Fiducial Reference Measurements for validation of Surface Temperature from Satellites (FRM4STS) - Laboratory Calibration of Participants Radiometers and Blackbodies

Protocol for the FRM4STS LCE (LCE-IP)

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CONTENTS

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DOCUMENT APPROVAL

Contractor Approval

Name	Role in Project	Signature & Date (dd/mm/yyyy)
Dr Nigel Fox	Technical Leader	
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CUSTOMER APPROVAL

Name	Role in Project	Signature	Date (dd/mm/yyyy)
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APPLICABLE DOCUMENTS

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EOP-SM/2642	1	Fiducial Reference Measurements for Thermal Infrared Satellite Validation (FRM4STS) Statement of Work

ACRONYMS AND ABBREVIATIONS

AMBER	Absolute Measurements of Black-body Emitted Radiance
CEOS	Committee on Earth Observation Satellites
DMI	Danish Meteorological Institute
IR	Infra-Red
ISO	International Organization for Standardization
KIT	Karlsruhe Institute of Meteorology
LST	Land Surface Temperature
NIST	National Institute of Standards and Technology (USA)
NMI	National Metrology Institute
NPL	National Physical Laboratory
PTB	Physikalisch Technische Bundesanstalt
SST	Sea Surface Temperature
SI	Système Internationale
WGCV	Working Group for Calibration and Validation
WST	Water Surface Temperature

1. INTRODUCTION

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

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

The "IR Cal/Val community" is well versed in the need and value of such comparisons having held highly successful exercises in Miami and at NPL in 2001 [1, 2] and 2009 [3, 4]. However, six years will have passed and it is considered timely to repeat/update the process. Plans are in place for the comparisons to be repeated in 2016. The 2016 comparison will include:

i. Laboratory comparisons of the radiometers and reference radiance blackbodies of the participants.
ii. Field comparisons of Water Surface Temperature (WST) scheduled to be held at Wraysbury fresh water reservoir, near NPL.
iii. Field comparisons of Land Surface Temperature (LST) scheduled to be held on the NPL campus.
iv. Field comparisons of Land Surface Temperature (LST) scheduled to be held at two sites (Gobabeb Training and Research Centre on the Namib plain and the "Farm Heimat" site in the Kalahari bush) in Namibia in 2016.
v. Field comparisons of Ice Surface Temperature (IST) scheduled to be held in the Arctic.

This document describes the protocol which is proposed for the laboratory comparisons of the radiometers and reference radiance blackbodies of the participants during the 2016 comparison activities to be held at NPL. Note that, following an initial review by participants and an assessment of number of participants, some of the introductory sections of this protocol will be revised and made more generic to allow the protocol to be a standalone document for future use.

2. OBJECTIVES

The overarching objective of this comparison is "*To establish the "degree of equivalence" between surface 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 standards laboratories".*

The objective can be sub-divided into the following:

1) Evaluation of the differences in IR radiometer primary calibrations

a. Reference standards used (blackbodies) and traceability (laboratory based).
b. Radiometers response to common blackbody target (laboratory based).
c. Evaluation of differences in radiometer response when viewing Water/Land surface targets in particular the effects of external environmental conditions such as sky brightness.

2) Establishment of formal traceability for participant black bodies and radiometers

The purpose of this document is to describe the protocol which is proposed for the laboratory calibrations of the blackbodies and radiometers of the participants during the 2016 comparisons.

3. ORGANIZATION

3.1 PILOT

NPL, the UK national metrology institute (NMI) will serve as pilot for this comparison supported by the PTB, the NMI of Germany. NPL, the pilot, will be responsible for inviting participants and for the analysis of data, following appropriate processing by individual participants. NPL, as pilot, will be the only organisation to have access and to view all data from all participants. This data will remain confidential to the participant and NPL at all times, until the publication of the report showing results of the comparison to participants.

3.2 PARTICIPANTS

The list of the potential participants, based on current contacts and expectation who will be likely to take part is given in the Section 3.3. Dates for the comparison activities are provided in Section 3.6. A full invitation to the international community through CEOS and other relevant bodies will be carried out to ensure full opportunity and encouragement is provided to all. All participants should be able to demonstrate independent traceability to SI of the instrumentation that they use, or make clear the route of traceability via another named laboratory.

By their declared intention to participate in this key comparison, the participants accept the general instructions and the technical protocols written down in this document and commit themselves to follow the procedures strictly. Once the protocol and list of participants have been reviewed and agreed, no change to the protocol may be made without prior agreement of all participants. Where required, demonstrable traceability to SI will be obtained through participation of PTB and NPL as pilot.

3.3 PARTICIPANTS' DETAILS

NB: This is not the full list

Table 1. Contact Details of Participants

Contact person	Short version	Institute	Contact details
Nigel Fox	NPL	National Physical Laboratory	email: nigel.fox@npl.co.uk; Tel: +44 20 8943 6825
Carol Anne Clayson	Woods Hole Oceanographic Institution	266 Woods Hole Road, Woods Hole, MA 02543-1050 U.S.A	email: cclayson@whoi.edu; Tel: +1 508 289 3626
Jacob Høyer	DMI	Danish Meteorological Institute (DMI), Centre for Ocean and Ice, Lyngbyvej 100, 2100 København Ø	email: jlh@dmi.dk; Tel: +4539157203
Frank Goettsche	KIT	Institute for Meterology and Climate Research (IMK-AF), Kaiserstr. 12, 76131, Karlsruhe, Germany	email: frank.goettsche@kit.edu; +49 721 608-23821

Contact person	Short version	Institute	Contact details
Helen Beggs	Bureau of Meteorology, Australian Govt.	Ocean Modelling Research Team Research and Development Branch Bureau of Meteorology GPO Box 1289 Melbourne VIC 3001 Level 11, 700 Collins Street, Docklands VIC 3008	email: h.beggs@bom.gov.au; Tel: +61 3 9669 4394; Fax: +613 9669 4660
Nicole Morgan	CSIRO	Seagoing Instrumentation Team, Oceans and Atmosphere Flagship, CSIRO, GPO Box 1538, Hobart, TAS, 7001, AUSTRALIA	email: Nicole.Morgan@csiro.au; Ph: +613 6232 5222
Leiguan Ouc	OUC-CN	Ocean Remote Sensing Institute Ocean University of China 5 Yushan Road,Qingdao, 266003 China	email: leiguan@ouc.edu.cn
Manuel Arbelo	GOTA	Grupo de Observacion de la Tierra y la Atmosfera (GOTA), ULL, Spain	email.: marbelo@ull.es
Simon Hook	JPL-NASA	Carbon Cycle and Ecosystems MS 183-501, Jet Propulsion Laboratory 4800 Oak Grove Drive, Pasadena, CA 91109 USA	email: simon.j.hook@jpl.nasa.gov
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Tim Nightingale	STFC	STFC Rutherford Appleton Laboratory Chilton, Didcot,Oxon OX11 0QX United Kingdom	Tel: +44 1235445914; Tim.Nightingale@stfc.ac.uk
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Caroline Sloan	MOD, NAVY SHIPS-HM FEIO	Fleet Environmental Information Officer NAVY SHIPS-HM FEIO | Navy Command Headquarters, MP 2.3, Leach Building, Whale Island, Portsmouth, Hampshire, PO2 8B	Tel: 023 9262 5958 | Mil: 93832 5958; NAVYSHIPS-HMFEIO@mod.uk; caroline.sloan104@mod.uk
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Dr. César Coll	UV-ES	Dept. of Earth Physics and Thermodynamics Faculty of Physics, University of Valencia Dr. Moliner, 50. 46100 Burjassot Spain	email: Cesar.Coll@uv.es
Raju Datla	NIST	100 Bureau Drive, Gaithersburg, MD 20899 USA	email: rdatla@nist.gov
William (Bill) Emery	EDU-USA	Univ of Colorado, Aerospace Eng. Sci. Dept CB 431, Boulder,CO, 80309-0431 USA	email: emery@colorado.edu
Dr. Frank-M. Goettsche	IMK-FZK	Forschungszentrum Karlsruhe Institute of Meteorology and Climate Research, Atmospheric Trace Gases and Remote Sensing, Meteorological	email: frank.goettsche@imk.fzk.de; Tel: +49-(0)7247-82-3821

Contact person	Short version	Institute	Contact details
		Satellite-Data Analysis, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen Germany	
Peter J Minnett	RSMAS	University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149 USA	email: pminnett@rsmas.miami.edu

3.4 OVERVIEW OF THE FORM OF COMPARISONS

This protocol covers a number of individual comparisons. Each comparison will have its own specific characteristics but will all in principle take the same form i.e. they will all seek to observe a common entity. In the case of the blackbody radiator comparison, traceability to SI will also be established through the direct participation of reference radiance blackbodies characterised at national standards laboratories and associated transfer standard radiometers. Viewing of these blackbodies by participant radiometers will allow that traceability to be extended to the radiometers.

3.5 COMPARISON OVERVIEW

The laboratory calibration comparison exercise consists of two separate comparisons. The following sections outline the principle scope of each comparison.

3.5.1 Comparison 1: Blackbodies

In this comparison, any portable blackbodies provided by participants will be compared relative to a reference radiance blackbody using well-characterised transfer standard radiometers. The transfer radiometers used will be the NPL AMBER radiometer [5] which will be used to measure the brightness temperature of the blackbodies for a wavelength of 10.1 μm and the PTB infrared broadband radiometer which is will be used to measure 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, 293 K and 303 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, whereas for blackbodies which are used to support ice surface temperature measurements, the comparison will be over the 253 K to 323 K temperature range.

3.5.2 Comparison 2: Radiometers (laboratory)

For this comparison all participant radiometers will be compared to a reference radiance blackbody calibrated traceable to SI. The reference blackbody will be variable in temperature, have a well-characterised and high spectral emissivity and have an aperture sufficiently large to accommodate the field of view of any participant radiometer.

The reference radiance blackbody will be set to a fixed known temperature and then viewed by all participating radiometers. Radiometers which are used to measure sea/water surface temperature will perform measurements of the reference radiance blackbody at nominal temperatures of 278 K, 283 K, 293 K and 303 K. Radiometers which are used to measure land surface temperatures will perform measurements of the reference blackbody 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 and up to 293 K.

3.6 TIMETABLE

There are three main phases to the comparison activity. The first phase prepares for the measurements; the second phase is the execution of the measurements themselves and the third phase is the analysis and report writing.

Table 2. Comparison activity- Phases

PHASE 1: PREPARATION	
Invitation to participate	October 2015
Preparation and formal agreement of protocol	Jan - March 2016
PHASE 2: MEASUREMENTS	
Participants measure primary blackbody	June 2016
Comparison of participants' blackbodies	June 2016
Participants send all data and reports to pilot	July 2016
PHASE 3: ANALYSIS AND REPORT WRITING	
Participants send preliminary report of measurement system and uncertainty to pilot and forwarded to all	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

Table 3 below shows the top-level plan for the comparison activity at NPL during 2016. The first week starting on Monday 20th June 2016 has been allocated to laboratory measurements of the reference blackbody using the participants' radiometers as well as the measurement of the participants' blackbodies using the reference radiometers of NPL and PTB. These measurements are expected to last for the whole of that week.

The second week starting on Monday 27th June 2016 has been allocated to field measurement of the Water Surface Temperature (WST) of the large water reservoir at Wraysbury, near NPL. Measurements will be done from the platform located in the middle of the reservoir. These measurements are expected to finish by the end of that week (Friday 1st July 2016).

The third and final week of the comparison has been allocated to field measurements of Land Surface Temperature (LST). These will be done at a site on the NPL campus. The plan is to start the LST measurements on Monday 4th July 2016. The LST measurements are expected to finish on Friday 8th July.

This protocol deals with the laboratory comparison activities which are due to take place during the first week of the comparison, staring on Monday 20th June 2016.

Table 3. Comparison Activity Plan

Week No.	Experiment No.	Start Date	End Date	Experiment	Venue
1	1	20 JUNE 2016	24 JUNE 2016	Laboratory calibration of participants’ radiometers against reference blackbody. Simultaneously, laboratory calibration 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

3.7 TRANSPORTATION OF INSTRUMENTATION

It is the responsibility of all participants to ensure that any instrumentation required by them is shipped with sufficient time to clear any customs requirements of the host country, in this case the UK. This includes transportation from any port of entry to the site of the comparison and any delay could result in them being excluded from the comparison. NPL can provide some guidance on the local processes needed for this activity. It is recommended that where possible any fragile components should be hand carried to avoid the risk of damage. The pilot and host laboratory have no insurance for any loss or damage of the instrumentation during transportation or whilst in use during the comparison, however all reasonable efforts will be made to aid participants in any security. Any queries should be directed to Theo Theocharous at the address shown in Appendix F.

Electrical power (220 V ac) will be available to all participants, with a local UK plug fitting. Participants who require a 110 V ac supply should provide their own transformer.

3.8 PRELIMINARY INFORMATION

Three months prior to the start of the comparison participants will be required to supply to the pilot a description of the instrumentation that they will bring to the comparison. This will include any specific operational characteristics where heights/mountings may be critical as well as a full description of its characterisation, traceability and associated uncertainties under laboratory conditions. These uncertainties will be reviewed by NPL for consistency and circulated to all participants for comment and peer review. Submitted uncertainty budgets can be revised as part of this review process but only in the direction to increase the estimate in light of any comments. No reduction will be allowed for the purpose of this comparison but post the comparison process participants may choose to re-evaluate their uncertainties using methods and knowledge that they may acquire during the review process.

4. MEASUREMENT INSTRUCTIONS

4.1 TRACEABILITY

All participant instruments should be independently traceable to SI units with documentary evidence of the route and associated uncertainty. If this traceability is provided as part of a "calibration" from the instrument manufacturer, then the manufacturer should be contacted and asked to supply the appropriate details.

4.2 MEASUREMENT WAVELENGTHS

The comparison will be analysed as a set of comparisons for each wavelength where appropriate or as wavelength band e.g. 3 to 5 μm and 8 to 12 μm. Participants must inform the pilot laboratory prior to the start of the comparison which wavelengths the participant will be taking measurements at.

4.3 MEASURAND

The principle measurand in all comparisons is brightness temperature.

4.4 MEASUREMENT INSTRUCTIONS

4.4.1 Comparison 1: Blackbodies

- The transfer radiometers used to view the participating blackbodies should be calibrated traceable to NPL and PTB primary scales prior to use. These radiometers will 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 needs to be taken 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.

- The description of each participant's blackbody and its route of traceability should be provided by completing the form shown in Appendix B.

- Participants will set their blackbody to the nominal temperature specified by the pilot. They will indicate to the pilot when the blackbodies have reached equilibrium. They will then 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 occur during the measurement period to be accounted for.

- The operators of the transfer radiometers will record the readings of the radiometers continuously during the nominal 10 minute period over which each participant blackbody is being monitored. The operators of the transfer radiometers will also record the identity of the participant and all the information supplied by the participant.

- Data should be given to the Pilot on the form given in Appendix A.

- The participant will not be informed of the result at this stage.

- The process will be repeated for each of the three nominal temperatures, and any others temperatures deemed necessary. In practise it is expected that other participants 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.

4.4.2 Comparison 2: Radiometers (Laboratory)

- The variable temperature blackbody used for this comparison must be well characterised with demonstrable traceability to SI. The reference temperature blackbody which is being planned to be used is the NPL ammonia heat-pipe blackbody. This blackbody is capable of operating anywhere in the -50 ºC to +50 ºC temperature range.
- The description of each participant's radiometer and its route of traceability should be provided by completing the form shown in Appendix C.
- Each participant radiometer should be mounted so that it can be easily aligned to the reference blackbody.
- The reference blackbody should then be set to one of the nominal temperatures specified in this protocol. (NB, this should not necessarily be the exact temperature, so as to ensure "blindness" to participants).
- Each participant radiometer should then be aligned to view the reference blackbody and when they are ready, to make at least ten measurements of the brightness temperature of the blackbody over the 10 minute measurement period. This information should be recorded and unless it needs further processing should be provided to the pilot at this 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 this 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 given in Appendix A, which will also be available electonically.

- The host laboratory will collect measurements of the air temperature and relative humidity during the measurement period and make these available to the participants.

5. MEASUREMENT UNCERTAINTY

The uncertainty of measurement 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 are given below. Example tables corresponding to blackbody uncertainty contributions and radiometer uncertainty contributions are given in Appendices D and E respectively. The participating laboratories should complete these tables and are encouraged to follow this breakdown as closely as possible, and adapt it to their instruments and procedures. Other additional parameters may be felt appropriate to include, dependent on specific measurement facilities and these should be added with an appropriate explanation and/or reference. As well as the value associated with the uncertainty, participants should give an indication as to the basis of their estimate. All values should be given as standard uncertainties, in other words for a coverage factor of $k = 1$. Note this table 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. It is expected that the uncertainty associated with the full characterisation of the instrument will be presented in a separate document. Guidance on establishing such uncertainty budgets can be obtained by review of the NPL training guide which can be found at http://www.emceoc.org/documents/uaeo-int-trg-course.pdf. An example which deals with the development of the uncertainty budget for a blackbody can be found elsewhere [6]. Reference 7 describes the development of the uncertainty budget for an ambient temperature measuring radiometer.

5.1 TYPE A UNCERTAINTY CONTRIBUTIONS

5.1.1 Repeatability of measurement

This describes the repeatability of measurement process without re-alignment of the participants' instrument. This component should be largely caused by the instrumentation stability/resolution related to the output from the reference standard and any associated measuring instrument. In effect it is the standard deviation of a single set of measurements made on the reference standard. This should be presented as a relative quantity.

5.1.2 Reproducibility of measurement

This describes the reproducibility (run to run) following re-alignment of the instrument with the comparison transfer standard. This should be, largely caused by the measurement set-up related to the output from the transfer standard. This should be presented in terms of percentage of the assigned result.

5.2 TYPE B UNCERTAINTY CONTRIBUTIONS

5.2.1 Participants disseminated scale

This is the total uncertainty of the participant's instrument. This includes its traceability to any primary reference standard, underpinning scale as disseminated by them. This should include the uncertainty in the primary SI realisation, or in the case of a scale originating from another laboratory, the uncertainty of the scale disseminated to it by that laboratory. It should of course reference the originating laboratory. All uncertainties contributing to this parameter should be itemised as part of the report, or if published, a copy of this publication attached. These should include spectral emissivity and its uniformity in the case of the black body, together with any thermometry.

5.2.2 Wavelength

This is the uncertainty in the absolute value of the wavelength used for the comparison. This should only be taken account of in terms of the instrumentation being used and should include details relating to bandwidth, where appropriate.

5.2.3 Drift in the radiometer responsivity

The responsivity of all instruments is known to change with time. The responsivity of a radiometer is expected to drift since it was last calibrated. The amount of drift in the responsivity of the radiometer should be quantified and used to introduce an uncertainty contribution due to this drift in the uncertainty budget.

5.2.4 Ambient temperature/relative humidity fluctuations

Changes in ambient temperature can affect the output of a radiometer as well as the transmittance of the atmosphere. Although corrections can be added to account for the fluctuations in the ambient temperature, an uncertainty is also required to account for the uncertainty of the corrections. Similarly changes in the atmospheric humidity can affect the responsivity of the radiometer as well as the transmittance of the atmosphere at the operating wavelength, hence an uncertainty contribution is also required in the uncertainty budget to account for this effect.

6. REPORTING OF RESULTS

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 can be identified and potentially corrected during the course of the comparison whilst still keeping results blind.

The measurement results are to be supplied in the Template provided by the pilot laboratory at the beginning of the comparison (see Appendix A for the Templates for reporting the results of the blackbody and radiometer laboratory comparisons). The measurement results should also be provided in an Excel format. The measurement report is to be supplied in the Word Template as a .doc file provided by the pilot. This will simplify the combination of results and the collation of a report by the pilot and reduce the possibility of transcription errors.

The measurement report forms and templates will be sent by e-mail to all participating laboratories. It would be appreciated if the report forms (in particular the results sheet) could be completed by computer 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 using the form shown in Appendix F. In case of any differences, the paper forms are considered to be the definitive version.

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 stands and the complete set of final results will be sent to all participants. Note that 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.

7. 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 this 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 participant blackbodies.

8. REFERENCES

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

APPENDIX A: REPORTING OF MEASUREMENT RESULTS

The attached measurement summary should be completed by each participant for each completed set of laboratory measurements. A complete set being one, which may include multiple measurements on, or using the same instrument but does not include any realignment of the instrument. For each realignment a separate measurement sheet should be completed.

For clarity and consistency the following list describes what should be entered under the appropriate heading in the tables.

Time	The time of the measurements should be UTC.
Measured Brightness temperature	Brightness temperature measured or predicted by participant.
Measurement uncertainty	Combined/total uncertainty of the measurement.
Uncertainty	The total uncertainty of the measurement of brightness temperature separated into Type A and Type B. The values should be given for a coverage factor of k=1.
Wavelength	This describes the assigned centre wavelength used for the measured brightness temperature. For the case of Fourier Transform spectrometers, the wavelength range and wavelength resolution should be specified.
Bandwidth	This is the spectral bandwidth of the instrument used for the comparison, defined as the Full Width at Half the Maximum.
Standard Deviation	The standard deviation of the number of measurements made to obtain the assigned brightness temperature without realignment
Number of Runs	The number of independent measurements made to obtain the specified standard deviation.

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 % B	

Participant: ……………………………………………………………………………………

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

Measurement Laboratory Results: Radiometer Comparison

Instrument Type ...…… …………………………. Identification No ………………………….

Date of measurement: …………………………… Ambient temperature …………………….

Time of measurement (UTC)	Measured Brightness Temperature K	Combined Measurement Uncertainty mK	Wave-length µm	Band-width nm	Uncertainty A	% B	No. of Runs

Participant: ……………………………………………………………………………………

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

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:*..…...

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....

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:...

....

....

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....

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Participant: ………………………………………………………………………………

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

APPENDIX C: DESCRIPTION OF RADIOMETER 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 Radiometer ....

....

Outline Technical description of instrument: *this could be a reference to another document but should include key characteristics for radiometers such as type of detector used, spectral selecting component(s), field of view etc.:* ....

....

....

....

....

....

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 instrument:* ....

....

....

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

....

....

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

....

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Participant: ……………………………………………………………………………………

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

APPENDIX D: UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH BLACKBODIES

The table shown below is a suggested layout for the presentation of uncertainties for the calibration of blackbodies. It should be noted that some of these components may sub-divide further depending on their origin. For example emissivity may have a modelling term, a measurement term of the coating and/or a measurement term for the cavity as a whole. Similarly the Type A uncertainties shown in the table assume that some intermediate radiometer has been used to transfer a scale from a primary blackbody to this one. If the basis of traceability for this blackbody is independent in nature then only source stability is likely to be important. The RMS total refers to the usual expression i.e. square root of the sum of the squares of all the individual uncertainty terms as shown in the example for Type A uncertainties.

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	$((u_{Repeat})^2+(u_{Repro})^2)^{½}$		

APPENDIX E: UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH RADIOMETERS

The table shown below is indicative of the component uncertainties associated with the calibration of a radiometer. It should be noted that some of these components may sub-divide further depending on their origin. The RMS total refers to the usual expression i.e. square root of the sum of the squares of all the individual uncertainty terms as shown in the example for Type A uncertainties.

Uncertainty Contribution	**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}
Primary calibration		U_{Prim}	U_{Prim}
Linearity of radiometer		U_{Lin}	U_{Lin}
Drift since calibration		U_{Drift}	U_{Drift}
Ambient temperature fluctuations		U_{amb}	U_{amb}
Atmospheric absorption/emission		U_{atm}	U_{atm}
RMS total	$((U_{repeat})^2+(U_{Repro})^2))^{½}$		

APPENDIX F: DATA RECEIPT CONFIRMATION

All data should be sent to the pilot NPL. The details of the contact person for this are:

To: **(participating laboratory, please complete)**

From: **Dr Theo Theocharous**
National Physical Laboratory
Hampton Road
Teddington
Middlesex
United Kingdom
TW11 0LW

Tel: ++44 20 8943 6977
e-mail: theo.theocharous@npl.co.uk

We confirm that we have received your data which resulted from the CEOS key comparison of "techniques/instruments used for surface IR radiance/brightness temperature measurements" on ....(date).

....
....
....

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

-END OF DOCUMENT-