Fiducial Reference Measurements for Validation of Surface Temperature from Satellites (FRM4STS)

Technical Report 3
A Framework to Verify the Field Performance of TIR FRM

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ACRONYMS AND ABBREVIATIONS

AMBER	Absolute Measurements of Black-body Emitted Radiance
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CEOS	Committee on Earth Observation Satellites
DMI	Danish Meteorological Institute
FICE	Field Comparison Exercise
FOV	Field of View
GED	Global Emissivity Dataset
GTRC	Gobabeb Training and Research Centre
IR	Infra-Red
ISO	International Organization for Standardization
KIT	Karlsruhe Institute of Meteorology
LSE	Land Surface Emissivity
LST	Land Surface Temperature
MET	Ministry of Environment and Tourism
MODIS	Moderate Resolution Imaging Spectroradiometer
NIST	National Institute of Standards and Technology (USA)
NMI	National Metrology Institute
NPL	National Physical Laboratory
PTB	Physikalisch Technische Bundesanstalt
SST	Sea Surface Temperature
SI	Système Internationale
WGCV	Working Group for Calibration and Validation
WST	Water Surface Temperature
ASL	Above Sea Level
CEOS	Committee on Earth Observation Satellites

1 INTRODUCTION

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 [1, 2] and 2009 [3, 4]. However, six years will have passed since the last comparison 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 during 2016.

This document provides an overview of the instrumentation used to make surface temperature 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 [5]. It spans the requirements of all domains, i.e. 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. The principle issue in Ice Surface Temperature measurements, 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.

1.2 TERMINOLOGY AND DEFINITIONS

This section provides the terminology and definitions relevant to the in-situ validation of LST, which closely follows the list of [6]. More detailed information on statistical concepts and on expressing uncertainty in measurement is provided by [7].

Absolute bias	A systematic error between a measurement and the true value. Note: the ‘true’ value of a quantity cannot be known due to measurement error.
Accuracy	Defined as the degree of conformity of the measurement of a quantity and an accepted (‘true’) value.
Brightness Temperature	The temperature a black body in thermal equilibrium with its surroundings would have to be to duplicate the observed intensity of a grey body object at a specific wavelength. In practice: the temperature obtained from a radiance measurement when assuming emissivity = 1.
Calibration	The process of quantitatively defining the system response to known, controlled system inputs.
Discrepancy	The lack of similarity between two measurements.
Emissivity	A material’s effectiveness in emitting energy as thermal radiation, usually defined as the ratio of the energy radiated from a material's surface to that radiated from a blackbody (a perfect emitter).
Error	Result of a measurement minus a true value of the measurand. Note that in practice a ‘true’ value cannot be determined and therefore a conventional true value is used instead [7].
Land Surface Temperature	Radiometric (or skin) temperature of the land surface. For homogeneous and isothermal surfaces radiometric and thermodynamic temperatures are equivalent [8].
Measurand	A particular quantity to be measured.
Precision	Closeness of agreement between independent measurements of a quantity under the same conditions.
Protocol	A methodology used to carry out a specific operation such as a measurement, data comparisons, or data merging.
Relative error	The error of measurement divided by a true value of the measurand.
Random error	Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions [7].

Relative bias	A systematic discrepancy between measurements obtained from different data sources.
Reference	Standard Measurement standard designated for the calibration of other measurements standards for quantities of a given kind in a given organization or at a given location.
Systematic error	Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand [7].
True value	The value consistent with the definition of a given particular quantity.
Uncertainty	A parameter associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand.
Validation	The 'process of assessing, by independent means, the quality of the data products derived from the system outputs' (CEOS definition).

1.3 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.

1.3.1 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.

1.3.2 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.

ICE and snow emissivity

This uncertainty contribution arises due to the uncertainty in the knowledge of the emissivity of the snow and ice at the appropriate wavelength.

Angle of view to nadir (angle of incidence)

The snow and ice 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 snow and ice.

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.

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2 A FRAMEWORK TO VERIFY THE FIELD PERFORMANCE OF TIR FRM: SEA SURFACE TEMPERATURE DETERMINATION.

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2.1 OCEAN PROPERTIES

2.1.1 Sea surface temperature

Sea Surface Temperature (SST) is a difficult parameter to define exactly because the upper ocean (~10 m) has a complex and variable vertical temperature structure that is related to ocean turbulence and the air-sea fluxes of heat, moisture and momentum [8]. Standard definitions for SST have been agreed by the International Community 0 that are shown schematically in *Figure 1*. The hypothetical idealized vertical profiles of temperature in low wind speed conditions during the night and day shown in the figure encapsulate the effects of the dominant heat transport processes and time scales of variability associated with distinct vertical and volume regimes (horizontal and temporal variability is implicitly assumed). The interface temperature (SST_{int}) is a theoretical temperature at the precise air-sea interface. It represents the hypothetical temperature of the topmost layer of the ocean water and could be thought of as an even mix of water and air molecules. SST_{int} is of no practical use because it cannot be measured using current technology. However, it is important to note that it is the SST_{int} that interacts with the atmosphere.

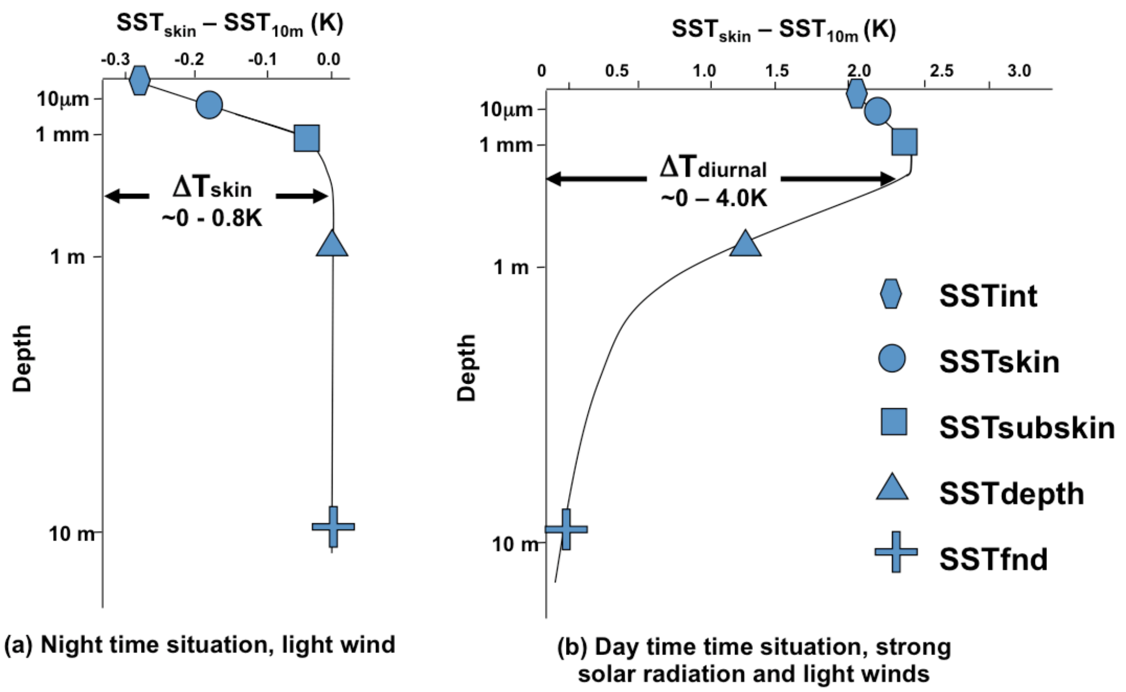

Figure 1. Definitions of sea surface temperature in the upper 10m of the ocean. (a) shows an idealised vertical temperature profile during early night –time/early morning conditions and (b) an idealised vertical profile during the early afternoon following intense solar inputs in low wind speed conditions.

The sea surface skin temperature (SST_{skin}) is the temperature measured by an infrared radiometer typically operating at wavelengths in the range 3.7 µm – 12 µm. It represents the temperature within the conductive diffusion-dominated sub-layer [39] at a depth of ~10 µm – 20 µm (depending on the spectral wavelength used to measure the SST_{skin}) below the air-sea interface. SST_{skin} is subject to a large potential diurnal temperature cycle including cool skin layer effects (especially at night under clear skies and low wind speed conditions [8] and warm layer effects in the daytime [7]. This definition was chosen for consistency with the majority of infrared satellite and ship borne radiometer measurements.

The sea surface subskin temperature ($SST_{subskin}$) is the temperature at the base of the conductive laminar sub-layer of the ocean surface, that is, at a depth of approximately 1 mm – 1.5 mm below the air-sea interface. For practical purposes, this quantity can be well approximated to the measurement of surface temperature by a microwave radiometer operating in the 6 GHz – 11 GHz frequency range [7], but the relationship is neither direct nor invariant to changing physical conditions or to the specific geometry of the microwave measurements. Measurements of $SST_{sub\text{-}skin}$ are also subject to a large potential diurnal cycle due to thermal stratification of the upper ocean layer in low wind speed high solar irradiance conditions.

All measurements of water temperature beneath the $SST_{subskin}$ are referred to as depth temperatures (SST_{depth}) and is measured using a wide variety of platforms and sensors such as drifting buoys, vertical profiling floats, or deep thermistor chains. These temperature measurements are distinct from those obtained using TIR or passive microwave radiometers (SST_{skin} and $SST_{subskin}$ respectively) and must be qualified by a measurement depth in meters (e.g., or SST(z) e.g. SST5m). The foundation SST, SST_{fnd}, is defined as the temperature of the water column free of diurnal temperature variability (daytime warming or nocturnal cooling). SSTfnd provides a connection with the historical concept of a “bulk” SST considered representative of the oceanic mixed layer temperature and represented by any $SST_{\mathbf{depth}}$ measurement within the upper ocean over a depth range of 1 m to 20+ m.

Drifting buoy SST_{depth} [4] measurements have been used to validate satellite SST retrievals in an operational context for many years [5]. The much larger number of drifter SST matchups compared to other *in situ* sources allows the inherent resolution and accuracy limitations (0.1 K and 0.2 K respectively) of drifter SST to statistically overcome these limitations (assuming all drifters are measuring a “statistically stationary” ocean). However, drifting buoy SST_{depth} was never designed for satellite SST validation activities: it is not traceable to SI standards and, cannot currently meet climate requirements [2][3][5]. Furthermore, near-surface temperature gradients in the upper ocean [6][7] (*Figure 1*) complicate the interpretation of sub-surface drifter SST_{depth} (typically measured at a depth of ~0.2 m) when compared to satellite SST_{skin} [8].

2.1.2 Sea surface emissivity

Figure 2 shows the emissivity calculated for pure water as a function of viewing angle from nadir, θ, and wavelength, λ. The emissivity of pure water ε is slightly less than unity with a dependence on θ and λ with a minimum value at a wavelength of ~11 µm ($\rho_\lambda \approx 0.0015$) [26]. As ε of the sea surface is close to unity, the temperature of the thin skin layer largely determines the intensity of TIR radiation leaving the sea surface. The difference between the reflective properties of pure water and artificial salt solutions representing seawater has been investigated by [33] at near-normal incidence angles. Results suggest that the 8 µm – 12 µm window is most affected by typical seawater solute [32] concentrations. In fact [32] go as far as to recommend that the 8 µm – 12 µm waveband should *not* used to measure SST_{skin} due to the poor characterisation and sensitivity of the refractive index of sea water to temperature at larger θ. However, the effects of salinity on sea surface emissivity are found to be well modelled [35] using standard refractive index corrections proposed in [66] with a significant temperature dependence is evident in the 11.5 µm – 13 µm region (although interestingly, not at ~10.5 µm as suggested by [32]).

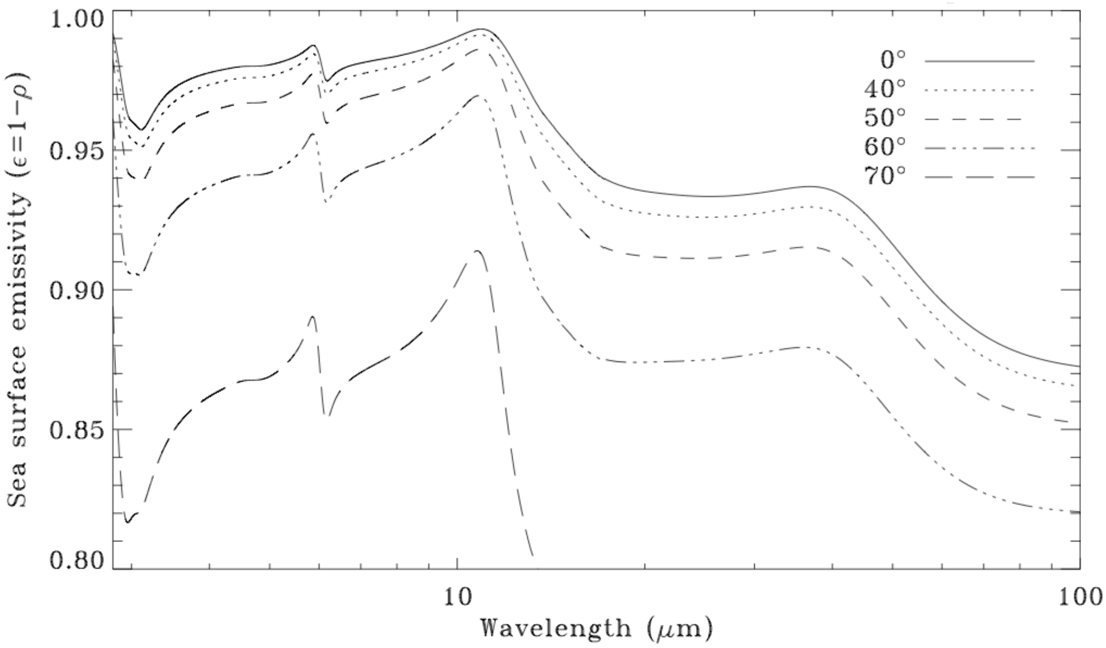

Figure 2. The spectral emissivity, ε(λ,θ), of pure water as a function of viewing incidence angle (in the absence of surface roughness). The strong impact of incidence angles < 40° and peak emissivity at ~11μm is clearly visible.

While the spectral emission angle properties are known for still water surfaces at θ < 40° [26], they are poorly quantified for a roughened sea surface. When the sea surface is rough, radiance from many parts of the sky can be specularly reflected (as $L_{scat}(\lambda)$) from suitably oriented facets of surface waves into the radiometer field of view [34]. Numerical models [27] – [31] have been developed to consider the uncertainty associated with the variation of $\varepsilon(\lambda,\theta)$ through a sea state and wind speed dependence. For θ > 40°, ε decreases significantly although this is contested by [32] who suggest that ε remains constant at θ = 40° for wind speeds of 3 to 13 m/s.

From ship borne TIR radiometer design perspective, the above discussion suggests an optimal SST_{skin} FRM measurement will be obtained when viewing a calm sea surface at θ of 15° – 40° (to minimise ε variations) in the 3.5 µm – 4.1 µm and/or the 10.5 µm – 12.5µm spectral waveband. However, it is clear that more work is required to develop better knowledge of sea surface emissivity.

2.2 RADIOMETRIC MEASUREMENTS OF SEA SURFACE TEMPERATURE

Because ε for seawater is slightly less than unity, a small proportion of radiation originating from the atmosphere is reflected at the sea surface into the field of view of the radiometer complicating a simple measurement approach. Near to 10 µm, the brightness temperature of the sky typically is anywhere from a few kelvin cooler than the ocean surface (low cloud) to more than 100 K cooler (clear, dry air). If no allowance were made for reflected sky radiation the resulting SST_{skin} retrieval would be too cold, with errors ranging from ~0.1 K to more than 1 K. To measure SST_{skin} accurately from a ship, radiometric measurements of both the sea surface radiance and the downwelling atmospheric radiance must be obtained at the appropriate view-angles and the value of seawater emissivity, ε, must be known accurately.

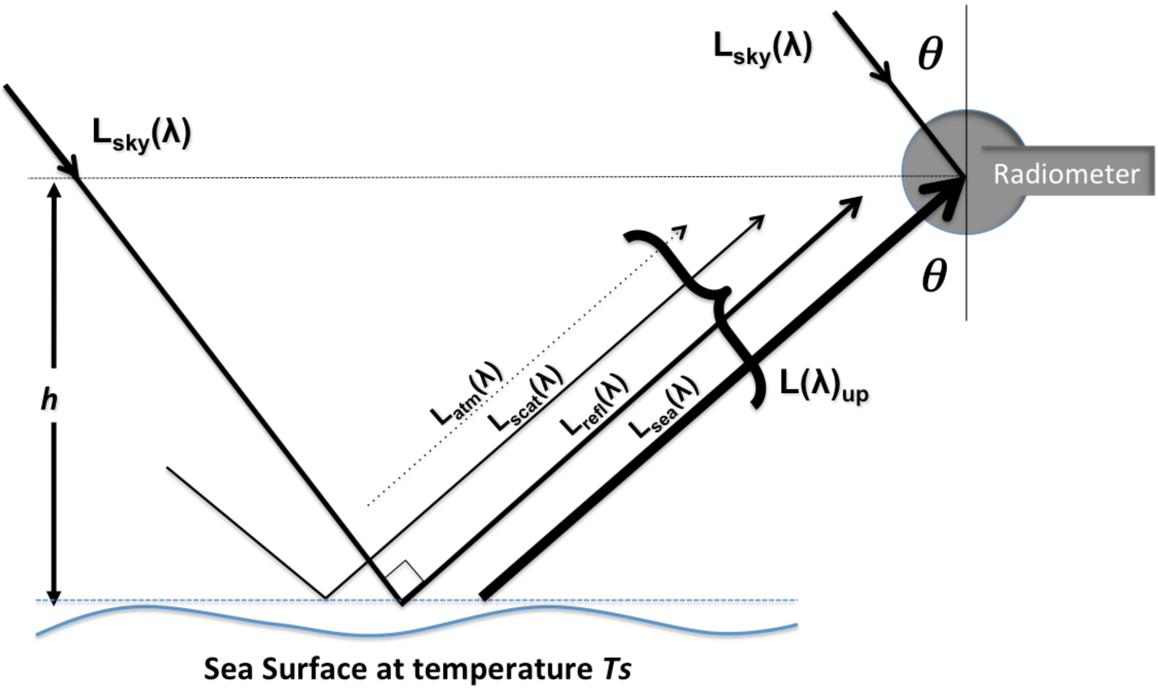

Figure 3. Geometrical arrangement and spectral radiative components that must be considered when measuring the radiative temperature of the ocean surface.

Consider a TIR radiometer mounted on a ship or a platform (*Figure 3*) at height, *h,* above the sea surface viewing a sea surface at temperature T_s and view angle *θ.* The spectral radiance components that must be considered when measuring the SST_{skin} include:

$L_{sea}(\lambda)$: the radiance originating from the sea surface (the required signal);
$L_{refl}(\lambda)$: a proportion of $L_{sky}(\lambda)$ (the downwelling radiance emitted from the atmosphere) *directly* reflected at the sea surface into the radiometer field of view;
$L_{scat}(\lambda)$: a proportion of $L_{sky}(\lambda)$ *indirectly* scattered at the sea surface into the radiometer field of view;
$L_{atm}(\lambda)$: radiance originating from atmospheric emission between the sea surface and radiometer at height *h* above the sea surface.

To perfectly measure SST_{skin} by a radiometer measuring the total upwelling radiance, $L_{up}(\lambda)$, the contribution of each spectral radiance component must be accounted for.
Assuming the atmospheric path is homogenous over the atmospheric depth *h* and the transmittance, τ_{path}, of that path is close to unity, the downwelling radiance, $L_{down}(\lambda)$, incident on the sea surface is given by:

$$L_{down}(\lambda) \approx \tau_{path} L_{sky}(\lambda) + (1 - \tau_{path}) \overline{B(T_{air}, \lambda)} \quad \ldots\ldots..(1)$$

where *B(T, λ)* is the Planck function providing the spectral radiance emitted by a black body and $\overline{B(T_{air}, \lambda)}$ is the spectral radiance emitted at air temperature T_{air}, averaged over the atmospheric path. Typically, in order to proceed practically, $L_{scat}(\lambda)$ is neglected and $L_{reflec}(\lambda)$ is assumed to represent the average of all reflected sky radiance (i.e. that from the direction that reflects in a calm sea surface). This approach has proven satisfactory for many authors [8] – [24].

The upwelling radiance, $L_{up}(\lambda)$, from the sea surface is given by:

$$L_{up}(\lambda) = \varepsilon(\lambda,\theta)B(SST_{skin},\lambda) + (1-\varepsilon(\lambda,\theta))L_{down} \qquad \text{........(2)}$$

The spectral radiance arriving at the radiometer aperture in the direction of the sea surface is then:

$$L_{sea}(\lambda) \approx \tau_{path}L_{up}(\lambda) + (1-\tau_{path})\overline{B(T_{air},\lambda)}$$

(3)

$$= \tau_{path}\varepsilon(\lambda,\theta)B(SST_{skin},\lambda) + \tau_{path}^{2}(1-\varepsilon(\lambda,\theta))L_{sky} + (1-\tau_{path})\left[(1-\varepsilon(\lambda,\theta))\tau_{path} + 1\right]\overline{B(T_{air},\lambda)} \qquad \text{.........(4)}$$

As τ_{path} approaches unity, L_{sea} is given by:

$$L_{sea}(\lambda) = \varepsilon(\lambda,\theta)B(SST_{skin},\lambda) + (1-\varepsilon(\lambda,\theta))L_{sky} \qquad \text{.........(5)}$$

If h < ~40 m, considered an upper bound for ship and platform deployments [25], and the relative humidity is below 95%, τ_{path} is very close to unity for IR measurements in the region 8 µm – 12 µm. A multi-band radiometer or spectro-radiometer could be used to account for the effect of $L_{atm}(\lambda)$ explicitly if the system were sufficiently sensitive [38][41]. The assumption $\tau_{path} = 1$ in (12) when the radiometer is close (< 15 m) to the sea surface is considered valid [41] but, when radiometer deployment heights are much above this, the assumption introduces errors of into SST_{skin} retrievals. While this error is small, it is not insignificant when the goal is an uncertainty of 0.1 K.

Eqn. (5) requires that ε for a given spectral interval and viewing geometry is known accurately. The approach described above assumes that the ocean surface is flat and that $L_{reflec}(\lambda)$ originates from angle θ. [32] and [34] discuss the ε and SST_{skin} errors associated with poor knowledge of radiometer viewing geometry related to wind speed, cloud cover and sea state effects. For radiometer θ of 55° or greater, (particularly in the 8 µm – 12 µm wavelength range) an angular offset of ±3° – 4° can result in SST errors of up to 0.6 K [32]. If θ is 15° – 40° the impact of a wind roughened surface and ship movement will be considerably reduced [34] except in heavy seas. Under clear sky or overcast sky conditions, errors associated with poor knowledge of ε are limited by the assumed homogenous emission from the atmosphere. However, even at small θ, if scattered clouds are present, significant errors of up to 0.3 K may still occur unless truly contemporaneous measurements of the sea surface and sky are made, ship/platform movements are small and, the time difference between such measurements is very small. Further work is required to systematically reduce uncertainties in the values used for $\varepsilon(\lambda,\theta)$ which remain the largest source of uncertainty in the determination of SST_{skin} from ship-borne radiometers (assuming a well calibrated radiometer).

For these reasons, ship borne TIR radiometers observe the sea surface at θ = ~15 – 55°. At lower θ, direct reflection of the ship superstructure at the sea surface and into the radiometer field of view can be significant [37]. Furthermore, it is difficult to view an undisturbed area of the sea surface that is free of the ships bow wave and wake. When θ > 55°, sea surface ε is dramatically reduced (*Figure 5*) and interpretation of TIR measurements critically depends on accurate knowledge of both θ and ε.

2.2.1 Measurements of SSTskin with an in situ filter radiometer

Consider the signal measured by a single channel TIR field radiometer detector designed to measure SST_{skin}. The radiometer spectral response function, $\zeta(\lambda)$, is defined by the combined detector, pass-band filter and all optical components (e.g. mirrors, protective windows, detector band-pass). The signal output from the detector in output-units per unit radiance, S_{sea}, when viewing the sea surface is then:

$$S_{sea} = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda)\left[\varepsilon(\lambda,\theta)B(SST_{skin},\lambda) + (1-\varepsilon(\lambda,\theta))L_{sky}(\lambda)\right]\mathrm{d}\lambda \quad \text{............(6)}$$

where the limits of integration are chosen to span the spectral bandwidth $\zeta(\lambda)$. The detector output when viewing the sky, S_{sky} is:

$$S_{sky} = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda)L_{sky}(\lambda)\mathrm{d}\lambda \quad \text{............(7)}$$

Assuming a narrow waveband (10.5 μm – 12.5 μm) radiometer viewing the sea surface at an angle <40°, $\varepsilon(\lambda,\theta)$ and $B(\lambda,T)$ vary only slowly with wavelength and so Eqn (6) can be separated, to a good approximation, into a combination of the band-averaged values $\varepsilon_B(\theta)$, L_{sky} and $B_B(T)$ giving:

$$S_{sea} = \zeta_B\left[\varepsilon_B(\theta)B_B(SST_{skin}) + (1-\varepsilon_B(\theta))L_{B,sky}\right] \quad (8)$$

where:

$$\zeta_B = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda)d\lambda \quad (9a)$$

$$\zeta_B\varepsilon_B(\theta) = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda)\varepsilon(\lambda,\theta)d\lambda \quad (9b)$$

$$\zeta_B L_{B,sky} = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda)L_{sky}(\lambda)d\lambda \quad (9c)$$

$$\zeta_B B_B(T) = \int_{\lambda_1}^{\lambda_2} \zeta(\lambda)B(\lambda,T)d\lambda \quad (9d)$$

Eqn. (7) can be written as:

$$S_{sky} = \zeta_B L_{B,sky} \quad (10)$$

so that, finally:

$$\zeta_B B_B(SST_{skin}) = \frac{S_{sea} - (1-\varepsilon_B(\theta))S_{sky}}{\varepsilon_B(\theta)} \quad (11)$$

In Equation 11 two fundamental measurements, S_{sea} and S_{sky} in one or more spectral bands, are required to determine the SST_{skin}. Both must be obtained near-contemporaneously by viewing the sea surface at the incidence angle θ and the atmosphere at the zenith angle θ.

As discussed by [62], the time difference between S_{sea} and S_{sky} measurements must be small to limit errors associated with rapidly changing atmospheric radiance conditions i.e. varying clouds of different species and height have different radiative temperatures that are reflected at the sea surface into the radiometer field of view. Finally, we note that a 1% change in $\varepsilon(\lambda,\theta)$ corresponds to a change in retrieved SST_{skin} of 0.66 K (at λ = 10 μm), 0.73 K (at λ = 12 μm), or 0.24 K (at λ = 3.5 μm) [60]. To approach the SST_{skin} measurement accuracy required for climate research, *$\varepsilon(\lambda,\theta)$ for each measurement* must be known to better than 0.5% uncertainty in the 8 μm – 12 μm wavelength region, and better than 1% in the 3–4.5 μm window [32]. This is a challenge given our current knowledge of how to practically determine $\varepsilon(\lambda,\theta)$ while at sea.

2.3 CONSIDERATIONS FOR FIELD DEPLOYMENTS

This section discusses some of the main considerations when mounting radiometers on ships or stationary platforms.

2.3.1 General

A few general mounting considerations valid for ship or fixed platform installations:

i. Work safely. Can the mounting position be accessed safely? What extra measures are required to ensure safe working? Have you carried out a risk assessment? There is usually a legal requirement to ensure safe working and this is in any case good practice. There may be a number of additional hazards when working on ships that are not familiar to land-based scientists, including: working at height, falling objects (on others below as well as on yourself), sudden movement, strong winds, slippery surfaces and difficulty communicating or attracting attention when in isolated positions.

ii. How much power does the instrument need? Can this power be provided by the platform (ship or fixed)?

iii. Does the instrument need a dedicated data logging system and does the logging system need be close to the instrument?

2.3.2 Mounting on ships

For a ship-mounted radiometer the following points should be considered:

- The instrument should be mounted so that the sea view is of undisturbed water forward of the bow wave and the sky view is clear of obstructions (i.e. superstructure). This normally means a mounting position as far forward on the ship as practicable. Such a position should also avoid views of heated engine cooling water, which is discharged behind the bow wave.

- To avoid sea spray and, in difficult conditions, the instrument should be mounted as high as practicable. This could be a forward instrument mast (e.g. research vessel) or the bridge roof on a vessel with a bridge near to the bow of the ship (e.g. cruise ship, passenger ferry).

- On research ships that often hold station for instrument deployments or for sampling, bow thrusters can disrupt the thermal skin. Similarly in windy conditions, the ship is often oriented with the working deck or winch to windward, so that the wind does not push the ship onto the wire. As the ship is pushed downwind, water in the radiometer field of view may have passed under the hull and become mixed.

- Avoid contamination of the measurements by exhaust and other effluents, such as hot air outlets, from the ship.
- In choosing the sea viewing angle, it is important to consider how the emissivity of the ocean, which changes with view angle (roll of the ship). Common view angles from vertical are 15 to 55 degrees.
- Mounting the instrument on the ship will, in general, require a specialized frame for the instrument. The ease of instrument installation and removal should be an important point in the mounting frame design as radiometers need to be calibrated every few months. If the instrument needs alignment in the frame, alignment marks or a self-aligning frame can be useful.
- Consider access to power from the ship, and what wiring is needed for the instrument. Can the instrument access existing ship infrastructure or does specialized wiring have to be installed to operate the instrument? If specialized wiring is needed, the ship operator may require that this be installed by their preferred contractor which can add long lead times to the installation.
- If possible, install the instrument on a part of a passenger ship where passengers do not have access.
- If near real time data transmission to shore is needed to determine instrument status, the installation of a dedicated system (e.g. Iridium modem) may be required. In some cases this can be achieved using the ship's existing internet infrastructure.
- Other installation considerations include: predominant wind direction, sun angle, possible superstructure shielding from wind, spray and the sun and the potential effects on the measurement.

2.3.3 Mounting on other platforms

Additional considerations for installations other than ships:

- The power supply might be difficult to sustain if the platform is powered by solar cells and batteries. How can the instrument be made safe if power is interrupted?
- Tidal effects should be considered before installing the instrument in coastal regions.
- Sun angle might have a bigger effect than on ships as the instrument will have the same relative position to the sun every day.
- Water may move round or under a platform, driven by tides or prevailing winds. This may disrupt its temperature structure.

2.4 PROTOCOLS FOR TRACEABLE RADIOMETRIC MEASUREMENTS

The following subsections contain a summary protocol for the deployment of a shipborne infrared radiometer. They should be read in conjunction with Sections 2.3 and 2.5, which discuss some aspects of the deployment cycle in more detail.

2.4.1 Safety

Work safely. Assess all working areas and activities before starting. Use safety equipment where appropriate. ***Do not work if the tasks cannot be carried out safely, or if you do not feel confident that you can complete them safely.***

2.4.2 Data and documentation

In addition to high level products (e.g. geolocated SSTs), always record data at the lowest level that is available (e.g. detector counts), so that it can be reprocessed if required. Where possible, record the complete state of the instrument, including internal temperatures, mechanism positions and other housekeeping data.

In all products, always include a reliable UTC timestamp (GPS receivers are a good source), and include geolocation data or ensure that external geolocation data are available.

Where available, use agreed data standards (e.g. netCDF, HDF5), metadata standards (e.g. CF convention, ISO 8601) and product formats (e.g. L2R).

Ensure that all data are recorded securely. If possible, make secondary copies on independent media. A USB stick or SD card may be suitable.

Assure the quality of your data. Check the format. Check any flags. Check that the data is realistic.

Document the instrument, data format, data processing methods and deployment, including:

- The spectral characteristics of the instrument,
- The value used for seawater emissivity,
- Any calibration coefficients, including those for on-board thermometers
- The SST algorithm,
- A description of the radiometer mounting arrangements and the geometric configuration of the radiometer with all measurement angles accurately documented
- The steps taken to ensure that measurements are free of ship effects (bow wave, radiative emission from the ship superstructure, emissions from ship exhaust plumes, etc.)
- On-board instrument software used (version, release date, etc.)
- Data post-processing software (version, release date, etc.)
- Any other aspect considered relevant to better understanding the quality of the measurements obtained.
- Make the documentation publicly available and reference it in the data products.
- Plan for the long-term archival and maintenance of your data and documentation. National data centres (e.g. CEDA, UK; Ifremer, France) may be appropriate.

2.4.3 Deployment

Ensure that your instrument and any ancillary equipment are properly maintained. Inspect and test them before each deployment, and clean, refurbish or replace parts as required.

Recalibrate components essential to your traceability chain (e.g. blackbody thermometers, external reference thermometers) on a regular basis.

Validate the instrument calibration immediately before and after every deployment. Do not alter the instrument in any way between the validation and deployment measurements.

Ensure that the instrument is mounted so that it has unobstructed views to undisturbed seawater, and to the sky at the complementary angle. Confirm and record the mounting orientation.

When deploying, make sufficient functional tests of the instrument and ancillary equipment to ensure that data is being recorded and that at the least, any functions essential for instrument safety are operating correctly (e.g. weather protection, uninterruptable power supply). If not, remove the instrument, repair and redeploy.

Be aware of other factors that may affect your deployment and the quality of your data (e.g. RF interference from HF radio antennas and RADAR, window washing sprays, engine exhaust, stray light from navigation lights and searchlights)

Consider collecting additional contextual measurements, including SST at depth (hull or inlet sensors), air temperature, humidity, wind speed and direction, longwave downwelling radiation.

2.5 CALIBRATION VERIFICATION METHODOLOGY AND PROCEDURES

Infrared radiometers typically are calibrated using on-board calibration reference radiance sources (blackbodies). The purpose of performing calibration verifications is to assess the accuracy and repeatability of the internal calibration system, and to provide a link in an unbroken chain of comparisons from the shipborne radiometer to an SI reference.

The exact methodology and procedures used to perform a laboratory calibration and verification of a radiometer must be defined and documented. In particular, the calibration of an in situ radiometer must be verified immediately before and after every deployment.

2.5.1 Pre-deployment calibration verification

The calibration performance of a shipborne radiometer should 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 calibration target should be capable of being operated at fixed temperatures or at a temperature that changes very slowly compared with an instrument calibration cycle (e.g. a few kelvin per hour). The thermometric temperature of the target must be an accurate representation of its brightness temperature, or alternatively, the brightness temperature must be derived from the thermometric temperature(s) using a calibration target mathematical model with an accuracy sufficient for the calibration verification. The calibration target brightness temperature uncertainty must, at the most, be equal to the required verification uncertainty and should preferably be significantly smaller.

The calibration target aperture must be sufficiently large and its cavity design such that the target aperture does not vignette the instrument beam, and the instrument field of view falls completely on the intended surfaces of the target cavity.

The radiometer hardware, on-board configuration, on-board processing software, and data post-processing software must not be modified in any way between the collection of the verification measurements and the sea deployment (with the exception of transporting and mounting the instrument on its deployment platform).

Where possible, the instrument should be operated in the orientation and with the viewing geometry used for sea surface observations.

All calibration measurements must be securely archived.

2.5.2 Post-deployment calibration verification

The calibration performance of a shipborne radiometer must also be verified immediately after deployment, following the same procedure as the pre-deployment calibration verification, and again without modification of the instrument in any way, including the cleaning of optical surfaces, or any other intervention that might influence the state of the instrument calibration.

2.6 VALIDATION OF MEASUREMENT UNCERTAINTIES

Measurement uncertainties can be validated by the intercomparison of independent measurements of the same signal. The basic radiometric uncertainties associated with an instrument are best assessed against carefully designed laboratory targets (discussed elsewhere).

The uncertainties associated with a measurement of SST_{skin} retrieved from radiometric measurements include additional contributions from the completeness and accuracy of the instrument's SST radiative model, the quality and representativeness of any ancillary data included in the retrieval, and the effect of the operating environment on the instrument operation. These can only fully be captured by an intercomparison of direct independent *in situ* SST measurements.

The minimum requirement is for a comparison between two independent instruments, mounted in close proximity and viewing the same body of water. Even then, this is not an exact comparison as variability in the environmental signals may be captured differently, depending, for instance, on differences in the spectral responses, fields of view and sampling strategies of the two instruments. Nonetheless, a direct comparison can show whether the uncertainties ascribed to the two derived instrument SST measurements are consistent with the actual measurement differences.

Other approaches include three-way (and greater) intercomparisons between instrument measurements, which could include those from satellite instruments [42]. The three-way approach allows estimates for uncertainties associated with each instrument to be derived. The approach is effective, but does make the important assumptions that the errors associated with each instrument are independent and Gaussian. In practice neither may be completely true. In either case, it is important to collect as large an intercomparison dataset as possible, both to ensure that any statistical analyses are effective and to sample as wide a range of environmental conditions as possible.

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3 A FRAMEWORK TO VERIFY THE FIELD PERFORMANCE OF TIR FRM: LAND SURFACE TEMPERATURE DETERMINATION

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3.1 INTRODUCTION

Satellite remote sensing of surface parameters is an essential part of the global observation system and provides inputs for weather forecast, climate studies and many other applications. One of the important parameters is surface temperature. Satellites have been monitoring global surface temperature for several decades and have established sufficient consistency and accuracy between in-flight sensors to claim that it is of “climate quality”. [45] provide a classification and protocol for various methods of validating Land Surface Temperature (LST) derived from space borne thermal infrared instruments. The authors distinguish between four categories of LST validation:

(A) validation with in situ data
(B) radiance-based validation
(C) multi-sensor intercomparison
(D) time series analysis.

The most accurate of these is ‘category A’ validation with in-situ LST obtained from measurements with field deployed IR radiometers. The 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 in-flight and as link to future sensors, so that any differences in the results obtained between them are understood. This knowledge will allow potential biases to be removed and not transferred to satellite sensors. The required knowledge can only be determined through formal comparison of the instrumentation, both in terms of its primary “lab based” calibration and in its use in the field. The provision of a fully traceable link to SI ensures that the data are robust and can claim the status of a “climate data record”.

Subject of this part of the ESA Technical Report TR-3 (D120) is the determination and verification of in situ LST with ground-based thermal infra-red (TIR) fiducial reference measurements (FRM). In order to qualify for ‘category A’ validation [45], in situ LST must be derived from completely independent measurements, which need to be fully anchored to SI units and have direct correlation with ‘true’ surface based quantities. There are currently several systems and instruments which provide state of the art ground based measurements for obtaining in-situ LST. However, so far neither the instruments nor their field deployment have been compared and there are no established standards to ensure SI-traceability. Here we provide a critical review of the exact methodology used to obtain in situ LST with FRM TIR radiometers under field conditions, propose best practice approaches and protocols for LST FRM TIR radiometer field deployments, and define procedures and protocols to maintain their pre-deployment and post-deployment calibration verification.

3.2 TERMINOLOGY AND DEFINITIONS

The terminology and definitions of terms is given in Chapter 1 of this report.

3.3 LST DETERMINATION USING TIR FRM RADIOMETERS

Depending on the particular site, diurnal LST amplitudes of 40 K and surface-overheating of 20 K or more have to be expected. Due to strong surface gradients and local perturbations the thermodynamic temperature at the surface of non-isothermal bodies, e.g. as obtained with thermometers in contact with natural bodies, may be very difficult to measure [5]. In contrast, surface-leaving TIR radiance is directly measurable by radiometers, whether they are space borne or ground based. However, the radiance leaving a heterogeneous non-isothermal body depends on its temperature and emissivity distribution, i.e. the fractions with different temperatures in the ground instantaneous field of view (GIFOV) of the radiometer and their respective emissivities. Therefore, an interpretation of the measured radiances over a heterogeneous non-isothermal body in terms of temperature requires additional information about the surface. Before addressing this more general case, we define spectral emissivity and radiometric temperature for a homogeneous isothermal body.

3.3.1 Spectral emissivity

Planck's law relates the radiance emitted by a black body (emissivity ε = 1) to its surface temperature T. However, most objects relevant to remote sensing applications are non-black bodies with $0 < \varepsilon(\lambda) < 1$. Spectral emissivity $\varepsilon(\lambda)$ is defined as the ratio between the spectral radiance R emitted by a surface at wavelength λ and the spectral radiance emitted by a black body $B(T, \lambda)$ at the same wavelength and temperature. Spectral emissivity $\varepsilon(\lambda)$ is then given [12]:

$$\varepsilon(\lambda) = \frac{R(T, \lambda)}{B(T, \lambda)} \quad (1)$$

where ε is assumed to be temperature independent, λ is in meters, R is in W m^{-3} sr^{-1}, and T is in Kelvin. For homogeneous isothermal surfaces T equals thermodynamic temperature.

3.3.2 Radiometric temperature of isothermal surfaces

For a sensor located near the surface and measuring within an atmospheric TIR window the atmospheric influence on the surface-leaving radiance along its path can be neglected. With known emissivity, the simplified radiative transfer equation ([4], [12]) can be used to account for reflected down-welling TIR radiance from the atmosphere and for the non-black body behaviour of the surface. The blackbody equivalent spectral radiance B emitted by the surface at temperature T is given by:

$$B(T, \lambda) = \frac{R(T, \lambda) - \left(1 - \varepsilon(\lambda)\right) \cdot R_{sky}(\lambda)}{\varepsilon(\lambda)} \quad (2)$$

where R is the measured surface-leaving spectral radiance and R_{sky} is the measured down-welling hemispherical sky radiance. In situ measurements of R_{sky} are usually performed by a dedicated radiometer aligned at the zenith angle of about 53° ([27], [53], [41]), which depends slightly on spectral band and atmospheric conditions [39], or via a known relationship (equation 8) between the radiance measured at zenith and hemispherical radiance [39]. Once the blackbody equivalent spectral radiance B is known, inverting

Planck's law gives the 'radiometric temperature' T of the surface. The spectral response functions of many radiometers are approximately symmetric, while Planck's function and the spectral emissivity of natural surfaces generally vary slowly over a 'narrow band' radiometer's spectral range. Therefore, LST is usually retrieved by evaluating Planck's function at the radiometer's centre wavelength [18].

3.3.3 Radiometric temperature of non-isothermal surfaces

A single well-calibrated radiometer can be sufficient to obtain representative in situ LST for homogeneous sites [19]. However, natural surfaces are rarely homogenous and isothermal at a given pixel size. Therefore, heterogeneous sites require at least one radiometer for each of the site's endmembers, which have to be sufficiently homogeneous and their relative area fractions have to be known ([26], [20], [15]). Furthermore, the definitions given in section 0 for homogeneous isothermal surfaces have to be re-expressed in terms of end-member fractions and their respective emissivities ([5], [38]). Following [5], for a flat surface consisting of N homogeneous and isothermal sub-elements having normalised fractional areas S_k we obtain

$$\langle \varepsilon \rangle_{\lambda} = \sum_{k=1}^{N} \varepsilon_{\lambda k} S_k \qquad (3)$$

$$\langle T \rangle_{\lambda} = B_{\lambda}^{-1} \left[\frac{\sum_{k=1}^{N} \varepsilon_{\lambda k} B_{\lambda}(T_k) S_k}{\langle \varepsilon \rangle_{\lambda}} \right] \qquad (4)$$

The definition of 'radiometric temperature' given by equation 4 is scale-invariant and in the 10-12 µm band leads to very similar values as the alternative definition of 'radiative temperature'; for a more in-depth treatment on temperature definitions for non-isothermal heterogeneous surface please refer to [5].

3.4 EMISSIVITY

It is obvious from section 3.2 that accurate information about surface emissivity must be available for converting brightness temperature (BT) measurements into accurate in situ LST. Emissivity can be obtained from in situ measurements ([10], [39]) or from spectral libraries [3]. Whereas for spatially and temporally homogeneous field sites, e.g. Lake Tahoe or dense rice fields, it can be sufficient to provide a single emissivity value, heterogeneous sites require an emissivity estimate for each endmember. In addition, some sites might exhibit phenology-dependent emissivity values or emissivity changes with surface moisture. For deriving accurate in situ LST it is essential that the estimated emissivity is representative of the observed endmembers at the time of the BT measurements.

Comparing broadband emissivities in the 8-12 µm range obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and from the Moderate Resolution Imaging Spectroradiometer (MODIS), [33] found that LSE over arid regions varies over a wide range of 0.86 to 0.96. ASTER spectral library [3] data for rocks, soils, and sand, which are frequently encountered components of land covers in (semi-)arid regions, typically show emissivity variations of about ±0.04 about their mean over the 8 - 12 µm spectral range; in contrast, for completely vegetated surfaces the corresponding LSE variations are typically ±0.01.

3.4.1 In situ emissivity

While channel-effective in situ emissivities can be determined with the 'emissivity box method' in the field ([48], [39]), spectral emissivities are usually obtained for samples in the laboratory [43]. For sites consisting of well-known static endmembers it may also be feasible to use representative values from spectral emissivity libraries (e.g. [3]) or from literature. However, in case in situ emissivity is not well known and/or suspected to change over time, e.g. due to vegetation cycles, it may be advisable to use a dynamic emissivity estimate derived from satellite observations instead, e.g. as provided by the monthly 'ASTER Global Emissivity Dataset' (GEDv4) at 5 km spatial resolution [23], the 1 km MOD21 daily product retrieved from MODIS ([22], [21]), or the 'UW-Madison baseline fit (BF) global emissivity data base' (monthly at 1 km spatial resolution; [46]).

3.4.2 Emissivity box method

The 'one-lid emissivity box method' ([10], [40]) is well suited to determine LSE for sufficiently open, relatively flat, and unobstructed field sites with frequent clear sky conditions. [39] studied the one-lid and the two-lid method in detail and derived correction terms for the two methods. While the 'two-lid emissivity box method' is independent of sky conditions [48], it is technically more demanding and requires an isothermally heated lid with near unit emissivity. Therefore, we recommend the one-lid emissivity box method, which consists of the sequence of radiance measurements shown in Figure 1 and an additional measurement of sky radiance.

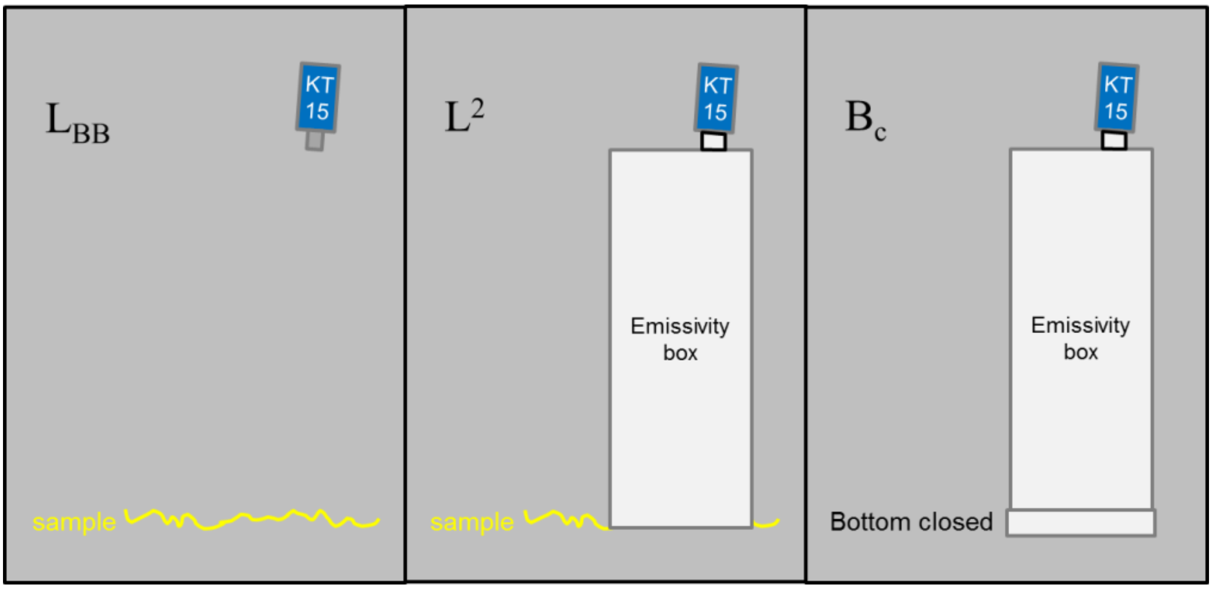

Figure 1 Radiance measurements performed for the one-lid emissivity box method.

Using the same nomenclature as [**Error! Reference source not found.**], uncorrected LSE ε_0 is obtained from a sequence of three radiance measurements (see Figure 1):

$$\varepsilon_0 = \frac{L_{BB} - L_a^{\downarrow}}{L^2 - L_a^{\downarrow}} \qquad 5$$

where L_{BB} is the sample radiance measured under clear sky conditions (i.e. without the box), $L_a^{\downarrow}$ is the downwelling sky radiance, and L^2 is the radiance measured through the bottomless box when it is placed on the sample. Corrected LSE is then given by:

$$\varepsilon = \varepsilon_0 + \delta\varepsilon \qquad 6$$

with correction

$$\delta\varepsilon = (1 - \varepsilon_0)\left\{1 - \frac{L^2 - L_a^{\downarrow}}{L^2 - L_a^{\downarrow} - R(L^2 - B_c)}\right\} \qquad 7$$

where R is a box-specific factor, which depends on box geometry and the spectral response of the inner walls. For box dimensions of 30 cm x 30 cm x 80 cm and an emissivity of $\varepsilon_c = 0.03$ for highly polished aluminum [39] obtained $R = 0.265$. The term B_c is the radiance measured through the box when its bottom is closed with a sheet of aluminum, i.e. it corresponds to the temperature of the 'cold' aluminum. In order to avoid the 'narcissus' effect, i.e. the radiometer observing its own reflection, the opening in the top of the emissivity box can be slightly off-centre so that the inserted radiometer is inclined by 5° w.r.t. nadir [18].
Down-welling hemispherical sky radiance $L_a^{\downarrow}$ is usually approximated with the radiance measured at the 'representative' zenith angle of about 53° ([27], [53], [6], [8]) or estimated as

$$L_a^{\downarrow} = 1.3 \times B[T(0^\circ)] \qquad 8$$

where B is the Planck function evaluated at the radiometer's centre wavelength and $T(0^\circ)$ is brightness temperature measured at zenith ([18], [39]).

The larger the difference between clear sky brightness temperature and surface temperature, the higher the signal to noise ratio of the box method and the smaller the emissivity correction $\delta\varepsilon$. The box method assumes that the temperature of the sample remains (approximately) constant between the measurements over the sample (Figure 1, left and center), which requires quick handling of the box and fast readings. [18] recorded brightness temperatures automatically once per second, which also allows choosing the optimum measurements in terms of thermal stability 'off-line'.

3.5 IN SITU LST DETERMINATION WITH TIR FRM RADIOMETERS

Early experimental determinations of in situ LST used networks of 10 to 25 contact temperature Early experimental determinations of in situ LST used networks of 10 to 25 contact temperature transducers (CTT) laid out over 1 km^2 homogeneous field sites in Australia and their performance was compared against TIR radiometers ([35], [37], [36]); it was found by [35] that on scales from 10 m to 10 km spatial temperature variations over the sites had similar magnitudes with standard deviations of up to 5°C. [57] and [55] performed field campaigns for LST validation on lake and land sites. In situ LST obtained at night-time with four radiometers (GIFOV of 32 cm) distributed 50 m apart from each other over a uniform grassland area showed differences of up to 2 K. Increasing the radiometers' GIFOV to 1.5 m by raising them 3.5 m above ground reduced night-time spatial variation of in situ LST to 0.6 K. Over snow a spatial variation of in situ LST of 0.2 K was determined, while validation results for satellite-retrieved LST were comparable for a single radiometer (GIFOV of 1.5 m) placed in a rice paddy. [57] estimate site-specific errors associated with uncertainty in surface emissivities as ±0.2 K for lakes, ±0.5 K for grassland/snowcover/rice field, and ±0.9 K for silt playa.

Over a rice paddy near Valencia, Spain spatially distributed radiometers were used to obtain surface temperature [9]. The field campaigns used 5 to 7 different radiometers (CIMEL CE 312-1; Everest model 112.2L; AGA model 80; Apogee IRTS), which were deployed over a rice paddy about 150 m apart from each other. The emissivity of the rice crops (≈ 0.985 for the used radiometers) was determined with the emissivity box method [39] and hemispherical sky irradiance was estimated as down-welling radiance measured at 53° zenith angle ([6], [8], [53]). The radiometers were carried over 3 minutes along 100 m transects and sky radiance was measured at each end. The crop surface was observed at near nadir angles (GIFOV ≈ 30 cm) and the typical standard deviation between the radiometers of less than 0.5 K was used to characterise spatial and temporal LST variability. On Lake Tahoe custom-built radiometers are permanently deployed on four moored buoys and automatically measure surface-leaving TIR radiance; additionally, the bulk temperature of the water is measured at various depths [9]. Sky radiance is obtained via radiative transfer calculation performed for interpolated NCEP atmospheric profiles, while the emissivity of water was determined from ASTER spectral library data [3].

Four dedicated LST validation stations in large homogeneous areas in Africa and Europe are operated by Karlsruhe Institute of Technology (KIT). Due to the high cost and complexity associated with operating stations that provide in situ LST observations, few such stations worldwide exist and even fewer were specifically set up and designed to validate LST. The four stations are currently the only ‘category A2’ stations on the solid surface [45] and have been used to validate various LST products ([16], [19], [25], [61], [29], [30], [14]). The stations are equipped with long-term stable precision radiometers Heitronics KT15.85 IIP [26], which were shown to have an absolute accuracy of better than ±0.3 K over the relevant temperature range [51]. At each station separate radiometers observe the relevant surface endmembers, e.g. grass/soil and tree crown, which allows to form composite in situ LST, e.g. using eq. 4 ([5], [52]) or by modelling ([20], [15]); additionally, a separate radiometer measures sky radiance at 53° zenith angle. With an emissivity uncertainty of ±0.015 [18] the in situ LST uncertainty over the gravel plains at Gobabeb, Namibia, is estimated at ±0.8 K. [31] obtained in situ LST over shrub land and over a rice paddy in Eastern Spain; At the shrub land site two Apogee SI-121 radiometers observed the surface from 4 m and 8 m height, yielding target footprint areas of approximately 24 m^2, while a third measured sky radiance at 55.4° zenith angle (adjusted to match the radiometer’s spectral range). At the rice paddy an Apogee SI-111 radiometer observed the surface at nadir from 2 m height, which yielded a footprint area of 2 m^2, and a second radiometer measured sky radiance at 55.4° zenith angle. Due to the high level of homogeneity of the rice field [31] considered a 2 m^2 footprint area to be sufficient, which agrees with the findings of [57]. The surface emissivity of each site was determined with the ‘vegetation cover method’ [54] and bare ground and vegetation emissivities were obtained with the box method [39]. Three minutes of in situ LST were averaged and the corresponding standard deviation was about ±0.07 K; based on analyses of satellite LST data spatial variability was estimated as ±0.5 K for the rice paddy and as ±1.1 K for the shrub land. An emissivity uncertainty of ±0.01 yields an LST uncertainty of about ±0.4 K and [31] estimated the overall uncertainty of in situ LST as ±0.8 K for the rice paddy and as ±1.2 K for the shrub land.

More recently [32] developed an autonomous radiometer system for field LST determination that angularly scans land and sky hemispheres with a single radiometer and allows assessing ground-truth LST and relative-to-nadir emissivity. The measured sky radiances can be angularly interpolated and integrated to obtain the down-welling hemispheric sky radiance. For horizontally homogeneous atmospheres, e.g. totally cloud-free or cloud covered, [32] obtain down-welling hemispheric sky radiance via a regression of the sky radiances on zenith angles. The autonomous scanning system will be used for testing satellite TIR sensors with multi-angular or bi-angular capabilities, e.g. SLSTR on-board Sentinel-3A, over thermally-homogeneous surfaces such as rice paddies.

In-situ LST have also been obtained for SURFRAD stations ([1], [2]): however, these are equipped with broadband hemispherical radiance sensors, which measure radiance in the wavelength range between 4.5 µm and 42 µm. Therefore, [28] and [58] obtained broadband emissivity from narrow band MODIS emissivities via a relationship determined by [59]. In situ LST have also been obtained from broadband radiance measurements of Fluxnet and other stations ([50], [60]). Since these stations were not specifically set up for obtaining in-situ LST, they are frequently located in heterogeneous areas and observe a part of the land surface that is unrepresentative of spatially coarser satellite observations. Therefore, validation with in situ LST is frequently limited to night-time when land surfaces tend to be close to isothermal [60].

3.6 BEST PRACTISES FOR OBTAINING IN SITU LST

In situ LST is not directly measured but derived from measurements of surface brightness temperature (BT), sky BT and land surface emissivity (LSE). However, in situ observations of LST taken under the right conditions over large and homogeneous sites currently allow the most accurate validation of LST products (‘Category A validation’; [45]). For in situ LST to be representative over a large range of spatial scales, i.e. from the ground-based radiometer’s GIFOV to the satellite pixel scale, a field site needs to be either homogeneous over all relevant scales or it must be possible to obtain a representative LST by combining radiance measurements performed over a few ‘endmembers’, e.g. via equation 4 or by modelling ([34], [15], [20]). The homogeneity of a site can be assessed by studying its spatial LST variability (standard deviation) with ground-based radiometers ([57], [9]) or by analysing high-resolution TIR imagery (e.g. from ASTER; GIFOV ≈ 100 m). For the latter [45] recommend a standard deviation of no more than 0.5 K. In situ measurements over rice fields and uniform grasslands yielded a similar spatial variability ([9], [57]).

3.6.1 Measurement protocol for In situ LST

Measurements with FRM TIR radiometers are often performed to validate satellite-derived LST products; since all satellite data are subject to geolocation error, for validation purposes it is recommended that the sites should be homogenous over at least 3 × 3 pixels. Field campaigns for obtaining in situ LST typically last between a few days and a few weeks and are most often performed over naturally homogenous (and relatively isothermal) sites, e.g. rice fields ([6], [7], [31]), grasslands [56], arid regions ([56], [19]), or agricultural sites [47]: this ensures that the in situ measurements are representative of the immediate surroundings. Here, we propose a measurement protocol for obtaining in-situ LST with a single radiometer placed over a highly homogeneous natural target:

- The radiometer shall be traceably calibrated to ±0.3 K or better against a primary reference blackbody, e.g. from NPL, PTB, or NIST (achievable accuracy depends on radiometer type, expected temperature range and environmental conditions).
- Observed surfaces have to be approximately homogeneous and isothermal on the spatial scale of the radiometer (e.g. about 1.6 m GIFOV Ø over dense rice fields). This can be verified with spatially distributed radiometers, by moving a single radiometer ‘quickly’ across the site, or by spatial analyses of high-resolution satellite data.
- Surface observations shall be performed at near-nadir view angles (<30°) to minimise differences due to LST anisotropy ([11], [49])
- Measurements should not be performed next to obstructions like trees or buildings.

- Down-welling hemispherical sky irradiance has to be measured 'simultaneously' with the surface measurements. This can be achieved with a second identical radiometer (i.e. same FOV and spectral range) or by measuring with the same radiometer at short intervals, e.g. every 3 minutes.
- Favourable conditions for estimating down-welling hemispherical sky irradiance from a single directional radiance measurement are completely clear and skies covered completely by uniform stratus clouds [39].
- Instrument-specific Land Surface Emissivity (LSE) should be determined under favourable environmental conditions, e.g. at night-time for clear sky and low wind speeds; the two-lid emissivity box method works under less favourable conditions.
- All clocks involved in the campaign shall be synchronised to time UTC
- The time of each measurement shall be recorded in UTC and the corresponding geolocation in decimal degrees latitude / longitude
- All data shall recorded in a common table format, e.g. as for the FRM4STS LCE
- Relevant technical details of each instrument shall be documented, e.g. make & type, serial number, spectral range and calibration details
- Information about wind, cloud-cover, air temperature and humidity, land cover, etc. shall be documented

3.6.2 Down-welling hemispherical sky radiance

Down-welling hemispherical sky irradiance is usually estimated from one of the following measurements performed with the LST FRM field TIR radiometer:

1. Sky BT at the 'representative zenith angle' of about 53° ([27], [53], [41])
2. Sky BT at 0° zenith angle and a known relationship (equation 8; [39])
3. BT measured over a diffuse gold plate or crinkled aluminium foil ([42], [62])

The first approach directly yields an estimate of down-welling hemispherical sky irradiance for the spectral range of the radiometer, while the second approach is easier to implement in terms of directional alignment. The third approach requires that the reflector's temperature and emissivity spectrum are known. However, since the gold plate and aluminium foil have very high reflectance in the TIR (about 97%), their emitted radiance is a relatively small part of the measured signal ([42], [62]). [17] compared four different methods for retrieving hemispherical down-welling irradiance (the three above and radiative transfer calculations for atmospheric profile data): for clear-sky conditions and an unobstructed upper hemisphere the methods produced comparable results. Depending on the spectral range of the radiometer, measured sky BT can be very low, e.g. -100 °C for clear dry atmospheres over deserts when measuring at 0° zenith angle [18]. 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 [44].

3.6.3 Land Surface Emissivity

Before in situ LST can be obtained, directional spectral emissivity matching the radiometer has to be estimated; the spatial sampling has to be appropriate to provide representative LSE at all scales of interest, e.g. at the scale of the in situ radiometer and the satellite pixel. In situ emissivities can be estimated with the emissivity box method (section 0) or from spectroscopic measurements over samples in the laboratory. For some land surface covers, e.g. dense green vegetation, LSE values are well known and may also be obtained from spectral libraries or literature. When obtaining in situ LST, it has to be ensured that the corresponding LSE has remained approximately the same since it was determined (e.g. no change in land cover due to vegetation, fire, etc.).

3.6.4 In situ LST for heterogeneous surfaces

For heterogeneous surfaces consisting of several ‘flat’ endmembers (i.e. their cover fractions are independent of viewing and illumination geometry) the measurement protocol for homogenous surfaces (section 0) is applied to each endmember and LST can be obtained using equation 4. However, this usually requires multiple radiometers since the BT and LSE of each endmember need to be simultaneously available. For non-flat endmembers, e.g. trees, cover fractions need to be projected to the ground for a specific viewing and illumination geometry, e.g. for a satellite at overpass time, so that a matching in situ LST can be obtained. A further complication arises from the associated variable shadow fraction. Therefore, obtaining accurate in situ LST over non-flat (‘vertically structured’) heterogeneous land surfaces usually requires some modelling ([34], [20], [15]) or is limited to night-time.

3.7 FIELD CALIBRATION OF LST FRM TIR RADIOMETERS

Following the same methodology as in the laboratory, a portable blackbody allows calibrations of LST FRM TIR radiometers on the field site, which may be important during extended measurement campaigns. Ideally FRM TIR radiometers should be continuously calibrated to an accuracy of ±0.1 K, which can be achieved with radiometers stabilised by two blackbodies ([13], [45], [51]). However, such systems are relatively expensive and difficult to operate under field conditions, particularly by a single person; therefore, their typical use is in SST determination and in inter-calibration experiments ([13], [26]). Furthermore, natural land surfaces tend to be heterogeneous on various spatial scales and obtaining representative in-situ LST may require several radiometers. Therefore, commercially available and more affordable radiometers are used, which typically achieve accuracies better than ±0.3 K over the temperature range relevant for the land surface [51]. The radiometers should be independently calibrated at regular intervals, which depend on radiometer type: this is the usual calibration process under laboratory conditions. However, land surface temperature is a highly dynamic quantity, with diurnal temperature amplitudes of up to 40 K and differences between target and instrument reaching more than 20 K, which has a considerable effect on measurements with un-cooled radiometers. Although limited by their natural heterogeneity and spatial LST variability, surfaces that are approximately homogeneous on the spatial scale of the ground-based radiometer can be used for inter-calibration. 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 (from mean BT) exceeding a certain threshold, 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.

- Identical ‘sky’ radiometers can be inter-calibrated using a sequence of zenith angles, e.g. from 70° (and thus avoiding the horizon) to 0°, which typically provides a range of BTs from below surface air temperature to zenith sky BT.

- Inter-calibration of *different type* radiometers: 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: as for the two cases above, but covering a wider range of target and instrument temperatures. Generally requires automatic data recording.

The following field (inter-)calibration protocol for LST FRM TIR radiometers is proposed:

- All radiometers shall be calibrated (e.g. to better than ±0.3 K) and traceable to primary reference blackbodies, e.g. from NPL, PTB, or NIST.
- Ideally, radiometers are re-calibrated against a blackbody (e.g. at the high and low end of the expected temperature range) before and after a field campaign
- 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
- 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.
- Radiometer inter-calibrations over natural surfaces require that their 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 by simultaneous measuring with several radiometers at different locations or by quickly moving a single radiometer across the site (i.e. within 1-3 minutes).
- Spatial LST variability over homogeneous surfaces is the least for low wind speeds under completely clear or cloud-covered skies; at night-time land surfaces are often close to isothermal and provide the most favourable inter-calibration conditions.

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Appendix A Protocol for the comparison of Land surface Temperature Measurements under Field conditions in Namibia

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A1 INTRODUCTION

Seven years will have passed since the last radiometer/blackbody comparison [1, 2] and it is considered timely to repeat/update the process. Plans are in place for the comparisons to be repeated in 2016/2017. The 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 the Gobabeb Training and Research Centre, Namibia, in 2017.
v. Field comparisons of Ice Surface Temperature (IST) scheduled to be held in the Greenland.

This document describes the procedures which are to be followed during the **Land Surface Temperature (LST) Field Comparison Exercise (FICE)**, scheduled to be performed near Gobabeb Research & Training Centre (GRTC), Namibia, during 2017.

A2 OBJECTIVES

The overarching objective of the LST FICE 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.

The objective can be sub-divided into the following:
a. Comparisons of the radiometer response to a common portable blackbody target immediately before and after the completion of the field measurements.
b. Evaluation of differences in radiometer response when viewing Land surface targets in particular the effects of external environmental conditions such as sky brightness.
c. Evaluation of differences in radiometer response when viewing the sky under different zenith angles
d. Comparison of LST obtained with the participant radiometers
e. Comparison of emissivities determined for the participant radiometers

The purpose of this document is to describe the procedure which is proposed for the LST FICE, scheduled to be held near Gobabeb Research & Training Centre, Namibia, during 2017.

A3 ORGANIZATION

A3.1 Pilot

NPL, the UK national metrology institute (NMI) will serve as pilot for this comparison. The pilot, will be responsible 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.

A3.2 Participants

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.

A3.3 Overview of the Form of LST FICE

This protocol deals with the LST FICE due to take place near GRTC, Namibia, during 2017. The FICE will cover a number of individual comparisons. Each comparison will have its own specific characteristics but will in principle take the same form, i.e. it will seek to observe a common entity of a 'target'. The main aim of the FICE is the comparison of the in-situ LST determined by the different measurement teams.

A3.4 Comparison overview

The LST FICE will take place on the gravel plains and sand dunes near GRTC. Gobabeb is located at the transition between the vast Namib sand sea and large gravel plains. Continuous in-situ measurements are performed from KIT's permanent stations 'Wind tower' and 'Plains' (see Figure 1). Both stations are located at ~ 400 m ASL in hyper arid desert climate.

Figure 1: 360 degree panorama of KIT Site 'Plains' in the Namib. The 20 m mast is left of the car.

For the LST FICE, all participant radiometers will be monitoring the LST of the same natural targets. The experiments consist of daytime and night-time measurements of all radiometers viewing a variety of natural targets, e.g. sand, gravel, dry grass, and rocks. In order to minimise differences due to LST anisotropy, the measurements will be performed at near-nadir view angles (<30°). Where instruments allow this, continuous measurements of up to 2 days will be performed.

A3.5 Timetable

The LST FICE is foreseen to take place in the first half of May 2017. Actual measurements and comparisons are expected to last 8 days; a further 7 days will be required for logistics (e.g. transfer between Windhoek to GTRC, catering, refuelling & resupplying).

A3.6 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 Namibia. 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. Namibia allows import and export on a carnet lasting up to one year, which is the method of choice. KIT 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. Any queries should be directed to:

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There are two standard options for shipping: by Air Cargo or by sea container. If the equipment is heavy, i.e. more than 100 kg, or if large batteries without IATA certificate need to be shipped, the sea container is the best choice. The participants might agree on sharing a container that is loaded in Europe and then shipped to Gobabeb with one transport. However, this is a slow method and 6 weeks of shipping time should be allowed (shipments are known to have lasted even longer). More reliable, faster and thus better for smaller equipment is air cargo. In both cases, we strongly recommend to use the services of Trans World Cargo in Windhoek: KIT has good experience with their custom clearing and handling. The cargo can either be picked up in Windhoek or delivered to Gobabeb. The latter method has the risk of rough handling and transport on the Namibian gravel roads. Therefore, we recommend the pick-up in Windhoek.

Please note that neither the Pilot nor the host have insurance for any loss or damage of the instrumentation during transportation or whilst in use during the LST FICE; however all reasonable efforts will be made to aid participants in any security.

If an instrument requires a power-line, its measurements are limited to targets found on the premises of GTRC or a generator must be provided. Only on the premises of GTRC electrical power (220 V ac) will be available to the participants, with Namibian plug fittings. Adapters can be bought in Windhoek and participants requiring a 110 V ac supply should provide their own transformer.

The participants will organise their own transport from GTRC to the LST comparison sites. Therefore, all equipment needs to fit into the 4x4 off-road vehicle rented in Windhoek. Figure 2 shows the area around GTRC (‘Gobabeb’) and gives an idea about locations and distances to the targets.

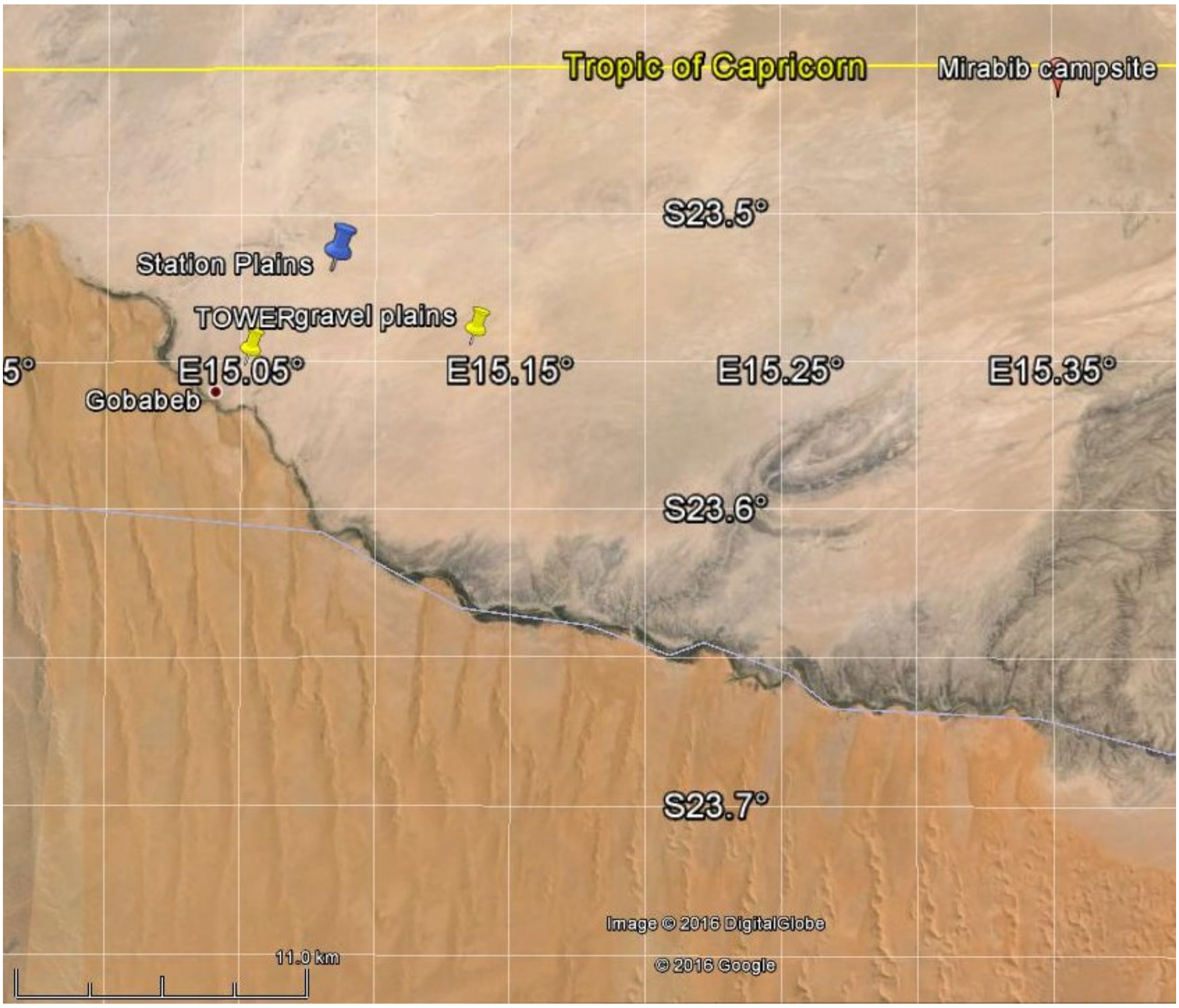

Figure 2: Landsat image of the LST FICE site. 'Gobabeb' marks Gobabeb Research & Training Centre, 'TOWER' and 'Station Plains' are KIT's permanent LST validation stations, 'gravel plains' is on the highly homogeneous part of the plains, and 'Mirabib campsite' is next to a large rock formation.

A3.7 Preliminary Information

Six months prior to the field campaign in Namibia, participants will be required to supply to the pilot a description of the instrumentation that they will bring to the LST FICE. 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 after the comparison process, participants may choose to re-evaluate their uncertainties using methods and knowledge that they may acquire during the review process.

A3.8 Visa and Permits

Officially all participants need ‘conference visa’, which requires an application some weeks before the trip; please check the current regulation for your country. However, you may decide to combine work with tourism and put the main emphasis of your trip on touristic aspects (Namibia offers fantastic landscapes and wild life): in this case you can simply obtain a tourist visa on arrival in Windhoek. However, in order to smoothly pass through immigration, you then must state that your ONLY purpose for visiting Namibia is tourism (it is NOT possible to declare several purposes).

Gobabeb Training and Research Centre (GTRC; www.gobabebtrc.org) is located in the Namib National Park and therefore all activities need allowance from the Ministry of Environment and Tourism (MET); a lengthy procedure. Since KIT co-operates with GTRC the application is much easier: The field campaign must be announced to GTRC well before the beginning of the planned activities with a brief description and a two page form needs to be filled out.

A3.9 Car rental

The Namibian gravel roads and the access to the measurement sites require a 4x4 off-road vehicle. KIT has good experience with ‘ASCO Car Hire’ in Windhoek (www.ascocarhire.com). ASCO also provides transfer from WDH Airport to downtown Windhoek, even if customers arrive at odd and different times. Participants should note that Gobabeb is – by European standards – a rather remote location. The travelling time between Windhoek, the country’s only major airport, and Gobabeb is one day. Refuelling of cars, shopping, and drawing of cash (the only excepted method of payment at Gobabeb) all requires a trip back to the nearest ‘town’, which for Gobabeb means a 120 km one-way drive on gravel roads to Walvis Bay.

A3.10 Accommodation

All sustenance and accommodation costs will be at the expense of the participants. Gobabeb provides self-catering accommodation: there is no ‘restaurant’. However, partial catering (cooked dinner) can be arranged and the various accommodations provide beds, cooking on a gas stove, a fridge and bathroom. Rooms with two beds, 5 beds and some so-called “villas” with separate sleeping rooms, a shared kitchen, bath- and living room are available. Gobabeb also provides tents and has a large number of camping facilities. Gobabeb has a simple workshop, provides slow internet access and has mobile phone reception. Electric power (220V) is limited (the entire Research Centre runs on solar power), e.g. a hair dryer will trigger the fuse. Also be aware that Namibia and South Africa use electric plugs NOT included in the usual “world traveller adapter”: it is recommended to buy an appropriate adapter on arrival in Windhoek.

A4 MEASUREMENT INSTRUCTIONS

A4.1 Traceability

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

A4.2 Measurement wavelengths

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

A4.3 Measurand

The principle measurand in this comparison is land surface temperature.

A4.4 Measurement instructions

Transportation of radiometers and all other equipment from GRTC to the field site (gravel plains, sand dunes, rock outcrops) is to be performed by the participants using their 4x4 off-road vehicles. It will be the responsibility of the owners to ensure that the radiometers are taken to the comparison site safely. Similarly it will be the responsibility of the owners to mount them to their own tripods or to the telescopic masts, which will be set up by KIT at the field site.

Due to the homogeneity and isotropy of the large sand areas the choice of sampling method for the Namib sand sea is expected to be uncritical. In contrast, the sampling of the gravel plains, which represent a mixture of gravel and dry grass, has to account for the different FOVs of the radiometers: among others, it has to be ensured that the FOVs are representative of the same gravel and dry grass mixture, which requires that they cover several square meters. For narrow FOV radiometers this can be achieved by raising them sufficiently above the ground: KIT's telescopic masts can accommodate about 4 lightweight radiometers at a time (Figure 3, left). One mast has a top load of about 5 kg and can be carried by two people. The other mast has 50 kg top load and weighs ~ 200 kg, i.e. trailer transport has to be arranged. KIT will arrange this transport and will set the mast up at the chosen locations before the start of the field work. In order to mount the instruments to the masts, KIT will provide 1 1/3" (~34 mm) metal tubes: participants need to ensure that their instruments can be fitted to this diameter. Additional tubes and fittings can be made available on request; please contact Folke Olesen at KIT to enquire.

The beginning of first day of the comparison will be spent assembling/preparing and installing the radiometers on the participants' own tripods or on KIT's telescopic mast, so they can view the surface of the targets at the appropriate angle.

Figure 3, left shows a mobile mast near 'gravel plains' on Figure 2. A single Heitronics KT15.85 IIP radiometer is mounted to its top; up to four light-weight radiometers can be fitted alongside each other. Figure 3, right shows the mounting head of the horizontal beam used for mobile measurements: the head carries one nadir looking KT15 radiometer and a second KT15 attached to a scanner. Figure 4 shows the 4x4 off-road vehicle with the beam in front of 'Station Plains' (see Figure 2).

Figure 3: Telescopic mast on the gravel plains (left) and two radiometers and a scanner mounted to the horizontal beam on top of a 4x4 off-road vehicle (see Figure 4).

Figure 4: 'Station Plains' (see Figure 2) and 4x4 off-road vehicle with horizontal beam attached to its roof for performing mobile radiometric measurements across the gravel plains.

- The test radiometers participating in this comparison must be well characterised with demonstrable traceability to SI.
- The description of each participant's radiometer and its route of traceability should be provided by completing the form shown in Appendix B.
- All participating radiometers should be mounted so that they can all view the same area of the sample being monitored.
- Four different types of targets are being envisaged. These include: gravel, sand, dry grass and rock, e.g. near Mirabib (Figure 2).

- Different approaches for obtaining hemispherical sky radiance will be compared (via representative angle of 53°, zenith observation of BT, crinkled aluminium foil).
- Participating radiometers should be mounted around the sample indicated by the Pilot and can start measurements of that sample at any time, provided all measurements are time stamped with the date and the time in UTC. This will allow the output of all participating radiometers to be compared, just as in the 2009 comparison at the University of Miami [1].
- Once all participants indicate that they have acquired sufficient data, all participants should remove their radiometers and install them on the next sample indicated by the Pilot. For radiometers mounted to KIT's telescopic mast the respective participants have to decide together when sufficient data have been acquired.
- Once measurements on the second sample have been completed, radiometers should be moved to the next sample, and so on until the LST of all samples has been measured.
- After completing a measurement sequence, participants will have to carry out any necessary post processing, e.g. calculation of emissivity and correction for reflected down-welling sky radiance etc., before submitting their final results to the pilot. This will include processed Land Surface Temperatures (LST) as well as independently estimated LSE values for each target.
- Choosing favourable environmental conditions, e.g. at night-time for clear sky and low wind speeds, the host will provide 'true' LST at one specific time for each target, allowing the participants to obtain an instrument-specific Land Surface Emissivity (LSE) that will also be part of the evaluation.
- For lightweight radiometers additional measurements from a 4x4 off-road vehicle along a 20 km track across the gravel plains will be performed (Figure 4), which will increase the number of samples and the representativeness of the results considerably [4].
- Data should be given to the Pilot in an electronic form as well as hard copy. The data for each sample should be in a table in its own excel spreadsheet. Each spreadsheet should clearly state which sample the measurements refer to. The first column of each table will give the date and UTC of each particular measurement, the second column will give the LST as measured by the participant, while the third column will give the combined uncertainty of the measurement (k=1) as estimated by the participant. The fourth column should provide other useful information such as the wavelength at which the radiometer operates and the angle at which a particular measurement was done.
- The results should be given to the Pilot at the end of the LST FICE, unless the results require further processing. However, the LST obtained from the measurements should be sent to the Pilot laboratory no later than the 2 weeks after the completion of the FICE.
- KIT will collect measurements of air temperature and relative humidity during the measurement period and make these available to the participants in case they are required in the processing of their measurements.
- Figure 5 shows the results of the continuously measuring radiometers acquired during the 2009 SST comparison at the University of Miami [1]. The results of the LST FICE will be presented in a similar form.

- Figures corresponding to Figure 5 will be created for the measurements taken on every sample measured during the LST FICE.

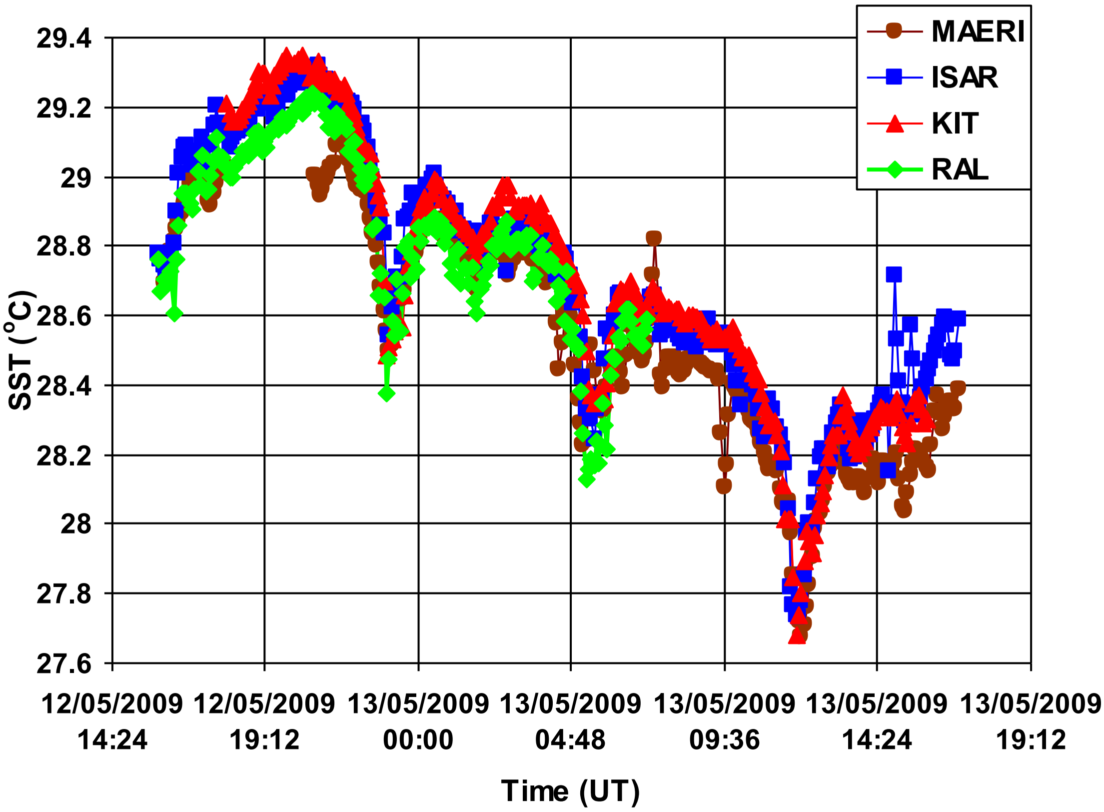

Figure 5: The results of the continuously measuring radiometers during the 2009 WST radiometer comparison. The results of the 2016 LST radiometer comparison will be presented in a similar form.

- Participants will be welcome to comment on the contents of the report and the report will be published when all queries have been clarified and issues resolved.
- A shorter version of the report will be prepared and it will be submitted for publication in a peer reviewed journal, once approved by all labs which participate in the LST FICE.

A5 MEASUREMENT UNCERTAINTY

Information on the calculation of the combined uncertainty of surface temperature measurements of sea/water/land and ice can be found in Chapter 1.

A6 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 LST FICE in Namibia). The measurement results should also be provided in an Excel format as indicated earlier in this report. The measurement report is to be supplied in a Word Template as a .doc file. 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 by 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. This will be circulated to the participants for comments, additions and corrections.

A7 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.

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APPENDIX I REPORTING OF LST MEASUREMENT RESULTS

The attached measurement summary should be completed by each participant.

The measurements for each sample should be given in separate spreadsheets.

Each spreadsheet (corresponding to each sample) should include a table consisting of four columns

The title and content of each column are given below:

Date and Time	The date and time of the measurements. The time should be UTC.
Land Surface Temperature	LST measured or predicted by participant.
Measurement uncertainty	Combined/total uncertainty of the measurement.
Other information	Other useful information, e.g. wavelength, emissivity, angle, sky BT, etc. should be given in this column. Wavelength describes the assigned centre wavelength used by the radiometer. For the case of Fourier Transform spectrometers, the wavelength range and wavelength resolution should be specified.

Later Surface Temperature Measurement Results

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

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

Time (UTC) of the measurement	Land Surface Temperature K	Measurement Uncertainty mK	Other information	

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 THE MEASUREMENTS OF LST BY THE RADIOMETER

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}
Target emissivity		$U_{Emiss.}$	$U_{Emiss.}$
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}
Down-welling skyradiance		U_{srad}	U_{srad}
RMS total	$((U_{repeat})^2+(U_{Repro})^2))^{½}$		

APPENDIX IV DATA RECEIPT CONFIRMATION

All data of the 2016 NPL LST comparison should be sent to the pilot NPL. The details of the contact person to whom the data should be sent to are:

Dr Theo Theocharous
National Physical Laboratory
Hampton Road
Teddington
United Kingdom
TW11 0LW

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

Receipt of the data will be acknowledged using the completed form shown below.

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

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

We confirm that we have received your data which resulted from the Land Surface Temperature at
NPL which were completed on .... (date).

....

....

....

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

Appendix B Protocol for the comparison of Field calibration of radiometers at ICE Temperatures (polar regions) *TIR FRM'-ICE*

Jacob Høyer
Danish Meteorological Institute

B1. INTRODUCTION

B1.1 Overview

This document describes the protocol which is proposed for the Ice Surface Temperature comparisons of the participants' radiometers during the 2016 comparison activities to be held on the Sea ice Off Qaanaaq, Greenland but linked to Laboratory based exercises to evaluate the primary calibration uncertainty of the instruments. Note that, following an initial review by participants and an assessment of by a 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.

B2 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 targets (laboratory based).
   c. Evaluation of differences in radiometer response when viewing Water/Land/Ice surface targets, in particular the effects of external environmental conditions such as sky brightness.
2) Establishment of formal traceability for participant blackbodies and radiometers

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

B3 ORGANIZATION

B3.1 Pilot

DMI, will serve as pilot for this comparison supported by NPL, the NMI of the UK. The pilot, will be responsible for inviting participants and for the analysis of data, following appropriate processing by individual participants. DMI, as pilot, will be the only organisation, other than NPL as an independent observer to have access and to view all data from all participants. This data will remain confidential to the participant and DMI/NPL at all times, until the publication of the report showing results of the comparison to participants.

B3.2 Participants

The list of participants, who will 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 NPL and PTB during the laboratory phase of this comparison series.

B3.3 Participants' details

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
Werenfrid Wimmer	Soton	National Oceanography Centre, Southampton, European Way, Southampton, SO19 9TX, United Kingdom	email: w.wimmer@soton.ac.uk

B3.4 Overview of the Form of comparisons

This protocol covers the comparison of the responsivity of the radiometers of participants, when the radiometers are observing a common entity. In the case of the IST comparison activity, the radiometers will be located on the Sea ice off Qaanaaq, Greenland and will be measuring the skin temperature of the snow and sea ice surface.

B3.5 Comparison overview

The ice surface temperature calibration comparison exercise ideally consists of all radiometers simultaneously viewing the same part of the sea ice from racks and scaffolds which are located about 4 to 5 km out on the ice from the coasts, for a variety of view angles: 25, 35º, 45º and 55°. Measurements will be performed during both daytime and night-time conditions.

B3.6 Timetable

There are three main phases to the 2016 comparison activity. The first phase prepares for the measurements; the second phase is the execution of the measurements themselves and the third phase is the analysis and report writing.

Table 2. Comparison activity- Phases

PHASE 1: PREPARATION	
Invitation to participate	October 2015
Preparation and formal agreement of protocol	Jan - March 2016
PHASE 2: MEASUREMENTS	
Field comparison experiment	March-April, 2016
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

B3.7 Transportation of instrumentation

It is the responsibility of all participants to ensure that any instrumentation required by them is shipped with sufficient time to clear any customs requirements of the host country, in this case Greenland/Denmark. 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. DMI 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 Jacob Høyer at jlh@dmi.dk .

Electrical power (220 V ac) from a mobile generator on the ice, will be available to all participants. In addition, 24 V dc batteries will be available at the site on the ice. Participants who require a 110 V ac supply should provide their own adaptor.

B3.8 Preliminary Information

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

B4 MEASUREMENT INSTRUCTIONS

B4.1 Traceability

All participant radiometers should be independently traceable to SI units with documentary evidence of the route and associated uncertainty [5]. 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.

B4.2 Measurement wavelengths

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

B4.3 Measurand

The principle measurand in all comparisons is brightness temperature.

B4.4 Measurement instructions for IST comparison

Day-time IST 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 a rack or scaffold next to the observation area 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 ice 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 and aligned to view the area of the ice 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 and snow-proof enclosure to protect the radiometer components. A better protection is provided by using a rain or snow sensor that can trigger a protective response.

- Under conditions of high wind, the mounting position should be chosen to avoid any snow piles 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 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 (Ice 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, in and outgoing radiation, relative humidity and wind speed during the measurement period and make these available to the participants.

- The host will collect measurements of the ice and snow surface conditions, such as the snow depth, grain size, density and the ice thickness. The observations will be made 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 mounting rack as well as having to deal low ice emissivities which occur for large view angles.

- After completing the above measurement sequence and upon returning to the Qaanaaq settlement, participants will have 14 days to carry out any necessary post processing e.g. sky brightness correction etc. before submitting final results to the pilot, which will include processed Ice Surface Temperature (IST) 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 IST 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.

B4.5 Declaration of Comparison completion

The above process should ideally be considered as a single comparison and the results analysed. Before declaring the results to the participants, the pilot will consult with all participants about the nature of the meteorological conditions of the comparison and with additional knowledge of the variance between declared results determined if a repeat should be carried out. At this stage participants may be told the level of variance between all participants but no information should be given to allow any individual result or pair of results to be determined. If the participants consider that the process should be repeated, as a result of poor conditions, then the results of that "day-night" will remain blind except to the pilot.

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

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

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

B5 MEASUREMENT UNCERTAINTY

Information of the calculation of the combined uncertainty of the surface temperature measurement of ice can be found in Chapter 1 of this document.

B6 REPORTING OF RESULTS

On completion of the acquisition of measurements, as indicated above, they should be reported to the pilot. In the case that an SI lab calibration experiment is carried out after the field campaign, which is the case for the IST FICE, an update can be performed to the data set, adjusting for the offsets found in the lab.

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

B7 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.

The results will be analysed based on results and instrument calibrations declared by the participants and also as corrected for any variances to SI following the laboratory comparison exercises carried out at NPL.

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.

B8 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.

5. E. Theocharous, N. Fox, F. Göttsche Olesen, J. L. Høyer, W. Wimmer and T Nightingale, "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", ESA Contract No. 4000113848_15I-LG, 2016.

Appendix I: Reporting of Measurement results

The attached measurement summary should be completed by each participant for each completed set of IST 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 Ice 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 ice from Nadir.

IST Measurement Results at Inglefield Bredning, off Qaanaaq, Greenland

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

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

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

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

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 IST measurements at Inglefield Bredning, off Qaanaaq, Greenland

The table shown below is a suggested layout for the presentation of uncertainties for the measurement of the IST at Inglefield Bredning off Qaanaaq, Greenland. 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}
Ice/snow emissivity		U_{emiss}	U_{emiss}
Ice/snow 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 IV: Data receipt confirmation

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

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

From:

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-