Protocols of the 2016 FRM4STS NPL comparisons

E. Theocharous (Theo) and N. P. Fox

Earth Observation, Climate & Optical Group

NPL, UK

e.theo@npl.co.uk

17th October 2017

fiducial reference temperature measurements

NPL National Physical Laboratory

CONTENTS

Definition of a Protocol (in science)

Protocol (in science) is defined as the written procedural method of conducting an experiment.

How comparisons are organised?

Under the Mutual Recognition Arrangement (MRA), the metrological equivalence of national measurement standards (of the different National Measurements Institutes) is determined by a set of key comparisons chosen and organised by the consultative committees of CIPM.

Take the key comparison of the spectral responsivity scales from 900 nm to 1600 nm in which NPL is acting as the pilot laboratory. How was this comparison developed?

A call for participants to take part in this comparison was put through.

In response to this call, a number institutes submitted a request to take part in the comparison.

Institutes who asked to participate, were approved to take part in the comparison.

Among the participants, a task group was formed to draw up the **technical protocol** for the comparison.

The final version of the technical protocol was agreed by all the participants.

How was the 2016 FRM4STS comparison organised?

For the 800 nm to 1700 nm spectral responsivity scale comparison, the procedure used follows the guidelines of the BIPM and is based on current best practice in the use of standard detectors**. It also takes account of the experience reported from the previous spectral responsivity comparisons in this wavelength range.**

The protocol for the 2016 FMR4STS comparison also relied on experience acquired during the 2001 and 2009 radiometer comparisons.

This presentation summarises the technical procedures which were prepared and followed during the completion of the 2016 FRM4STS comparisons at NPL.

The 2016 comparison included:

- Laboratory comparisons of the **radiometers** and reference radiance **blackbodies** of the participants.
- Field comparisons of **Water Surface Temperature** (WST) measurements, held at Wraysbury fresh water reservoir.
- Field comparisons of **Land Surface Temperature** (LST) measurements held on the NPL campus.
- SST comparison of two ship-borne radiometers.
- Field comparisons of Land Surface Temperature (LST), held in Namibia in 2017.
- Field comparisons of Ice Surface Temperature (IST) in the Arctic.

Protocol development

- A version of the protocols for the various 2016 comparisons of the radiometers and reference radiance blackbodies was proposed in October 2015 (see report OFE-D80-V1-Iss-1-Ver-1, "Fiducial Reference Measurements for Validation of Surface Temperature from Satellites (FRM4STS)", Technical Report 1, "Procedures and Protocols for the verification of TIR FRM Field Radiometers and Reference Blackbody Calibrators")
- Following an initial review by participants and an assessment by a number of participants, some of the introductory sections of this protocol were revised and made more generic to allow the protocol to be a standalone document for future use.

What the final version of the protocol stated:

The protocol stated that NPL was to serve as pilot for the 2016 FRM4STS comparison supported by the PTB, the NMI of Germany.

NPL, the pilot, was given the responsibility of (among other things):

i. inviting participants and

ii. for the analysis of data, following appropriate processing by individual participants.

NPL, was to be the only organisation to have access and view all data from all participants.

This data remained confidential to the participant who provided it and NPL at all times, until the publication of the report showing results of the comparison to participants.

What the protocol stated:

- The Protocol included the list of the potential participants, based on current contacts and expectation that were likely to take part.
- Dates for the comparison activities were also provided.
- A full invitation to the international community through CEOS and other relevant bodies was carried out to ensure full opportunity and encouragement is provided to all.
- The Protocol stated that all participants were expected to demonstrate independent traceability to SI of the instrumentation that they planning to use.
- Participants were also expected to make clear the route of traceability of their measurements.

What the protocol stated:

- By their declared intention to participate in the comparison, the participants deemed to accept the general instructions and the technical protocols written down.
- Participants committed themselves to follow the procedures described in the protocols, strictly.
- Once the protocol and list of participants were reviewed and agreed, no change to the protocol could be made without prior agreement of **all** participants.
- Where demonstrable traceability to SI was required during the comparison activity, this will be obtained through the participation of PTB and NPL as pilot.

Timetable for the 2016 FRM4STS comparison

PHASE 1: PREPARATION	
Invitation to participate	October 2015
Preparation and formal agreement of the protocols	Jan - March 2016
PHASE 2: MEASUREMENTS	
Comparison of participants' radiometers and blackbodies	June 2016
Field comparison of participants' radiometers at NPL	June/July 2016
Participants send all data and reports to pilot	July 2016
PHASE 3: ANALYSIS AND REPORT WRITING	
Participants send preliminary report describing their measurement system and uncertainties to the pilot. This will be circulated to all participants.	April 2016
Receipt of comments from participants	May 2016
Draft A (results circulated to participants)	July 2016
Final draft report circulated to participants	August 2016
Draft B submitted to CEOS WGCV	September 2016
Final Report published	October 2016

Plan for Comparison Activity at NPL

Week No.	Experiment No.	Start Date	End Date	Experiment	Venue
1	1a	20 JUNE 2016	24 JUNE 2016	Laboratory comparison of participants' radiometers against a reference blackbody.	NPL, UK
	1b	20 JUNE 2016	24 JUNE 2016	Simultaneously, laboratory comparison of participants' blackbodies using the NPL AMBER facility and PTB's IR radiometer.	NPL, UK
2	2	27 JUNE 2016	1 JULY 2016	Water surface temperature measurement inter-comparison of participants' radiometers.	Wraysbury reservoir, near NPL, UK
3	3	04 JULY 2016	08 JULY 2016	Land Surface Temperature measurements comparison of radiometers.	Near NPL, UK

fiducial reference temperature measurements

NPL National Physical Laboratory

Transportation and electrical power

The protocol made it clear that:

- It was the responsibility of participants to ensure that any instrumentation required by them was shipped with sufficient time to clear any customs requirements of the host country.
- NPL could provide some guidance on the local processes needed for this activity (queries should be directed to Theo Theocharous).
- It was recommended that, where possible, any fragile components should be hand carried to avoid the risk of damage.
- Electrical power (220 V ac) will be available to all participants, with a local UK plug fitting. Participants who required a 110 V AC supply should provide their own transformer.

Preliminary information required

- Three months prior to the start of the comparison, participants were required to supply to the pilot a description of the instrumentation that they will bring to the comparison. This should include any specific operational characteristics where heights/mountings may be critical as well as a full description of its characterisation, traceability and associated uncertainties.

- The uncertainties were to be reviewed by NPL for consistency and circulated to all participants for comment and peer review.

- Uncertainty budgets submitted by participants could be revised as part of this review process but only in the direction to increase the estimate in light of any comments.

- Post the comparison process, participants could choose to re-evaluate their uncertainties using methods and knowledge that they acquired during the review process.

The protocols made it clear that:

- By their declared intention to participate in this comparison, the laboratories accepted the general instructions and the technical procedures written down in the protocols and committed themselves to follow the procedures strictly.

- Once the protocol was agreed, no change to the protocol could be made without prior agreement of all the participants.

The 2016 FRM4STS blackbody lab comparison

20th to 24th June 2016

fiducial reference temperature measurements

NPL National Physical Laboratory

Blackbody comparison protocol

- In this comparison, the blackbodies provided by participants will be compared relative to the standards of two NMIs, using well-characterised transfer standard radiometers.
- The transfer radiometers to be used are the NPL AMBER radiometer which measures the brightness temperature of the participating blackbodies at a wavelength of 10.1 μm (FWHM = 1 μm) and the PTB infrared broadband radiometer which measures the brightness temperature of the blackbodies in the 8 μm to 14 μm wavelength range.
- The blackbodies which are used to support sea/water surface temperature measurements will be compared at nominal temperatures of 283 K, 288 K, 293 K, 298, 303 and 308 K. For blackbodies which are used to support land surface temperature measurements, the comparison will be extended down to 273 K and up to 323 K, although measurements as high as 348 K were performed.
- For blackbodies which are used to support ice surface temperature measurements, the comparison will to go down to 253 K.

According to the protocol:

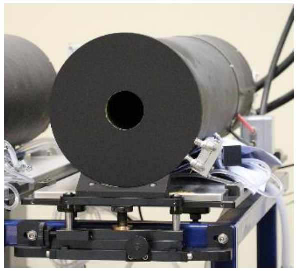
- The transfer radiometers used to view the participating blackbodies should be calibrated traceable to NPL and PTB primary scales prior to use. These radiometers should be calibrated before and after their use in this comparison to demonstrate their stability.

- The transfer radiometers should be mounted so that they can be easily aligned to be coaxial to the participant blackbodies.

- Care will be needed to avoid significant reflections or emissions from the transfer radiometers into the blackbody under test or at least so that any interaction is such that its impact on any measurements is minimised.

FRM4STS - PTB traceability scheme

Initial calibration at PTB



NH$_3$ Reference Black Body

Linked to the ITS-90
Uncertainty (*k=1*) = 33 mK
at t_{90} = -20 ° C to 75 ° C

Calibration of Transfer Radiation Thermometer

Transfer Radiation Thermometer TRT IV

NETD (10s) < 9 mK
SSE corr. uncertainty < 2 mK
SSE = 0.999 at Ø 40 mm

Calibration of Reference Source

Travelling Reference Source

Plate radiator for stability check of TRT IV at NPL

Comparison campaign at NPL

Travelling Reference Source

Stability check of TRT IV

Transfer Radiation Thermometer TRT IV

Calibration of partner BBs

Recalibration at PTB

NH$_3$ Reference Black Body

Recalibration and investigation of aging

Transfer Radiation Thermometer TRT IV

Recalibration and investigation of aging

Travelling Reference Source

Assessment of final uncertainty

Combined uncertainty (*k=1*) = 67 mK

AMBER traceability scheme:

- The melting point of gallium is a fixed point on the ITS-90 temperature scale.
- The brightness temperature of a gallium blackbody was checked against the NPL ammonia heat-pipe reference blackbody prior to the 2016 FRM4STS comparison.
- The gallium blackbody was used to calibrated AMBER during the comparison.
- The operation of this gallium blackbody was checked against a second gallium blackbody at the end of the comparison.

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	

Systematic standard uncertainties when AMBER measures the radiance temperature of a test blackbody at -30 ˚C to +70 ˚C temperature range

Contribution	Standard Uncertainty / mK	Comment
Uncertainty in the Ga blackbody radiance temperature	**32**	Taken from Ga blackbody uncertainty budget
Uncertainty due to the lock-in amplifier non-linearity in the - 60 °C to +50 °C temperature range	**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 reference [7]
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**	

The description of each participant's blackbody and its route of traceability should be provided by completing the form provided

OFE-D-90A-V1-Iss-1-Ver-1-DRAFT

APPENDIX B: DESCRIPTION OF THE BLACKBODY AND ROUTE OF TRACEABILITY

This template should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated.

Make and type of the Blackbody ....

....

Outline Technical description of the blackbody: *this could be a reference to another document but should include key characteristics for the blackbody such as aperture size and cavity dimensions, type of black coating (and its spectral characteristics) used, model used to determine emissivity, location, number and type of thermometers used:* ....

....

....

....

....

....

Establishment or traceability route for primary calibration including date of last realisation and breakdown of uncertainty: *this should include any spectral characterisation of components or the complete blackbody:* ....

....

....

Operational methodology during measurement campaign: *method of alignment, sampling strategy, data processing methods:* ....

....

....

Blackbody usage (deployment), previous use of instrument and planned applications. If activities have targeted specific mission please indicate: ....

....

....

....

....

....

Participant: ....

Date: .... Signature: ....

What the protocol stated:

- Participants should set their blackbodies to the nominal temperature specified by the pilot.
- They should indicate to the pilot when their blackbodies have reached equilibrium.
- The operators of the transfer radiometers will move their radiometers in front of the test blackbody and record the readings of the radiometers continuously during the nominal 10 to 15 minute period over which each participant blackbody was being monitored.
- Participants will provide to the pilot their estimated brightness temperature of their blackbody, together with the associated uncertainty at different times during the measurement period. This will allow drifts in the brightness temperature of the blackbodies which may occur during the measurement period to be accounted for.
- Data will be given to the Pilot on the form provided (see form overleaf).
- The participants will not be informed of the result at that stage.
- The process will be repeated for each of the remaining nominal temperatures, and any other temperatures deemed necessary. In practise it is expected that other participating blackbodies will be measured sequentially whilst blackbodies re-stabilise to any new temperature.
- The sequence should then be repeated for all temperatures to assess reproducibility.

Blackbody comparison data should be given to the Pilot on the form shown below:

fiducial reference temperature measurements

OFE-D-80-V1-Iss-1-Ver-1-DRAFT

Measurement Laboratory Results: Blackbody Comparison

Instrument Type .... **Identification No** ....

Date of measurement: .... **Ambient temperature** ....

Time of measurement (UTC)	Blackbody Brightness Temperature K	BB Brightness Temperature Uncertainty mK	Uncertainty % A	Uncertainty % B

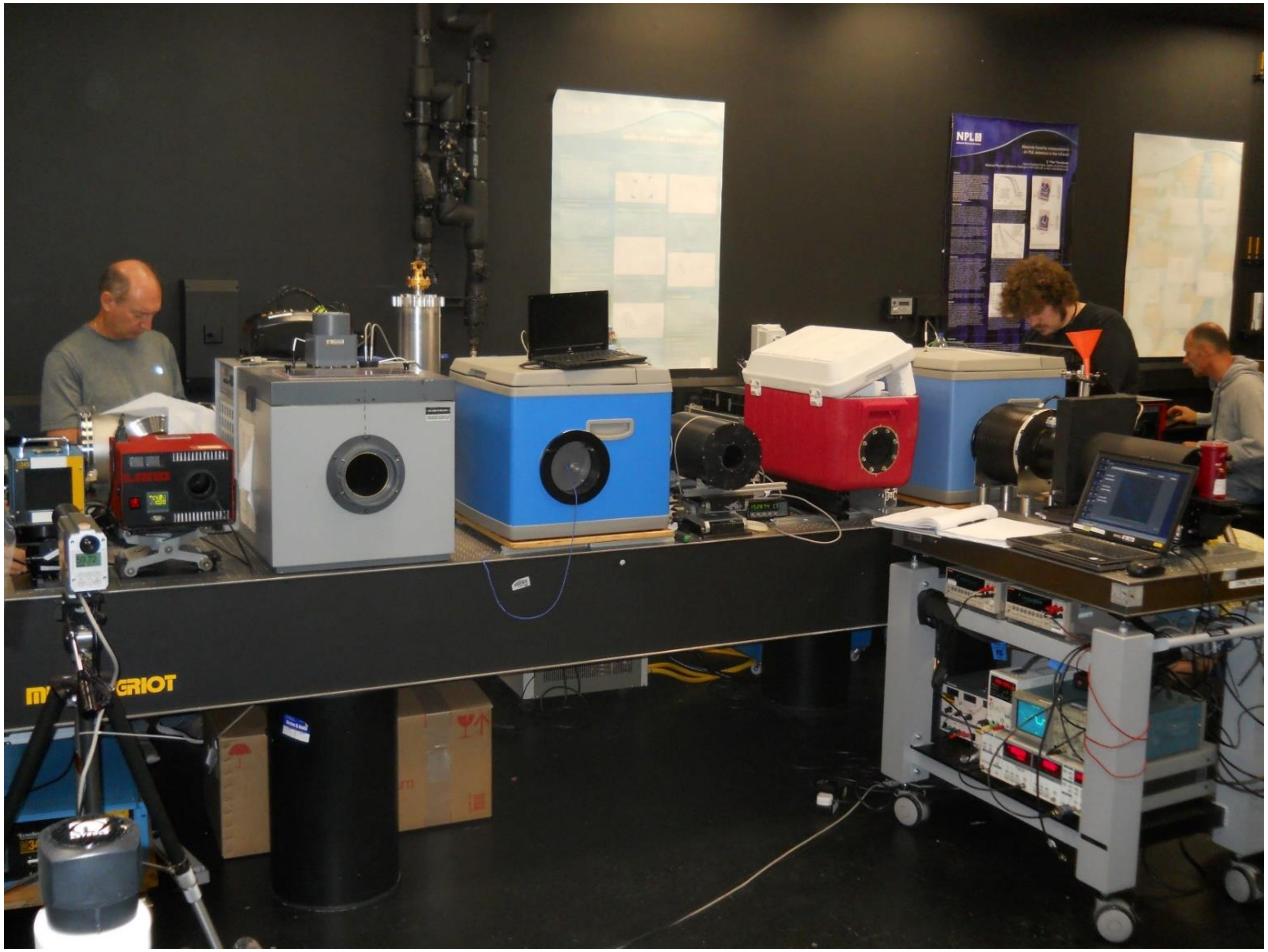
Participant: ....

Signature: .... **Date:** ....

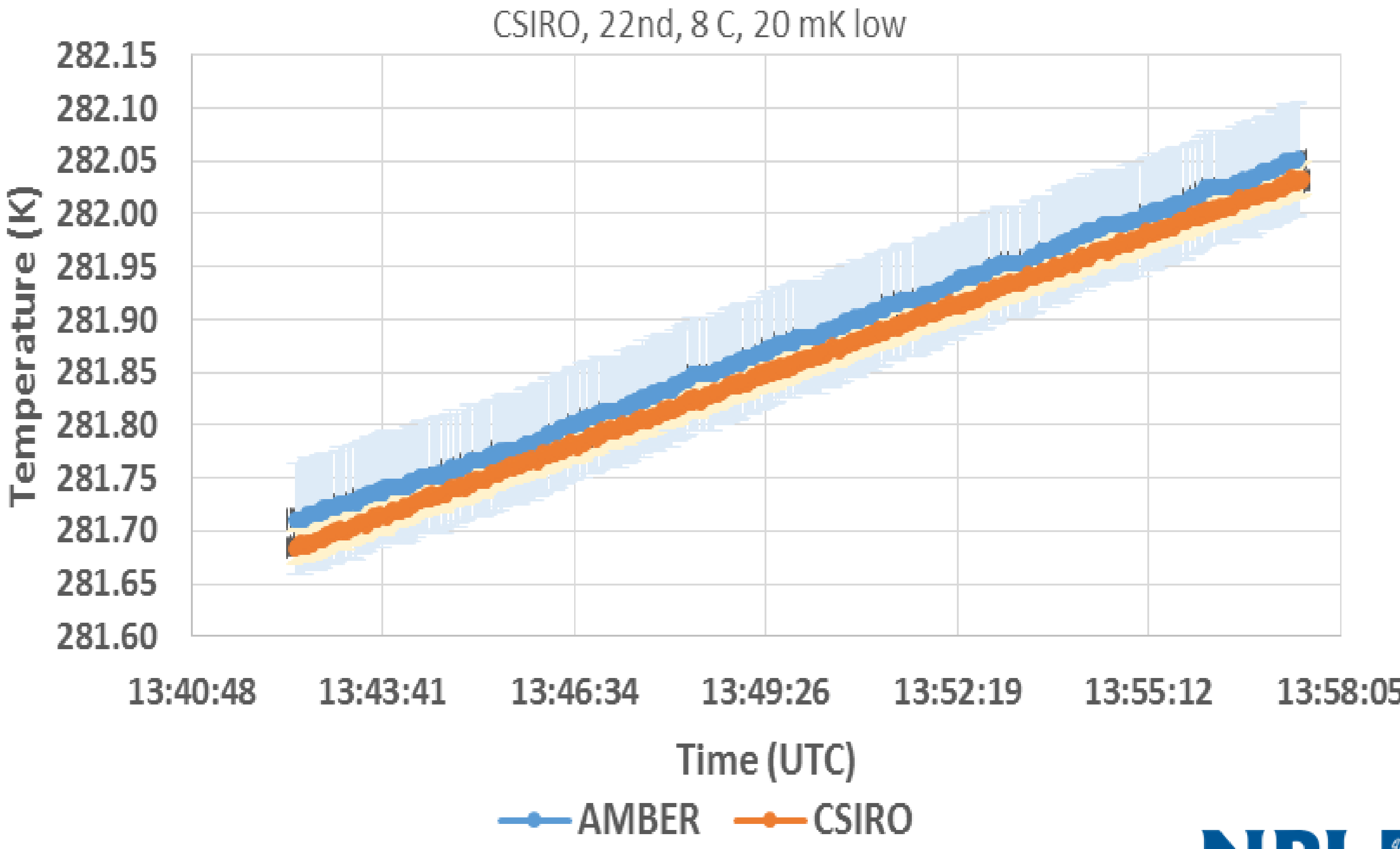
fiducial reference temperature measurements

NPL National Physical Laboratory

The eight blackbodies which participated in the 2016 FRM4STS blackbody comparison lined up on an optical bench.



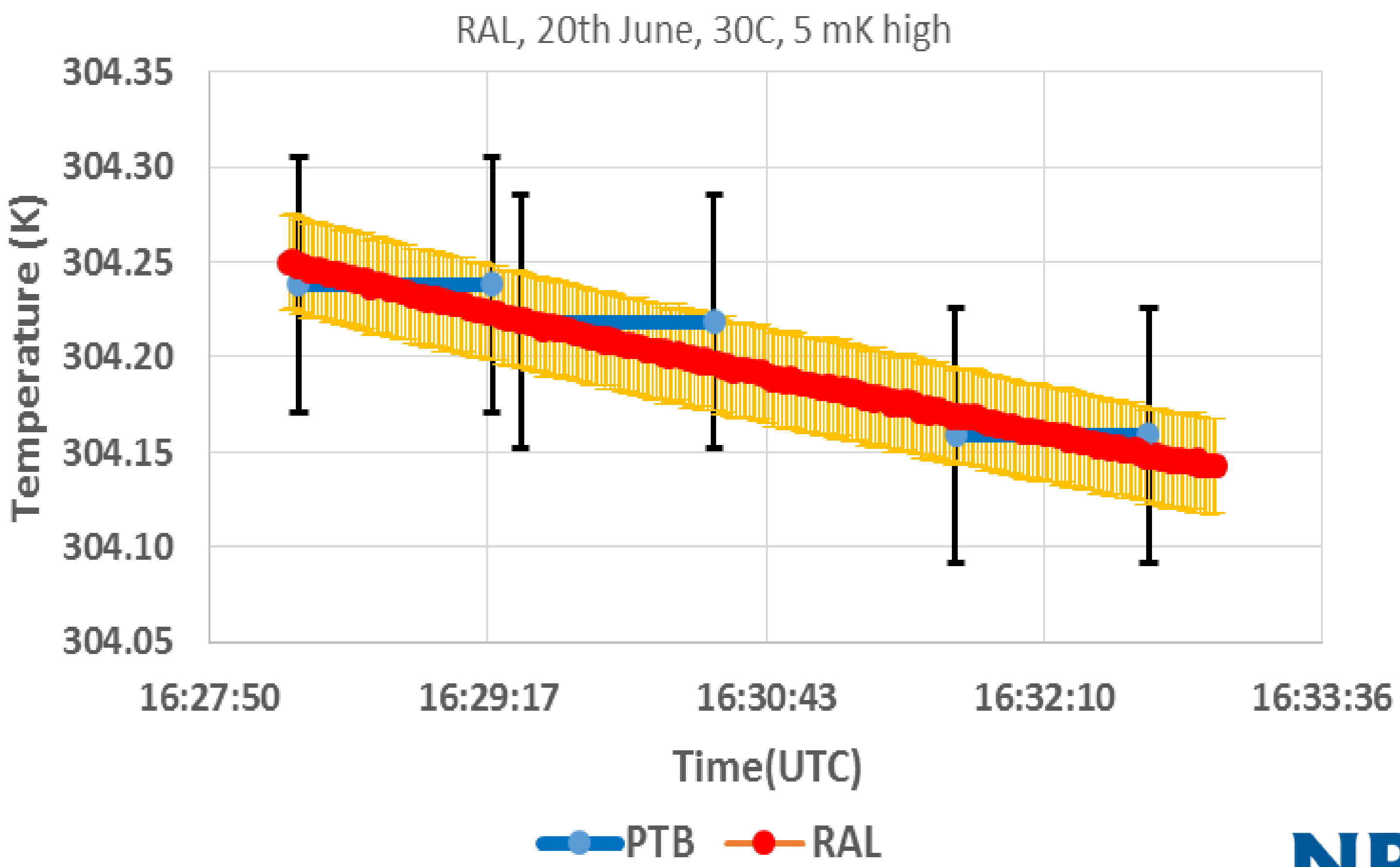
Measurements (as a function of time) reported by the CSIRO blackbody as well as the temperature of the same blackbody measured by the AMBER radiometer.



fiducial reference temperature measurements

National Physical Laboratory

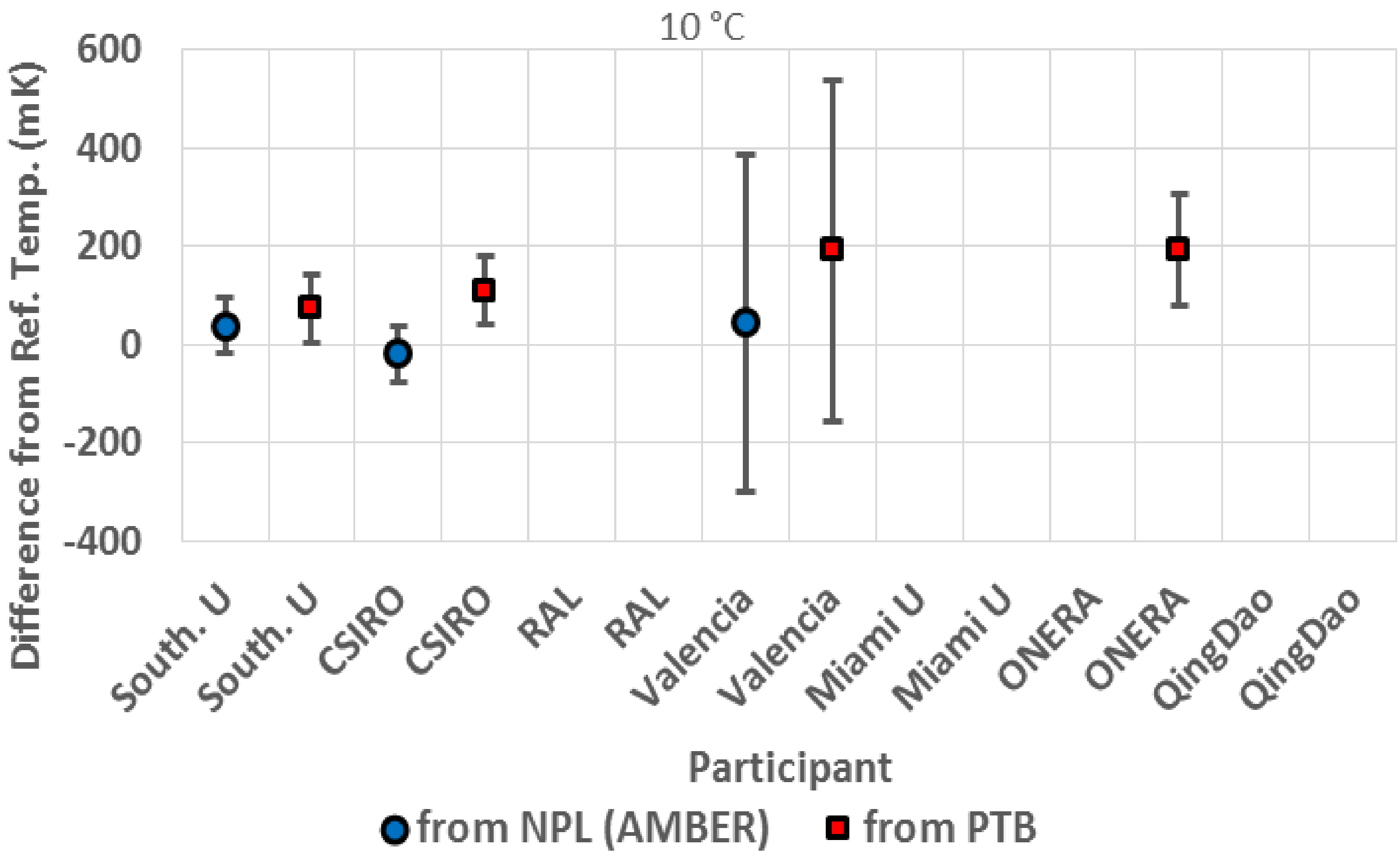
Measurements (as a function of time) reported by the RAL blackbody as well as the temperature of the same blackbody measured by the PTB IR radiometer.



fiducial reference temperature measurements

NPL National Physical Laboratory

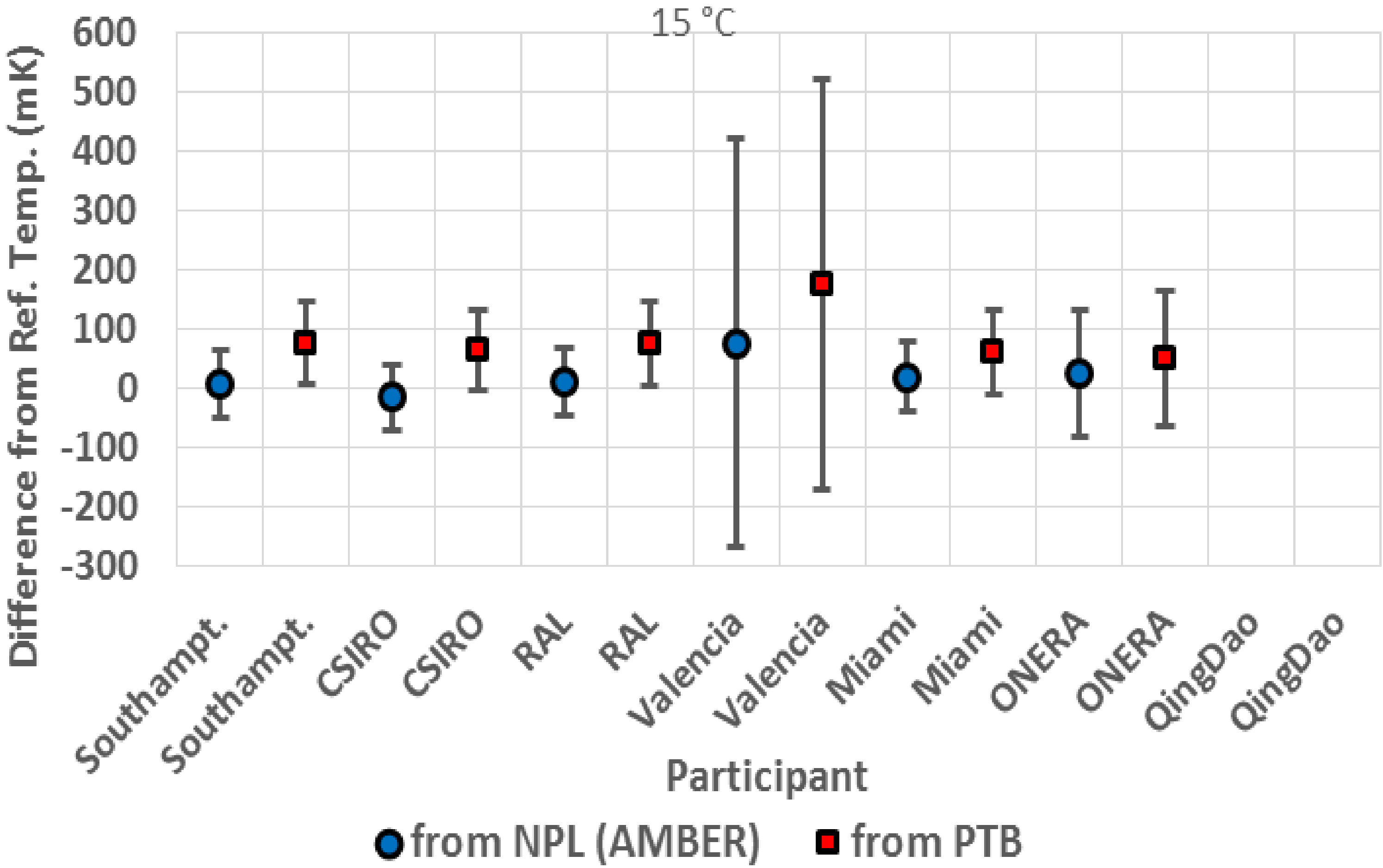
Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 10 ºC.



fiducial reference temperature measurements

National Physical Laboratory

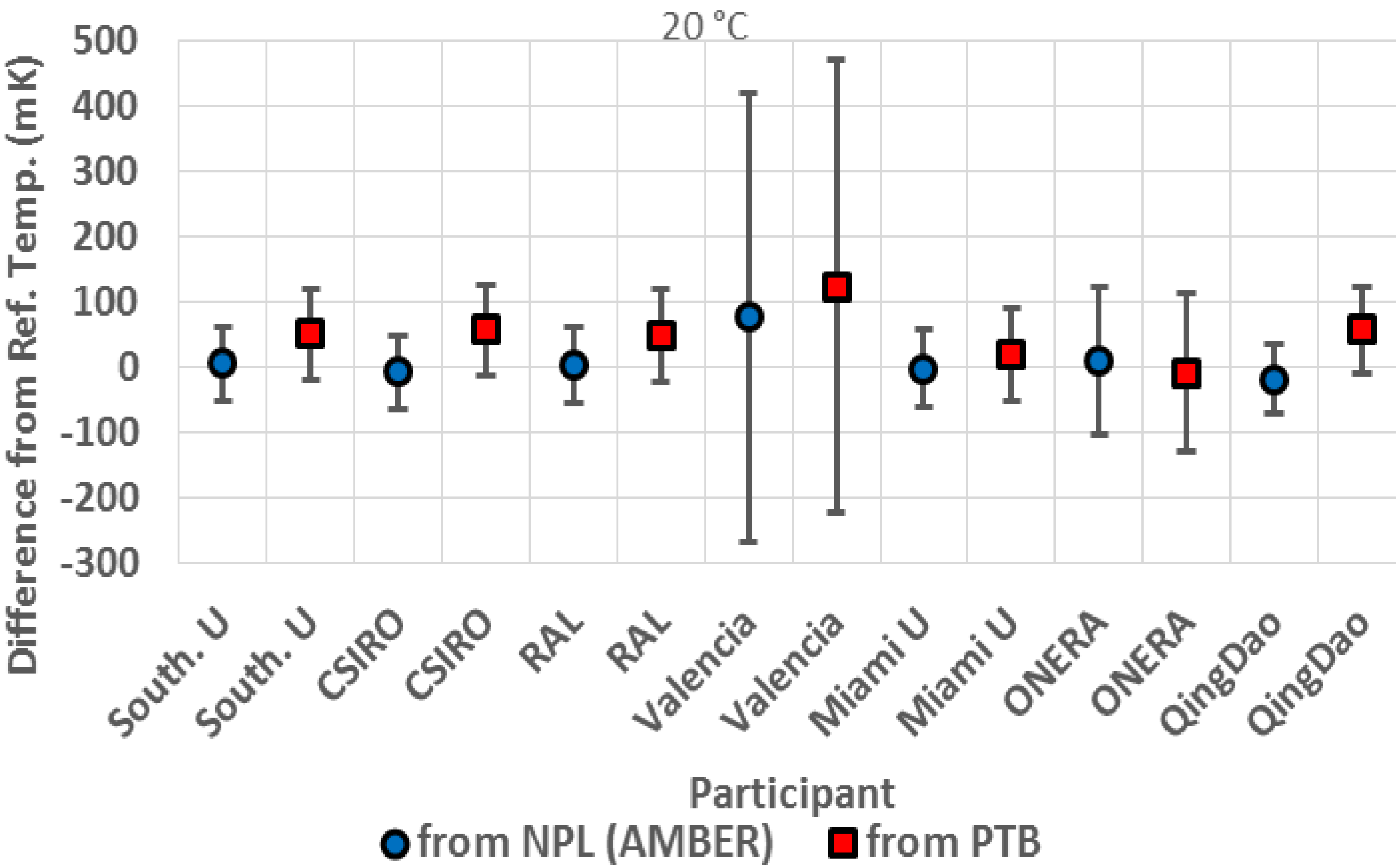
Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 15 ^{o}C.



fiducial reference temperature measurements

NPL National Physical Laboratory

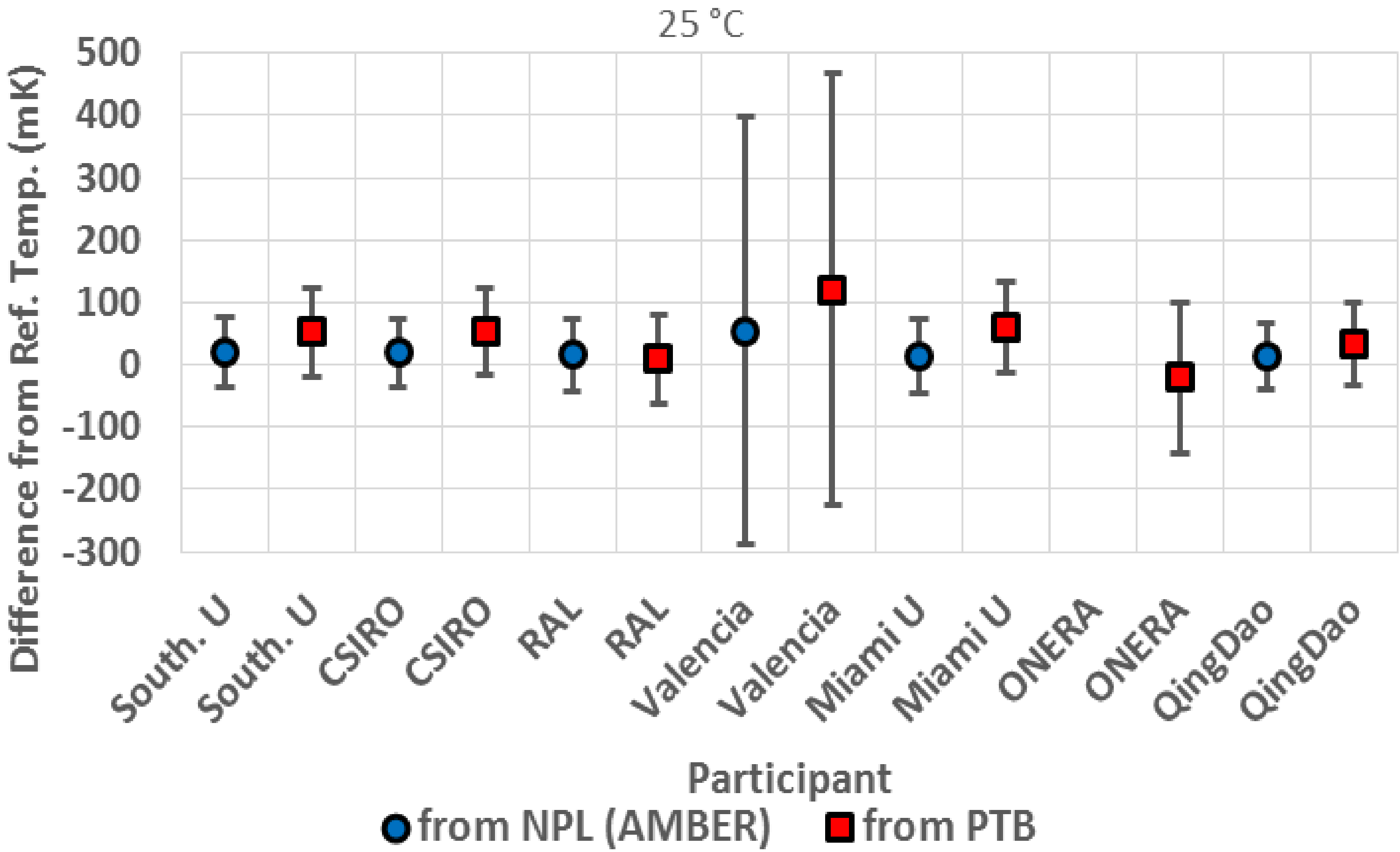
Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 20 ºC.



fiducial reference temperature measurements

NPL National Physical Laboratory

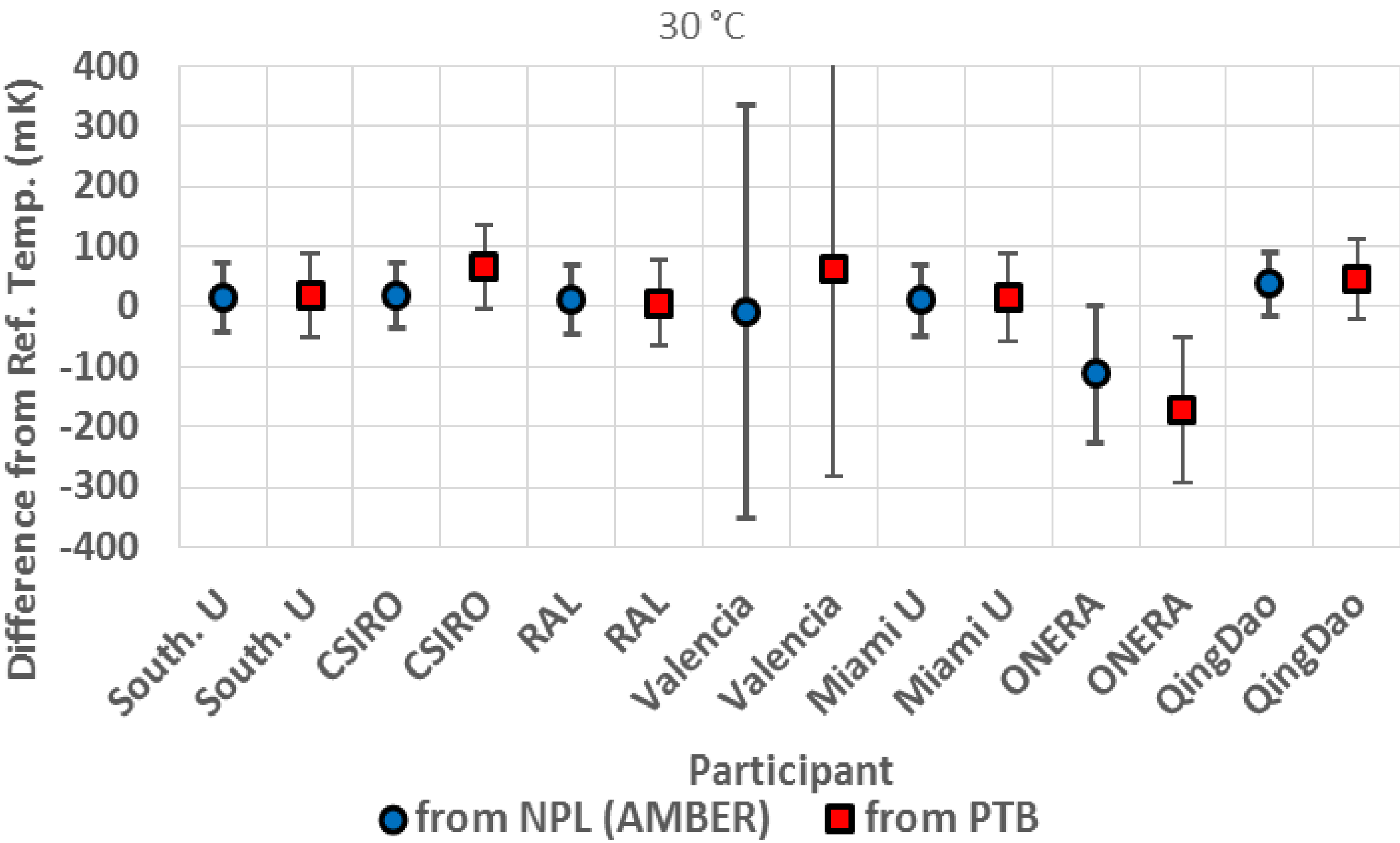
Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 25 °C.



fiducial reference temperature measurements

NPL National Physical Laboratory

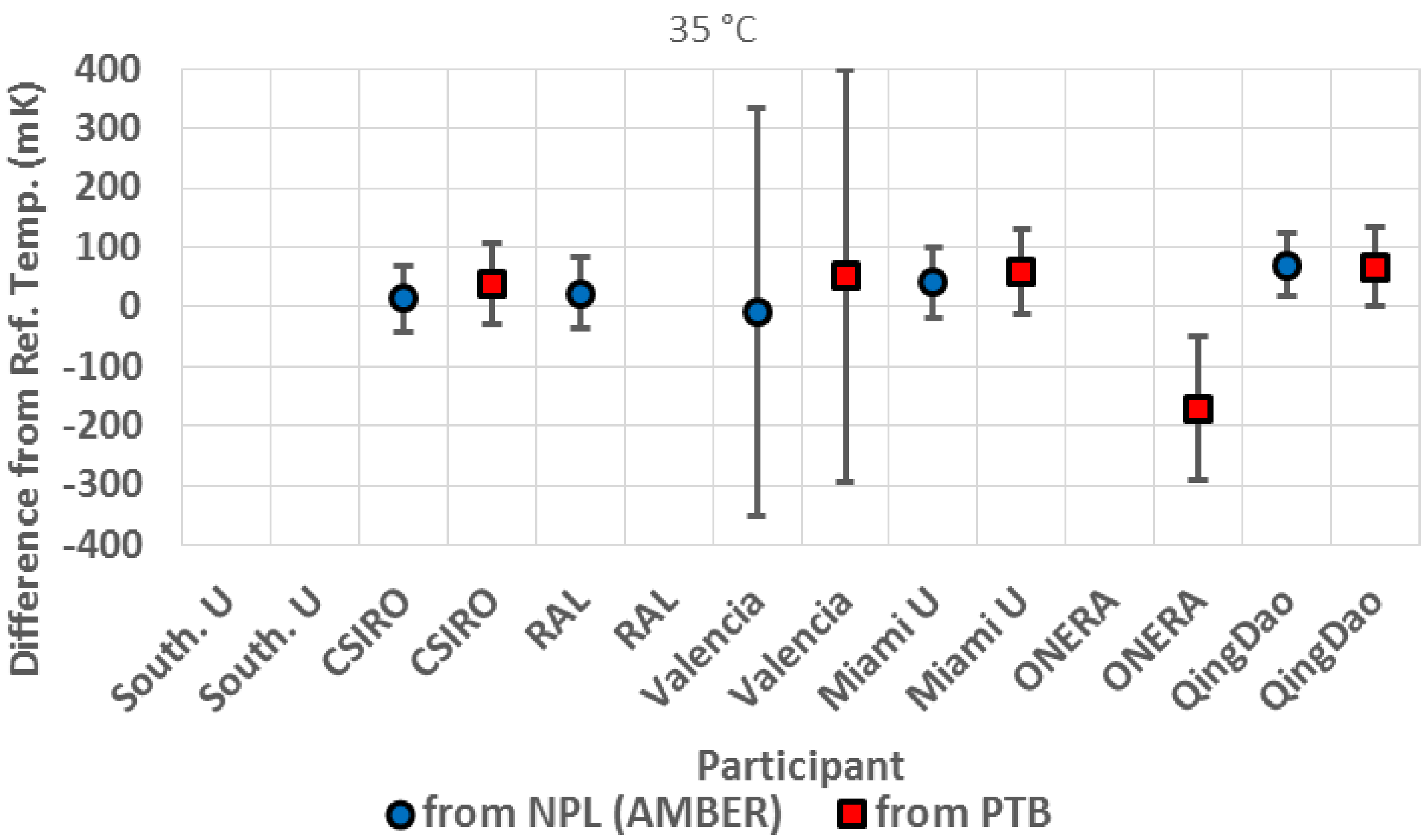
Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 30 °C.



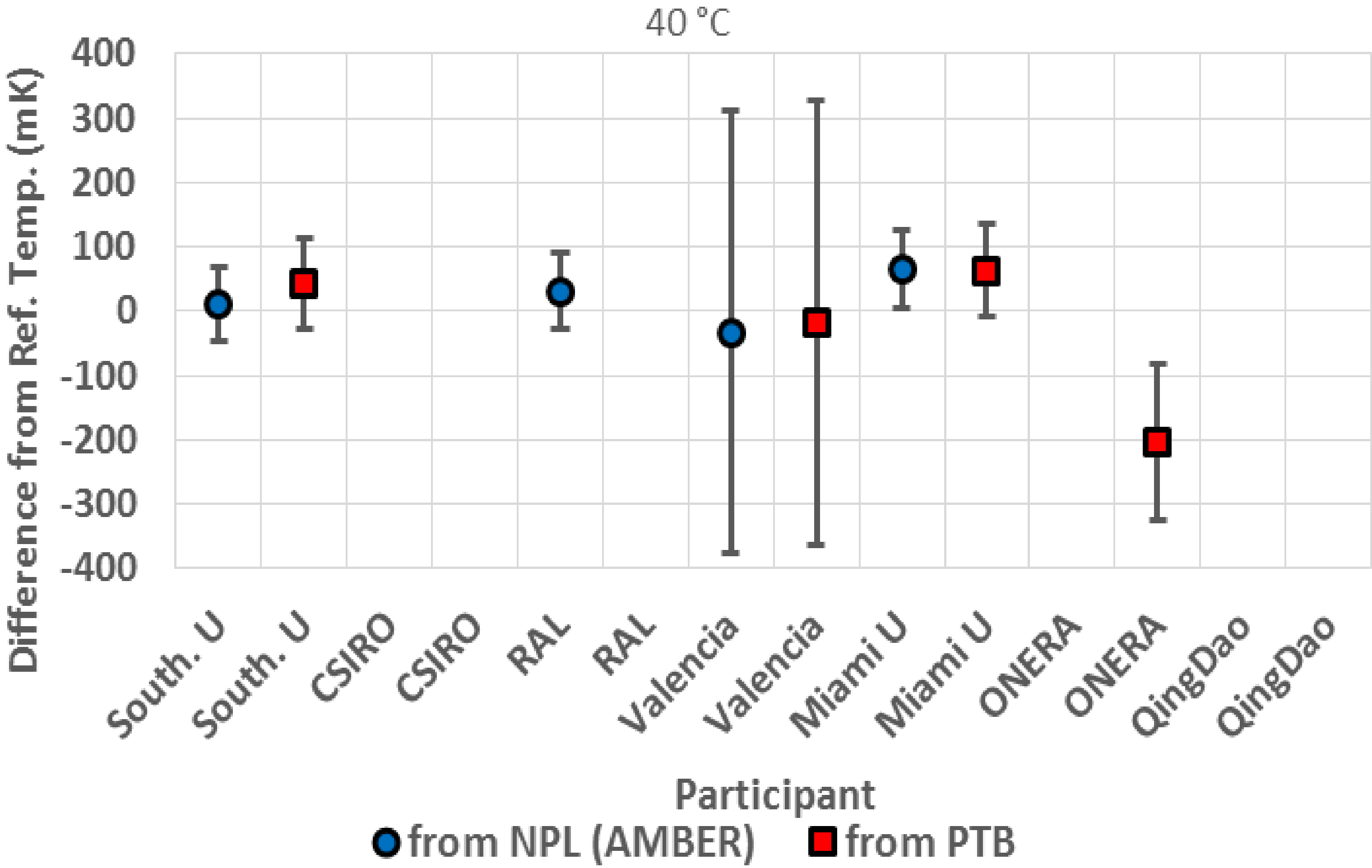
fiducial reference temperature measurements

NPL National Physical Laboratory

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



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



fiducial reference temperature measurements

NPL National Physical Laboratory

The FRM4STS 2016 radiometer lab comparison

20th to 24th June 2016

Protocol of Radiometer lab comparison

- The responsivity of all participating radiometers was to be compared to a reference radiance blackbody calibrated traceable to SI.

- The reference blackbody:
  - To be variable in temperature,
  - To have a well-characterised and high spectral emissivity and
  - To have an aperture sufficiently large to accommodate the field of view of all participant radiometers.

- The reference blackbody will be set to a fixed temperature (only known by the pilot laboratory) and viewed by all participating radiometers, in sequence.

- The protocol stated that radiometers which are used to measure sea/water surface temperature should perform measurements of the reference blackbody at nominal temperatures of 278 K, 283 K, 293 K and 303 K.

- Radiometers which are used to measure land surface temperatures should perform measurements down to 273 K and up to 323 K, whereas radiometers which are used to measure ice surface temperatures will perform measurements of the blackbody down to 253 K.

According to the protocol:

- The variable temperature blackbody used for this comparison must be well characterised with demonstrable traceability to SI.
- The reference temperature blackbody which was selected was the NPL ammonia heat-pipe blackbody. This blackbody is capable of operating anywhere in the -50 ^{o}C to +50 ^{o}C temperature range.
- The description of each participant's radiometer and its route of traceability should be provided by completing the form provided to all participants (similar to the blackbody from).
- Each participating radiometer should be mounted so that it can be easily aligned to the reference blackbody.

Uncertainty budget for the ammonia heat-pipe blackbody

Source of uncertainty	Type	Divisor	Radiance temperature/ °C				
			-40	-20	0	20	50
PRT calibration(*k*=2)	B	2	0.002	0.002	0.002	0.002	0.002
PRT stability	B	√3	0.011	0.011	0.011	0.011	0.011
Resistance bridge accuracy	B	√3	0.006	0.006	0.006	0.006	0.006
Resistance bridge resolution	B	√3	0.0006	0.0006	0.0006	0.0006	0.0006
Emissivity (0.9993)	B	√3	0.017	0.020	0.023	0.027	0.032
Emissivity calculation	A	1	0.007	0.008	0.010	0.011	0.013
Cavity bottom uniformity	B	√3	0.015	0.015	0.010	0.010	0.010
Convection	B	√3	0.007	0.006	0.005	0.004	0.003
Cavity bottom heat exchange	B	√3	0.001	0.001	0.000	0.000	0.001
Reflected ambient radiation	B	√3	0.058	0.050	0.040	0.030	0.020
combined			*0.06*	*0.06*	*0.05*	*0.045*	*0.04*
Expanded uncertainty (*k*=2)			**0.13**	**0.12**	**0.10**	**0.09**	**0.09**

fiducial reference temperature measurements

NPL National Physical Laboratory

According to the protocol:

- The reference blackbody will be set to one of the nominal temperatures specified in the protocol.
- Each participating radiometer should then be aligned to view the reference blackbody and when they are ready, to measure the brightness temperature of the blackbody over a 10 to 15 minute measurement period.
- This information should be recorded and (unless it needs further processing) should be provided to the pilot at that time.
- The pilot will record the actual temperature of the reference blackbody and any drift which may occur during the time period of each participant's measurements, together with the results from the participant.
- The above process should be repeated for all temperatures specified in the protocol.
- The complete sequence should be repeated for all temperatures, including realignment of radiometers, to assess repeatability.
- Data should be given to the Pilot on the form provided by the Pilot, which was also be available electronically.
- The host laboratory will collect measurements of the lab air temperature and relative humidity during the measurement period and make these available to the participants.

Treatment of Uncertainties (all four comparisons)

- The uncertainty of the measurements shall be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement* (QA4EO-CEOS-DQK-006).
- In order to achieve optimum comparability, a list containing the principal influence parameters for the measurements and associated instrumentation was given.
- Example tables corresponding to blackbody uncertainty contributions and radiometer uncertainty contributions will be given to participants (see overleaf).
- The participating laboratories will be asked to complete these tables and will be encouraged to follow this breakdown as closely as possible, and adapt it to their instruments and procedures.
- The participants may include additional parameters, dependent on specific measurement facilities and these should be added to the uncertainty budget
- All values should be given as standard uncertainties, (i.e. for a coverage factor of $k = 1$).
- The table provided largely refers to the uncertainties involved in making the measurement during the comparison process, and as such includes the summary result of the instruments' primary traceability, etc.
- Guidance on establishing such uncertainty budgets can be obtained by review of the NPL training guide which could be found at http://www.emceoc.org/documents/uaeo-int-trg-course.pdf.
- References which deal with the development of the uncertainty budget for a blackbody and an ambient temperature measuring radiometer will also be provided.

Uncertainty contributions associated with the Blackbody comparison

Parameter	Type A Uncertainty in Value / %	Type B Uncertainty in Value / (appropriate units)	Uncertainty in Brightness temperature K
Repeatability of measurement	U_{Repeat}		U_{Repeat}
Reproducibility of measurement	U_{Repro}		U_{Repro}
Blackbody emissivity		U_{emis}	U_{emis}
BB Thermometer Calibration		U_{therm}	U_{therm}
BB cavity temperature non-uniformity		U_{Unif}	U_{Unif}
BB temperature stability		U_{stab}	U_{stab}
Reflected ambient radiation		U_{Refl}	U_{Refl}
Radiant heat/loss gain		$U_{Radiant}$	$U_{Radiant}$
Convective heat/loss gain		$U_{Convect}$	$U_{Convect}$
Primary Source		U_{Prim}	U_{Prim}
RMS total	$((u_{Repeat})^2+(u_{Repro})^2)^{½}$		

fiducial reference temperature measurements

National Physical Laboratory

Reporting of results (for all comparisons)

- On completion of each set of results, as indicated above, they should be reported to the pilot. Where possible, these should be sent in electronic form as well as hard copy at the time of the comparison. In this way any immediate anomalies could be identified and potentially corrected during the course of the comparison whilst still keeping results blind.

- The measurement results should be supplied in the Template provided by the pilot laboratory at the beginning of the comparison (see Template provided for reporting the results of the blackbody laboratory comparison).

- The measurement results should also be provided in an Excel format. The measurement report is to be supplied in the Word Template. This should simplify the combination of results and the collation of the final report by the pilot and thus reduce the possibility of transcription errors.

- The measurement report forms and templates will be sent by e-mail to all participating laboratories. The report forms (in particular the results sheet) should be completed and sent back electronically to the pilot. A signed report must also be sent to the pilot in paper form by mail or as a scanned document.

- Receipt of the report will be acknowledged by the pilot laboratory. In case of any differences, the paper forms are considered to be the definitive version.

Reporting of results (cont.)

- If, on examination of the complete set of provisional results (ideally during the course of the comparison), the pilot institute finds results that appear to be anomalous, all participants will be invited to check their results for numerical errors without being informed as to the magnitude or sign of the apparent anomaly. If no numerical error is found the result would stand and the complete set of final results will be sent to all participants.

- Once all participants have been informed of the results, individual values and uncertainties may be changed or removed, or the complete comparison abandoned, **only with the agreement of all participants** and on the basis of a clear failure of instrumentation or other phenomenon that renders the comparison, or part of it, invalid.

- Following receipt of all measurement reports from the participating laboratories, the pilot laboratory will analyse the results and prepare a first draft report on the comparison (draft A). This will be circulated to the participants for comments, additions and corrections.

Comparison analysis

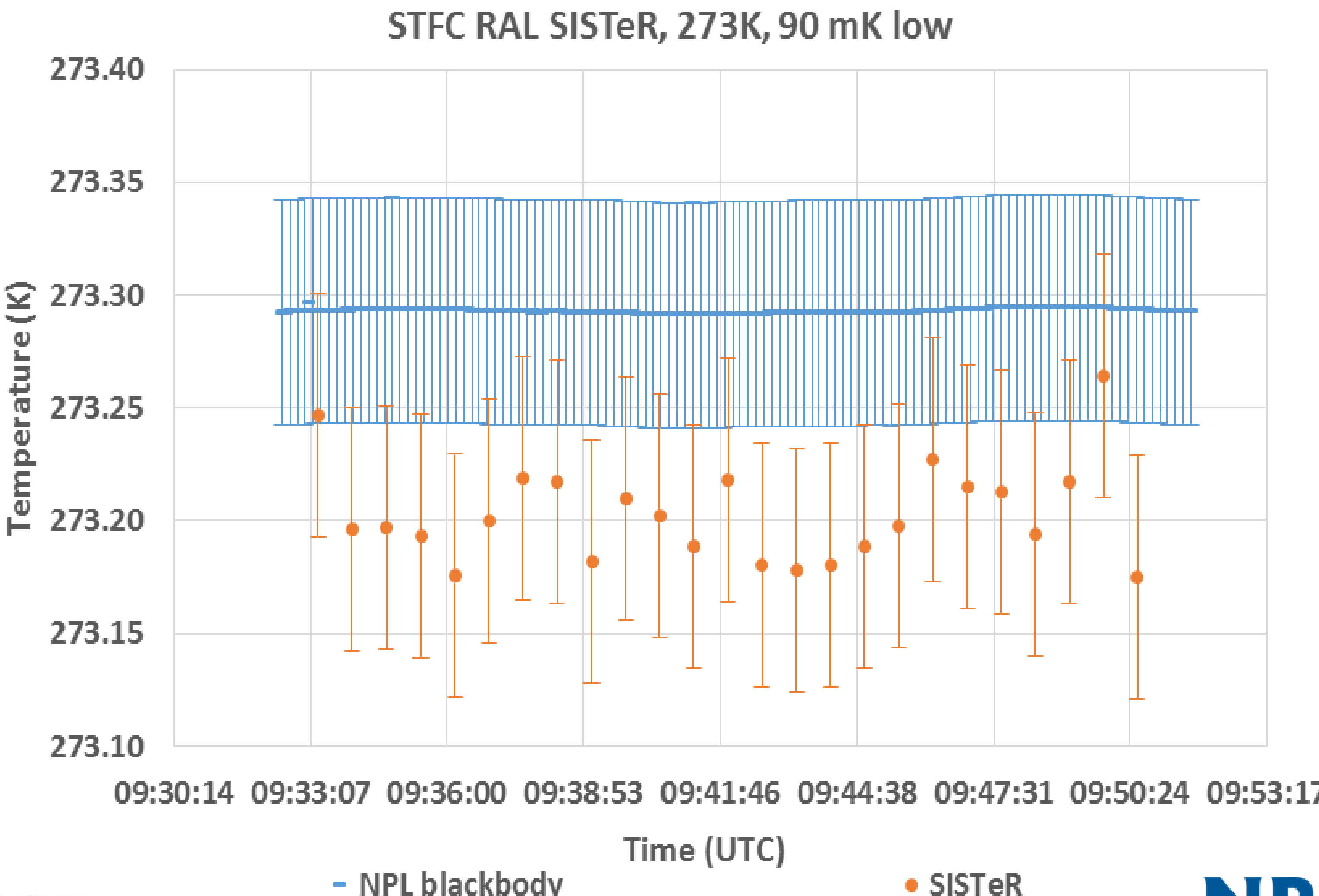
- Each comparison will be analysed by the pilot according to the procedures outlined in QA4EO-CEOS-DQK-004. In every case, analysis will be carried out **based solely** on results declared by each participant.
- Unless an absolute traceable reference to SI of sufficient accuracy is a-priori part of the comparison and accepted as such by all participants, all participants will be considered equal. All results will then be analysed with reference to a common mean of all participants weighted by their declared uncertainties.
- In the blackbody comparison, primary standard radiometers of both PTB and NPL will be used. The participation of these, will allow a direct linkage and the consequential establishment of formal traceability to be established for all measurements. The nominally independent scales from NPL and PTB will be linked through the participant blackbodies.

The RSMAS radiometer viewing the NH3 heat-pipe blackbody

fiducial reference temperature measurements

National Physical Laboratory

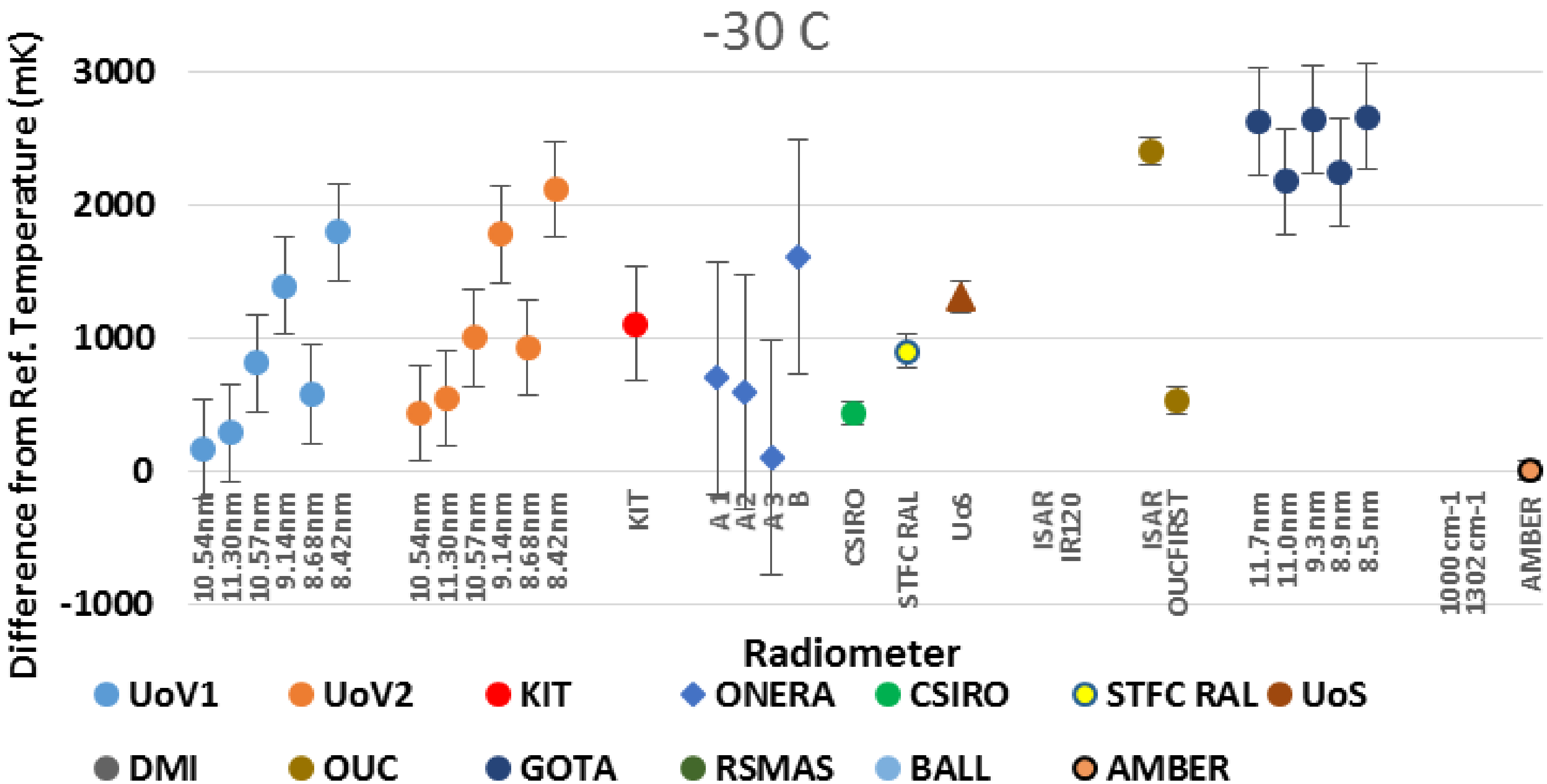
Temperature of the NH3 reference blackbody at about 0°C (shown in blue) and the corresponding measurements of the RAL radiometer.



fiducial reference temperature measurements

NPL National Physical Laboratory

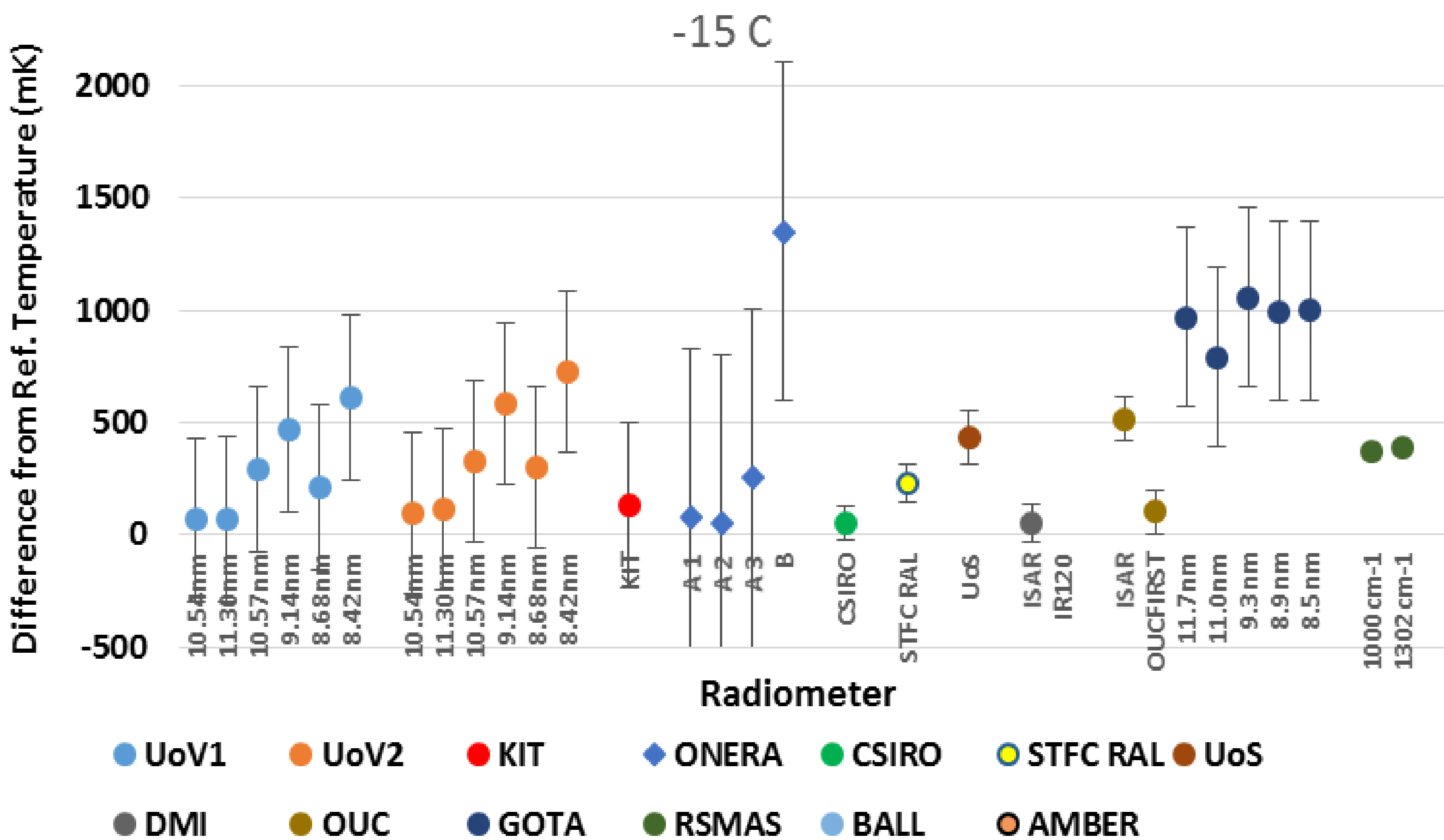
Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of -30°C.



fiducial reference temperature measurements

NPL National Physical Laboratory

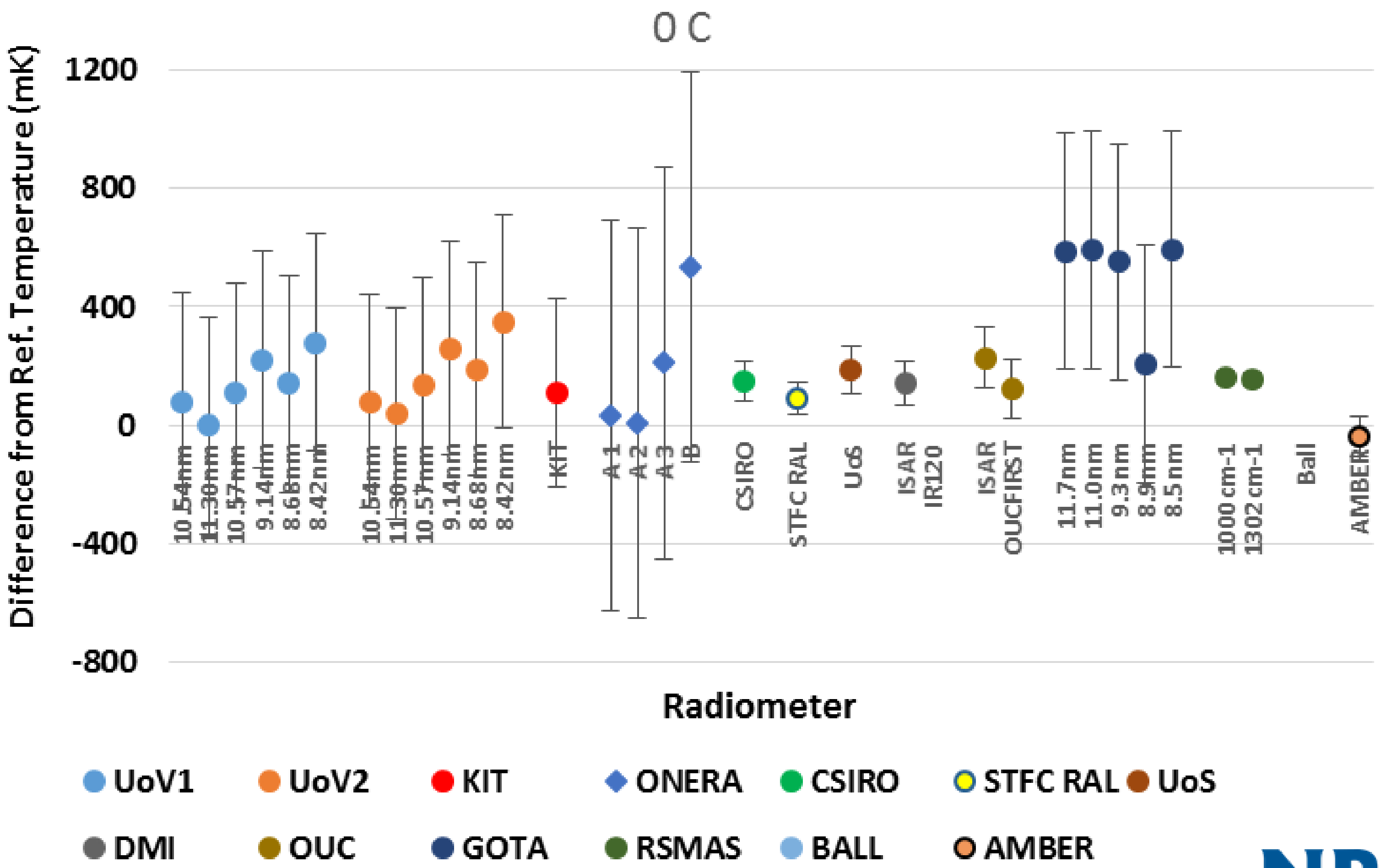
Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of -15°C.



fiducial reference temperature measurements

NPL National Physical Laboratory

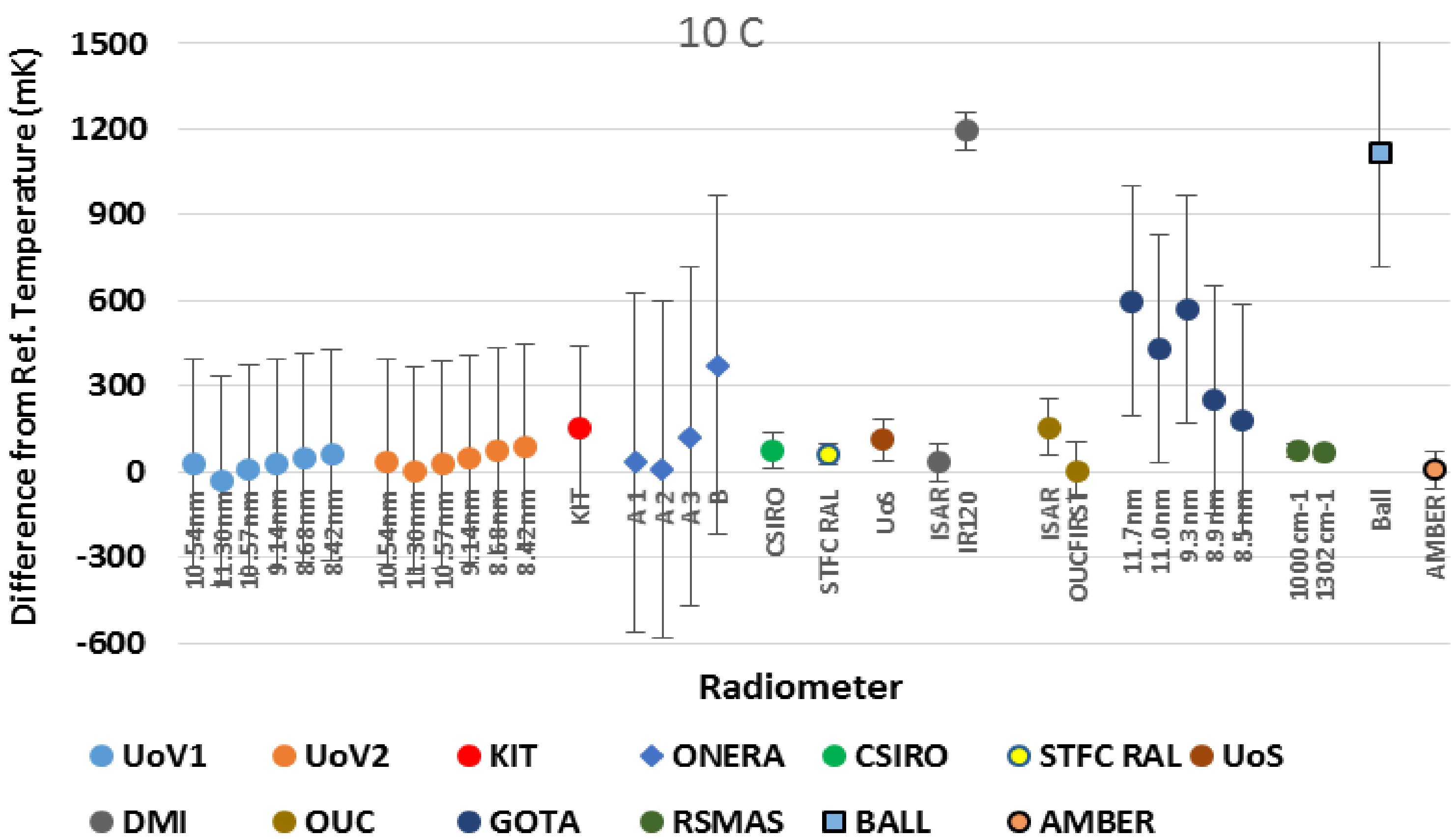
Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 0°C.



fiducial reference temperature measurements

NPL National Physical Laboratory

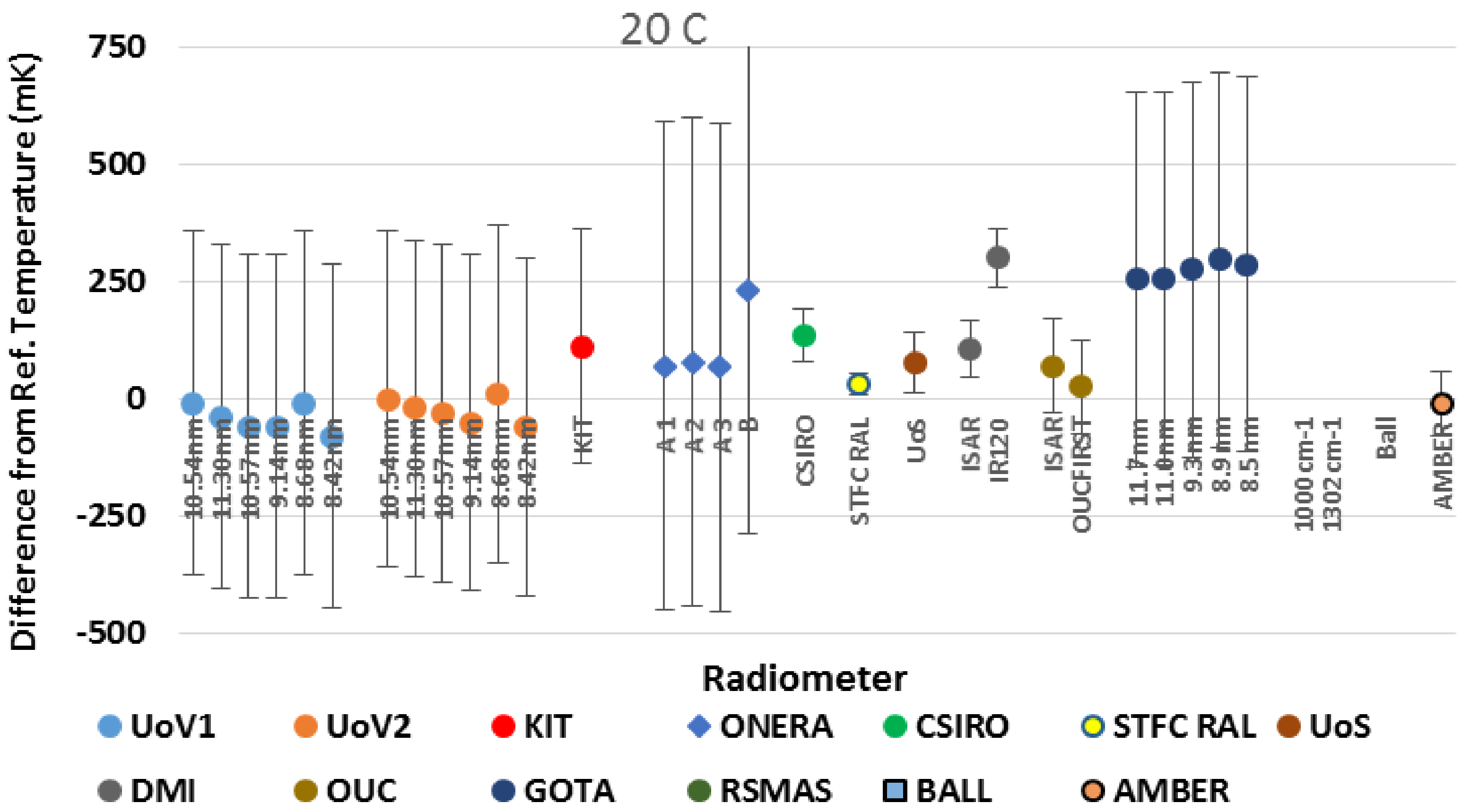
Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 10°C.



fiducial reference temperature measurements

National Physical Laboratory

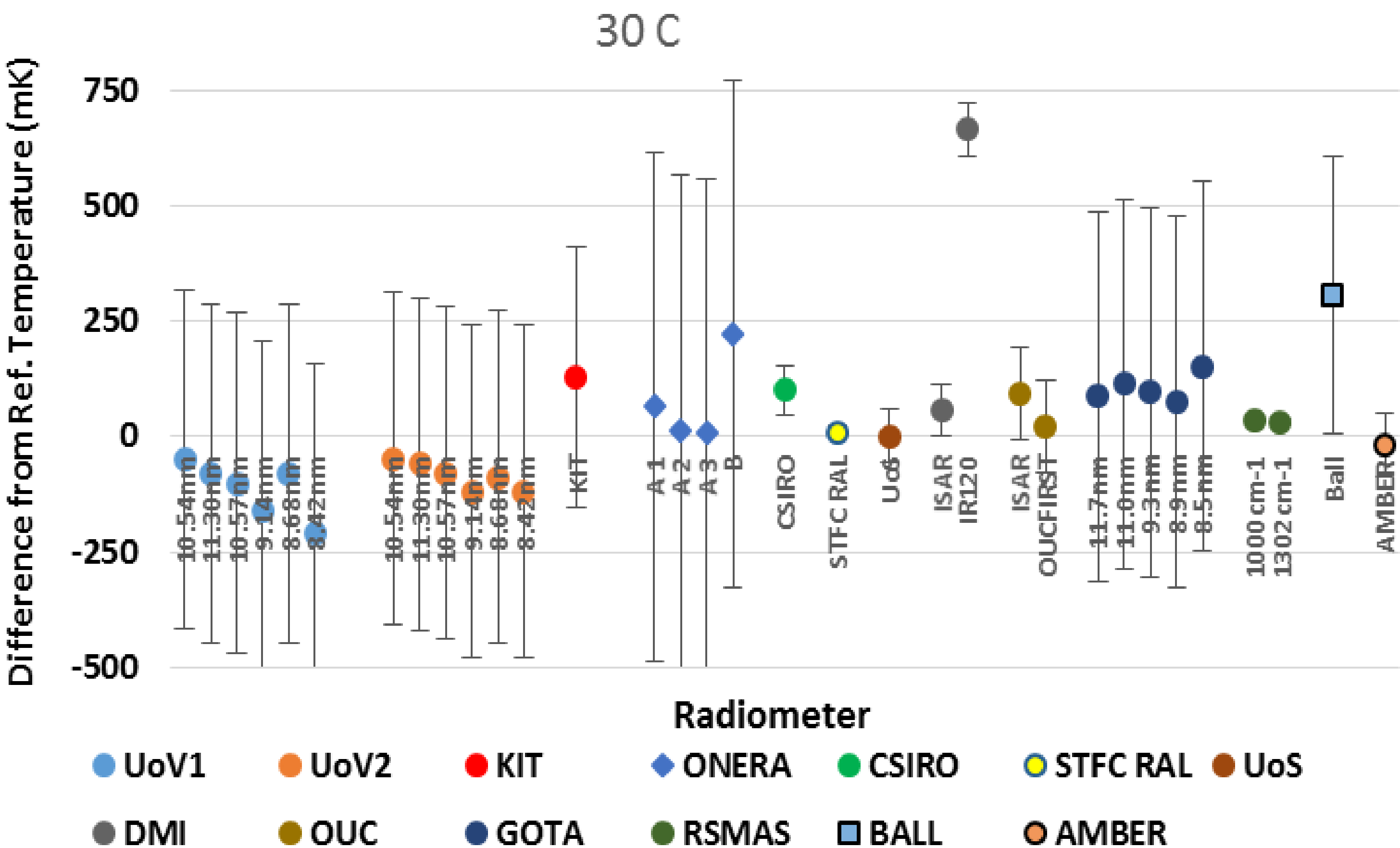
Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 20°C.



fiducial reference temperature measurements

NPL National Physical Laboratory

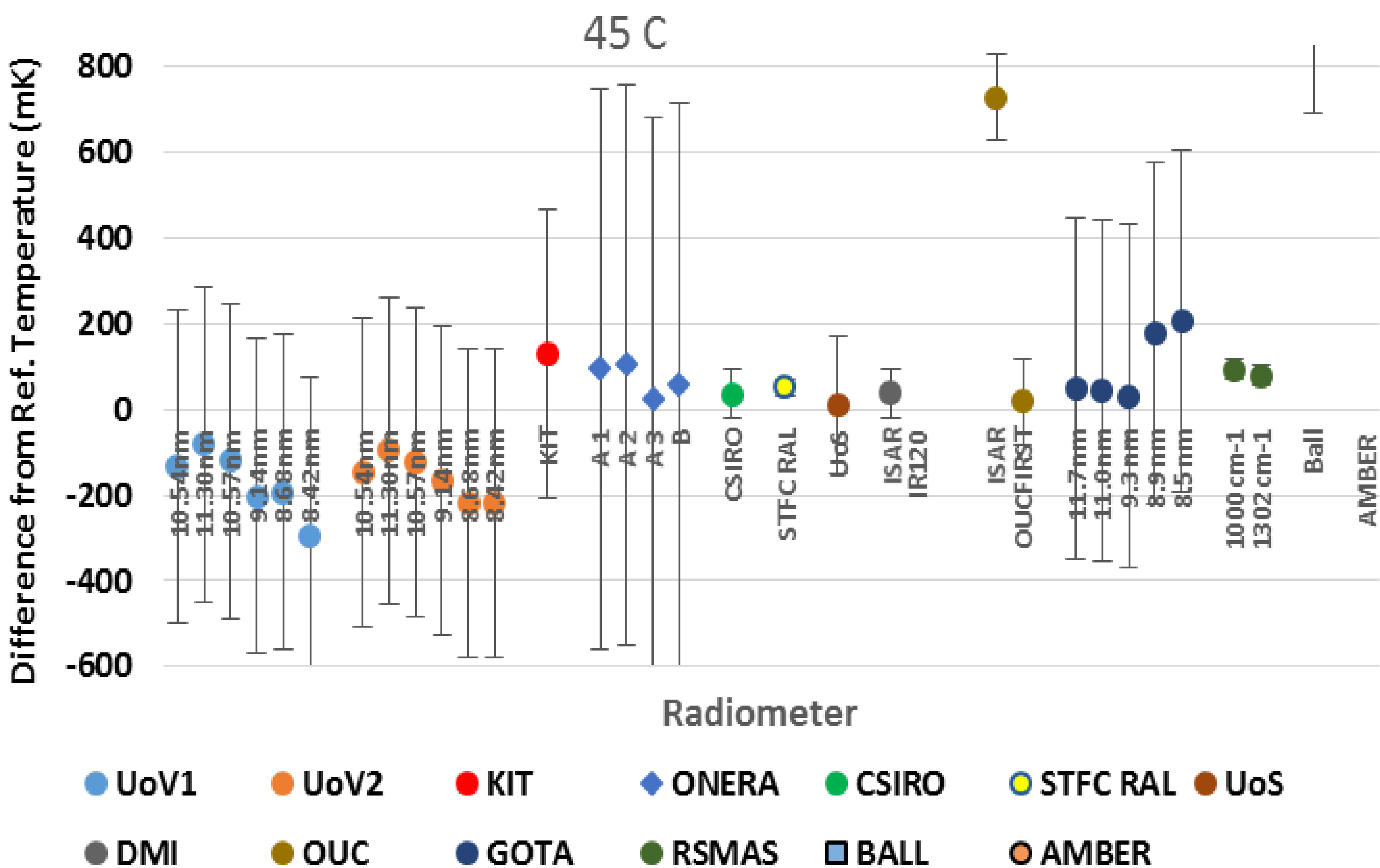
Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 30°C.



fiducial reference temperature measurements

NPL National Physical Laboratory

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



fiducial reference temperature measurements

National Physical Laboratory

The 2016 WST radiometer comparison at Wraysbury reservoir

27th June to 1st July 2016

Important points of the WST protocol:

- The radiometers must have a pre and post deployment calibration/verification in order to demonstrate traceability.
- The description of each participant's radiometer and its route of traceability should be provided by completing the form provided.
- The radiometers should be mounted securely on the platform which is located in the middle of Wraysbury reservoir using an appropriate mounting frame which allows the easy installation and removal of the radiometers.
- The radiometers should be mounted in such a way that the water surface view and the sky view are clear of any physical obstructions as well as exhaust and other effluents.
- Each participant radiometer should be mounted on the platform and aligned to view the area of the surface of the water reservoir indicated by the pilot.
- The radiometers need to have their optical components, such as the mirrors, windows or blackbodies, protected from the environment.
- Under conditions of high wind, the mounting position should be chosen to avoid any water spray from reaching the radiometer.

According to the WST protocol:

If a radiometer requires specialized wiring to operate (e.g. for real time data transmission), the pilot should be informed early enough so that the required specialized wiring can be installed on the platform prior to the beginning of the comparison.

The "clock" of each participant should be synchronised to that of UTC.

Following an indication from the pilot, each participant will measure the "target" and record its brightness temperature (Water and Sky as correction) at time intervals which suit each radiometer. The effective UTC time of each observation should be clearly indicated.

Measurements could be repeated for different wavelengths.

Meteorological data such as air temperature, relative humidity and wind speed will be collected during the measurement period and made available to the participants.

Measurements could be repeated for different view angles during the measurement period.

The view angle from the vertical should be selected to be in the 15^{o} to 55^{o} range. This should prevent the radiometer from viewing reflections from the platform as well as having to deal with low water emissivities which occur for large view angles.

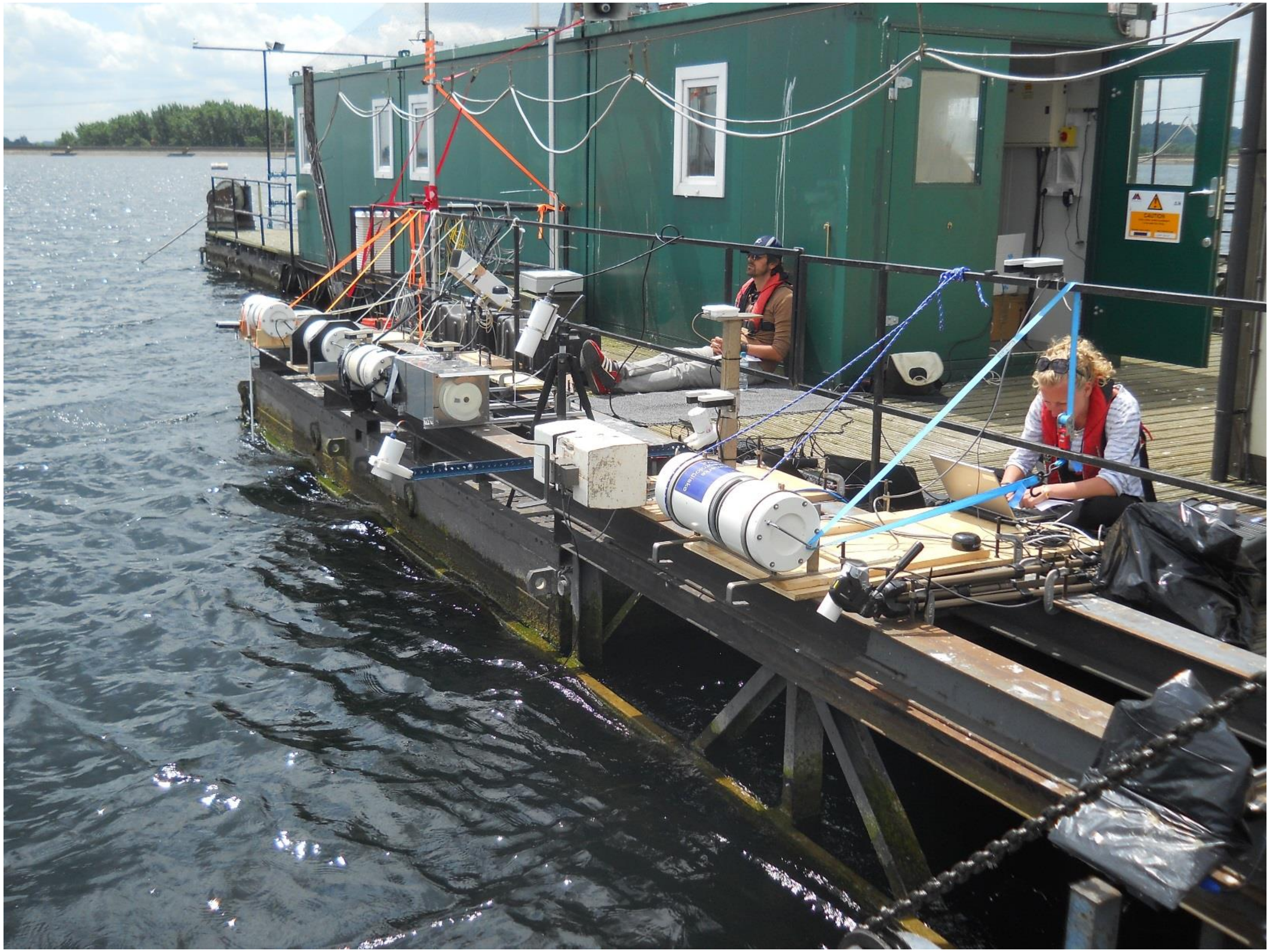
After completing the above measurement sequence, participants will have 3 hours to carry out any necessary post processing e.g. sky brightness correction etc. before submitting final results to the pilot, which will include processed Water Surface Temperature (WST) values.

The results should not be discussed with any participant other than the pilot until the pilot gives permission.

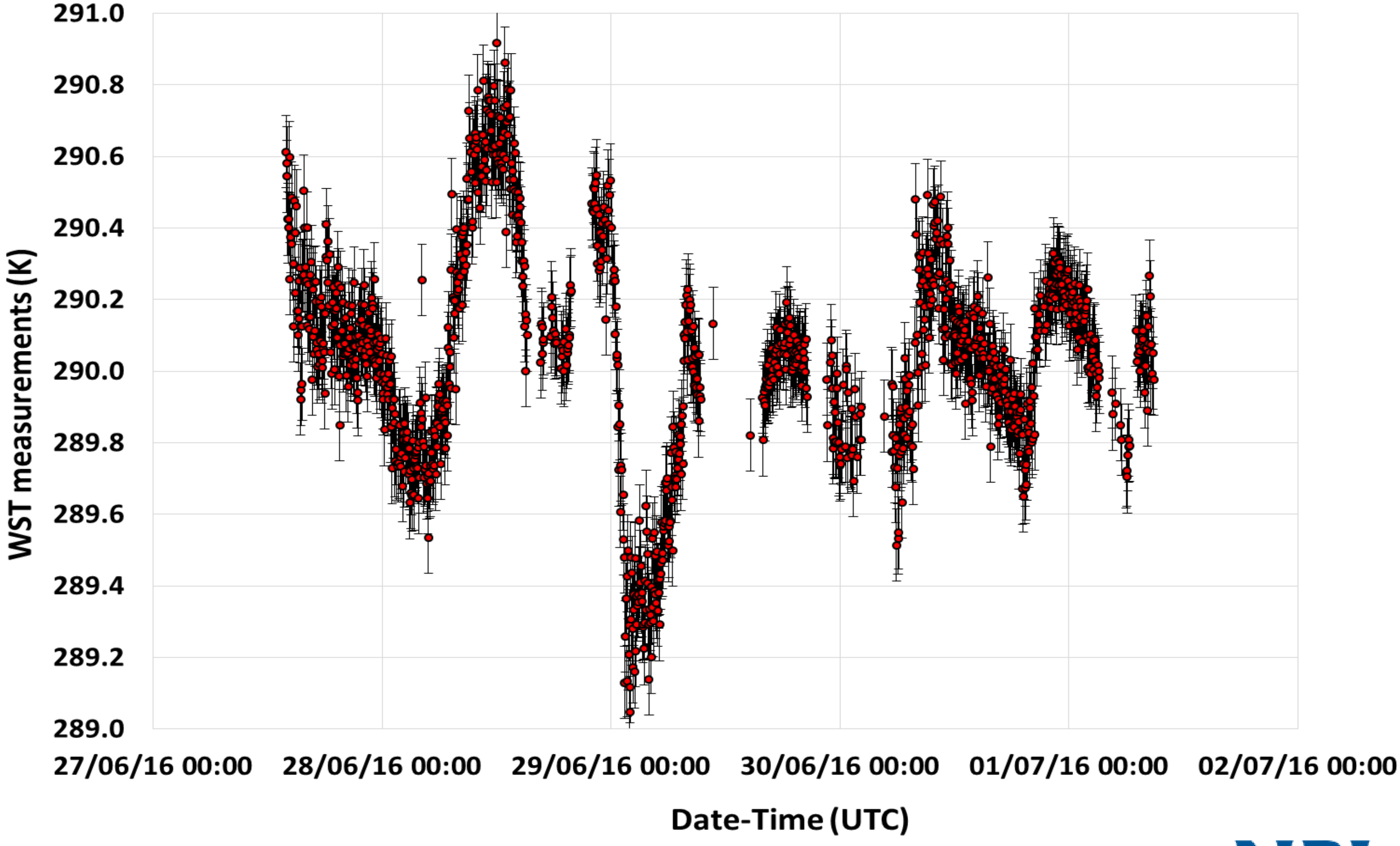
Data should be given to the Pilot on the form provided, which will also be available electronically.

Radiometers were installed with the aid of a boat

Radiometers measuring WST during the 2016 comparison



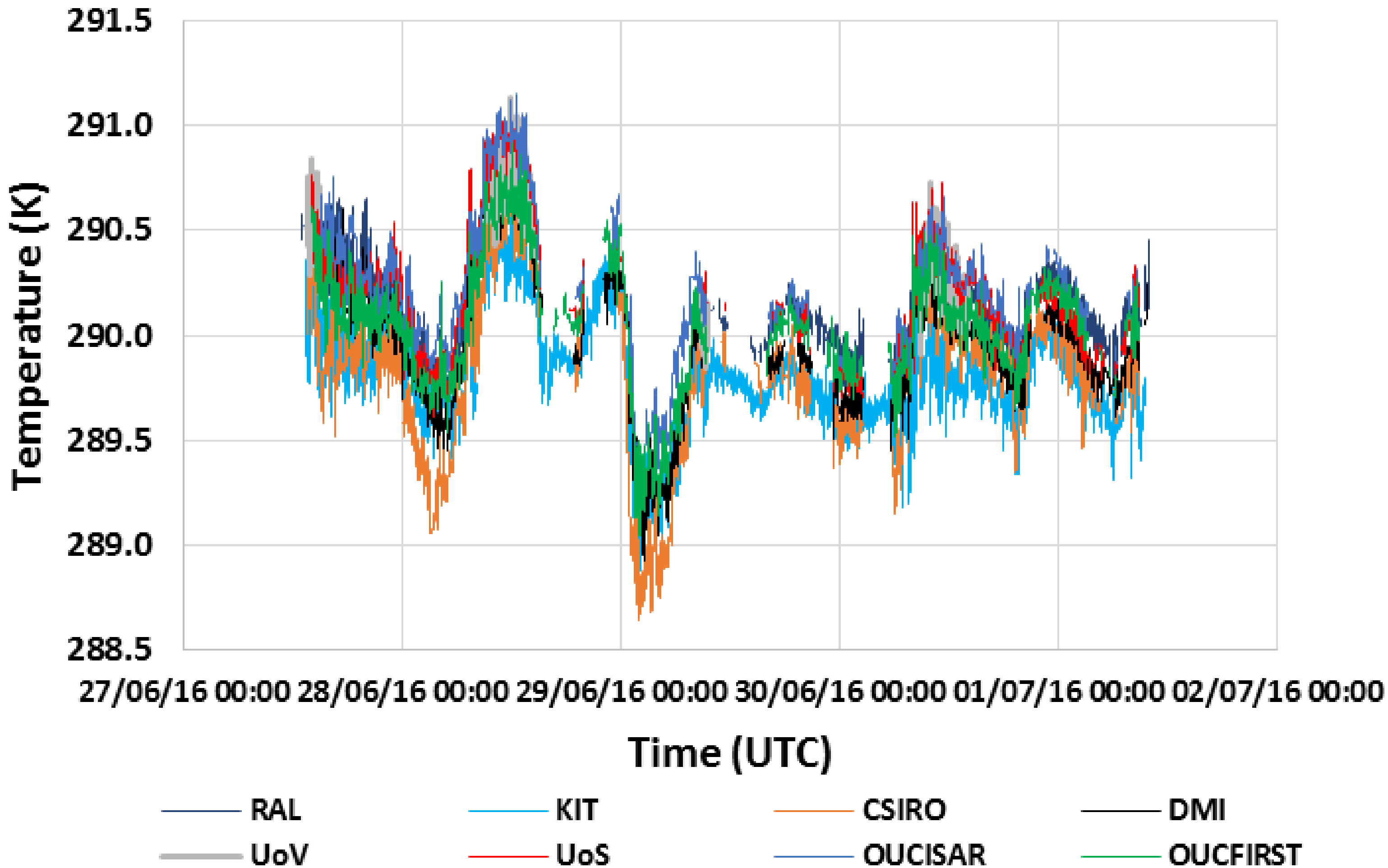
Measurements of the water surface temperature of Wraysbury reservoir made by the OUCFIRST



fiducial reference temperature measurements

NPL National Physical Laboratory

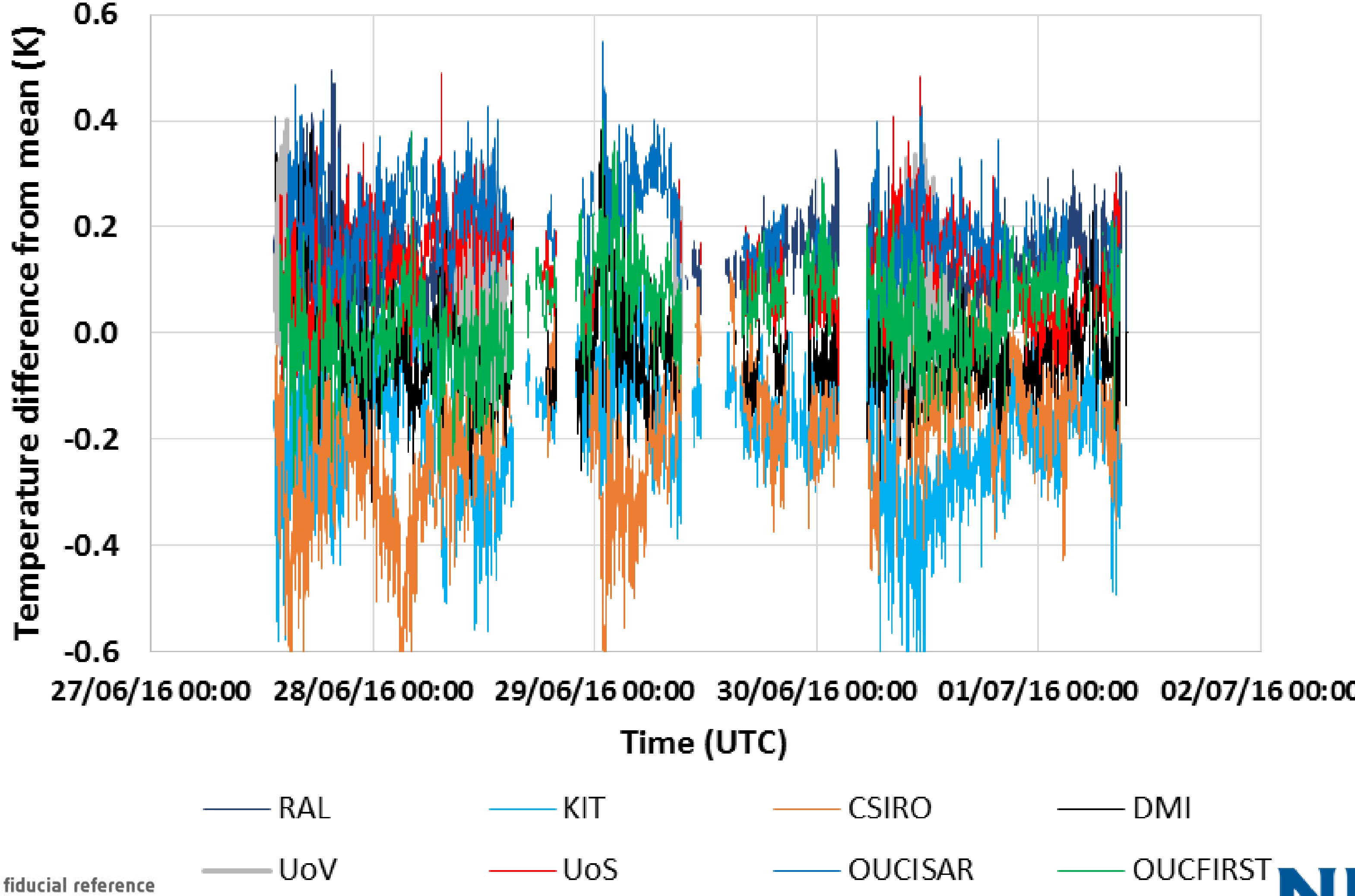
WST measurements of the various participants, over the five-day comparison period



fiducial reference temperature measurements

National Physical Laboratory

Plot of the difference of the WST measurements of the various participants from their arithmetic mean, over the five-day comparison period.



fiducial reference temperature measurements

NPL National Physical Laboratory

The FRM4STS 2016 LST comparison at NPL

4th to 7th July 2016

fiducial reference temperature measurements

National Physical Laboratory

LST comparison protocol included:

- The land surface temperature comparison exercise at NPL will consists of all radiometers simultaneously viewing the same part of the targets set up by the pilot laboratory, under the same (or similar) viewing conditions.
- For logistical reasons (number of instruments), it may become necessary to break up the comparison into a series of linked sub-comparisons. In this event it will be detailed in the final protocol and each sub-comparison group will have at least two common radiometers to provide a linkage.
- The following targets will be measured by the radiometers during the 2016 LST comparison:
  - Short green grass.
  - Short dry grass.
  - Sand
  - Gravel with different SiO_2 content and grain sizes.
  - Dark soil
  - Tarmac

LST comparison protocol included:

- The radiometers must have a pre and post deployment calibration/verification in order to demonstrate traceability. The description of each radiometer and its route of traceability should be provided by completing the form provided by the Pilot Lab.

- The radiometers should be mounted securely on their mounts which will be located next to the target being measured.

- **The participants will only be given the name and some limited information about the targets being measured. It is up to each participant to estimate the instrument-specific emissivity values of the different targets.**

- The radiometers will be mounted in such a way that the land surface target and the corresponding part of the sky are viewed clearly by the radiometers, without any physical obstructions nor any exhaust or other effluents.

- **Each participant radiometer should be mounted on its mount and aligned to view the area of the surface of the land surface target indicated by the pilot. An angle of view (to the Nadir) of 25º is recommended for all measurements completed during this phase of the comparison.**

- **The radiometers should be mounted at a height so that they view an area of the target which is elliptical in shape and has a long axis of approximately 0.73 m.**

LST comparison protocol included:

- If a radiometer requires specialized wiring to operate (e.g. for real time data transmission), the pilot should be informed early enough so that the required specialized wiring can be installed on the platform prior to the beginning of the comparison.
- **The "clock" of each participant should be synchronised to that of UTC.**
- **Following an indication from the pilot, each participant will then measure the "target" and record its viewed brightness temperature (Land and Sky as correction) at time intervals which suit each radiometer. The effective (UTC) time of each observation should be clearly indicated.**
- Measurements can be repeated for different wavelengths.
- Participants will be encouraged to measure the LST of the samples for small view angles, preferably smaller than 30^{o} in order to avoid directional effects.
- Because of the large FoV angles of some radiometers (e.g. Apogee radiometers have a full view angle of 40^{o}), it is recommended that the measurements are completed while the radiometers view the target at an angle of 25^{o} relative to nadir in order to keep this angle as small as possible, while preventing the radiometer from viewing reflections from the base of its own mount.

LST comparison protocol included:

- After completing the above measurement sequence, participants will have 3 hours to carry out any necessary post processing e.g. sky brightness correction etc. before submitting final results to the pilot, which will include processed Land Surface Temperature values.

- The results should not be discussed with any participant other than the pilot until the pilot gives permission.

- Data should be given to the Pilot on the form provided by the Pilot, which will also be available electronically.

- **For night-time LST measurements!**

- The same procedure can be used to acquire measurements during night-time.

- The radiometers could be left unattended during night time.

- **Measurements can be made at night time under unattended operation of the radiometers.**

fiducial reference temperature measurements

National Physical Laboratory

Declaration of completion of the comparison

- Before declaring the results to the participants, the pilot will consult with all participants about the nature of the meteorological conditions of the comparison and, with additional knowledge of the variance between declared results, determine if a repeat should be carried out.

- At this stage participants may be told the level of variance between all participants but no information should be given to allow any individual result or pair of results to be determined.

- If the participants consider that the process should be repeated, as a result of poor conditions, then the results will remain blind except to the pilot.

Declaration of completion of the comparison

- The comparison process will continue until all participants are happy that meteorological conditions are good or that time has run out. At this point the comparison will be considered final and the results provided to all participants. This will constitute the final results and no changes will be allowed, either to the values or uncertainties associated with them.

- However, if a participant considers that the results that they have obtained are not representative of their capability and they are able to identify the reasons and correct it, they can request of the pilot (if time allows) to have a new comparison. This comparison, would require participation of at least one other participant (and ideally two) and sufficient time.

- If the above conditions can be met then the above comparison process can be repeated.

Set-up for the 2016 FRM4STS LST comparison.

fiducial reference
temperature
measurements

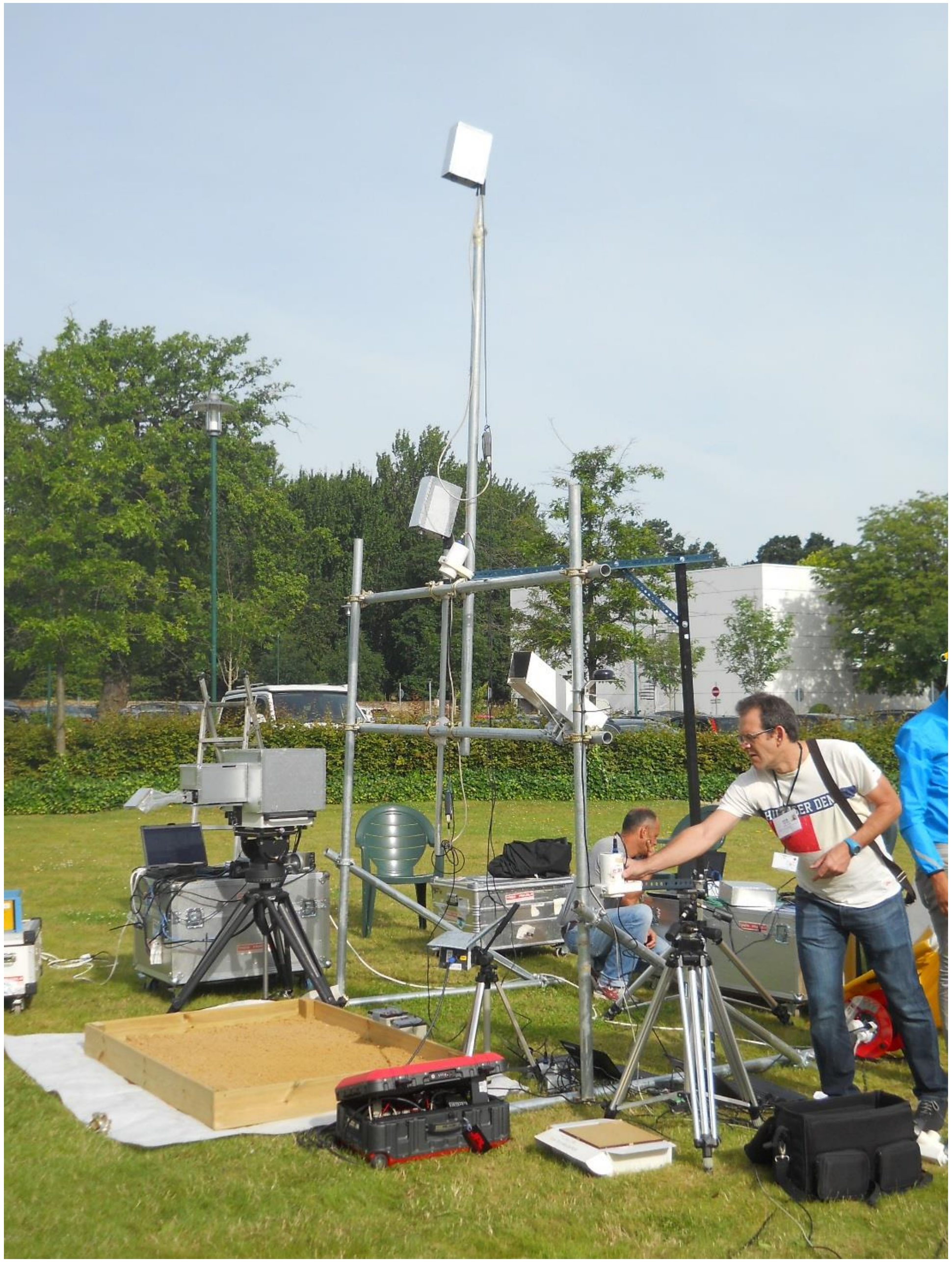
National Physical Laboratory

Some of the targets used for the 2016 LST comparison.

fiducial reference
temperature
measurements

NPL
National Physical Laboratory

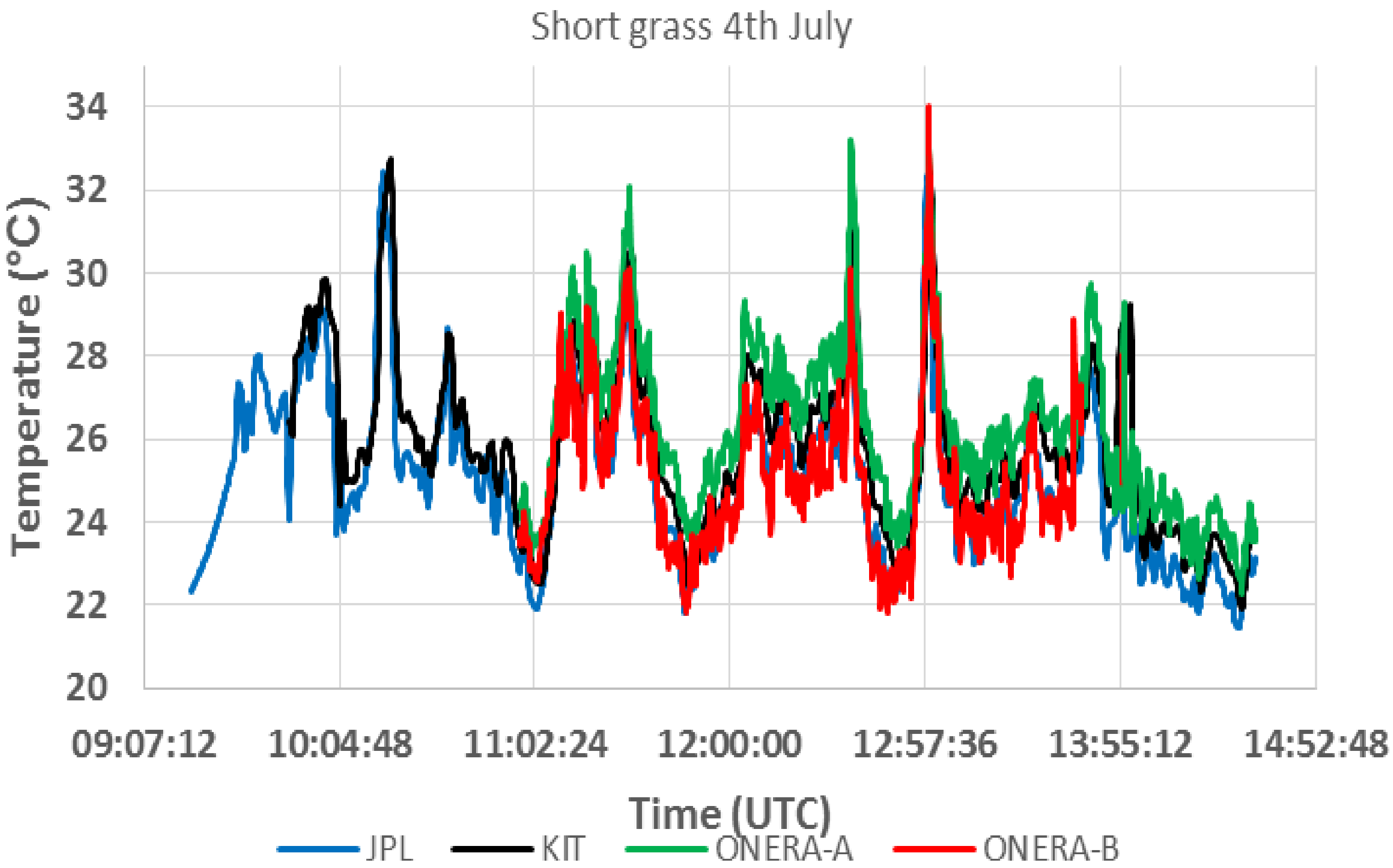
Radiometers measuring the surface temperature of the sand sample, with one of the radiometers placed at a height of approximately 4 m



fiducial reference temperature measurements

National Physical Laboratory

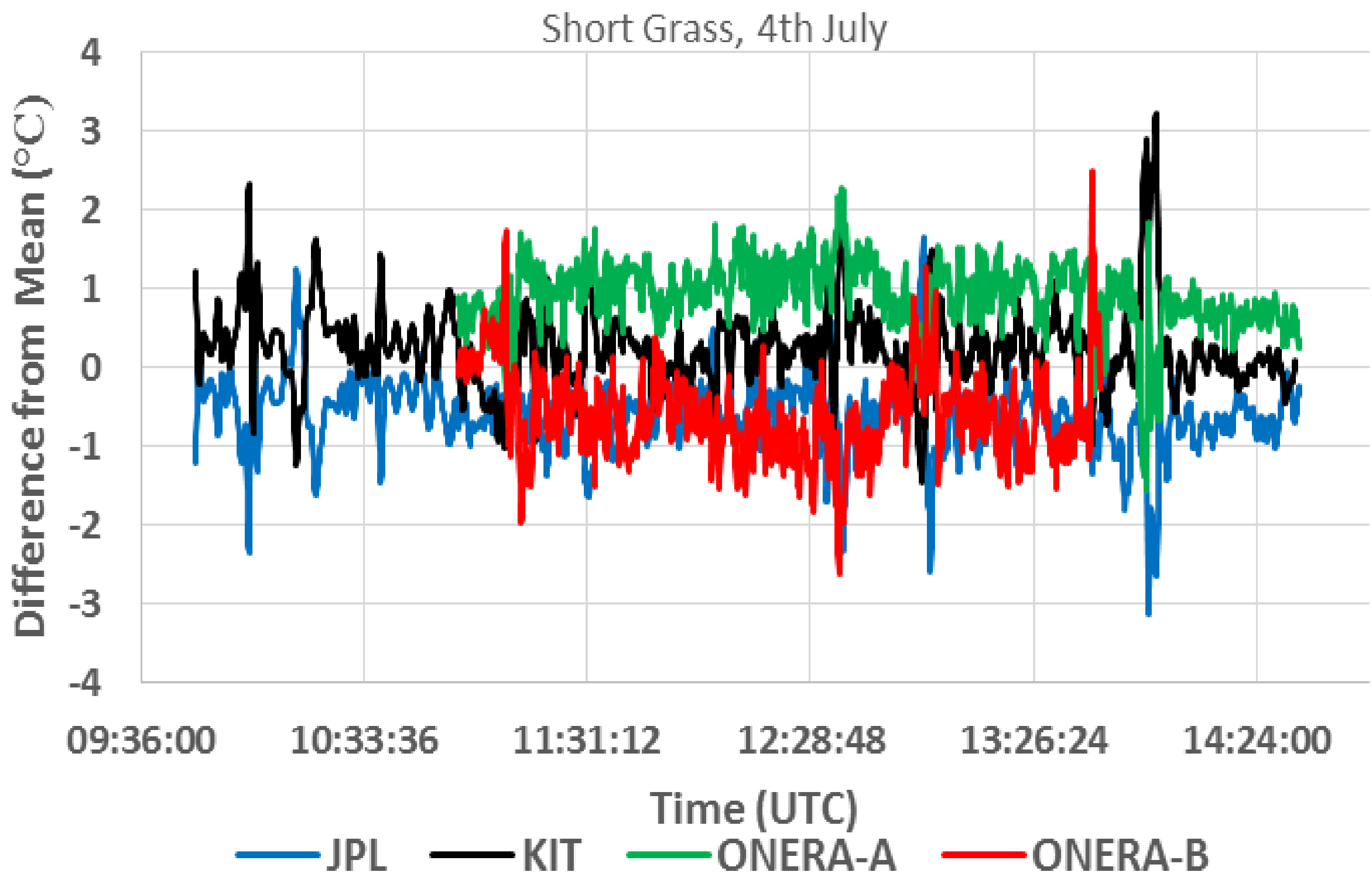
Surface temperature of short grass sample measured by the participating radiometers on the 4th July 2016.



fiducial reference temperature measurements

NPL National Physical Laboratory

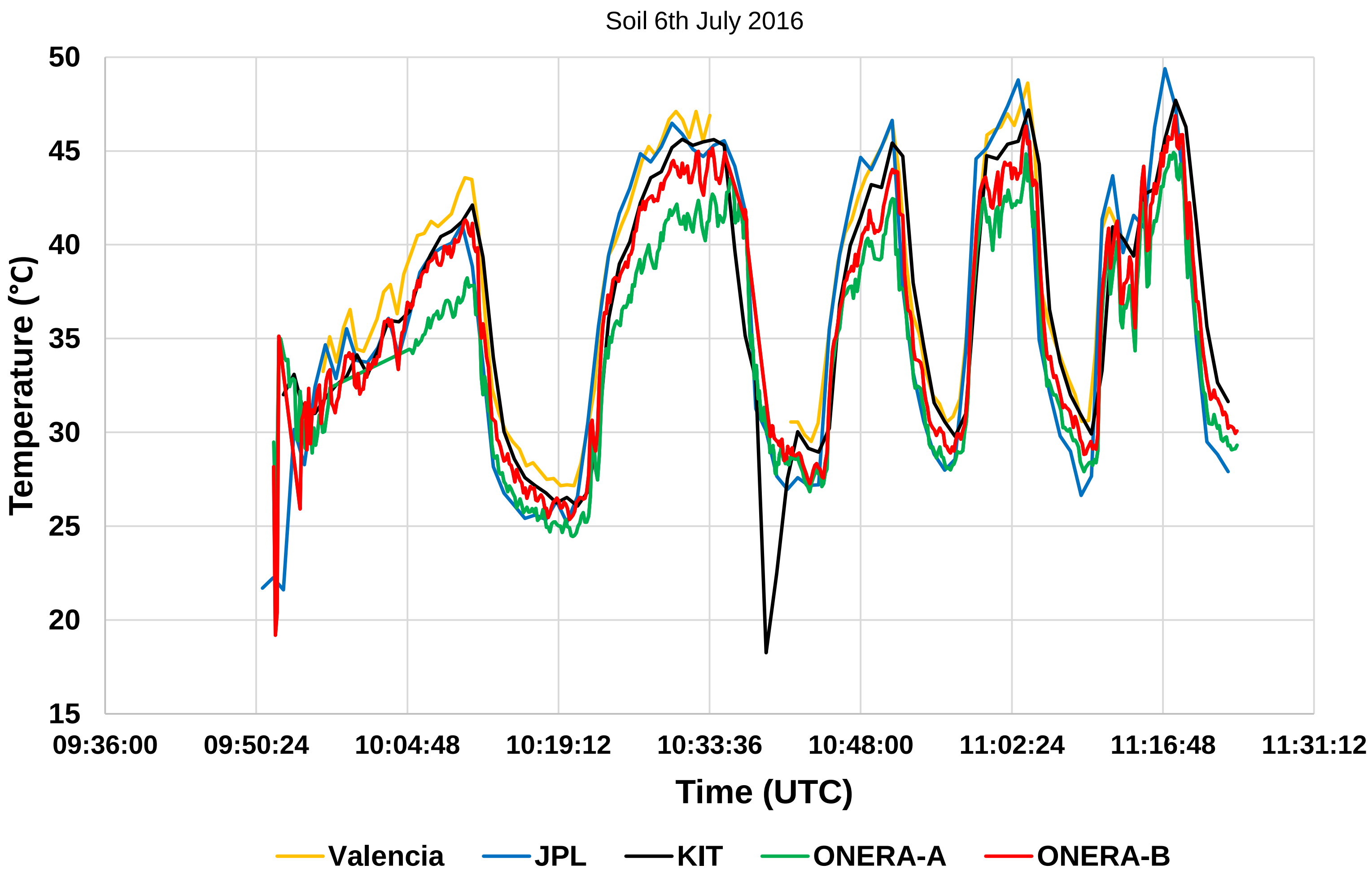
Difference of the measurements of measuring radiometers on the short grass sample from their mean. This Figure shows that the difference is within ±3 ºC throughout the monitoring period (mostly within ±2 ºC).



fiducial reference temperature measurements

NPL National Physical Laboratory

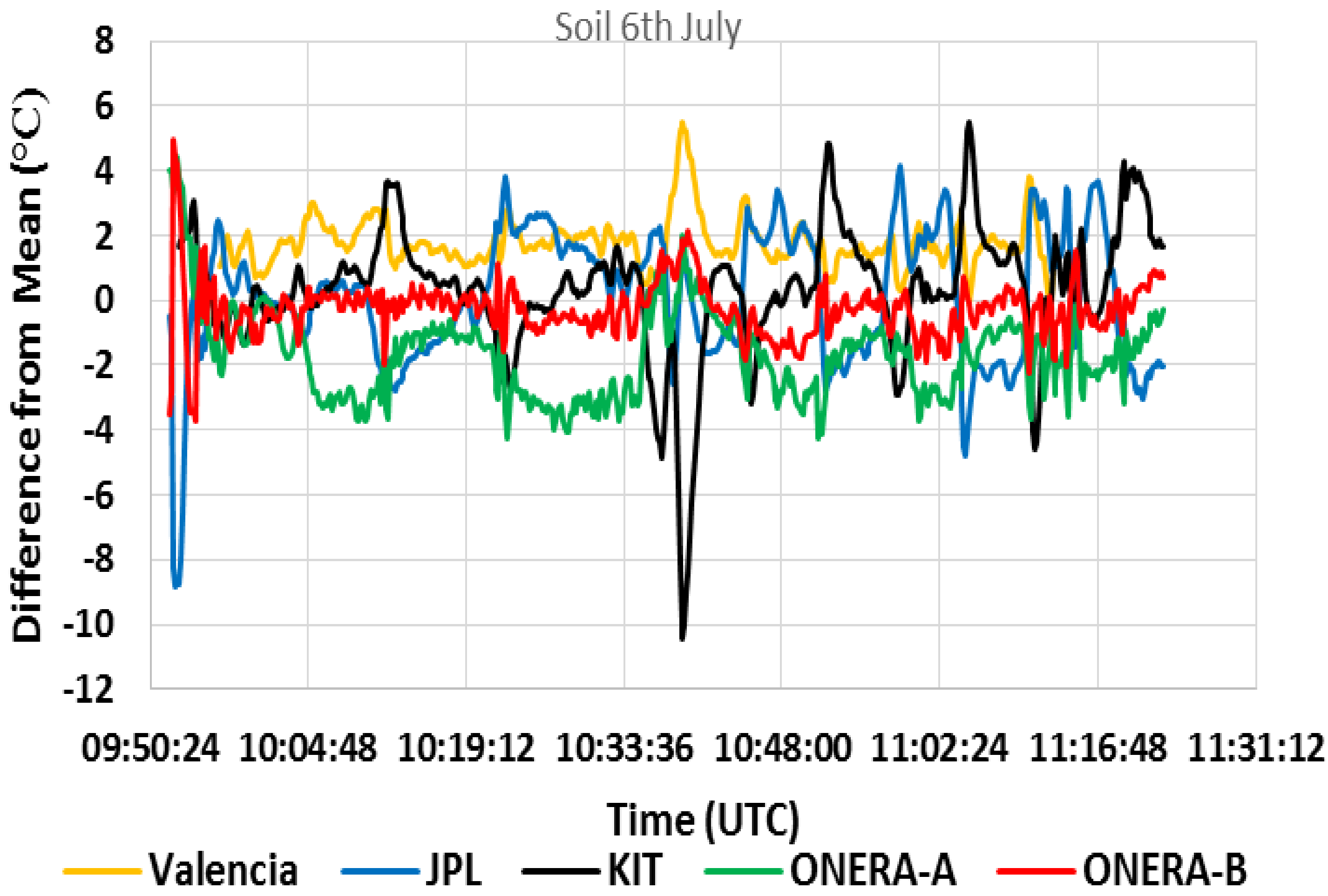
Surface temperature of dark soil measured by the participating radiometers on the 6th July 2016



fiducial reference temperature measurements

NPL National Physical Laboratory

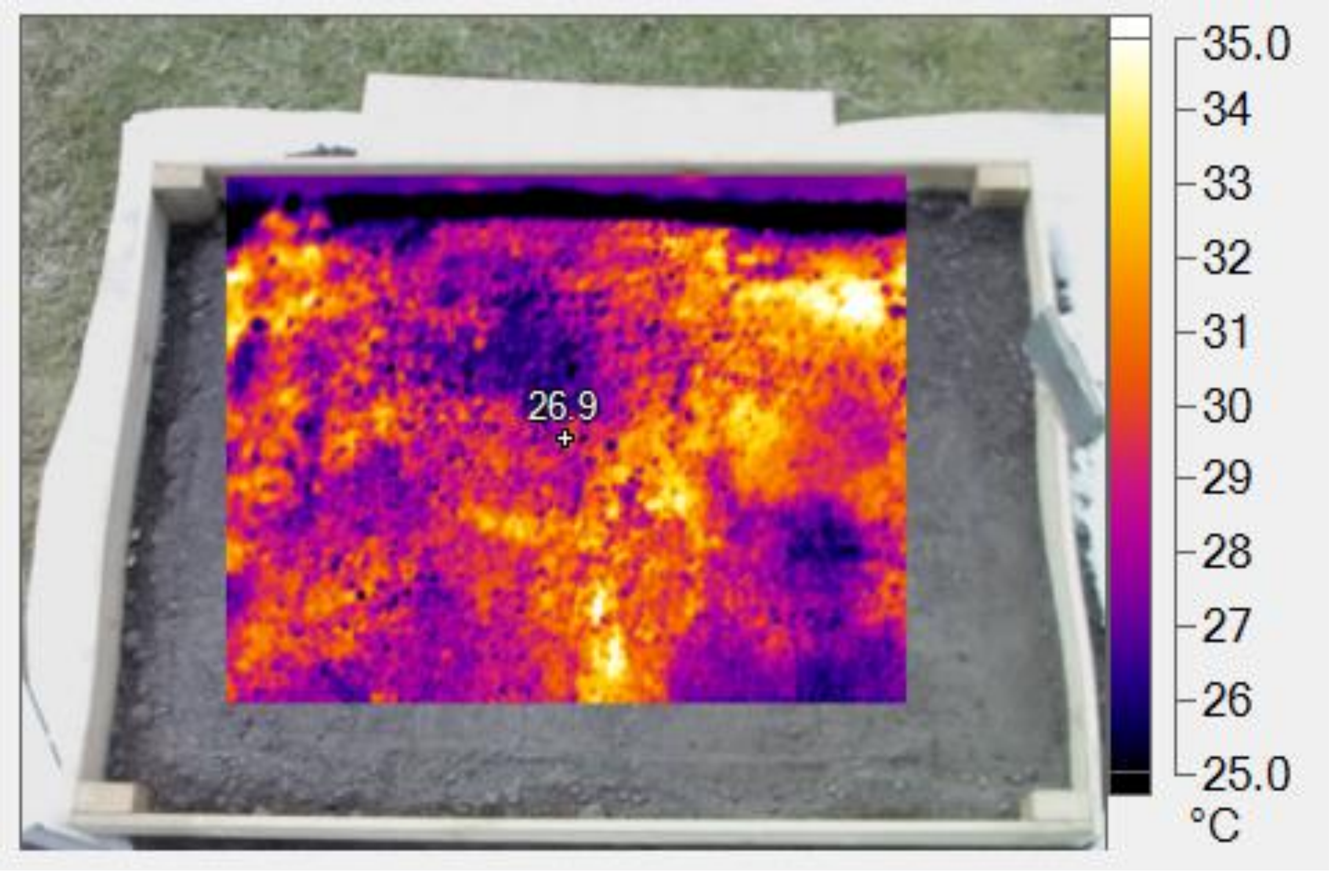
Difference of the measurements of the five measuring radiometers made on the 6th July on the dark soil sample from their mean.



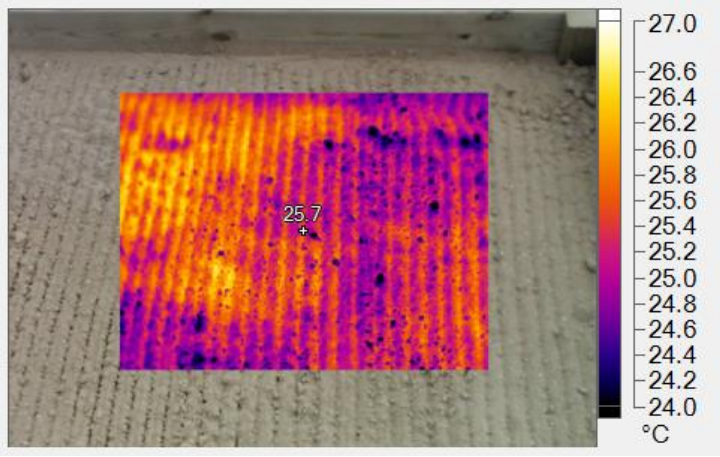
fiducial reference temperature measurements

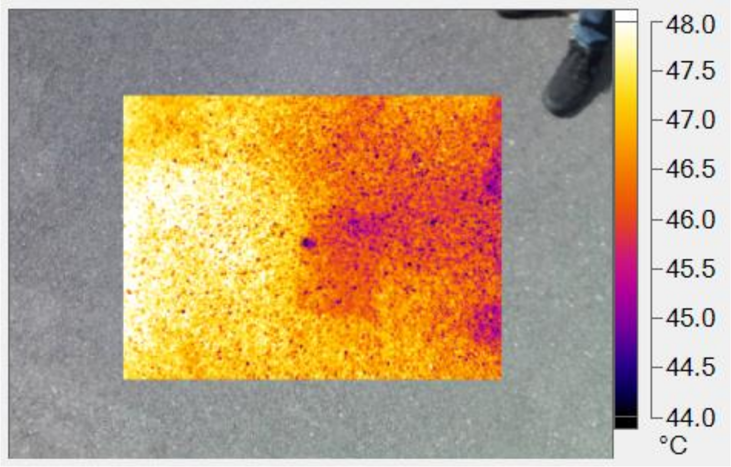
NPL National Physical Laboratory

Combination of a thermal image of the dark soil sample with a black and white, visible image of the same target. The Figure shows that the apparent surface temperature of the sample was varying by about 10 °C over the measured area.



The "smoothness" of the sand sample was critical in determining the variations in temperature on the surface of the sample.

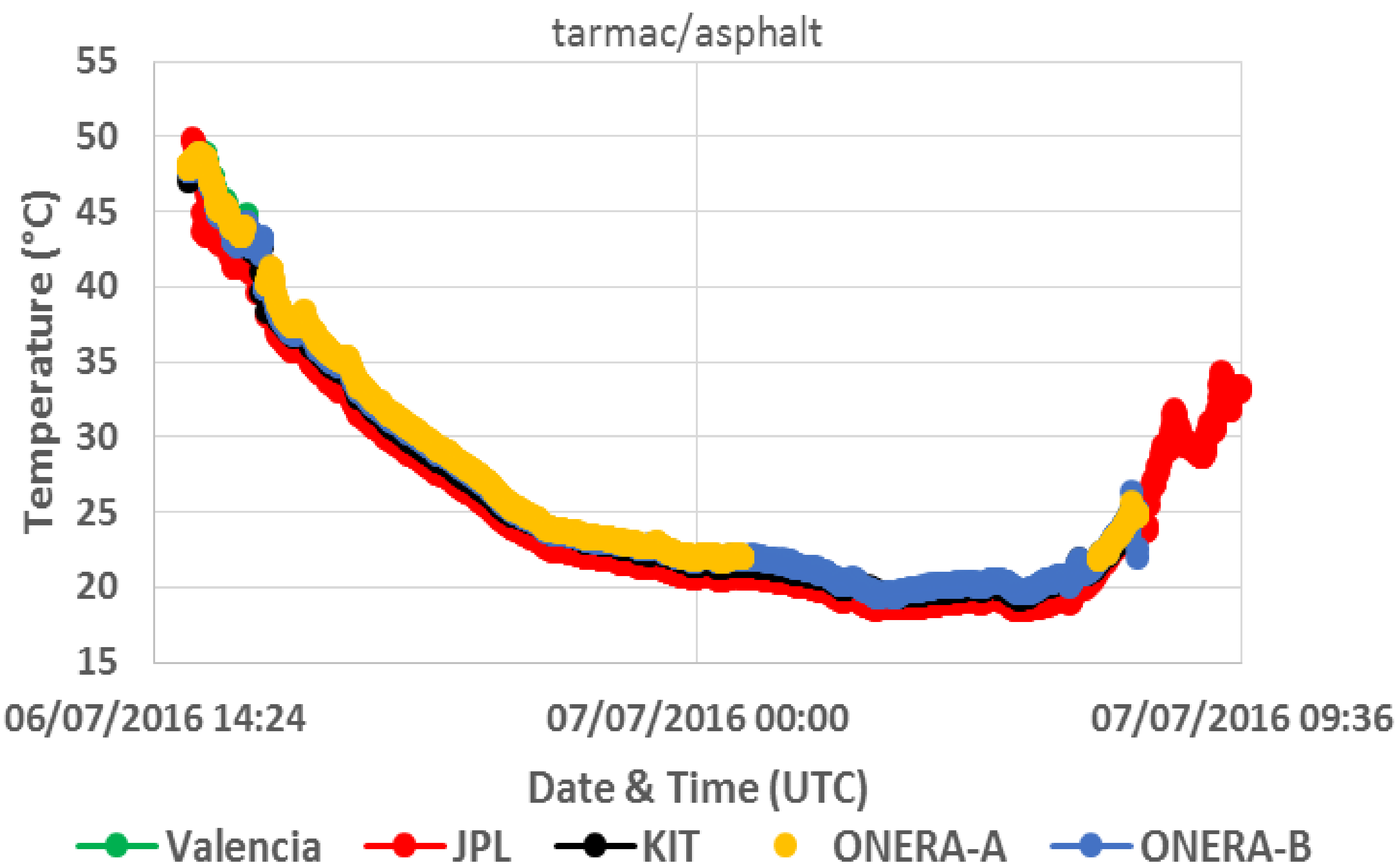




fiducial reference temperature measurements

NPL National Physical Laboratory

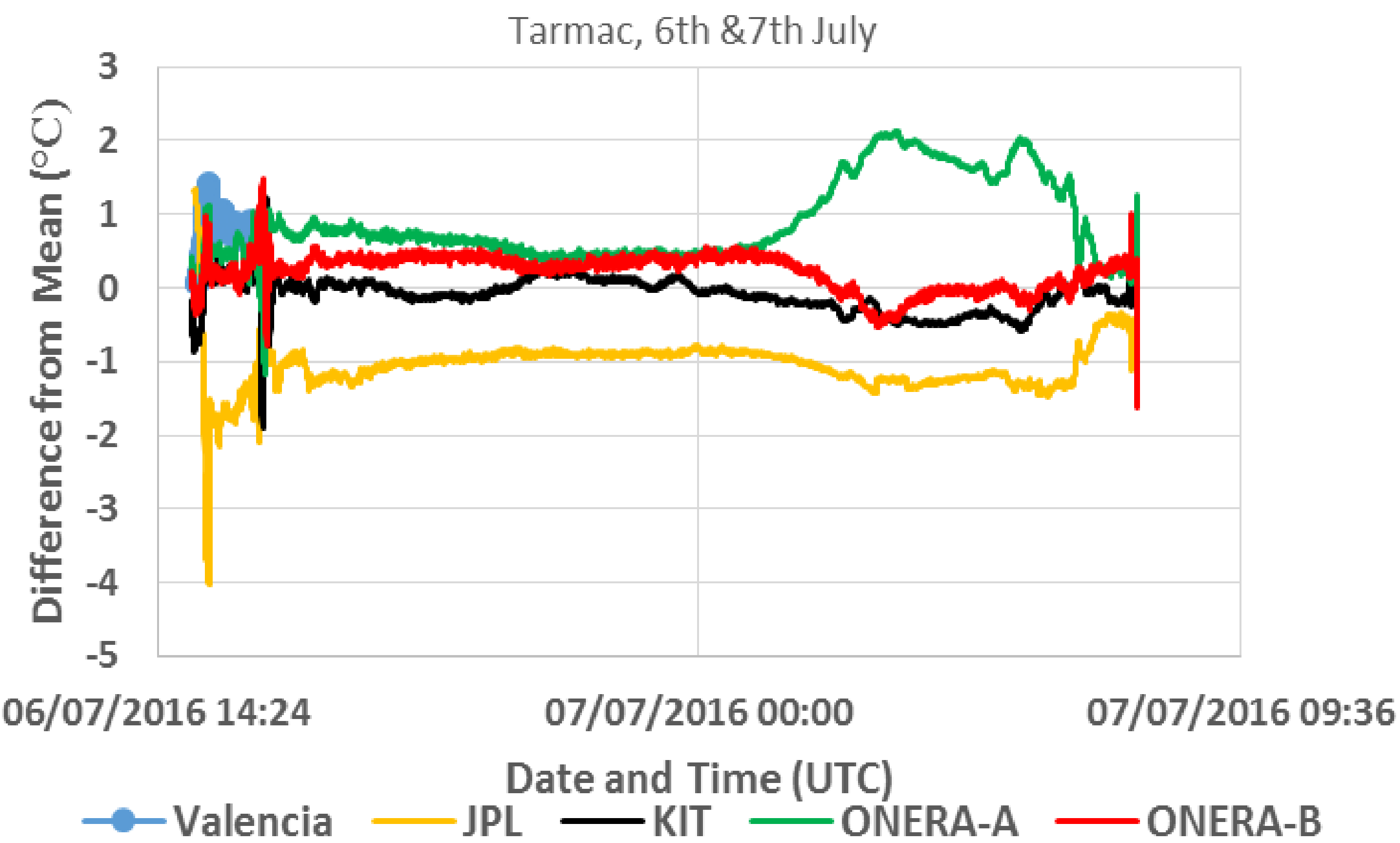
Surface temperature of tarmac measured by the participating radiometers on the 6th & 7th July 2016



fiducial reference temperature measurements

National Physical Laboratory

Difference of the measurements of the five measuring radiometers made on the 6th July on the tarmac sample from their mean. The bulk of the difference of all five radiometers from their mean is within ±2 °C throughout the monitoring period



fiducial reference temperature measurements

National Physical Laboratory

Summary

1. The important steps of the protocols of the 2016 FRM4STS comparison activities were highlighted.
2. Protocols for the 2016 FRM4STS comparisons (Lab Radiometer, Lab Blackbody, WST and LST) at NPL were prepared and agreed by all participants prior to the start of the comparisons.
3. The protocols were largely adhered to but in some cases, slightly different procedures were adopted with the agreement of all the participants.
4. The development of the 2016 protocols relied heavily on the experience gained from previous comparisons (in 2001 and 2009).
5. The protocols developed for the 2016 FRM4STS comparisons can be used as the basis for future comparisons.

Thank you for listening

e.theo@npl.co.uk

What is the need for the comparisons?

- The Earth's surface temperature is an essential parameter for climate monitoring.
- Currently satellites provide the obvious means of monitoring the Earth's surface temperature.
- **It is essential for long-term records that satellite measurements are fully anchored to SI units (to provide traceability).**
- At the moment field-deployed infrared radiometers are used to provide surface-based measurements which are used for Calibration/Validation.
- These radiometers are in principle calibrated traceably to SI units, generally through a blackbody radiator.
- However, the blackbodies and radiometers used 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 assigned to satellite sensors.

The 2016 FRM4STS comparison

- Comparisons of ground-based infrared radiometers used to support calibration and validation of satellite borne sensors (along with blackbody comparisons) were completed in 2001 and 2009.
- At NPL most of our standards are recalibrated EVERY YEAR!
- Re-calibrations also allows us to get a “history” for our standards (do they drift?).
- Seven years had passed, so plans were put into place to repeat the comparisons, during 2016.

The objectives of the 2016 comparison were:

- To establish the “degree of equivalence” between terrestrially based IR Calibration and 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 (not one but two) National Standards Laboratories.