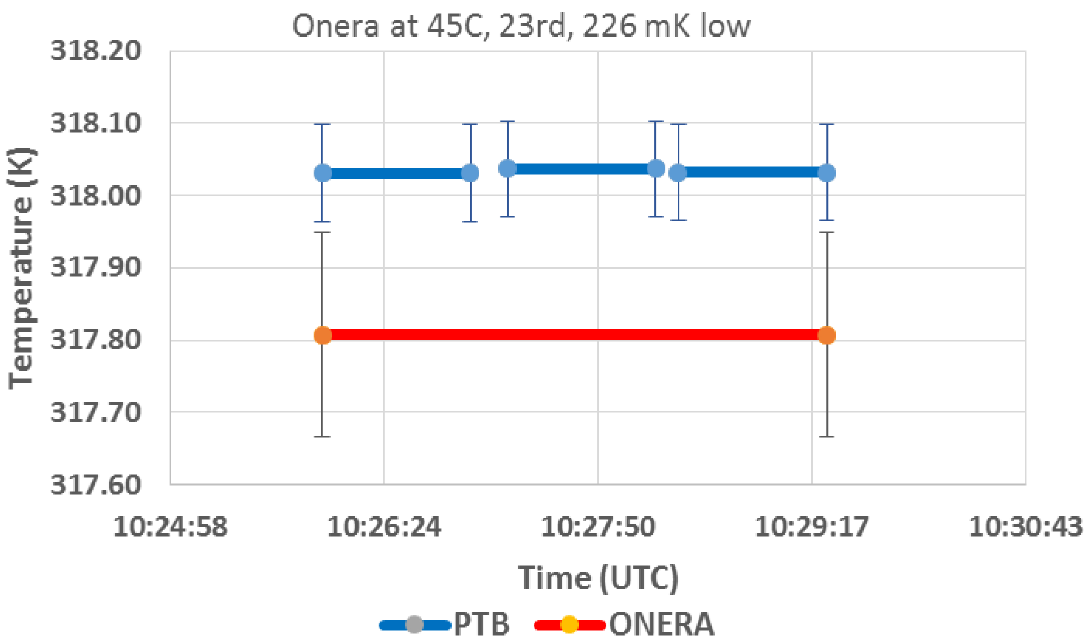

Figure 3.4.4.13: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 226 mK lower than the corresponding value measured by the PTB radiometer.

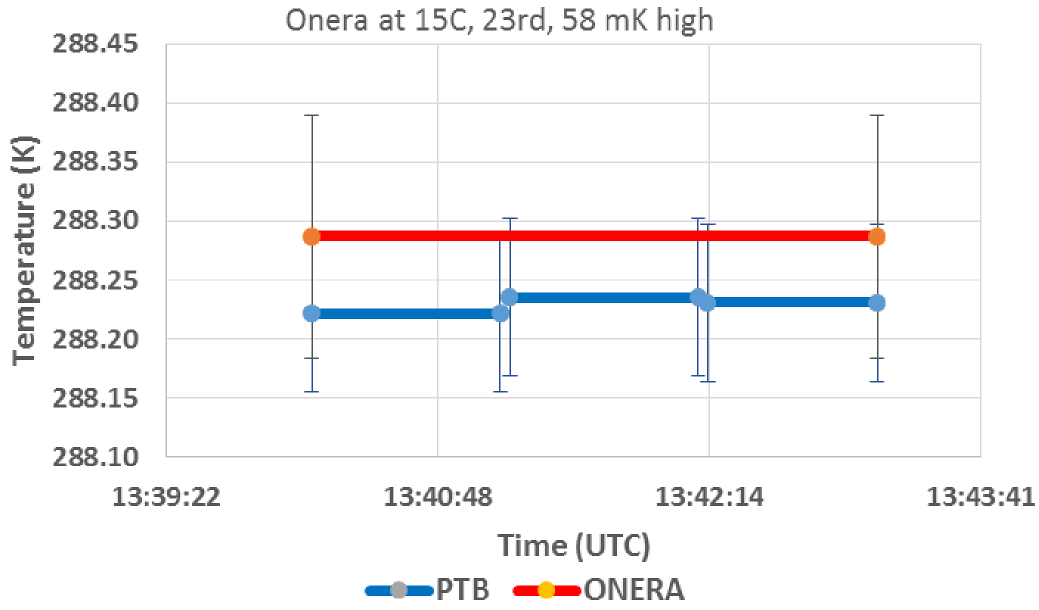

Figure 3.4.4.14: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 58 mK higher than the corresponding value measured by the PTB radiometer.

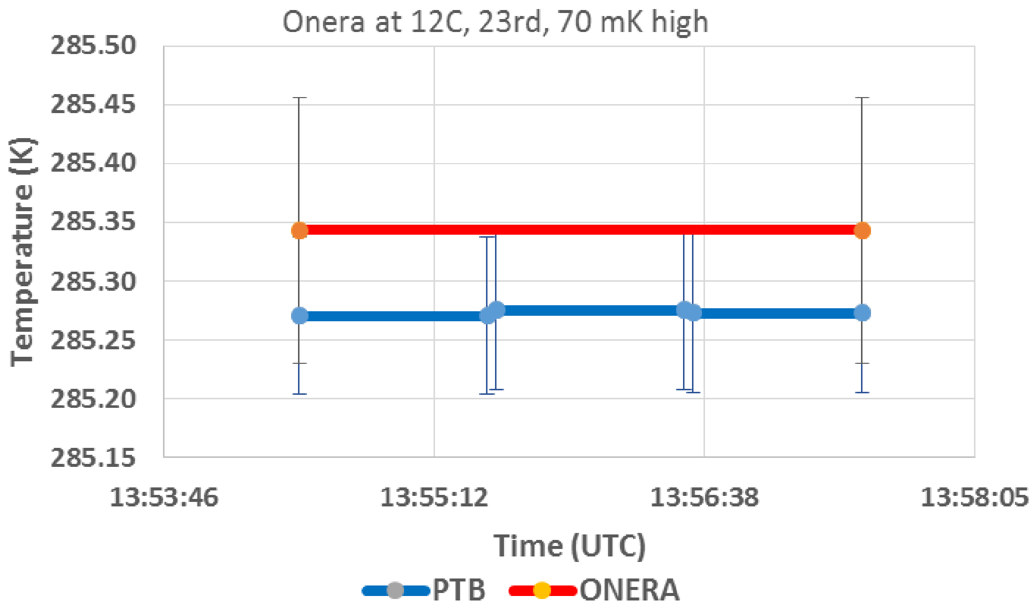

Figure 3.4.4.15: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 12 °C. The average measurement of the blackbody was 70 mK higher than the corresponding value measured by the PTB radiometer.

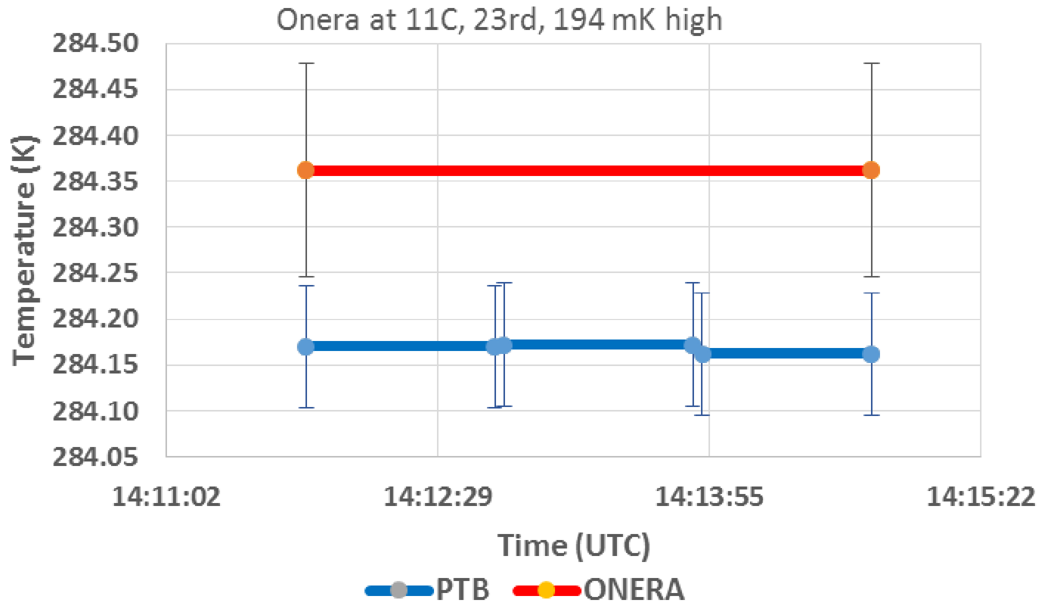

Figure 3.4.4.16: Measurements (as a function of time) reported by the ONERA blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 11 °C. The average measurement of the blackbody was 194 mK higher than the value measured by the PTB radiometer.

3.5 MIAMI BLACKBODY

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3.5.1 The Miami University Blackbody:

The University of Miami blackbody is a NIST-designed Water Bath Black Body manufactured by Hart Scientific, in the USA. Full information on this type of blackbody can be found in Fowler, J. B. (1995). The blackbody has an exit aperture of 10.8 cm and can cover temperatures in the 0 °C to 80 °C range.

3.5.2 Uncertainty budget for the Miami Water Bath Blackbody

Table 3.5.1 below, shows the uncertainty budget of the brightness temperature of the Miami Water Bath Blackbody at different temperatures in the 288 K to 318 K temperature range.

Table 3.5.1: The uncertainty budget of the brightness temperature of the Miami Water Bath Blackbody at different temperatures in the 288 K to 318 K temperature range.

Uncertainty Contribution	**Set point temperature (K)**							**Comments**
All values in mK	**288**	**293**	**298**	**303**	**308**	**313**	**318**	
Thermometer calibration	4.24	4.24	4.24	4.24	4.24	4.24	4.24	Average of two thermometers, each with uncertainty (k=2) of 6.0 mK (Fluke calibration reports, 5 April, 2016)
Blackstack thermometer resistance measurement	0.54	0.12	0.35	0.42	0.13	0.35	0.19	k=2. Fluke calibration report.
Conversion of resistance to temperature	0.35	0.23	0.08	0.07	0.19	0.27	0.30	k=2. Fluke calibration report.
Stability of the water bath	0.16	0.16	0.17	0.17	0.18	0.19	0.17	k=2. 2x standard error of temperature measurements at set points.
Emissivity uncertainty	50.0	50.0	50.0	50.0	50.0	50.0	50.0	Fowler, 1995; Rice et al, 2004. Upper bound. (k=2)
Temperature drop across copper cone	0.5	0.0	0.5	1.0	2.6	2.2	2.8	Fowler, 1995, Table 4. (k=2)
Spatial temperature gradients in cavity	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Thermal imager – no gradients detectable with FLIR SC3000 with sensitivity of 20mK
Radiative heat exchange with environment	15.0	15.0	15.0	15.0	15.0	15.0	15.0	Assumes uncertainty in knowledge of ambient temperature of 0.5K and uncertainty in cone reflectivity of 0.0003; Fowler, 1995.
Convective heat exchange with environment	1.0	1.0	1.0	1.0	1.0	1.0	1.0	From uncertainty budget of NPL Gallium reference BB

<u>Notes associated with Table 3.5.1</u>

1. The largest contribution is the uncertainty in the cone emissivity, taken here as 0.0003 from Fowler (1995) and Rice et al. (2004)
2. Second largest term is the reflected ambient radiation, due to uncertainties in the estimate of the ambient temperature, and is linearly dependent on the estimate of the emissivity.

3. There is a systematic difference of about 2 mK between the measurements of the two reference thermometers in the water bath. Both were recently calibrated by Fluke, and the offset is below the stated accuracy of the calibration. However, the systematic behavior of the difference implies there is a cause that, once identified, can be corrected. This is currently being looked at.

3.5.3 Miami University Blackbody Measured by NPL AMBER

Figures 3.5.3.1 to 3.5.3.6 show the measurements reported by the Miami University blackbody as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 15 °C to 45 °C temperature range. The blackbody measurements are shown in red, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK) and is shown in light blue. The uncertainty of the Miami University blackbody is shown as black error bars at the beginning and end of each run.

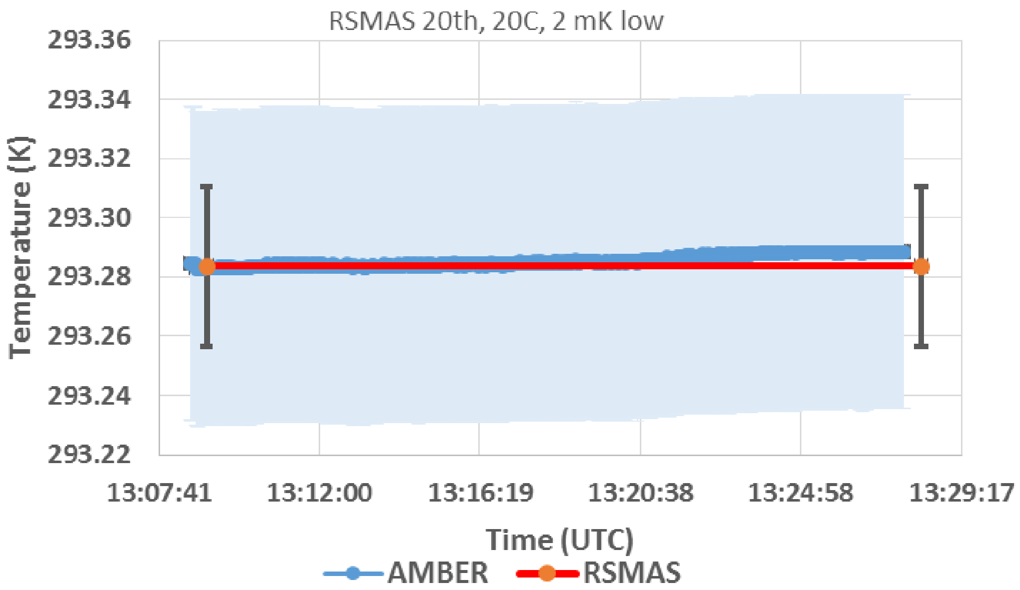

Figure 3.5.3.1: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 2 mK lower than the corresponding value measured by the AMBER radiometer.

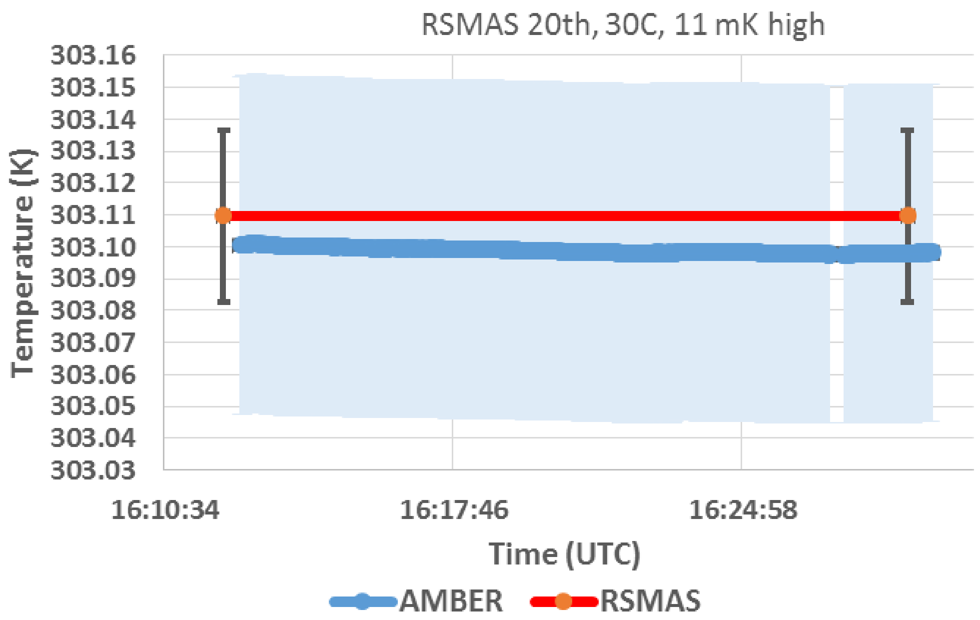

Figure 3.5.3.2: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 11 mK higher than the corresponding value measured by the AMBER radiometer.

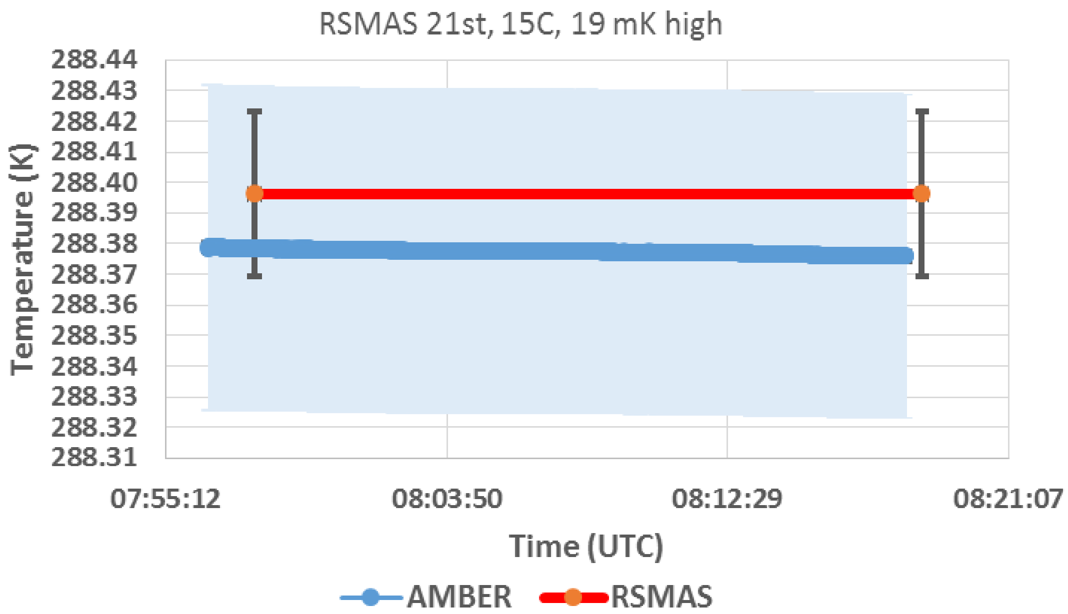

Figure 3.5.3.3: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 19 mK higher than the corresponding value measured by the AMBER radiometer

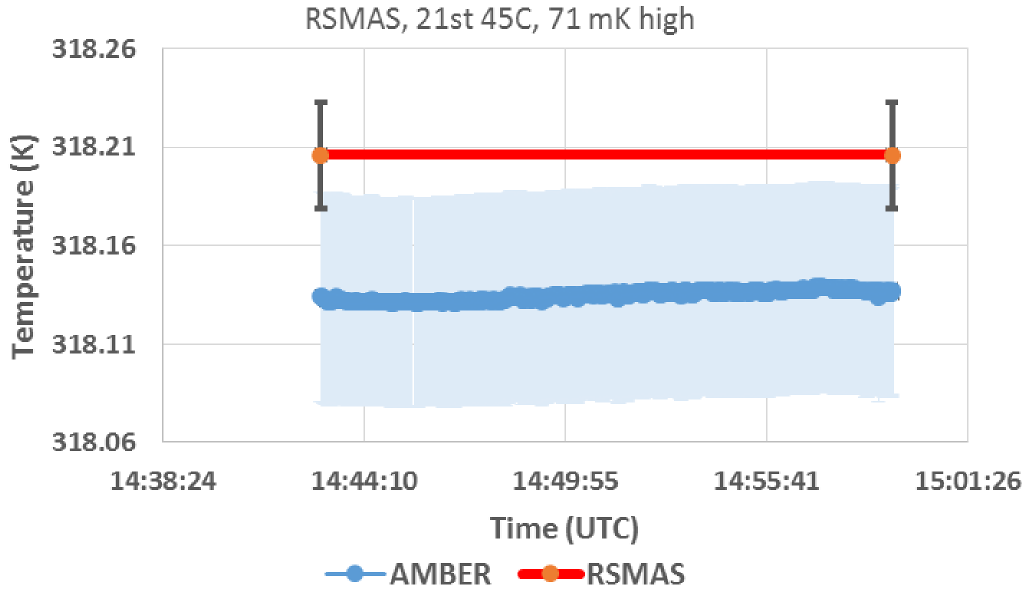

Figure 3.5.3.4: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 71 mK higher than the corresponding value measured by the AMBER radiometer

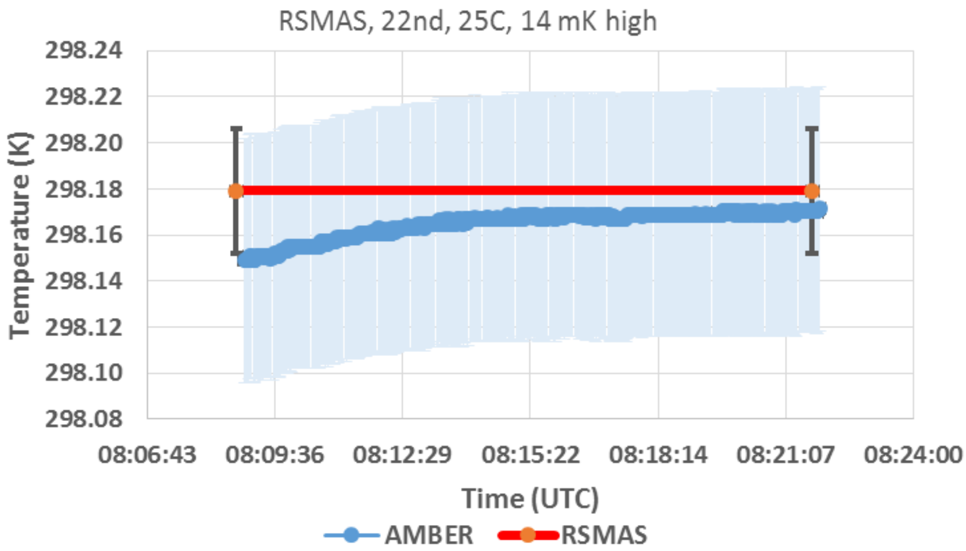

Figure 3.5.3.5: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 14 mK higher than the corresponding value measured by the AMBER radiometer.

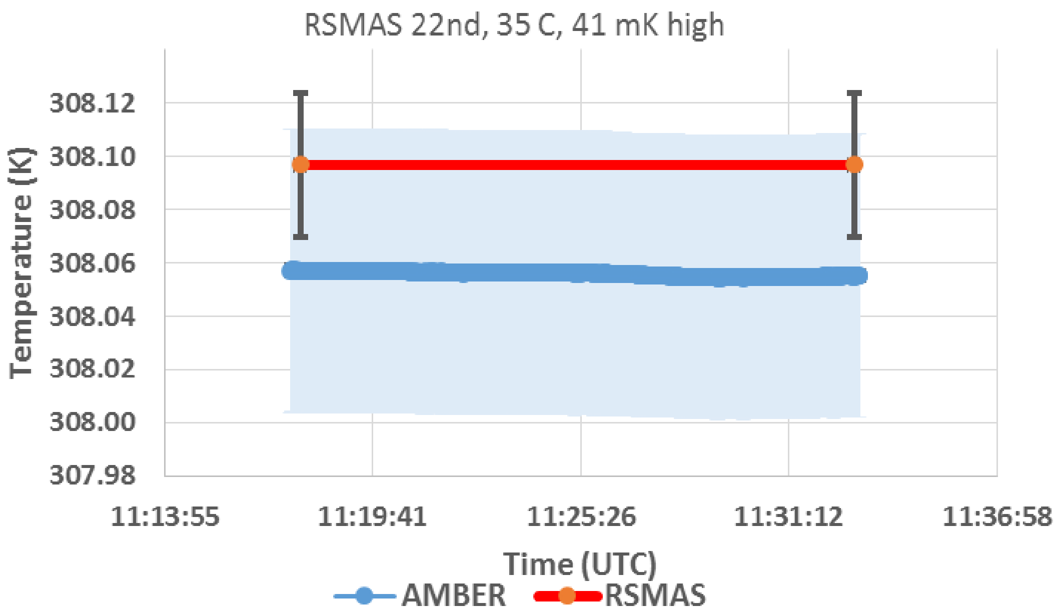

Figure 3.5.3.6: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 41 mK higher than the corresponding value measured by the AMBER radiometer.

3.5.4 Miami University blackbody Measured by the PTB Radiometer

Figures 3.5.4.1 to 3.5.4.7 show the measurements reported by the Miami University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 15 °C to 45 °C temperature range. The blackbody measurements reported by Miami University are shown in orange, while the PTB radiometer measurements are shown in blue. Also shown as black error bars in these Figures is the uncertainty of the Miami University blackbody (as reported by Miami University), as well as the uncertainty of the PTB radiometer during these measurements.

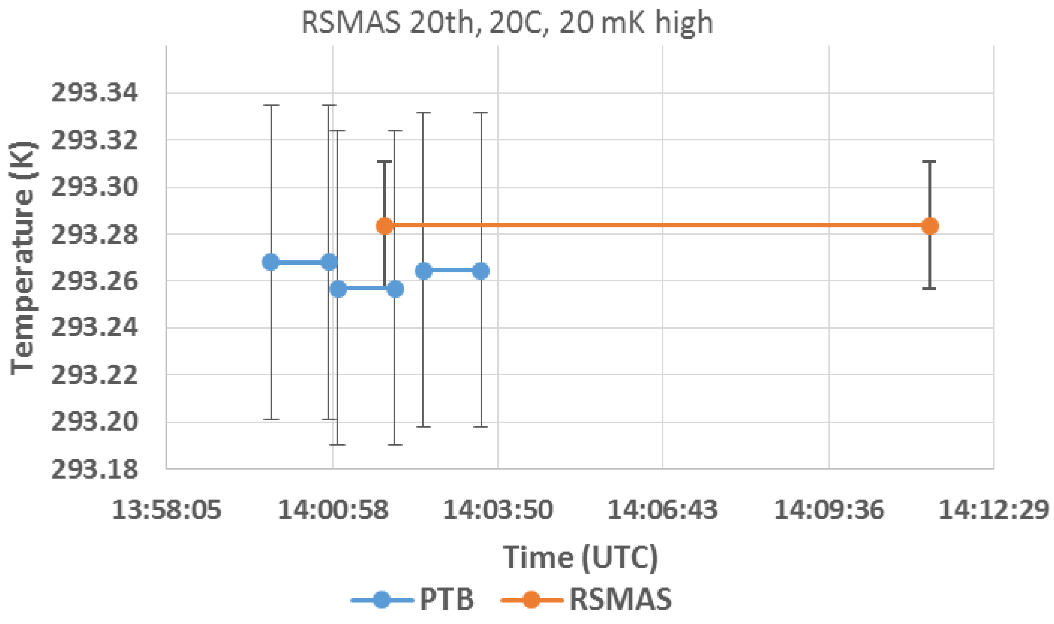

Figure 3.5.4.1: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 20 mK higher than the corresponding value measured by the PTB radiometer.

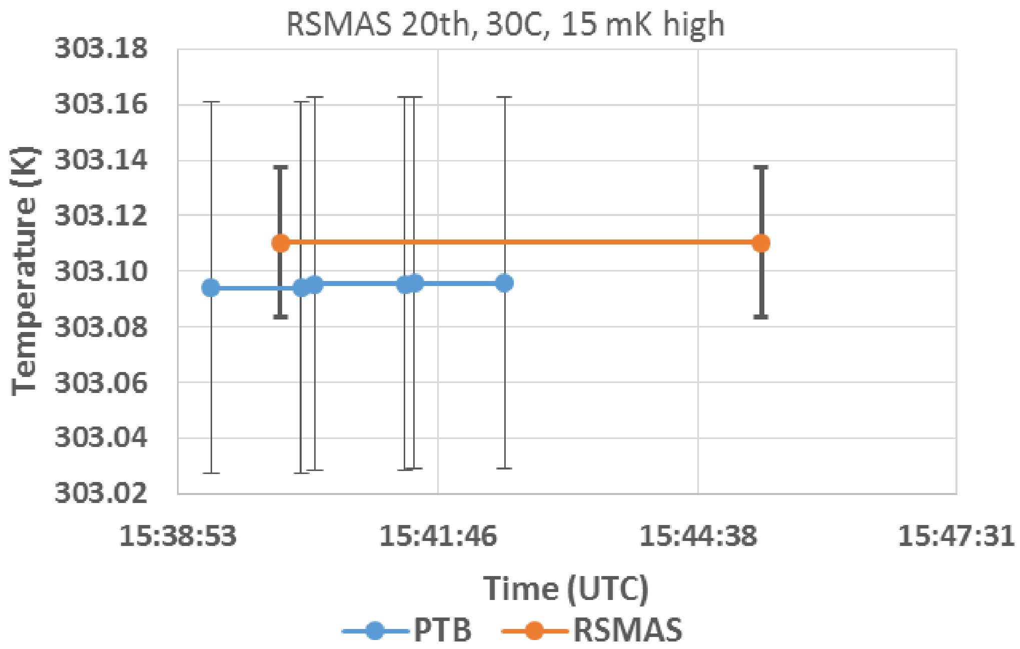

Figure 3.5.4.2: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 15 mK higher than the corresponding value measured by the PTB radiometer.

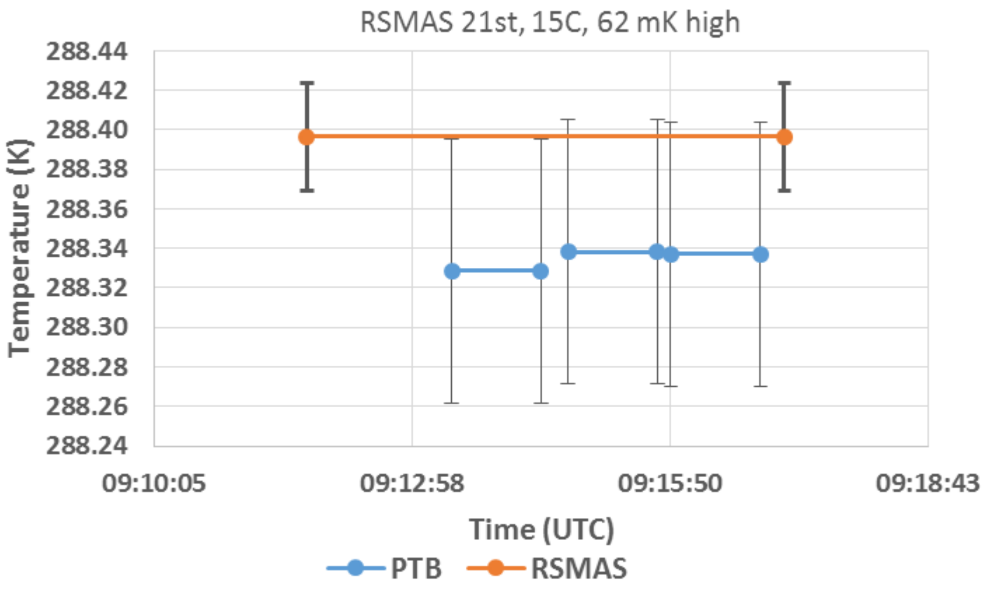

Figure 3.5.4.3: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 62 mK higher than the corresponding value measured by the PTB radiometer.

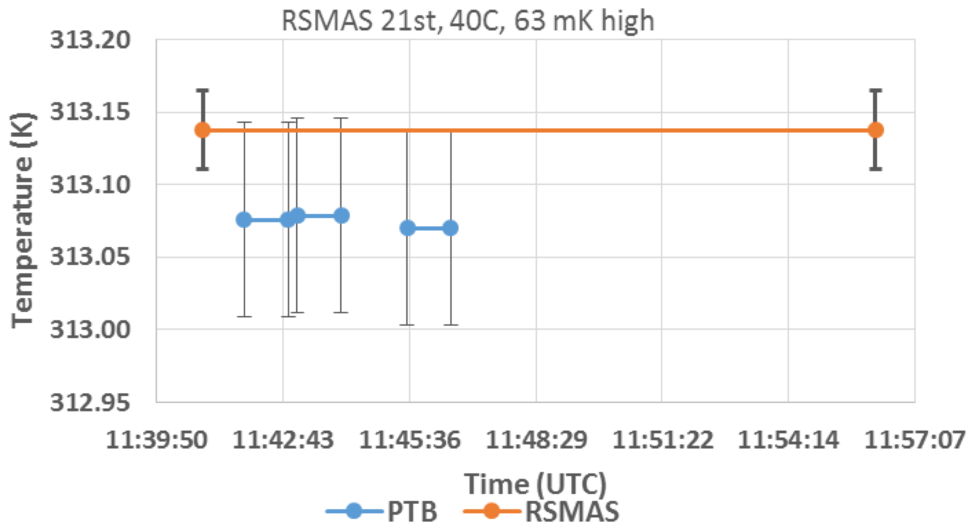

Figure 3.5.4.4: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 63 mK higher than the corresponding value measured by the PTB radiometer.

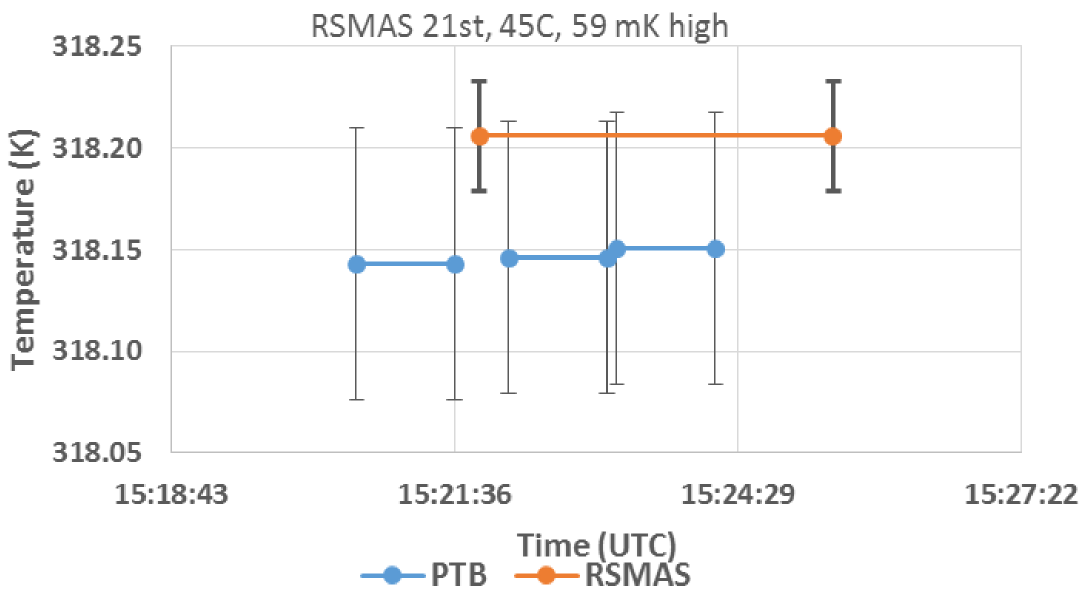

Figure 3.5.4.5: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 59 mK higher than the value measured by the PTB radiometer.

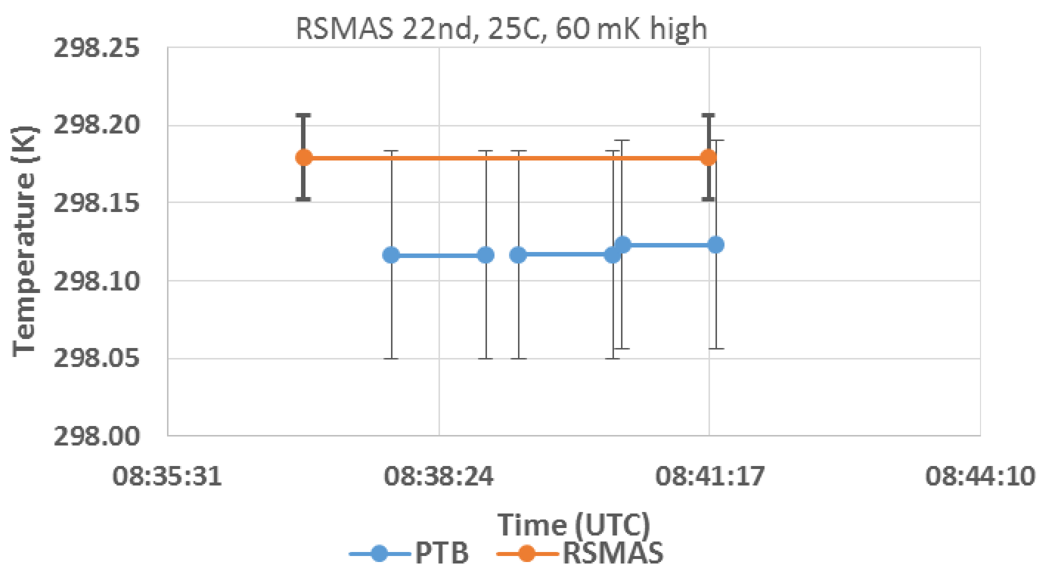

Figure 3.5.4.6: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 60 mK higher than the corresponding value measured by the PTB radiometer.

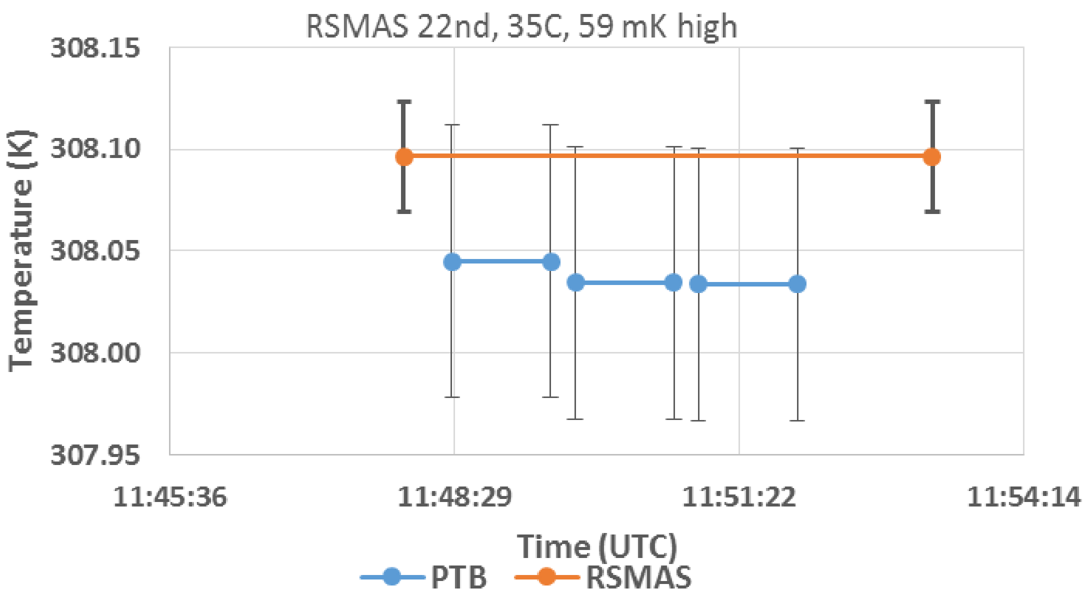

Figure 3.5.4.7: Measurements (as a function of time) reported by the University of Miami blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 35°C. The average measurement of the blackbody was 59 mK higher than the corresponding value measured by the PTB radiometer.

3.6 QINGDAO BLACKBODY

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e-mail: zhangkl@ouc.edu.cn

3.6.1 Descrption of the Qingdao Blackbody:

The Qingdao Blackbody was purchased from LR Tech Inc. of 47 Saint-Joseph, Lévis (Québec) G6V 1A8, Canada (www.lrtech.ca). The manufacturer of the Qingdao blackbody reported that the "blackbody absolute temperature accuracy is ±5mK at room temperature (25°C) over the spectral range of 500 to 2200 cm^{-1}". This spectral range includes the spectral response of the AMBER and PTB radiometers which were used in this comparison.

3.6.2 Uncertainty of the Qingdao Blackbody.

LR Tech Inc., the manufacturer of the Qingdao blackbody, reported that the "blackbody absolute temperature accuracy is ±5mK at room temperature (25 °C) over the spectral range of 500 to 2200 cm^{-1}".

3.6.3 Qingdao Blackbody Measured by NPL AMBER

Figures 3.6.3.1 to 3.6.3.6 show the measurements reported by the Qingdao blackbody, as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 25 °C to 35 °C temperature range. The blackbody measurements are shown in orange, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK) and is shown in light blue. The uncertainty of the Qingdao blackbody is also displayed as error bars in these Figures.

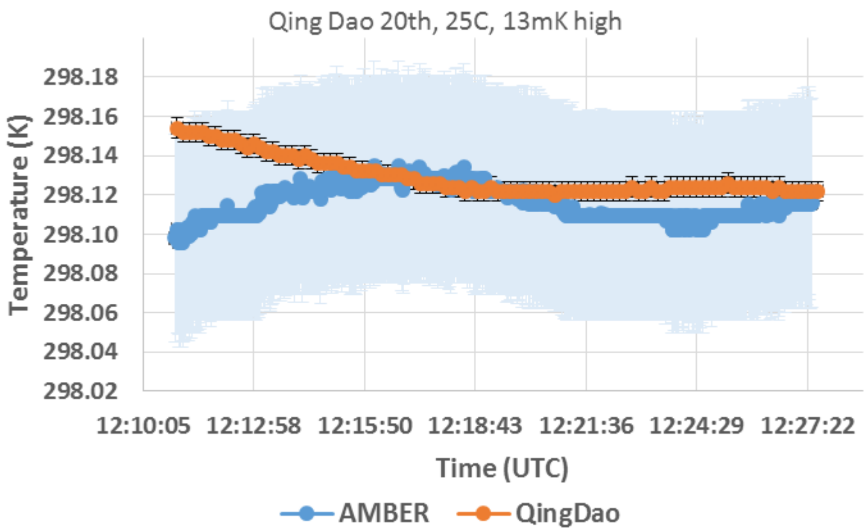

Figure 3.6.3.1: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 13 mK higher than the corresponding value measured by the AMBER radiometer.

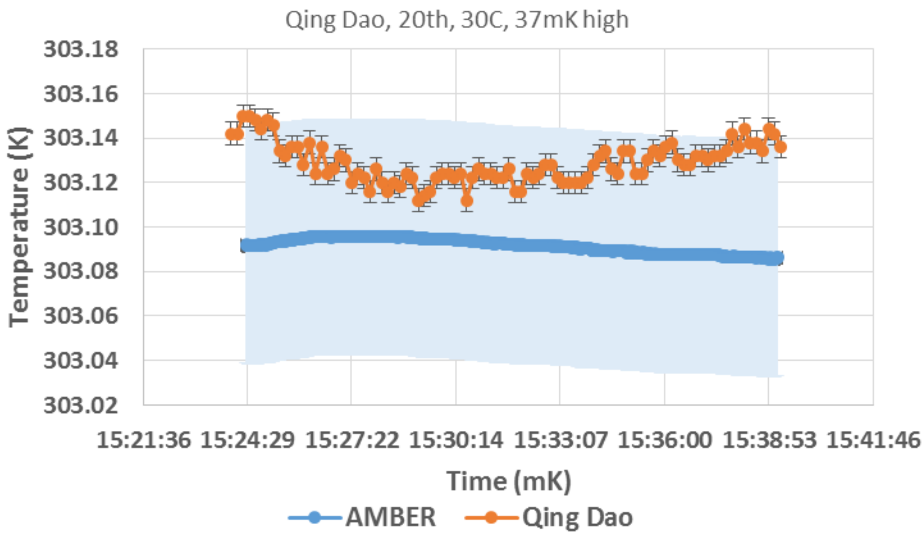

Figure 3.6.3.2: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 37 mK higher than the value measured by the AMBER radiometer.

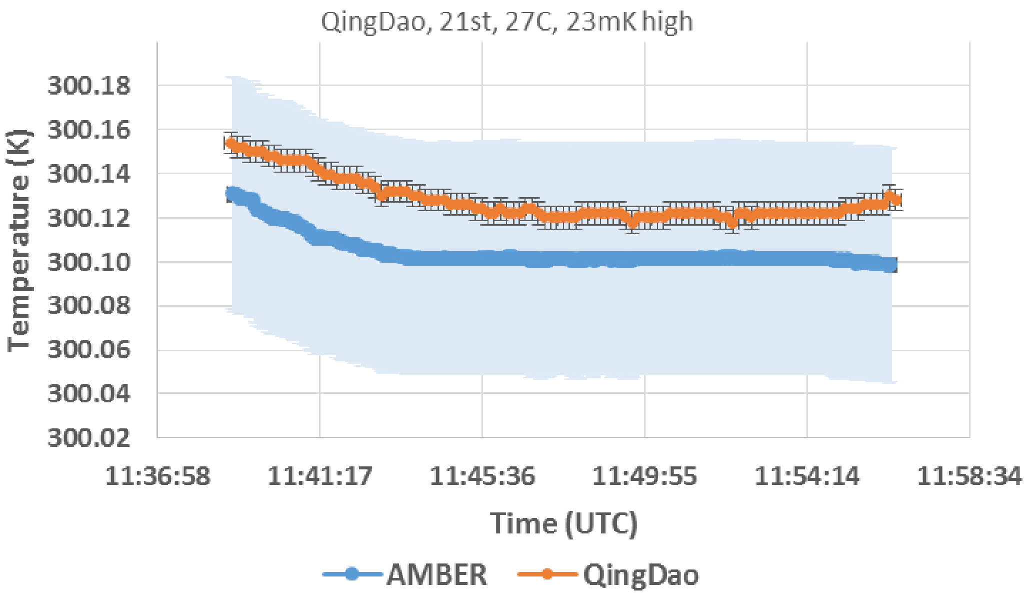

Figure 3.6.3.3: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 27 °C. The average measurement of the blackbody was 23 mK higher than the value measured by the AMBER radiometer.

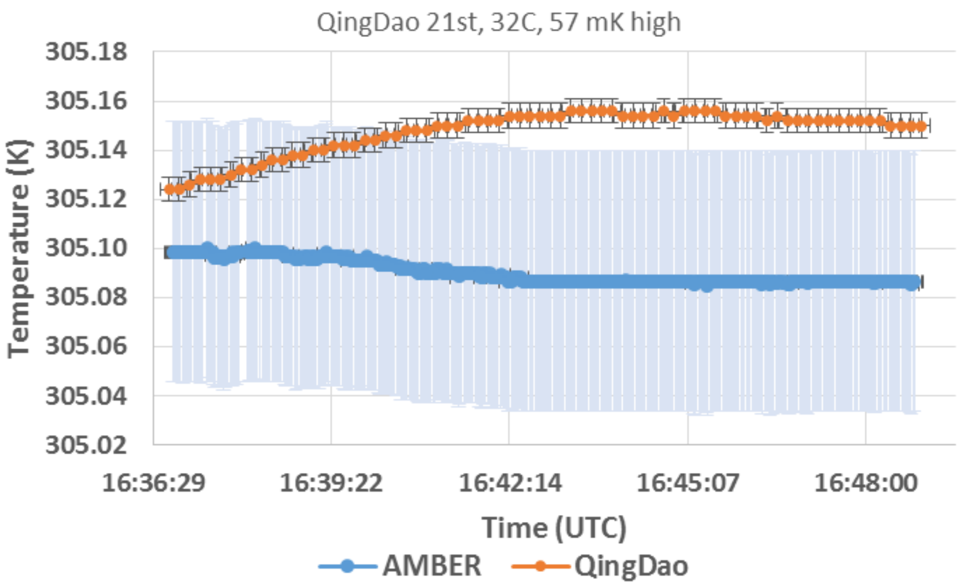

Figure 3.6.3.4: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 32 °C. The average measurement of the blackbody was 57 mK higher than the value measured by the AMBER radiometer.

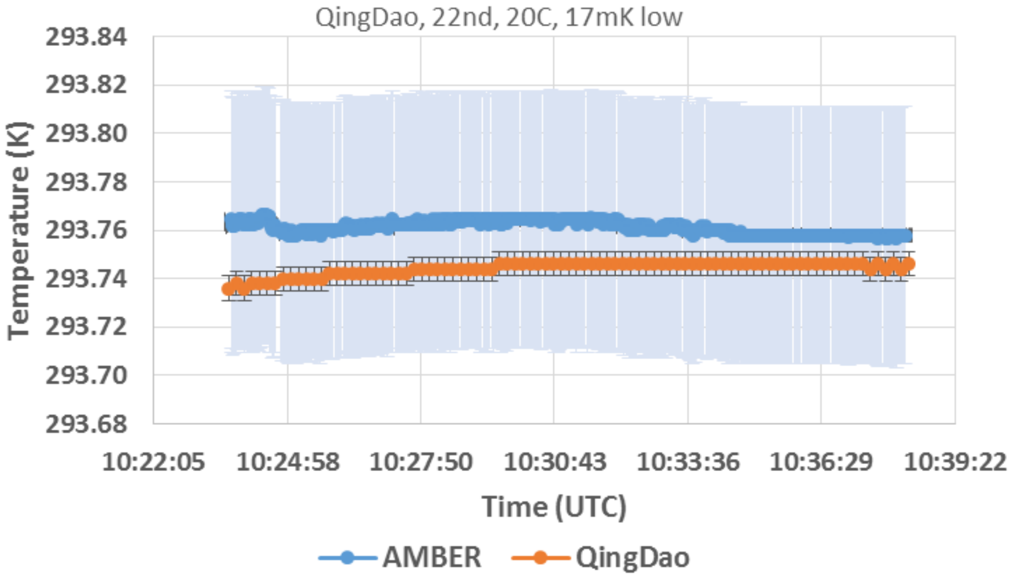

Figure 3.6.3.5: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 17 mK lower than the value measured by the AMBER radiometer.

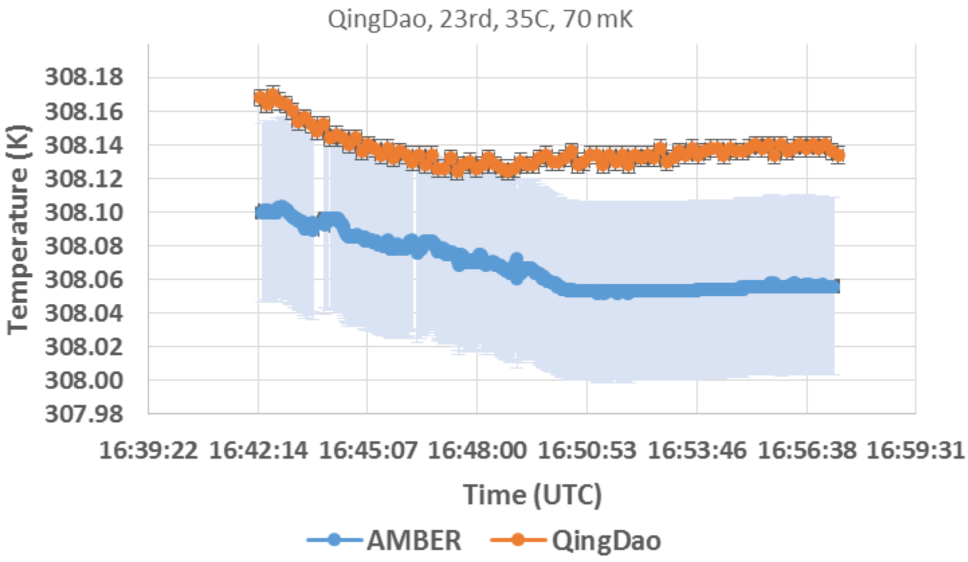

Figure 3.6.3.6: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 35°C. The average measurement of the blackbody was 70 mK higher than the value measured by the AMBER radiometer.

3.6.4 QingDao Blackbody Measured by the PTB Radiometer

Figures 3.6.3.1 to 3.6.3.7 show the measurements reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by PTB radiometer, as a function of time, at different temperatures in the 20 °C to 35 °C temperature range. The blackbody measurements are shown in orange/red, while the PTB radiometer measurements are shown in blue. Also shown as black error bars in these Figures is the uncertainty of the PTB radiometer as well as the uncertainty of the Qingdao blackbody during these measurements.

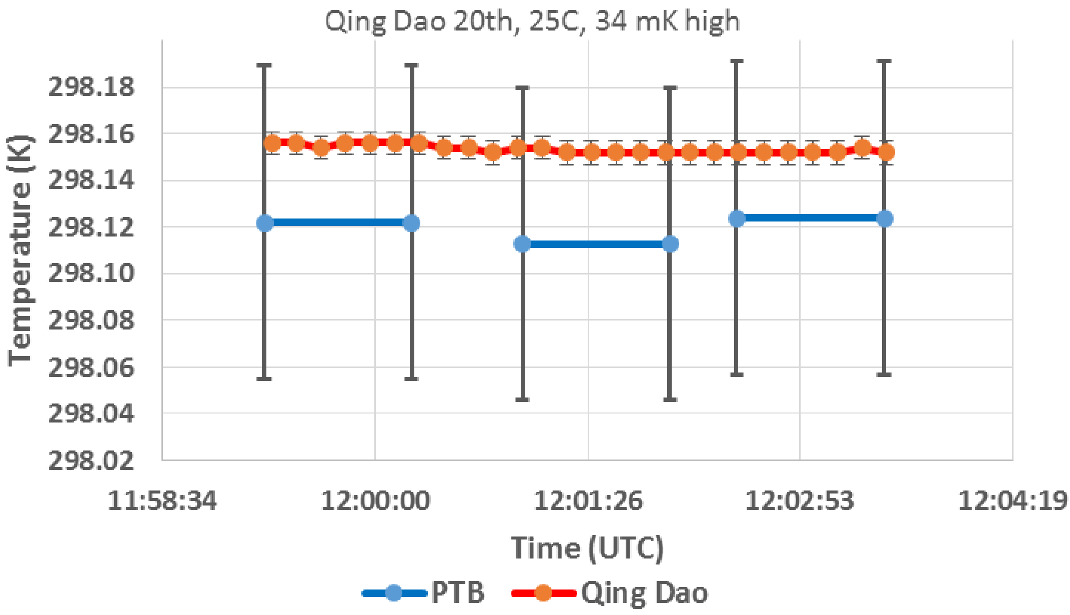

Figure 3.6.4.1: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 34 mK higher than the corresponding value measured by the PTB radiometer.

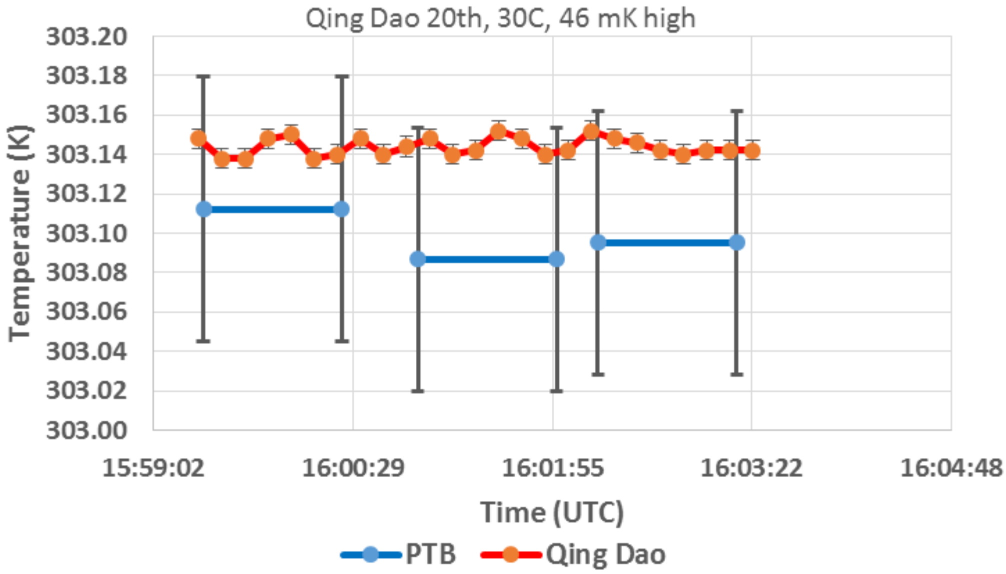

Figure 3.6.4.2: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 46 mK higher than the corresponding value measured by the PTB radiometer.

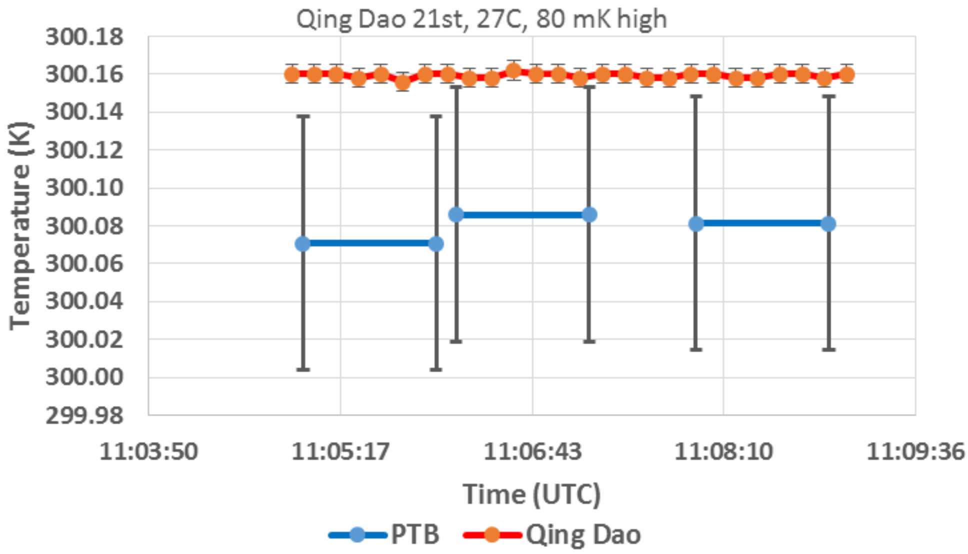

Figure 3.6.4.3: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 27 °C. The average measurement of the blackbody was 80 mK higher than the corresponding value measured by the PTB radiometer.

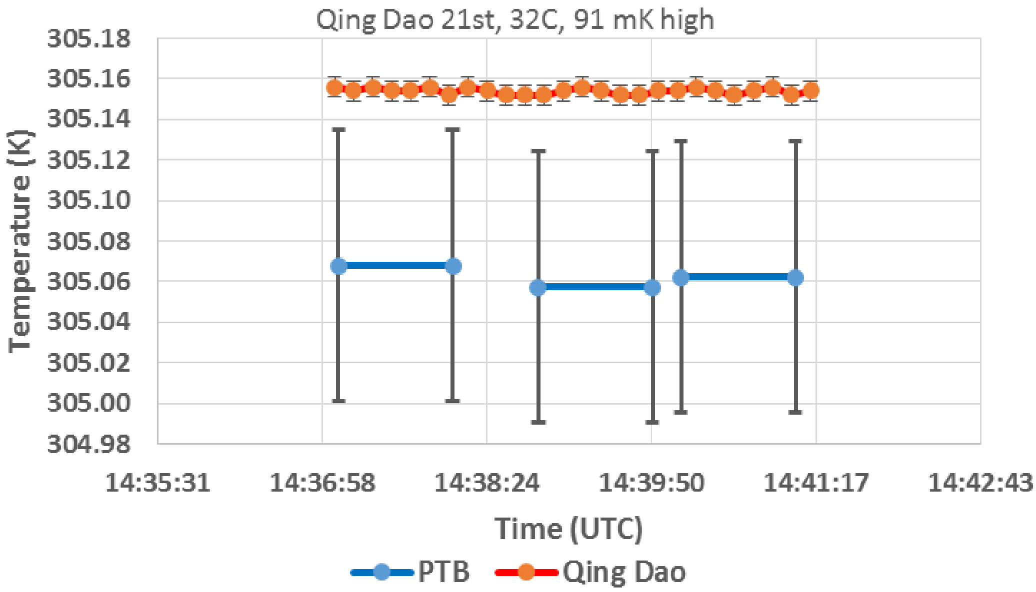

Figure 3.6.4.4: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 32 °C. The average measurement of the blackbody was 91 mK higher than the corresponding value measured by the PTB radiometer.

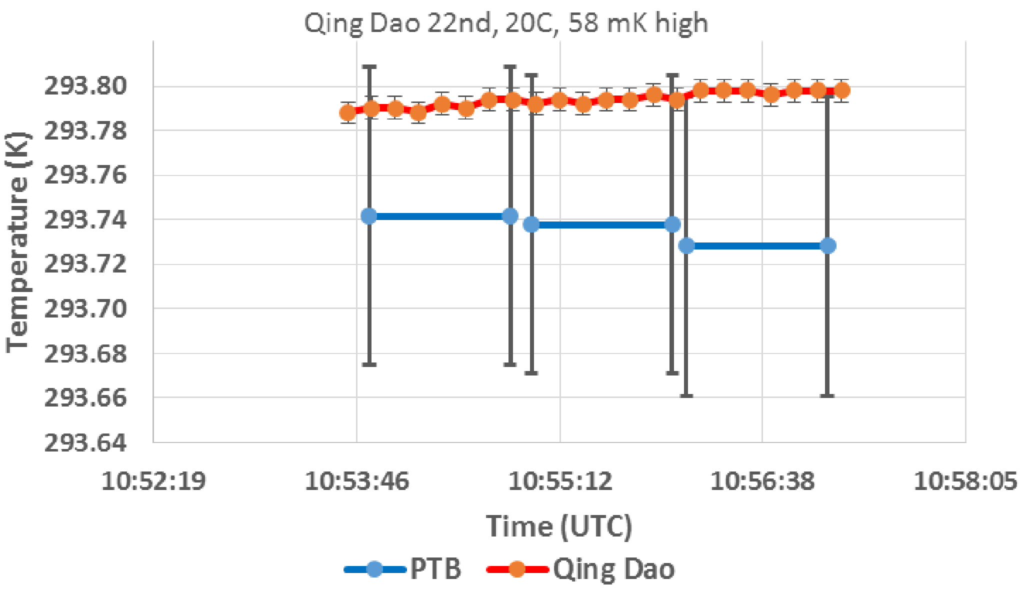

Figure 3.6.4.5: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 58 mK higher than the corresponding value measured by the PTB radiometer.

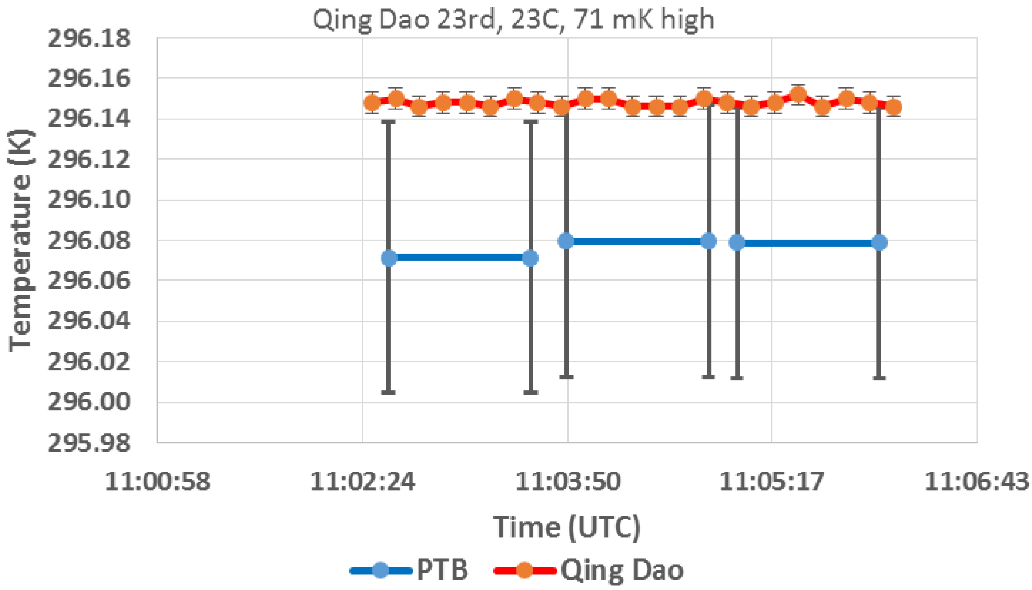

Figure 3.6.4.6: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 23 °C. The average measurement of the blackbody was 71 mK higher than the corresponding value measured by the PTB radiometer.

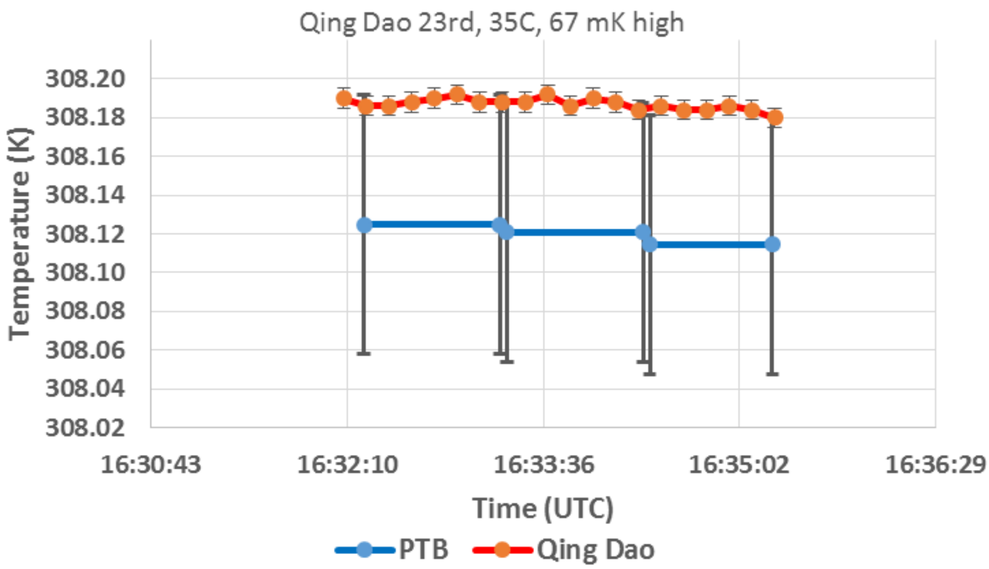

Figure 3.6.4.7: Measurements (as a function of time) reported by the Qingdao blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 67 mK higher than the corresponding value measured by the PTB radiometer.

3.7 RAL SPACE BLACKBODY

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Contact: Tim Nightingale
Email: tim.nightingale@stfc.ac.uk

3.7.1 Description of the RAL Blackbody

The RAL blackbody was a CASOTS Mk1 blackbody which had a 10 cm diameter exit aperture and can cover the temperature range from the Dew point (with ice cooling) to approximately 32°C.

3.7.2 Uncertainty of the RAL Blackbody

RAL provided combined uncertainty values for all their blackbody laboratory measurements. Three uncertainty components contributed to a combined uncertainty for the RAL blackbody readings. The first uncertainty contribution was due to the blackbody emissivity and varied between 1 mK to 17 mK over the blackbody temperatures used during the 2016 comparison. The second was due to the blackbody cavity geometry (24 mK for all temperatures used) while the third uncertainty contribution was due to radiation from the surrounding air and it ranged from 3 mK to 4 mK over the range of temperatures used. The combined uncertainty of the RAL blackbody ranged from 24 mK to 30 mK over the range of temperatures used, with a minimum when the cavity was at the estimated room temperature of 21 °C.

3.7.3 RAL Blackbody Measured by AMBER

Figures 3.7.3.1 to 3.7.3.9 show the measurements reported by the RAL blackbody as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 15 °C to 45 °C temperature range. The blackbody measurements are shown in orange, while the AMBER measurements are shown in blue. Also shown in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK) and is shown in light blue. The uncertainty of the RAL blackbody is shown as yellow throughout the duration of the comparison.

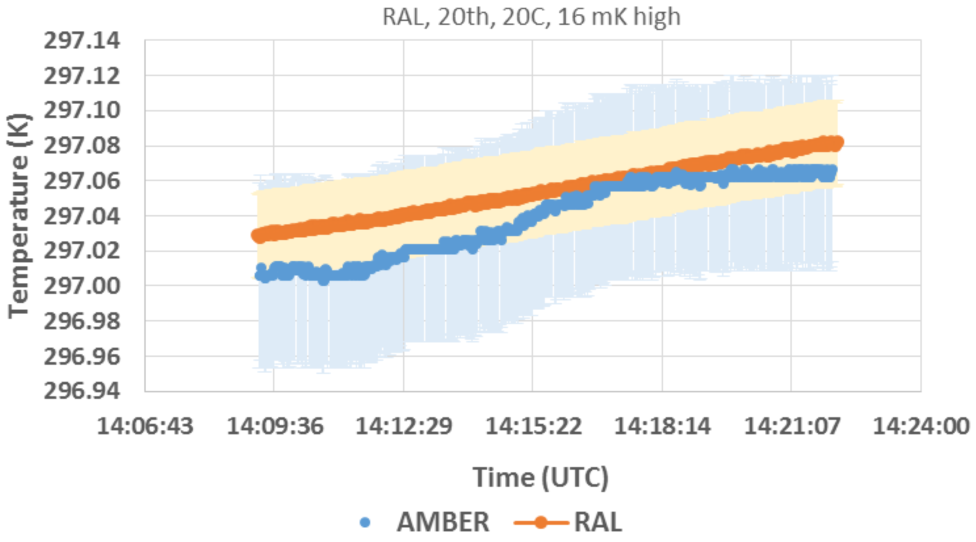

Figure 3.7.3.1: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 16 mK higher than the value measured by the AMBER radiometer.

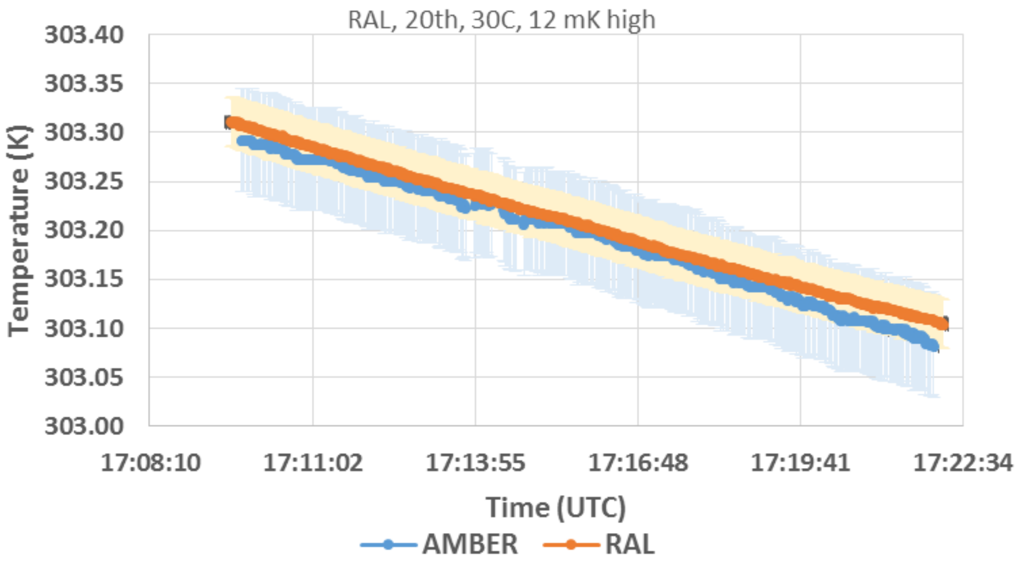

Figure 3.7.3.2: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 12 mK higher than the value measured by the AMBER radiometer.

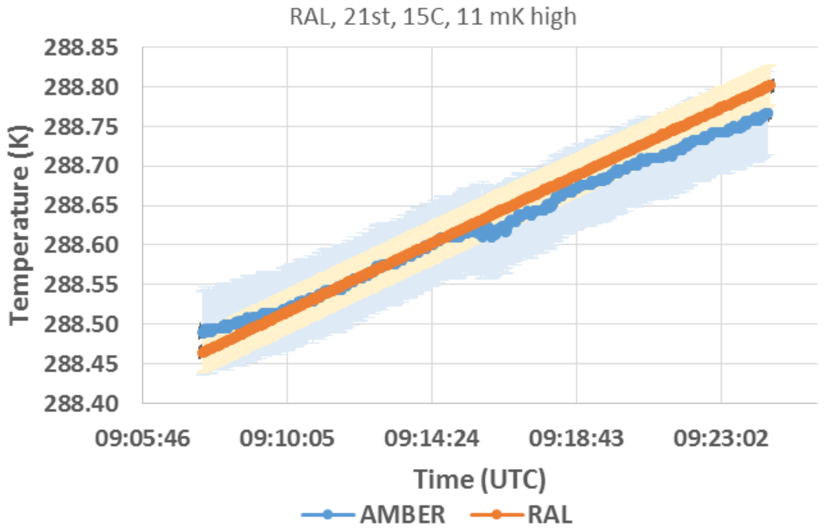

Figure 3.7.3.3: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 11 mK higher than the value measured by the AMBER radiometer.

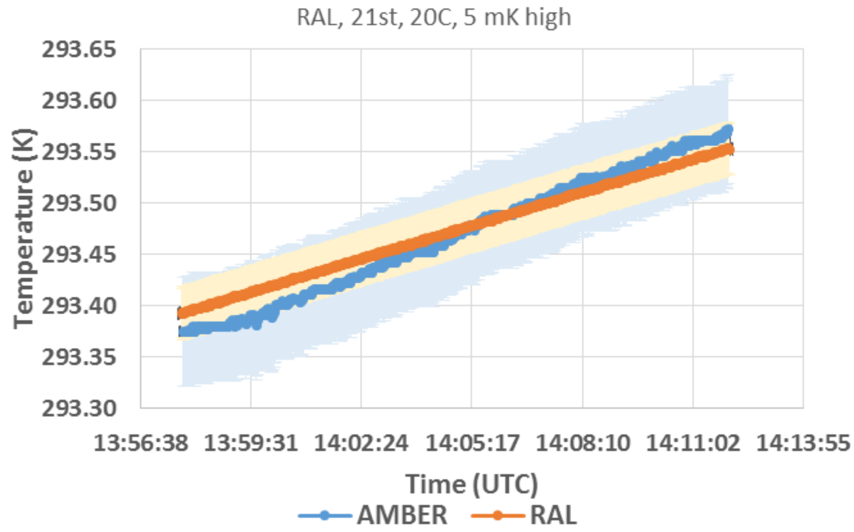

Figure 3.7.3.4: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 5 mK higher than the value measured by the AMBER radiometer.

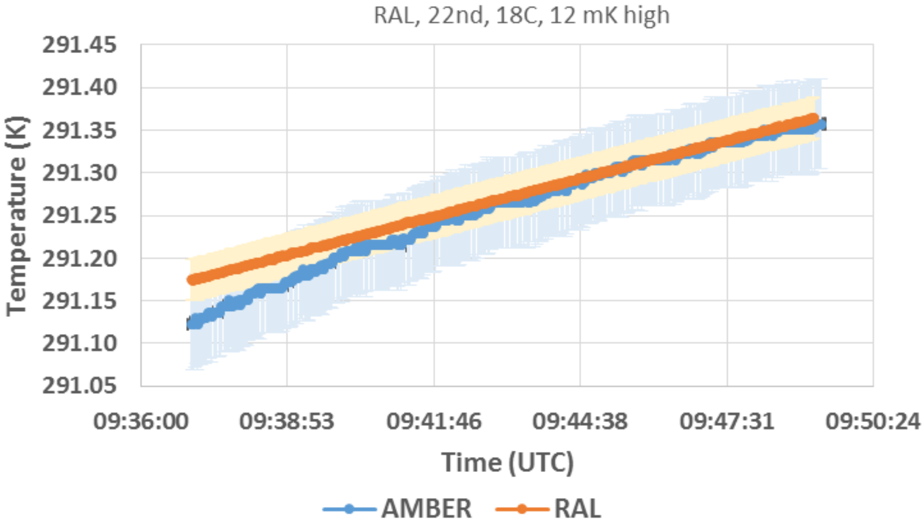

Figure 3.7.3.5: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 18 °C. The average measurement of the blackbody was 12 mK higher than the value measured by the AMBER radiometer.

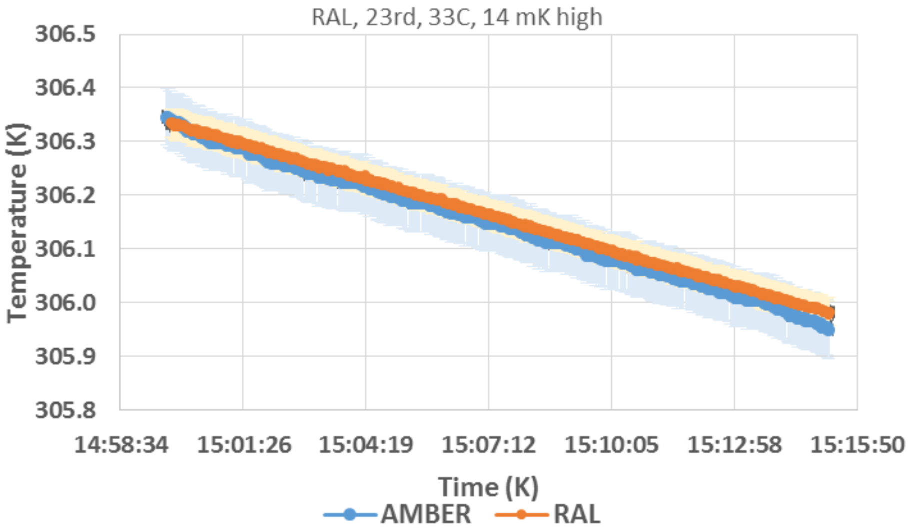

Figure 3.7.3.6: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 33 °C. The average measurement of the blackbody was 14 mK higher than the value measured by the AMBER radiometer.

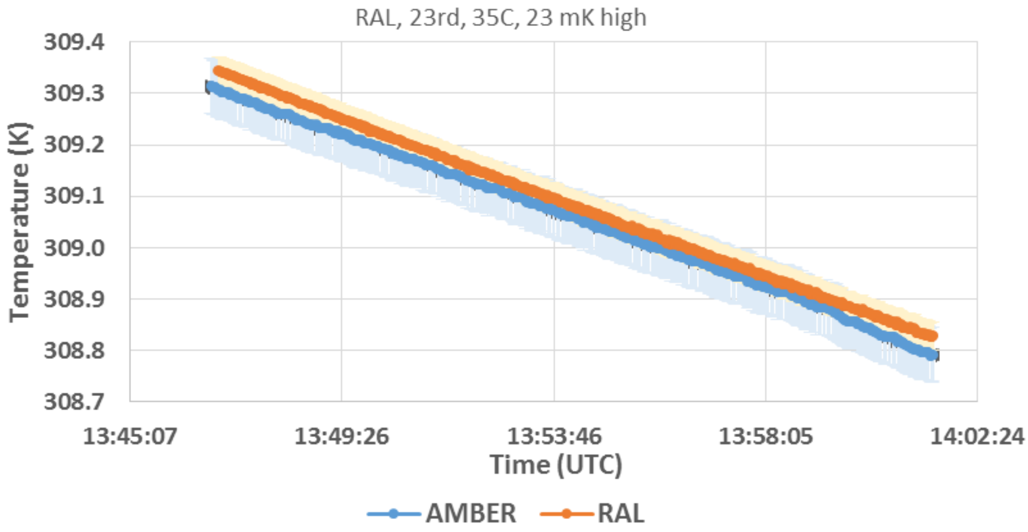

Figure 3.7.3.7: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 35 °C. The average measurement of the blackbody was 23 mK higher than the value measured by the AMBER radiometer.

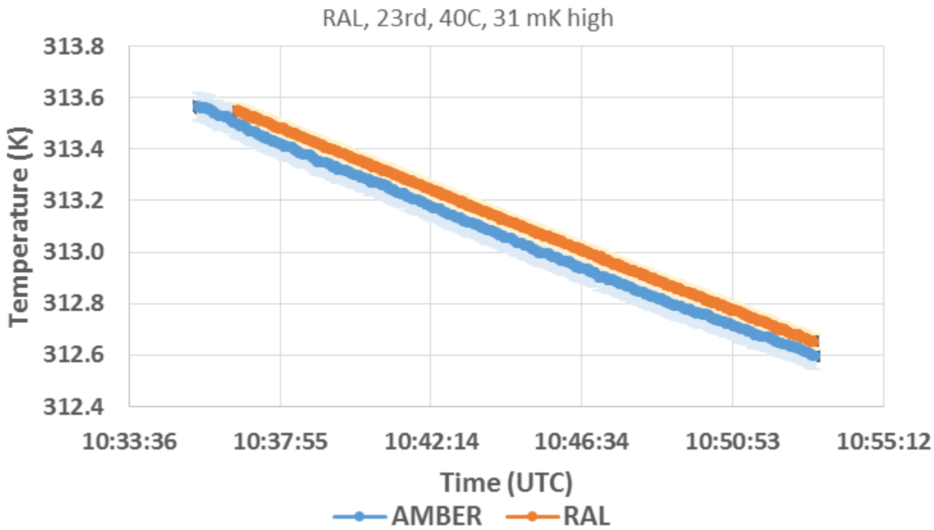

Figure 3.7.3.8: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 31 mK higher than the value measured by the AMBER radiometer.

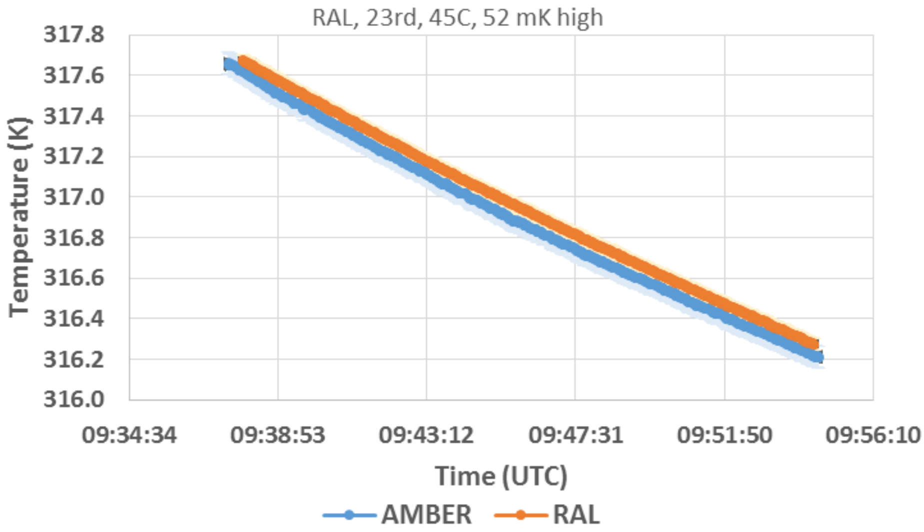

Figure 3.7.3.9: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 52 mK higher than the value measured by the AMBER radiometer.

3.7.4 RAL Blackbody Measured by the PTB Radiometer

Figures 3.7.4.1 to 3.7.4.7 show the measurements reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 15 °C to 45 °C temperature range. The RAL blackbody measurements are shown in red, while the PTB measurements are shown in blue. Also shown in these Figures is the uncertainty of the PTB radiometer during these measurements (shown as black error bars). The uncertainty of the RAL blackbody is shown as orange throughout the duration of the comparison.

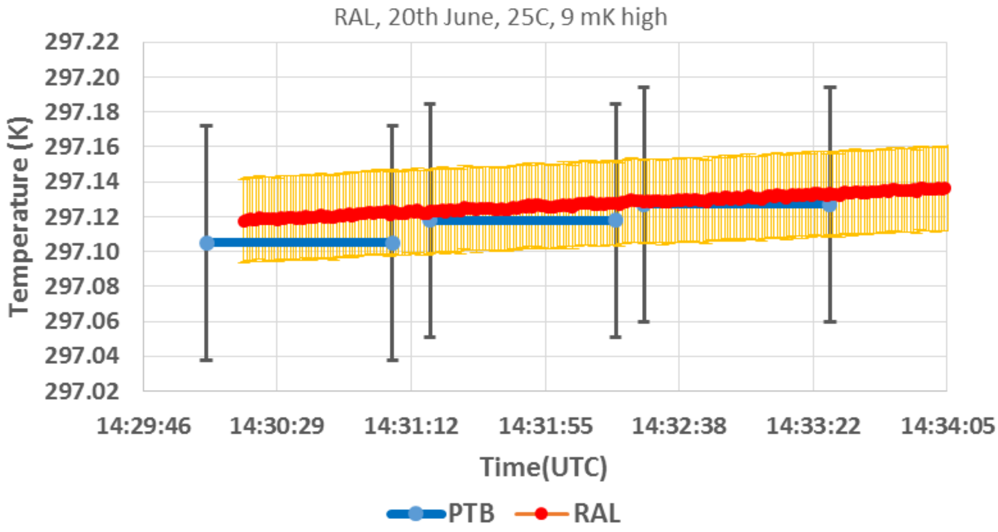

Figure 3.7.4.1: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 25 °C. The average measurement of the blackbody was 9 mK higher than the value measured by the PTB radiometer.

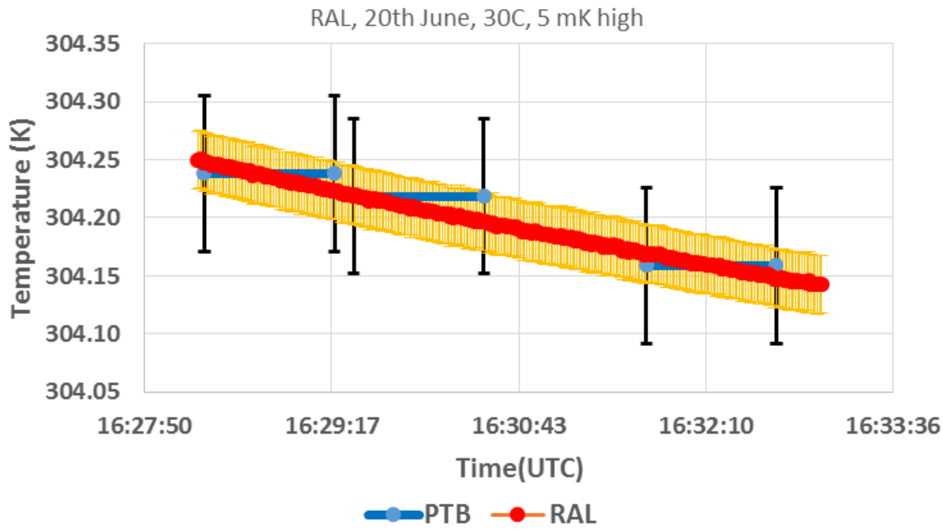

Figure 3.7.4.2: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 5 mK higher than the value measured by the PTB radiometer.

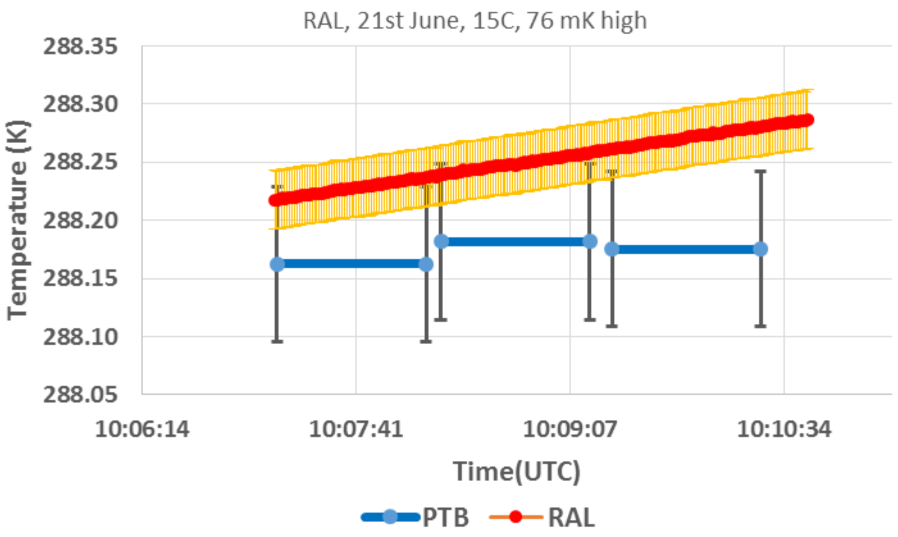

Figure 3.7.4.3: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 76 mK higher than the value measured by the PTB radiometer.

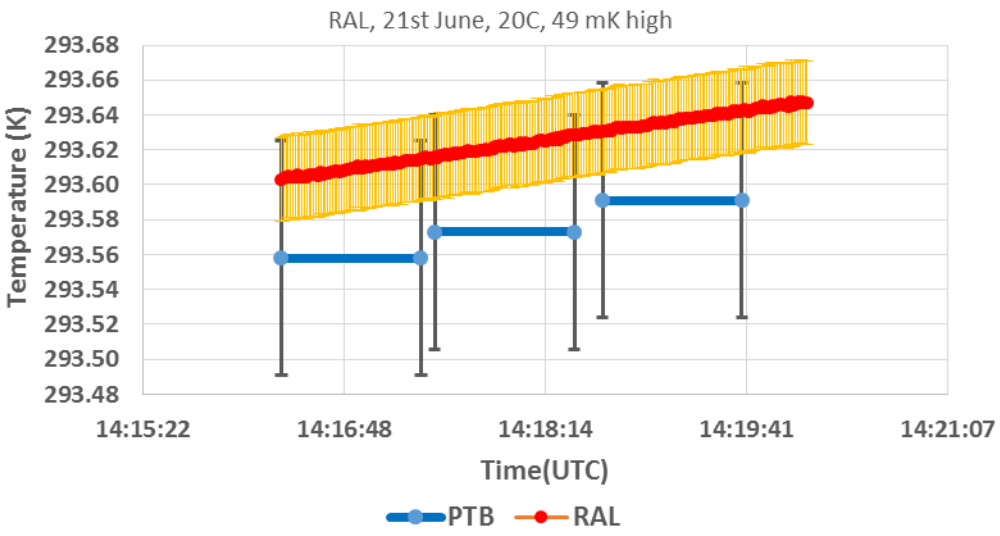

Figure 3.7.4.4: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 49 mK higher than the value measured by the PTB radiometer.

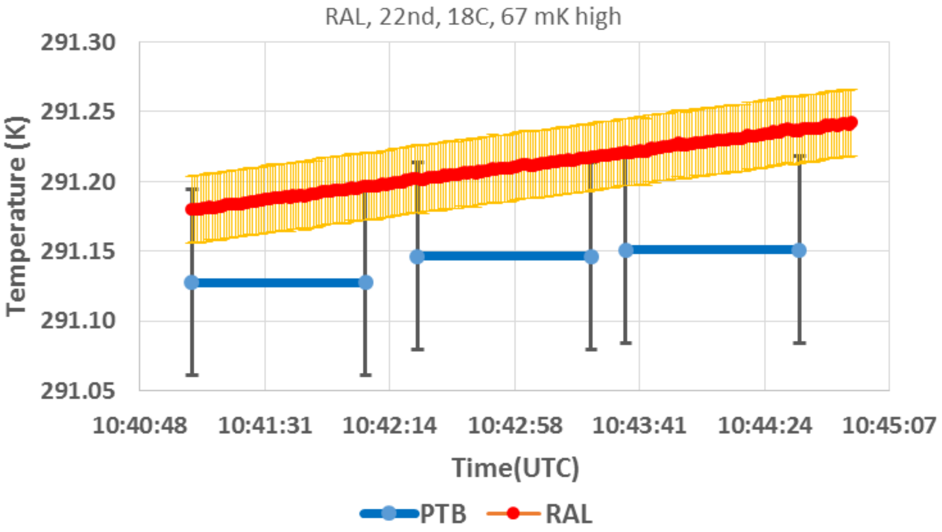

Figure 3.7.4.5: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 18 °C. The average measurement of the blackbody was 67 mK higher than the value measured by the PTB radiometer.

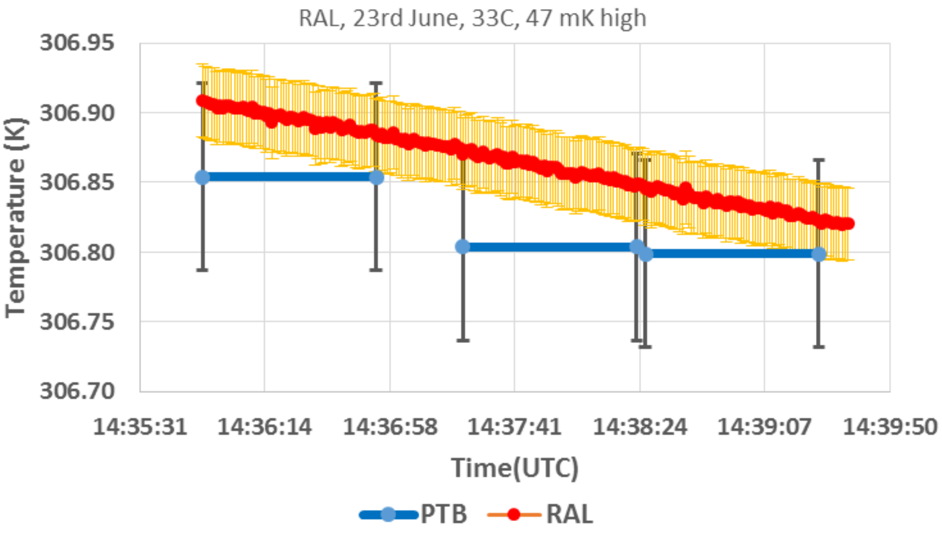

Figure 3.7.4.6: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 33 °C. The average measurement of the blackbody was 47 mK higher than the value measured by the PTB radiometer.

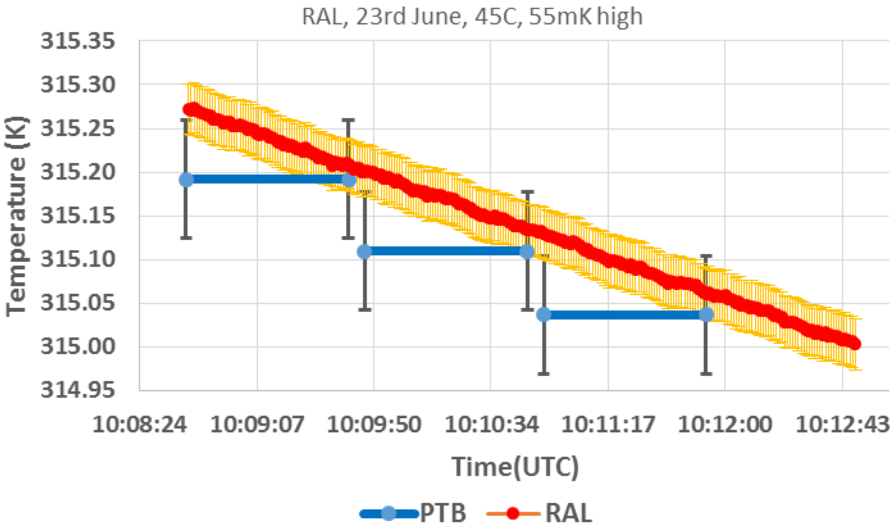

Figure 3.7.4.7: Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 45 °C. The average measurement of the blackbody was 55 mK higher than the value measured by the PTB radiometer.

3.8 SOUTHAMPTON UNIVERSITY

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3.8.1 The Southampton University Blackbody

The Southampton University blackbody was a CASOTS 2 type blackbody. This blackbody had a user selectable exit aperture of 50 mm in diameter and could cover the temperature range from the Dew point to 20 K above the Dew point. Full information on this type of blackbody can be found in: C. J. Donlon, W. Wimmer, I. Robinson, G. Fisher, M. Ferlet, T. Nightingale, and B. Bras, "A Second-Generation Blackbody System for the Calibration and Verification of Seagoing Infrared Radiometers", J. Atmos. Oceanic Technol. 31, 1104–1127, 2014.

3.8.2 Uncertainty of the Southampton University Blackbody

Table 3.8.1 shows the uncertainty budget provided by Southampton University for their CASOTS II blackbody. The Table shows the values of the different uncertainty contributions corresponding to three different blackbody apertures. A 50 mm diameter aperture was used during the 2016 blackbody comparison, resulting in a combined uncertainty of 0.02 °C. Full information on the uncertainty budget of CASOTS II blackbody can be found in the paper by Donlon et al., 2014, highlighted in Section 3.8.1.

Table 3.8.1: Uncertainty budget of the Southampton University for their CASOTS II blackbody for three different blackbody apertures.

Source of uncertainty	110 mm °C	40mm °C	50mm (est.) °C
NEXTEL paint emissivity	0.043	0.0062	0.012
Stray radiance error	0.036	0.004	0.008
Thermometry system	0.0067	0.0067	0.0067
Heating rate error	0.0076	0.0076	0.0076
Water bath thermal gradients	0.0096	0.0096	0.0096
Cavity wall–paint thermal gradient	0.006	0.001	0.0015
Combined uncertainty	**0.0585**	**0.0158**	**0.0201**

3.8.3 Southampton University Blackbody Measured by AMBER

Figures 3.8.3.1 to 3.8.3.9 show the measurements reported by the Southampton University CASOC II blackbody as well as the temperature of the same blackbody measured by AMBER, as a function of time, at different temperatures in the 12 °C to 40 °C temperature range. The blackbody measurements are shown in red, while the AMBER measurements are shown in blue. Also shown as light blue error bars in these Figures is the uncertainty of the AMBER radiometer during these measurements (which was 53 mK). The uncertainty of the Southampton University blackbody is shown as yellow error bars throughout the duration of the comparison.

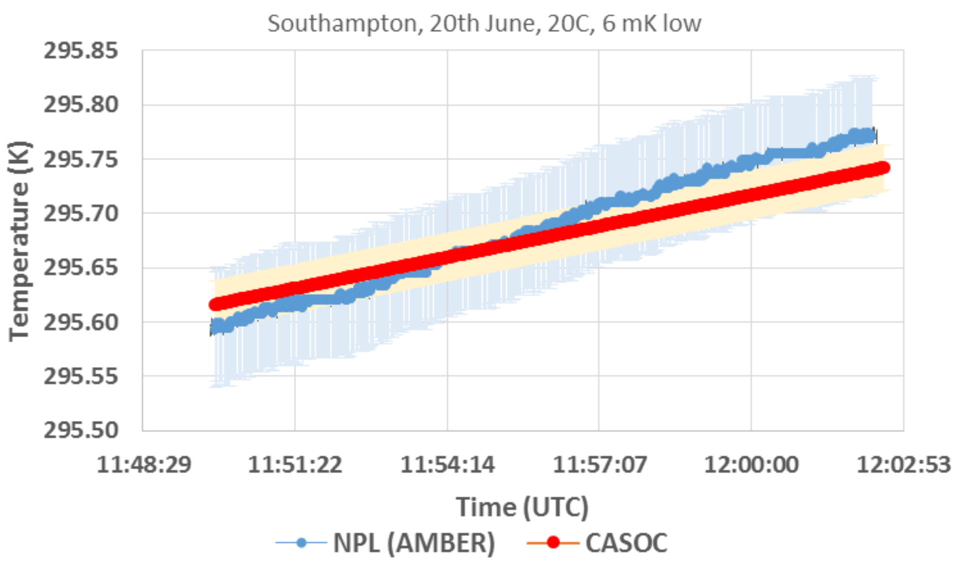

Figure 3.8.3.1: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 6 mK lower than the corresponding value measured by the AMBER radiometer.

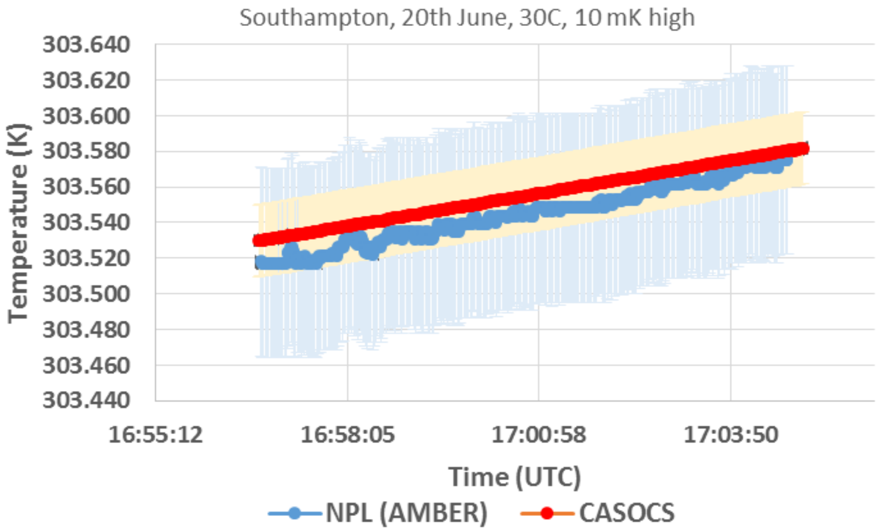

Figure 3.8.3.2: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 10 mK higher than the corresponding value measured by the AMBER radiometer.

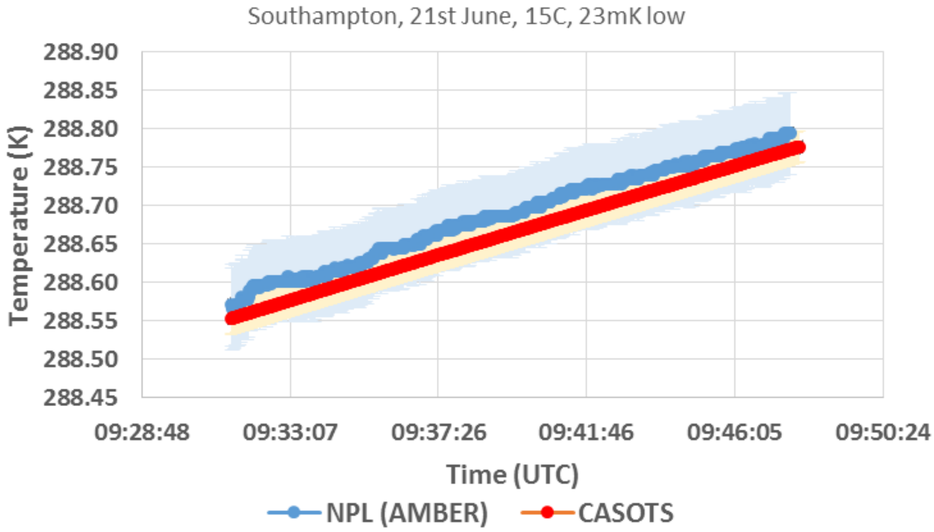

Figure 3.8.3.3: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 23 mK lower than the corresponding value measured by the AMBER radiometer.

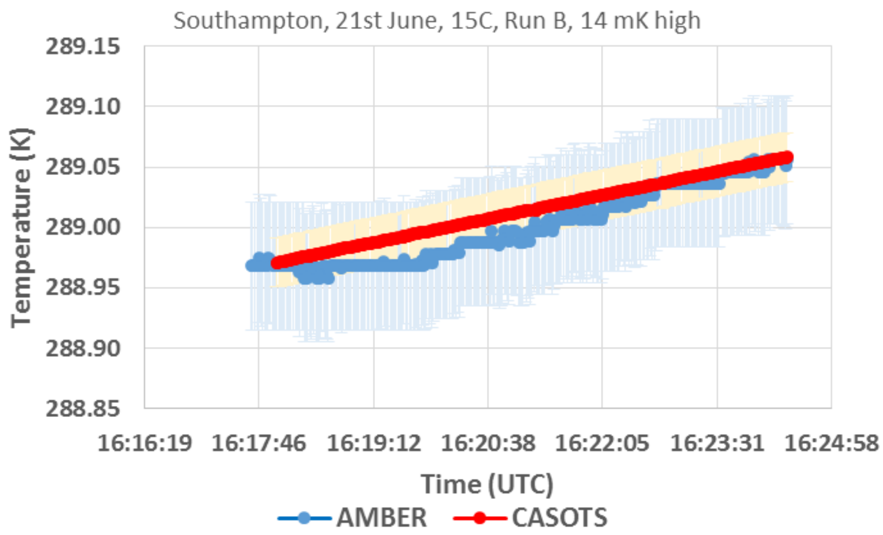

Figure 3.8.3.4: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 15 °C (2nd run). The average measurement of the blackbody was 14 mK higher than the corresponding value measured by the AMBER radiometer.

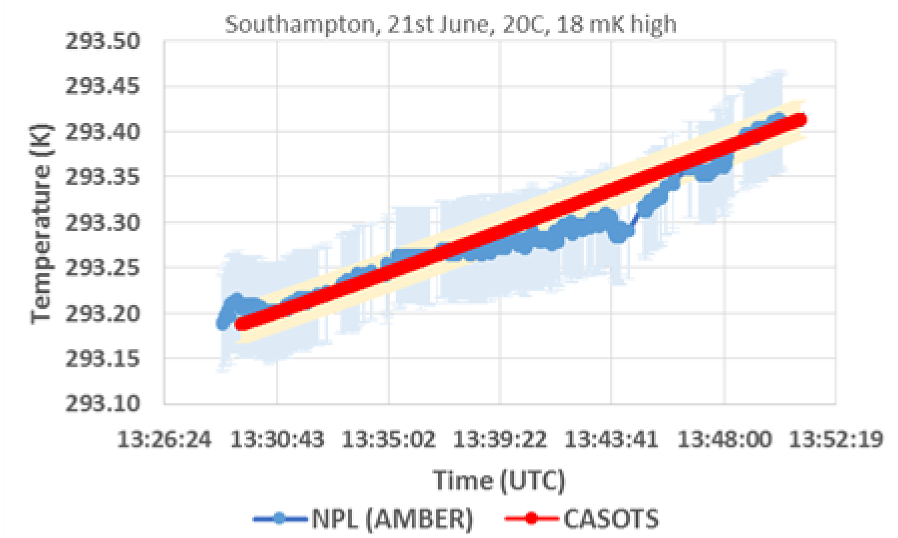

Figure 3.8.3.5: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 21st June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 18 mK higher than the corresponding value measured by the AMBER radiometer.

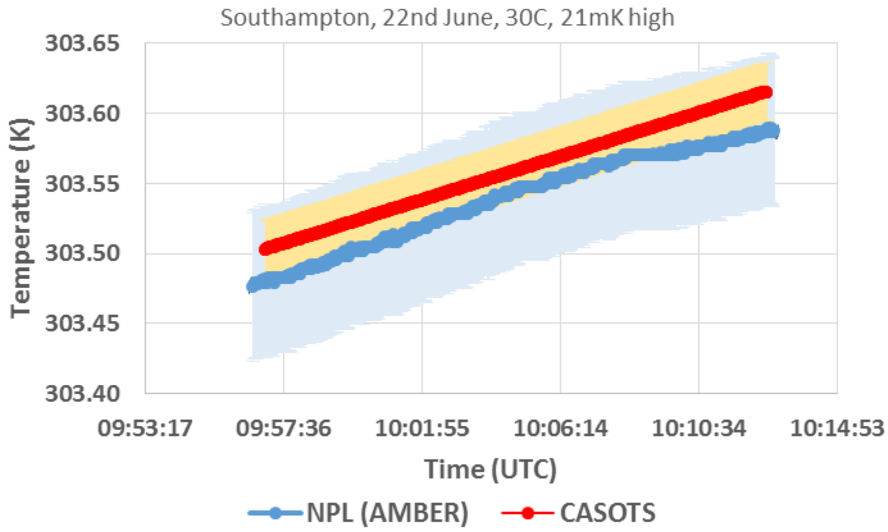

Figure 3.8.3.6: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 21 mK higher than the corresponding value measured by the AMBER radiometer.

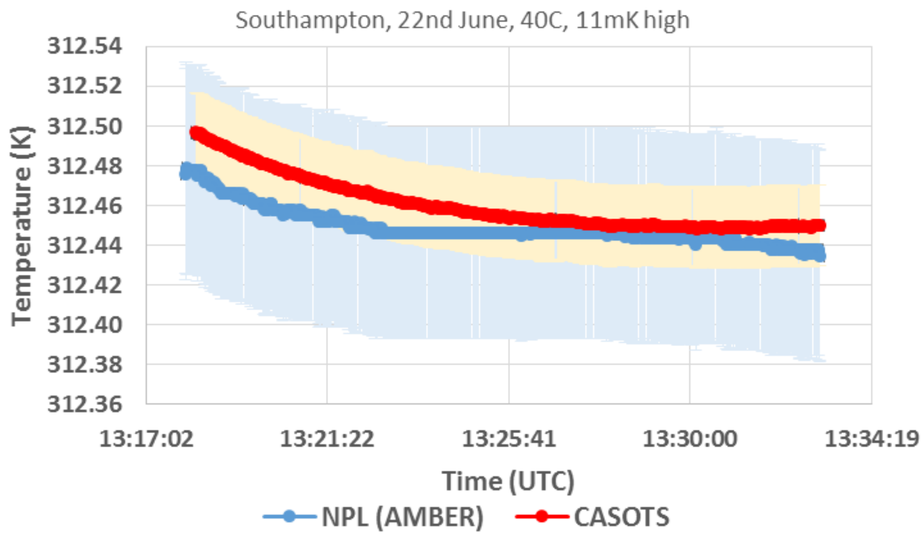

Figure 3.8.3.7: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 22nd June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 11 mK higher than the corresponding value measured by the AMBER radiometer.

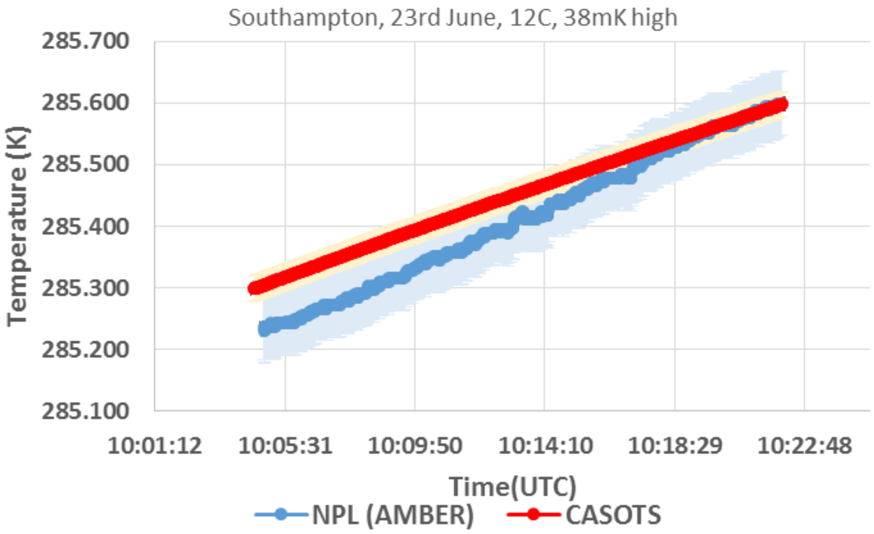

Figure 3.8.3.8: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 12 °C. The average measurement of the blackbody was 38 mK higher than the corresponding value measured by the AMBER radiometer.

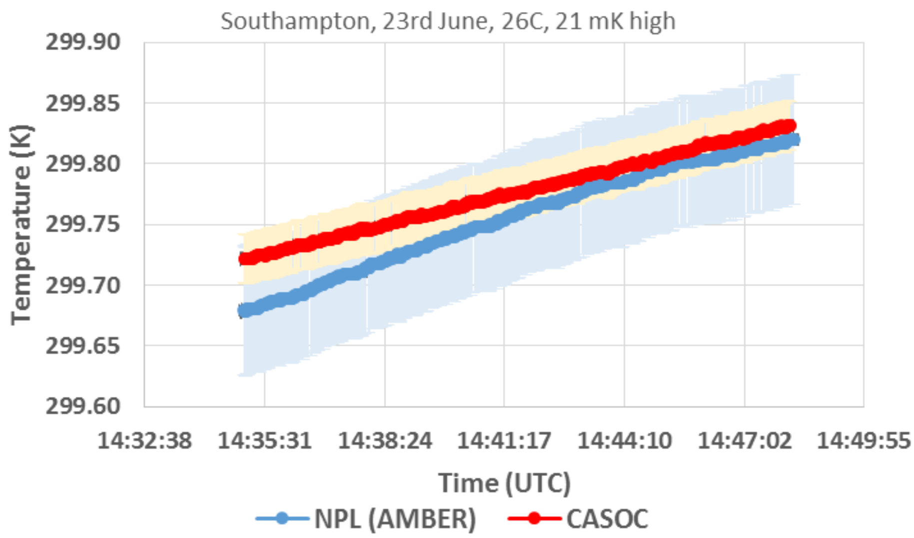

Figure 3.8.3.9: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer on the 23rd June, while the blackbody was operating at about 26 °C. The average measurement of the blackbody was 21 mK higher than the corresponding value measured by the AMBER radiometer.

3.8.4 Southampton University Blackbody Measured by the PTB Radiometer

Figures 3.8.4.1 to 3.8.4.9 show the measurements reported by the Southampton University CASOC II blackbody as well as the temperature of the same blackbody measured by the PTB radiometer, as a function of time, at different temperatures in the 12 °C to 40 °C temperature range. The blackbody measurements are shown in red, while the PTB radiometer measurements are shown in blue. Also shown as black error bars in these Figures is the uncertainty of the PTB radiometer during these measurements. The uncertainty of the Southampton blackbody is shown as light orange throughout the duration of the comparison.

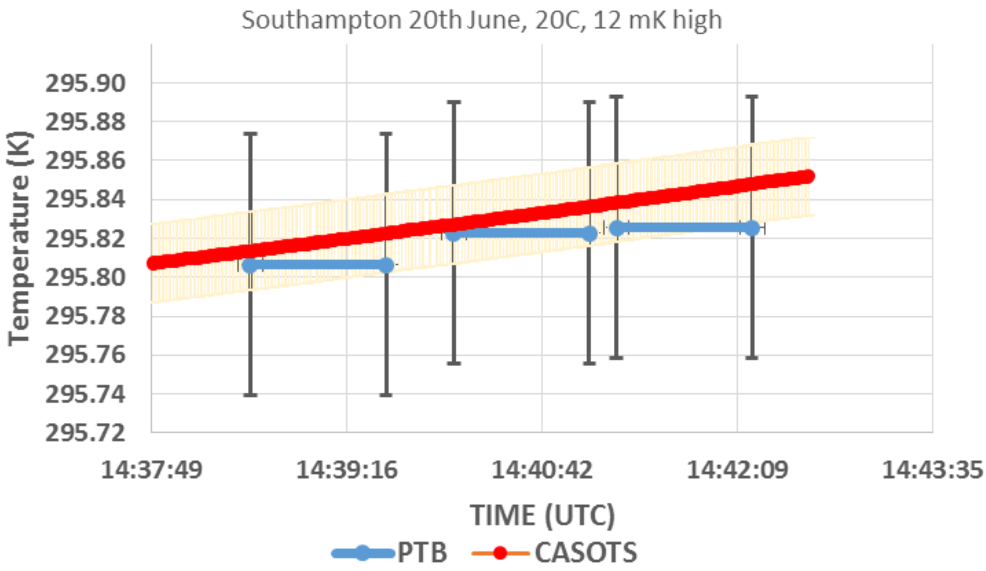

Figure 3.8.4.1: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 12 mK higher than the value measured by the PTB radiometer.

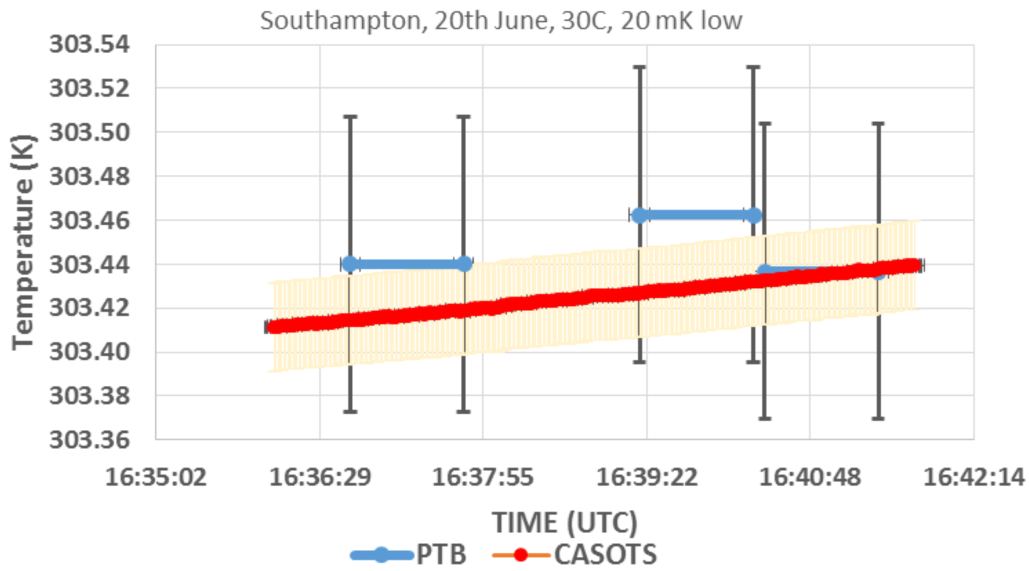

Figure 3.8.4.2: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 20th June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 20 mK lower than the value measured by the PTB radiometer.

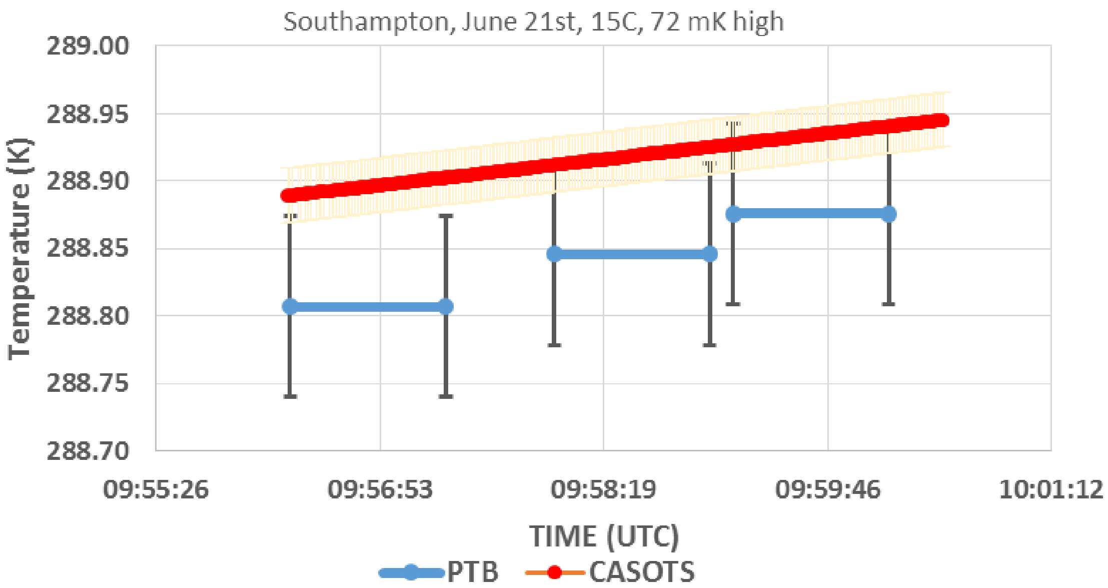

Figure 3.8.4.3: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 15 °C. The average measurement of the blackbody was 72 mK higher than the value measured by the PTB radiometer.

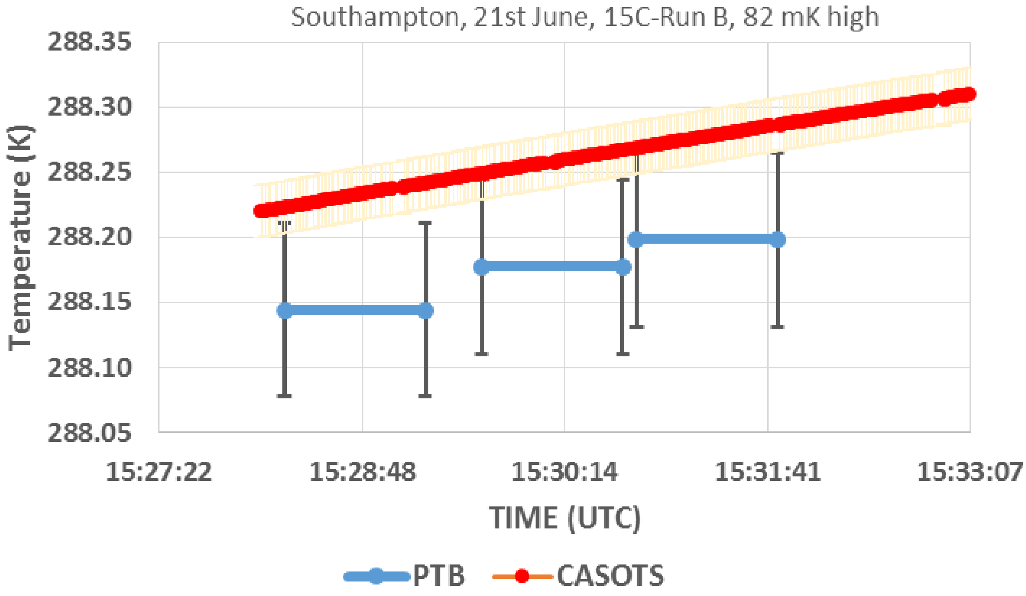

Figure 3.8.4.4: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 15 °C (2nd run). The average measurement of the blackbody was 82 mK higher than the corresponding value measured by the PTB radiometer.

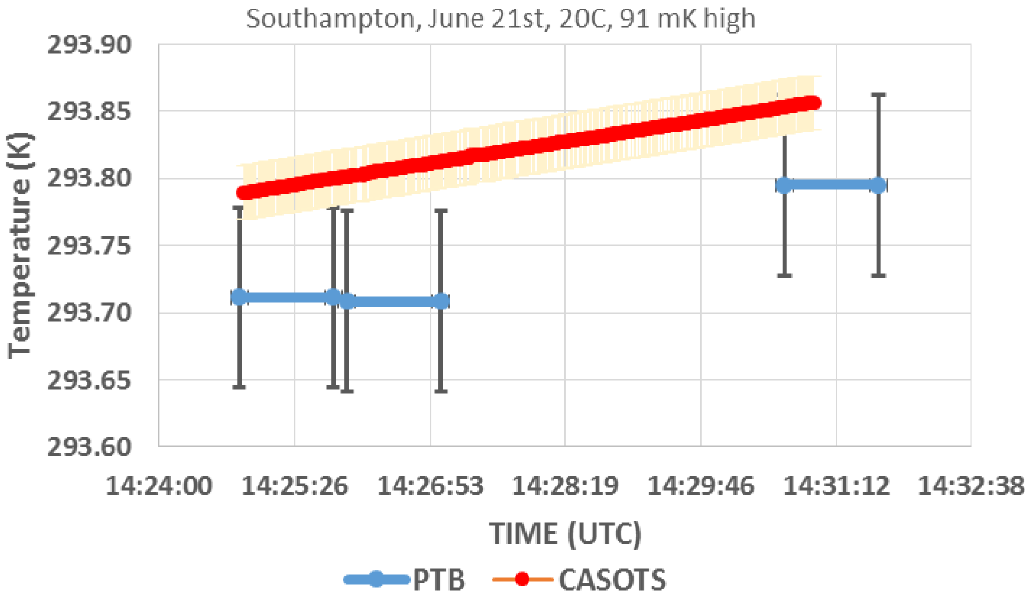

Figure 3.8.4.5: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 21st June, while the blackbody was operating at about 20 °C. The average measurement of the blackbody was 91 mK higher than the corresponding value measured by the PTB radiometer.

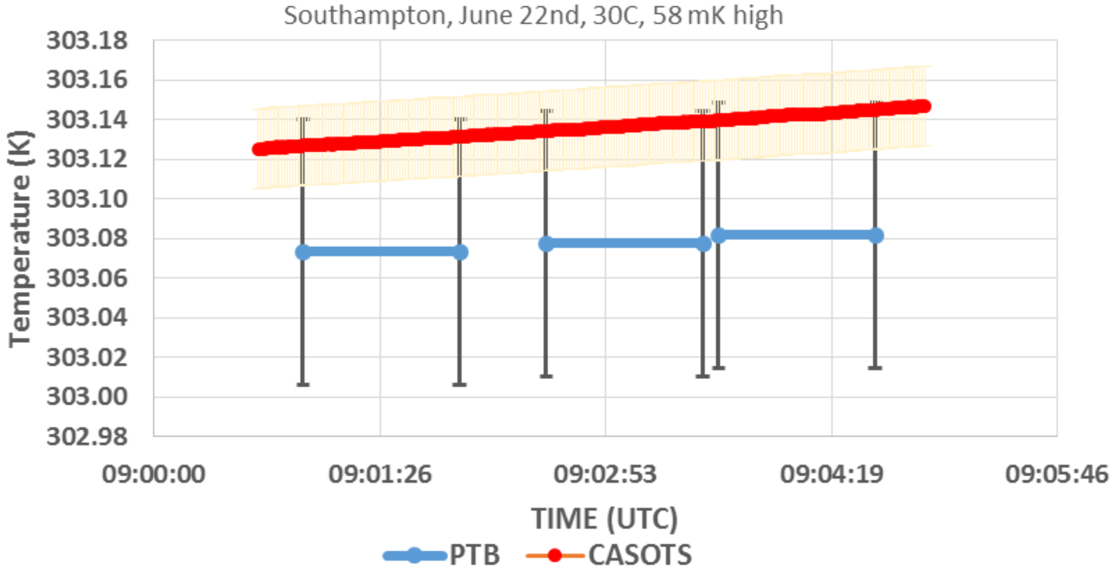

Figure 3.8.4.6: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 30 °C. The average measurement of the blackbody was 58 mK higher than the corresponding value measured by the PTB radiometer.

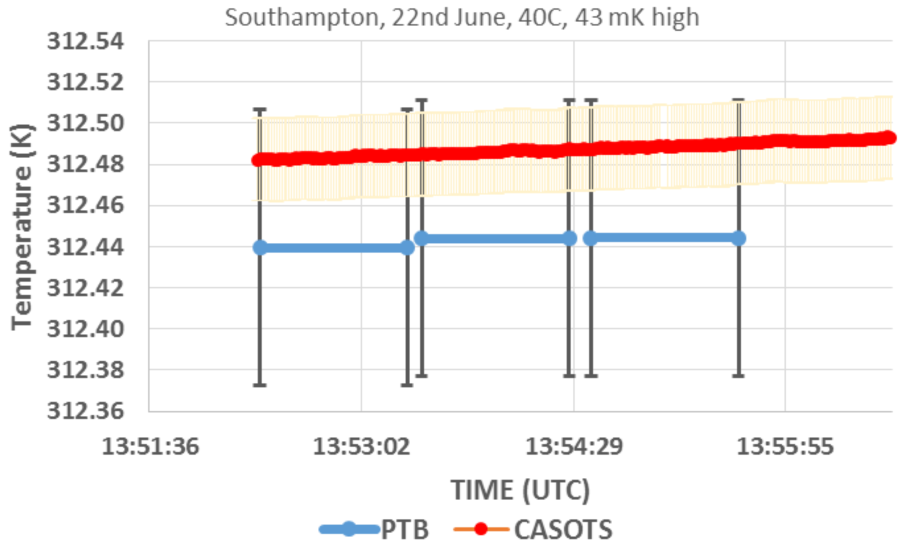

Figure 3.8.4.7: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 22nd June, while the blackbody was operating at about 40 °C. The average measurement of the blackbody was 43 mK higher than the corresponding value measured by the PTB radiometer.

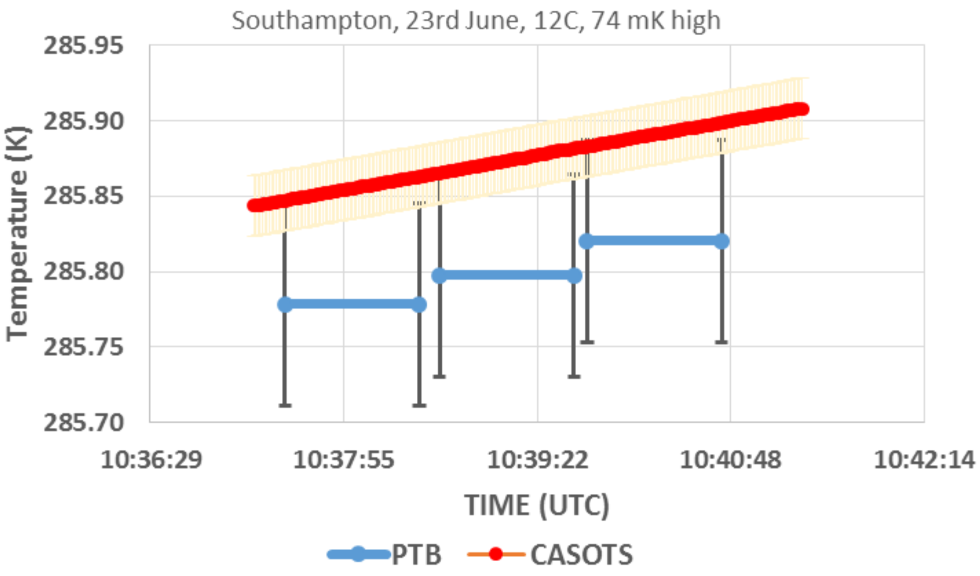

Figure 3.8.4.8: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 12 °C. The average measurement of the blackbody was 74mK higher than the corresponding value measured by the PTB radiometer.

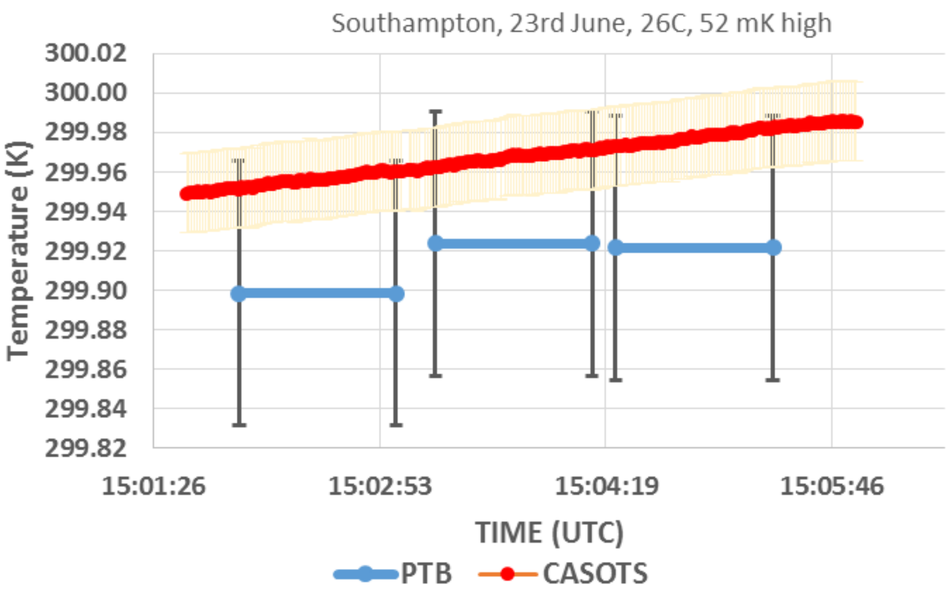

Figure 3.8.4.9: Measurements (as a function of time) reported by the Southampton University blackbody as well as the temperature of the same blackbody measured by the PTB radiometer on the 23rd June, while the blackbody was operating at about 26 °C. The average measurement of the blackbody was 52 mK higher than the corresponding value measured by the PTB radiometer.

4. COMPARISON OF THE MEASUREMENTS

Table 4.1 shows the summary of the difference between the temperature of the blackbodies provided by participants and the temperature of the same blackbodies measured by AMBER and the PTB radiometer at different nominal blackbody temperatures.

Table 4.1: Difference between the temperature of the blackbody provided by participants and the temperature of the same blackbodies measured by AMBER and the PTB radiometer at different nominal blackbody temperatures

Participant	Nominal Temperature	versus AMBER	versus PTB
	°C	mK	mK
Southampton	12	38	74
CASOTS II	15	-27	72
	15	14	82
	18	-9	
	20	-6	12
	20	18	91
	26	21	52
	30	10	-20
	30	21	58
	40	11	43
CSIRO	8	-20	110
CASOTS II	15	-12	75
	15	-18	55
	20	-11	66
	20	-3	50
	25	19	53
	30	33	55
	30	4	71
	30		72
	35	13	38
RAL	15	11	76
SISTeR	18	12	67
	20	5	49
	25		9
	25	16	
	30	12	5
	33	14	45
	35	23	
	40	31	
	45	52	55
Valencia	0	1	199
	0	57	196
	10	44	202
	10		180

	15	77	175
	20	71	96
	20	83	154
	25	55	120
	30	57	-23
	30	-12	76
	35	-8	51
	40	-40	-22
	40	-26	-13
	50	-19	-19
	50	-19	-16
MIAMI	15	19	62
	20	-2	20
	25	14	60
	30	11	15
	35	41	59
	40	65	63
	45	71	59
ONERA	11		194
	12		70
	15	26	44
	15		58
	20	10	-8
	25		-21
	30	-112	-172
	35		-171
	40		-204
	45		-244
	45		-226
	50	-221	-289
	55		-401
	60		-516
	65		-574
	70		-660
	75		-734
Qingdao	20	-17	58
	23		71
	25	13	34
	27	23	80
	30	37	46
	32	57	91
	35	70	67

Figures 4.1 to 4.7 show the difference between the mean of the measurements reported by the participating blackbodies and the temperatures measured by AMBER (shown in blue) and the PTB radiometer (shown in red) at nominal blackbody temperatures of 10 ºC, 15 ºC, 20 ºC, 25 ºC, 30 ºC, 35 ºC and 40 ºC. Also shown in these Figures are error-bars representing the combined uncertainty of the measurements.

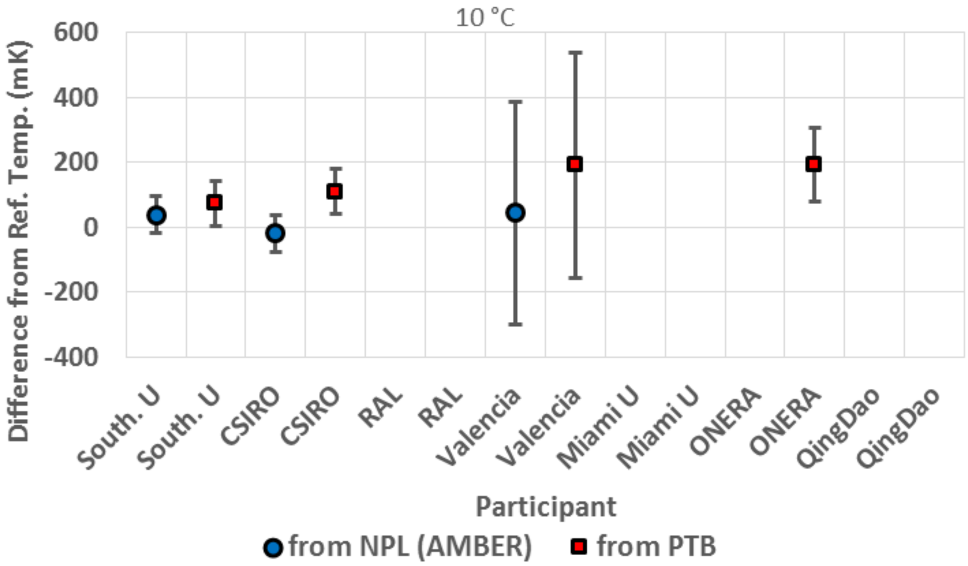

Figure 4.1: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 10 ºC.

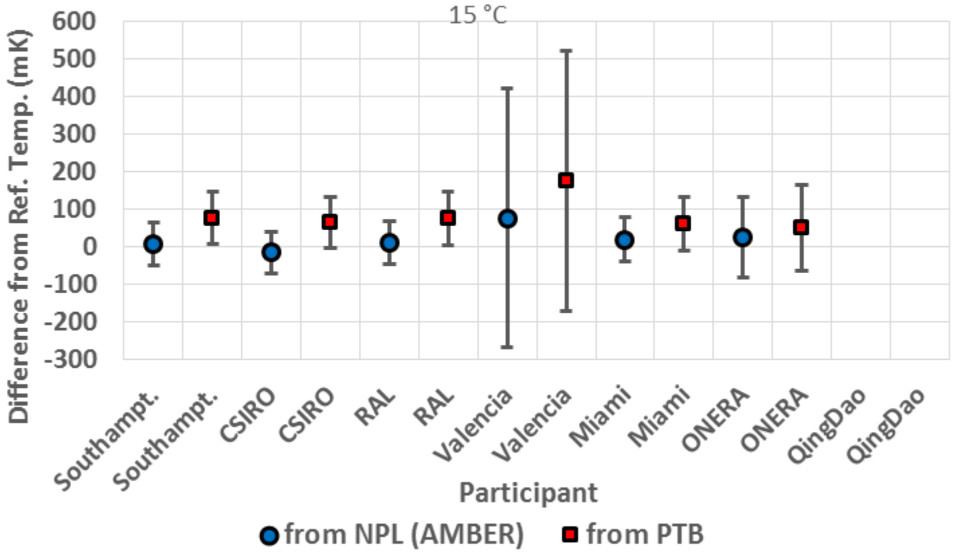

Figure 4.2: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 15 ºC.

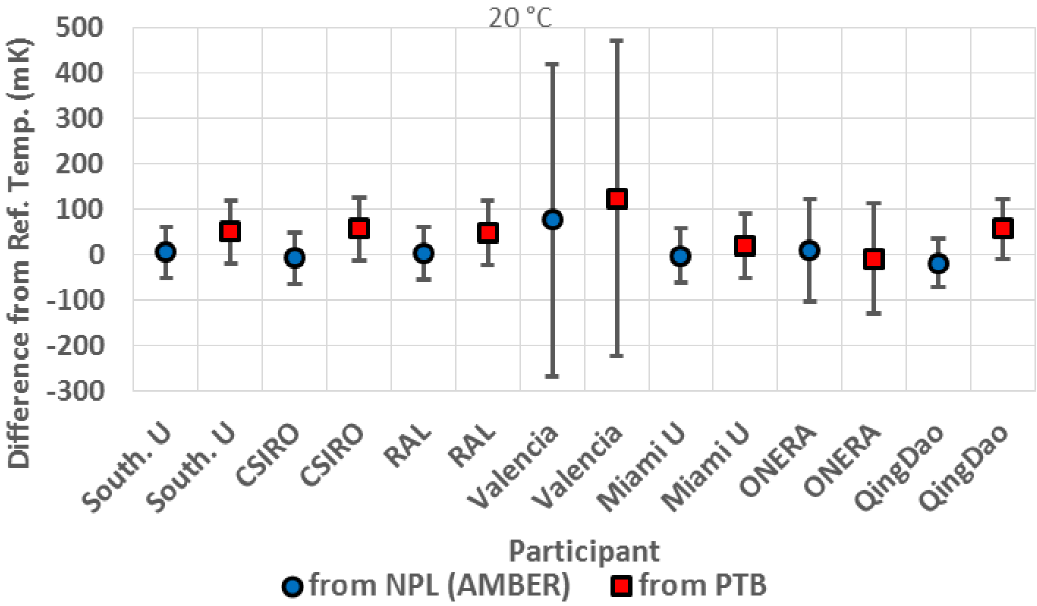

Figure 4.3: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 20 ^{o}C.

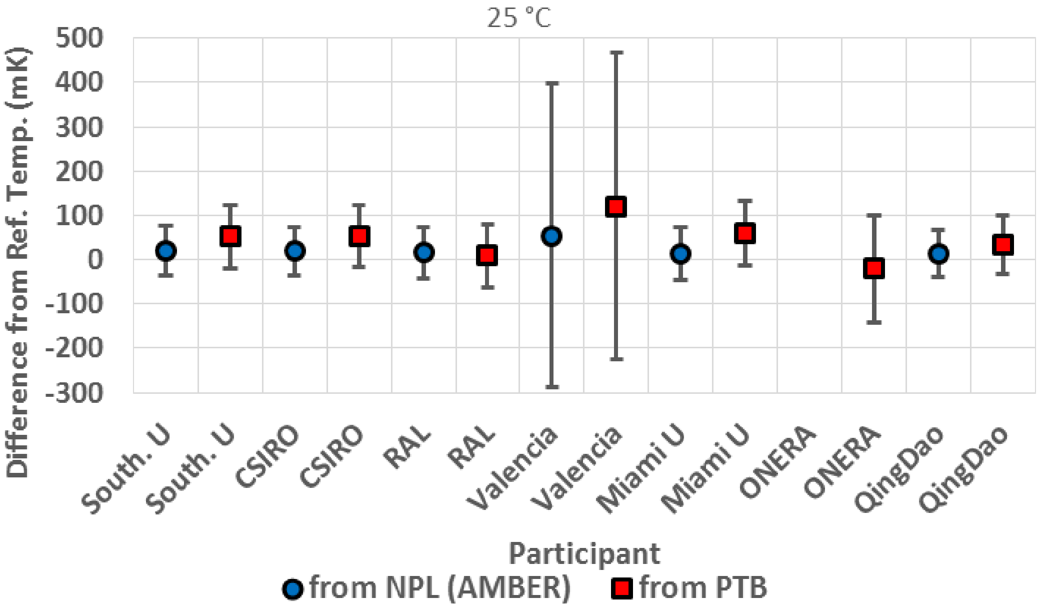

Figure 4.4: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 25 ^{o}C.

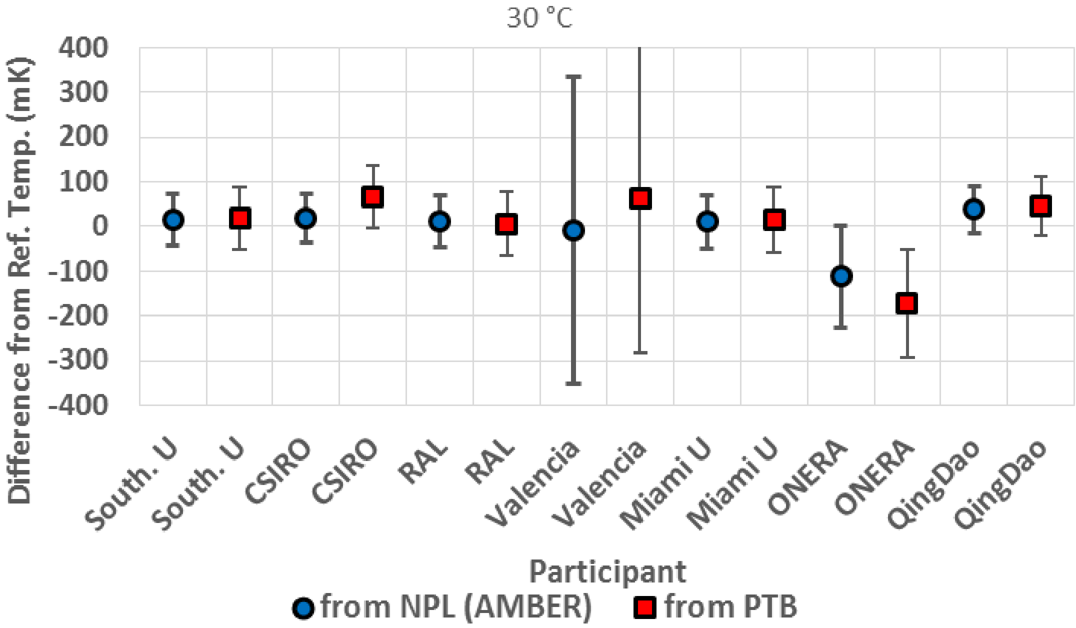

Figure 4.5: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 30 ºC.

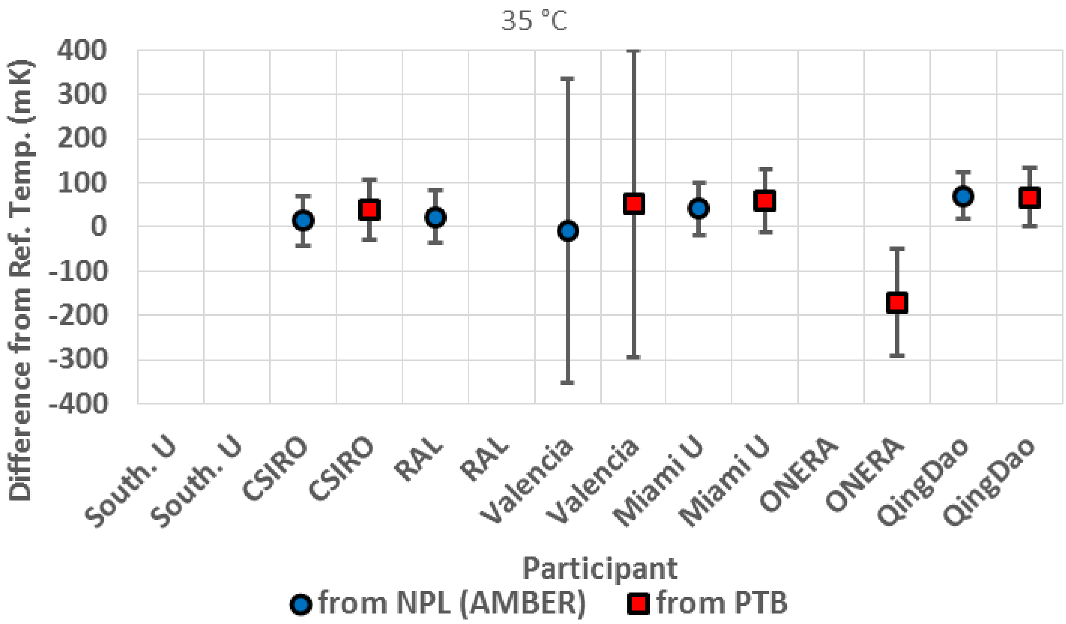

Figure 4.6: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 35 ºC.

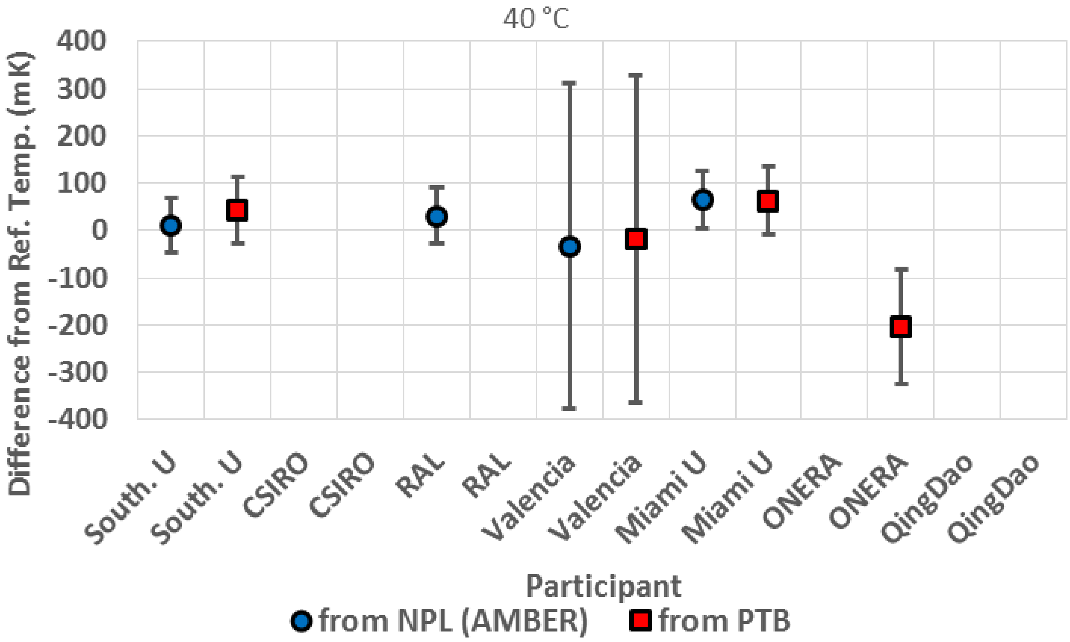

Figure 4.7: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 40 ^{o}C.

Figure 4.8 shows the difference between the mean of the temperature measurements reported by the Valencia University blackbody and the mean of the temperatures measured by AMBER (shown in blue) and the PTB radiometer (shown in red) at nominal blackbody temperatures in the 0 ^{o}C to 50 ^{o}C range. Also shown are the combined uncertainties of the measurements made by AMBER and the PTB radiometer. Figures 4.9, 4.10, 4.11, 4.12 4.13 and 4.14 show the corresponding plots for the blackbodies of the University of Southampton, CSIRO, RAL, Qingdao, ONERA and Miami University, respectively.

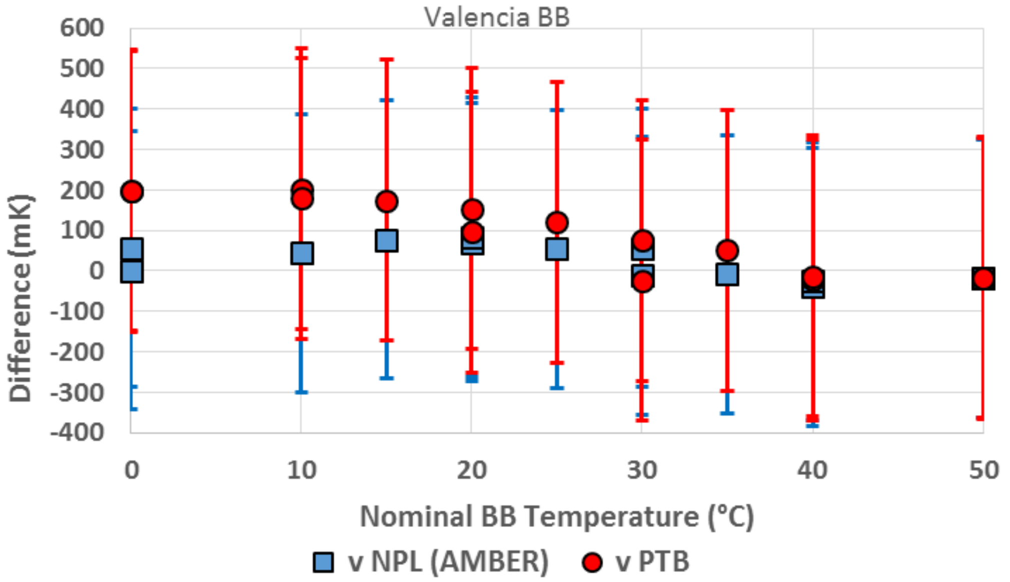

Figure 4.8: Plots of the difference between the mean of the measurements reported by the Valencia University blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 0 °C to 50 °C range.

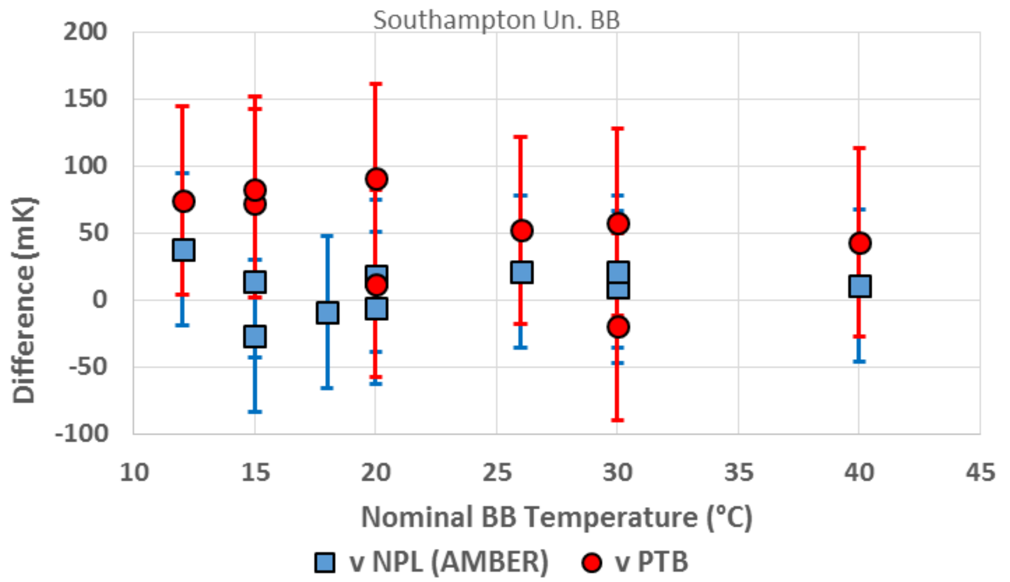

Figure 4.9: Plots of the difference between the mean of the measurements reported by the Southampton University CASOTS II blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 12 °C to 40 °C range.

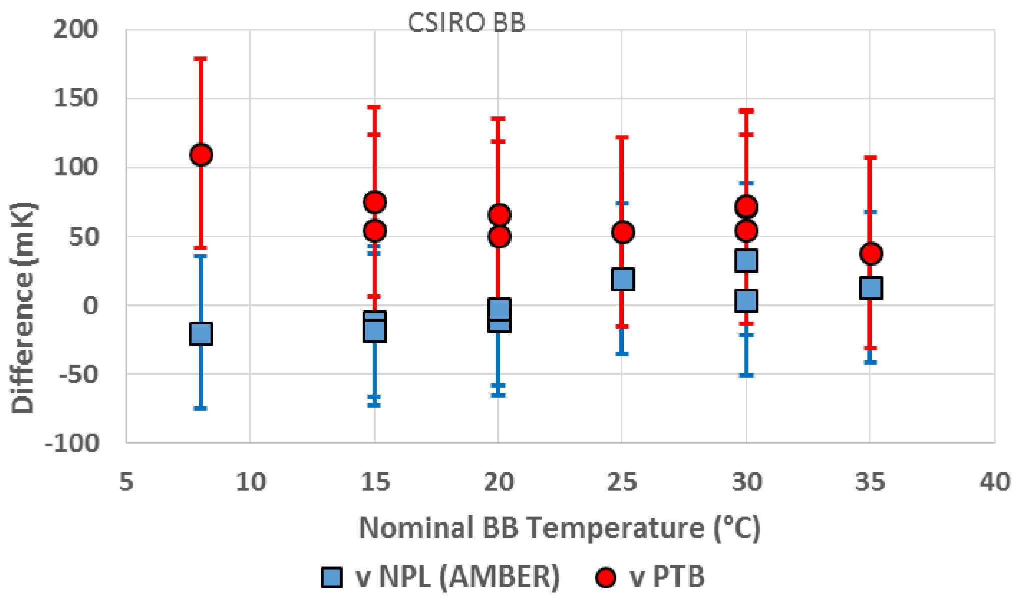

Figure 4.10: Plots of the difference between the mean of the measurements reported by the CSIRO CASOTS II blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 8 °C to 35 °C range.

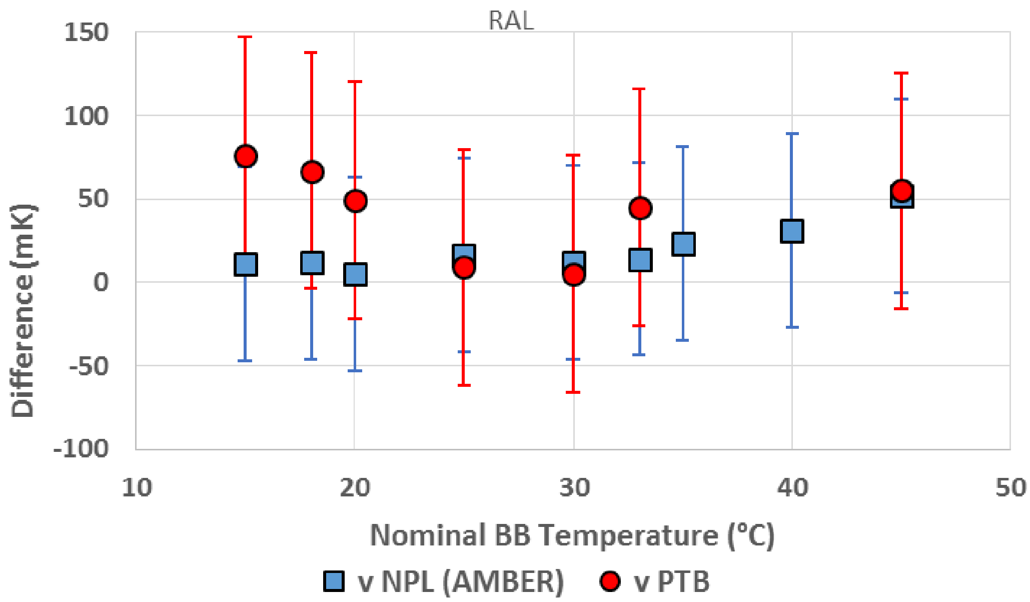

Figure 4.11: Plots of the difference between the mean of the measurements reported by the RAL blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 15 °C to 45 °C range.

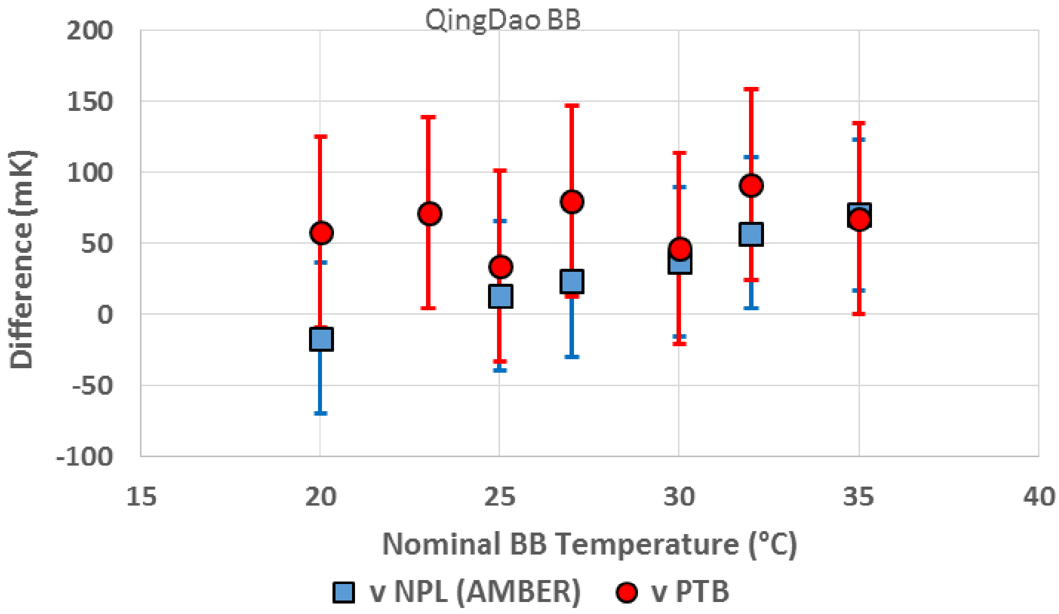

Figure 4.12 Plots of the difference between the mean of the measurements reported by the Qingdao blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 20 °C to 35 °C range.

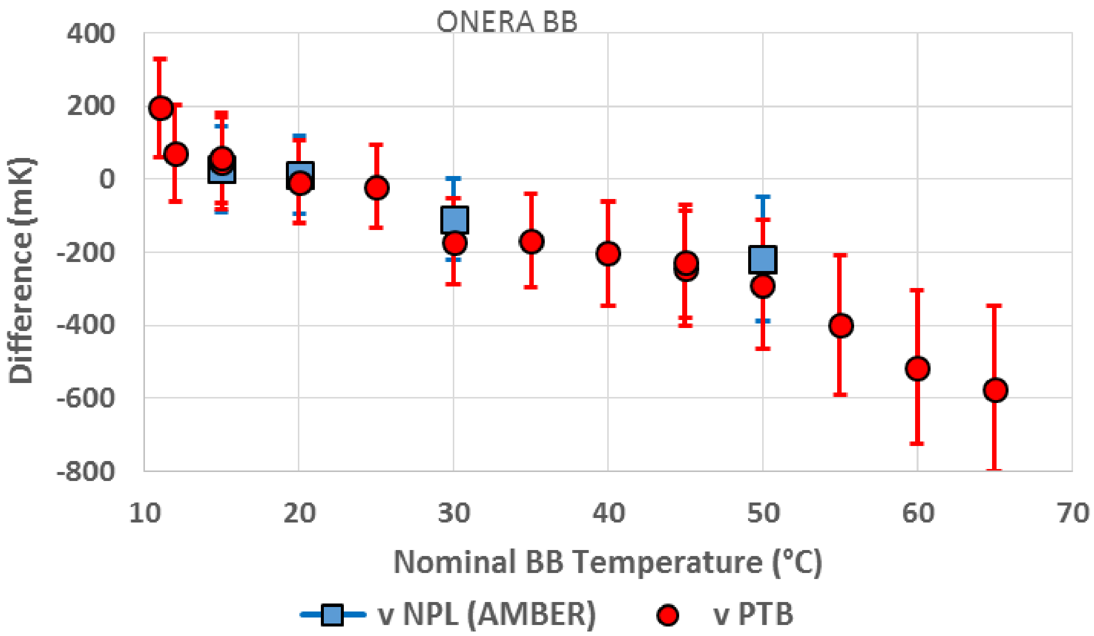

Figure 4.13: Plots of the difference between the mean of the measurements reported by the ONERA blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 12 °C to 65 °C range.

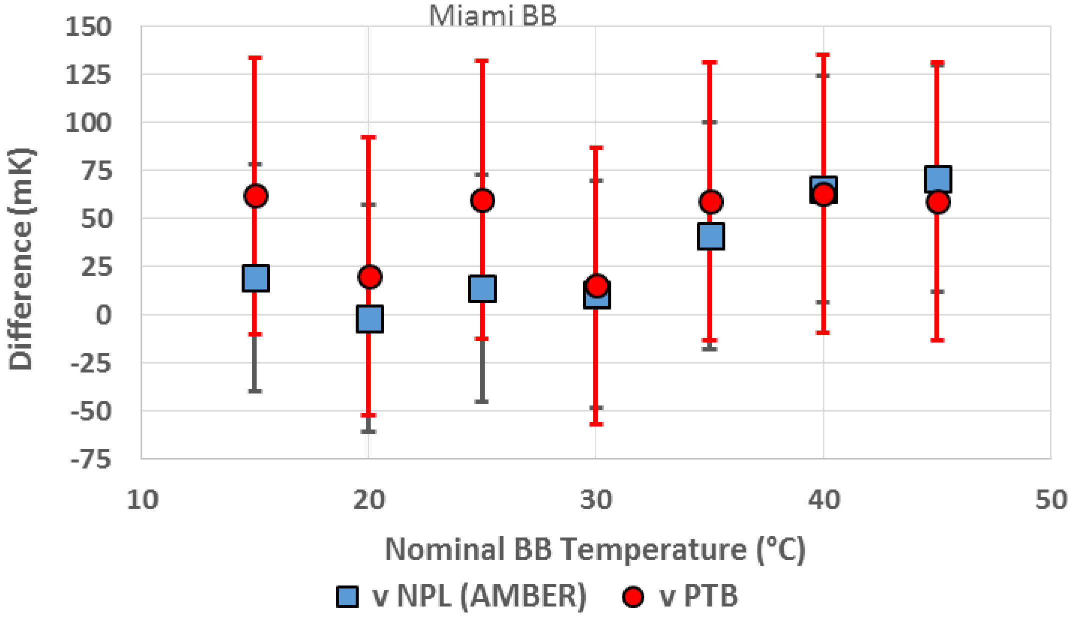

Figure 4.14: Plots of the difference between the mean of the measurements reported by the Miami University blackbody and the mean of the temperatures measured by AMBER (shown in blue) and PTB (shown in red) at nominal blackbody temperatures in the 12 °C to 45 °C range.

5. DISCUSSION AND CONCLUSIONS

Figures 4.1 to 4.7 show the difference between the mean of the measurements reported by the participating blackbodies and the temperatures measured by AMBER and the PTB radiometer at nominal blackbody temperatures of 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C and 40 °C. Also shown in these Figures are error-bars representing the combined uncertainty (k=1) of each measurement. Figures 4.8, 4.9, 4.10, 4.11, 4.12 4.13 and 4.14 show the difference between the mean of the temperature measurements reported by Valencia University, University of Southampton, CSIRO, RAL, Qingdao, ONERA and Miami University, respectively and the temperatures measured by AMBER and the PTB radiometer at nominal blackbody temperatures in the 0 °C to 50 °C range. Also shown are the combined uncertainties of the measurements made by AMBER and the PTB radiometer. Figures 4.1 to 4.14 show that in most cases, the difference between the measurements made by the participating radiometers and the measurements made by AMBER and the PTB radiometers are within the combined uncertainty of the measurements, so the conclusion is that in the bulk of the measurements, the participating blackbodies agree with the measurements made by the AMBER radiometer and the PTB radiometer.

One obvious exception is provided by the ONERA blackbody. While measurements made by the AMBER and PTB radiometers on the ONERA blackbody agree well with each other for all temperatures (see Figure 4.13), the measurements seem to disagree with the measurements provided by the ONERA blackbody for temperatures higher than 30 °C. ONERA investigated this behaviour when it was made aware of these results. It appears that the blackbody was calibrated using a radiative method instead of a thermometric method so that the set temperature was incorrectly considered as the surface temperature. ONERA recalculated the bias between the set temperature and the surface temperature, in accordance with the manufacturer radiative calibration procedure. The results obtained with this new compensation are shown in Figure 5.1. The deviation of the bias with temperature is clearly improved.

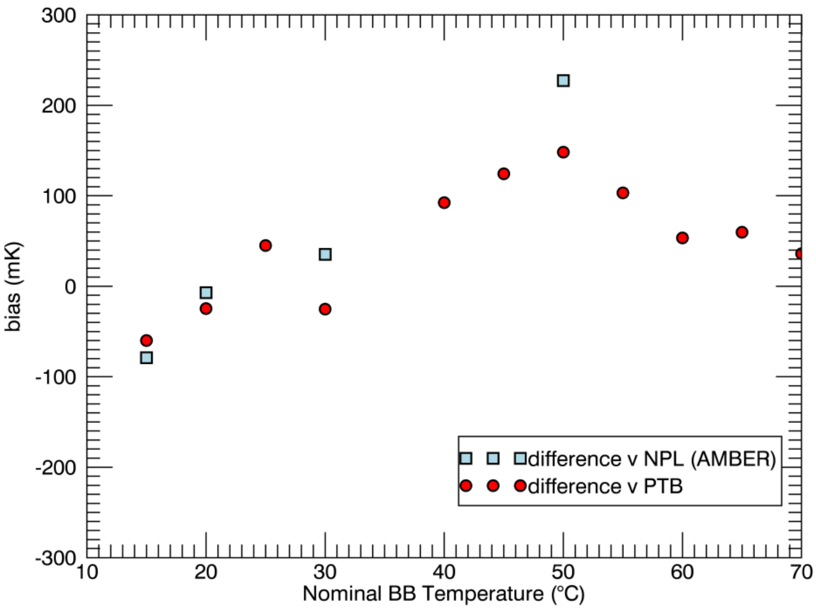

Figure 5.1: Plots of the difference between the mean of the measurements recalculated by ONERA and the mean of the temperatures measured by AMBER and PTB at nominal blackbody temperatures in the 12 °C to 70 °C range.

Another conclusion is that for low temperatures, the difference between the measurements provided by the test blackbodies and that of the PTB radiometer is generally larger than the difference of the measurement of the same blackbody and the AMBER radiometer. However, the difference in these measurements is within the combined uncertainty of the measurements, so the measurements are deemed to be in agreement.

Appendix 1 shows the uncertainty budget associated with the measurements made by the AMBER radiometer.

6. LESSONS LEARNT

The aim of this section is to highlight issues and lessons learnt during the 2016 blackbody laboratory comparison, so they can be avoided or their effects diminished in future comparisons.

i. The FoV of the reference radiometers being used should be small enough to ensure that they are well overfilled by the aperture of the cavity of the blackbodies participating in the comparison.
ii. In cases where the reference radiometers cannot be placed close to the aperture of the cavity of a participating blackbody, the extra distance between the blackbody

cavity aperture and the radiometer should be included in the calculations to ensure that the blackbody aperture still overfills the FoV of the reference radiometers.

iii. The temperature of the cavity of participating blackbodies being viewed by the reference radiometers should be as spatially uniform as possible. The reference radiometer should be measuring and reporting the temperature along the optical axes of the participating blackbodies.

iv. When two or more reference radiometers are used to measure the participating blackbodies, the areas of the cavity of the blackbody observed by the different radiometers should be the identical. Furthermore, the areas viewed should be large enough to average out possible spatial non-uniformities in the temperature present in the blackbody cavities.

v. Because different reference radiometers being used could have different FoVs, it is recommended that in future reference radiometers should be placed at different distances from the apertures of the participating blackbodies to ensure that the FoVs of the radiometers “cover” the same (identical) area of the back walls of the blackbodies. The aim of this is to ensure that the same temperature non-uniformities of the blackbodies are seen (and averaged out) by every reference radiometer.

vi. Participating blackbodies whose cavity temperatures are not actively stabilised but are allowed to drift should endeavour to keep the magnitude of the drifts as low as possible in order to minimise any differences which could arise due to the timing of the measurements.

7. REFERENCES

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Acknowledgements

The authors wish to thank all the participants for all their patience in the execution of the laboratory blackbody comparison at NPL. The authors also wish to thank Max Reiniger and his colleagues at PTB for their input in the same comparison. The University of Valencia participation in the 2016 FRM4STS comparison was funded by the Spanish Ministerio de Economía y Competitividad and the European Regional Development Fund (FEDER) through the project CGL2015-64268-R (MINECO/FEDER, UE) and by the Ministerio de Economía y Competitividad through the project CGL2013-46862-C2-1-P (MINECO).

APPENDIX 1: UNCERTAINTY OF THE AMBER RADIOMETER.

The AMBER radiometer was designed as an absolute radiometer. However, the measurement uncertainty when this radiometer is used with a HgCdTe-based filter radiometer in the absolute mode in the 8 µm to 12 µm wavelength range is relatively high. This is mainly due to the temporal responsivity drift associated with HgCdTe detectors due to the "Theo-squared" effect, where the absolute responsivity of HgCdTe detectors is affected by the radiance of the objects in their field of view and therefore their temperature (E. Theocharous and O. J. Theocharous, "Practical limit of the accuracy of radiometric measurements using HgCdTe detectors" *Applied Optics*, **45**, 7753-7759, 2006), and to a lesser extent due to drifts in the responsivity of cryogenically-cooled detectors (E. Theocharous, "On the stability of the spectral responsivity of cryogenically cooled HgCdTe infrared detectors", Infrared Physics and Technology, **48**, 175-180, 2006). A much lower measurement uncertainty is achieved when the HgCdTe detector-based AMBER radiometer is used in a relative mode, i.e. it is used to compare the radiance temperature of the test blackbody with that of a primary reference blackbody such as a gallium fixed-point blackbody. In this case, the AMBER radiometer additionally monitors a reference blackbody (gallium fixed-point blackbody) and thus eliminates the drifts in the responsivity of the HgCdTe-based filter radiometer. The gallium melting point is a defined fixed-point on the ITS-90 temperature scale, so it provides a very attractive reference for the calibration of the radiance temperature of near-ambient-temperature blackbodies. When used in the relative mode, the absolute calibration of the filter radiometer employed by the AMBER radiometer is no longer needed. What is required is the relative spectral irradiance responsivity of the filter radiometer and this is calibrated on the NPL infrared spectral responsivity measurement facility against the NPL spectral irradiance responsivity standards (E. Theocharous, "The establishment of the NPL infrared relative spectral response scale using cavity pyroelectric detectors" *Metrologia*, **43**, S115-S119, 2006). Even then, the uncertainty contribution due to the relative spectral irradiance responsivity calibration of the filter radiometer is small (6 mK at 20 °C, see table A1).

Table A1 shows the systematic (Type B) uncertainty contributions arising when the radiance temperature of a test blackbody maintained in the 10 °C to 50 °C is measured using AMBER, with AMBER utilizing the 10.1 µm filter radiometer. The first uncertainty contribution listed in table A1 is the uncertainty due to the gallium blackbody radiance temperature itself. Although the melting point of gallium is a fixed-point on the ITS-90 and has no inherent uncertainty, other parameters contribute to the uncertainty of the practical realization of the radiance temperature of the gallium blackbody, such as the cavity emissivity.

Table A2 provides the uncertainty budget for the radiance temperature of the gallium blackbody. It shows that the dominant uncertainty contribution is provided by the blackbody emissivity (50 mK with rectangular distribution, which is equivalent to a 29 mK standard uncertainty). Another important uncertainty contribution is provided by the temperature drop due to the "gallium casing" i.e. the temperature outside the gallium reservoir is slightly lower than the actual melting point of gallium due to the temperature drop across the wall of the container containing the metal. The temperature drop was estimated to be 22 mK and a correction to account for this was introduced in the spreadsheet used to calculate the radiance temperature of the test blackbody. A 22 mK uncertainty contribution (rectangular distribution) which is equivalent to a standard uncertainty of 13 mK was also introduced in the uncertainty budget of the gallium blackbody radiance temperature. Table A2 shows that the combined standard uncertainty of the radiance temperature of the gallium blackbody is 32 mK.

Table A1. Systematic standard uncertainties when AMBER measures the radiance temperature of a test blackbody at 20 ˚C radiance temperature

Contribution	Standard Uncertainty / mK	Comment
Uncertainty in the Ga blackbody radiance temperature	32	Taken from Ga blackbody uncertainty budget (see table 3)
Uncertainty due to the lock-in amplifier non-linearity in the -60 °C to 50 °C temperature range [10]	36	0.1% non-linearity in the lock-in amplifier (maximum in the -50 °C to 30 °C temperature range). Depends on the difference between the Ga melting point temperature and the temperature of the target being measured.
Uncertainty in the relative spectral responsivity calibration of 10.1 µm filter radiometer	6	From the calibration of the relative spectral responsivity of the 10.1 µm filter radiometer
Uncertainty due to the definition of the "radiometric zero"	4	From monitoring the AMBER output when the 77 K blackbody is being viewed
Uncertainty in the measurement of the ZnSe AMBER window transmission	1	Common to all blackbody measurements, hence the uncertainty due to this window is small.
Uncertainty in the measurement of the ZnSe AMBER lens transmission	1	Common to all blackbody measurements, hence the uncertainty due to this window is small.
AMBER stability/drift over the period of a measurement	18	based on 0.05% drift over a measurement period i.e. 5 minutes
Uncertainty due to ambient temperature fluctuations	12	See E. Theocharous and N. P. Fox "CEOS comparison of the IR Brightness temperature measurements in support of satellite validation. Part II: Laboratory comparisons of the brightness temperature of blackbodies", NPL Report OP4, September 2010.
Uncertainty due to chopper frequency fluctuations	2	Based on a 0.2 Hz drift in the chopper frequency during a measurement cycle.
Combined uncertainty (*k*=1)	**53 mK**	

Table A2. Standard uncertainty budget of the radiance temperature of the Ga fixed-point blackbody

Contribution	Standard Uncertainty / mK	Comment
Uncertainty due to Ga blackbody emissivity	29	Difference of cavity emissivity (0.9993) from unity is taken to be the uncertainty contribution (with rectangular distribution). The standard uncertainty is provided in mK.
Uncertainty due to Ga blackbody temperature "drop"	13	Estimated from the temperature drop between the Ga metal and the inside surface of the Ga blackbody cavity.
Stability of the Ga blackbody radiance temperature (as indicated by a high resolution radiometer such as AMBER). (type A uncertainty)	4	Standard deviation of measurements over the measurement period i.e. 5 minutes
Uncertainty due to radiation heat loss to the environment	2	Small since the Ga blackbody is operating just above ambient.
Uncertainty due to convective heat loss to the environment	2	Small since the Ga blackbody is operating just above ambient.
Uncertainty due to (spatial) temperature variation inside the cavity	3	
Uncertainty due to ambient temperature fluctuations	2	
Uncertainty due to the purity of the Ga metal	1	The Ga metal used to fill the blackbody cavity was 99.9999% pure.
Combined uncertainty (*k*=1)	**32 mK**	