



fiducial reference  
temperature  
measurements



## Fiducial Reference Measurements for validation of Surface Temperature from Satellites (FRM4STS) – Land Surface Temperature Comparison of Participants Radiometers

### Technical Report 1 Protocol for the FRM4STS LCE (LCE-IP)

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# Fiducial Reference Measurements for validation of Surface Temperature from Satellites (FRM4STS): Land Surface Temperature Comparison of Participants Radiometers

Protocol for the FRM4STS LCE (LCE-IP)

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## CONTENTS

DOCUMENT VERSION HISTORY

DOCUMENT APPROVAL

<b>APPLICABLE DOCUMENTS .....</b>	<b>7</b>
<b>ACRONYMS AND ABBREVIATIONS .....</b>	<b>8</b>
<b>1. INTRODUCTION .....</b>	<b>9</b>
<b>2. OBJECTIVES.....</b>	<b>9</b>
<b>3. ORGANIZATION.....</b>	<b>10</b>
3.1 PILOT .....	10
3.2 PARTICIPANTS .....	10
3.3 PARTICIPANTS' DETAILS.....	10
3.4 OVERVIEW OF THE FORM OF COMPARISONS.....	12
3.5 COMPARISON OVERVIEW .....	12
3.6 TIMETABLE.....	13
3.7 TRANSPORTATION OF INSTRUMENTATION.....	14
3.8 PRELIMINARY INFORMATION .....	14
<b>4. MEASUREMENT INSTRUCTIONS.....</b>	<b>15</b>
4.1 TRACEABILITY.....	15
4.2 MEASUREMENT WAVELENGTHS .....	15
4.3 MEASURAND .....	15
4.4 MEASUREMENT INSTRUCTIONS FOR LST COMPARISON .....	15
4.4.1 Day-time LST measurements.....	15
4.4.2 Night-time LST measurements.....	16
4.5 DECLARATION OF COMPARISON COMPLETION .....	16
<b>5. MEASUREMENT UNCERTAINTY .....</b>	<b>17</b>
5.1 TYPE A UNCERTAINTY CONTRIBUTIONS .....	17
5.1.1 Repeatability of measurement .....	17
5.1.2 Reproducibility of measurement.....	17
5.2 TYPE B UNCERTAINTY CONTRIBUTIONS.....	17
5.2.1 Participants disseminated scale .....	17
5.2.2 Wavelength.....	18
5.2.3 Land target emissivity .....	18
5.2.4 Angle of view to nadir (angle of incidence).....	18
5.2.5 Drift in the radiometer responsivity.....	18
5.2.6 Ambient temperature/relative humidity fluctuations.....	18
<b>6. REPORTING OF RESULTS .....</b>	<b>18</b>
<b>7. COMPARISON ANALYSIS .....</b>	<b>19</b>
<b>8. ACKNOWLEDGEMENTS .....</b>	<b>19</b>
<b>9. REFERENCES .....</b>	<b>19</b>
<b>APPENDIX A: REPORTING OF MEASUREMENT RESULTS .....</b>	<b>20</b>
<b>APPENDIX B: DESCRIPTION OF RADIOMETER AND ROUTE OF TRACEABILITY.....</b>	<b>22</b>
<b>APPENDIX C: UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH LST</b>	
<b>MEASUREMENTS ON THE NPL CAMPUS .....</b>	<b>23</b>
<b>APPENDIX D: DATA RECEIPT CONFIRMATION .....</b>	<b>24</b>



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<b>Name</b>	<b>Role in Project</b>	<b>Signature</b>	<b>Date (dd/mm/yyyy)</b>
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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
FoV	Field of View
IR	Infra-Red
KIT	Karlsruhe Institute of Meteorology
LST	Land Surface Temperature
NMI	National Metrology Institute
NPL	National Physical Laboratory
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 Land Surface Temperature comparisons of the participants' radiometers during the 2016 comparison activities to be held on NPL campus. Note 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 the 2016 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"*.

This 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 blackbodies and radiometers

The purpose of this document is to describe the protocol which is proposed for the Land Surface Temperature comparisons of the participants' radiometers during the 2016 comparison activities.

### 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

**Table 1. Contact Details of Participants**

Contact person	Short version	Institute	Contact details
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Frank Goettsche	KIT	Institute for Meteorology and Climate Research (IMK-AF), Kaiserstr. 12, 76131, Karlsruhe, Germany	email: frank.goettsche@kit.edu; +49 721 608-23821
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



Contact person	Short version	Institute	Contact details
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Raquel Niclos			email.: Raquel.Niclos@uv.es
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### 3.4 OVERVIEW OF THE FORM OF COMPARISONS

This protocol covers the comparison of the responsivity of the radiometers of participants, when the radiometers are observing a common entity. In the case of the LST comparison activity at NPL, the radiometers will be located on the grounds of the NPL campus and will be measuring the surface temperature of different land targets.

### 3.5 COMPARISON OVERVIEW

The land surface temperature calibration comparison exercise ideally 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. It may for logistical reasons (number of instruments) 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 are currently being considered to be measured by the radiometers during the 2016 comparison:

- i. Short green grass.
- ii. Short dry grass.
- iii. Sand or gravel with different SiO<sub>2</sub> content and grain sizes.
- iv. Dark soil
- v. Tarmac

Some of these samples, such as the short green grass, will be available in a natural form so there is no restriction on the target area. However, other samples such as sand or gravel are not available in a natural form on the NPL campus so these samples will be assembled in large area, open containers. The aim will be that the minimum area of these containers is larger than 1 m by 1 m. This introduces some restrictions to the distance of the radiometers from the target. For example, the Apogee radiometer responds over a 40° full view angle, so when it is viewing the target at a view angle (from Nadir) of 25° from a height of 1 m, it will view an elliptical area of the target of 0.73 m long axis and a 0.643 m short axis. This means that an Apogee radiometer should be ideally mounted at a height of 0.8 m above the target surface so that its full view angle covers an area much smaller than the area of the target and ensures that the area of the proposed target well overfills the Field of View (FoV) of this radiometer. On the other hand, a Heitronics KT15.85 IIP radiometer has an 8.5° full view angle, so when it is viewing the target at a view angle of 25° (same angle as the Apogee radiometer), from a height of 1 m, it will view an elliptical area of the target with a long axis of only 0.181 m and the short axis of 0.164 m). This means that a Heitronics KT15.85 IIP radiometer should ideally be mounted on a higher mount in order to ensure that it views a similar area of the target to the Apogee radiometer. Mounting the Heitronics KT15.85 IIP radiometer at a height of 4 m from the target will actually allow the KT15.85 IIP radiometer to view an elliptical area of the target of 0.725 m long axis and 0.656 m short axis. These dimensions are similar to those of the area being viewed by the Apogee radiometers mounted at a height of 0.8 m.

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 from emissivity spectral of targets, literature values or from dedicated measurements using the emissivity box method. This, in combination with the measurement of the radiance emitted by the surface of the target and the down-welling radiance of the sky, should allow the participants to calculate the LST of the targets, at different times. Note that the value of the target emissivity, along with the associated uncertainty used in the calculation of each LST given by each participant should be shown in the Table in Appendix A.

During the comparison, the bulk temperature of the targets (near the surface) will be measured using contact thermometers in order to compare these values with the LST measurements made by the participants.

Measurements will be performed during both daytime and night-time conditions.

### 3.6 TIMETABLE

There are three main phases to the 2016 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**

<b>PHASE 1: PREPARATION</b>	
Invitation to participate	October 2015
Preparation and formal agreement of protocol	Jan - March 2016
<b>PHASE 2: MEASUREMENTS</b>	
Participants measure primary blackbody	June 2016
Comparison of participants' blackbodies	June 2016
Participants send all data and reports to pilot	July 2016 (during comparison)
<b>PHASE 3: ANALYSIS AND REPORT WRITING</b>	
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 20<sup>th</sup> 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 27<sup>th</sup> June 2016 has been allocated to field measurement of the Water Surface Temperature 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. These will be done at a site on the NPL campus. The plan is to start the LST measurements on Monday 4<sup>th</sup> July 2016. The LST measurements are expected to finish on Friday 8<sup>th</sup> July.

This protocol deals with the LST comparison activities which are due to take place during the third week of the comparison, starting on Monday 4<sup>th</sup> July 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 D.

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 adaptor.

### 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 field 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 radiometers 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  $\mu\text{m}$  and 8 to 12  $\mu\text{m}$ . 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 FOR LST COMPARISON

### 4.4.1 Day-time LST measurements

- 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 shown in Appendix B.
- 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 should 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  $25^\circ$  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.
- 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 time of each observation should be clearly indicated.

- Measurements can be repeated for different wavelengths.
- The host will collect measurements of meteorological data such as air temperature, relative humidity and wind speed during the measurement period and make these available to the participants.
- The bulk temperature of the targets (near the surface) will be measured using contact thermometers in order to compare these values with the LST measurements made by the participants. This will not be made available to participants until the publication of the final report.
- Participants will be encouraged to measure the LST of the samples for small view angles, preferably smaller than  $30^\circ$  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  $40^\circ$ ), it is recommended that the measurements are completed while the radiometers view the target at an angle of  $25^\circ$  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.
- 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 given in Appendix A, which will also be available electronically.

#### 4.4.2 Night-time LST measurements

- The same procedure can be used to acquire measurements during night-time.
- It should be noted that the radiometers cannot be left unattended during night time. However, night time measurements can be made under attended operation of the radiometers.

### 4.5 DECLARATION OF COMPARISON COMPLETION

The above process should ideally be considered as a single comparison and the results analysed. 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 determined 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 of that “day-night” will remain blind except to the pilot.

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 unless they can be shown to be an error of the pilot.





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.

## 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 in Appendix C. The participating laboratories should complete this table 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 that the table shown in Appendix C 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 and evaluated as part of the laboratory comparison. Any corrections due to potential biases from this exercise will be evaluated in the final report. 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>.

### 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' radiometers. 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 should be attached.

### **5.2.2 Wavelength**

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

### **5.2.3 Land target emissivity**

This uncertainty contribution arises due to the uncertainty in the knowledge of the emissivity of the target at the appropriate wavelength.

### **5.2.4 Angle of view to nadir (angle of incidence)**

The emissivity of some targets may decrease as the angle of incidence increases, hence any uncertainty in the angle of incidence could manifest as an uncertainty in the emissivity of the land/target.

### **5.2.5 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.

### **5.2.6 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 the acquisition of measurements, 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 LST comparison (see Appendix A for the Template for reporting the results of the radiometer LST field 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 D. 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.

## 8. ACKNOWLEDGEMENTS

The authors wish to thank Dr. Frank-M. Goettsche of KIT for many useful discussions.

## 9. REFERENCES

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2. Rice, J. P., Butler, J. I., Johnson, B. C., Minnett, P. J., Maillet K. A., Nightingale, T. J, Hook, S. J., Abtahi, A., Donlon, and. Barton, I. J., 2004, "The Miami 2001 infrared radiometer calibration and intercomparison. Part I: Laboratory characterisation of blackbody targets", *Journal of Atmospheric and Oceanic Technology*, **21**, 258-267.
3. Theocharous, E., Usadi, E. and Fox, N. P., "CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part I: Laboratory and ocean surface temperature comparison of radiation thermometers", NPL REPORT OP3, July 2010.
4. Theocharous E. and Fox N. P., "CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part II: Laboratory comparison of the brightness temperature comparison of blackbodies", NPL Report COM OP4, August 2010.

## APPENDIX A: REPORTING OF MEASUREMENT RESULTS

The attached measurement summary should be completed by each participant for each completed set of LST field measurements at NPL. A complete set being one, which may include multiple measurements using the same instrument but does not include any realignment of the instrument. For each realignment a separate measurement sheet should be completed. A separate measurement sheet should also be completed if a different view angle from nadir, or a different wavelength or bandwidth is used by the same radiometer.

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

<b>Time</b>	The time of the measurements should be UTC.
<b>Measured Land Surface Temperature</b>	Brightness temperature measured or predicted by participant.
<b>Measurement uncertainty</b>	Combined/total uncertainty of the measurement.
<b>Measured Sky Temperature</b>	Brightness sky temperature measured or predicted by participant.
<b>Uncertainty</b>	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 $k=1$ .
<b>Wavelength</b>	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.
<b>Bandwidth</b>	This is the spectral bandwidth of the instrument used for the comparison, defined as the Full Width at Half the Maximum.
<b>Standard Deviation</b>	The standard deviation of the number of measurements made to obtain the assigned brightness temperature without realignment
<b>Number of Runs</b>	The number of independent measurements made to obtain the specified standard deviation.
<b>View angle from Nadir</b>	The angle of view of the radiometer to the surface of the target from Nadir.



### LST Measurement Results on the at NPL site

Instrument Type ..... Identification Number ..... Ambient temperature .....

Date of measurement: ..... View angle from nadir (degrees).....

Wavelength ( $\mu\text{m}$ ) ..... Bandwidth ( $\mu\text{m}$ ) .....

Time (UTC)	Measured LST K	Combined LST Uncertaint. K	Measured sky temperat. K	Uncert. in sky temper. K	Uncertainty		No. of Runs	Target emissivity used	Uncert. in emissiv.
					A	% B			

Participant: .....

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



## APPENDIX B: 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: .....

Participant: .....

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



**APPENDIX C: UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH LST MEASUREMENTS ON THE NPL CAMPUS**

The table shown below is a suggested layout for the presentation of uncertainties for the measurement of the LST on the NPL campus. 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.

<b>Uncertainty Contribution due to</b>	<b>Type A Uncertainty in Value / %</b>	<b>Type B Uncertainty in Value / (appropriate units)</b>	<b>Uncertainty in Brightness temperature K</b>
<b>Repeatability of measurement</b>	$U_{Repeat}$		$U_{Repeat}$
<b>Reproducibility of measurement</b>	$U_{Repro}$		$U_{Repro}$
<b>Primary calibration</b>		$U_{Prim}$	$U_{Prim}$
<b>Land target emissivity</b>		$U_{emiss}$	$U_{emiss}$
<b>Angle of view to nadir</b>		$U_{angle}$	$U_{angle}$
<b>Linearity of radiometer</b>		$U_{Lin}$	$U_{Lin}$
<b>Drift since last calibration</b>		$U_{Drift}$	$U_{Drift}$
<b>Ambient temperature fluctuations</b>		$U_{amb}$	$U_{amb}$
<b>Atmospheric absorption/emission</b>		$U_{atm}$	$U_{atm}$
<b>RMS total</b>	$((U_{repeat})^2+(U_{Repro})^2)^{1/2}$		



## APPENDIX D: DATA RECEIPT CONFIRMATION

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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-