NPL REPORT OP 4

CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part II: Laboratory comparison of the brightness temperature of blackbodies.

E. Theocharous and N. P. Fox

September 2010

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Engineering Measurement Division

Executive summary

A comparison of terrestrial based Infrared (IR) radiometric instrumentation used to support calibration and validation of satellite-borne sensors with emphasis on sea/water surface temperature was completed at National Physical Laboratory (NPL) and at the University of Miami during April and May 2009. The objectives of the 2009 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 National Metrology Institutes (NMI)s. The 2009 comparison consisted of two stages in order to allow maximum participation and enable the traceability chain to be established to both NPL and the National Institute of Standards and Technology (NIST). Stage 1 took place at NPL in April 2009 and involved the comparison of the participants' blackbodies using the NPL reference transfer radiometer (AMBER). During stage 1, participants' radiometers were also calibrated using the NPL variable temperature blackbody. Stage 2 took place at the Rosenstiel School of Marine and Atmospheric Science (RSMAS) in May 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NIST Thermal-Infrared Transfer radiometer (TXR). During stage 2, participants' radiometers were also calibrated using the RSMAS and NIST water bath blackbodies. Stage 2 also included the testing of the same radiometers alongside each other, completing direct day-time and night-time measurements of the surface temperature of the ocean. A previous report (Theocharous et al., 2010) provided the results, together with uncertainties as provided by the participants, for the comparison of the participants' radiometers, when they were monitoring the radiance temperature of the NPL variable temperature blackbody, the RSMAS water bath blackbody and NIST water bath blackbody. The same report also presented the results of the measurement of the ocean surface temperature completed at RSMAS. The current report describes the comparison of the participants blackbodies at NPL using the NPL AMBER radiometer as well the comparison of the participants' blackbodies at RSMAS using the NIST TXR radiometer. During the 2009 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.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by Dr Ian Severn, Head, Engineering Measurement Division.

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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 currently provide the most accurate surface-based measurements which are used for Cal/Val. These radiometers are in principle calibrated traceably to SI units, generally through a blackbody radiator. It is essential for the integrity of their use, that any differences in their calibrations are understood, so that any potential biases can be removed and not transferred to satellite sensors.

A comparison of terrestrial based Infrared (IR) radiometric instrumentation 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). However, eight 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 2009. The objectives of the 2009 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 National Measurement Institutes (NMI)s.

A previous report (Theocharous et al., 2010) provided the results, together with uncertainties as provided by the participants, for the comparison of the participants' radiometers, when they were monitoring the radiance temperature of the NPL variable temperature blackbody, the RSMAS water bath blackbody and NIST water bath blackbody. The same report also presented the results of the measurement of the ocean surface temperature completed at RSMAS. Some of the participants use external, traceably calibrated blackbodies in order to calibrate their radiometers, while others use external blackbodies in order to confirm the calibration of their radiometers which rely on blackbodies which are internal to the radiometers. The current report describes the comparison of the participants blackbodies which are either used to calibrate their radiometers or to confirm the calibration of their radiometers. One part of the blackbody comparison was completed at NPL using the NPL AMBER radiometer, while another part of the same comparison was completed at RSMAS using the NIST TXR radiometer. During the 2009 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 presented are in this report.

2. ORGANISATION OF THE COMPARISON

During the 2009 blackbody comparison, NPL acted as the pilot laboratory and provided traceability to SI units during laboratory comparisons in Europe. NIST provided traceability to SI units during laboratory measurements at RSMAS. The 2009 comparison consisted of two stages (NPL and RSMAS) in order to allow maximum participation and enable the traceability chain to be established to both NPL and NIST. Stage 1 took place at NPL in April 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NPL reference transfer radiometer (AMBER) (Theocharous et al., 1998). The performances of 4 blackbodies were compared during Stage 1. Stage 2 took place at RSMAS in May 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NIST Thermal-Infrared Transfer radiometer (TXR) (Rice and Johnson, 1998). The performance of two blackbodies was completed during stage 2.

The current report provides the results, together with uncertainties as provided by the participants, of the comparison of the participants' blackbodies, using the NPL AMBER radiometer (Stage 1) and the NIST TXR radiometer (Stage 2). During the 2009 comparison, all participants were encouraged to develop uncertainty budgets for their blackbodies. In order to achieve optimum comparability, tables containing the principal influence parameters for the measurements were provided to all participants.

All measurements reported by the participants, along with their associated uncertainties were analysed by the pilot laboratory and are presented in this report.

3. PARTICIPANTS MEASUREMENTS AND RESULTS

Section 3 provides the results of the comparison of the participants' blackbodies, completed using the NPL AMBER radiometer and the NIST TXR radiometer. Section 3 also provides the uncertainties (and, when available, the uncertainty budgets) of the blackbodies which took part in the comparisons, 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 being included in this report, along with a summary of the results for each participant for each stage of the comparison.

3.1 Dept. of Earth Physics and Thermodynamics (DEPT), University of Valencia

3.1.1 Contact information

DEPT contact for the comparison: Dr Cesar Coll
Address: Dept. of Earth Physics and Thermodynamics, Faculty of Physics, University of Valencia, Dr. Moliner, 50. 46100, Burjassot, Spain.
Email: cesar.coll@uv.es

3.1.2 Blackbody used for the comparison

Land Infrared Landcal Blackbody Source P80P.
(http://landinstruments.net/infrared/products/calibration_sources/p80p.htm).

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

Reference: Landcal Blackbody Source Type P80P Operating Instructions.

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

The blackbody has not undergone a traceable primary calibration. The following error analysis is based on estimates, experience and laboratory measurements (April 6 and 7, 2009):

Type A
- Repeatability: 0.01% or 0.03 K (variations of 0.01 Ω in external PRT-100 measurements).
- Reproducibility: 0.01% or 0.03 K (variations of 0.01 Ω in external PRT-100 measurements).
- Stability of source: 0.004% or 0.01 K (variations of 0.01 Ω in external PRT-100 measurements).

Total Type A uncertainty (RSS): 0.015% or 0.04 K

Type B
- Emissivity: uncertainty <0.005 (according to manufacturer), which corresponds to a temperature error of 0.3 K at 8-14 μm
- Blackbody thermometer calibration: 0.1 K (External PRT calibration with an ice point apparatus, and comparison with an identical blackbody from the University of La Laguna, Spain, which has a UKAS certificate.
- Blackbody isothermal variance: 0.3 K (value provided by manufacturer)
- Primary source: 0.6 K. Primary source calibration is not available for this blackbody. The assigned value is the same for the identical University of La Laguna blackbody (calibrated with UKAS certificate) corresponding to the uncertainty (coverage factor k=1) of the standard radiation thermometer used in the blackbody calibration for temperature range from 10 °C to 30 °C.

Total Type B uncertainty (RSS): 0.7 K.

Type A + Type B uncertainty (RSS): 0.7 K.

Operational methodology during measurement campaign

The blackbody was set to a fixed temperature (0.0 °C) and sufficient time was allowed for the source to reach the fixed point. Temperatures were read from the internal thermometer, the external PRT-100 and another available PRT. An ice point apparatus was used to calibrate the external PRTs. In some cases, we assumed the same uncertainty values reported by the UKAS certified calibration of the identical blackbody mentioned above. Such calibration data reports differences between the blackbody internal temperature, the external PRT temperature, and a standard radiation thermometer temperature with traceable calibration, including the uncertainty of the latter.

Uncertainties associated with the Landcal P80P blackbody

Black body Land Infrared Landcal Blackbody Source P80P

Parameter	Type A Uncertainty in Value / %	Type B Uncertainty in Value / (appropriate units)	Uncertainty in Brightness temperature K
Repeatability of measurement	0.01(1)		0.03(1)
Reproducibility of measurement	0.01(1)		0.03(1)
Stability of source	0.004(2)		0.01(2)
Emissivity		0.005(3)	0.3
BB Thermometer cal		0.1 K(4)	0.1
BB Isothermal variance		0.3 K(3)	0.3
Primary Source		0.6 K(5)	0.6
RMS total	0.015 % 0.04 K	0.7 K	0.7

(1) Variations of 0.01 Ω in external PRT.
(2) Variations in internal temperature readout.
(3) Provided by manufacturer.
(4) External PRT calibration with an ice point apparatus, and comparison with same blackbody from University of La Laguna, Spain (calibrated with UKAS certificate).
(5) Not available for this black body. The assigned value is the uncertainty (k=1) of the standard radiation thermometer used in the UKAS certificated calibration of the identical University of La Laguna black body for temperature range from 10 to 30 °C.

3.1.3 Results

The DEPT blackbody took part in the NPL blackbody comparison. Figure 3.1.1 shows the DEPT blackbody cavity temperature values measured by the AMBER radiometer when the blackbody cavity temperature was set to 10 °C. These measurements were acquired on the 21st April and show that the DEPT blackbody brightness temperature was 74 mK lower than the set value. The combined uncertainty of the DEPT blackbody brightness temperature at 10 °C (provided by DEPT) is 0.7 °C (see table above) so the discrepancy was well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the AMBER radiometer calibration). Figure 3.1.2 shows the corresponding measurements acquired on the 22nd April. These measurements show that the DEPT blackbody brightness temperature was 87 mK lower than the set value. The combined uncertainty of the DEPT blackbody brightness temperature at 10 ^{o}C (provided by DEPT) is 0.7 ^{o}C so the discrepancies were well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer).

Figure 3.1.3 shows the DEPT blackbody cavity temperature values measured by the AMBER radiometer when the blackbody cavity temperature was set to 20 ^{o}C. These measurements were acquired on the 21st April and show that the DEPT blackbody brightness temperature was 143 mK lower than the set value. The combined uncertainty of the Valencia University blackbody brightness temperature at 20 ^{o}C (provided by Valencia University) is 0.7 ^{o}C so the discrepancy was well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the AMBER radiometer calibration). Figure 3.1.4 shows the corresponding measurements acquired on the 22nd April. Measurements shown in Figure 3.1.4 indicate that the DEPT blackbody brightness temperature was 166 mK lower than the set value. The combined uncertainty of the DEPT blackbody brightness temperature at 20 ^{o}C (provided by DEPT) is 0.7 ^{o}C so the discrepancies were well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer).

Figure 3.1.5 shows the DEPT blackbody cavity temperature values measured by the AMBER radiometer when the blackbody cavity temperature was set to 30 ^{o}C. These measurements were acquired on the 21st April and show that the Valencia University blackbody brightness temperature was 167 mK lower than the set value. The combined uncertainty of the DEPT blackbody brightness temperature at 20 ^{o}C (provided by Valencia University) is 0.7 ^{o}C so the discrepancy was well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the AMBER radiometer calibration). Figure 3.1.6 shows the corresponding measurements acquired on the 22nd April. Measurements shown in Figure 3.1.6 indicate that the DEPT blackbody brightness temperature was 185 mK lower than the set value. The combined uncertainty of the DEPT blackbody brightness temperature at 30 ^{o}C (provided by DEPT) is 0.7 ^{o}C so the discrepancies were well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer).

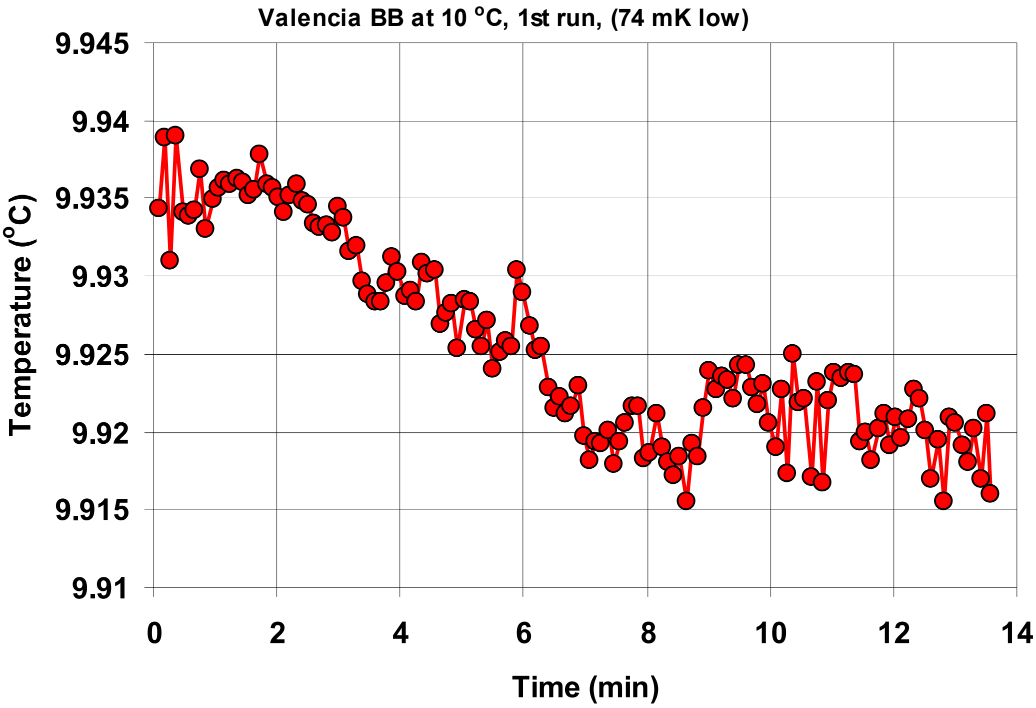

Figure 3.1.1: The DEPT blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 10 °C (1st measurement completed on the 21st April 2009). The average blackbody brightness temperature was 74 mK lower than the set value.

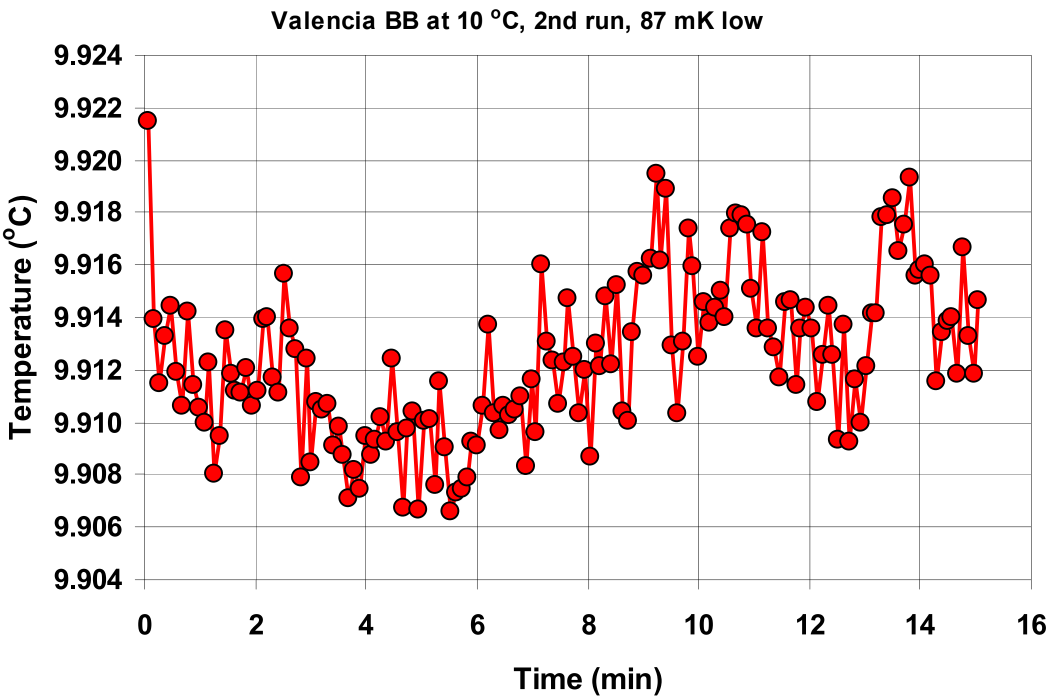

Figure 3.1.2: The DEPT blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 10 °C (2nd measurement completed on the 22nd April 2009). The average blackbody brightness temperature was 87 mK lower than the set value.

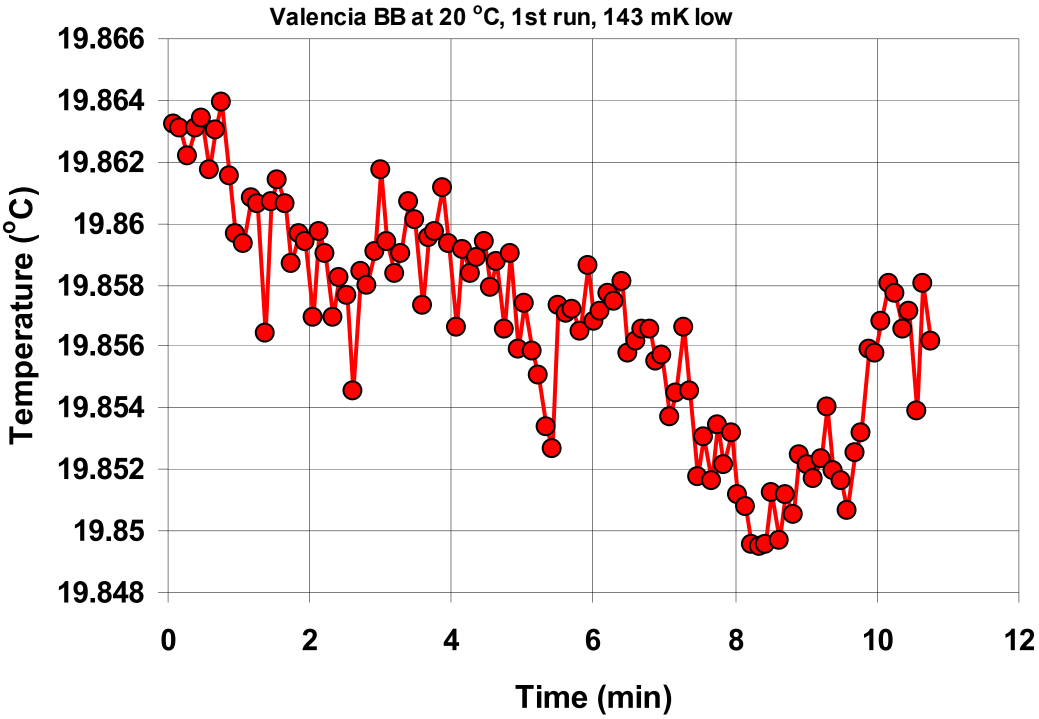

Figure 3.1.3: The DEPT blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 20 °C (1st measurement completed on the 21st April 2009). The average blackbody brightness temperature was 143 mK lower than the set value.

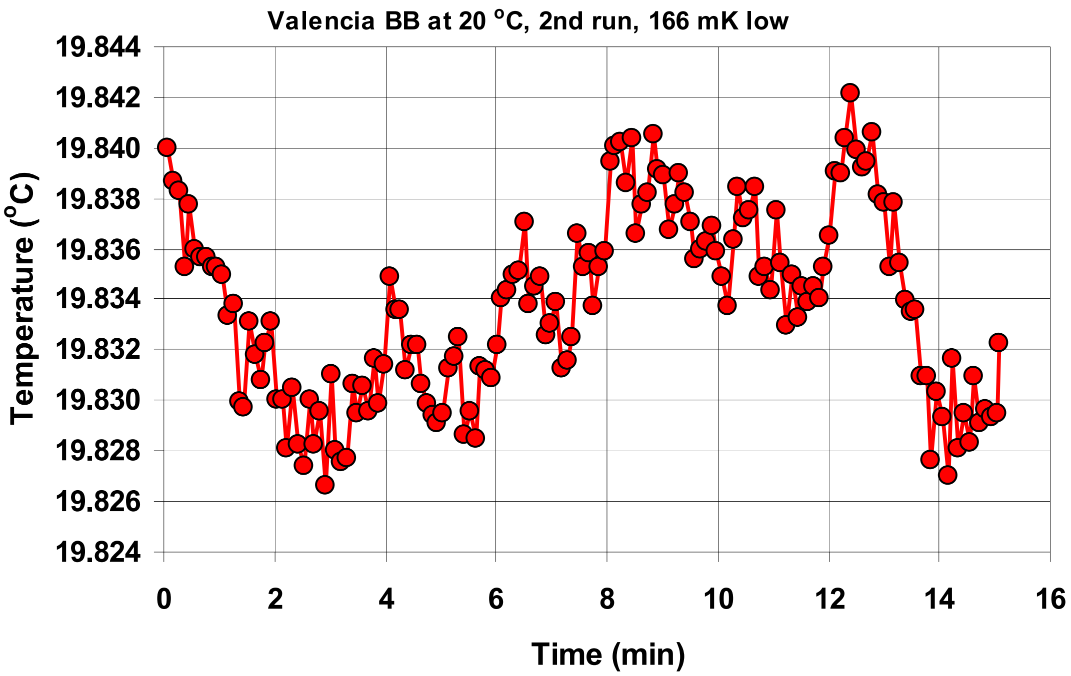

Figure 3.1.4: The DEPT blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 20 °C (2nd measurement completed on the 22nd April 2009). The average blackbody brightness temperature was 166 mK lower than the set value.

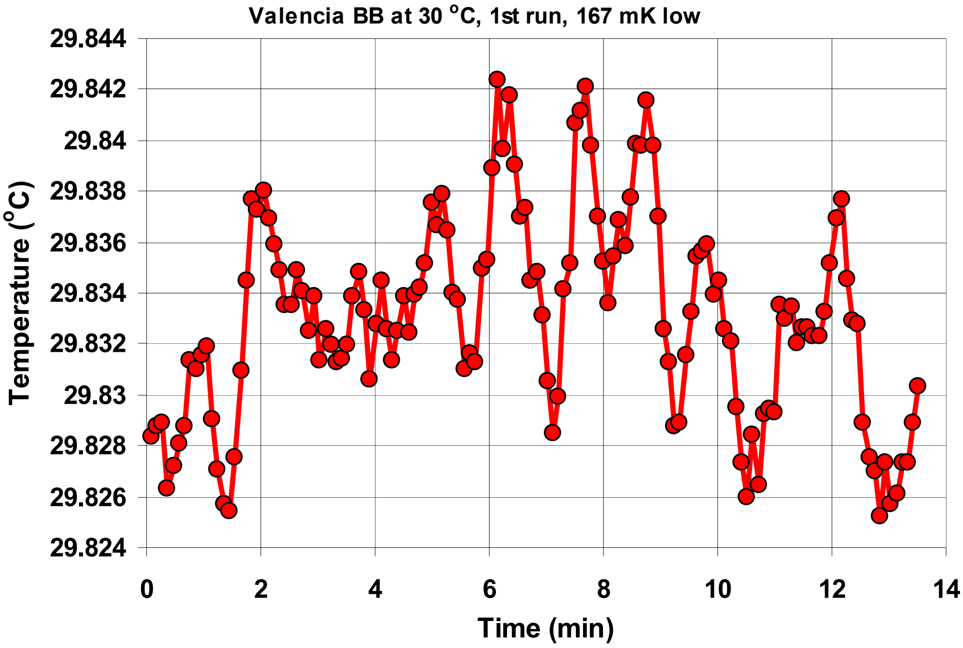

Figure 3.1.5: The DEPT blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 30 °C (1st measurement completed on the 21st April 2009). The average blackbody brightness temperature was 167 mK lower than the set value.

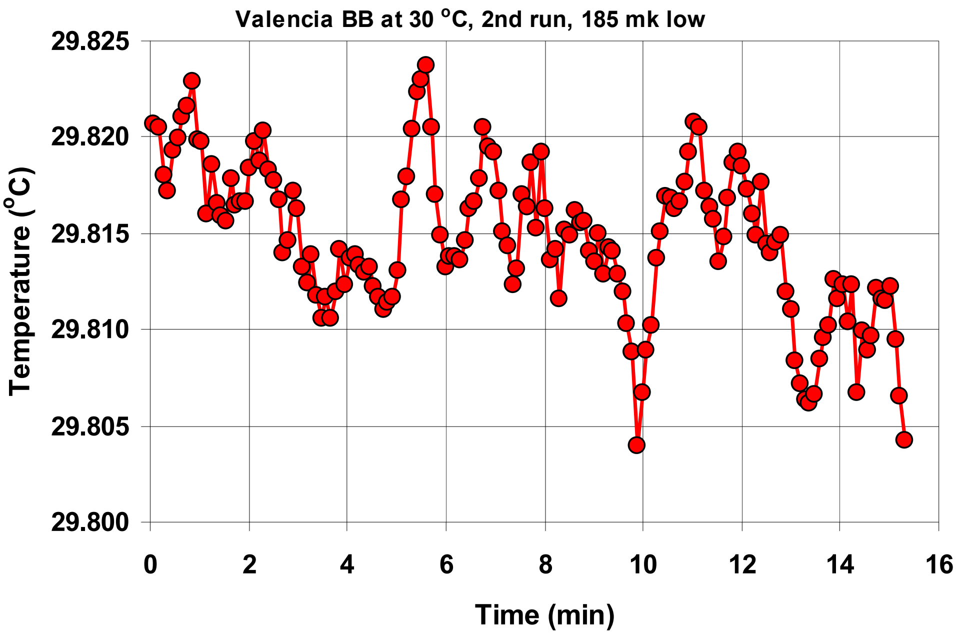

Figure 3.1.6: The DEPT blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 30 °C (2nd measurement completed on the 22nd April 2009). The average blackbody brightness temperature was 185 mK lower than the set value.

3.2 Grupo de Observacion de la Tierra Y la Atmosfera (GOTA), University of Laguna

3.2.1 Contact information

GOTA contact for the comparison: Dr Manuel Arbelo
Address: GOTA, Avda. Astrofisico FCO. Sanchez, Facultad de Fisica, 38206 La Laguna, Spain
Email: marbelo@ull.es

3.2.2 Blackbody used in the comparison

Land Infrared Landcal Blackbody Source P80P.
(http://landinstruments.net/infrared/products/calibration_sources/p80p.htm).

Make and type of Instrument (Radiometer and/or black body) Black body Land Infrared Landcal Blackbody Source P80P.

Outline Technical description of instrument:

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

Reference: Landcal Blackbody Source Type P80P Operating Instructions.

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

The black body has undergone a traceable primary calibration on April 8, 2008 (Attached UKAS certificate of calibration number 17379).

Operational methodology during measurement

See the attached UKAS certificate of calibration number 17379.

Black body usage (deployment)

Laboratory calibration of thermal infrared radiometers.

Uncertainty of measurement

Black body Land Infrared Landcal Blackbody Source P80P

Parameter	Type A Uncertainty in Value / %	Type B Uncertainty in Value / (appropriate units)	Uncertainty in Brightness temperature K
Repeatability of measurement			
Reproducibility of measurement			
Stability of source			
Emissivity			
BB Thermometer cal			
BB Isothermal variance			
Primary Source			
RMS total			0.6 K[(1)]

[(1)] As indicated in Certificate of Calibration (UKAS) number 17379 (April 8th, 2008) for k=1.

3.2.3 Results

The GOTA blackbody took part in the NPL blackbody comparison. Figure 3.2.1 shows the GOTA blackbody cavity temperature values measured by the AMBER radiometer when the blackbody cavity temperature was set to 10 ^{o}C. These measurements were acquired on the 21st April and show that the GOTA blackbody brightness temperature was 164 mK lower than the set value. The combined uncertainty of the GOTA blackbody brightness temperature at 10 ^{o}C (provided by GOTA) is 0.6 ^{o}C so the discrepancy was well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer). Figure 3.2.2 shows the corresponding measurements acquired on the 22nd April. These measurements show that the average GOTA brightness temperature was 177 mK lower than the set value. The combined uncertainty of the GOTA blackbody brightness temperature at 10 ^{o}C (provided by GOTA) is 0.6 ^{o}C so the discrepancies were well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer).

Figure 3.2.3 shows the GOTA blackbody cavity temperature values measured by the AMBER radiometer when the blackbody cavity temperature was set to 20 ^{o}C. These measurements were acquired on the 21st April and show that the GOTA blackbody brightness temperature was 152 mK lower than the set value. The combined uncertainty of the GOTA blackbody brightness temperature at 20 ^{o}C (provided by GOTA) is 0.6 ^{o}C so the discrepancy was well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer). Figure 3.2.4 shows the corresponding measurements acquired on the 22nd April. These measurements show that the GOTA brightness temperature was 181 mK lower than the set value. The combined uncertainty of the GOTA blackbody brightness temperature at 20 ^{o}C (provided by GOTA) is 0.6 ^{o}C so the discrepancies were well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer).

Figure 3.2.5 shows the GOTA blackbody cavity temperature values measured by the AMBER radiometer when the blackbody cavity temperature was set to 30 ^{o}C. These measurements were acquired on the 21st April and show that the GOTA blackbody brightness temperature was 176 mK lower than the set value. The combined uncertainty of the GOTA blackbody brightness temperature at 30 ^{o}C (provided by GOTA) is 0.6 ^{o}C so the discrepancy was well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer). Figure 3.2.3 shows the corresponding measurements acquired on the 22nd April. These measurements show that the GOTA brightness temperature was 188 mK lower than the set value. The combined uncertainty of the GOTA blackbody brightness temperature at 30 ^{o}C (provided by GOTA) is 0.6 ^{o}C so the discrepancies were well within the uncertainty of the blackbody (see Appendix 1 for the uncertainty associated with the blackbody calibration using the AMBER radiometer).

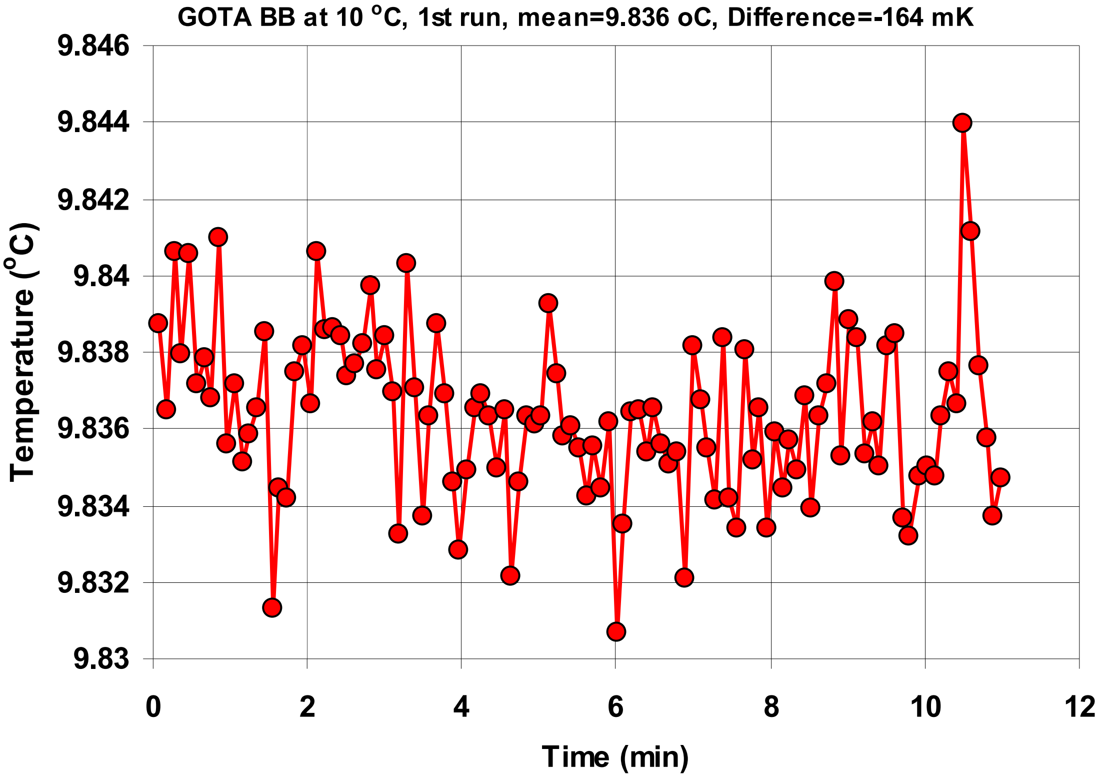

Figure 3.2.1: Plot of the GOTA blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 10 °C (1st measurement completed on the 21st April 2009). The average blackbody brightness temperature was 164 mK lower than the set value.

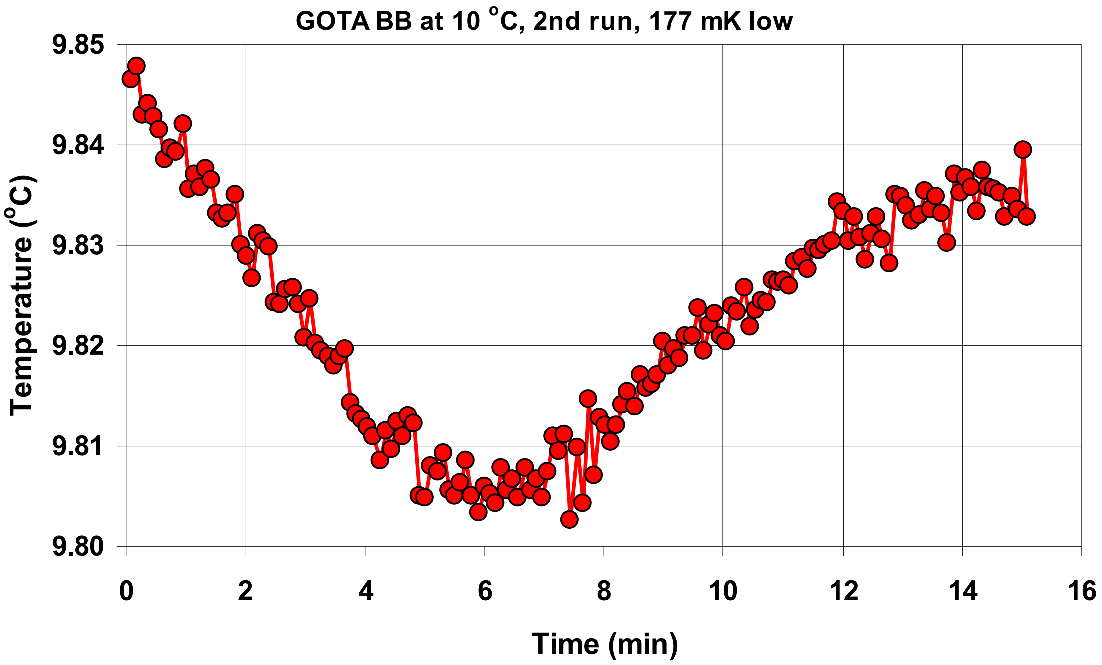

Figure 3.2.2: Plot of the GOTA blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 10 °C (2nd measurement completed on the 22nd April 2009). The average blackbody brightness temperature was 177 mK lower than the set value.

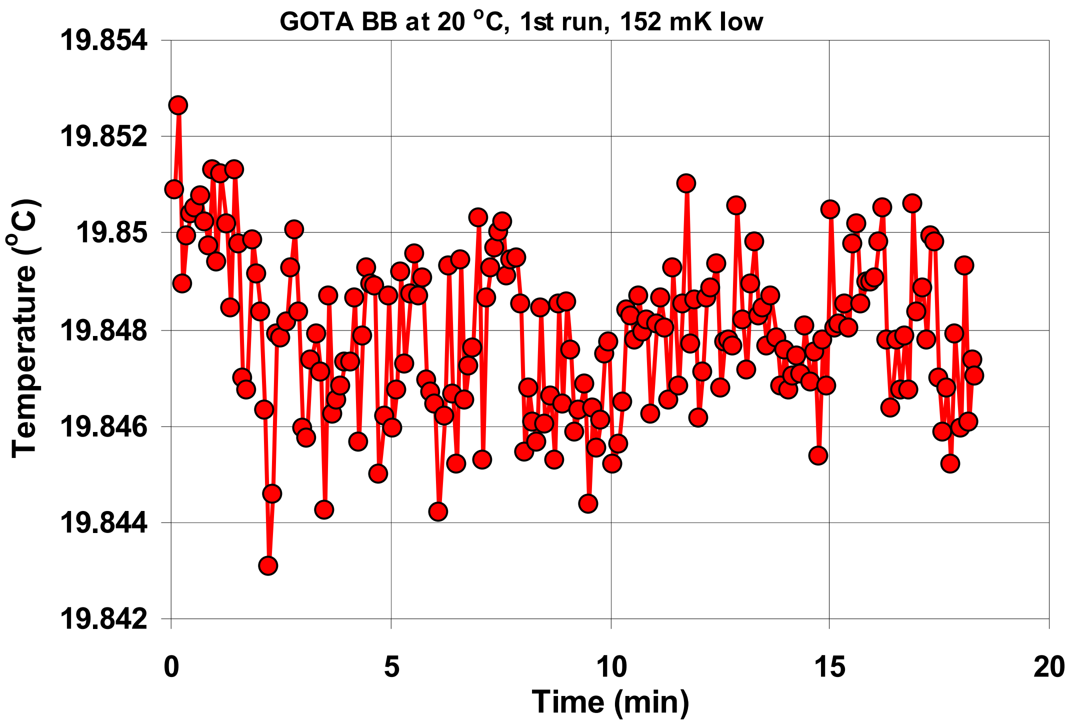

Figure 3.2.3: Plot of the GOTA blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 20 °C (1st measurement completed on the 21st April 2009). The average blackbody brightness temperature was 152 mK lower than the set value.

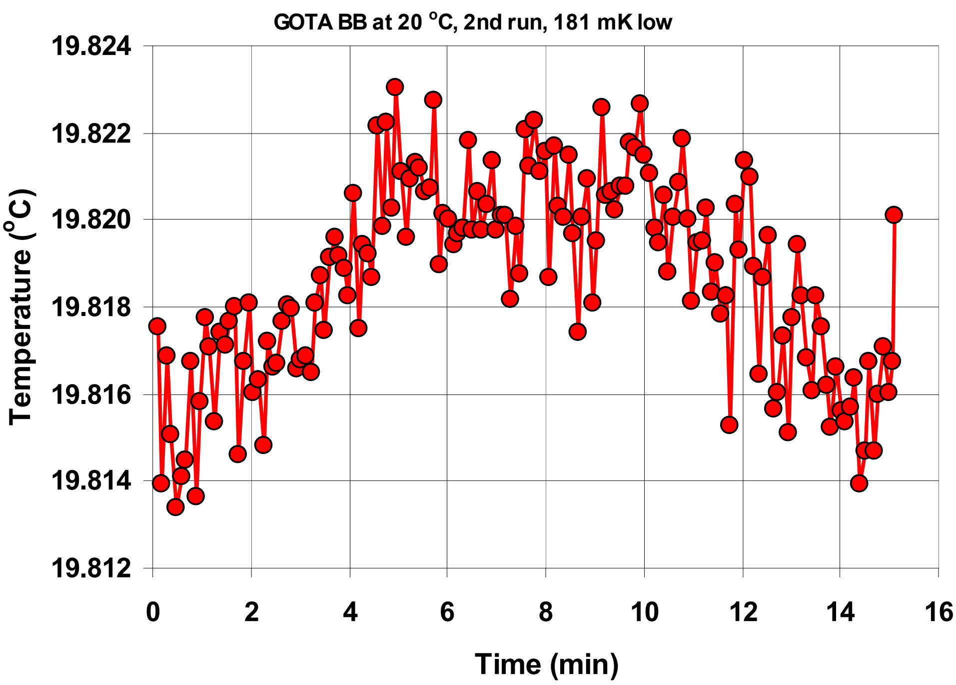

Figure 3.2.4: Plot of the GOTA blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 20 °C (2nd measurement completed on the 22nd April 2009). The average blackbody brightness temperature was 181 mK lower than the set value.

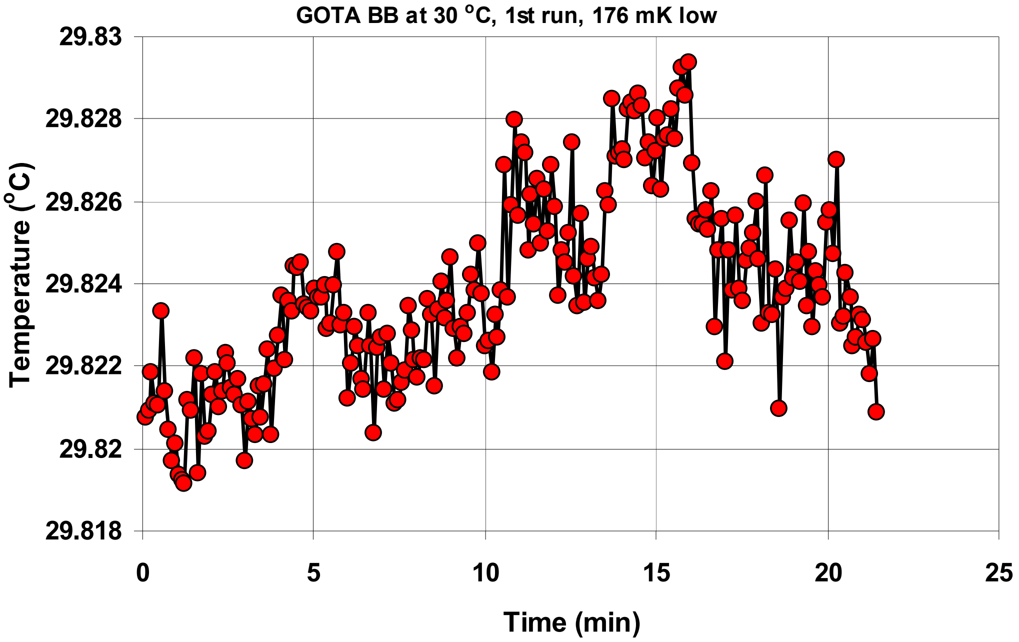

Figure 3.2.5: Plot of the GOTA blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 30 °C (1st measurement completed on the 21st April 2009). The average blackbody brightness temperature was 176 mK lower than the set value.

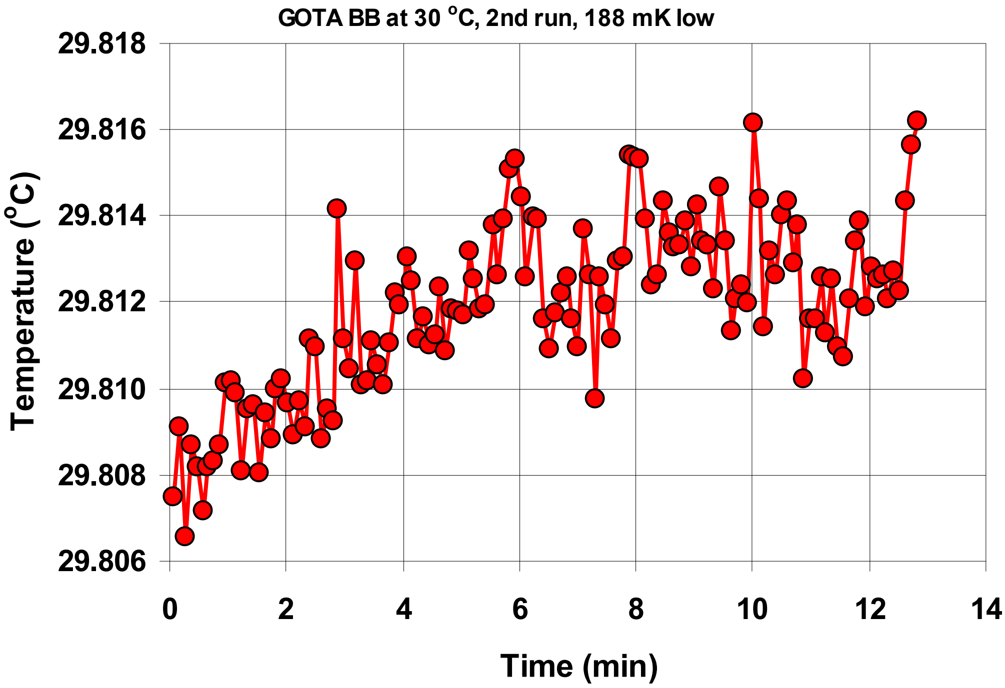

Figure 3.2.6: Plot of the GOTA blackbody brightness temperature values measured by the AMBER radiometer when the blackbody temperature was set to 30 °C (2nd measurement completed on the 22nd April 2009). The average blackbody brightness temperature was 188 mK lower than the set value.

3.3 STFC Rutherford Appleton Laboratory (RAL)

3.3.1 Contact information

STFC RAL contact for the comparison: Dr Tim Nightingale
Address: Chilton, Didcot, Oxon, OX11 0QX, UK
Email: tim.nightingale@stfc.ac.uk

3.3.2 Blackbody used in the comparison

Make and type of blackbody: (SISTeR) manufactured by RAL. Further information on this radiometer can be found at: (http://www.atsr.rl.ac.uk/validation/sister/sis_inst/index.shtml)

The temperature of the cavity of the RAL blackbody is NOT actively controlled. Instead, it is allowed to drift slowly as the mechanical stirrer dumps some energy in the fluid surrounding the blackbody cavity.

Uncertainty
No information provided

3.3.3 Results

The RAL blackbody took part in the NPL blackbody comparison. Figure 3.3.1 shows the RAL blackbody cavity temperature values measured by the AMBER radiometer as well as the RAL blackbody brightness temperature values reported by RAL when the blackbody temperature was in the vicinity of 10 ^{o}C on the 21st April (1st measurement). Figure 3.3.2 plots the difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 10 ^{o}C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by RAL was 15 mK lower than the average brightness temperature measured by the AMBER radiometer. Figure 3.3.3 shows the RAL blackbody cavity temperature values measured by the AMBER radiometer as well as the RAL blackbody brightness temperature values reported by RAL when the blackbody temperature was in the vicinity of 10 ^{o}C on the 22nd April. Figure 3.3.4 plots the difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 10 ^{o}C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by RAL was 14 mK lower than the average brightness temperature measured by the AMBER radiometer.

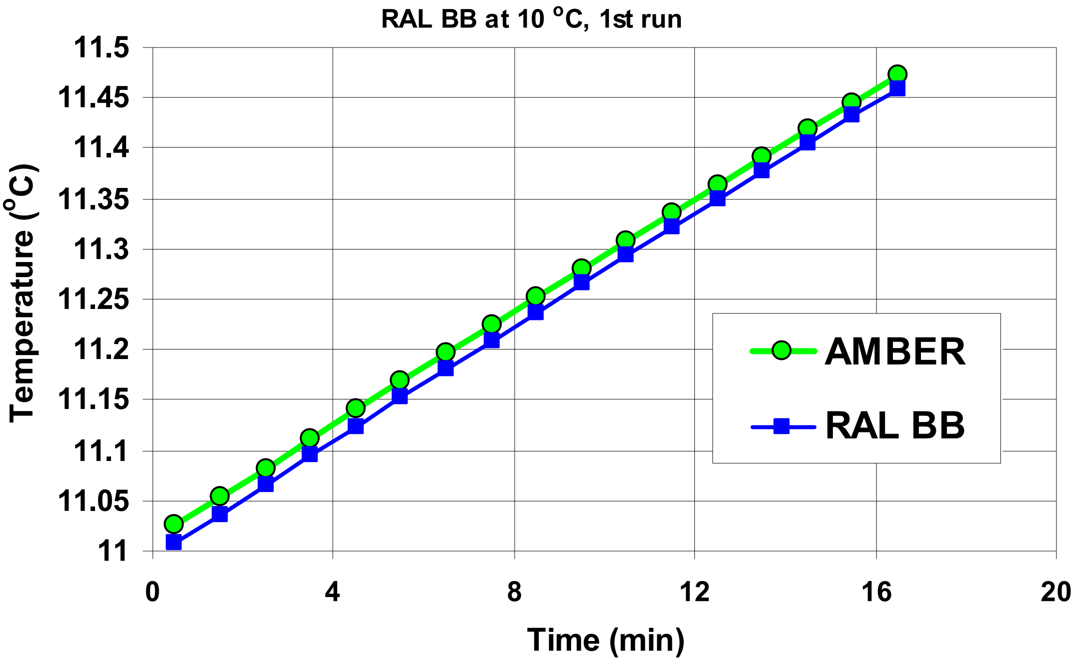

Figure 3.3.1: The RAL blackbody brightness temperature values measured by the AMBER radiometer when the RAL blackbody cavity temperature was set in the vicinity of 10 °C (1st measurement completed on the 21st April 2009). Also shown are the corresponding blackbody brightness temperatures reported by RAL.

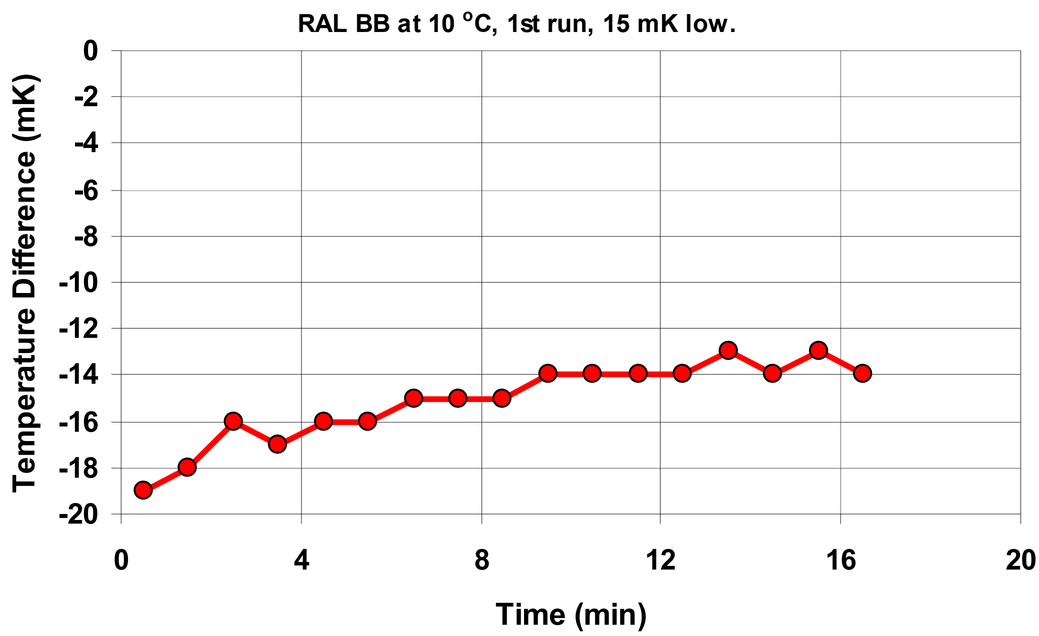

Figure 3.3.2: Difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 10 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by the RAL blackbody was 15 mK lower than the average brightness temperature measured by the AMBER radiometer.

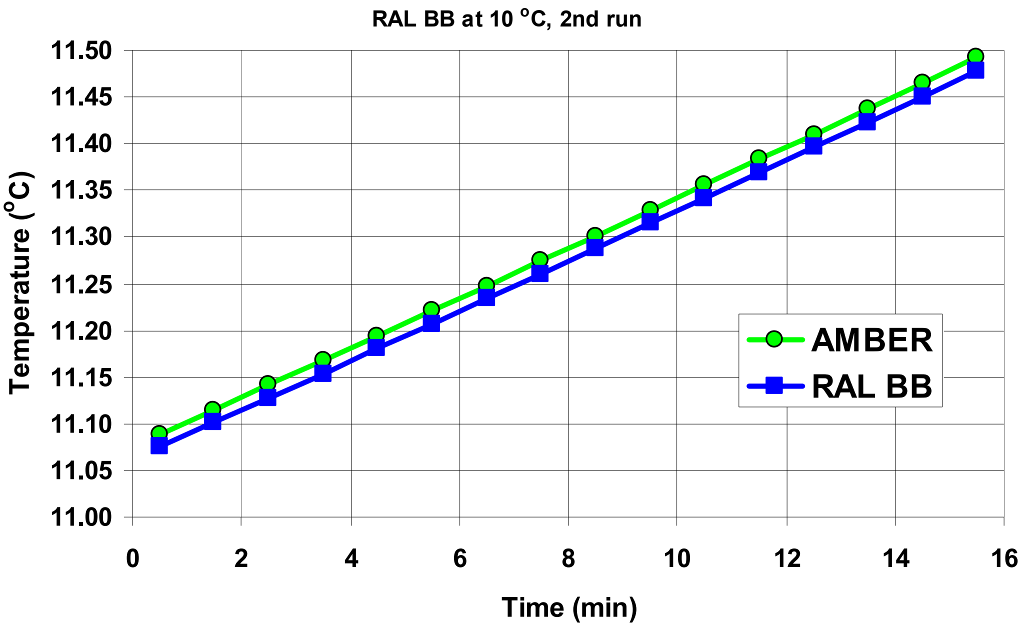

Figure 3.3.3: The RAL blackbody brightness temperature values measured by the AMBER radiometer when the RAL blackbody cavity temperature was set in the vicinity of 10 °C (2nd measurement completed on the 22nd April 2009). Also shown are the corresponding blackbody brightness temperature values reported by RAL.

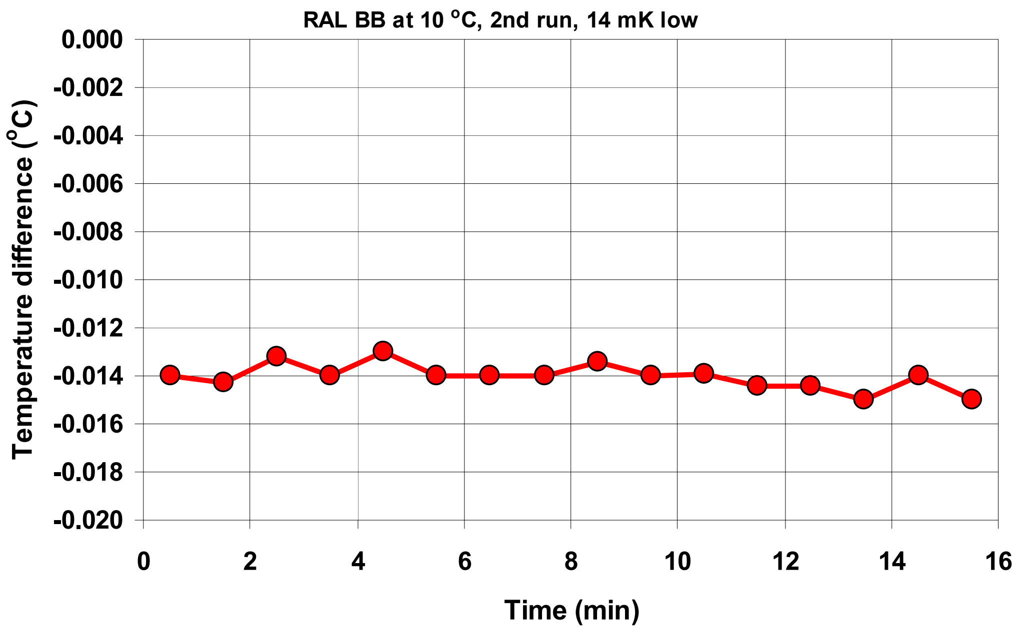

Figure 3.3.4: Difference between the RAL blackbody brightness temperatures reported by RAL minus the corresponding blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 10 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by the RAL blackbody was 14 mK lower than the average brightness temperature measured by the AMBER radiometer

Figure 3.3.5 shows the RAL blackbody cavity temperature values measured by the AMBER radiometer as well as the RAL blackbody brightness temperature values reported by RAL when the blackbody temperature was in the vicinity of 20 °C on the 21st April (1st measurement). Figure 3.3.6 plots the difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the region of 20 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by RAL was 8 mK lower than the average brightness temperature measured by the AMBER radiometer. Figure 3.3.7 shows the RAL blackbody cavity temperature values measured by the AMBER radiometer as well as the RAL blackbody brightness temperature values reported by RAL when the blackbody temperature was in the vicinity of 20 °C on the 22nd April (2nd measurement). Figure 3.3.8 plots the difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 20 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by RAL was 5 mK lower than the average brightness temperature measured by the AMBER radiometer.

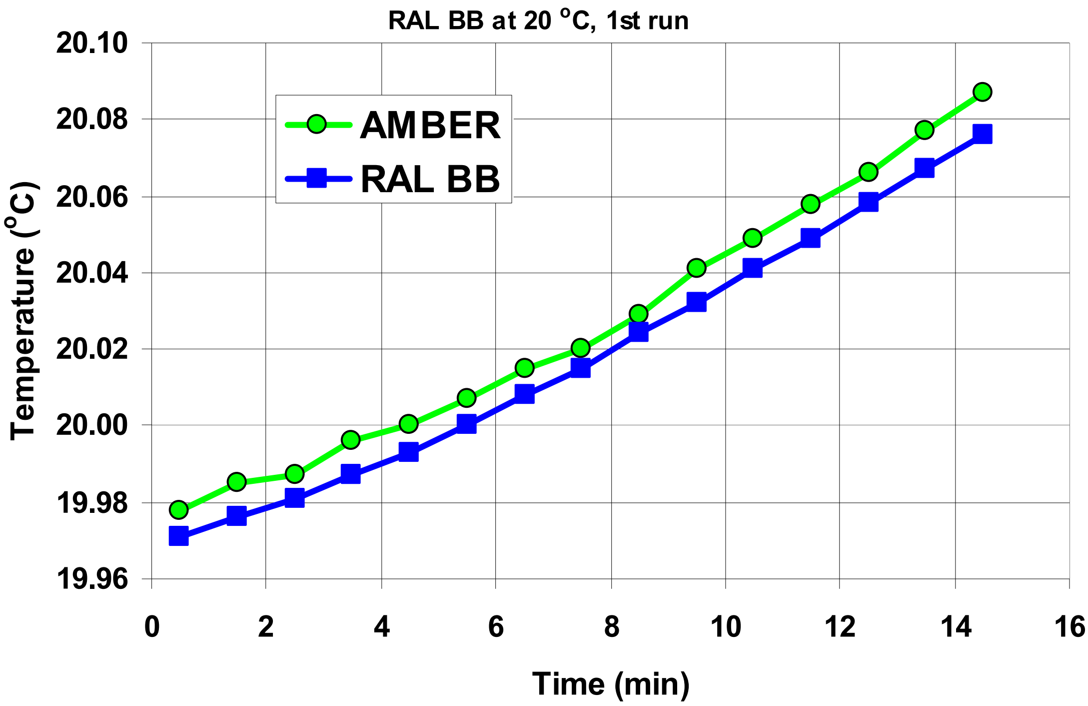

Figure 3.3.5: The RAL blackbody brightness temperature values measured by the AMBER radiometer when the RAL blackbody cavity temperature was set in the vicinity of 20 °C (1st measurement completed on the 21st April 2009). Also shown are the blackbody brightness temperature values reported by RAL.

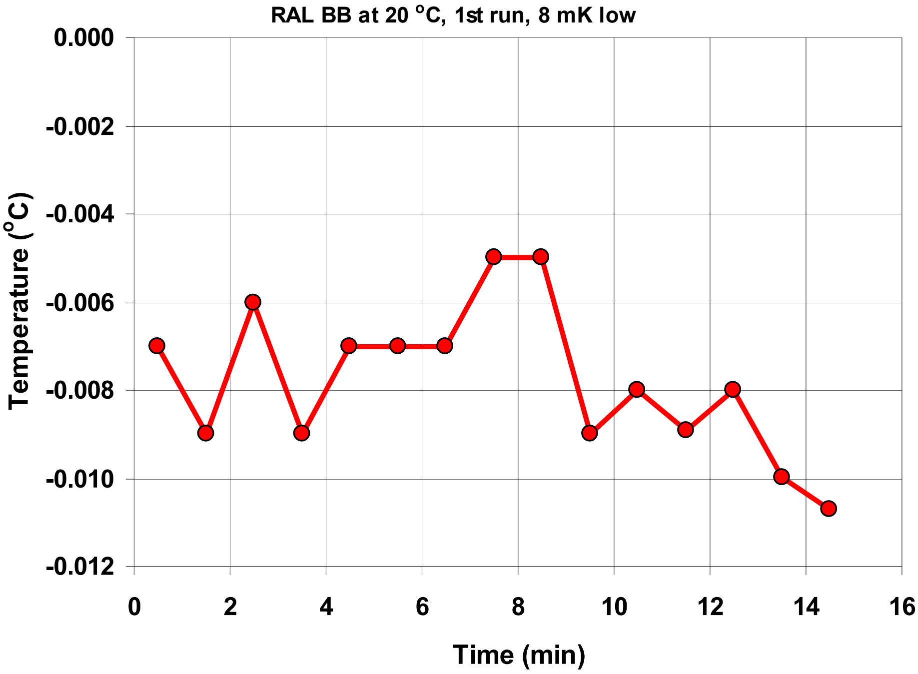

Figure 3.3.6: Difference between the RAL blackbody brightness temperatures reported by RAL minus the corresponding blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 20 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by the RAL blackbody was 8 mK lower than the average brightness temperature measured by the AMBER radiometer

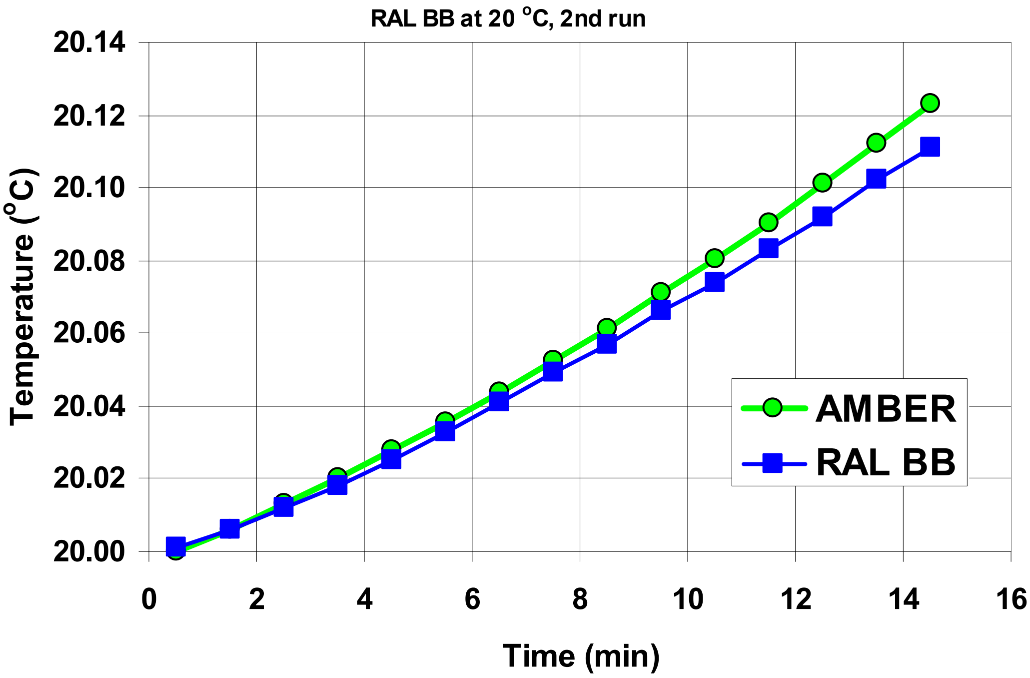

Figure 3.3.7: The RAL blackbody brightness temperature values measured by the AMBER radiometer when the RAL blackbody cavity temperature was set in the vicinity of 20 °C (2nd measurement completed 22nd April 2009). Also shown are the corresponding blackbody brightness temperature values reported by RAL.

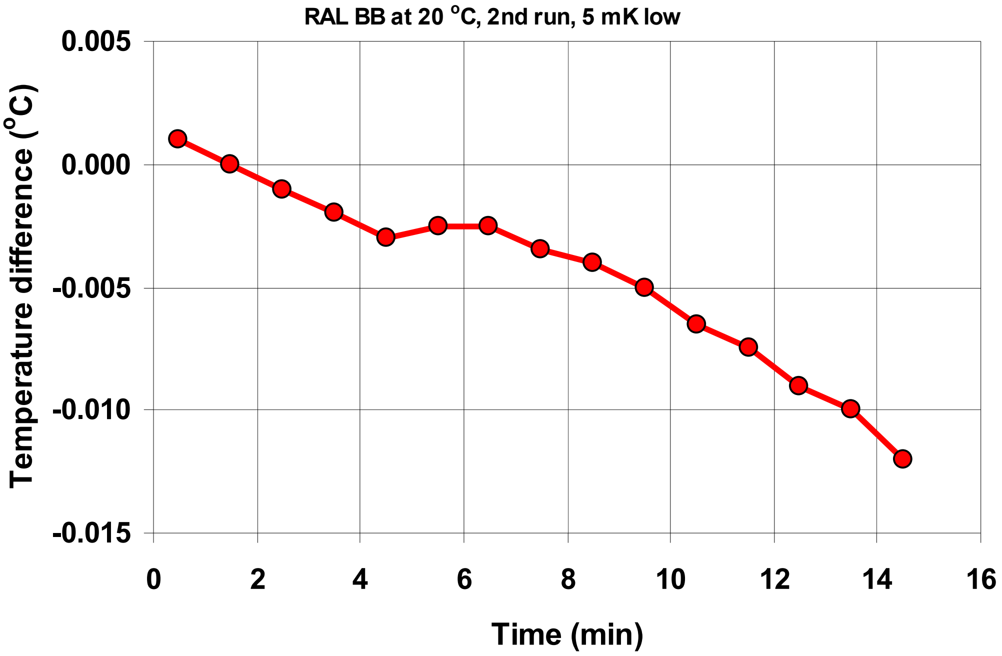

Figure 3.3.8: Difference between the RAL blackbody brightness temperature reported by RAL minus the blackbody brightness temperature measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 20 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by the RAL was 5 mK lower than the average brightness temperature measured by the AMBER radiometer.

Figure 3.3.9 shows the RAL blackbody cavity temperature values measured by the AMBER radiometer as well as the RAL blackbody brightness temperature values reported by RAL when the blackbody temperature was set in the vicinity of 30 °C on the 21st April (1st measurement). Figure 3.3.10 plots the difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 30 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by RAL was 14 mK higher than the average brightness temperature measured by the AMBER radiometer. Figure 3.3.11 shows the RAL blackbody cavity temperature values measured by the AMBER radiometer as well as the RAL blackbody brightness temperature values reported by RAL when the blackbody temperature was in the vicinity of 20 °C on the 22nd April (2nd measurement). Figure 3.3.12 plots the difference between the RAL blackbody brightness temperatures reported by RAL minus the blackbody brightness temperatures measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 20 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by RAL was 6 mK higher than the average brightness temperature measured by the AMBER radiometer.

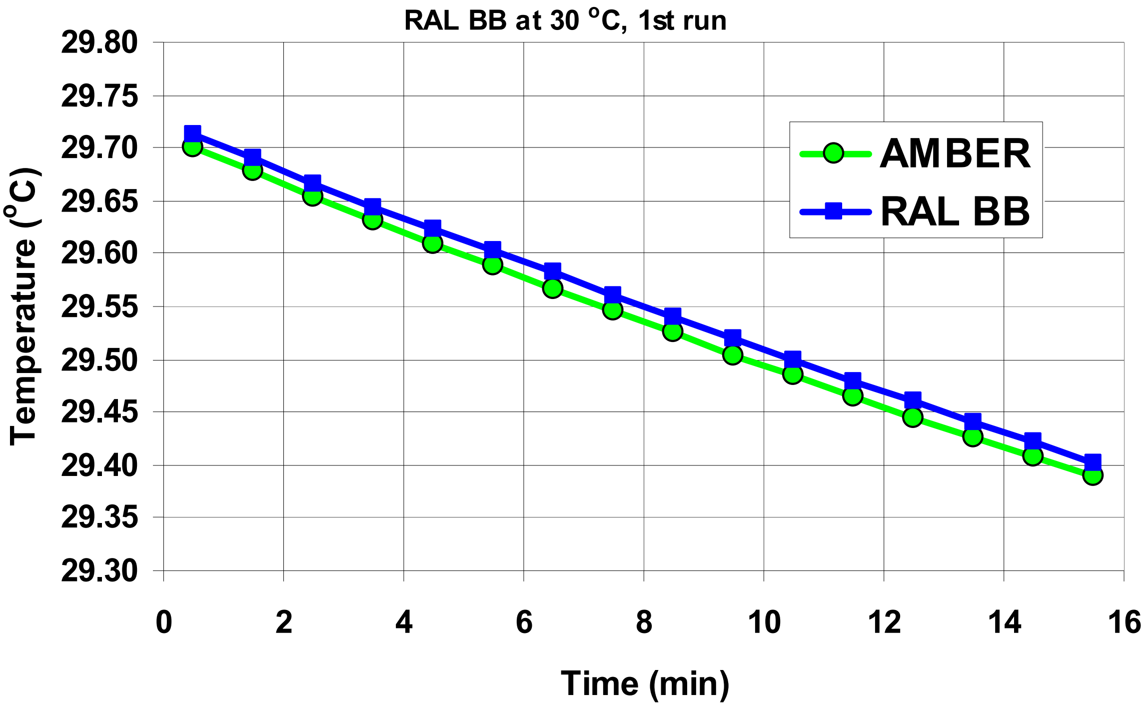

Figure 3.3.9: The RAL blackbody brightness temperature values measured by the AMBER radiometer when the RAL blackbody cavity temperature was set in the vicinity of 30 ^{o}C (1st measurement completed 21st April 2009). Also shown are the blackbody brightness temperatures reported by RAL.

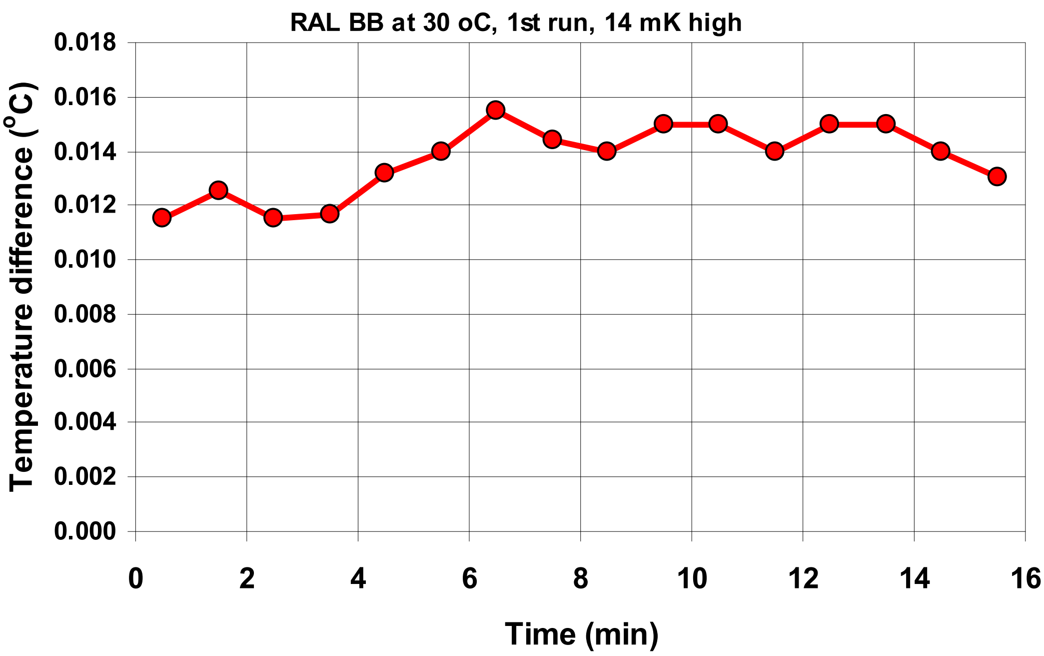

Figure 3.3.10: Difference between the RAL blackbody brightness temperature reported by RAL minus the blackbody brightness temperature measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 30 ^{o}C (1st measurement completed 21st April 2009). The average brightness temperature reported by the RAL blackbody was 14 mK higher than the average brightness temperature measured by the AMBER radiometer

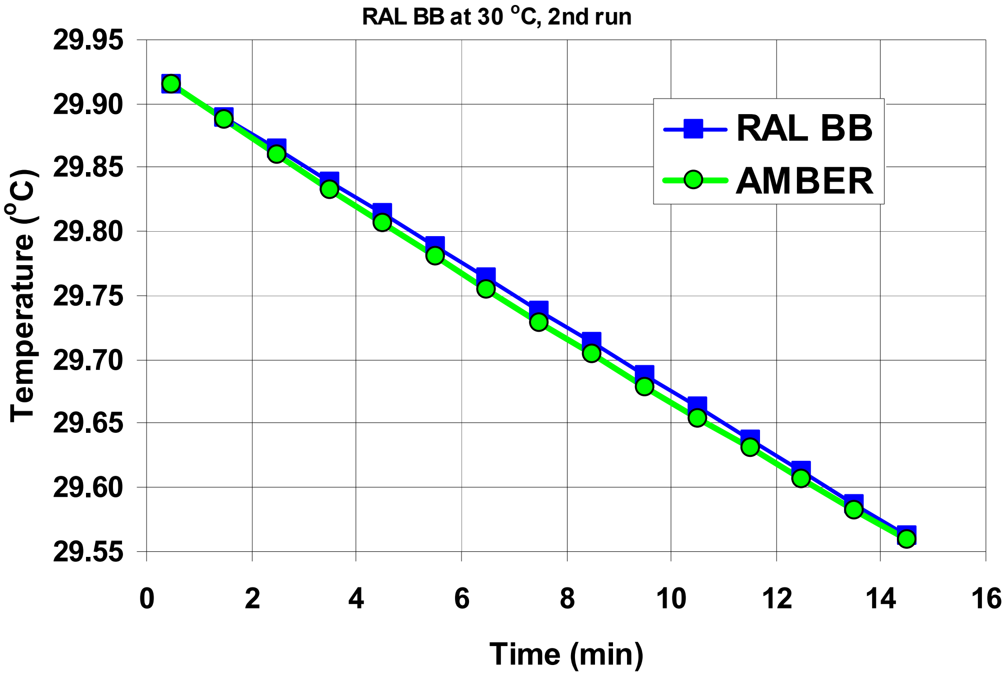

Figure 3.3.11: The RAL blackbody brightness temperature values measured by the AMBER radiometer when the RAL blackbody cavity temperature was set in the vicinity of 30 °C (2nd measurement completed 22nd April 2009). Also shown are the corresponding blackbody brightness temperatures reported by RAL.

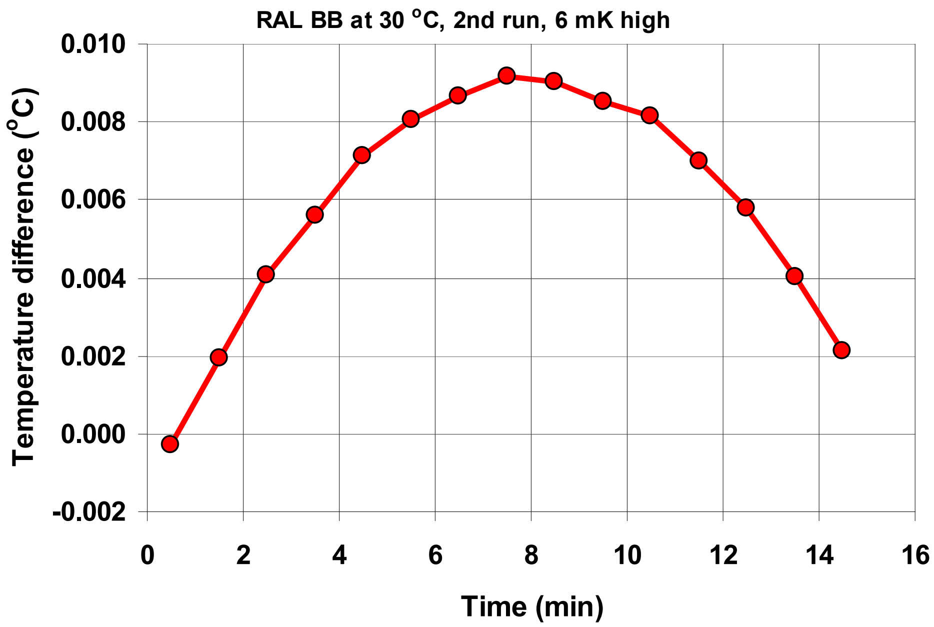

Figure 3.3.12: Difference between the RAL blackbody brightness temperature reported by RAL minus the blackbody brightness temperature measured by the AMBER radiometer when the RAL blackbody was set in the vicinity of 30 °C (2nd measurement completed 22nd April 2009). The average brightness temperature reported by the RAL blackbody was 6 mK higher than the average brightness temperature measured by the AMBER radiometer

3.4 National Oceanography Centre (NOC), University of Southampton

3.4.1 Contact information

NOC contact for the comparison: Dr Weinfrid Wimmer
Address: National Oceanography Centre, University of Southampton, European Way, Southampton, SO19 9TX, UK
Email: W.wimmer@soton.ac.uk

3.4.2 Blackbody used in the comparison

Blackbody type: CASOTS II. This blackbody is used to validate the calibration of the NOC's Infrared Sea Surface Temperature Autonomous Radiometer (ISAR) and is therefore referred to in this report as the "ISAR blackbody".
Exit aperture: Up to 80 mm in diameter
Temperature range: Dew-point to about 310 K
Further information on the ISAR blackbody are provided by Donlon et al., (1999).

The temperature of the cavity of the ISAR blackbody is NOT actively controlled. Instead, it is allowed to drift slowly as the mechanical stirrer dumps some energy in the fluid surrounding the blackbody cavity.

3.4.3 Results

The ISAR blackbody took part in the NPL blackbody and Miami blackbody comparisons.

3.4.3.1 AMBER radiometer viewing the ISAR blackbody

Figures 3.4.1 shows the ISAR blackbody cavity temperature values measured by the AMBER radiometer as well as the ISAR blackbody brightness temperature reported by Southampton University when the blackbody temperature was set in the vicinity of 10 ^{o}C on the 21st April 2009. Figure 3.4.2 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 10 ^{o}C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by Southampton University was 19 mK lower than the average brightness temperature measured by the AMBER radiometer. Figures 3.4.3 shows the ISAR blackbody cavity temperature values measured by the AMBER radiometer, as well as the ISAR blackbody brightness temperature reported by Southampton University, when the blackbody temperature was set in the vicinity of 10 ^{o}C on the 22nd April 2009. Figure 3.4.4 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 10 ^{o}C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by Southampton University on the 22nd of April was 18 mK lower than the average temperature measured by the AMBER radiometer.

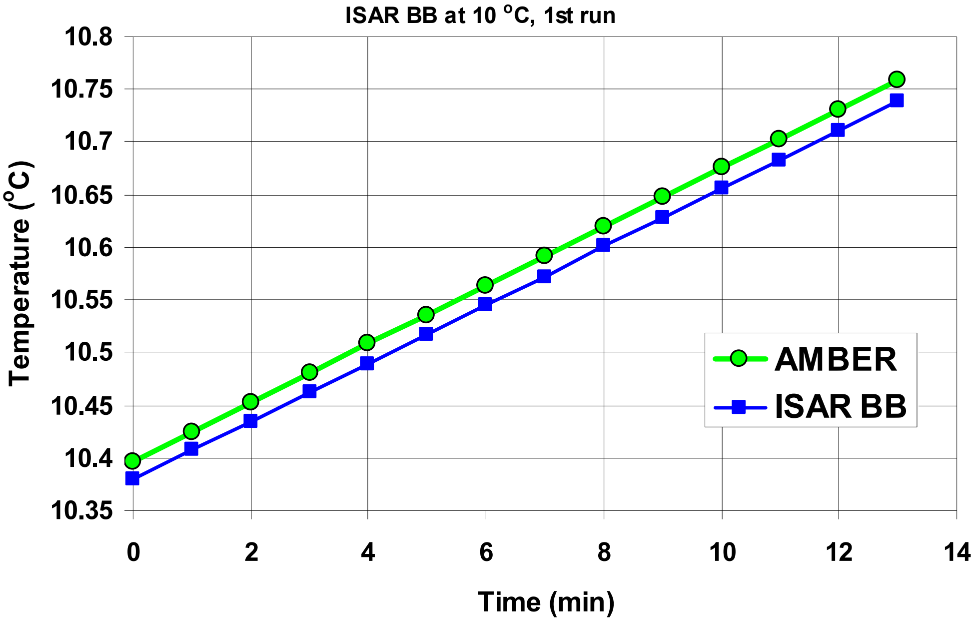

Figure 3.4.1: The ISAR blackbody brightness temperature values measured by the AMBER radiometer when the ISAR blackbody cavity temperature was set in the vicinity of 10 °C (1st measurement completed on the 21st April 2009). Also shown are the blackbody brightness temperatures reported by Southampton University.

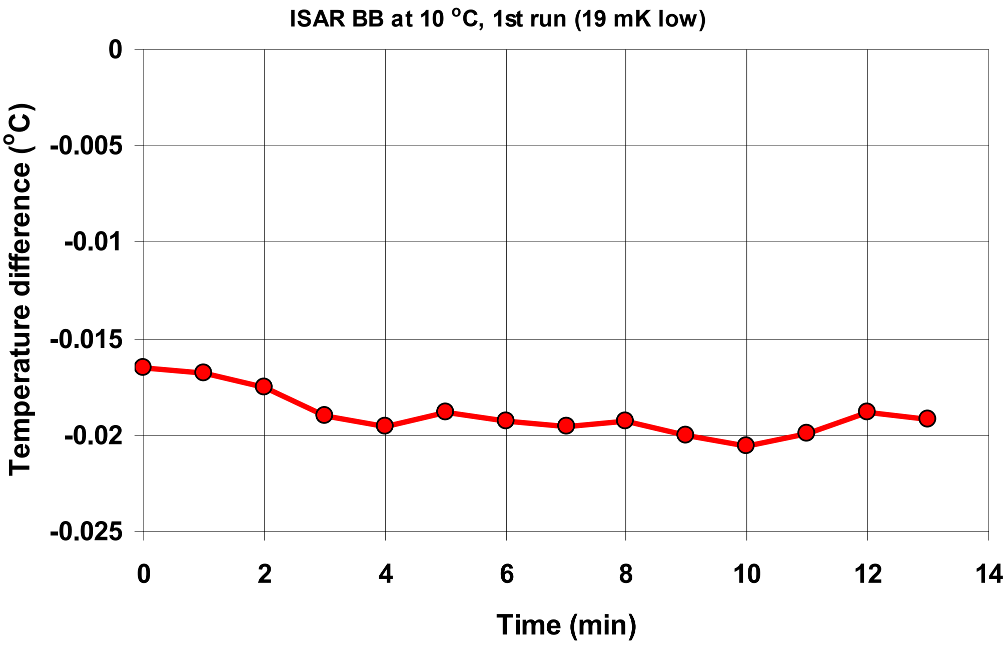

Figure 3.4.2: Difference between the ISAR blackbody brightness temperatures reported by Southampton minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 10 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by the ISAR blackbody was 19 mK lower than the average brightness temperature measured by AMBER radiometer.

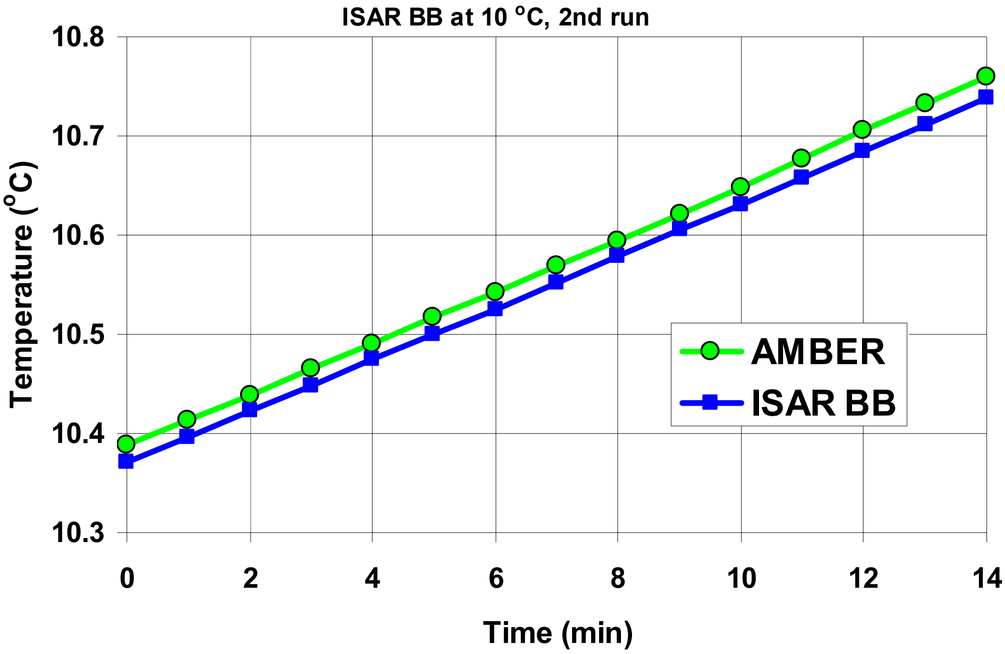

Figure 3.4.3: The ISAR blackbody brightness temperature values measured by the AMBER radiometer when the ISAR blackbody cavity temperature was set in the vicinity of 10 °C (2nd measurement completed on the 22nd April 2009). Also shown are the blackbody brightness temperature values reported by Southampton University.

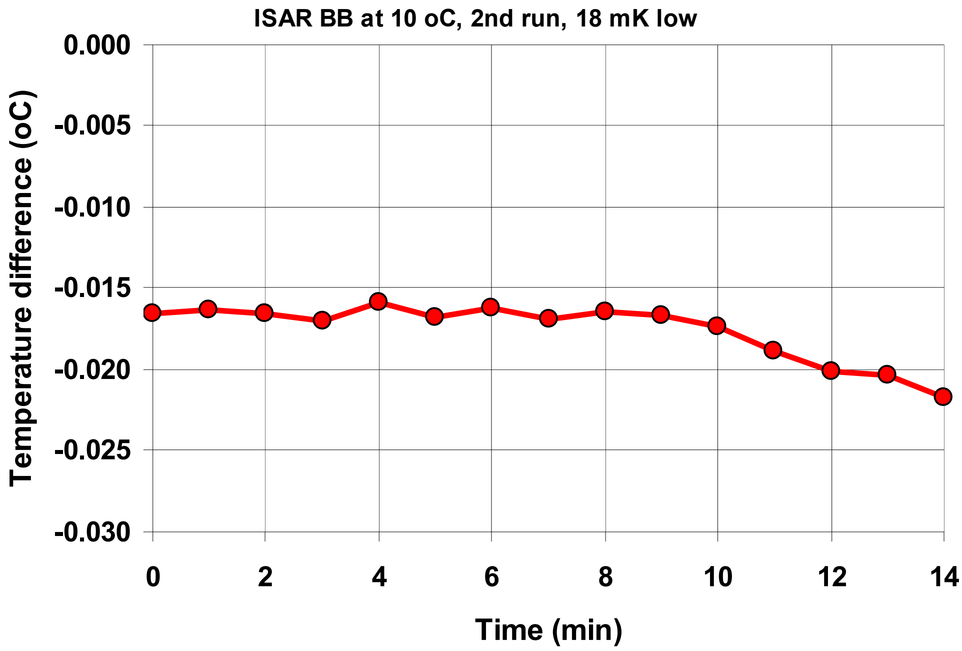

Figure 3.4.4: Difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the corresponding blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 10 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by the ISAR was 18 mK lower than the average brightness temperature measured by the AMBER radiometer.

Figure 3.4.5 shows the ISAR blackbody cavity temperature values measured by the AMBER radiometer as well as the ISAR blackbody brightness temperature reported by Southampton University when the blackbody temperature was set in the vicinity of 20 °C on the 21st April 2009. Figure 3.4.6 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 20 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by Southampton University was 16 mK lower than the average brightness temperature measured by the AMBER radiometer. Figure 3.4.7 shows the ISAR blackbody cavity temperature values measured by the AMBER radiometer, as well as the ISAR blackbody brightness temperature reported by Southampton University, when the blackbody temperature was set in the vicinity of 20 °C on the 22nd April 2009. Figure 3.4.8 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 20 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by Southampton University on the 22nd of April was 14 mK lower than the average temperature measured by the AMBER radiometer.

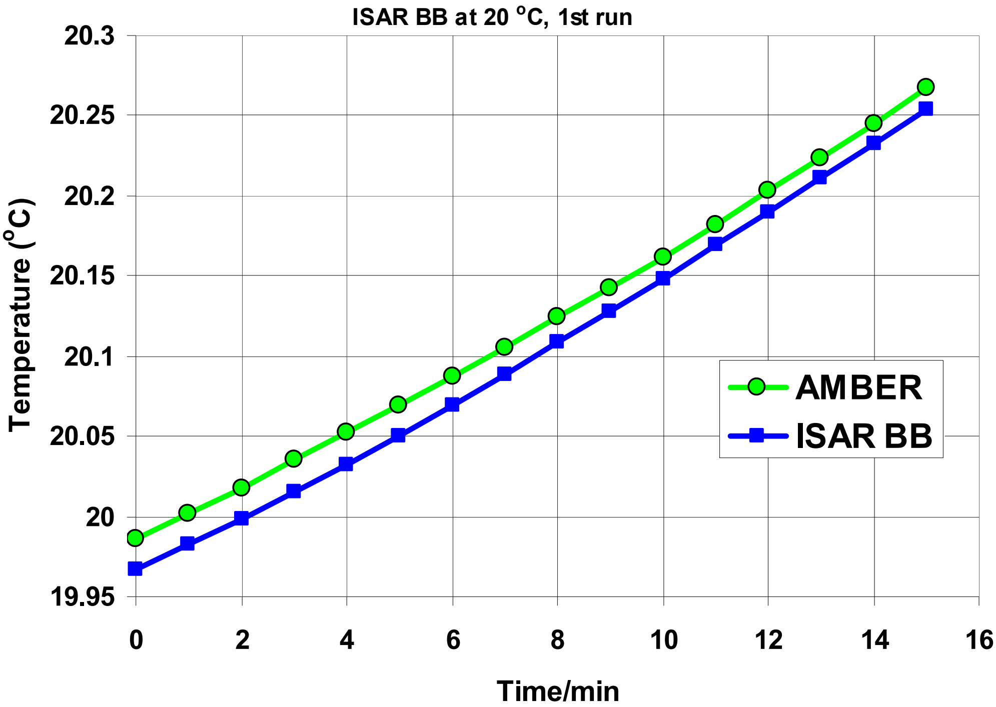

Figure 3.4.5: The ISAR blackbody brightness temperature values measured by the AMBER radiometer when the ISAR blackbody cavity temperature was set in the vicinity of 20 °C (1st measurement completed on the 21st April 2009). Also shown are the blackbody brightness temperature values reported by Southampton University.

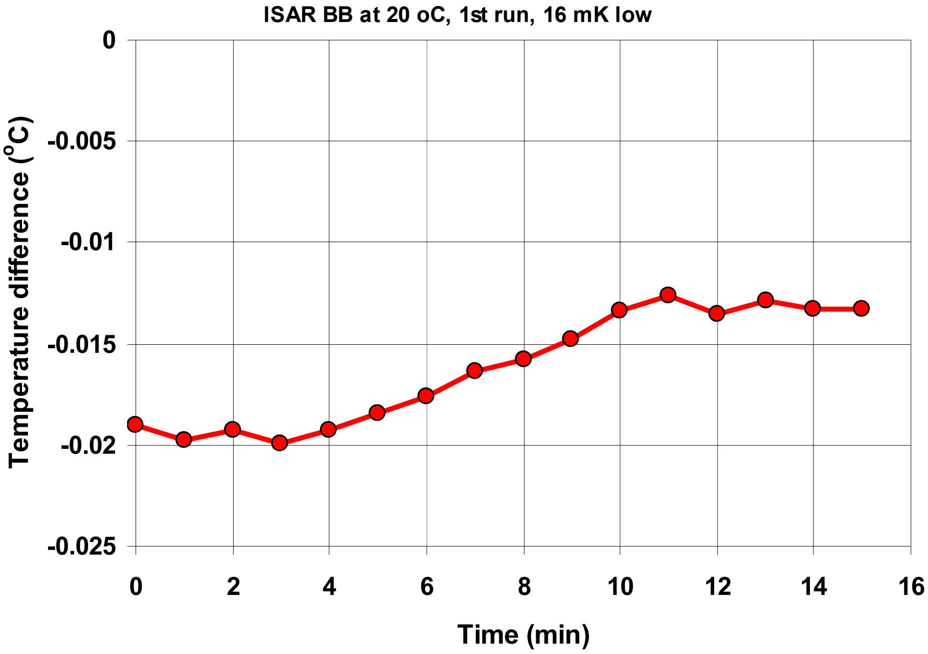

Figure 3.4.6: Difference between the ISAR blackbody brightness temperatures reported by Southampton minus the corresponding blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 20 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by the ISAR was 16 mK lower than the average brightness temperature measured by AMBER radiometer.

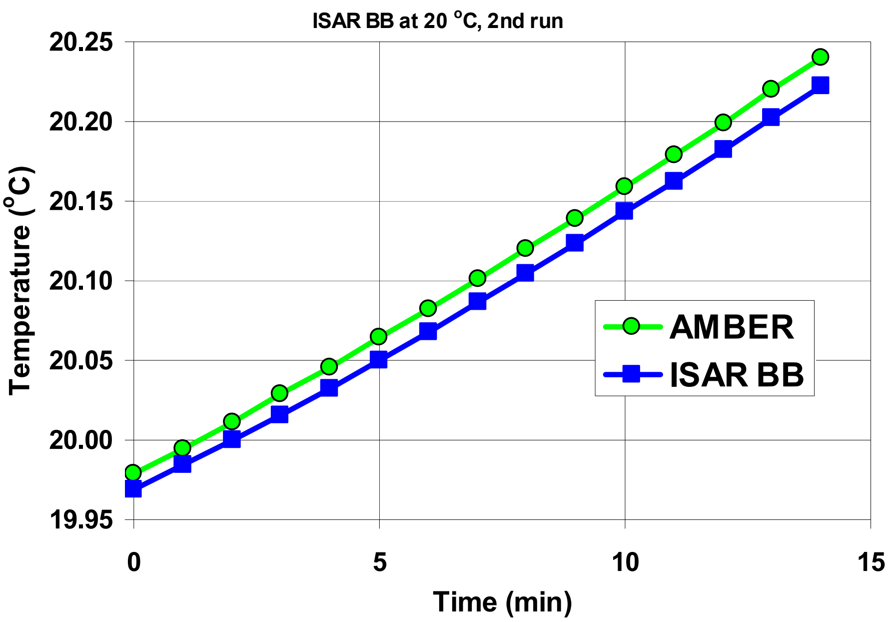

Figure 3.4.7: The ISAR blackbody brightness temperature values measured by the AMBER radiometer when the ISAR blackbody cavity temperature was set in the vicinity of 20 °C (2nd measurement completed on the 2nd April 2009). Also shown are the corresponding blackbody brightness temperatures reported by Southampton University.

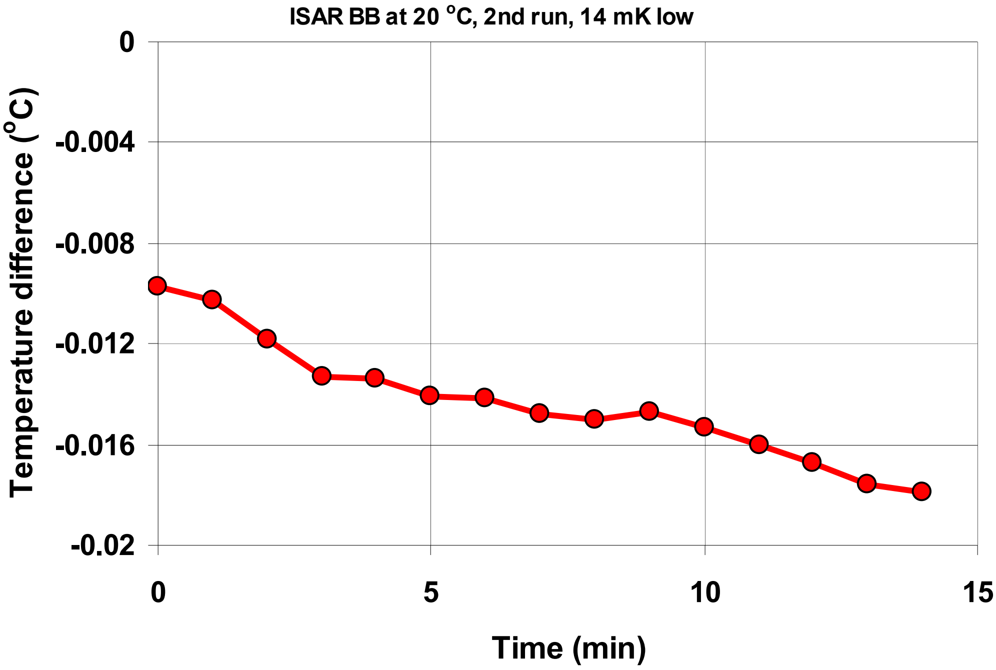

Figure 3.4.8: Difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 20 °C (2nd measurement completed on the 22nd April 2009). The brightness temperature reported by the ISAR was 14mK lower than the average temperature measured by the AMBER radiometer.

Figures 3.4.9 shows the ISAR blackbody cavity temperature values measured by the AMBER radiometer as well as the ISAR blackbody brightness temperature reported by Southampton University when the blackbody temperature was set in the vicinity of 30 °C on the 21st April 2009. Figure 3.4.10 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 30 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by Southampton University was 7 mK lower than the average brightness temperature measured by the AMBER radiometer. Figure 3.4.11 shows the ISAR blackbody cavity temperature values measured by the AMBER radiometer, as well as the ISAR blackbody brightness temperature reported by Southampton University, when the blackbody temperature was set in the vicinity of 30 °C on the 22nd April 2009. Figure 3.4.12 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 30 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by Southampton University on the 22nd of April was 3 mK higher than the average temperature measured by the AMBER radiometer.

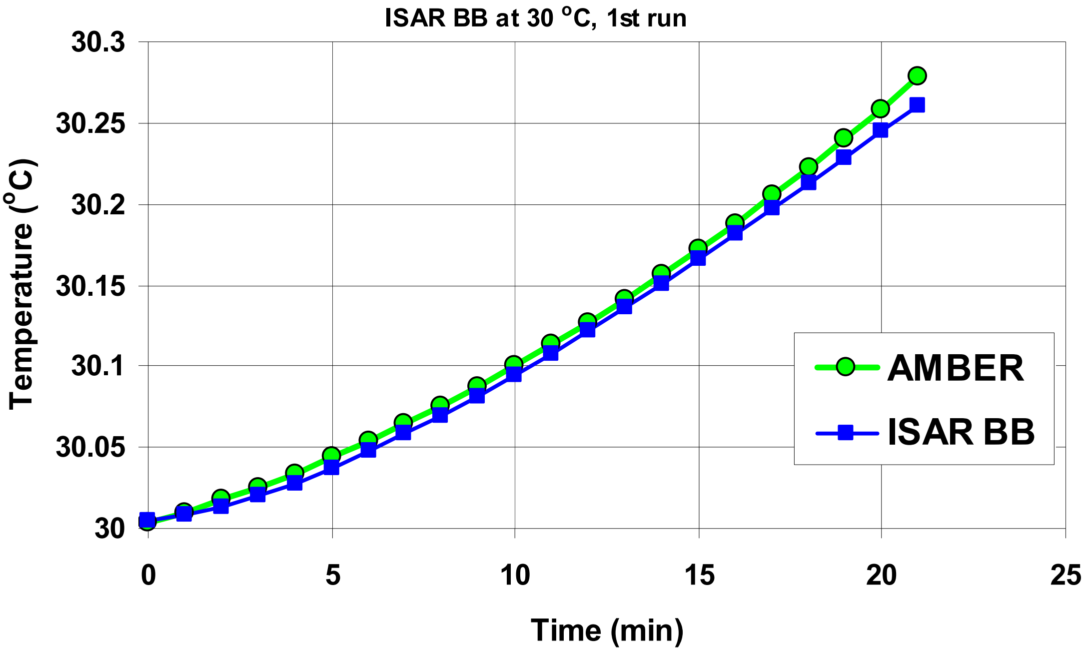

Figure 3.4.9: The ISAR blackbody brightness temperature values measured by the AMBER radiometer when the ISAR blackbody cavity temperature was set in the vicinity of 30 °C (1st measurement completed on the 21st April 2009). Also shown are the blackbody brightness temperature values reported by Southampton University.

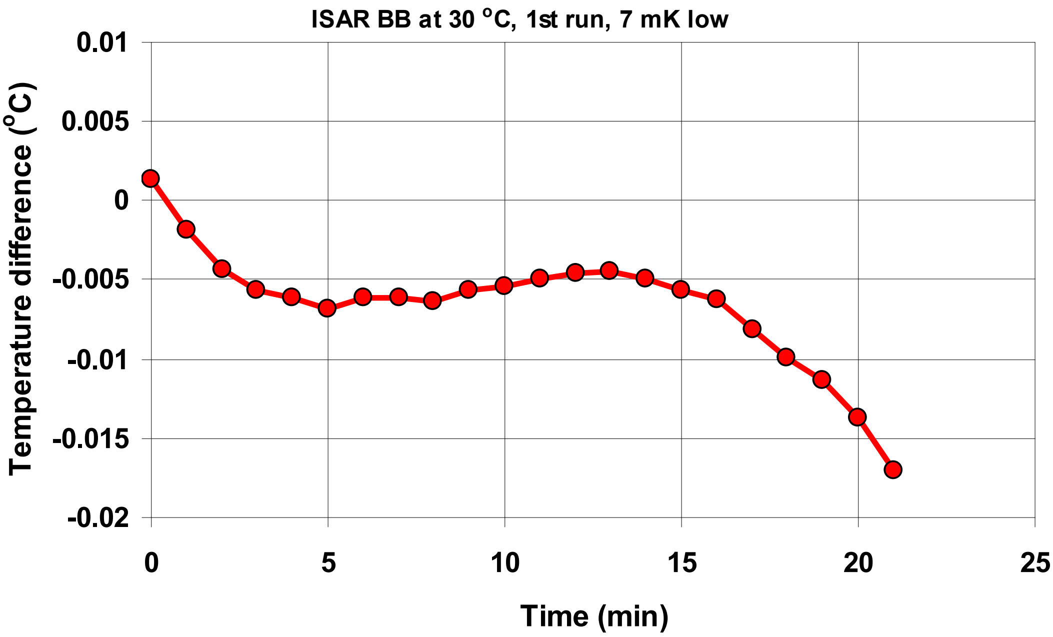

Figure 3.4.10: Difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the corresponding blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 30 °C (1st measurement completed on the 21st April 2009). The average brightness temperature reported by the ISAR blackbody was 7 mK lower than the average temperature measured by the AMBER radiometer.

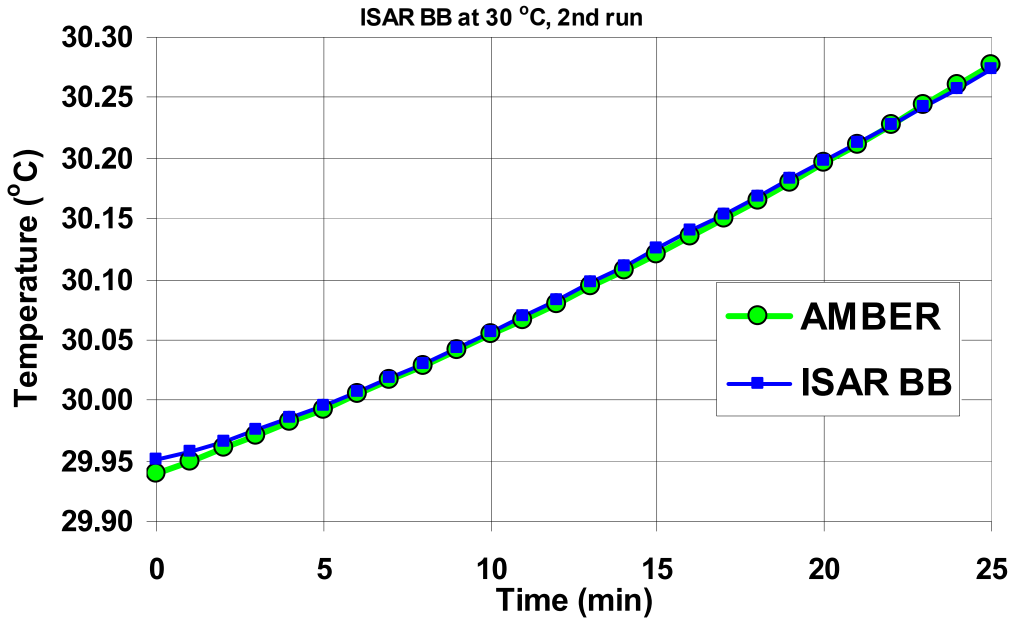

Figure 3.4.11: The ISAR blackbody cavity temperature values measured by the AMBER radiometer when the ISAR blackbody brightness temperature was set in the vicinity of 30 °C (2nd measurement completed on the 22nd April 2009). Also shown are the corresponding blackbody brightness temperature values reported by Southampton University.

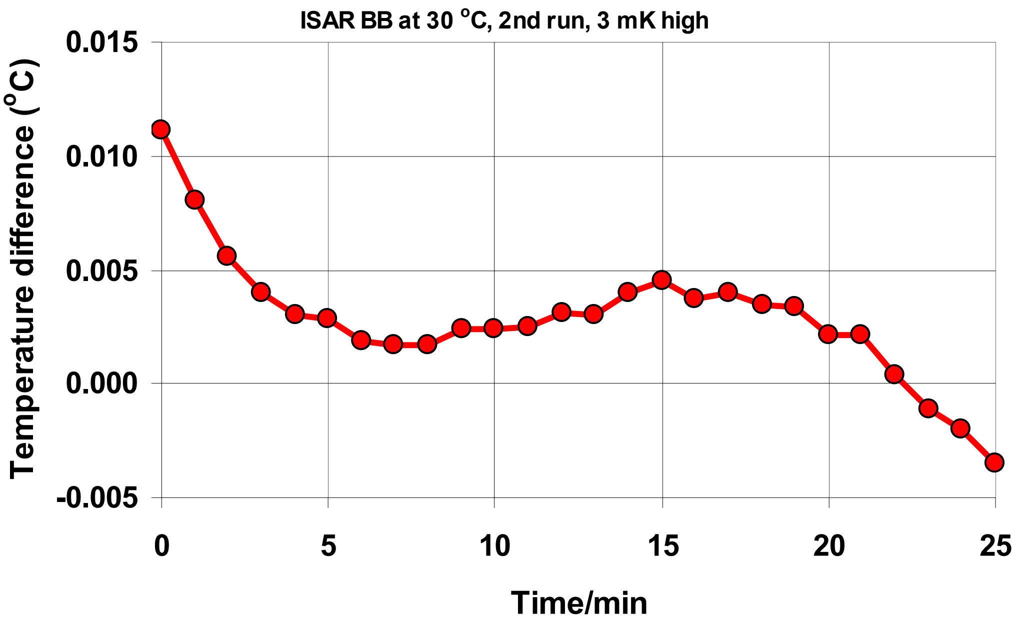

Figure 3.4.12: Plot of the difference between the ISAR blackbody brightness temperatures reported by Southampton minus the corresponding blackbody brightness temperatures measured by the AMBER radiometer when the ISAR blackbody was set in the vicinity of 30 °C (2nd measurement completed on the 22nd April 2009). The average brightness temperature reported by the ISAR was 3 mK higher than the average temperature measured by the AMBER radiometer.

3.4.3.2 TXR radiometer viewing the ISAR blackbody

Figure 3.4.13 shows the ISAR blackbody cavity temperature values measured by the TXR radiometer as well as the ISAR blackbody brightness temperature reported by Southampton University when the blackbody temperature was maintained in the vicinity of 20 °C (1st measurement at 20 °C). Figure 3.4.14 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 20 °C (1st measurement at 20 °C). The average brightness temperature reported by Southampton University was 37 mK lower than the average brightness temperature measured by the TXR radiometer. Figure 3.4.15 shows the ISAR blackbody cavity temperature values measured by the TXR radiometer, as well as the ISAR blackbody brightness temperature reported by Southampton University, when the blackbody temperature was maintained in the vicinity of 20 °C (2nd measurement at 20 °C). Figure 3.4.16 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 20 °C (2nd measurement at 20 °C). The average brightness temperature reported by Southampton University for the 2nd measurement at 20 °C was 95 mK lower than the average temperature measured by the TXR radiometer.

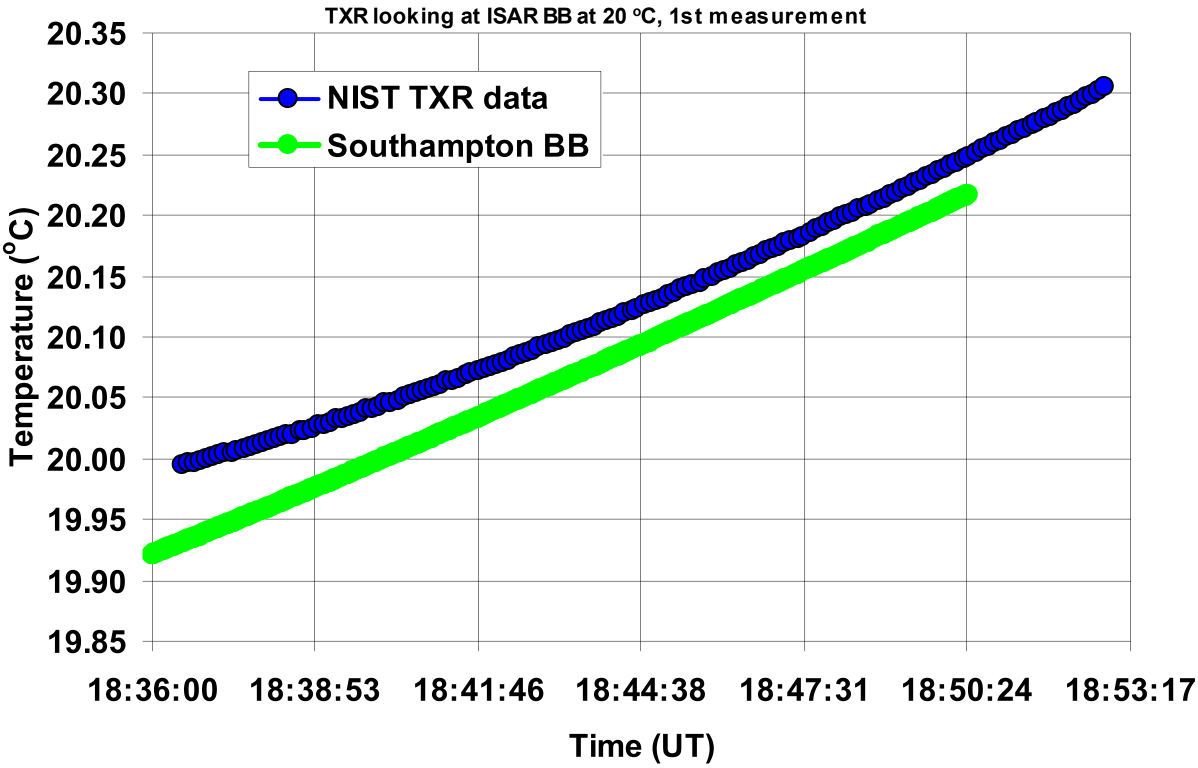

Figure 3.4.13: Plot of the ISAR blackbody cavity temperature values measured by the TXR radiometer when the ISAR blackbody brightness temperature was set in the vicinity of 20 °C, first measurement. Also shown are the corresponding blackbody brightness temperature values reported by Southampton University.

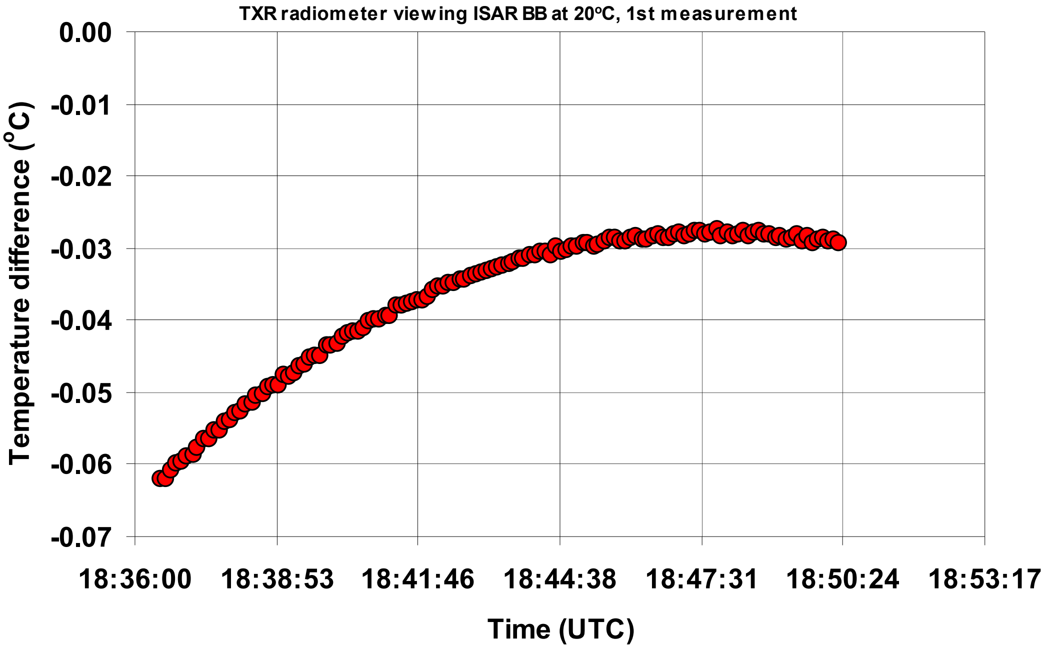

Figure 3.4.14: Plot of the difference between the ISAR blackbody brightness temperatures reported by Southampton minus the corresponding blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 20 °C (1st measurement). The temperature read by TXR is 37 mK higher than the blackbody temperature provided by Southampton University.

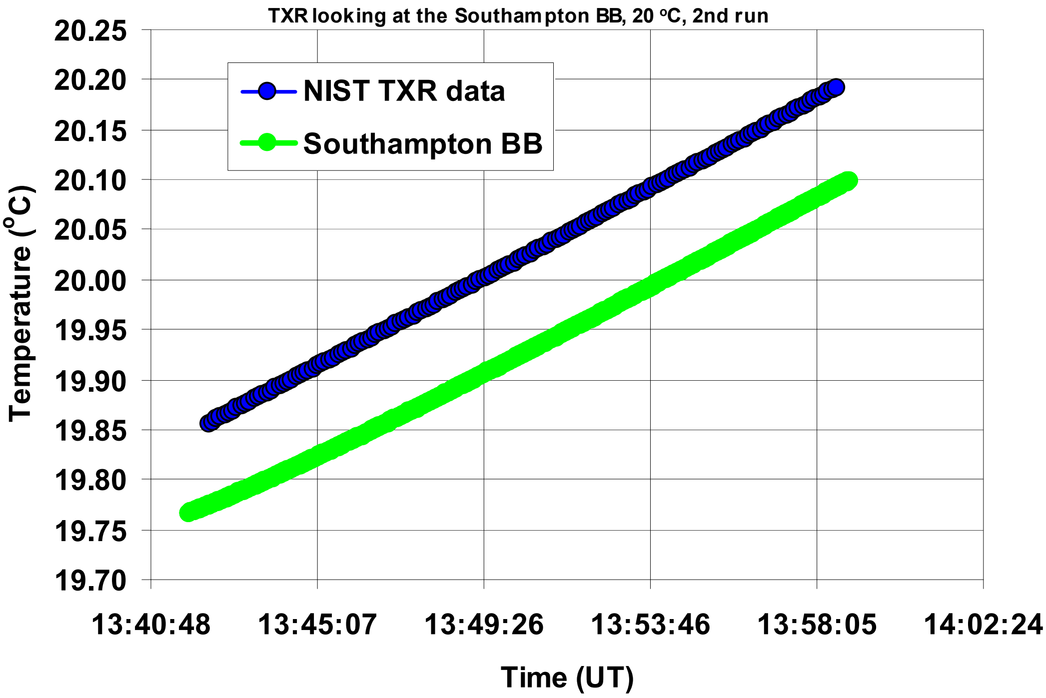

Figure 3.4.15: Plot of the ISAR blackbody cavity temperature values measured by the TXR radiometer when the ISAR blackbody brightness temperature was set in the vicinity of 20 °C, second measurement. Also shown are the corresponding blackbody brightness temperature values reported by Southampton University.

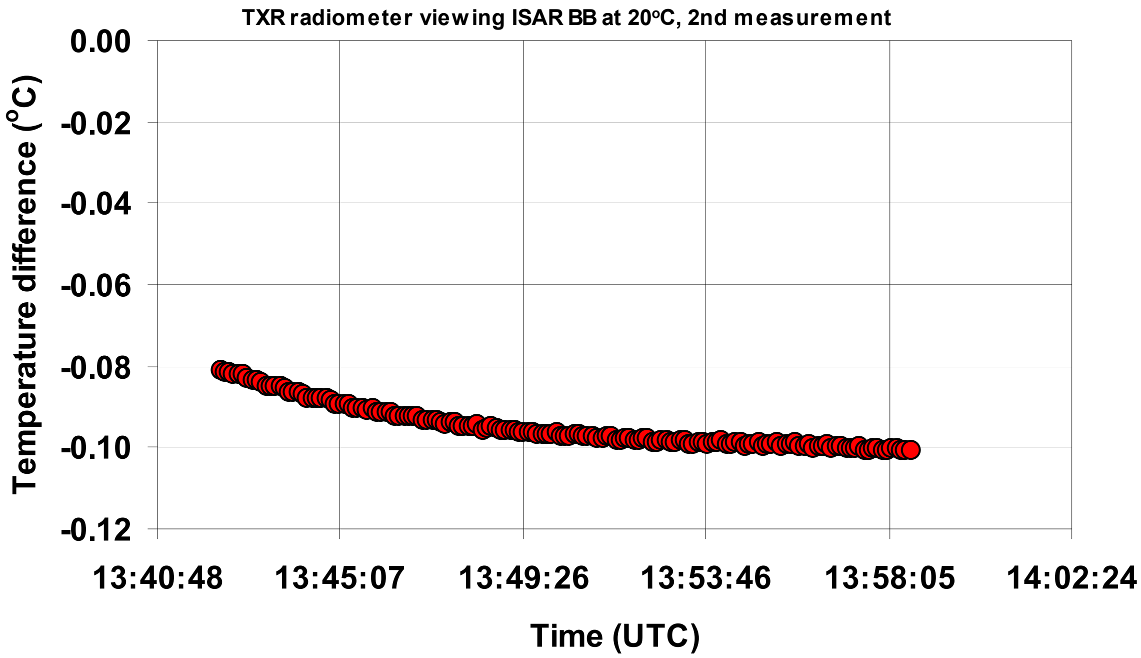

Figure 3.4.16: Plot of the difference between the ISAR blackbody brightness temperatures reported by Southampton minus the corresponding blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 20 °C (2nd measurement). The temperature read by TXR radiometer is 95 mK higher than the blackbody temperature provided by Southampton University.

Figure 3.4.17 shows the ISAR blackbody cavity temperature values measured by the TXR radiometer as well as the ISAR blackbody brightness temperature reported by Southampton University when the blackbody temperature was maintained in the vicinity of 30 °C (1st measurement at 30 °C). Figure 3.4.18 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 30 °C (1st measurement at 30 °C). The average brightness temperature reported by Southampton University was 144 mK lower than the average brightness temperature measured by the TXR radiometer. Figure 3.4.19 shows the ISAR blackbody cavity temperature values measured by the TXR radiometer, as well as the ISAR blackbody brightness temperature reported by Southampton University, when the blackbody temperature was maintained in the vicinity of 30 °C (2nd measurement at 30 °C). Figure 3.4.20 plots the difference between the ISAR blackbody brightness temperatures reported by Southampton University minus the blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 30 °C (2nd measurement at 30 °C). The average brightness temperature reported by Southampton University for the 2nd measurement at 30 °C was 223 mK lower than the average temperature measured by the TXR radiometer.

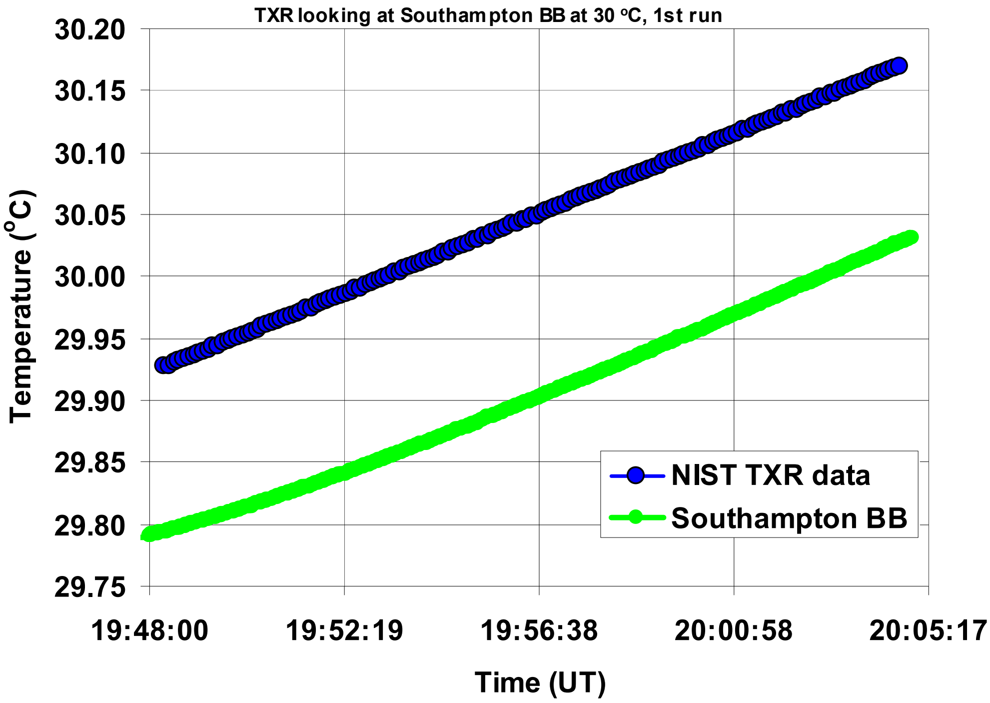

Figure 3.4.17: Plot of the ISAR blackbody cavity temperature values measured by the TXR radiometer when the ISAR blackbody brightness temperature was set in the vicinity of 30 °C, first measurement. Also shown are the corresponding blackbody brightness temperature values reported by Southampton University.

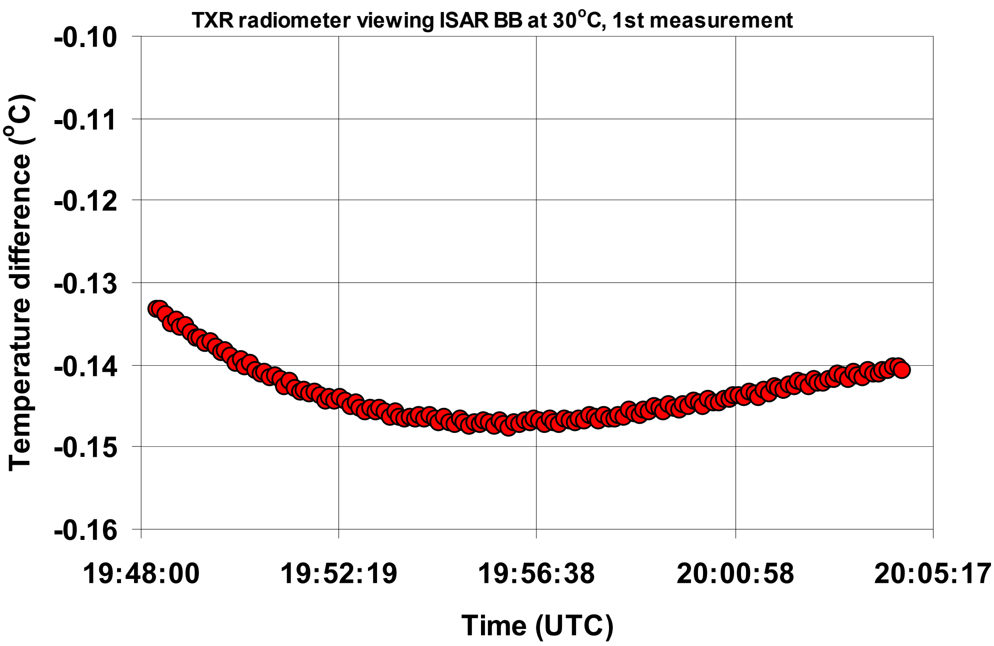

Figure 3.4.18: Plot of the difference between the ISAR blackbody brightness temperatures reported by Southampton minus the corresponding blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 30 °C (1st measurement). The temperature read by TXR is 144 mK higher than the blackbody temperature provided by Southampton University.

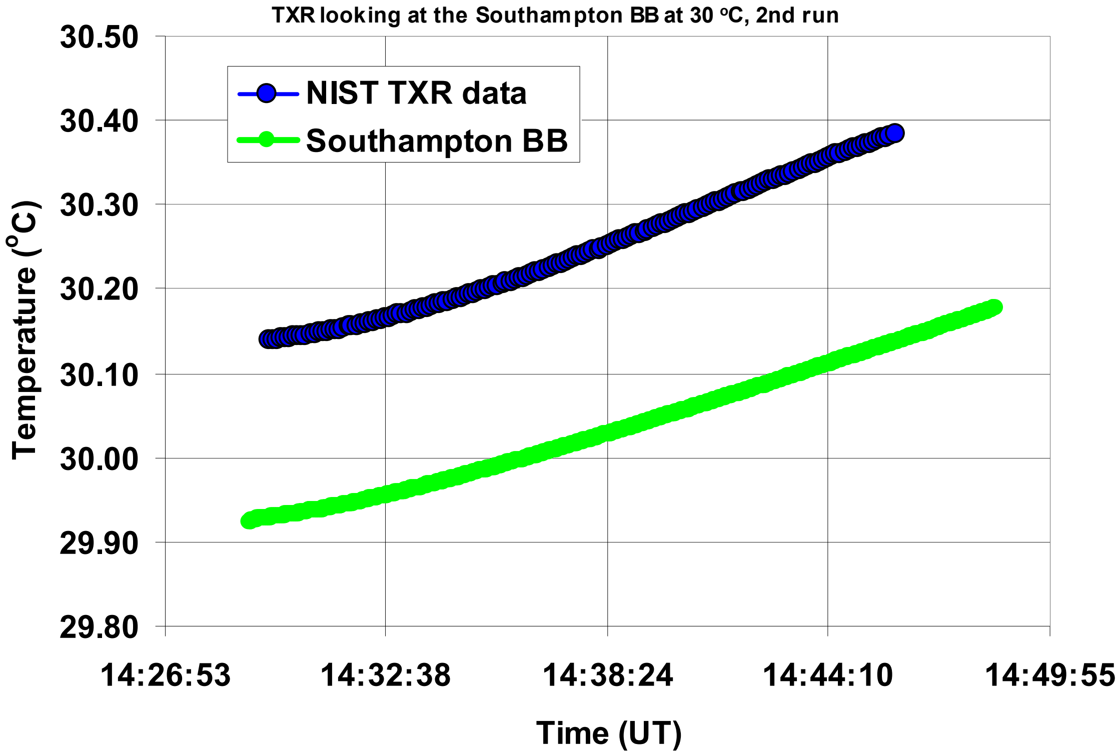

Figure 3.4.19: Plot of the ISAR blackbody cavity temperature values measured by the TXR radiometer when the ISAR blackbody brightness temperature was set in the vicinity of 30 °C, second measurement. Also shown are the corresponding blackbody brightness temperature values reported by Southampton University.

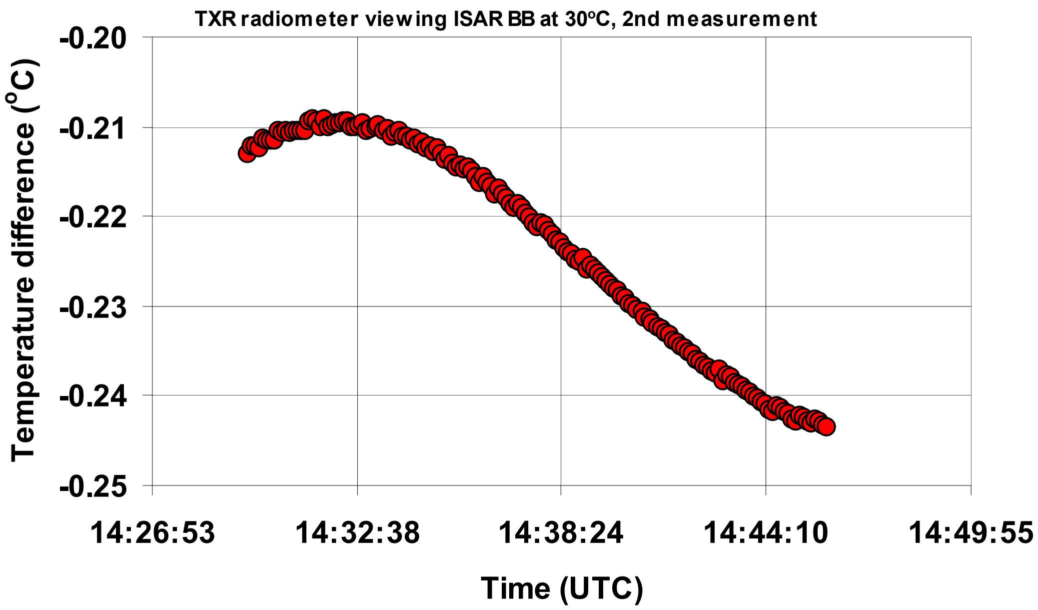

Figure 3.4.20: Plot of the difference between the ISAR blackbody brightness temperatures reported by Southampton minus the corresponding blackbody brightness temperatures measured by the TXR radiometer when the ISAR blackbody was set in the vicinity of 30 °C (2nd measurement). The temperature read by TXR is 223 mK higher than the blackbody temperature provided by Southampton University.

3.5 University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS)

3.5.1 Contact information

RSMAS contact for the comparison: Prof. Peter J Minnett
Address: RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA.
Email: pminnett@rsmas.miami.edu

3.5.2 Blackbody used in the comparison

Blackbody type: Hart Scientific, NIST design. This blackbody is used to validate the calibration of the RSMAS MAERI radiometer. Full information on this blackbody were published by Fowler (1995).
Exit aperture: 100 mm in diameter
Temperature range: -5 °C to 60 °C

3.5.3 Results

The RSMAS blackbody took part in the Miami blackbody comparison. The RSMAS blackbody was set at a particular temperature and its temperature was allowed to stabilise. The cavity temperature of the RSMAS blackbody was measured by the TXR radiometer over a 20 minute to 25 minute period. During the same period, the temperature of the same blackbody, was logged by RSMAS. Measurements were averaged over the measurement period and the average values corresponding to each nominal temperature studied are shown in Table 3.5.1. Measurements were repeated at 10 °C, 15 °C, 20 °C, 25 °C and 30 °C. Table 3.5.1 also shows the difference between the RSMAS blackbody reading and the corresponding measurement provided by the TXR radiometer.

Table 3.5.1: The RSMAS blackbody readings and the corresponding measurements provided by the TXR radiometer, at different blackbody temperatures. Also shown are the differences between the RSMAS blackbody reading and the corresponding measurement provided by the TXR radiometer for the different blackbody temperatures.

Nominal temperature (°C)	RSMAS BB reading (°C)	TXR reading (°C)	Difference (°C)
10 °C	10.306	10.243	0.064
15 °C	15.260	15.220	0.040
20 °C	20.156	20.181	-0.025
25 °C	25.056	25.157	-0.100
30 °C	29.983	30.144	-0.161

3.6 Summary of the results

This section provides a summary of the results provided by the participants of the CEOS IR comparison of the brightness temperature of the reference (SI traceable) blackbodies completed at NPL and at the University of Miami in April and May 2009 respectively.

Table 3.6.1 shows the difference between the temperature of the blackbody cavity provided by the participants and the brightness temperature of the same blackbody measured by the AMBER radiometer, at different blackbody set temperatures.

Table 3.6.1:Difference between the temperature of the blackbody cavity provided by the participants and the brightness temperature of the same blackbody measured by the AMBER radiometer at different blackbody set temperatures.

Participant	Set temperature °C	Temperature "error" 21st April run mK	Temperature "error" 22nd April run mK
RAL	30	14	6
SISTeR BB	20	-8	-5
	10	-15	-14
Southampton	30	-7	3
ISAR BB	20	-16	-14
	10	-19	-18
GOTA	30	-176	-188
La Laguna Univ.	20	-152	-181
Canary Island	10	-164	-177
DEPT	30	-167	-185
Valencia University	20	-143	-166
LAND P80P	10	-74	-87

Table 3.6.2 shows the difference between the temperature of the ISAR blackbody provided by Southampton University minus the brightness temperature of the same blackbody measured by the TXR radiometer, at different blackbody temperatures.

Table 3.6.2: Difference between the temperature of the ISAR blackbody provided Southampton University minus the brightness temperature of the same blackbody measured by the TXR radiometer, at different blackbody temperatures.

Participant	Set temperature °C	Temperature "error" 1st measurement mK	Temperature "error" 2nd measurement mK
Southampton	30	-144	-223
ISAR BB	20	-37	-95

Table 3.6.3 also shows the difference between the RSMAS blackbody reading provided by RSMAS minus the brightness temperature of the same blackbody measured by the TXR radiometer, at different blackbody temperatures.

Table 3.6.3: Difference between the temperature of the RSMAS blackbody provided RSMAS minus the brightness temperature of the same blackbody measured by the TXR radiometer, at different blackbody temperatures.

Nominal temperature (°C)	Difference (°C)
10 °C	0.064
15 °C	0.040
20 °C	-0.025
25 °C	-0.100
30 °C	-0.161

4. DISCUSSION

Table 3.6.1 shows that there is excellent agreement between the cavity temperatures of the RAL SISTeR blackbody measured by the AMBER radiometer and the brightness temperature of the same blackbody as reported by RAL. The largest temperature differences measured were limited to less than ±15 mK for all three temperatures (10 °C, 20 °C and 30 °C) at which this blackbody was evaluated. These differences are well within the combined uncertainty of the measurements by the AMBER radiometer (48 mK, *k*=1, see Appendix 1).

Table 3.6.1 also shows that the same applies for the Southampton University ISAR blackbody. The largest temperature differences measured between the cavity temperatures read by the AMBER radiometer and the corresponding brightness temperatures of the same blackbody reported by Southampton University were limited to less than ±30 mK for all three temperatures (10 °C, 20 °C and 30 °C) at which this blackbody was evaluated. These differences are well within the combined uncertainty of the measurements by the AMBER radiometer (48 mK, *k*=1, see Appendix 1).

The largest temperature differences measured between the cavity temperatures of the GOTA blackbody read by the AMBER radiometer and the corresponding brightness temperatures of the same blackbody reported by GOTA were larger than those seen in the RAL SISTeR and Southampton ISAR blackbodies (see Table 3.6.1). However, the GOTA blackbody readings were consistently low by up to 188 mK. Although this is well outside the uncertainty of the measurement of the AMBER radiometer (48 mK, *k*=1, see Appendix 1), it is well within the uncertainty of the GOTA blackbody (600 mK at k=1, see section 3.2). The consistently low measurements of the GOTA blackbody cavity temperatures could possibly arise from the low cavity emissivity of this blackbody. The emissivity of the cavity is only 0.995 and it is not clear whether a correction was used to account for the low emissivity of the blackbody cavity.

The DEPT blackbody was identical to the GOTA blackbody and the performance of these two blackbodies was found to be very similar. The largest temperature differences measured between the cavity temperatures of the DEPT blackbody, read by the AMBER radiometer, and the corresponding brightness temperatures of the same blackbody reported by DEPT were also much larger than those seen in the RAL SISTeR and Southampton ISAR blackbodies (see Table 3.6.1). The DEPT blackbody readings were consistently low by up to 185 mK. For cavity temperatures around 10 °C the differences between the GOTA blackbody readings and the AMBER radiometer readings were also low but limited to less than 87 mK. The differences between the cavity temperatures of the DEPT blackbody, read by the AMBER radiometer, and the corresponding brightness temperatures of the same blackbody reported by DEPT are well within the uncertainty of the DEPT blackbody (700 mK at k=1, see section 3.1). As for the GOTA blackbody, the consistently low measurements of the DEPT blackbody cavity temperatures could possibly arise from the low cavity emissivity of this blackbody. The emissivity of the cavity is only 0.995 and it is not clear whether a correction was used to account for the low emissivity of the blackbody cavity.

Tables 3.6.2 and 3.6.3 show the brightness temperature values for the Southampton ISAR Blackbody and the RSMAS blackbody respectively measured by the NIST TXR radiometer at the Miami deployment. The differences noted for the Southampton ISAR blackbody by the TXR measurements, shown in Table 3.6.2, are larger than expected and may be a result of transportation. The RSMAS blackbody results shown in Table 3.6.3 show good agreement within the uncertainties of TXR and comparison. Overall the comparison in Tables 3.6.2 and 3.6.3 show the results are within the combined expanded uncertainties (k=2) of the TXR and the two blackbodies measured at Miami. The TXR uncertainties are described in Appendix 2.

5. REFERENCES

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APPENDIX 1

AMBER RADIOMETER UNCERTAINTY BUDGET AND MEASUREMENT TRACEABILITY

Although the AMBER radiometer was designed as an absolute radiometer, the measurement uncertainty when this radiometer is used in the absolute mode is relatively high. This is mainly due to the high uncertainty contribution arising from the absolute calibration of the filter radiometer employed by the AMBER radiometer. A much lower measurement uncertainty is achieved when the AMBER radiometer is used in a relative mode, i.e. it is used to compare the brightness temperature of a test blackbody with that of a primary reference blackbody such as a Ga freezing point blackbody. In this case, the AMBER radiometer looks sequentially at the test blackbody and reference blackbody (Ga blackbody). The gallium melting point is a defined fixed point on the ITS-90 temperature scale, without any uncertainty and provides a very attractive source for the calibration of the brightness 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. Although the relative spectral irradiance responsivity of the filter radiometer is required when the AMBER radiometer is used in the relative mode, the uncertainty contribution due to the relative spectral irradiance responsivity of the filter radiometer is small (10 mK).

Table A1-1 shows the uncertainty budget for comparing the brightness temperature of a variable temperature blackbody with that of the Ga blackbody in the 10 ^{o}C to 30 ^{o}C temperature range using the AMBER radiometer. The first uncertainty contribution listed in Table A1-1 is the uncertainty due to the Ga blackbody brightness temperature itself. A breakdown of this uncertainty contribution is shown in Table A1-2. Table A1-2 shows that the uncertainty contributions due to the Ga blackbody emissivity (20 mK) and the temperature drop due to the “Gallium casing” (10 mK) provide the dominant uncertainty contributions in the Ga blackbody brightness temperature uncertainty budget. Table A1-1 shows that the uncertainty contributions due to the Ga blackbody brightness temperature (23 mK), the uncertainty due to the non-linearity of the lock-in amplifier (29 mK) (E. Theocharous, “Absolute linearity characterisation of lock-in amplifiers” *Applied Optics*, 47, 1090-1096, 2008) and the uncertainty contribution due to the long term drift in the AMBER radiometer (28 mK) provide the dominant uncertainty contributions in the uncertainty budget of the comparison of the brightness temperature of a variable temperature blackbody with that of the Ga blackbody in the 10 ^{o}C to 30 ^{o}C temperature range. Table A1-1 shows that the combined standard uncertainty of comparing the brightness temperature of a variable temperature blackbody with that of the Ga blackbody in the 10 ^{o}C to 30 ^{o}C temperature range using AMBER is 48 mK (k=1).

Table A1-1: Uncertainty budget for measuring the brightness temperature of a variable temperature blackbody by comparison to the Ga blackbody in the 10 ^{o}C to 30 ^{o}C temperature range using AMBER

Contribution	Standard Uncertainty Value (mK)	Comment
Uncertainty in the Ga blackbody brightness temperature	23	Taken from Ga blackbody uncertainty budget (see Table A1-2)
Uncertainty due to the lock-in amplifier/electronics non-linearity in the 10 ^{o}C to 30 ^{o}C temperature range	29	0.1% non-linearity in the lock-in amplifier (maximum in the 10 ^{o}C to 30 ^{o}C temperature range). Depends on the difference between the Ga melting point and the temperature of the target being measured.
AMBER Radiometer relative spectral responsivity calibration	10	
AMBER Radiometer relative spectral responsivity stability/ageing	2	Small for ambient temperature blackbodies
AMBER "long term" stability	28.4	0.1% fluctuation
Uncertainty due to ambient temperature fluctuations	2	
Uncertainty due to chopper frequency fluctuations	1	
Combined uncertainty	**48**	**mK**

Table A1-2: Uncertainty budget for the brightness temperature of the Ga blackbody

Contribution	Standard Uncertainty Value (mK)	Comment
Uncertainty due to Ga BB emissivity	20	Difference of Ga BB emissivity (0.9993) from unity is assume to be the standard uncertainty contribution. Value is wavelength and temperature dependent.
Uncertainty due to Ga BB temperature "drop"	10	Estimated temperature drop between the Ga metal and the inside surface of the Ga blackbody cavity.
Stability of the Ga blackbody brightness temperature (as indicated by a high resolution radiometer such as AMBER). This is a type A uncertainty.	1	Standard deviation of measurements over a typical measurement period e.g. 5 minutes
Uncertainty due to radiative heat loss to the environment	1	Small when the Ga blackbody is operating just above ambient.
Uncertainty due to convective heat loss to the environment	1	Small when the Ga blackbody is operating just above ambient.
Uncertainty due to (spatial) temperature variation inside the cavity	5	
Uncertainty due to ambient temperature fluctuations	2	
Uncertainty due to the purity of the Ga	0.5	
Combined uncertainty (k=1)	**23**	**mK**

APPENDIX 2

NIST THERMAL-INFRARED TRANSFER RDIOMETER (TXR) UNCERTAINTY BUDGET

NIST developed and fielded the TXR for verification of radiance scales in the thermal-infrared spectral region at vendor sites where near-room-temperature extended-area blackbody sources are used for calibrations. The TXR is a two channel portable filter radiometer that can be used at ambient or in cryo-vacuum environments. Its two channels are at 5 μm and 10 μm with the use of filters that have approximately 1 μm band width. The detectors are photovoltaic InSb for the 5 μm channel and a photovoltaic Mercury Cadmium Telluride (MCT) for the 10 μm channel. The detectors, filters, and reflective optics are built into a liquid-nitrogen cryostat, and the entire radiometer is vacuum/cryogenic compatible. The TXR is equipped with a ZnSe window and has a self-contained vacuum jacket and liquid-nitrogen reservoir, and so can be used at ambient pressure and room temperature. The TXR has been extensively tested for its radiometric performance at NIST. The space simulating chamber called Medium Background Infrared (MBIR) Facility at NIST was used for much of its characterization using a cryogenic blackbody having a 10.8 cm diameter black coated cavity and a temperature range 180 K to 350 K. The various parts of the TXR, the detectors, filters and reflective optics have been independently characterized. The TXR optical set up is modelled using a measurement equation for radiance and calibrated as a system using the Kelvin scale derived from the MBIR cryogenic blackbody Platinum Resistance Thermometers (PRT) for cryogenic operation. The references 1, 2 and 3 below provide description of the TXR and discuss its uncertainty budget. The absolute uncertainty in radiance temperature measurements was estimated to be 120 mK (k=1) for cryogenic operation and much of it is also contributed by the MBIR cryogenic blackbody PRT sensor drifts.

However, as shown in reference 4, TXR is also calibrated with NIST Waterbath blackbody for temperatures 17.5 ^{o}C to 70 ^{o}C and the uncertainties are smaller for deployments that run at ambient background temperatures. The calibration becomes robust especially when the NIST Waterbath blackbody accompanies the TXR for in situ measurements as any effect of TXR responsivity drift with time is minimized. The 5 μm channel is not used in the ambient environment as it was found to be influenced by the water vapour absorption. The 10 μm channel is used for calibrations. The TXR and the NIST Waterbath blackbody were deployed for the intercomparison campaign at the University of Miami's Rosenthal School of Marine and Atmospheric Science (RSMAS) during May 2009. The uncertainty budget for the TXR deployment during this period is listed in Table A2-1. The combined standard uncertainty is estimated at 44 m K (k=1).

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Table A2-1: TXR uncertainty Budget for the 2009 Miami Deployment

	Contribution	Standard Uncertainty (mK)	Comment
1.	NIST Water blackbody temperature uncertainty for temperatures between 17.5 °C to 30 °C after all corrections are applied.	5	Taken from the NIST Waterbath blackbody uncertainty table given in Part I of this report
2	The NIST Waterbath blackbody thermometer readout	7	
3	TXR radiometer responsivity uncertainty that includes evaluation of calibration coefficients for the filter channels	30	
4	TXR radiometer stability	30	Upper limit for a 30 minute time period
5	Digitization noise in signal readout from Lock-in amplifier	8	
	Combined uncertainty	44	