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Title : **Report on planning the next CEOS international TIR radiometer inter-comparison exercise.**

Abstract : This document contains the report for the planning of the next CEOS international TIR radiometer inter-comparison exercise.

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1. INTRODUCTION

This report covers the planning of the next CEOS international thermal Infra-red (TIR) radiometer inter-comparison exercise. The report is part of the work carried out under FRM4SST CCN1 work package 60 (D-190).

Inter-comparisons of TIR radiometers are an essential part of a traceability chain needed to tie measurements of sea surface temperature (SST) to a common international SI standard maintained by a National Metrological Institute (NMI) such as NPL or NIST. These exercises have to be done at regular intervals of 3 to 5 years to verify the stability of, and to make improvements to, TIR radiometer measurements and the protocols guaranteeing the quality of such measurements. Furthermore inter-comparisons are a crucial part in the assessment of TIR radiometer uncertainty models, which are a critical part of the measurement system that enable these measurements to be called fiducial reference measurements (FRM).

This report first looks at the protocols written for the 2016 inter-comparison; secondly, the lessons learned from the 2016 inter-comparison. Then we look at the engagement of the National Physics Laboratory (NPL) and potential participants from the TIR radiometer network. Finally, we provide a conclusion with recommendations.

2. REVIEW OF LAST INTER-COMPARISON

The last inter-comparison of TIR radiometers was carried out in 2016 at NPL in Teddington, UK for the laboratory based activates and at Wraysbury, UK for the field based part of the SST measurements.

Theocharous et al (2016) defines two ways of achieving traceable calibration of radiation thermometers; either using internal blackbodies or external laboratory-based blackbodies. Regardless of what approach is used, the blackbodies must be fully characterised to have traceability of the measurements of the radiation thermometers to international SI standards. The inter-comparison in 2016 focused on the verification of the external laboratory-based blackbodies used by the radiation thermometer operators. These external blackbodies are either used to verify the calibration of the internal blackbodies in the case of operators using instruments following the internal blackbody traceability route or used for the calibration and traceability of the instrument in the case where operators adjust the internal calibration to an external blackbody.

For the purposes of the traceable measurement of SST using radiation thermometers such as SISTeR (Barton et al. 2004), ISAR (Donlon et al., 2008) or M-AERI (Minnett et al. 2001), Theocharous et.al (2016) recommend that the traceability chain is via an external transfer standard blackbody which is itself calibrated by an NMI against a reference standard blackbody or directly against the NMI reference standard. This calibration chain would require the following minimum calibration steps:

1) Calibration of the radiance temperature (related to spectral radiance via Planck's equation) of an external transfer standard blackbody against SI units (e.g. an NMI-owned reference standard blackbody). The calibrated transfer standard blackbody will then be used to calibrate the SST, land surface temperature (LST) or ice surface temperature (IST) -measuring radiation thermometer (see next step);

2) Calibration of the SST/LST/IST-measuring radiation thermometer against the calibrated transfer standard blackbody (which was calibrated under step (1));

3) Measurement of the target surface temperature using the calibrated radiation thermometer (calibrated under step (2));

4) Comparison with one or more (ideally at least three for statistical purposes) independently calibrated radiation thermometers whilst viewing a common target.

Theocharous et.al (2016) states step(4) as not necessary if looking at the minimal requirements for a traceability chain, but recommends this step to establish the evidence needed to demonstrate that the user of the instrumentation follows an appropriate and consistent procedure when taking measurements. Theocharous et.al (2016) goes further in claiming that, from a NMI point of view, step (4) is fundamental as it is the only true way of establishing the robustness and reliability of the declared uncertainty budgets.

QA4EO recommends that an uncertainty budget should be developed for each of the steps in the traceability chain. This means that, for the four steps above, that each previous step's uncertainty is a component of the following step, for example the uncertainty of step (1) is a component of the uncertainty budget of step (2) and so on.

2.1 Blackbody inter-comparison

Looking at the protocols as published above and in Theocharous et.al (2016) and Theocharous et.al (2017), the principle is sound and the main improvements for the next inter-comparison come from the practical implementations of those principles. The main issues found in 2016 are listed in the lessons learned in Table 1. In general the arrangement at the blackbody inter-comparison in 2016 worked quite well, with the blackbodies being arranged all in a line on an optics table and the reference radiometer on a height adjustable table that was moved to the measured blackbody at each measurement time slot, as shown in Figure 1. However, as shown in Table 1, there were a few areas that could be improved, with the main issues being in positioning the reference radiometer (supplied by NPL) in such a way that it fills the blackbody aperture and the time needed to set up the blackbodies before the measurements, which was a bigger issue for the non-temperature-stabilized blackbodies, as the temperature will move and any delay from the proposed measurement start time will change the start temperature.

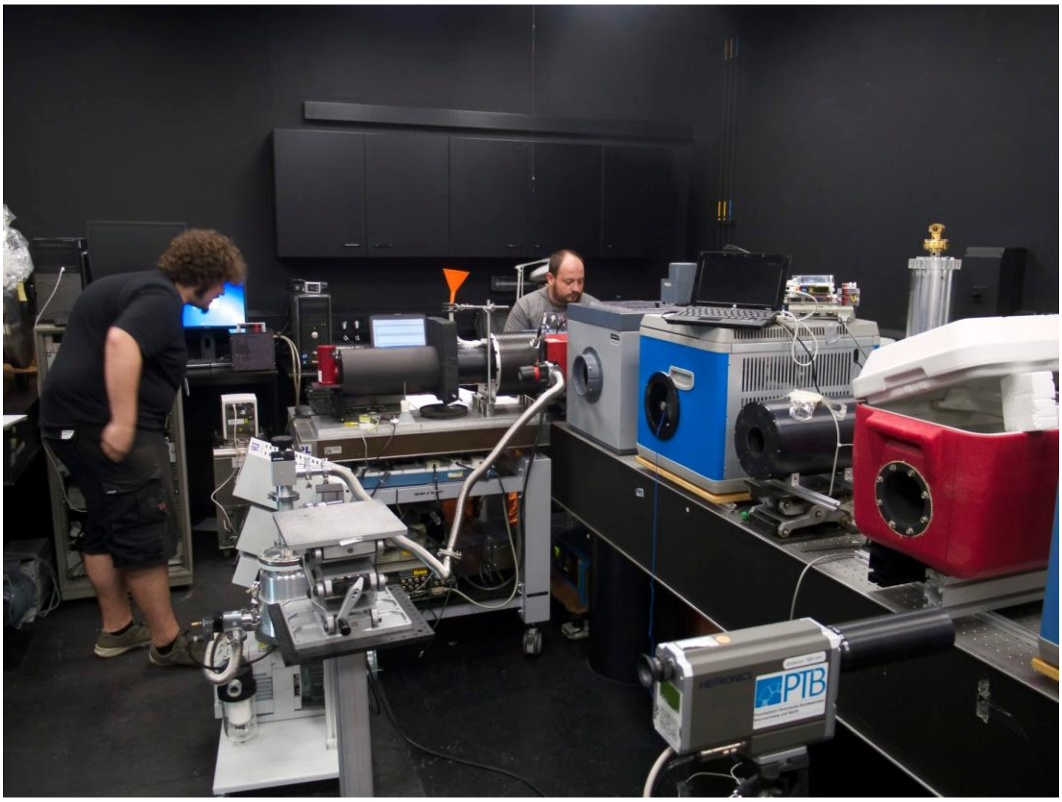

Figure 1: Blackbody inter-comparisons at NPL in 2016. The coloured boxes on the optical bench are participants' blackbodies with the PTB (right) and NPL (left) reference radiometers in the foreground.

Table 1: Lessons learned from the 2016 blackbody laboratory inter-comparisons (see Theocharous et.al (2017)).

No	Area	Comment
1	FoV	The FoV of the reference radiometers being used should be small enough to ensure that they are well overfilled by the aperture of the cavity of the blackbodies participating in the comparison.
2	Positioning / FoV	Because different reference radiometers being used could have different FoVs, it is recommended that in future, reference radiometers should be placed at different distances from the apertures of the participating blackbodies to ensure that the FoVs of the radiometers "cover" the same (identical) area of the back walls of the blackbodies. The aim of this is to ensure that the same temperature non-uniformities of the blackbodies are seen (and averaged out) by every reference radiometer.
3	Positioning	In cases where the reference radiometers cannot be placed close to the aperture of the cavity of a participating blackbody, the extra distance between the blackbody 102 cavity aperture and the radiometer should be included in the calculations to ensure that the blackbody aperture still overfills the FoV of the reference radiometers.

4	Positioning	When two or more reference radiometers are used to measure the participating blackbodies, the areas of the cavity of the blackbody observed by the different radiometers should be the identical. Furthermore, the areas viewed should be large enough to average out possible spatial non-uniformities in the temperature present in the blackbody cavities.
5	Temperature	Participating blackbodies whose cavity temperatures are not actively stabilised but are allowed to drift should endeavour to keep the magnitude of the drifts as low as possible in order to minimise any differences which could arise due to the timing of the measurements.
6	Temperature	The temperature of the cavity of participating blackbodies being viewed by the reference radiometers should be as spatially uniform as possible. The reference radiometer should be measuring and reporting the temperature along the optical axes of the participating blackbodies.

2.2 TIR radiometer inter-comparison

This section covers the laboratory-based part of the TIR radiometer inter-comparison. Here the reference blackbody, as provided by NPL was fixed and the participants' radiometers were moved in front of the reference blackbody when it was time to be measured. The arrangement is shown in Figure 2 with ISAR 03 as an example TIR radiometer.

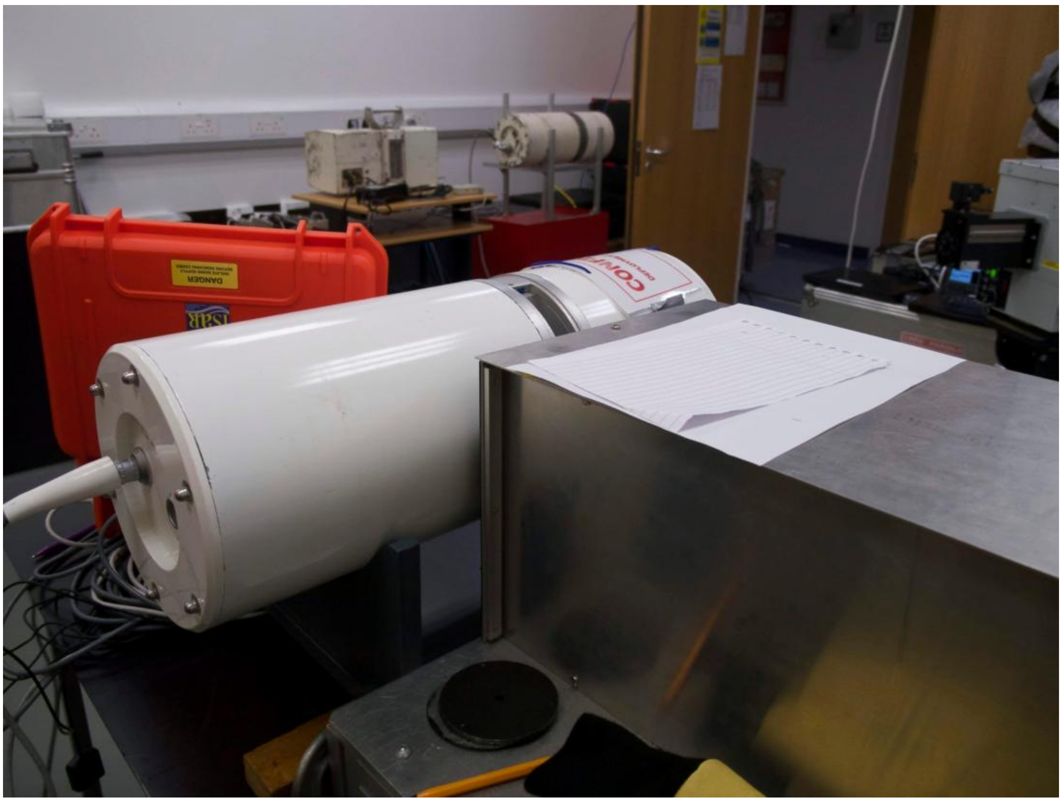

Figure 2: ISAR 03 in front of the reference blackbody at NPL in 2016.

As before, the main issues during the inter-comparison are listed in Table 2. The main issues for the TIR radiometer inter-comparison were again field of view and timing related. While the field of view issue can mainly be improved by a more standardised setup, the timing issue is a bigger problem to solve. This is mainly because of the following points:

1. The TIR radiometers have heated (blackbodies) and cooled (detectors, only some) elements which need between 30 and 60 min to stabilize, so the TIR radiometers need to be setup and powered before their allocated time slot in front of the reference blackbody.

2. Moving the TIR radiometers in a powered state in front of the reference radiometer is logistically not trivial, as the TIR radiometers are different shapes and sizes ranging in weight from a few kg to 100kg. Figure 2 shows an ISAR which is in the middle of the range size-wise and weight-wise, whereas Figure 3 shows a M-AERI which is one of the larger instruments both in weight and size.

3. The different shapes and sizes of TIR radiometers also mean the field of view (FoV) is different which needs addressing when using a reference blackbody with a fixed aperture size.

Figure 3: M-AERI mark 2 in front of the reference black body at NPL in 2016.

Table 2: Lessons learned from the TIR radiometer inter-comparison at NPL in 2016.

No	Area	Comment
1	FoV / Aperture	The aperture of the reference blackbody should be large enough to enable the FoV of the participating radiometers to be well overfilled by the reference blackbody aperture.
2	Positioning / FoV	In cases where the radiometer cannot be placed close to the reference blackbody aperture, the extra distance between the reference blackbody and the radiometer should be included in the calculations to ensure that the reference blackbody aperture still overfills the FoV of the radiometer.
3	Positioning	Because different radiometers have different FoVs, it is recommended that in future participating radiometers should be placed at different distances from the reference blackbody so that the FoVs of the radiometers “cover” the same (identical) area of the back wall of the reference blackbody. The aim of this is to ensure that the same temperature non-uniformities of the blackbody cavity are seen (and averaged out) by every participating radiometer.
4	Positioning	The area of the reference blackbody observed by the different radiometers should be large enough to average out possible spatial non-uniformities in the temperature of the cavity of the blackbody.
5	Temperature	The temperature of the reference blackbody which is viewed by the radiometers should be as spatially uniform as possible.
6	Emissivity of BB	The emissivity of the reference blackbody should be provided to all participants in order to enable them to calculate the corrections which will account for the reflections from the blackbody cavity.
7	Timings to align and measure	During the 2016 radiometer comparison, a 30 minute period was allocated to each participant to allow for the alignment of the radiometer to the reference blackbody aperture and the making of the measurements at a particular blackbody temperature. Some participants reported that 30 minutes was not enough. However, because of the number of radiometers participating in the 2016 comparison and the number of temperatures which had to be completed over the week-long comparison, the 30 minute period could not be extended. It is recommended that in future comparisons, participants should be asked to state how long they would ideally like to align and complete a measurement (at a particular blackbody temperature). If the total duration of the comparison could not be extended, or the number of participating radiometers could not be reduced, then the number of reference blackbody temperatures at which measurements are done should be reduced to allow participants the extra time periods they require to complete their measurements.

2.3 SST field inter-comparison

The SST field inter-comparison in 2016 was held at Wraysbury; a fresh water reservoir near Heathrow, UK. Figure 4 shows a number of TIR radiometer mounted on the pontoon at Wraysbury. The main lessons learned are listed in Table 3 and are mainly around the positioning of the instruments so that they view the same part of the water and sky which is not possible with a linear side by side arrangement as used in Wraysbury. Other issues were the potential of emissivity differences and potential shadows or obstructions from buildings on the pontoon.

Figure 4: TIR radiometers on the NPL platform at Wraysbury in 2016.

Table 3: Lessons learned from the SST field inter-comparison at Wraysbury in 2016.

No	Area	Comment
1	Positioning / FoV	Because different radiometers have different FoVs, it is recommended that in future WST comparisons, radiometers should be placed at different distances from the target being monitored so that the FoVs of the radiometers “cover” the same (identical) area of the water. The aim of this is to ensure that the same temperature non-uniformities on the surface of the water are seen (and averaged out) by every participating radiometer.
2	Positioning	The area of the water observed by the different radiometers should be large enough to average out possible water surface temperature non-uniformities of the target.
3	Positioning	Care should be taken to ensure that all participating radiometers are observing the same area of the surface of the water.
4	Temperature and surrounding	The surface temperature of the target should be as spatially uniform as possible, at least in the region covered by the FoV of the participating radiometers. This is usually achieved under no wind and under calm water

	environment	conditions. The wind speed and the condition of the surface of the water should be continuously monitored during the entire duration of future WST comparisons.
5	Sky conditions	WST/SST measurements should ideally be performed in clear sky conditions. Failing that, measurements should be performed when the sky is completely covered in cloud. Measurements performed under partly cloudy conditions should be avoided because of the difficulties in estimating the corrections due to the sky radiance which a partly cloudy condition introduces.
6	Emissivity	Ideally, each participant should either measure or obtain the emissivity of the sea/water from tables and use these emissivity values in calculating the surface temperature of the targets by taking into account the angle between the FoV of the radiometer and the surface of the water, as well as the wavelength band over which the radiometer has a finite response. However, it was recommended by some participants that in future comparisons, participants should be provided with a common emissivity estimate which could be used by the participants to calculate the WST of the targets.
7	Surrounding environment	When WST measurements are performed from platforms, care should be taken to prevent measurements being affected by possible blocking of surface water ripple by the structure of the platform on which the radiometers are mounted.
8	Surrounding environment	Care should be taken to prevent shadows of objects on the platform (on which the radiometers are mounted) from being in the radiometer viewing footprints. This can be achieved by mounting the radiometers on an extended arm so that they view footprints which are as far as possible away from the area affected by the shadows of the platform structure.
9	Surrounding environment	The effects of the shadows of the platform structure can be avoided/minimised by mounting the radiometers so that they face in a southern direction.

3. ENGAGEMENT OF NPL AND PARTICIPANTS

NPL has been contacted and two teleconferences have been held to discuss NPLs involvement in another exercise, similar to that in 2016. NPL has agreed that they would host another inter-comparison with two laboratory-based activities and an SST field activity. The local location for the two laboratory-based activities, the blackbody characterisation and the TIR radiometer characterisation will be at NPL in Teddington, subject to funding. NPL was also happy to implement the lessons learned from the previous inter-comparison as long as these recommendations are achievable in the time frame and funding envelope available.

Initial discussion on a location for the SST field inter-comparison centred around repeating the experiment at Wraysbury, for ease of use and the cost-effectiveness of using another NPL site. However, discussions with potential inter-comparison participants made it clear that other arrangements, with easier access for the larger instruments such as a pier, would be preferred to Wraysbury.

To engage potential users early, two teleconferences were held on 22 October 2020 at 12.00 and 15.00. The reason for two teleconferences was to engage people around the globe and allow for time differences. In total 14 people participated, with discussions centring around the lessons learned, but also on improvements and new avenues. The minutes are available from the FRM4SST project; see Wilson and Kelliher (2020).

To summarize, the main discussion points were on the laboratory timings and setup space and the SST field experiments. From these discussions it became clear that while there are some issues with the laboratory experiments, they are mainly around small improvements of the system used in 2016 while the SST field experiments need some more work in a future inter-comparison.

Not only is a more accessible location for the larger TIR radiometers needed for the field work but also some work needs to be done on improving the arrangement of the TIR radiometers so that the view is the same or that the instruments have at least overlapping views of the same part of the sea and sky. Also, a sea inter-comparison of at least two instruments should be conducted on a regular basis as this ties back into point (4) in chapter 2 of this report; however this is subject to funding.

4. RECOMMENDATION

After reviewing the lessons learned of the 2016 CEOS inter-comparison held at NPL and Wraysbury and after a user consultation, we have the following recommendations for the next inter-comparison:

1. The laboratory-based parts of the inter-comparison, the blackbody inter-comparison and the TIR radiometer inter-comparison are to be held at NPL in a similar format as in 2016.

2. Improve the timings and set-up space for the inter-comparison at NPL as much as possible, within the framework of the funding.

3. Find a new SST field inter-comparison site, which is within driving distance of NPL and accessible for the larger TIR radiometers.

4. The new SST field inter-comparison site should address the issues encountered at Wraysbury:

    1. The TIR radiometers are looking at the same area of water and sky.

    2. No obstruction or shadows from superstructures and buildings.

    3. The water is free from localised currents and surface contamination.

    4. The site is secure and has 24 access.

5. CONCLUSION

The CEOS inter-comparison at NPL in 2016 was well organised and produced good results; however there is some room for improvements for the next inter-comparison. The improvements mainly centre around adjusting the protocols to allow for a large group of operators using the reference blackbody and the NPL transfer radiometer in a very limited space and time frame.

The changes for the SST field experiment are more involved than for the laboratory experiments but the proposed changes should help to understand some of the differences shown in the 2016 experiments between the TIR radiometers at Wraysbury. A better control and characterisation of the field site should make it easier to interpret such results. This in turn will give participants not only confidence but also clear guidance so that they can improve their measurement protocols and therefore results.

Lastly, while outside this TIR inter-comparison exercise, the participation in bi- and multilateral inter-comparison on ships is highly recommend, especially by the users of TIR radiometer data in order to understand the at sea uncertainties and their verification in more detail.

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