Fiducial Reference Measurements for validation of Surface Temperature from Satellites (FRM4STS) – Methodologies for maintaining FRM TIR radiometer calibration under LST field conditions

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Fiducial Reference Measurements for validation of Surface Temperature from Satellites (FRM4STS) – Methodologies for maintaining FRM TIR radiometer calibration under LST field conditions

Protocol for the FRM4STS LST FICE (FICE-IP)

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ACRONYMS AND ABBREVIATIONS

ASL	Above Sea Level
CEOS	Committee on Earth Observation Satellites
FICE	Field Inter-comparison Experiment
FOV	Field of View
GTRC	Gobabeb Training and Research Centre
KIT	Karlsruhe Institute of Meteorology
LSE	Land Surface Emissivity
LST	Land Surface Temperature
MET	Ministry of Environment and Tourism
NPL	National Physical Laboratory
PTB	Physikalisch-Technische Bundesanstalt
SST	Sea Surface Temperature

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 variables 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”. However, it is essential that such quantities are fully anchored to SI units and that there is a direct correlation with “true” surface/in-situ based quantities, which must be derived from completely independent measurements, i.e. without using any data from the satellite data processing.

There are currently several systems and instruments which provide state of the art ground based validation 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. Thus it is intended to complement the laboratory comparison experiments (LCE) in this project with field inter-comparison experiments (FICE). The most accurate of these surface based measurements (used for validation) are derived from field deployed IR radiometers. These are in principle calibrated traceably to SI units, generally through a reference radiance blackbody. Such instrumentation is of varying design, operated by different teams in different parts of the globe. It is essential for the integrity of their use, to provide validation data for satellites both in-flight and to provide the link to future sensors, so 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 in 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”.

This document reviews methodologies used to maintain and verify calibration of LST FRM field TIR radiometers and how calibration is practically verified and describes a protocol for evaluating and documenting differences in FRM TIR radiometer performances under field conditions. Note: following an initial review by participants and an assessment of number of participants some of the introductory sections of this protocol will be revised and made more generic to allow the protocol to be a standalone document for future use.

2 OBJECTIVES

The purpose of this part of Technical Report 1 (D-80) is to give a review of methodologies used to maintain and verify calibration of FRM field TIR radiometers in Land Surface Temperature Comparisons.

3 REVIEW OF CALIBRATION METHODOLOGIES (LST)

Measurement campaigns with FRM TIR radiometers are often performed to validate satellite-derived LST products. Typically such campaigns last between a few days and a few weeks and are performed over naturally homogenous sites, e.g. rice fields ([1], [2], [3]), grasslands [4], arid regions ([4], [5]), or agricultural sites [6]. Ideally all deployed radiometers should be calibrated against blackbodies before and after each field campaign; in practise calibration activities are limited by resources and performed less frequently: the permissible interval depends on the stability declared by the instrument manufacturers. Portable blackbodies, e.g. the 'Landcal P80P' (www.landinst.com), are used by several researchers ([7], [8]). Following the same methodology as in the laboratory, a portable blackbody allows calibrations of LST FRM TIR radiometers in 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 ([9], [10], [7]). 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 ([9], [11]). 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 [7]. 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. Ideally, radiometers should be calibrated over the entire range of expected combinations of target and instrument temperatures, where the latter is often close to environment (e.g. air) temperature. In practise, calibration exercises that include variable instrument temperatures are not readily performed by users and, therefore, are frequently limited to the calibration performed at the manufacturers.

The potentially large differences between target and instrument temperature mean that field radiometers used for LST determination have to have some type of 'internal blackbody' which they can use to perform a bias adjustment. This is usually achieved by measuring the instrument's temperature with a precision resistance thermometer and applying non-linear calibration functions. Two types of radiance sensors are commonly used for TIR radiometers: thermopile detectors (e.g. Apogee SI-111, Apogee Instruments, Inc., Logan, UT, USA) and pyroelectric sensors (e.g. KT15.85 IIP, Heitronics GmbH, Wiesbaden, Germany). Pyroelectric sensors only respond to radiation differences and, therefore, must use an optical chopper (blades interrupting the incident radiation); main advantages are long-term stability (KT15.85

IIP radiometers drift by less than 0.01% per month) and high spatial resolution ([11], [5]). The high stability is achieved by linking the radiance measurements via beam-chopping (a differential method) to internal reference temperature measurements and was confirmed by a long-term parallel run with the self-calibrating radiometer “RotRad” from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), which is continuously stabilized with 2 blackbodies [11]. Using external blackbodies, the Heitronics KT15.85 IIP radiometer was shown to have an absolute accuracy of better than ±0.3 K over the relevant temperature range [7].

Additionally, experimenters use several practical methodologies to monitor instrument calibration in the field, i.e. to detect abnormal instrument behaviour or possible drift. Essential for inter-calibrations is that the radiometers observe an area that over-fills the FOVs of all radiometers and is (approximately) homogenous and isothermal on the scale of their footprints. For night-time measurements with four radiometers (FOV of 32 cm) distributed 50 m apart from each other over a uniform grassland [12] and [13] obtained temperature differences of up to ±2 K. Increasing the FOV of two radiometers 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 while over snow a spatial variation of in situ LST of ±0.2 K was determined. [14] used spatially distributed radiometers to obtain surface temperature over a rice paddy near Valencia, Spain. The radiometers were about 150 m apart from each other and carried in 3 minutes along 100 m transects; sky radiance was measured at each end. The crop surface was observed at near nadir angles (FOV ≈ 30 cm) and spatial and temporal LST variability was characterised by a standard deviation of typically ±0.5 K; at the same time this procedure inter-calibrates the radiometers. The following practical field methods for inter-calibrating LST FRM TIR radiometers can be used:

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

- Inter-calibration of *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.

For LST determination down-welling hemispherical 'sky' irradiance has to be obtained (approximately) at the time as the BT measurements over the target; favourable conditions are complete clear skies and complete cloud-covers [15]. Down-welling hemispherical radiance can be estimated from directional radiometric measurements of

1. sky BT at the 'representative zenith angle' of 53° ([1], [16], [17])
2. sky BT at 0° zenith angle and a known relationship [15]
3. BT over a diffuse gold plate or crinkled aluminium foil ([18], [19])

The first approach does not require any further calculations or measurements while the second approach is easier in terms of directional alignment. The third approach requires that the reflector's temperature and emissivity spectrum are known; however, since the used targets have very high reflectance in the TIR (e.g. 97%), the TIR radiance emitted by them is a relatively small part of the measured signal ([18], [19]). Depending on the spectral range of the radiometer the measured sky BT can be very low, e.g. down to -100 °C for clear dry atmospheres over deserts when measuring at 0° zenith angle [20]. 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 [21]. When identical 'sky' radiometers are available they can be inter-calibrated using a sequence of zenith angles, e.g. from 70° (and thus avoiding the horizon) to 0°, which provides a range of BTs from below surface air temperature to zenith sky BT.

4 FIELD CALIBRATION OF LST FRM TIR RADIOMETERS

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

- 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
- 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.
- 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 [22]
- Radiometers with different FOVs (e.g. 44° vs. 8.5°) shall be inter-calibrated over surfaces with negligible anisotropy, e.g. dense rice fields.
- Radiometers with different spectral ranges (e.g. 8-14 µm vs. 9.6-11.5 µm) shall be inter-calibrated over surfaces with TIR emissivity ≈ 1, e.g. water.
- All clocks shall be synchronised to time UTC
- Each measurement time shall be given in UTC and its corresponding geolocation shall be given in decimal degrees latitude / longitude
- All data shall be recorded in a common table format, e.g. as for the FRM4STS LCE
- Relevant technical details of each instrument shall be recorded, e.g. make & type, serial number, spectral range and calibration details
- Information about wind, cloud-cover, air temperature and humidity, the type of land cover, etc. shall be recorded

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