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

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D-180 FRM4STS Final Report

Nigel Fox

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DOCUMENT APPROVAL

Contractor Approval

Name	Role in Project	Signature & Date
Prof Nigel Fox	Technical Leader	Digitally signed by Craig Donlon Date: 2019.12.17 10:38:29 +01'00'
Dr Andrew Brown	Project Manager	Andrew Brown, NPL 14 June 2019

Customer Approval

Name	Role in Project	Signature	Date
Craig Donlon	ESA Technical Officer		

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EOP-SM/2642	1	Fiducial Reference Measurements for Thermal Infrared Satellite Validation (FRM4STS) Statement of Work

ACRONYMS AND ABBREVIATIONS

AMBER	Absolute Measurements of Black-body Emitted Radiance
ASL	Above Sea Level
AVHRR	Advanced very-high-resolution radiometer
BAMS	Bulletin of the American Meteorological Society
CDR	Climate Data Records
CEOS	Committee on Earth Observation Satellites
DBCP	Buoy Data Co-operation Panel
ECV	Essential Climate Variable
FCDR	Fiducial Climate Data Records
FIDUCEO	Fidelity and uncertainty in climate data records from Earth Observations
FICE	Field Inter-comparison Experiment
FOV	Field of View
GCOS	Global Climate Observing System
GHRSST	Group for High Resolution Sea Surface Temperature
GTRC	Gobabeb Training and Research Centre
ICOADS	International Comprehensive Ocean–Atmosphere Data Set
KIT	Karlsruhe Institute of Meteorology
LSE	Land Surface Emissivity
LST	Land Surface Temperature
MET	Ministry of Environment and Tourism
MODIS	Moderate Resolution Imaging Spectroradiometer
NMI	National Metrology Institute
NPL	National Physical Laboratory
PTB	Physikalisch-Technische Bundesanstalt
QA4EO	Quality Assurance Framework for Earth Observation
SI	(Système International d'Unités) is a globally agreed system of units
SLSTR	Sea and Land Surface Temperature Radiometer
SST	Sea Surface Temperature
TIR	Thermal Infrared Radiometers
VIIRS	Visible Infrared Imaging Radiometer Suite
WGCV	Working Group on Calibration and Validation
WMO	World Meteorological Organization
WST	Water Surface Temperature

1. INTRODUCTION

Satellite remote sensing of the Earth’s surface is essential to help develop our understanding of the effects and reasons for weather patterns and impacts of climate change. For example, by following the trends of surface temperature across the world, we can further our understanding of the air-sea-land-ice interaction and use this as a stepping stone to improve our predictions of the scale and impact of climate change. However, the trends are very small and subject to a range of regional and seasonal fluctuations.

Satellite measurements, therefore, need to be as accurate as possible and provide long term (multi-decadal), data that can be robustly linked between different sensors of many space agencies flying now and with those of the past and future. The recently launched EU Copernicus Sentinel 3A and 3B spacecraft are the first two of a series of four satellites to be launched over the next two decades and follows on from the previous ATSR+ series of the last two decades. Long-time base Fundamental Climate Data Records (FCDRs) from the harmonised data of these missions requires anchoring all measurements to an invariant common reference, the international system of units (SI). This also means that we need to ensure that data from these satellites can be regularly validated across the globe through the use of surface-based measurements derived from Ocean Buoys and most accurately, field deployed radiometers (on-board ships) These Thermal Infrared (TIR) Radiometers for water bodies, land/Ice, must both also be rigorously tied to SI units.

As part of this project NPL worked with a number of international institutes, supported by European Space Agency (ESA) on behalf of the Committee for Earth Observation Satellites (http:www.CEOS.org) to identify optimal ways to improve measurement procedures and ensure consistency in uncertainty of measurements. Through the FRM4STS project we have begun to lay the foundations for greater accuracy in temperature measurements for all of the World’s surfaces and geographical climatic zones. With scientific teams operating from different countries and using different designs of instrumentation, it can be difficult to ensure that there is global consistency at the levels needed to unequivocally detect climate induced trends from natural variability. This is why it is so important to have international intercomparisons of field radiometers, like the ones organised by NPL during the project.

During the study, we were able to perform experiments in a multitude of environments. These are detailed in the following four phases of the project:

1. Phase1: Laboratory (and near laboratory) Intercomparison Exercise

2. Phase 2A: Shipborne Comparison

3. Phase 2B: Land Surface Temperature, Gobabeb

4. Phase 2C: Ice Surface Temperature, Greenland

This work isn’t just helping scientists learn how to use their instruments to their fullest or how to establish links to the international system of units, it is creating the framework of good practise for the next generation to combat impact of climate change by giving them the best tools to use and reference data from which to monitor change.

We would like to also acknowledge the considerable contribution and effort of all the participants and their funding agencies in supporting this initiative.

This report provides a summary of the activities that have been carried out and the reader is referred to the website www.FRM4STS.org for more details or the detailed reports associated with this document.

2. PROTOCOLS, AND GOOD PRACTISES

As an essential pre-cursor to the establishment of any international comparison and most importantly, coordinated framework to validate the post-launch performance of satellites requires a review and consolidation of instrumentation and methods used. For the FRM vision we then as a community need to establish what processes and activities that need to be carried out to ensure they provide consistent measurements and if appropriate the ways in which these should be done or at least reported on. This may include maintenance of instrumentation, sampling strategies, calibrations, uncertainty reporting etc. as well how to carry out comparisons to evidence capabilities and consistencies between different measurement teams operating in different conditions using differing technologies and underpinning a range of potential applications. For example, in this project the same instrument may be used to make measurements over land, ocean and ice.

For some activities and processes where consistency and repeatability is the dominant driver and where there is a reasonable level of maturity in terms of development and understanding it may be desirable to have highly prescriptive ‘recipe’ based protocols. However, for much of EO and particularly where long-time base climate quality (high accuracy) measurements are needed it is at this stage important to focus on the key aspects that allow satellite interoperability and international comparability whilst providing the freedom for on-going innovation.

The FRM4STS project has carried out a detailed review of instrumentation used, radiometers and Buoys, how they are calibrated, (in lab and in field conditions), and methods for taking measurements including associated ancillary data for all satellite surface temperature validation requirements: Land, Ice, water bodies (including from ships). The produced ‘good practises’ (D80, D90, D120) and those reported in OP 20 and OP 30 have described how traceability should be ensured and uncertainties evaluated and reported. They have subsequently been endorsed by the community.

The project similarly produced detailed protocols on how best to carry-out comparisons under a range of conditions. These comparison protocols were drafted following the same structure as those used by National Metrology institutes for formal comparisons of primary standards, adapted to meet the specific needs of EO and in some cases field conditions. These comparison protocols have been drafted so they can be used for future comparison exercises with minor updates/adaptations and are all publicly available on the FRM4STS portal. They were each developed to allow testing of performance of not only instruments and their assessed uncertainties but also the methodology of use scoping the full range of applications whilst avoiding unintentional bias that might arise from specific instrument designs.

Protocols and good practises were not only developed for radiometer based instrumentation but also for deployment and use of drifting buoys on ice (OP 70) and also for drifting non-returnable buoys for ocean temperature validation OP 20.

For the latter, drifting buoys, the project supported a number of international workshops to develop consensus on strategies resulting in the following:

- Acceptance in principle of the GHRSST Standard (Annex A Table 1) for global drifter SST implementation and reporting, subject to the eventual validation of its usefulness;
- Critically, recognition (through a preliminary study by Gary Corlett) that drifter HRSST reports were indeed driving down the uncertainty in satellite SST retrievals;
- Acknowledgement that the space component and the drifter array are elements of a composite network and that both are required for different but complementary purposes;
- Acceptance of the requirement for SI traceability of drifter SST;
- Endorsement of the efforts to harmonize and publish available drifter metadata in a global dataset;

- Agreement that mechanisms must be found to maintain the harmonized metadata dataset in the future;
- Agreement that the routine reporting of diagnostic data (e.g. drifter internal temperature) and access to collateral information (e.g. wave spectral estimates) are important components of best practice for developing drifter capability in general and SI traceability in particular;
- Agreement that a working group be established to take forward the above and to further develop standards and best practices, possibly through reactivation of the DBCP's PP-HRSST that had been disbanded in 2014.

3. PHASE 1: CEOS LABORATORY IR INTERCOMPARISON, NPL, HAMPTON, UK

Field-deployed infrared radiometers are currently being used to provide surface-based temperature measurements which are used for Calibration/Validation. These radiometers are in principle calibrated traceably to SI units, generally through a blackbody radiator. However, blackbodies and radiometers used are of varying design and are operated by different teams in different parts of the globe. It is essential for the integrity of their use, that any differences in their measurements are understood, so that any potential biases are removed and are not assigned to satellite sensors. The "comparison" with peers is one of the best ways to obtain and demonstrate such evidence and for this reason, a number of previous highly successful comparisons have taken place in Miami and at NPL. However, 6 years have passed since the last comparison and it was time to repeat/update the process and to take account more fully of Land and Ice temperature measuring communities.

Taking place for the fourth time, the results of these experiments are used as a comparison for both methodology and metrology, inviting research institutions from around the world to take part. The 2016 laboratory comparison exercise lasted three weeks and was made up of three types of comparison which are all useful for validation of satellite temperature data:

i. Controlled laboratory testing,
ii. Water Surface Temperature (WST) measurements and
iii. Land surface temperature measurements.

Both the lab and land measurements took place on site at NPL, while the WST measurements took place aboard the NPL research raft on the Wraysbury reservoir, near Heathrow airport. The latter two, were considered to be representative of real environmental conditions to evaluate sensitivities to some of these effects. Further comparisons to address these effects more fully were conducted in later phases of the project.

3.1 BLACKBODY COMPARISON

The blackbodies which participated in the 2016 blackbody lab comparison were lined up on an optical bench and their brightness temperature was sequentially measured using the NPL AMBER radiometer and the PTB infrared radiometer (see Figure 1). Measurements were made with the test blackbodies in the temperature range 0 ^{o}C to +45 ^{o}C. Figure 2 shows the difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 30 ^{o}C.

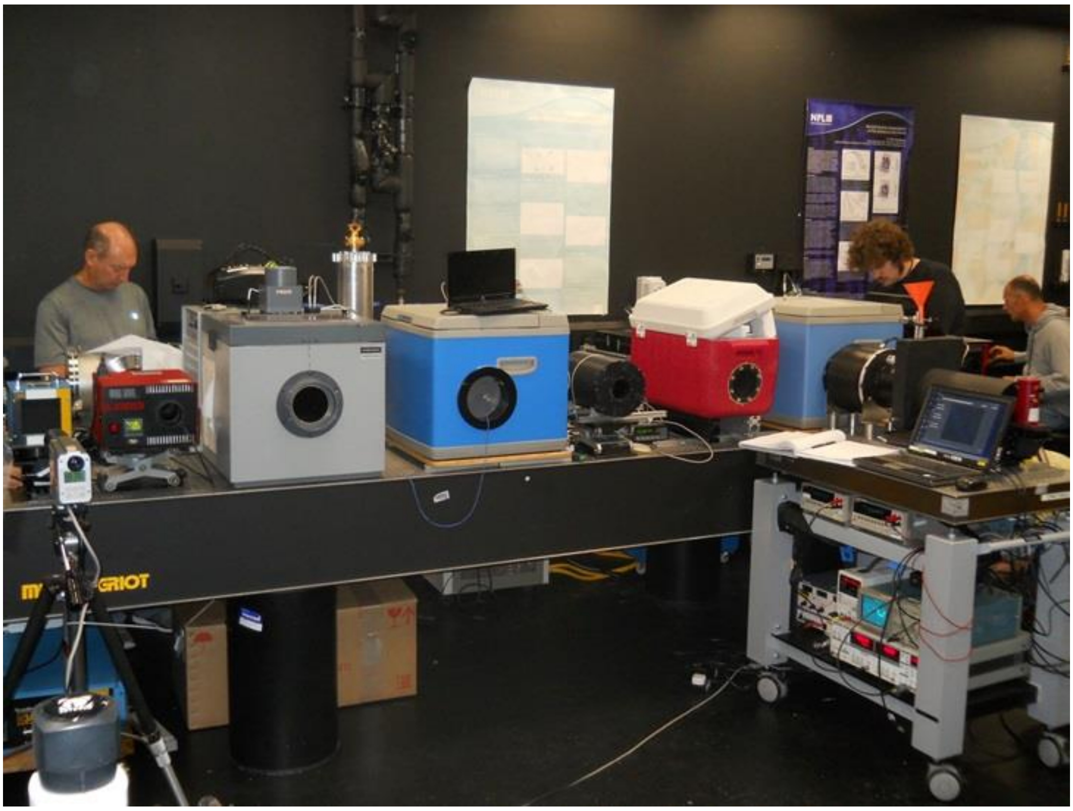

Figure 1: Eight of the blackbodies which participated in the 2016 blackbody lab comparison can be seen lined up on an optical bench. The NPL AMBER radiometer (seen on the right hand side) and the PTB radiometer (seen on the left hand side) were sequentially moved in front of each blackbody and measured their radiance temperature.

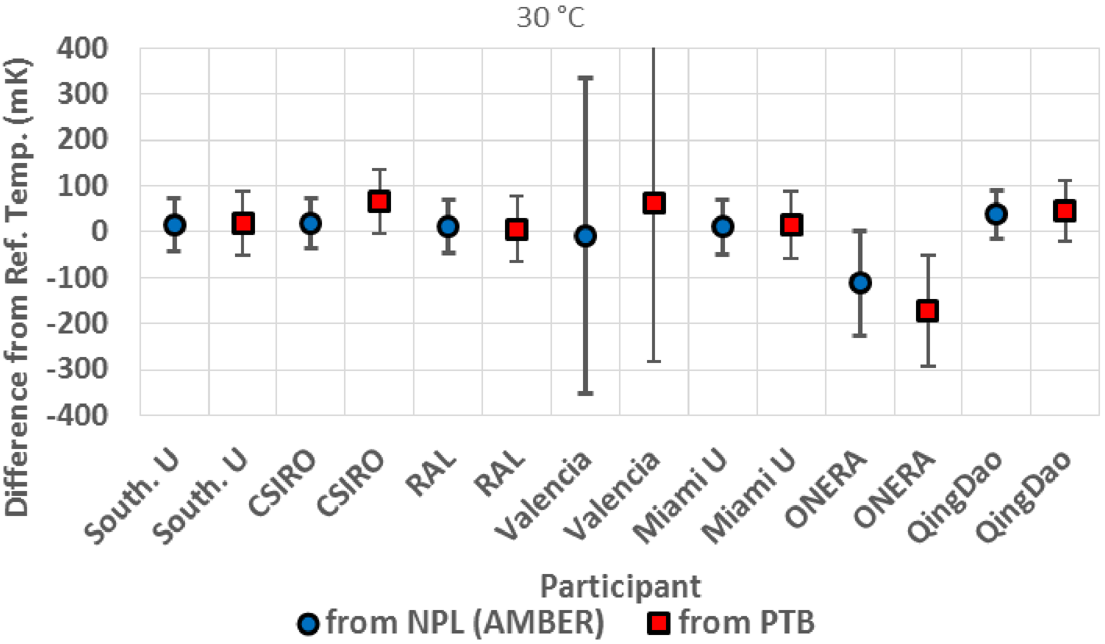

Figure 2: Difference between the mean of the values reported by participating blackbodies from the mean of the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 30 ºC.

The 2016 blackbody lab comparison shows that in most cases, the difference between the measurements made by the participating radiometers and the measurements made by AMBER and the PTB radiometers were within the combined uncertainty of the measurements. We can therefore conclude that for the bulk of the measurements, the participating blackbodies agree with the measurements made by the AMBER radiometer and the PTB radiometer in the 0 ºC to +45 ºC temperature range. Full details of the 2016 blackbody lab comparison can be found in [1] and in report *D100 - Technical Report 2: Results from the 4th CEOS TIR FRM Field RadiometerLaboratory Inter-comparison Exercise - Part 1 of 4: Blackbody laboratory comparison* which is available from the Project Documents page of the project website http://www.frm4sts.org/project-documents/.

3.2 RADIOMETER LAB COMPARISON

The radiometer lab comparison involved sequentially moving the participating radiometers in front of the NPL reference ammonia heat-pipe blackbody and measuring the brightness temperature of its cavity. Figure 3 shows the RSMAS radiometer viewing/measuring radiance temperature of the reference blackbody. Measurements were made by the participating radiometers while the temperature of the cavity of the reference blackbody was maintained at discrete temperatures in the -30 ºC to +45 ºC range.

Figure 3: The radiometer lab comparison involved sequentially moving the participating radiometers in front of the NPL reference ammonia heat-pipe blackbody and measuring its radiance temperature. The photo above shows the RSMAS radiometer viewing/measuring radiance temperature of the reference blackbody.

Figure 4 shows the plot of the mean of the differences of the radiometer readings from the temperature of the NPL ammonia reference blackbody, maintained at a nominal temperature of 30 °C. Full results of the 2016 radiometer lab comparisons can be found in reference [2] and in report *D100 - Technical Report 2: Results from the 4th CEOS TIR FRM Field Radiometer Laboratory Inter-comparison Exercise Part 2 of 4: Laboratory comparison of radiation thermometers* available from the Project Documents page of the project website http://www.frm4sts.org/project-documents/. The results of the comparison show that the differences of the radiometer readings from the corresponding temperature of the NPL reference blackbody are within the uncertainty of the measurements (with few exceptions) for blackbody temperatures above 0 ºC. However, these differences become progressively larger as the reference blackbody temperature decreased to -15 ºC and to -30 ºC. Reasons which explain these deviations are discussed in the report but in part stem from the fact that the radiometers are not primarily designed to operate in these temperature regions and most certainly not when the ambient temperature is very different.

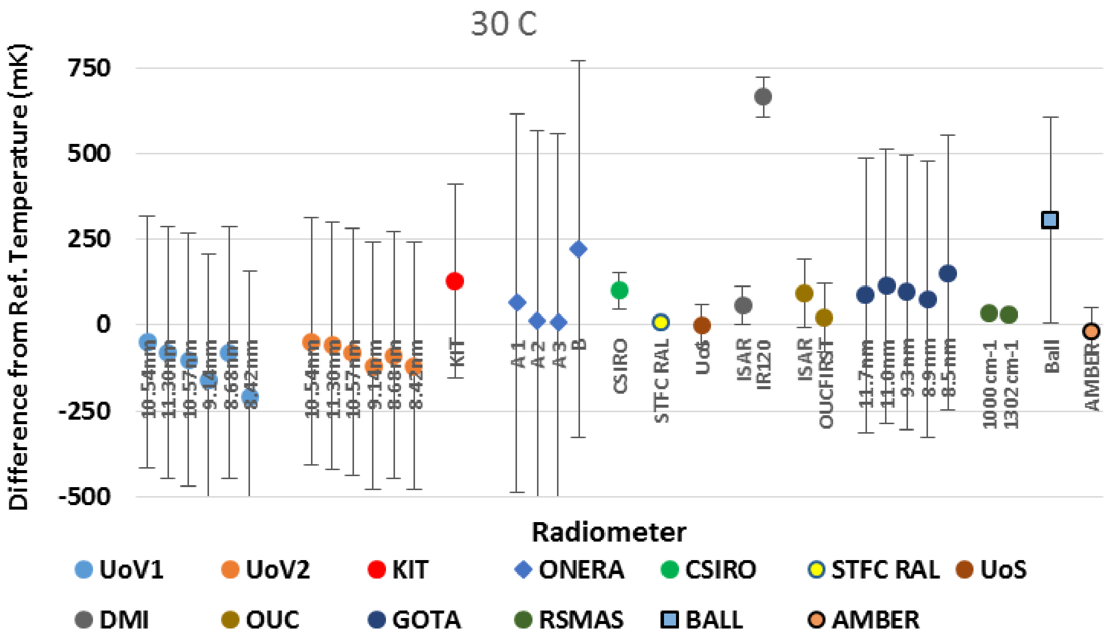

Figure 4: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL reference blackbody, maintained at a nominal temperature of 30 °C.

3.3 WST COMPARISON

The 2016 WST radiometer comparison was completed with the participating radiometers mounted on the NPL platform which is located in the middle of Wraysbury water reservoir, Middlesex, UK. Figure 5 shows a photo of Wraysbury reservoir with the platform from which the measurements were made positioned in the middle of the reservoir. Access to the platform was by boat only. Nine organisations with ten radiometers participated in the 2016 WST comparison. Figure 6 shows the radiometers mounted along the rails on the platform on Wraysbury reservoir.

Figure 5: Wraysbury reservoir with the platform on which the radiometers were mounted located in the middle of the reservoir

Figure 6: The participating radiometers mounted on the platform at Wraysbury reservoir and making measurements of the WST during the 2016 WST comparison.

Figure 7 shows the plot of the WST measurements reported by the KIT radiometer during the five-day comparison period.

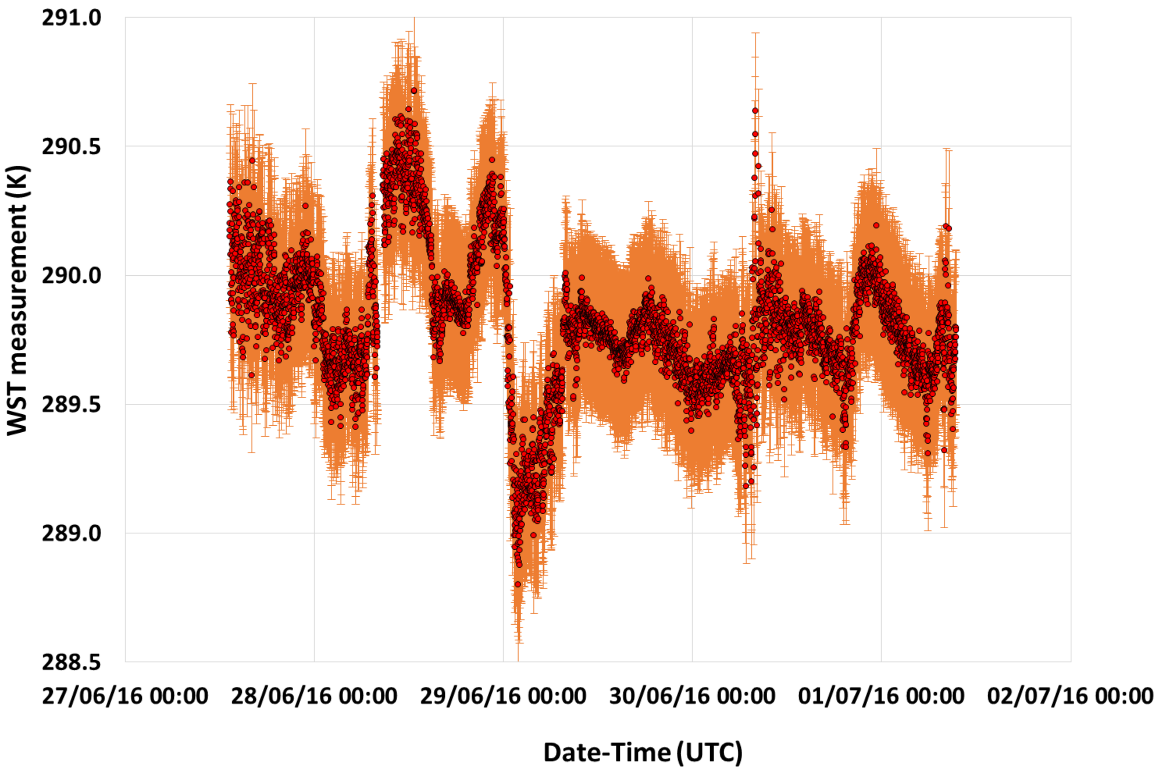

Figure 7: Plot of the WST measurements reported by the KIT radiometer during the five-day comparison period, along with the reported uncertainty shown in orange.

The radiometers participating in the 2016 WST comparison provided their results at different times and at different temporal resolutions. In order to be able to compare the measurements of the different participants, a standard interpolation method was used to estimate the WST of the participants at the same 10 second time intervals.

WST measurements should ideally be compared to a mean, determined from the WST obtained with the different radiometers, weighted by their uncertainties. However, to do this requires a full breakdown of uncertainties so that the weights can be fully evaluated and agreed upon by participants in advance. This was not possible from the data provided by some participants. An alternative approach was adopted which uses the simple mean of the radiometer measurements.

Figure 8 shows a plot of the difference of the WST measurements of the various participants from their arithmetic mean of the measurements reported by the participants, over the five-day comparison period. The comparison indicates that there are some discrepancies between the measurements of different participants, with differences of ±0.4 °C evident from the average of all measurements.

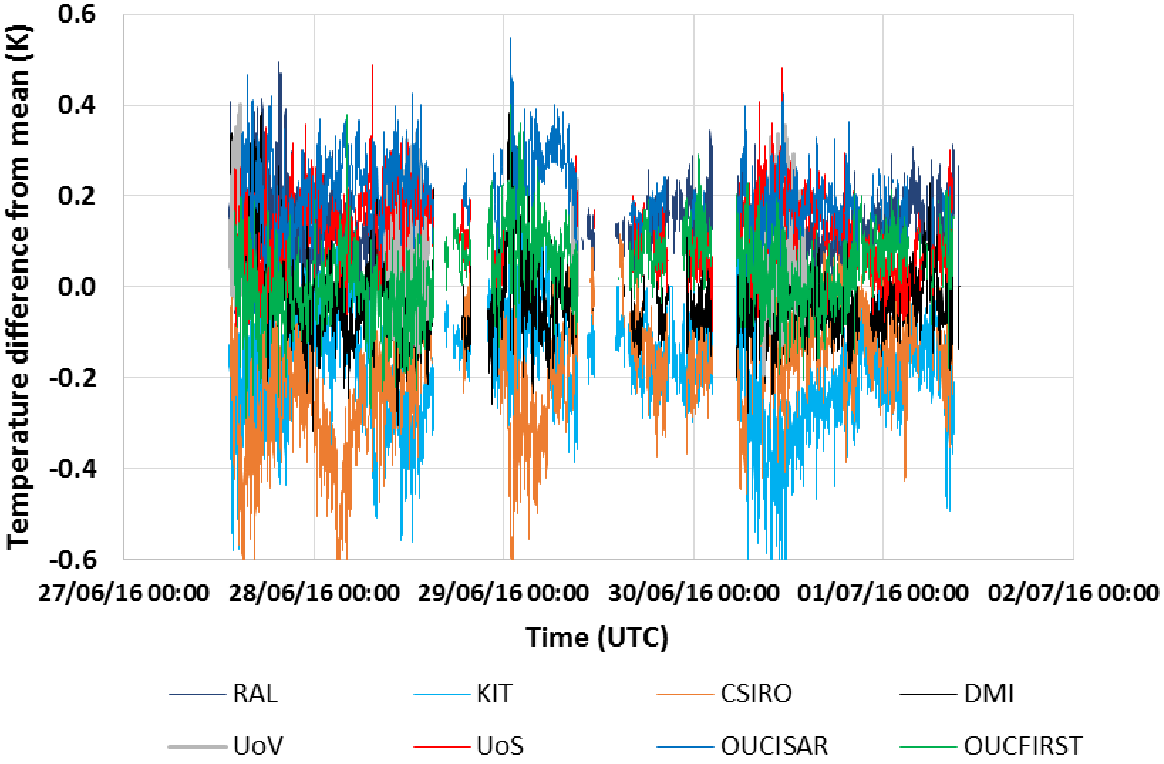

Figure 8: Plot of the difference of the WST measurements of the various participants from their arithmetic mean, over the five-day comparison period.

Full details of the 2016 WST comparison can be found in references [3] and [4] and in report *D100 - Technical Report 2: Results from the 4th CEOS TIR FRM Field Radiometer Laboratory Inter-comparison Exercise Part 3 of 4: Water surface temperature comparison of radiation thermometers* which is available from the Project Documents page of the project website; http://www.frm4sts.org/project-documents/.

3.4 LAND SURFACE TEMPERATURE COMPARISON

The 2016 LST radiometer comparison was completed with the participating radiometers mounted on steel frames in the grounds of NPL campus. Measurements were completed on a total of six different samples. Three of the samples (the short grass, clover and the asphalt/tarmac sample) monitored during the 2016 comparison occurred naturally in the NPL grounds whereas the remaining three (sand, soil and gravel) were specially set up by building wooden frames and filling them with samples purchased from a local store. Figure 9 shows one of the set ups used during this comparison activity where the participating radiometers measure surface temperature of a sand sample contained within a wooden enclosure.

Figure 10 shows a combination of a thermal image of a grass sample with a black and white visible image of the same target. The Figure shows that the apparent surface temperature of the sample was varying by about 5 ^{o}C over the measured area. The variation in temperature is due to a combination of true temperature changes due to the difference of the temperature of the sample and the air temperature as well as due to spatial emissivity variations on the surface of the sample and it is one of the contributions to the larger uncertainties associated with LST measurements.

Figure 9: Set-up for the 2016 FRM4STS LST comparison in the ground of NPL.

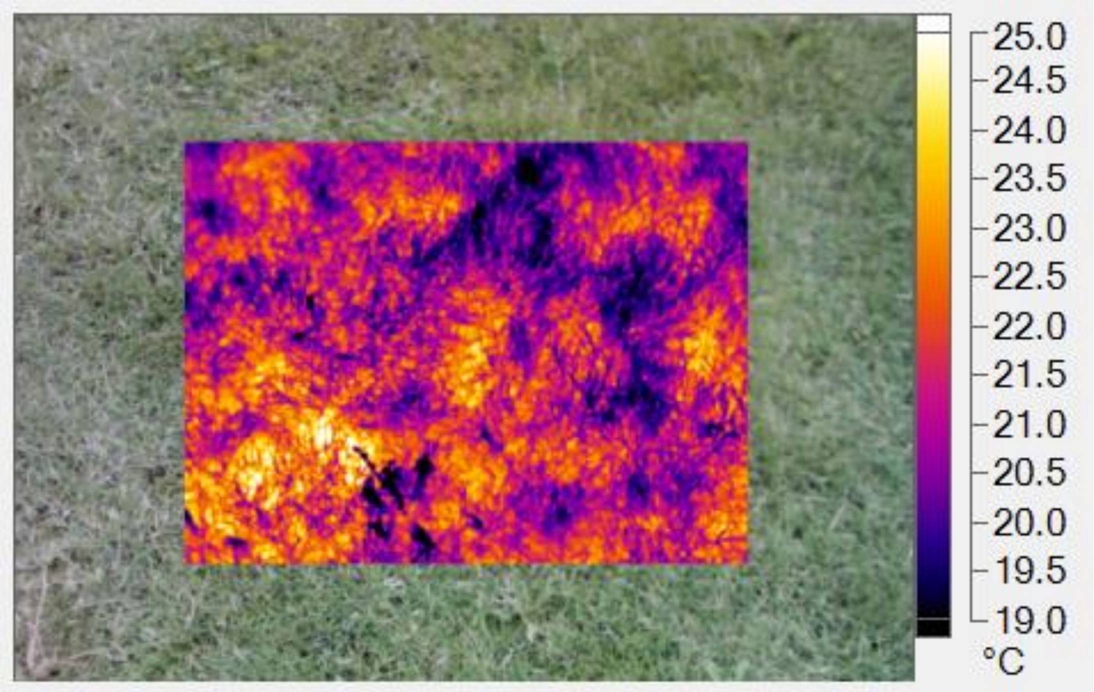

Figure 10: Image of the combination of a thermal image of the short grass sample with a black and white, visible image of the same target. The Figure shows that the apparent surface temperature of the sample was varying by about 5 ºC over the measured area.

Figure 11 shows a sample of the measurements of the surface temperature of the dark soil sample, reported by the different participants. Figure 12 shows the difference between the five measuring radiometers and their mean. Because participants provided their measurement at different times, a standard interpolation method was used to estimate the measurements of the different participants at 10 second intervals. The Figure shows that for the bulk of the measurements the difference between all five radiometers and their mean is within ±6 °C.

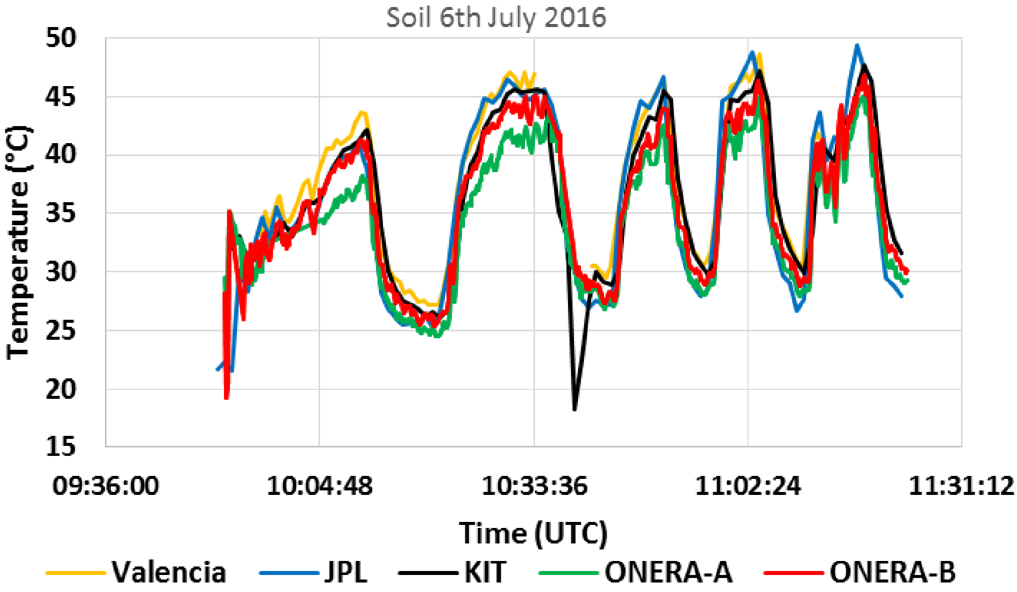

Figure 11: Surface temperature of dark soil measured using the participating radiometers on the 6th July 2016. The spike which appears at 10:39 AM on the measurements by KIT arose due to the partial obscuration of the radiometer FoV by a participant.

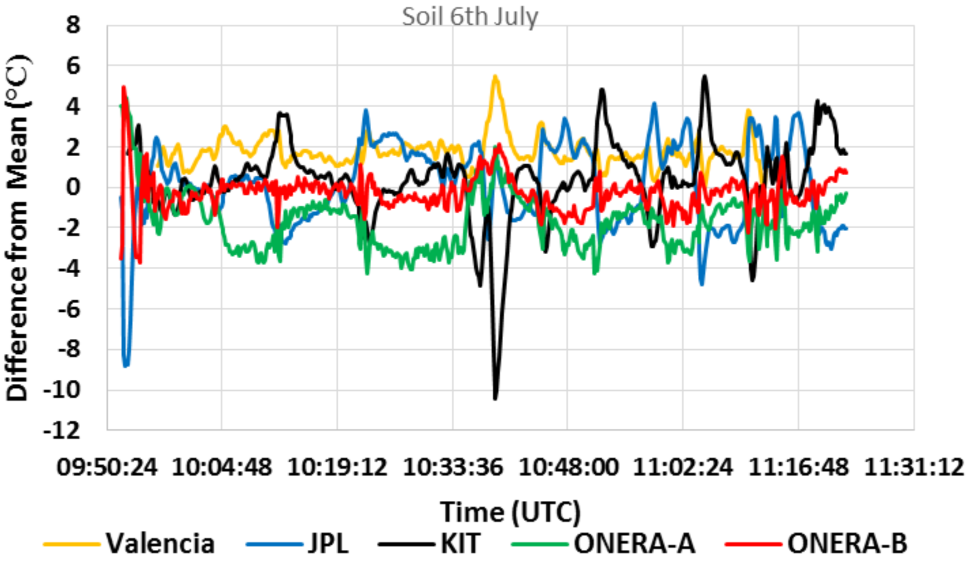

Figure 12: Difference between the measurements using each of the five measuring radiometers made on the 6th July for the dark soil sample and their mean.

The LST comparison showed some discrepancies between the measurements of different participants, with differences being typically less than ±2 °C from the average of all participant measurements. The exception appears to be the soil sample where measurements were within ±4 °C from the average of all participant measurements. This is partly due to the large surface temperature variations (up to 10 °C) present on the soil surface temperature.

Full information on the 2016 LST comparisons can be found in reference [5] and in report *D100 - Technical Report 2: Results from the 4th CEOS TIR FRM Field Radiometer Laboratory Inter-comparison Exercise Part 4 of 4: Land surface temperature comparison of radiation thermometers* available from the Project Documents page of the project website; http://www.frm4sts.org/project-documents/

4. PHASE 2A: SHIPBORNE COMPARISON

4.1 SHIP BASED SEA SURFACE TEMPERATURE (SST) COMPARISON

As part of the project, a successful SST comparison was carried out on the Cunard Queen Mary 2 between the 11th September to 5th November 2015. The two instruments which participated this SST Field Inter-Comparison Experiment (FICE) were the Rutherford Appleton Laboratory SISTeR (Scanning Infrared Sea Surface Temperature Radiometer) and the University of Southampton ISAR (Infrared Sea Surface Temperature Autonomous Radiometer). Figure 13 shows the two radiometers mounted side by side on the port side of the QM2 bridge roof.

Figure 13*: Left* - SISTeR and ISAR side by side on the port side of the QM2 bridge roof. *Right* - SISTeR (left) and ISAR (right) mounted side by side.

Unfortunately, an issue arose with the optical rain gauges used by the radiometers which reduced the usable SST data to those obtained between 18th October 2015 and 5th November 2015. While both instruments used the same rain gauge model, the bodies of the rain gauge are semi-transparent and one rain gauge did see the optical beam from the other which meant it was measuring rain at all times. The issue was fixed with a metal plate placed between the rain gauges. Figure 14 shows the two rain gauges mounted side by side with the metal plate between the two, shielding them from each other.

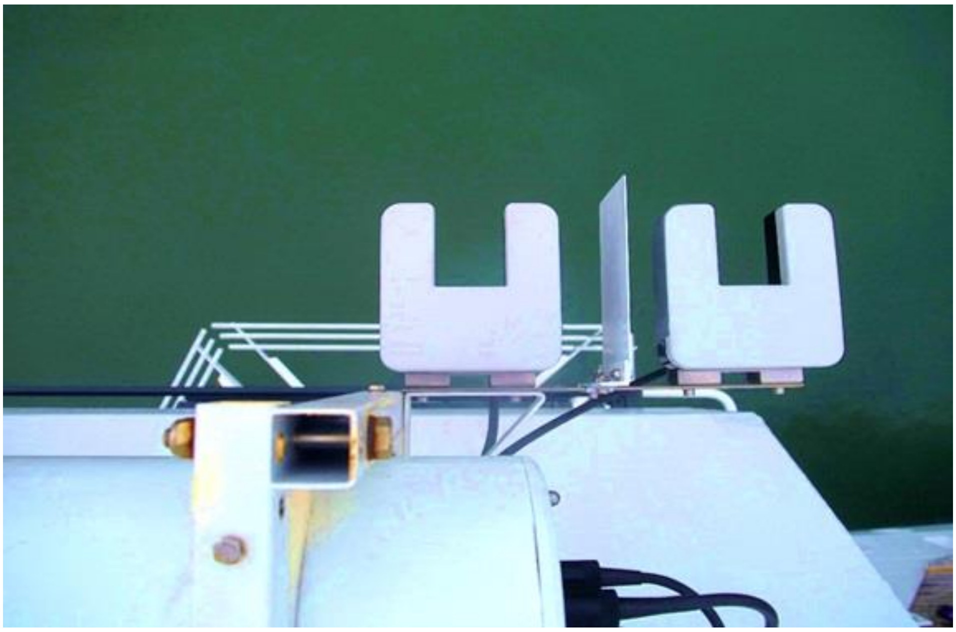

Figure 14: The two rain gauges mounted side by side with the metal plate between the two, shielding them from each other.

Overall it was found that rain gauges seem to give very high values at times – data from the rain gauge experiments are shown in Figure 15 below:

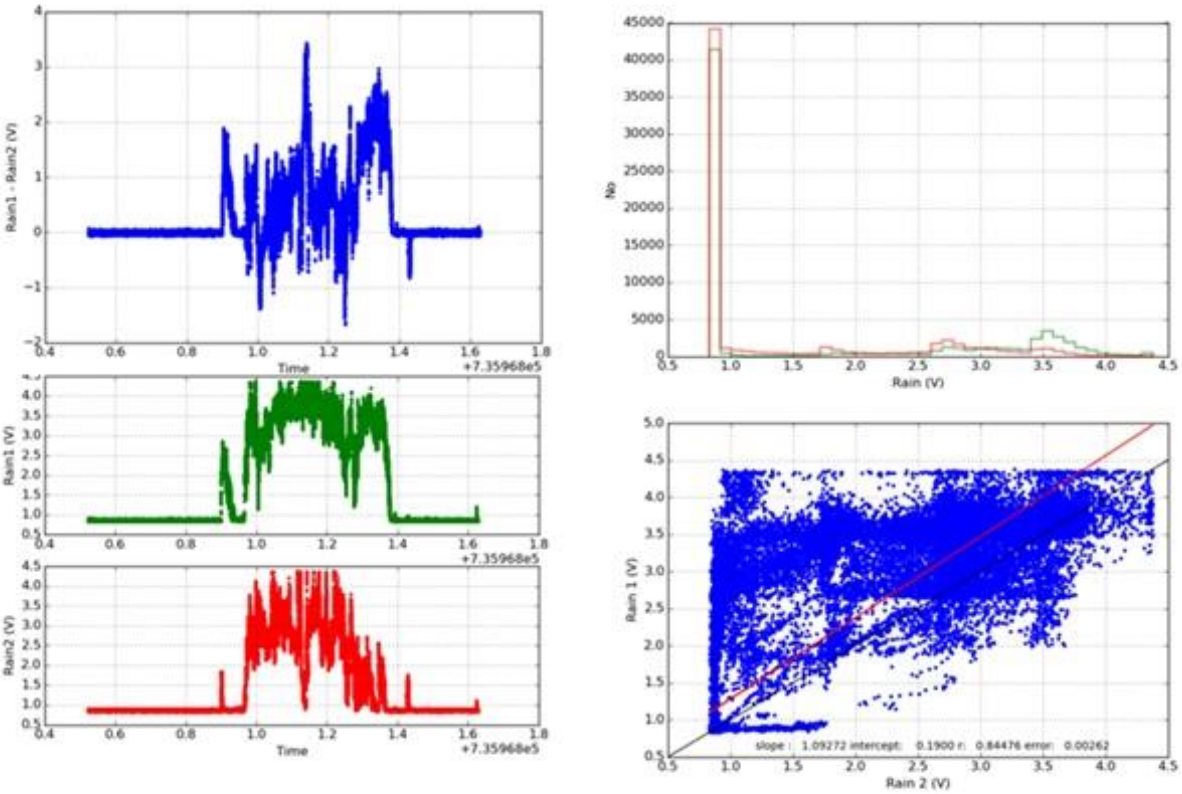

Figure 15: Illustrated above are the high values (left) and the tests with a shielded and unshielded rain gauge (right).

Figure 16 shows the SST mean data of SISTeR and ISAR as a scatter plot and histogram and the location of the data recorded on the Queen Mary 2, during the period 18th October 2015 and 5th November 2015. The 2015 radiometer shipborne comparison showed that the mean SST difference of the two instruments is 50 to 60 mK, which is within their stated uncertainty of 100 mK.

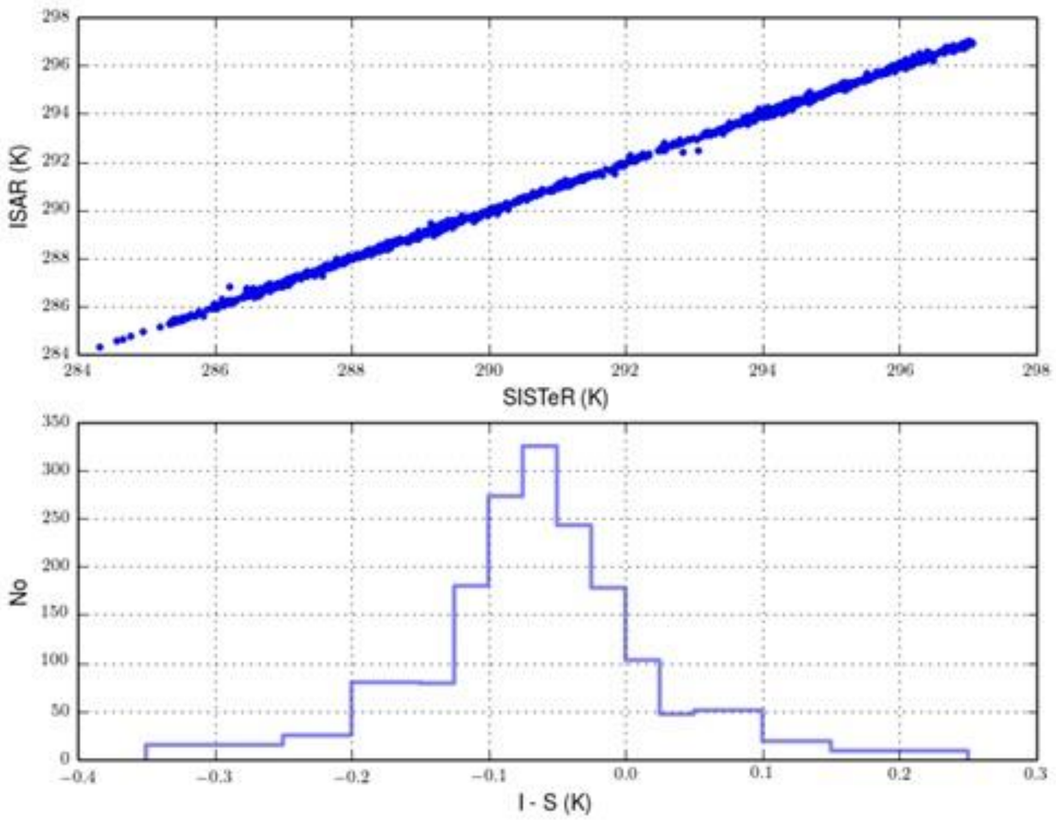

Figure 16: SST data comparison between ISAR-003(I) and SISTeR A (S) on the Queen Mary 2, 18th October 2015 and 5th November 2015.

ISAR-SISTeR Ship Track

The second part of the shipborne intercomparison was to compare the uncertainties of the two participating radiometers. This comparison is still ongoing, but early results show that the magnitude of uncertainties is smaller for SISTeR and larger for ISAR. While the Type A uncertainties seem to agree fairly well, the type B uncertainties differ for both instruments, in agreement with their current uncertainty models. Figure 17 summarises the mean difference between the SST measurements made by the SISTeR and ISAR radiometers.

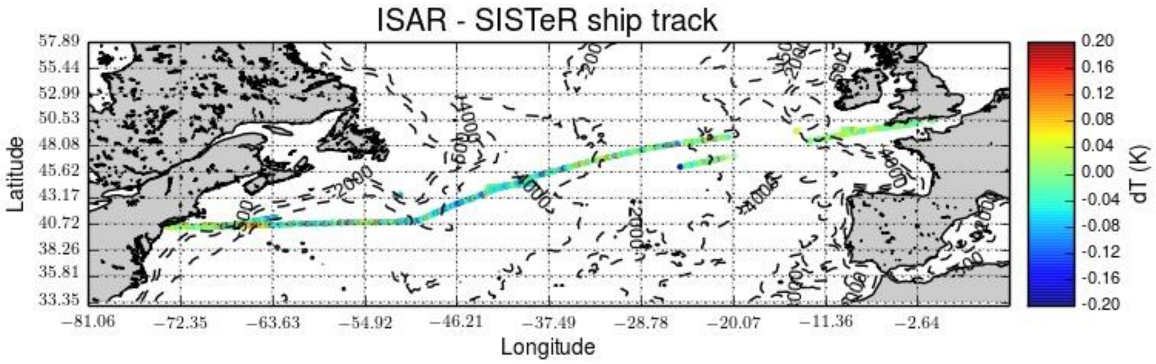

Figure 17: SST mean difference between SISTeR and ISAR.

2017 SISTeR radiometer cruises

Figures 18 and 19 show the sea surface temperature recorded in two recent measurement campaigns using the SISTeR radiometer, i.e. cruises 13 (January to May 2017) and 14 (data shown is from May – July 2017). The coloured lines shown in the ocean, indicate the measured sea service temperature (see scale for temperature chart).

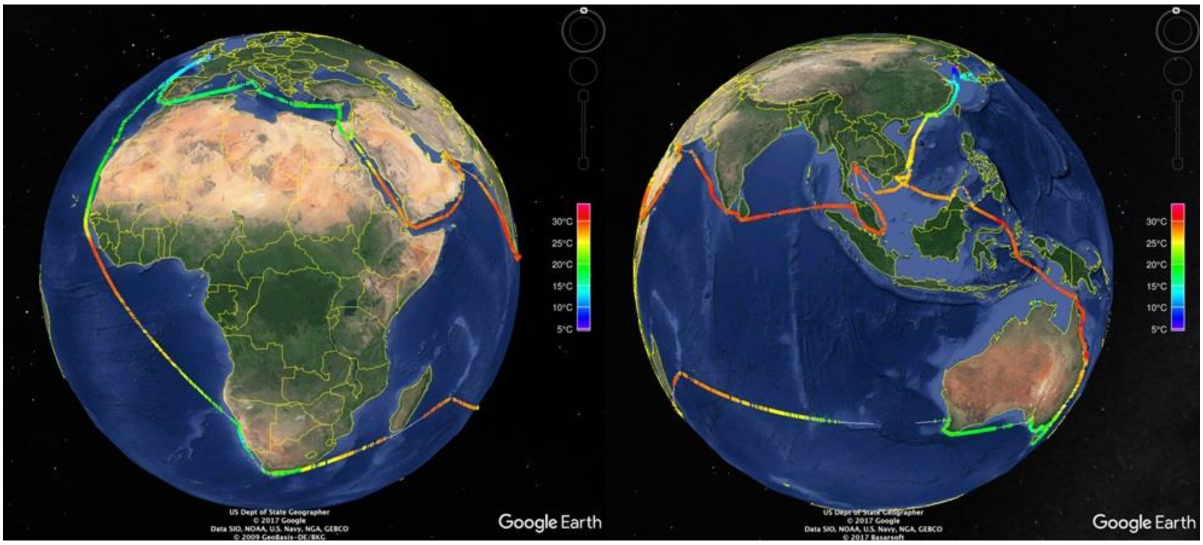

Figure 18: SST measurements recorded by SISTeR A cruise 13 (January to May 2017)

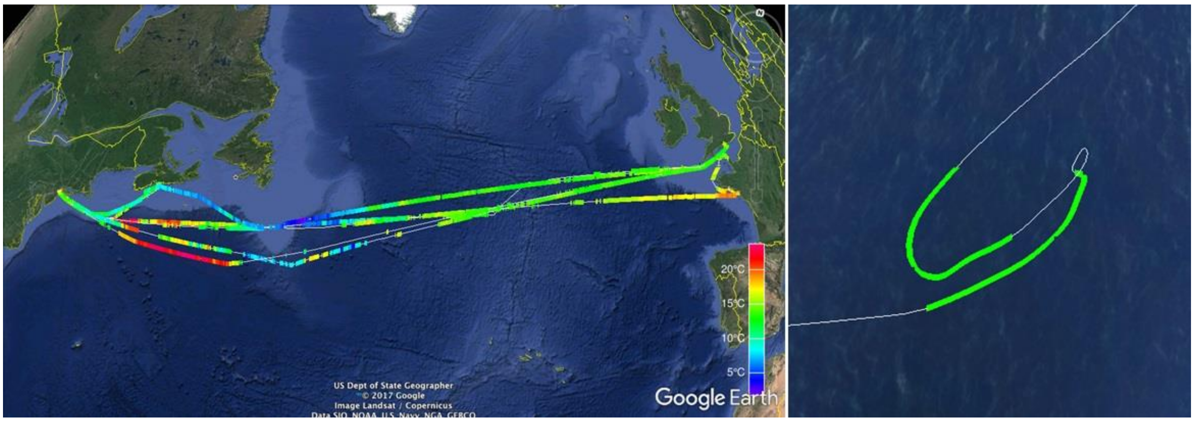

Figure 19: SST measures recorded by SISTeR A cruise 14 (May – July 2017)

5. PHASE 2B: LAND SURFACE TEMPERATURE COMPARISON, GOBABEB, NAMIBIA

There are currently several systems and instruments which provide state of the art ground-based validation measurements for obtaining in-situ Land Surface Temperature (LST). However, so far neither the instruments nor their field deployment have been compared and there are no established standards to ensure SI-traceability. The aim of this comparison was to complement the laboratory comparison experiments (LCE) completed under this project with Field Inter-Comparison Experiments (FICE).

The overarching objective of the TIR FRM Field Inter-comparison Experiments was “to coordinate and demonstrate field inter-comparison activities for TIR FRM”. Inter-comparison experiments in the field cannot be controlled to the same extent as in the laboratory. Therefore, selecting naturally homogenous sites is of key importance.

Using stable ground reference sites for such fields as data comparison, radiometric calibration and monitoring long-term satellite drift is a key technique in Earth Observation. It is common to use accessible desert sites where field-campaign measurements are made to coincide with a satellite overpass. The LST FICE comparison work was carried out at the Gobabeb Research Centre on the Namib gravel plains and sand sea as part of the project. The LST campaign spanned a two-week period (14 -27 June) and participants included KIT, GOTA (Universidad de La Lagun)a, ONERA, THEMACS Ingénierie, Universidad de Valencia and the University of Southampton. Figures 20 and 21 show some of the activities which were included during the Gobabeb LST comparison.

Full information on the LST FICE comparison at Gobabeb can be found in *Report from the Field Inter-Comparison Experiment (FICE) for Land Surface Temperature* available from the Project Documents page of the project website http://www.frm4sts.org/project-documents/

Figure 20: LST comparison work in Namibia during June 2017

Figure 21: Further images of the work completed under the FRM4STS LST FICE during June 2017

6. PHASE 2C: ICE SURFACE TEMPERATURE, GREENLAND

A successful field inter-comparison experiment over sea ice was conducted in March-April, 2016 on the sea ice off Qaanaaq, in Northwest Greenland. The site is well suited for conducting a field campaign on the sea ice and for measuring the ice surface temperature with radiometers. It is well within the high Arctic at 77°N with a dry Arctic atmosphere and cold temperatures in April. Three different research groups (DMI, Met Norway and University of Southampton) participated with six different thermal infrared radiometers in this inter-comparison, the first of its kind over sea ice, which included two Fiducial Reference Measurements Thermal Infrared Radiometers.

The activities for the one-week comparison included:

- **Temporal inter-comparison.** All thermal infrared radiometers observed the same sea ice area continuously for at least 2 days (48 hours).
- **Spatial inter-comparison.** A thermal infrared radiometer was moved within a satellite footprint to observe snow covered sea ice.
- **Freeze up measurement.** The radiometers observed the surface temperature for at least 1 day (24 hours) during a sea ice freeze up experiment to cover a broad temperature range.
- **Angular dependence measurements.** The radiometers observed the sea ice at different incidence angles, to assess the effect of angular emissivity dependence.
- **Snow in-situ measurements**. Snow parameters were measured throughout the experiment. Measured parameters were grain size, salt content and thermodynamic temperature

The extreme conditions were challenging for the radiometers and resulted in some data losses, but all six radiometers completed this inter-comparison campaign. The weather conditions were typical for a high Arctic environment, with surface temperatures between -30 and -10°C and low winds. A pairwise comparison of the 10 minute averaged brightness temperatures from all the radiometers showed mean differences between 0.2 K and 1 K.

The Figures 22, 23, 24, 25 and 26 show a few examples of the activities and data obtained during the 2016 ice surface temperature campaign in Greenland.

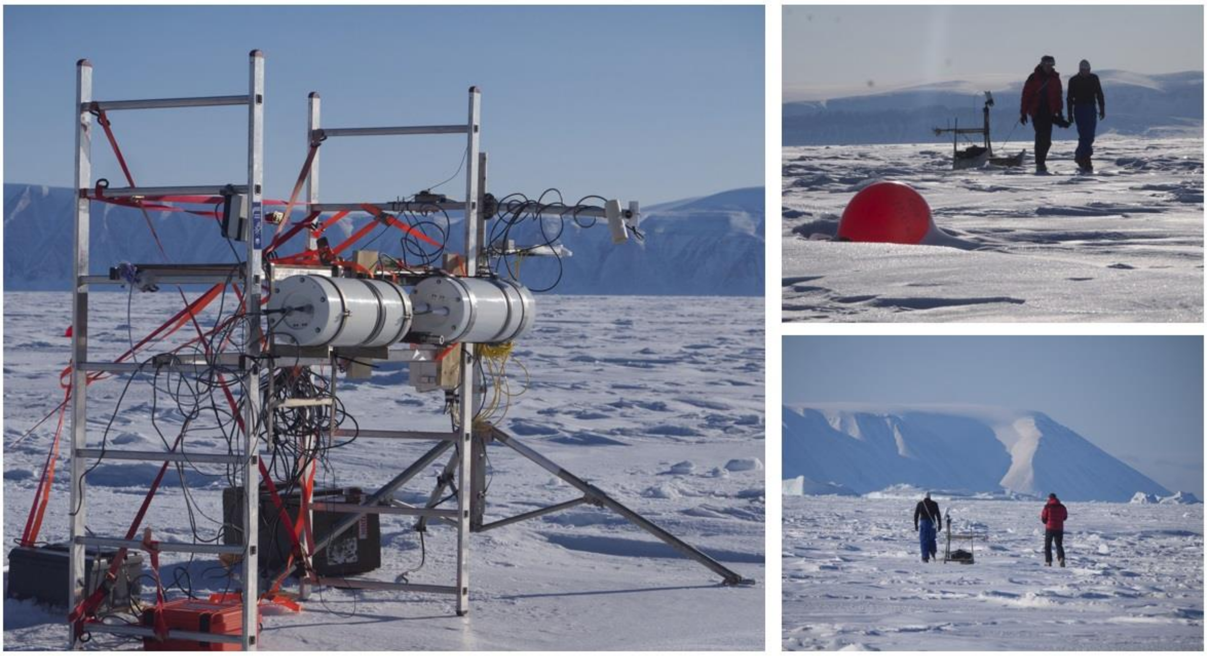

Figure 22: Ice surface Temperature measurements taking place in Qaanaaq, Greenland

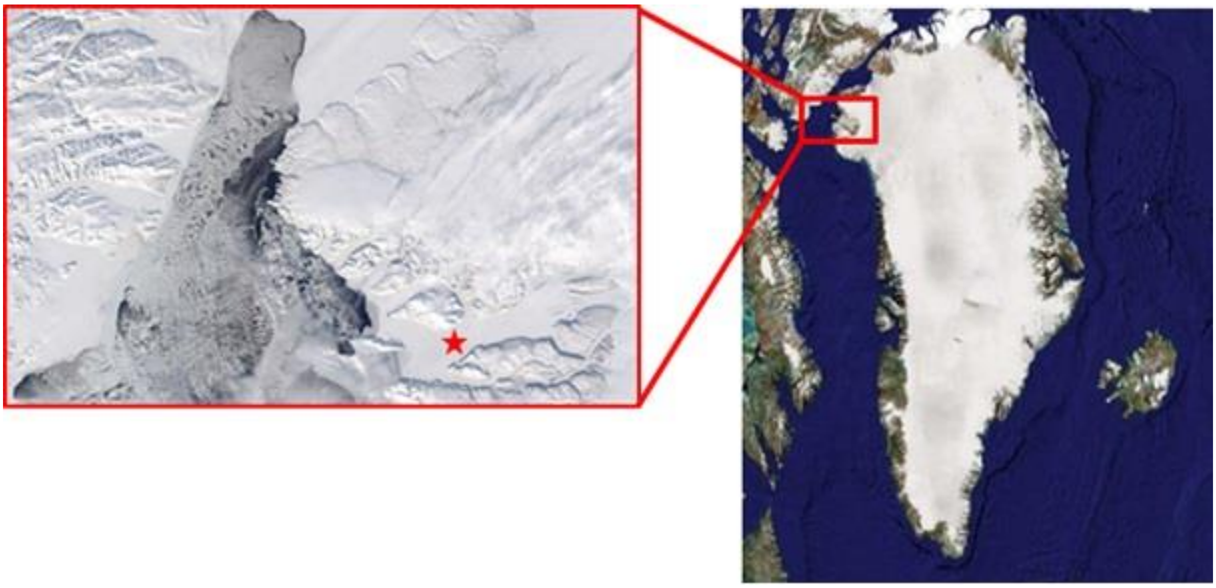

Figure 23: Location of the FRM4STS IST FICE. Qaanaaq is situated in Northwest Greenland at 77oN. The experiments were carried out on the sea ice off Qaanaaq in Inglefield Bredning (left) marked with a red star.

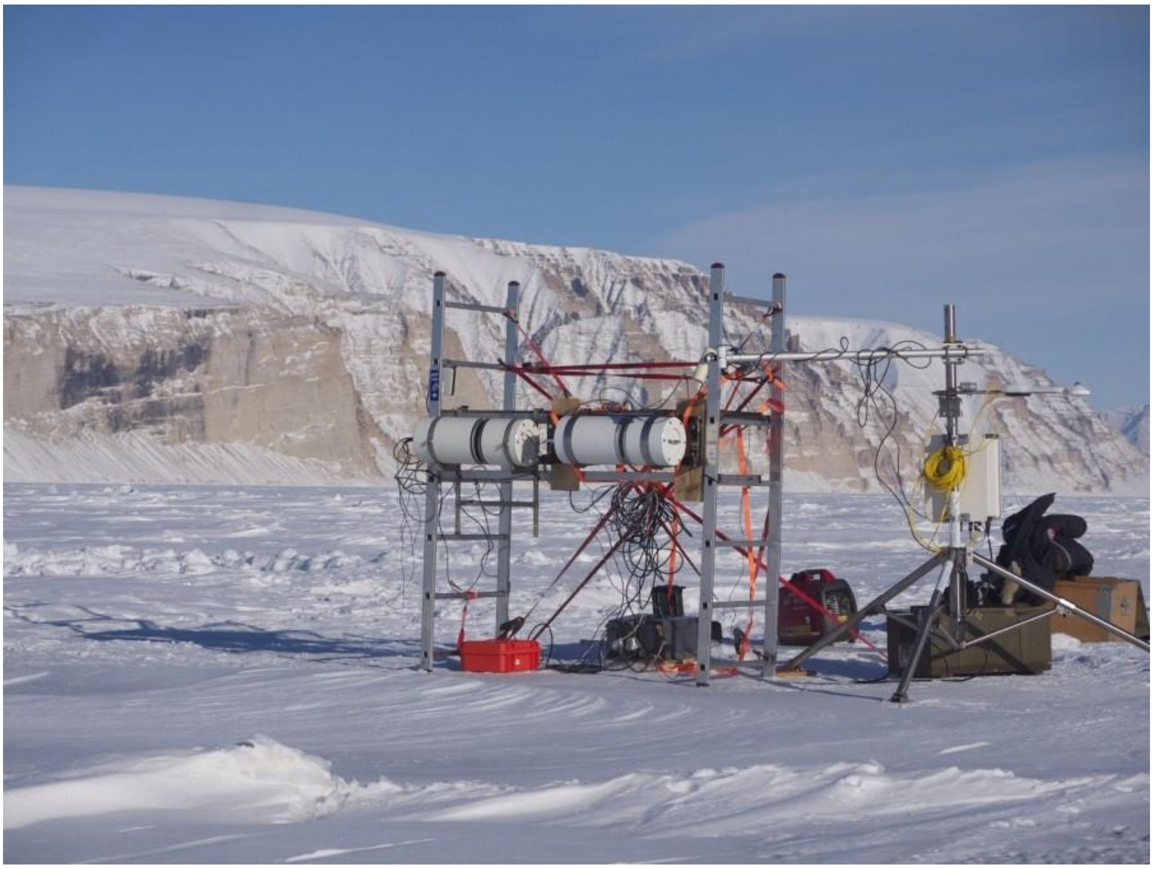

Figure 24: The spatial variability experiment was performed by dragging a sledge with mounted radiometers.

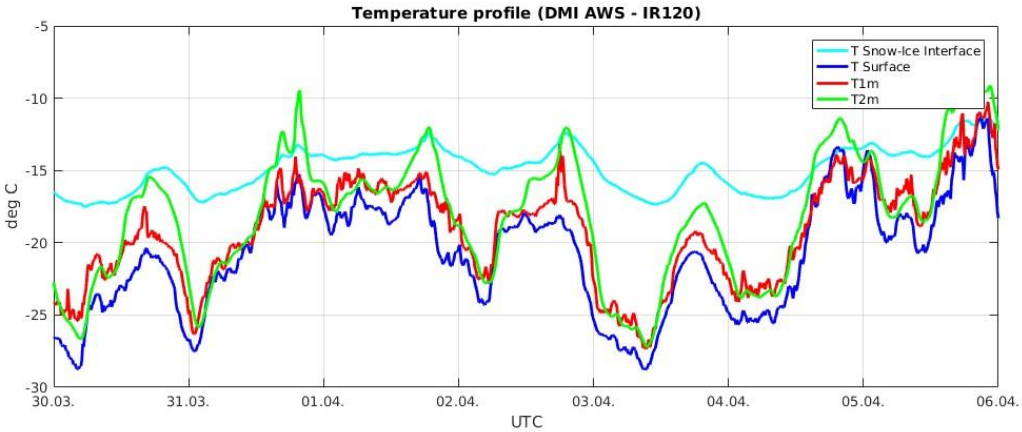

Figure 25: Temperature conditions at different vertical levels during the experiment, as observed by the DMI Automatic Weather Station. The snow-ice interface was under 9 cm of snow.

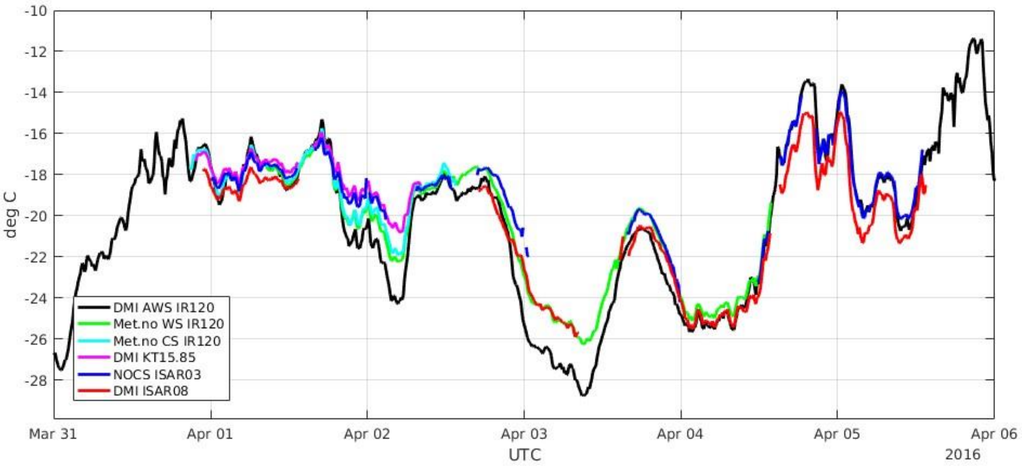

Figure 26: Time-series of brightness temperatures observed by the 6 radiometers participating in the inter-comparison experiment. The DMI AWS (black line) was mounted about 40 meters away from the other radiometers.

Full details about the 2016 ice temperature FICE comparison can be found in *Towards Field Inter-Comparison Experiment (FICE) for ice surface temperature*. The report is also available from the Project Documents page of the project website http://www.frm4sts.org/project-documents/

7. FRM4STS INTERNATIONAL WORKSHOP, NPL 16-18 OCTOBER 2017

An international workshop of world experts from four continents, in the collection, use and interpretation of measurements of the Earth’s surface (land, water and ice) temperature was held at the National Physical Laboratory, during 16th to 18th October 2017. The aim of the workshop was to review the current state of the art in both satellite derived and surface-based measurements and consider their adequacy to meet the varied needs of the user community. In particular, results of the recent set of comparisons of instruments and methods used for satellite validation carried out under the auspices of CEOS through the ESA funded project FRM4STS were presented and discussed. The workshop was structured to consider input from invited presentations spanning the domains of land, water and ice and through facilitated discussion come to a consensus view on priorities for each domain.

As a conclusion, the workshop defined a set of goals and actions (some domain specific) as an outline roadmap that the community considers necessary to implement to meet future needs. The full report dealing with this workshop, *D-160/D-170: FRM4STS Workshop Proceedings & FRM4STS Scientific Roadmap* is available from the project website http://www.frm4sts.org/project-documents/. The report summarises the science and evidence presented at the workshop and the resultant roadmap which is submitted to the worlds EO funding organisations for their urgent consideration.

Taking into account the discussions and recommendations from the various sessions of the workshop, the community developed sets of priorities grouped by domain area and listed in Tables 1, 2 and 3 below.

Table 1: Ocean Priorities

Priorities for the Oceans				
Activity/Requirement	**Justification/comments**	**Importance/ Impact**	**Degree of difficulty**	**When achievable (target)**
DV Model Verification / Validation	• Useful for historical analysis • New buoys with depth	5	5	CEOS WGCV
Study sampling errors	• Historical use • Find historic minimum • Plan future deployment	4	3	CEOS GHRSST
Additional buoy development for passive microwave		5	5	DBCP GHRSST
Sampling of coastal variability		5	5 Political geophysical small scale	APRS WMO CEOS CEMS
Improve buoy technology		5	3	DBCP
• Algorithm round-robin including cloud mask • Generate validation dataset		4	2	GHRSST
Traceability of validation data, require subset to BF traceability		5	4	CEOS FRM

Table 2: Priorities for Land

Priorities for Land				
Activity/requirement	**Justification/comments**	**Importance/ Impact**	**Degree of difficulty**	**When achievable (target)**
Plan to set up a network for land monitoring	• Useful for process studies, trend detection, instrument development • Have the community buy-in for the network • Have input from FRM/related communities to GCOS task team; • Ensure global buy-in from key stake-holders	Important	Medium	2019 (GCOS is doing it)
Identify representative locations (1 x 1, 5x5 km scales)	• Coordinate with other LPV groups and modelling / traditional measurement groups • Start from super sites (large-scale homogeneity sites are not available)	Important	Medium	2019

Metrology for station measurements Establish LPV protocols Standardization of practice & data formats	• Centralised data processing centre (with unified meta and raw data) • Confidence in the retrieval • Achieve consistent quality & enable reprocessing	Important	Medium (per instrument) Difficult (per variable/whole programme)	?
Development / Implementation of physical algorithm	• Making emissivity as retrieval parameters for process studies / applications • Dropping ancillary data, avoiding geo-location errors and wrong information	Medium	Medium	? 2020
• Upscaling algorithim / modelling • Correction for anisotropy	• Making in-situ/satellite and cross-satellite comparable • Have better relationship with SAT • Reduce the uncertainty of validation • Being able to handle complex situations	Medium	Difficult	≥ 2020

Table 3: Priorities for Ice

Priorities for Ice				
Activity/requirement	**Justification/comments**	**Importance/ Impact**	**Degree of difficulty**	**When achievable (target)**
Maintained IR radiometer, all year, ice surface temperature Automated – with campaign activity – several with contamination cycling, heater, with reference BB / Exists ISAR system ⇨ modified	• FRM to underpin satellite validation • Buoys not accurate enough / + better buoys to put out • Arms networks – no snow in summer • BB @ ambient, heat electronics • Power, generators…	10 If we don't know how accurate they are, everything else is in question	3 Technically challenge is finding funding	1 year from funding
	Don't get radiator temperature need to link ⇨ by installing (-develop and refine models) both next to each other (-some already) Distribute from FRM to wider range	8	3 Need to find interface	1 year from funding, to link to FRM + 6 months
Better Cloud mask – to remove clouds Especially night cloud mask	MM cloud radar upward looking to validate cloud masks ⇨ automated – all directions. All sky cameras. Especially high/turn clouds – common at poles Comparison between Cloudsat + cloud masks ↳ does it work in the Arctic	Cloud mask 10 Validation upwards looking radar 8 8 = day 10 = night	5 – 8 Technically depending on day/night & cloud types	Day – ongoing improvements Night – 5 years with sufficient funding Already have them need to be more part of process / routine 1-2 years

Comprehensive matchup databases between different wavelengths – to compare microwave to TIR to visible… To escribe whole state With well-tuned IMBS ⇨ air-to-water temperature channels	IMB data – there but not enough + needs analysis (human) to work out interfaces Not enough resolution Fiducial reference station to bring it all together at summit – similar to Antarctic	10	Bits exist 3 Multi agency	2 years from funding
Understanding the marginal ice zone - temperature signatures – mixture ocean, sea, ice	Dedicated field campaigns – difficult, drones, unmanned aircraft Also impact of melt on surface temperatures More icebridge flights (- due to end 2019 on launch of IceSat 2 -) and European / Russian equivalents Subset of icebridge containing fiducial needs Sustained measurements from aircraft – more than just validating IceSat 2	7	8	2-3 years Takes a lot of planning

8. SUMMARY

The overarching requirement identified for all three domains is the need to have greater number of FRM quality ‘test sites’, radiometers and buoys, and the development of methods to scale these point measurements to the satellites, including dealing with non-homogeneity of land and ice. The second is to have more robust methods for cloud detection and screening (satellite and terrestrial based). Finally, the need for training and case studies on uncertainty evaluation and propagation is also identified as a cross-cutting priority, the latter for both practitioners and users of data and information.

9. CONCLUSION

The D-160/D-170 report provides a summary of the discussion of the workshop of world experts on validation of surface temperature measurements made by satellites. The workshop considered the state of the art in validation measurement capabilities including a review of the results of the recent CEOS international comparisons. The principle conclusion of the workshop is a set of detailed technical recommendations together with a set of ‘community priorities’ that are needed to ensure that society’s science goals, driven by climate, are able to be met. The presentations, comparison results, protocols and draft best practices are all available on the FRM4STS web site (www.FRM4STS.org).

10. REFERENCES

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5. Theocharous, E., Barker Snook, I. and Fox, N. P**.,** 2017b, "2016 comparison of IR brightness temperature measurements in support of satellite validation. Part 4: Land surface temperature comparison of radiation thermometers", NPL Report ENV 13.

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