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

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ACRONYMS AND ABBREVIATIONS

AMBER	Absolute Measurements of Black-body Emitted Radiance
ASL	Above Sea Level
CEOS	Committee on Earth Observation Satellites
CDR	Climate Data Record
DMI	Danish Meteorological Institute
FICE	Field Inter-comparison Experiment
FOV	Field of View
GTRC	Gobabeb Training and Research Centre
IR	Infra-Red
ISO	International Organization for Standardization
IST	Ice Surface Temperature
KIT	Karlsruhe Institute of Meteorology
LSE	Land Surface Emissivity
LST	Land Surface Temperature
MET	Ministry of Environment and Tourism
NIST	National Institute of Standards and Technology (USA)
NMI	National Metrology Institute
NPL	National Physical Laboratory
PTB	Physikalisch Technische Bundesanstalt
QA4EO	Quality Assurance for Earth Observation
SST	Sea Surface Temperature
SI	Système Internationale
WGCV	Working Group for Calibration and Validation
WST	Water Surface Temperature

AN INTRODUCTION TO SEA, WATER, LAND AND ICE SURFACE TEMPERATURE MEASUREMENTS

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1.1 OVERVIEW

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.

Field deployed IR radiometers are currently being used to validate the measurements made by satellite-borne radiometers. These field deployed radiometers 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". Such measurements are now being assigned the term 'Fiducial Reference Measurements' to distinguish them from more routine in-situ and similar measurements where the full rigour of traceability and documentation is not necessarily required.

The "IR surface temperature Cal/Val community" particularly those making sea surface temperature measurements is well versed in the need and value of such rigour and the value of comparisons to assess compliance with declared uncertainties, having held highly successful exercises in Miami and at NPL in 2001 [Barton 2004, Rice 2004] and 2009 [Theocharous a, b]. This document provides an overview of the instrumentation used to make such measurements in the field together with that used to establish and maintain its performance when used in the field, including any laboratory pre-calibration activities, so that experiments can be devised to validate this and establish the degree of consistency worldwide.

This document should be seen as an overview, with more detailed references defining specific details. It spans the requirements of all domains Sea, Land and Ice and is structured in chapters to guide the reader through generic calibration/validation aspects through to domain specific issues. Starting in Chapter 2, SST, which as the most mature of the measurement domains where the key principles are discussed. The specific issues related to Land (greater temperature range, impact of emissivity variation) are then explored in Chapter 3. In Chapter 4, the relatively immature, Ice, domain is then described, here the principle issue from a calibration perspective is the extreme of temperatures for any reference standard and the operating environment. Chapter 5 provides an introduction to uncertainty assessment, sources of uncertainty, how to assess, how to combine. The culmination of this document is a set of protocols for a series of comparison experiments designed to validate the uncertainties assigned to the instrumentation and their usage under both ideal (laboratory) conditions and simulated operating conditions, which are provided as appendices.

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.

Further exercises are needed to evaluate performance under truly real operational conditions such as in Ice and desert conditions and these are the subject of further reports (Olesen et al., 2016) and will follow similar protocols.

1.2 INTRODUCTION

Radiometers are defined as instruments which are designed to measure one or more of the radiometric quantities or parameters used to quantify the characteristics of a source or beam or field of optical radiation. A number of instruments such as SISTeR (Barton et al. 2004), ISAR (Donlon et al., 2008) and MAERI (Minnett et al. 2001) have been developed to measure Sea Surface Temperature (SST) as part of satellite calibration and validation activities. The aim of these instruments is to measure the sea surface temperature (SST) and thus validate measurements of the same parameter (SST) measured by satellite-based instruments such as the ATSR+ series, MODIS etc. Other instruments are used to measure Land Surface Temperature (LST) and Ice Surface Temperature (IST). It should be noted that since the output of all these instruments is in units of temperature (^{o}C or K), they should really be called "radiation thermometers".

Radiation thermometers vary in design and construction. Radiation thermometers measuring SST, LST and IST have to operate in the infrared (normally in the 8 µm to 12 µm wavelength range) where there is an atmospheric transmission window and, more importantly, the spectral radiance of blackbodies operating at near ambient temperatures has a maximum (see Figure 1, which shows the spectral radiance of a perfect blackbody (i.e. emissivity = 1) whose cavity temperature is at 20 ^{o}C). Temperature measurements based on the 3 µm to 5 µm wavelength range are also possible but they are much more challenging and are best avoided for two main reasons:

i. The spectral radiance of near ambient temperature blackbodies in the 3 µm to 5 µm wavelength range is much lower than in the 8 µm to 12 µm wavelength range (see Figure 1), resulting in a lower signal and therefore measurements with poorer signal to noise ratio.
ii. Solar radiation levels are much higher in the 3 µm to 5 µm wavelength range (the sun can be considered a blackbody at about 5,500 K) so measurements in the 3 µm to 5 µm wavelength range are much more prone to solar radiation/sun reflection, resulting in their best performance being limited to night time observations.

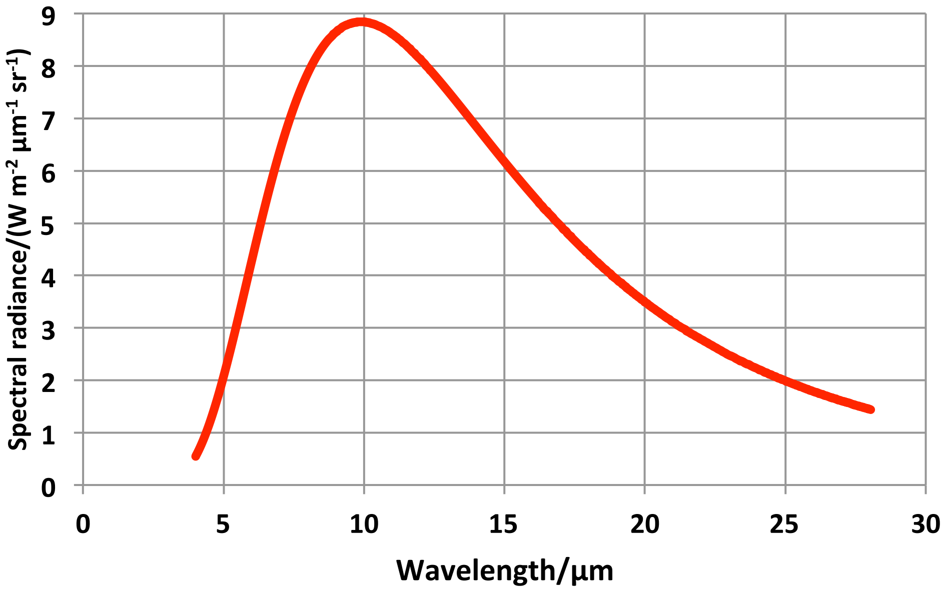

Figure 1: Spectral radiance of an ideal (emissivity = 1) blackbody whose cavity temperature is at 20 ^{o}C

A radiation thermometer or "radiometer" requires a minimum of:

i. means of defining the solid angle over which the radiometer accepts radiation,
ii. a bandpass filter which defines the range of wavelengths over which the radiometer responds
iii. a photodetector which converts the optical power incident on the detector into an electrical signal
iv. electronics to condition the output of the photodetector.

A number of different radiometers are used for SST, WST, LST and IST measurements. Some have the four basic components highlighted above. This means that they are low cost, have small size and have low electrical power requirements. These radiometers utilise a thermal detector (usually a thermopile) because thermal detectors are cheap to buy and can operate at ambient temperatures. Unfortunately thermal detectors have relatively poor Noise Equivalent Power (NEP) so by using a bandpass filter with a broad bandwidth (8 μm to 14 μm), the power which is available for detection is increased. The use of a broad bandwidth has its drawbacks, the main one being the inclusion of atmospheric absorption bands within the detection bandwidth. Furthermore, thermopiles have slow temporal response so that these radiometers are used in a DC mode which implies that the effect of "clutter"[1] is difficult to eliminate. The best way of minimising these effects is to frequently calibrate the radiometer by directing its FoV into the cavity of a large external reference blackbody immediately before and immediately after the SST, LST and IST measurements. Although frequent recalibration can reduce the effects of drifts, there is no way of predicting the behaviour of these simple radiometers during the period between the calibrations.

The performance of these simple radiometers can be improved by using a pyroelectric detector, instead of the thermopile detector. However, the pyroelectric detector responds to changing (alternating) signals so a mechanical chopper is used to modulate the incident radiation which is detected by the pyroelectric detector. The blades of the chopper are made reflective so that when they block the scene, the reflection by the chopper blades can allow the detector to view the output of a small blackbody contained within the housing and is part of the radiometer. This means that the radiometer compares the radiance of the scene with that of the blackbody reflected by the chopper blades. These pyroelectric radiometers offer superior performance to radiometers based on thermopiles but they are more expensive and can be slightly bulkier and more power hungry. However, their performance is superior to the radiometers which are based on thermopile detectors because their output is much more stable.

Unfortunately the performance, and in particular the stability, of photodetectors responding in the infrared is far inferior to that of photodetectors developed for the UV, visible and NIR spectral regions (Theocharous and Birch, 2002). For this reason, the minimum design of a SST-measuring radiation thermometer should include at least one internal reference blackbody to ensure that any drifts in the responsivity of the infrared photodetectors and the other components utilised by the SST-measuring radiation thermometers can be accounted for. This means that in practice these radiometers compare the spectral radiance of the observed scene (i.e. the surface of the sea/land/ice) with that of the internal reference blackbody which is maintained at a temperature similar to that of the target being measured. The stability of the spectral radiance of ambient temperature blackbodies is much more stable than the responsivity of infrared detectors so the use of internal blackbodies provides a good method of minimising the effect of some of the problems associated with infrared radiometers such as drift in their detector responsivity (Theocharous, 2006), ageing, non-linear response (Theocharous, 2004), effect due to variations in the thermal background (Theocharous and Theocharous 2006) and the

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[1] The signal from the photodetector of an optical instrument such as a radiometer consist (apart from the electrical noise) of a components which is due to the radiation arising from the target being monitored, as well as components due to radiation from (say) the room lights, which would have missed the photodetector but which has been reflected or scattered by optical components or the medium through which the radiation propagates, so it reaches the photodetector. The latter contribution is referred to as "clutter". Note that clutter is not "noise" (it cannot be minimised by averaging) but it is unwanted signal which may have originated from the room lights or from the target itself and it was directed into the instrument by reflection from the bench of the walls of the lab.

definition of "radiometric zero"[2] (Theocharous et al., 1998). Furthermore, some radiometers use more than one internal blackbody so a reflective chopper is no longer enough. The most advanced radiometers developed to-date use an internal mirror which, by rotating, allows the Field of View (FoV) of the radiometer to be sequentially directed to the scene as well as the internal blackbodies. It is relatively easy to extend this arrangement to allow the radiometer to also view the radiance of the sky in the direction from which radiation reflected from the sea surface enters the radiometer FoV. This is an important measurement since the emissivity of sea water, land and ice in the infrared is not unity. The emissivity of sea water, in fact, progressively decreases as the angle of incidence increases (Masuda, 2006). Monitoring the sky radiance, therefore, provides further advantages to this type of radiometer.

When radiometers are used in the field to measure SST, LST or IST, radiometers incorporating the internal blackbodies can be used unattended, since they can be programed to sequentially view the target (sea, land or ice surface), the sky radiance and the internal blackbodies. Simple radiometers based on thermopile or pyroelectric detectors cannot do that because they can only measure in one direction. Some workers have used two simple radiometers, one pointing at the sky while the second is looking at the surface of the sea (Jessup, 2002). While this arrangement provides a measurement of the sky spectral radiance at the same time and could potentially correct for the non-unity emissivity of the target surface, it cannot monitor the radiance of any internal blackbodies so its long term stability will never be as good as instruments which include internal blackbodies and can view the target surface, sky and the internal blackbodies sequentially. A neat development was the use of the commercially available simple radiometers into larger instruments which include one or more internal blackbodies and can view the target (e.g. sea surface), the sky, and the internal blackbodies sequentially. This type of instrument is far more expensive and far bulkier than a simple radiometer but it can provide the advantages of using the internal blackbodies and the measurement of the sky spectral radiance using a single "detector". This type of radiometer includes the ISAR which uses a commercially-available Heitronics radiometer which, itself, is based on a pyroelectric detector.

However, the use of an internal reference blackbody still leaves a number of issues which have to be addressed if these radiation thermometers are to be used for the acquisition/validation of Climate Data Records (CDR)s. Amongst other things, measurements provided by these radiometers have to be traceable to SI units and the uncertainties associated with these reference blackbodies have to be quantified and used as a component uncertainty in the uncertainty budget which is used to estimate the combined uncertainty of the final SST measurements acquired using these instruments.

There are two different approaches which can potentially be used to enable such a radiation thermometer to provide SI-traceable measurements; i) by calibrating the radiance temperature of the internal blackbodies contained within the radiometer and ii) by using an external, traceably calibrated blackbody.

1.3 USING THE INTERNAL BLACKBODIES CONTAINED WITHIN THE SST-MEASURING RADIATION THERMOMETER.

The first approach involves the traceable calibration of the radiance temperature of the internal blackbodies contained within the SST-measuring radiation thermometer. This requires that the thermometers used to measure the temperature of the internal blackbodies of the SST-measuring radiation thermometer are traceably calibrated to SI units. It is important to note that this condition on its own, is not sufficient. The internal blackbodies must also be fully characterised with respect to parameters that may affect their use in the particular application. Parameters such as their cavity

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[2] . In spectroradiometry, it is important to be able to identify the component of the signal which arises from sources other than the target. In the visible part of the spectrum, this is done by the addition of a shutter. In the infrared, this signal referred to as the "radiometric zero" can be measured by having a source (or a shutter) at a temperature near the absolute zero, or at least low enough so it does not contribute to the output of the instrument. The "radiometric zero" should be subtracted from all subsequent measurements to remove the contribution of sources other than the target.

emissivity and any temperature difference between the reading of the thermometers and the true temperature of the emitting surface of the blackbody cavity must also be known. The former requires that of the emissivity of the blackbody cavity coating over the range of wavelengths over which the radiation thermometer responds be known, along with the corresponding uncertainty. It also requires the emissivity of the blackbody is calculated, ideally using a Monde Carlo based method. For this calculation, the exact geometry of the blackbody cavity, along with the size of the blackbody aperture must also be known. Any temperature differences must also be determined and these will be governed by the position and means of attachment of the thermometers relative to the blackbody cavity, the cavity geometry, the material out of which the cavity is made, the cooling or heating of the cavity surface due to radiative and convective cooling/heating, temperature uniformity over the surface of the cavity etc.

The internal blackbodies are restricted in size and therefore in the size of their exit apertures, so a Size of Source (SoS) correction (Pusnik et al., 2006) will also be required, along with the associated uncertainty contribution. Full evaluation of all these parameters can be difficult but SI traceability will require that the magnitudes of all these effects to be estimated and any appropriate corrections and uncertainties applied.

1.4 USING OF AN EXTERNAL TRACEABLY-CALIBRATED BLACKBODY.

The second approach requires the traceable calibration of the radiance temperature of an external blackbody which can subsequently be used to calibrate the Sea, Land Ice surface temperature-measuring radiation thermometer. This is considered a much better approach because it involves the calibration of a blackbody whose physical size is not restricted by the external dimensions of the radiation thermometer housing and portability. This means that the external blackbody can be physically larger and can therefore be designed to have a higher emissivity than the internal blackbodies. Moreover, the performance of the external blackbody can be re-calibrated/checked far more frequently than that of the internal blackbodies. Figure 2 shows the Southampton University ISAR and the SISTeR radiometer viewing two water-bath blackbodies during the 2009 CEOS comparison (Theocharous et al., 2010).

Figure 2: Two radiometers viewing two water-bath blackbodies during the 2009 comparison.

The radiance temperature of the external blackbody can be calibrated in two ways. The first involves the calibration of the external blackbody against a reference standard blackbody, which may either be one used by NMIs, or one with formal traceability to an NMI blackbody. The external blackbody then becomes a transfer standard blackbody, and a certificate will be issued when it is calibrated against the reference standard blackbody stating its radiance temperature at various settings. The certificate will also include the combined uncertainty values associated with the radiance temperature of the transfer standard blackbody at the various temperature settings. The combined uncertainty values shown on the calibration certificate are calculated by the institute which would carry out the calibration of the transfer standard blackbody (usually an NMI or accredited organisation), so can be considered sufficient evidence of traceability.

The second method of calibrating the radiance temperature of the external blackbody would be similar to that used for the calibration of the radiance temperature of the internal blackbodies (see section 3.1), i.e. it would require:

α. The traceable calibration of the thermometers used to measure the temperature of the external blackbody.

β. The calculation of the temperature difference between the reading of the thermometers and the true temperature of the surface of the blackbody cavity. This is governed by the position of the thermometers relative to the inside of the blackbody cavity, the blackbody cavity geometry, the material out of which the blackbody cavity is made of, the cooling/heating of the cavity surface due to radiative and convective cooling/heating, how uniform is the temperature over the surface of the cavity, etc.

γ. Knowledge of the emissivity of the blackbody cavity coating over the range of wavelengths over which the radiation thermometer responds so that the cavity emissivity can be calculated (using Monte Carlo methods).

For the purposes of the traceable measurement of SST using radiation thermometers such as SISTER (Barton et al. 2004), ISAR (Donlon et al., 2008) or MAERI (Minnett et al. 2001), the authors recommend that the traceability chain is via an external transfer standard blackbody which is itself calibrated by an NMI against a reference standard blackbody or, of course, directly against the NMI reference standard. This calibration chain would require the following minimum calibration steps:

i. Calibration of the radiance temperature (related to spectral radiance via Planck's equation) of an external transfer standard blackbody against SI units (e.g. an NMI owned reference standard blackbody). The calibrated transfer standard blackbody will then be used to calibrate the SST, LST or IST-measuring radiation thermometer (see next step);
ii. Calibration of the SST/LST/IST-measuring radiation thermometer against the calibrated transfer standard blackbody (which was calibrated under step (i));
iii. Measurement of the target surface temperature using the calibrated radiation thermometer (calibrated under step (ii));
iv. Comparison with one or more (ideally at least three for statistical purposes) independently calibrated radiation thermometers whilst viewing a common target.

Step (iv) is not strictly a requirement as a calibration step in a minimal traceability chain to make a single point measurement of SST. However, it is highly valuable and recommended to establish the evidence needed to be demonstrated that the user of the instrumentation follows an appropriate and consistent procedure when taking measurements. This step is considered fundamental by NMIs as it is the only true way to evaluate that an uncertainty budget is complete and reliable. Consistency (within their combined uncertainties) between two independent measurements of the same parameter can be considered clear evidence and justification for a declared uncertainty, whereas deviations are an indication that there is something wrong with one or both measurements.

QA4EO recommends that an uncertainty budget should be developed for each of the steps in the traceability chain. Note that if the calibration chain incorporated more steps, then each of these additional steps must also have its own uncertainty budget. Furthermore the combined uncertainty derived from the uncertainty budget for step (i) will be a component uncertainty in the uncertainty budget for step (ii). Finally, the combined uncertainty derived from the uncertainty budget for step (ii) will be a component uncertainty in the uncertainty budget for step (iii) and this will then be in the combined uncertainty of the calibration. Note that the uncertainty budget for each of the calibration steps may be better broken down into smaller steps (and consequent uncertainty budgets) depending on how the actual measurements are conducted.

1.5 VALIDATION

The purpose of the validation of a radiometer is not its calibration but to confirm that its calibration (derived from either the calibration of the internal blackbodies or using an external reference blackbody) is valid. The validation process should be conducted in a laboratory environment under controlled conditions and requires the field radiometer to measure the radiance temperature of a blackbody of known emissivity at a known temperature. The temperature of this blackbody should be selectable and the uncertainty associated with this blackbody should be smaller or equal to that required of the measuring radiation thermometer. If the measurement provided by the radiometer is within the combined uncertainty of the blackbody and radiometer, then the validation process can be considered successful. If, on the other hand, the difference is greater than the combined uncertainty then the validation process can be considered unsuccessful and the procedure should be reconsidered. Figure 3 shows radiometers viewing the SST at the Miami University peer during the 2009 comparison. Figure 4 shows plots of the SST measured by the four continuously reading radiometers during the 2009 comparison at the University of Miami (Theocharous et al., 2010).

Figure 3: Radiometers viewing the SST at the University Miami peer during the 2009 comparison.

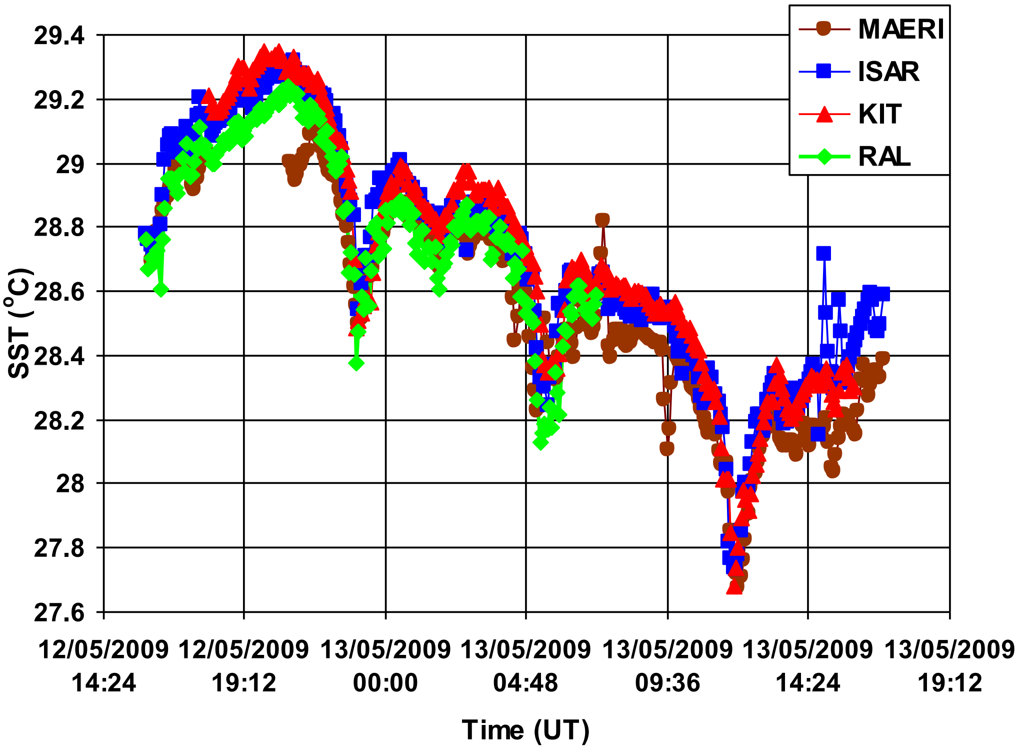

Figure 4: SST measured by the four continuously reading radiometers during the 2009 comparison at the University of Miami.

1.6 EXAMPLES OF UNCERTAINTY BUDGETS FOR SST MEASUREMENTS

The radiance temperature of a test blackbody is defined as the temperature at which the cavity of a perfect blackbody (i.e. a blackbody with a cavity emissivity equal to 1.000) would have to be maintained so that its spectral radiance would be equal to the spectral radiance of the test blackbody. Since the emissivity of the test blackbody is a function of wavelength, the radiance temperature of the test blackbody will also be a function of wavelength so the operating wavelength must be quoted when specifying the radiance temperature of the test blackbody.

The most common SI reference standard for the calibration of the radiance temperature of a transfer standard blackbody is a reference blackbody. The reference blackbody should ideally be the radiance temperature standard of a National Measurement Institute (NMI) such as NPL, NIST, PTB etc. but can be that of an organisation which can demonstrate robust traceability to an NMI. The radiance temperature of the reference blackbody is calculated by measuring its cavity temperature as well as the emissivity of its cavity at the operating wavelengths. International equivalence and thus validation of NMI primary SI scales such as radiance temperature are confirmed by regular formal comparisons with other NMIs (Gutschwager et al., 2012) as part of the Mutual Recognition Arrangement (BIPM MRA 1995). Traceability of the radiance temperature of the reference blackbody to SI units requires that the emitting surface temperature of the blackbody cavity be known as well as the emissivity of the of the same blackbody cavity at the wavelength of interest.

It is worth mentioning that the temperature of reference blackbodies operating at high temperatures (over 1000 K) can also be calibrated using “Absolute Radiation Thermometers”. In this case the traceability to SI units is derived from radiometric units traceable to the cryogenic radiometer. However, the performance of infrared detectors operating in the 8 µm to 12 µm wavelength range is not currently good enough for the reasons highlighted earlier, to enable this approach to have a sufficiently small uncertainty, so the traceability of the radiance temperature of all ambient temperature reference blackbodies is provided by either a fixed point blackbody or by a blackbody whose cavity temperature is measured using a calibrated contact thermometer. Measuring the temperature of the cavity alone is not sufficient to establish traceability to SI units. The cavity emissivity must also be known. The emissivity of the reference blackbody can be measured by direct cavity absorbance measurements, but is more frequently calculated using Monte-Carlo simulations. The latter approach requires that the emissivity of the material which forms the blackbody cavity be known over the range of wavelengths to which the radiation thermometer responds.

Note that the development of an uncertainty budget is also required in order to estimate the uncertainty with which the radiance temperature of the reference blackbody is known. This uncertainty budget will include a number of uncertainty contributions including:

α) the uncertainty in the calibration of the thermometer which is used to measure the temperature of the cavity of the reference blackbody (this is zero in the case of fixed-point blackbodies such as the gallium fixed-point blackbody);

β) the uncertainty in the knowledge of the emissivity of the cavity of the reference blackbody;

γ) the uncertainty due to the temperature drop between the position where the thermometer is located and the inside surface of the blackbody cavity. In blackbodies which operate above ambient temperature, the cavity temperature is always lower than the temperature indicated by the thermometer due to radiative and convective cooling of the cavity. Conversely, in blackbodies which operate below ambient temperature, the cavity temperature is always higher than the temperature indicated by the thermometer due to radiative and convective heating of the cavity;

δ) an uncertainty contribution to account for any ageing/drifts in the reference blackbody radiance temperature.

It is the responsibility of the primary calibration laboratory, ideally an NMI, to quantify these uncertainty contributions and collate them to produce an appropriate uncertainty budget to assign an overall combined uncertainty to the radiance temperature of the reference blackbody.

Note that the calibration of the radiance temperature of the transfer standard blackbody against an SI reference blackbody requires the use of a well characterised radiometer or radiation thermometer. This calibration step will usually be done by an NMI. The radiation thermometer will transfer the calibration from the reference blackbody to the transfer standard (test) blackbody. This calibration should be done at a number of temperatures spanning the range of radiance temperatures over which the transfer standard blackbody will be used. This calibration will also require its own uncertainty budget which will include the uncertainty contribution of the reference blackbody as well as the appropriate uncertainty contributions introduced by the radiation thermometer which is used to provide the transfer to the test blackbody. By using dedicated, well characterised radiometers such as AMBER (Theocharous et al., 1998) or TXR (Rice and Johnson, 1998), the uncertainties introduced by this calibration step can be minimised. However, it should be the responsibility of the calibration laboratory, usually the NMI which will be completing this calibration step, to prepare the appropriate uncertainty budget. The uncertainty budget must include all relevant uncertainty contributions for the calibration of the uncertainty of the radiance temperature of the transfer standard blackbody. Figure 5 shows a row of blackbodies participating in the 2009 comparison having their temperature measured by the AMBER radiometer (Theocharous and Fox 2010).

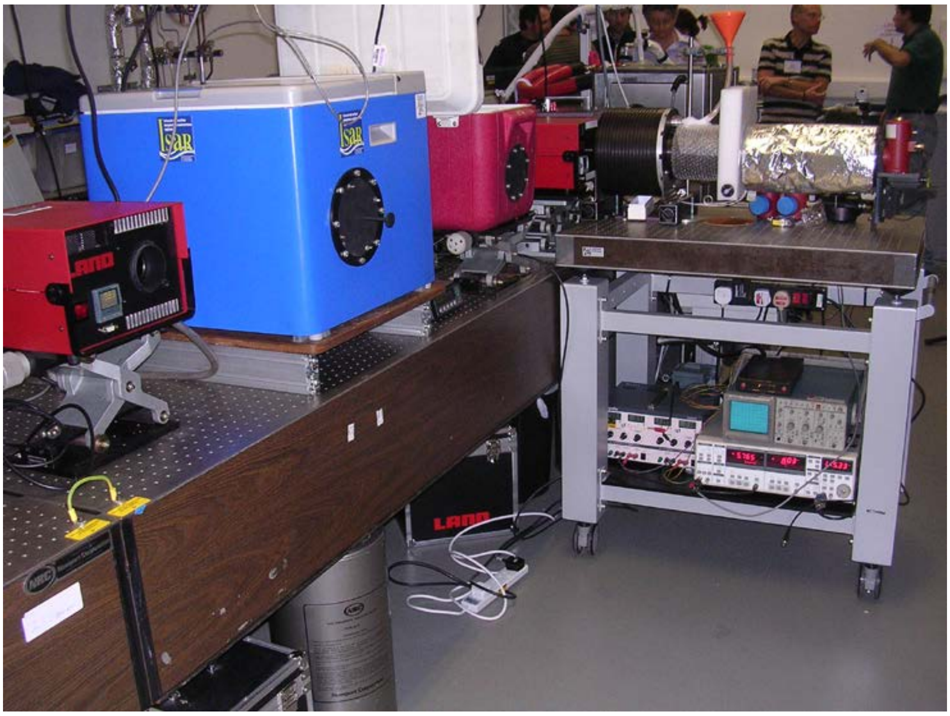

Figure 5: The temperature of blackbodies participating in the 2009 comparison is being measured by the AMBER radiometer.

Chapter 4 gives the uncertainty budget developed by NPL in order to calculate the combined uncertainty of the radiance temperature of a gallium fixed point blackbody which is used as a reference blackbody in radiance temperature calibrations in the -40 ^{o}C to +80 ^{o}C temperature range. The same chapter provides methods for treating uncertainties in SST measurements, as well as guidance on the preparation of uncertainty budgets which satisfy each calibration step.

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METHODOLOGIES FOR ESTABLISHING AND MAINTAINING FRM TIR RADIOMETER CALIBRATION USED FOR SST FIELD CONDITIONS

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2.1 DEFINITION OF MEASUREMENT METHODOLOGY

A number of groups around the world have been measuring SST with TIR radiometers since the 1990s (Jessups, et. al 2002, Minnett et. al, 2001, Donlon et. al 2008). The Protocols used by these groups for the measurements of SST are all similar and have been evaluated against each other at TIR inter-comparisons (Barton, et. al, 2004). However a more formalised version of these protocols was only recently published by Minnett, et. al (2012) and Donlon et. al (2014 & 2014a).

Donlon et. al (2014 & 2014a) define a set of 9 protocols intended to guide any group collecting ship borne infrared radiometer data for use in satellite SST validation activities towards a "common sense" best practice that will improve the quality and reduce the uncertainty in the satellite SST validation process. Each individual deployment of a ship-borne radiometer is highly specific and the protocols summarised below are considered as a minimum requirement for the FRM TIR SBRN.

The exact methodology used to measure SST_{skin} using a ship-borne radiometer shall be fully documented. This shall include:

- A full technical description of the radiometer instrument (e.g. spectral characteristics, sampling characteristics, measurement technique, a description of the instrument internal calibration approach etc.).
- The spectral characteristics of the measurement system (i.e. instrument band-pass).
- The value used for seawater emissivity.
- How the component of "sky radiance" reflected at the sea surface into the radiometer field of view is properly addressed (Donlon and Nightingale, 2000).
- A description of the radiometer mounting arrangements and the geometric configuration of the radiometer with all measurement angles accurately documented.
- A description of steps taken to ensure that measurements are free of ship effects (e.g. ship's bow wave, significant emission from the ship superstructure, emissions from ship exhaust plumes etc.).
- On-board instrument software used (e.g., version, release date, etc.).
- Data post processing software (e.g., version, release date, etc.).
- Any other aspect considered relevant to better understanding the quality of the measurements obtained.

2.2 DEFINITION OF LABORATORY CALIBRATION AND VERIFICATION METHODOLOGY AND PROCEDURES

Infrared radiometers typically used for satellite validation work are calibrated using on-board calibration reference radiance sources (blackbodies). The purpose of performing pre-and post-deployment verification using external reference blackbodies is to assess the accuracy of the internal calibration system, and to provide a link in an unbroken chain of comparisons linking the shipborne radiometer to an SI reference. The exact methodology and procedures used to perform a laboratory calibration and verification of a radiometer shall be defined and documented (Theocharous and Fox, 2010; Theocharous et. al., 2010)

2.3 PRE- AND POST-DEPLOYMENT CALIBRATION VERIFICATION

Following the defined methodology and procedures similar to those set out in the LCE protocol in Appendix A, the calibration performance of a shipborne radiometer used for satellite product validation shall be verified prior to deployment using an external reference radiance source that is traceable to SI standards over the full range of sea surface temperatures expected for a deployment at sea. Ideally, the verification measurements should be repeated over a range of ambient temperatures to assess the influence of stray radiation on the radiometer measurements. The radiometer hardware, on-board configuration, on-board processing software, and data post processing software shall not be modified in any physical way between the calibration and the sea deployment (with the exception of dismounting and transporting the instrument to the calibration laboratory).

Following the defined methodology and procedures set out under Protocols 2 and 3, the calibration performance of a shipborne radiometer used for satellite product validation shall be verified after deployment.

2.4 MOUNTING OF RADIOMETERS ON SHIPS AND PLATFORMS

When mounting radiometers on ships or stationary platforms, the following considerations should be given:

i. How much power does the radiometer requires and can this be provided by the platform?
ii. Does the radiometer requires a dedicated data logging system and does the logging system need be close to the instrument?
iii. The radiometer should be mounted in such a way that the sea view is clear of the bow wave and the sky view is clear of any obstructions. This normally means a mounting position as far forward on the ship as practical.
iv. The radiometer should be mounted at as high a position as possible such as a forward instrument mast or a bridge roof, in order to avoid sea spray.
v. Contamination of the measurements by exhaust and other effluents, such as hot air outlets, from the ship should be avoided.
vi. Choose a sea viewing angle by considering the emissivity of the ocean, (which changes with view angle and thus the roll of the ship.
vii. Choose a mounting position which allows the easy removal and re-installation of the radiometer. This will allow the easier removal of the radiometer for re-calibration.
viii. Choose a position which allows the radiometer easy access to the power from the ship.
ix. Try to avoid using specialized wiring as this can add long lead times to the installation.
x. When a radiometer is installed on a cruise ship, it is best to choose a position where passengers do not have access.
xi. For platform installations, the power supply might be difficult to sustain if the platform is powered by solar cells and batteries.
xii. Tidal effects should be considered before installing the instrument in coastal regions.
xiii. Sun angle might have a bigger effect than on ships as the instrument will have the same relative position to the sun every day.

2.5 OTHER CONSIDERATIONS

The GPS time and radiometer position should be recorded. The ship navigation data, e.g. speed, roll, pitch, heading, should be also be recorded and included in the measurements. The emissivity of sea water depends on the viewing angle so the change of ship attitude will influence the observation angle of the radiometer and thus the emissivity value. Wind speed, air temperature, relative/absolute humidity, down-welling shortwave radiation and longwave radiation should be also measured or calculated (Barton et al. 2004). The meteorological data will be used to analyse the temperature variation of the upper ocean layer as well as quality control of the skin temperature measured by the radiometers. The true wind speed is needed in order to calculate its effect on the apparent emissivity. If sub-surface temperature measurements are made, it is important that the depth of the measurement is known. Finally, measurement of the air temperature and humidity are required in order to calculate the fluxes of sensible and latent heat between the ocean and atmosphere.

2.6 IMPROVING TRACEABILITY OF CALIBRATION AND VERIFICATION MEASUREMENTS

Efforts should be made where possible to define community consensus schemes and measurement protocols for calibration and verification. Well-documented data processing schemes and quality assurance criteria shall be established to ensure consistency and traceability to SI standards of in situ radiometer measurements used for satellite validation. Ship-borne radiometer users must participate regularly (e.g. every 2 to 5 years) in inter-comparison 'round-robin" tests and comparison with international standards to establish SI traceability for their data. International radiometer and reference blackbody inter-calibration experiments (Kannenberg, 1998; Rice et al, 2004; Theocharous. and Fox, 2010; Theocharous et. al., 2010) are essential under this protocol and the need for regular activities of this type is obvious (Minnett et. al., 2012). They promote the dissemination of state-of-art knowledge on instrument calibration, measurement methods, data processing, training opportunities and quality assurance.

In preparation for the launch of new satellite instruments and the on-going validation of currently flying satellite instruments, the CEOS community has recognized the need for a fourth FRM infrared radiometer and reference blackbody inter-calibration experiment. The proposed 2016 comparison includes the following components:

i. A laboratory-based comparison of the calibration processes for FRM TIR radiometers
ii. A laboratory-based comparison and verification of blackbody sources which are used to maintain calibration of FRM TIR radiometers and provide traceability to SI.
iii. Initiation of field inter-comparisons using pairs of FRM TIR radiometers to build a database of knowledge over a period of several years.

The benefits of radiometer inter-comparison work includes:

i. The establishment and documentation of protocols and best practice for FRM TIR radiometer and reference blackbody inter-comparisons for future use.
ii. The establishment of community best practices for FRM TIR radiometer deployments.
iii. The evaluation and documentation of differences in IR radiometry primary calibrations and performances under a range of simulated environmental conditions,
iv. The establishment and documentation of formal SI-traceability and uncertainty budgets for participant blackbodies and radiometers.
v. The evaluation and documentation of protocols and best practice to characterise differences between FRM TIR radiometer measurements made in field (land, ocean, ice) operational conditions
vi. These activities should follow QA4EO principles and in particular Guidelines: QA4EO-QAEO-GEN-DQK-004, version 4.0 (Fox and Greening, 2010).

2.7 ACCESSIBILITY TO DOCUMENTATION

Documentation describing ship-borne radiometer calibration and verification process shall be made available to the user community to promote peer review and ensure appropriate promulgation of knowledge on shipborne radiometer calibration and verification.

2.8 ARCHIVING OF DATA

SST, LST and IST measuring radiometer calibration and verification data should be archived following good data stewardship practices providing access to records by research teams on request. Laboratory calibration and verification data shall be published in a format that is freely and openly available to users of the data.

2.9 PERIODIC CONSOLIDATION AND UPDATE OF CALIBRATION AND VERIFICATION PROCEDURES

SST, LST and IST measuring radiometer calibration and verification measurement procedures should be consolidated as a result of a critical review of those currently documented in peer-review literature or already included in compilations produced by former programs and "lessons learned" from deployments aboard ships and in the laboratory. Consolidated protocols should be maintained and published.

2.10 SUMMARY

This chapter lists the required steps needed to measure SST with FRM field TIR Radiometers. The aim was to keep some parts of this list fairly short so a good overview of all the steps can be given. A more detail discussion for each section can be found elsewhere (Donlon et al 2014 & 2014a) and (Minnett et. al. 2012a,) where the latter also discusses the design of FRM field TIR Radiometers.

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METHODOLOGIES FOR MAINTAINING FRM TIR RADIOMETER CALIBRATION UNDER LST FIELD CONDITIONS

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3.1 OBJECTIVES

The purpose of this part of Technical Report 1 (D-80) is to review methodologies to practically maintain and verify calibration of LST FRM field TIR radiometers under field conditions. Furthermore, a protocol for evaluating and documenting differences in FRM TIR radiometer performances is described.
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.

3.2 ESTABLISHING AND MAINTAINING CALIBRATION (LST)

Ideally FRM TIR radiometers should be continuously calibrated to an accuracy of ±0.1 K, which can be achieved by observing a 'cold' and a 'hot' blackbody between the actual measurements ([1], [2], [3]). However, such systems are relatively expensive and difficult to operate under conditions typically encountered during short field campaigns, where instruments have to be mounted to the top of mobile masts to increase their FOV or have to be moved rapidly across the site to 'synthesise' a larger FOV. Therefore, their typical use is in SST determination and in inter-calibration experiments ([1], [4]); however, radiometer systems such as the ISAR [1] could be mounted to a permanent mast. Furthermore, natural land surfaces tend to be heterogeneous on various spatial scales and obtaining representative in-situ LST may require several radiometers; the number of instruments needed depends on the radiometer's FOV and site heterogeneity. Therefore, commercially available and more affordable LST FRM field TIR radiometers are used, which typically achieve accuracies of about ±0.3 K [3] over the relevant temperature range (about -20°C to 65°C).

Accurate LST FRM field TIR radiometers have to have some type of 'internal blackbody' to perform a bias adjustment, e.g. they apply non-linear calibration functions depending on the difference between the instrument's internal temperature (measured with a precision resistance thermometer) and target temperature. Two types of radiance sensors are commonly used for TIR radiometers: pyroelectric sensors (e.g. KT15.85 IIP, Heitronics GmbH, Wiesbaden, Germany; Figure 1) and thermopile detectors (e.g. Apogee SI-111, Apogee Instruments, Inc., Logan, UT, USA; Figure 2). Pyroelectric sensors only respond to radiation differences and, therefore, must use an optical chopper (blades interrupting the incident radiation); main advantages are long-term and high spatial resolution ([4], [5]). The high stability is achieved by linking the radiance measurements via beam-chopping (a differential method) to internal reference temperature measurements [6] and was confirmed by a long-term parallel run with the self-calibrating radiometer "RotRad" from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), which was continuously stabilized with 2 blackbodies [4].

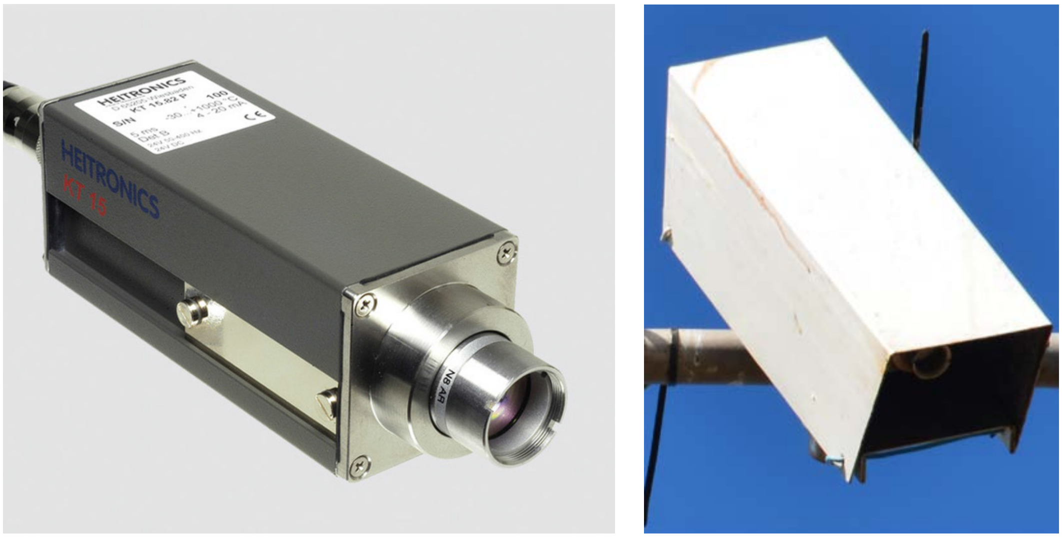

Figure 1 Heitronics Infrarot Messtechnik GmbH 'KT15' series radiometer using a pyroelectric sensor and chopped radiation method (www.heitronics.com). Left: instrument in its housing. Right: inside a sun & rain shield at one of Karlsruhe Institute of Technology permanent validations sites.

Figure 2 Apogee Instruments, Inc., 'SI-111' standard FOV infrared radiometer using a thermopile sensor. Left: with aluminium cylinder as thermal mass. Right: with sun shield. Source: www.apogeeinstruments.co.uk

In order to maintain calibration of LST FRM field TIR radiometers, they should be independently calibrated at regular intervals: this is the usual calibration process against SI traceable reference standards in the laboratory and intervals depend on radiometer type, e.g. Apogee IRR sensors have a long-term drift of less than 2% change in calibration slope per year while the Heitronics KT15.85 IIP drifts by less than 0.12% per year. However, LST is a highly dynamic quantity with diurnal amplitudes of up to 40 K and differences between target and instrument temperature can reach more than 20 K, which has a considerable effect on measurements with un-cooled radiometers [7]. Therefore, LST FRM field TIR radiometers need to be calibrated over the entire range of expected combinations of target and instrument temperatures, where the latter is often close to ambient temperature (for shaded instruments usually air temperature). In practise, calibration exercises that include variable instrument temperatures are not readily performed by users and, therefore, are frequently limited to calibrations performed at the manufacturers (Figure 3).

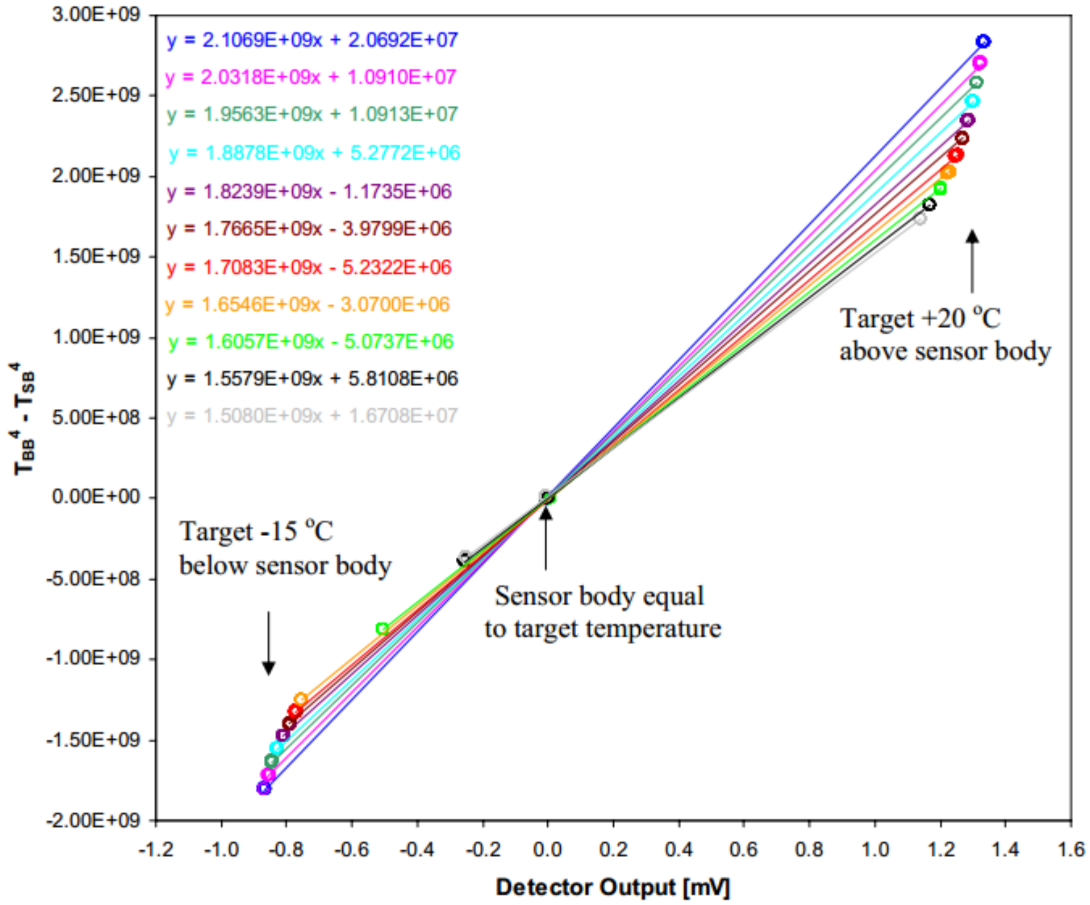

Figure 3 Manufacturer calibration of an Apogee IRR. Each line corresponds to a fit of the data points obtained at sensor body temperature T_{SB} (between 45°C to -5°C at 5°C intervals; 11 lines) for all possible target (blackbody) temperatures T_{BB} between T_{SB}-15°C and T_{SB}+20°C at 5°C intervals. Source: www.apogeeinstruments.co.uk

Focussing on conditions typically encountered over plant canopies, [7] obtained calibration accuracies of about ±0.2 K for thermopile sensors: this was achieved by adding thermal mass to the sensors, e.g. a tightly fitting aluminium cylinder preventing fast temperature changes (Figure 2), and by applying a sensor independent equation correcting for errors due to changing sensor body temperature *sb*. A parabolic correction function describes the relationship between a sensor correction term SEC and apparent target temperature BT and depends on *sb* [7]:

$$SEC = \frac{0.25}{P(sb)} \times \left[\left(BT - H(sb) \right)^2 - K(sb) \right]$$

where *P*, *H*, and *K* are second order calibration polynomials. The three calibration coefficients of the polynomials were determined by fitting *SEC* to series of measurements performed with a set of 4 Exergen IRt/c sensors held at 5 sensor body temperatures *sb* ranging from 15°C to 35°C; whereas this temperature range is suitable for vegetation measurements it is usually too small for bare surfaces. The corrected target temperatures are then obtained by

$$corrected\ target\ temperature = BT - SEC$$

The temperature of the observed target, a blackbody, was varied between 9°C above and below sensor body temperature *sb*. The results were additionally validated to within ±0.2 K using a ‘water cone calibrator’ [7], a simple and low cost method consisting of a 2 L beaker filled with water on a hot plate stirred rapidly to generate a deep cone-shaped vortex and, thus, increase effective emissivity (Figure 4).

Figure 4: Cone-shaped vortex in water as a simple calibrator.

[6] calibrated radiometers equipped with thermopile sensors using three different methods: a double-walled growth cabinet made of plexiglass, an inverted aluminium cone in a water bath (effectively a simple blackbody), and melting ice shaped into a circular cavity and covered by a reflective ceiling. The melting ice method offers a simple and low cost method to calibrate radiometers at 0°C. In order to calibrate multiple radiometers in parallel, [8] employed large flat radiators and painted them with matt black paint having an emissivity of 0.95. The two radiators, one taken from a truck and one purpose-built, had surfaces consisting of triangular-shaped cavities and were rested on polystyrene bases, which were covered with aluminium foil also painted black. The temperature of the radiators was controlled by circulating water through them and measured with multiple thermocouples soldered to their surfaces. Using a slightly modified calibration equation, [8] calibrated 21 LST FRM field TIR radiometers of several types: for radiometers equipped with internal temperature sensors all temperature residuals were to within ±0.15°C when varying radiator temperatures between 5°C and 60°C. However, the temperature of the radiometers was not systematically varied but defined by ambient temperature.

While calibration methods like those described above are simple and useful, they are no substitute for a calibration against SI traceable reference standards. Therefore, portable blackbodies, e.g. the ‘Landcal P80P’ (www.landinst.com), are by far the most common means to maintain calibration of LST FRM field TIR radiometers ([3], [9]). It follows from the above that LST FRM TIR radiometers are generally calibrated to about ±0.3 K using a SI traceable secondary reference standard in the laboratory: these need to be calibrated (e.g. every 5 years) and traceable to primary reference standards, e.g. from NPL, PTB, or NIST [3]. Following the same methodology as in the laboratory, portable blackbodies allow calibration of radiometers at the field site, which may be important during extended measurement campaigns. Ideally, radiometers are re-calibrated (e.g. at the high and low end of the expected temperature range) before and after a field campaign, e.g. [10] calibrated their instruments against a reference blackbody before and after the field measurements and additionally intercompared them in the field. For multispectral ‘Cimel CE 312’ radiometers, which are self-calibrating instruments based on the differential measurement principle, [10] obtained absolute accuracies better than ±0.2 K in all channels, while the Apogee radiometers (thermopile sensor with correction based on temperature difference between sensor and target) yielded accuracies better than ±0.3 K. Using the CE 312 radiometer as reference, linear calibration equations were derived each day of the campaign for less accurate radiometers, which yielded accuracies between ±0.5 K and ±0.9 K.

Whereas such inter-calibrations do not ensure SI traceability, they ensure the radiometers' stability during the field campaign.

3.3 PRACTICAL CALIBRATION METHODOLOGIES (LST)

Measurement campaigns with FRM TIR radiometers are often performed to validate satellite-derived LST products. Typically such campaigns last between a few days and a few weeks and are performed over naturally homogenous sites, e.g. rice fields ([11], [12], [13]), grasslands [14], arid regions ([14], [5]), or agricultural sites [15]. All deployed radiometers should be calibrated against SI traceable reference standards, ideally before and after each field campaign; in practise calibration activities are limited by resources and performed less frequently against secondary reference standards: the permissible interval depends on the stability declared by the instrument manufacturers and needs to be verified by the researcher. Systems like ISAR [1] allow calibrating after each measurement: however, this is infeasible with low-cost, hand operated LST FRM radiometers. Therefore, in addition to calibration against SI traceable reference standards, e.g. blackbodies, experimenters use several practical methodologies to monitor instrument calibration in the field, i.e. to detect abnormal instrument behaviour or possible drift.

Essential for inter-calibrations is that one radiometer has been calibrated against a SI traceable reference standard and can be used as a transfer standard. Furthermore, the radiometers must observe an area that over-fills their FOVs and is (approximately) homogenous and isothermal on the scale of their footprints, e.g. [16] and [17] obtained temperature differences of up to ±2 K for night-time measurements with four radiometers (FOV of 32 cm) distributed 50 m apart from each other over a uniform grassland. When they increased the FOV of two radiometers to 1.5 m by raising them 3.5 m above ground, the night-time spatial variation of in situ LST reduced to ±0.6 K; in contrast, the spatial variation of in situ LST over snow was only ±0.2 K. [10] used spatially distributed radiometers to obtain surface temperature over a rice paddy near Valencia, Spain. The radiometers were about 150 m apart from each other and were carried in 3 minutes along 100 m transects; sky radiance was measured at each end. The crop surface was observed at near nadir angles (FOV ≈ 30 cm) and spatial and temporal LST variability was characterised by a standard deviation of typically ±0.5 K; at the same time this procedure inter-calibrated the radiometers.

The following practical field methods for inter-calibrating LST FRM TIR radiometers can be used:

- Inter-calibration of *same type* radiometers: radiometers are aligned to a common target, which should be as homogeneous and isothermal as possible. Deviations between individual BTs (mean BT), i.e. double the radiometer's uncertainty (standard deviation), indicate instrumental problems and require re-calibration. Suitable natural targets are water, sand, dense grass/crop, and clear sky.

- Inter-calibration of radiometers with different FOVs, spectral characteristics, dynamic ranges, and sensitivities: procedure as for radiometers of the same type, but requires targets with emissivity ≈ 1 and negligible surface anisotropy. Natural targets approximating this are water and dense grass/crop.

- Inter-calibration over (parts of) the diurnal temperature cycle: applies to both cases above and covers a wider range of target and instrument temperatures. Generally requires automatic data recording.

Figure 5 shows an inter-calibration of two Heitronics KT15.85 IIP radiometers mounted next to each other at 10.5m height and observing about 3m^2 of dry soil and desiccated grass. BTs were recorded once per minute between 17:26 UTC on 14th of December 2015 and 08:07 UTC on 15th of December 2015 and had a mean difference of 0.14±0.03°C.

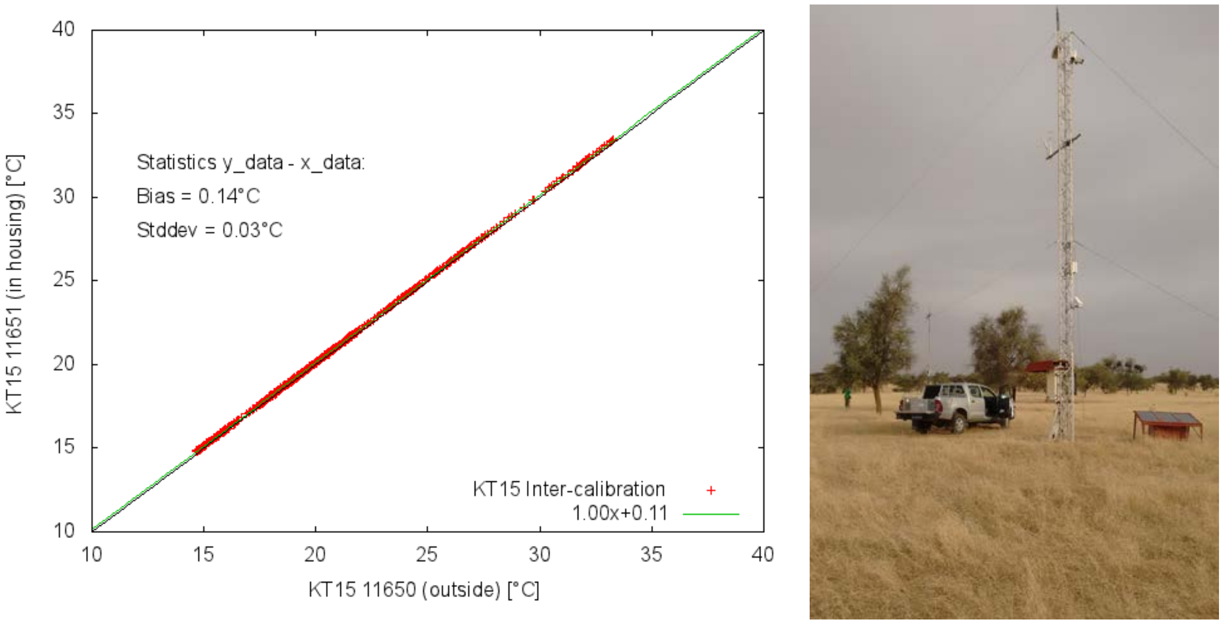

Figure 5: Left: Inter-calibration of two KT15.85 IIP radiometers. Right: KIT's permanent validation station at Dahra, Senegal. (Data courtesy Frank-M. Göttsche, KIT)

For LST determination down-welling hemispherical 'sky' irradiance has to be obtained (approximately) at the time as the BT measurements over the target; favourable conditions are clear skies and complete cloud-covers [18]. Down-welling hemispherical radiance can be estimated from directional radiometric measurements of:

1. sky BT at the 'representative zenith angle' of 53° ([11], [19], [20])
2. sky BT at 0° zenith angle and a known relationship [18]
3. BT over a diffuse gold plate or crinkled aluminium foil ([21], [22])

The first approach does not require any further calculations or measurements while the second approach is easier in terms of directional alignment. The third approach requires that the reflector's temperature and emissivity spectrum are known; however, since the used targets have very high reflectance in the TIR (e.g. 97%), the TIR radiance emitted by them is a relatively small part of the measured signal ([21], [22]). Depending on the spectral range of the radiometer the measured sky BT can be very low, e.g. down to -100 °C for clear dry atmospheres over deserts when measuring at 0° zenith angle [23]. Besides potentially exceeding their operating range, radiometers are generally difficult to calibrate for temperatures well below 0 °C, which may result in larger measurement errors. Fortunately, the typically high emissivity of natural land surfaces around 11 µm (e.g. between 0.92 and 0.99) reduces the impact of such errors on derived LST; the effect of emissivity errors is usually considerably more severe [24]. When identical 'sky' radiometers are available they can be inter-calibrated using a sequence of zenith angles, e.g. from 70° (and thus avoiding the horizon) to 0°, which provides a range of BTs from below surface air temperature to zenith sky BT.

3.4 FIELD CALIBRATION OF LST FRM TIR RADIOMETERS

Depending on the particular field site, diurnal LST amplitudes of 40 K and surface-overheating of 20 K or more have to be expected. In order to obtain in-situ LST that are representative of a range of spatial scales, radiance measurements are usually performed over homogeneous and isothermal natural targets, e.g. sand, gravel, grassland, and rice paddies. Although limited by the remaining surface heterogeneity and spatial LST variability, such sites can be used for inter-calibrating LST FRM TIR radiometers provided these observe sufficiently large areas. The following field (inter-)calibration protocol for LST FRM TIR radiometers is proposed:

- In accordance with manufacturer specifications, all radiometers shall be calibrated and SI traceable to primary reference standards, e.g. from NPL, PTB, or NIST.
- Before and after a field campaign radiometers should be re-calibrated against a secondary reference standard (e.g. at the high and low end of the expected temperature range); however, the required re-calibration frequency strongly depends on the stability of the radiometer.
- During a field campaign additional radiometer inter-calibrations over natural surfaces should be performed; these require that the radiometers' FOVs are overfilled by (approximately) homogeneous and isothermal surface areas.
- For natural surfaces to be homogenous and isothermal on the spatial scale of a radiometer they have to cover sufficiently large areas (e.g. 2 m^2 over dense rice fields); this can be achieved by raising the radiometer higher above the ground.
- Homogeneous and isothermal conditions within the FOVs shall be verified when simultaneously measuring with several radiometers at different locations; in this case the observed surface areas differ and isothermal conditions need to be ensured, e.g. by quickly moving a single radiometer across the site (i.e. within 1-3 minutes).
- Spatial LST variability over homogeneous surfaces is usually least at low wind speeds under skies that are completely clear or completely covered by uniform stratus clouds; at night-time land surfaces are often close to isothermal and provide the most favourable inter-calibration conditions.
- All surface observations shall be performed at the same near-nadir view angle (<30°) and at the same azimuth angle to minimise differences due to viewing geometry [25]
- Radiometers with different FOVs (e.g. 44° vs. 8.5°) shall be inter-calibrated over surfaces with negligible anisotropy, e.g. dense rice fields.
- Radiometers with different spectral ranges (e.g. 8-14 µm vs. 9.6-11.5 µm) shall be inter-calibrated over surfaces with TIR emissivity ≈ 1, e.g. water.
- All clocks shall be synchronised to time UTC
- Each measurement time shall be given in UTC and its corresponding geolocation shall be given in decimal degrees latitude / longitude
- All data shall be recorded in a common table format, e.g. as for the FRM4STS LCE
- Relevant technical details of each instrument shall be recorded, e.g. make & type, serial number, spectral range and calibration details
- Information about wind, cloud-cover, air temperature and humidity, the type of land cover, etc. shall be recorded

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METHODOLOGIES FOR MAINTAINING FRM TIR RADIOMETER CALIBRATION UNDER IST FIELD CONDITIONS

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4.1 REVIEW OF METHODOLOGY

The methods used to assess and maintain calibration of FRM TIR for use in ice surface temperature field campaigns are not very well established. This is due to the fact that the use of FRM TIRs within the field of Ice surface temperature calibration has been very limited so far.

The main validation measurements used for satellite IST observations are from temperature probes situated at the snow or ice surface, such as thermocrons or ice drifting buoys (Hall et al., 2015, Koenig & Hall, 2010, Dybkjær et al., 2012) or even 2 meter temperature sensors (see e.g. Hall et al., 2012).

The use of these observations introduces additional discrepancies in the validation and calibration due to the representativeness effect, which can be several degrees (see e.g. Shuman et al., 2014) and there is a need for increasing the use of FRM TIR for IST validation and to agree upon protocols or best practices for the calibration of the FRM TIRs to ensure the SI traceability.
It is anticipated that the methods used to establish the traceability and maintain the calibration of the FRM TIRs will follow the methods developed for Sea Surface Temperature validation, laid out in Rice et al., 2004, Barton et al., 2004 and Donlon et al., 2014a,b. For the IST applications and validation, emphasis should be put on the performance of the FRM TIRs in cold conditions. This applies both to cold targets and to cold instruments and sensors. The air and snow temperature can reach -60 deg. C in the high latitudes and the transparent atmosphere in the high latitudes results in very cold sky temperatures down to -100 Deg. C. In addition, the representativeness effects, from satellite and in situ mismatches in space and time, should be corrected to represent the conditions for the skin temperature of the sea ice.

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THE TREATMENT OF UNCERTAINTIES AND THE ESTABLISHMENT OF TRACEABILITY

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5.1 UNCERTAINTIES AND THEIR TREATMENT

Traceability to SI units requires documentary evidence of a correct treatment of measurement uncertainties. The definitions and meaning are clearly defined in the formal ISO guide to vocabulary in metrology recently revised in 2012 - Traceability is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (ISO, 2012) (Ehrlich and Rasberry, 1997). Bell (2001) provides a basic introduction to measurement uncertainty, while a more detailed exposition is given by UKAS M3003 (2007). Each calibration step has to have its own, appropriate, uncertainty budget. Unfortunately the concept of traceability by some instrument manufacturers and users who declare the calibration of their instruments as being traceable to National Standards Laboratories is not always as rigorous as it should be, and can lead to misunderstandings and inappropriate interpretations by customers and users.

It also not uncommon for there to be confusion and misuse of the terms 'measurement uncertainty' and 'measurement error'. The two terms are very different since measurement uncertainty refers to the limits within which the value of the parameter being measured may be reasonably presumed to lie, while measurement error refers to the difference between the value obtained from a measurement and the corresponding (presumed) true value. Since the true value is rarely if ever known, the value measured by a designated reference laboratory, typically one or more National Measurement Institutes (NMI)s, is usually considered to be representative of the true or SI value.

The calculation of the uncertainty of a measurement is very important because it allows the meaningful comparison of measurements made by different people or different institutions. Measurements made by two different people/institutions may differ, but if the difference is smaller than the combined uncertainty of their measurements, then the two results can be said to agree.

A brief and simplified overview of the steps required to calculate the overall uncertainty of a measurement is presented below. The reader is encouraged to consult Bell (2001), UKAS M3003 (2007), Woolliams (2015) and ISO (2012) and the references therein for more thorough discussion and detail.

5.2 ESTIMATING THE COMBINED UNCERTAINTY OF A MEASUREMENT.

The key steps to estimating the overall uncertainty of a measurement are as follows:

i. Identify all the parameters which can potentially affect the output of the measurement process being considered;
ii. Estimate the uncertainty of each parameter, and express all uncertainties in similar terms. Parameters that do not significantly affect the result can be ignored;
iii. Calculate the combined standard uncertainty of the measurement using standard techniques (ISO 2012). If the input quantities are not independent of each other, extra calculations may be required to take account of correlations;
iv. Express the uncertainty in terms of a coverage factor and state a level of confidence.

5.3 PARAMETERS WHICH CAN CONTRIBUTE TO THE COMBINED UNCERTAINTY OF A SST MEASUREMENT.

It is a well-established principle that a measurement has little if any meaning without an associated uncertainty value. For this reason an SI traceable calibration requires an associated uncertainty budget which is able to provide the combined uncertainty of that particular calibration. Every effort should be made to ensure that the radiation thermometers being used in SST measurements are fully characterised so that an appropriate uncertainty budget can be established.

A brief summary of the parameters which are likely to influence the measurement of SST using a radiation thermometer is given below. There are a large number of radiation thermometers currently being used for SST measurements, each of bespoke design (Theocharous et al., 2010). Each radiation thermometer may be affected differently by external influences and, therefore, may require a different approach in the development of the corresponding uncertainty budget.

All parameters, which determine (or could potentially contribute to) the performance of a radiation thermometer must be identified and fully characterised. This is essential in order to quantify the magnitude of their effect on the radiation thermometer output (i.e. determine the value of the appropriate sensitivity coefficient) and thus allow the uncertainty budget associated with measurements involving that radiation thermometer to be prepared. In cases when a measurement equation exists, the sensitivity coefficient for a particular external parameter can be estimated by the partial derivative of the measurement equation with respect to that parameter. In cases where a measurement equation does not exists, the uncertainty contribution due to an external influence x_i is most easily determined by changing the magnitude of the external influence by a known amount Δx_i (while leaving all other parameters the same) and measuring the resulting change in the radiation thermometer output ΔT. The ratio of the change in the in the radiation thermometer output ΔT divided by the change in the external influence Δx_i provides the value of the sensitivity coefficient corresponding to that external influence. A better method of measuring the sensitivity coefficient involves repeating the measurement of T for different values of x_i (while leaving all other parameters the same). Plotting T as a function of x_i allows the slope of the plot to be measured at the value of x_i of interest. This value is a good estimate the sensitivity coefficient corresponding to parameter x_i which can be used to determine the combined standard uncertainty.

The most important parameters which determine the performance of radiation thermometers are summarised below:

5.3.1 Responsivity

Responsivity is the main parameter measured during the calibration of the SST-measuring radiation thermometer against the transfer standard blackbody. The calibration procedure should include the development of an uncertainty budget which will provide the combined uncertainty of that calibration. That will in turn be used as a component uncertainty in the measurement of the SST when the calibrated radiation thermometer is used in SST measurements. If the transfer standard blackbody has a small aperture, then a correction will have to be included to account for the size-of-source (SOS) effect (Pusnik et al., 2006), along with the inclusion of the appropriate uncertainty component.

5.3.2 `Out-of-band response

The characterisation of the radiation thermometer should include a consideration for its out-of-band response. This can arise due to the imperfect blocking by the band-pass filter which is used to define the spectral response profile of the radiation thermometer. A number of SST measuring radiation thermometers employ thermal detectors (e.g. thermopiles and pyroelectric detectors) which have a flat, spectrally broad response. This means that if the wavelength selective filter has any out-of-band transmission, at any wavelength, this unwanted radiation passing through the filter will be detected by the radiation thermometer; the total effect of this out-of-band radiation can be large, even if the proportion at each individual wavelength is small. Characterisation of the out-of-band response can conveniently be done by adding a long-pass filter whose transmission starts just above the wavelength range of the radiation thermometer. If any signal is present, then there are likely to be issues with out-of-band rejection at longer wavelengths. Similarly, the out-of band response at shorter wavelengths can be evaluated by inserting a low-pass filter in front of the radiation thermometer. The filter transmission is chosen to block wavelengths just below the wavelength band of the radiation thermometer. If any signal is present then there may be issues with out-of-band rejection of the radiation thermometer at short wavelengths.

5.3.3 Linearity of response

The linearity of response of SST radiation thermometers is expected to be governed by the linearity characteristics of the photodetector they use. Unfortunately the responsivity of photodetectors responding in the infrared is particularly prone to deviations from linearity (Theocharous et al., 2004) (Theocharous and Theocharous 2006). The linearity characteristics of radiation thermometers of the type being used to measure SST benefit greatly by the fact that one or more internal blackbodies are used within the instrument, as reference sources. However, the linearity characteristics of the test instrument should be investigated by measuring the radiance temperature of a test blackbody at different temperatures and comparing these values with the true blackbody temperatures, as indicated by the blackbody itself. The plot of the temperature read by the radiation thermometer versus the "true" blackbody temperature can provide the instrument non-linearity which can be used to correct subsequent measurements carried out by that radiation thermometer. It can also be used to estimate an uncertainty component due to the instrument non-linearity which can be added as a component uncertainty to the uncertainty budget associated with measurements carried out by that radiation thermometer.

5.3.4 Temperature Coefficient of Response

The temperature coefficient of response of a radiation thermometer quantifies the effect of the ambient temperature on the responsivity of the instrument. It is usually given by the percentage change in the responsivity of the instrument, resulting from an increase of the ambient temperature of 1 ^{o}C. It is calculated by measuring the output of the radiation thermometer while it is sequentially maintained at a number of temperatures around ambient. Figure 1 shows the output of a radiometer located in an enclosure, as the temperature of the enclosure was increased every 20 minutes in steps of 2 ^{o}C, from 20 ^{o}C to 30 ^{o}C. It is clear that the responsivity of this particular radiometer increases with increasing ambient temperature. From Figure 1, another plot can be generated of the radiometer output at different ambient/enclosure temperatures. From the slope of that plot, the temperature coefficient of response of that particular radiometer was estimated to be +0.29% $^{o}C^{-1}$. Note that the temperature coefficient of response is no different from the "sensitivity coefficient" of ambient temperature.

It so happens that the temperature coefficient of response of that radiometer arose due to the band-pass filter used to define its spectral response. If this cannot be resolved through better technology or some temperature stabilisation process then the effect on the measurement has to be evaluated, corrected and an appropriate uncertainty assigned. This requires:

i. the ambient temperature to be recorded during the entire period during which measurements are acquired using this radiometer;
ii. the maximum deviation of the ambient temperature during that period to be calculated (say ±2 ^{o}C);
iii. the maximum per cent fluctuation on the radiometer output during the monitoring period (±2 ^{o}C at 0.29% per ^{o}C means a maximum deviation of ±0.58%) to be estimated. This is now treated as an uncertainty contribution with a rectangular profile (QA4EO Guideline 6) which is equivalent to a standard uncertainty contribution equal to 0.58% divided by √3;
iv. This uncertainty contribution should be added to the other uncertainty components to arrive at the combined uncertainty of the measurement completed with that radiometer.

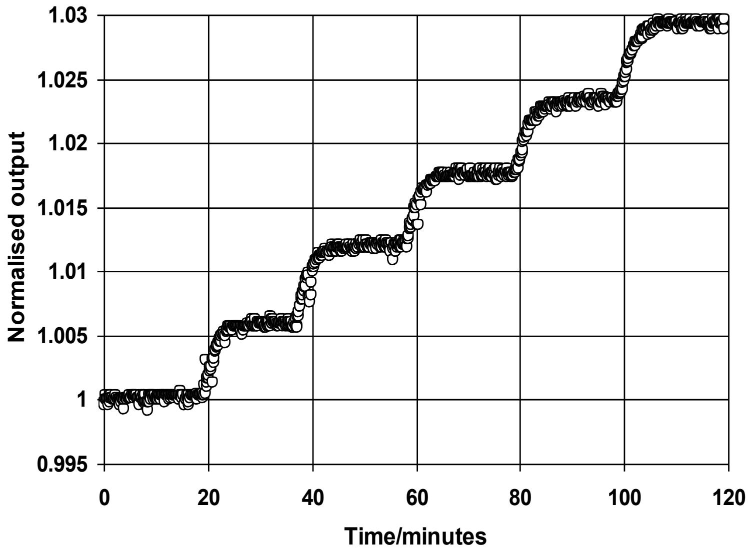

Figure 1: Normalised output of a radiometer as the ambient temperature was increased every 20 minutes in steps of 2 °C, from 20 °C to 30 °C.

One way of reducing the uncertainty contribution due to the temperature coefficient of response of the radiation thermometer is to actively stabilise the temperature around the instrument. However, this may not be practically feasible due to the extra power requirements which will be necessary. A second method would be to reduce the period of data acquisition to ensure that the drift in the ambient temperature during that period is minimised.

5.3.5 Ambient humidity fluctuations

The effect of humidity fluctuations can be treated in the exactly same way as the effect of ambient temperature fluctuation highlighted above. Water is known to absorb strongly in the infrared. Even though infrared radiation thermometers operate in one of the infrared atmospheric windows, it would not be surprising to find that the responsivity of a radiation thermometer is affected by the humidity of the environment in which it is operating. Again, dedicated experiments consisting of placing the radiation thermometer in an environmental chamber and measuring its responsivity to a constant input while the humidity in the chamber is changed allows a plot of the instrument output versus ambient humidity to be generated. The slope of this plot (humidity coefficient of response, or sensitivity coefficient corresponding to humidity) can be treated in exactly the same way as the temperature coefficient of response (see previous section) to estimate the uncertainty contribution due to fluctuations in humidity during the period of the acquisition of the data. Note that, for this to be done, it will be necessary to record the ambient humidity during the period of data acquisition with the radiation thermometer.

5.3.6 Polarisation

The absolute spectral responsivity of radiation thermometers generally exhibits some dependence on the state of polarisation of the radiation being measured. This is not an issue when blackbody sources are being viewed because their output can be considered completely unpolarised. However, the output of many other sources, including skylight and reflections from water, are known to be partially polarised. The dependence of the responsivity of the radiation thermometer on the state of polarisation of the incident radiation must be fully characterised. Each component of a radiation thermometer is expected to introduce some degree of polarisation (CIE, 1984). Alternatively, at least the linear polarisation characteristics of the complete radiation thermometer can be quantified. This can be done by measuring the instrument responsivity while the plane of polarisation of the incident radiation is rotated (CIE 1982) or vice versa.

5.6.7 Temporal response

The response time of a radiometric sensor defines how quickly the output of the sensor can follow a rapidly changing incident signal. Mathematically it specifies how quickly the output of the sensor rises in response to a step change in the incident signal. The temporal response of the radiation thermometers used for SST can be very long (well in excess of 10 minutes in some cases) because each measurement involves three separate measurements (the sea surface, the sky and the internal blackbody). During the period of such a measurement, the SST may change. An uncertainty component should be included in the uncertainty budget to account for any changes in the SST during the period of the measurement of the sea, the sky and the internal blackbodies.

5.3.8 Repeatability, Type A (random) uncertainty

Every uncertainty budget must include a repeatability or Type A uncertainty contribution. This is estimated by repeating the same measurement a number of times, without realignment and estimating the standard deviation of these measurements. In a properly designed measurement, the Type A uncertainty contribution should be small in comparison with the Type B uncertainty contributions.

5.3.9 Reproducibility

The uncertainty budget should contain an uncertainty component related to how well the measurement system can reproduce the measurement. This should be estimated by making a repeat measurement of an observable e.g. blackbody output or sea surface temperature after re-aligning the measurement system. This can be difficult to evaluate if the observable is not stable and in such cases it is likely that this component will be small compared to that due to the stability of the observable under test.

5.3.10 Radiation thermometer stability and ageing

The responsivity of all measuring instruments can change slowly with time and this is known as ageing. Ageing is accelerated when the instruments are operated in harsh environments such as on the exposed decks of ships. Instruments using interference filters sometimes exhibit large, sudden changes in their responsivity of 1% or more. These changes are believed to originate from the relaxation of the dielectric constituent layers of the interference filter. The effect of ageing is minimised by frequent calibration. SST measuring radiation thermometers benefit greatly from possessing at least one internal calibration blackbody which serves to provide a first order frequent calibration and thus minimises the effects of ageing. Another source of ageing which was identified in the responsivity of radiation thermometers utilising cryogenically cooled detectors arises due to the deposition of a thin film of ice on the cooled detectors (Theocharous, 2005) and cooled wavelength selecting filters (Theocharous et al., 2005). An uncertainty contribution due to instrument ageing should be estimated from the previous history of the instrument.

5.3.11 "Background" or "dark" measurements

When radiometers are used to acquire measurements, it is important to include "background" or "dark" readings. The aim of the "dark" measurements is to eliminate the effects of clutter and stray light as well as any biasing due to the photodetector dark signal and the electrical amplification circuitry. The positioning of the optical shutter is critical in the acquisition of "dark" measurement. Infrared measurements are further hindered by the fact that bodies whose absolute temperature is above absolute zero emit infrared radiation so the presence of bodies at ambient temperature in the FOV of a radiation radiometer can affect the instrument reading. SST measuring radiation thermometers benefit greatly by using an internal blackbody to compare the spectral radiance of the sea surface with that of the internal blackbody. This reduces the need to acquire proper "dark" measurements. However, the contribution of the internal blackbody only eliminates errors due to the definition of "zero" when the SST is the same as the temperature of the internal blackbody. When there is a difference between the two, the advantages of the "null reading" are reduced. An uncertainty contribution should be included in the uncertainty budget to account for the inadequate definition of "zero". This uncertainty component will depend on the temperature difference between the SST being measured and the temperature at which the internal blackbody is set. This uncertainty component is expected to be considerably smaller in SST-measuring radiation thermometers which include two internal reference blackbodies.

5.3.12 Uncertainty contribution due to out-of-field stray light

The response of a radiation thermometer to optical radiation incident from different directions should be the same irrespective of the angle of incidence, provided the radiation comes within the instrument's field of view. On the other hand, the response of the radiation thermometer to radiation which is outside its field of view should be zero. This is accomplished by placing a number of apertures/baffles at appropriate positions within the body of the radiation thermometer. In this case, radiation thermometers are characterised for their ability to reject the output from sources, which are not in their FOV. If the out-of-field stray light rejection of a radiation thermometer is poor then the appropriate uncertainty contribution should be added when the instrument is viewing a scene, with the sun or other radiation source being close to the field of view of the radiation thermometer.

5.3.13 Uncertainty contribution due to the water emissivity.

The sea water emissivity at particular angles is known from tables. These values should have uncertainty values associated with them. The uncertainty in the emissivity of sea water under the conditions of the measurement should be used as an uncertainty contribution in the calculation of the combined uncertainty.

5.3.14 Uncertainty contribution due to the viewing angle

Water emissivity is a function of the "angle of incidence". The observation angle of the radiation thermometer will depend on the tilting of the ship. The level of tilting of the ship should be recorded and the corresponding change in the observation angle should be estimated. The corresponding change in the water emissivity (due to changes in the observation angle) should then be calculated. The maximum and minimum emissivity values (corresponding to the smallest and largest angle of incidence to the sea surface) can be used to calculate the range of values, which will represent the uncertainty with rectangular distribution. This range should be divided by √3 to calculate the standard uncertainty due to changes in the viewing angle.

5.3.15 Other uncertainty contributions

In addition to the above the following sources of uncertainty should also be considered:

i. Uncertainty contribution due to the "state of the sea surface" i.e. the presence of waves and the "speed of the wind".

ii. Uncertainty contribution due to the measurement of the sky radiance.

iii. Uncertainty contribution due to relative spectral responsivity of the radiation thermometer response (partly covered by out of band response).

Table 1 below shows the uncertainty budget of the radiance temperature of a Ga fixed-point blackbody. This blackbody is used to calibrate the responsivity of a radiometer, so the combined uncertainty of the Ga blackbody is used as a component uncertainty in the uncertainty budget of the radiometer. This can be seen in Table 2 which tabulates the systematic standard uncertainties of the AMBER radiometer when it is used to measure the radiance temperature of a test blackbody in the 10 °C to 50 °C temperature range by comparison to a gallium fixed-point blackbody.

Table 1: Standard uncertainty budget of the radiance temperature of an NPL Ga fixed-point blackbody

Contribution	**Standard Uncertainty / mK**	**Comment**
Uncertainty due to the 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).	4	Standard deviation of measurements over the measurement period e.g. 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**	

Table 2: Systematic standard uncertainties of the AMBER radiation thermometer when it is used to measure the radiance temperature of a test blackbody in the 10 °C to 50 °C temperature range by comparison to a gallium fixed-point blackbody.

Contribution	**Standard Uncertainty / mK**	**Comment**
Uncertainty in the Ga blackbody radiance temperature	32	Taken from Ga blackbody uncertainty budget (see Table 1)
Uncertainty due to the lock-in amplifier non-linearity (Theocharous, 2008)	36	0.1% non-linearity in the lock-in amplifier. 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 (Theocharous and Theocharous, 2006)
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**	

5.4 COMPARISON EVIDENCE TO SUPPORT UNCERTAINTY EVALUATIONS.

This section emphasises the importance of regular independent comparison with peers to ensure that the uncertainty budgets developed above are internationally consistent with those of others. In principle, a comparison can be treated in exactly the same way as a calibration except that in this case there is no *a priori* true value to which one instrument is being referenced as in the case of a reference black body. In this case each participant in a comparison can be considered equal (or at least to a level commensurate with their uncertainties) and results or consistency can be determined with respect to a mean value from all the results of the comparison (ideally weighted by uncertainties if they can be considered reliable).

The uncertainty of the comparison and the level at which evidence of equivalence can be demonstrated is based on the combined uncertainties of the participants, which will be calculated from the recommendations in the treatment of uncertainties. If the radiation thermometers being compared exhibit differences in their readings when observing the common parameter, in this case SST, then an additional uncertainty to account for these differences should be added to the combined uncertainty of the comparison. If there are more than two participants in the comparison, as would be preferred, the comparison reference value will have an uncertainty determined by the combined uncertainties of all the participants but reduced by dividing by the square root of the number of participants. The level of agreement between any two participants in the comparison can be used as evidence to support the uncertainty they have estimated.

5.5 IMPROVING TRACEABILITY OF CALIBRATION AND VERIFICATION MEASUREMENTS

Efforts should be made where possible to define community consensus schemes and measurement protocols for calibration and verification. Well-documented data processing schemes and quality assurance criteria shall be established to ensure consistency and traceability to SI standards of in situ radiometer measurements used for satellite validation. Ship-borne radiometer users must participate regularly in inter-comparison ‘round-robin” tests and comparison with international standards to establish SI traceability for their data. International radiometer and reference blackbody inter-calibration experiments (Kannenberg, 1998; Rice et al, 2004; Theocharous. and Fox, 2010; Theocharous et. al., 2010) are essential under this protocol and the need for regular activities of this type is obvious (Minnett et. al., 2012). They promote the dissemination of state-of-art knowledge on instrument calibration, measurement methods, data processing, training opportunities and quality assurance. In preparation for the launch of new satellite instruments and the on-going validation of currently flying satellite instruments, the CEOS community has recognized the need for a fourth FRM infrared radiometer and reference blackbody inter-calibration experiment. The proposed experiment includes the following components:

i. A laboratory-based comparison of the calibration processes for FRM TIR SBRN radiometers and verification of blackbody sources used to maintain calibration of FRM TIR radiometers and provide traceability to SI.
ii. Initiation of field inter-comparisons using pairs of FRM TIR radiometers to build a database of knowledge over a period of several years.

The benefits of radiometer inter-comparison work includes:

i. Establish and document protocols and best practice for FRM TIR radiometer and reference blackbody inter-comparisons for future use.
ii. Establish community best practices for FRM TIR radiometer deployments,
iii. Evaluate and document differences in IR radiometry primary calibrations and performances under a range of simulated environmental conditions,
iv. Establish and document formal SI-traceability and uncertainty budgets for participant blackbodies and radiometers,
v. Evaluate and document protocols and best practice to characterise differences between FRM TIR radiometer measurements made in field (land, ocean, ice) operational conditions,
vi. Follow QA4EO principles and in particular Guidelines: QA4EO-QAEO-GEN-DQK-004, version 4.0 (Fox and Greening, 2010).

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APPENDIX A: PROTOCOL FOR THE COMPARISON OF BLACKBODIES & RADIOMETERS USED FOR VALIDATION OF SATELLITE MEASURED SURFACE TEMPERATURES UNDER LABORATORY CONDITIONS (FRM4STS – LCE)

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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.

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.

ORGANIZATION

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.

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.

Participants' details

NB: This is not the full list

Table 1. Contact Details of Participants

Contact person	Short version	Institute	Contact details
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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.

COMPARISON OVERVIEW

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

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.

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.

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

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.

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.

MEASUREMENT INSTRUCTIONS

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.

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.

Measurand

The principle measurand in all comparisons is brightness temperature.

MEASUREMENT INSTRUCTIONS

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.

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 ^{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 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 electronically.

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

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.

TYPE A UNCERTAINTY CONTRIBUTIONS

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.

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.

TYPE B UNCERTAINTY CONTRIBUTIONS

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.

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.

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.

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.

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.

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.

REFERENCES

1. Barton, I. J., Minnett, P. J., Maillet K. A., Donlon, C. J., Hook, S. J., Jessup, A. T. and Nightingale, T. J., 2004," The Miami 2001 infrared radiometer calibration and intercomparison: Part II Shipboard results", *Journal of Atmospheric and Oceanic Technology*, **21**, 268-283.

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.

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5. Theocharous, E., Fox, N. P., Sapritsky, V. I., Mekhontsev, S. N. and Morozova, S. P., 1998, "Absolute measurements of black-body emitted radiance", *Metrologia*, **35**, 549-554.

6. Donlon, C. J., Wimmer, W., Robinson I., Fisher G., Ferlet, M., Nightingale, T. and Bras, B., 2014, "A Second-Generation Blackbody System for the Calibration and Verification of Seagoing Infrared Radiometers", *Journal of Atmospheric and Oceanic Technology*, **31**, 1104–1127

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 I 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	Uncertainty % B	No. of Runs

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

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

APPENDIX II 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: ………………………………..

APPENDIX III 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 IV: 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 V: 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	$((U_{repeat})^2+(U_{Repro})^2))^{\frac{1}{2}}$		

APPENDIX VI: 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:…………………………

APPENDIX B: PROTOCOL FOR COMPARISON OF LAND SURFACE TEMPERATURE MEASUREMENTS IN SIMULATED FIELD CONDITIONS (FRM4STS LCE--LST)

Evangelos Theocharous & Nigel Fox

Environment Division

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 comparisons of measurements of Land surface temperature under simulated field conditions at NPL in 2016.

OBJECTIVES

The overarching objective of this suite of comparisons 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:

3) 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.
4) 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 comparison of measurements made by radiometers of Land Surface Temperature.

ORGANIZATION

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.

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.

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
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
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
J. A. Sobrino	IPL	Imaging Processing Laboratory (IPL) Parque Científico,Universitat de Valencia Poligono La Coma s/n, 46980 Paterna Spain	Tel: +34 96 354 3115; email: sobrino@UV.es
Raquel Niclos			email.: Raquel.Niclos@uv.es
Tim Nightingale	STFC	STFC Rutherford Appleton Laboratory Chilton, Didcot,Oxon OX11 0QX United Kingdom	Tel: +44 1235445914; Tim.Nightingale@stfc.ac.uk
Werenfrid Wimmer	Soton	National Oceanography Centre, Southampton,European Way, Southampton, SO19 9TX, United Kingdom	email: w.wimmer@soton.ac.uk
Willem Vreeling	DLR	DLR, Remote Sensing Technology Institute, Oberpfaffenhofen, D-82234 Wessling, Germany	email: willem.vreeling@dlr.de
Ian Barton	CSIRO Australia	Head office, PO Box 225,Dickson ACT 2602 Australia www.csiro.au	Tel: +61 3 9545 2176; email: Ian Barton@csiro.au
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
William (Bill) Emery	EDU-USA	Univ of Colorado, Aerospace Eng. Sci. Dept CB 431, Boulder,CO, 80309-0431 USA	email: emery@colorado.edu

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.

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. If 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_2 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^o full view angle, so when it is viewing the target at a view angle (from Nadir) of 25^o 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^o full view angle, so when it is viewing the target at a view angle of 25^o (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.

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

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 (during comparison)
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 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 4th July 2016. The LST measurements are expected to finish on Friday 8th 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 4th 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

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.

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.

MEASUREMENT INSTRUCTIONS

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.

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.

Measurand

The principle measurand in all comparisons is brightness temperature.

MEASUREMENT INSTRUCTIONS FOR LST COMPARISON

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^{o} 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^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.

- 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.

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.

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.

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.

TYPE A UNCERTAINTY CONTRIBUTIONS

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.

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.

TYPE B UNCERTAINTY CONTRIBUTIONS

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.

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.

Land target emissivity

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

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.

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.

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.

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.

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.

ACKNOWLEDGEMENTS

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

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 I 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.

Time	The time of the measurements should be UTC.
Measured Land Surface Temperature	Brightness temperature measured or predicted by participant.
Measurement uncertainty	Combined/total uncertainty of the measurement.
Measured Sky Temperature	Brightness sky temperature measured or predicted by participant.
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.
View angle from Nadir	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 (µm) …………………………… Bandwidth (µm) ……………………………

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

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

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

APPENDIX II 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 III 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.

Uncertainty Contribution due to	**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}
Land target emissivity		U_{emiss}	U_{emiss}
Angle of view to nadir		U_{angle}	U_{angle}
Linearity of radiometer		U_{Lin}	U_{Lin}
Drift since last 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 IVDATA 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:…………………………….

APPENDIX C: PROTOCOL FOR COMPARISON OF RADIOMETERS MEASURING SURFACE TEMPERATURE OF A WATER BODY

Evangelos Theocharous & Nigel Fox

Environment Division

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.
iii. Field comparisons of Water Surface Temperature (WST) scheduled to be held at Wraysbury fresh water reservoir, near NPL.
iv. Field comparisons of Land Surface Temperature (LST) scheduled to be held on the NPL campus.
v. 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.
vi. Field comparisons of Ice Surface Temperature (IST) scheduled to be held in the Arctic.

This document describes the protocol which is proposed for the comparisons of water surface temperature radiometers in simulated field conditions to be held near NPL in 2016.

OBJECTIVES

The overarching objective of the overall suite of comparisons 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 simulated field comparison of radiometer measurements of water surface Temperature near NPL in 2016.

ORGANIZATION

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.

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.

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
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
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
J. A. Sobrino	IPL	Imaging Processing Laboratory (IPL) Parque Científico,Universitat de Valencia Poligono La Coma s/n, 46980 Paterna Spain	Tel: +34 96 354 3115; email: sobrino@UV.es

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 WST comparison activity, the radiometers will be located on the platform in the middle of the Wraysbury water reservoir, which is located near NPL, and will be measuring the skin temperature of surface of the water of the reservoir.

COMPARISON OVERVIEW

The water surface temperature calibration comparison exercise ideally consists of all radiometers simultaneously viewing the same part of the water reservoir from the platform which is located in the middle of the Wraysbury reservoir for a variety of view angles: 40º, 45º, 50º and 55°. Measurements will be performed during both daytime and night-time conditions.

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

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 in 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 WST comparison activities which are due to take place during the second week of the comparison, starting on Monday 27th 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

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.

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 both laboratory and 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.

MEASUREMENT INSTRUCTIONS

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.

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.

Measurand

The principle measurand in all comparisons is brightness temperature.

MEASUREMENT INSTRUCTIONS FOR WST COMPARISON

Day-time WST measurements

- 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 shown in Appendix B.

- 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 radiometer. If the radiometer requires alignment within the frame, then alignment marks or a self-aligning frame should be used.

- 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. This target location will be chosen to allow comparisons to be made at a range of view angles.

- The radiometers need to have their optical components, such as the mirrors, windows or blackbodies, protected from the environment. This can partially be done using a water-proof enclosure to protect the radiometer components. A better protection is provided by using a rain or spray sensor that can trigger a protective response.

- Under conditions of high wind, the mounting position should be chosen to avoid any water spray from reaching the radiometer.

- 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 (Water 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.

- Participants will be encouraged to change viewing angle during the measurements 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 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 given in Appendix A, which will also be available electronically.

Night-time WST measurements

- The same procedure can be used to acquire measurements during night-time.
- Please note that night time measurements will be made under unattended operation of the radiometers.

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.

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 radiometer uncertainty contributions 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 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 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.

TYPE A UNCERTAINTY CONTRIBUTIONS

Repeatability of measurement

This describes the repeatability of measurement process without re-alignment of the participants' radiometer. 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.

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.

TYPE B UNCERTAINTY CONTRIBUTIONS

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.

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.

Water emissivity

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

Angle of view to nadir (angle of incidence)

The water emissivity decreases as the angle of incidence increases, hence any uncertainty in the angle of incidence will manifest as an uncertainty in the emissivity of the water.

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.

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.

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 WST comparison (see Appendix A for the Templates for reporting the results of the radiometer WST 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.

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.

REFERENCES

1. Barton, I. J., Minnett, P. J., Maillet K. A., Donlon, C. J., Hook, S. J., Jessup, A. T. and Nightingale, T. J., 2004," The Miami 2001 infrared radiometer calibration and intercomparison: Part II Shipboard results", *Journal of Atmospheric and Oceanic Technology*, **21**, 268-283.

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 I REPORTING OF MEASUREMENT RESULTS

The attached measurement summary should be completed by each participant for each completed set of WST field 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. 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.

Time	The time of the measurements should be UTC.
Measured Water Surface Temperature	Brightness temperature measured or predicted by participant.
Measurement uncertainty	Combined/total uncertainty of the measurement.
Measured Sky Temperature	Brightness sky temperature measured or predicted by participant.
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.
View angle from Nadir	The angle of view of the radiometer to the surface of the water from Nadir.

WST Measurement Results at Wraysbury Reservoir

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

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

Wavelength (µm) ……………………………   Bandwidth (µm) ……………………………

Time (UTC)	Measured WST K	Combined WST Uncertainty K	Measured sky temperature K	Uncert. in sky temperature K	Uncertainty %		No. of Runs
					A	B	

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

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

APPENDIX II 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 III UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH WST MEASUREMENTS AT WRAYSBURY RESERVOIR

The table shown below is a suggested layout for the presentation of uncertainties for the measurement of the WST at Wraysbury reservoir. 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}
Water emissivity		U_{emiss}	U_{emiss}
Water surface “roughness”		U_{rough}	U_{rough}
Angle of view to nadir		U_{angle}	U_{angle}
Linearity of radiometer		U_{Lin}	U_{Lin}
Drift since last 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 IVDATA 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 -