National Physical Laboratory

fiducial reference temperature measurements

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

ESA Contract No. 4000113848_15I-LG

D-160/D-170: FRM4STS Workshop Proceedings & FRM4STS Scientific Roadmap

Nigel Fox

AUGUST 2018

Reference	OFE-D-160/170 -V1-Iss-1-Ver-2
Issue	1
Revision	2
Date of Issue	22 August 2018
Document Type	FR / TDP

Digitally signed by Device Identity
9c6f8ccd4f5eaa531db70b0929b3
d2a06f1e6010
Reason: I am approving this
document
Location: Noordwijk, The
Netherlands
Date: 2018.09.29 18:58:35 +01'00'


NPL

FRM4STS International Workshop: Fiducial Reference Measurements (FRM) for satellite derived surface temperature product validation

D-160/D-170: FRM4STS Workshop Proceedings & FRM4STS Scientific Roadmap

Nigel Fox

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

CONTENTS

DOCUMENT VERSION HISTORY
DOCUMENT APPROVAL

DOCUMENT MANAGEMENT

Issue	Revision	Date of Issue/revision	Description of Changes
1	1	08.06.2018	Draft circulated to Workshop participants for comment
1	2	31.08.2018	Complete draft submitted for review

DOCUMENT APPROVAL

Contractor Approval

Name	Role in Project	Signature & Date (dd/mm/yyyy)
Dr Nigel Fox	Technical Leader	
Dr Andrew Brown	Project Manager	Andrew Brown, NPL 22 August 2018

Customer Approval

Name	Role in Project	Signature	Date (dd/mm/yyyy)
C Donlon	ESA Technical Officer		

1 APPLICABLE DOCUMENTS

AD Ref.	Ver./Iss.	Title
EOP-SM/2642	1	Fiducial Reference Measurements for Thermal Infrared Satellite Validation (FRM4STS) Statement of Work

2 ACRONYMS AND ABBREVIATIONS

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 on the ESA/EU GMES Sentinel-3
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

This page has been left intentionally blank

3 EXECUTIVE SUMMARY

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 spacecraft is the first 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. This means anchoring all measurements to an invariant common reference for the measurements, through international system of units (SI) and ensuring that these can be regularly validated across the globe through the use of surface based measurements derived from Ocean Buoys and most accurately, field deployed (on-board ships) Thermal Infrared (TIR) radiometers, which must both also be tied to SI units.

An international workshop was held at NPL, 16-18 October 2017. The objective of the ESA sponsored workshop was to bring together the worlds' expertise in Earth surface (Land, Water, Ice) temperature measurements under the auspices of Committee on Earth Observation Satellites (CEOS) to review the current state of the art in measurement accuracy for satellite validation. The workshop considered the outputs and results from the recent CEOS comparison of fiducial reference measurements/instruments and concluded with looking to develop an internationally coordinated strategy to ensure that the global reference measurement infrastructure is adequate to meet the future needs and aspirations of all users.

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

4 INTRODUCTION

4.1 OVERVIEW

An international workshop of world experts (See appendix A, from four continents, in the collection, use and interpretation of measurements of the Earth' surface (land, water and Ice) temperature was held at the National Physical Laboratory, the UK national metrology institute on October 16-18 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, now and the foreseeable future. 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 (by international science committee, see appendix B) 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. This document 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.

4.2 WORKSHOP STRUCTURE

The workshop was structured to follow a path from science need through to the development of a strategy in 7 sessions:

- **Session 1; Science requirements for LST, IST and SST applications: Climate, Meteorology and Oceanography**
- **Session 2; Retrieving Surface Temperatures from Space Keynote Ocean, Keynote Land, Keynote Ice**
- **Session 3; FRM4STS Overview**
- **Session 4; Metrological framework: Traceability and uncertainty, sampling and scaling, representativeness**
- **Session 5; Protocols for Post-launch validation of surface temperature measurements from Space**
- **Session 6; Post-launch validation: Buoys**
- **Session 7; Establishing a sustainable framework of measurements to ensure fit for purpose data to meet the needs of society**

At the end of each session there was a dedicated discussion period and opportunities throughout the workshop to add comment and input to the process. The final session 7, considered all inputs in a series of thematically grouped breakouts so that specific detailed discussion could take place allowing strategies to reflect differing levels of maturity and challenges of the domain to be considered in more detail.

The detailed agenda can be found in Appendix C and the presentations available to view/download at www.FRM4STS.org.

This document seeks to summarise the key inputs from each session and then to draw this together into a set of actions as an outline strategy/roadmap to ensure that surface temperature data, particularly that derived from satellites is ‘fit for purpose’ now and in the future.

4.3 CONTEXT

The demand to monitor the status, understand its processes and predict the future (near and long term) of the state of our planet and its impact on society continues to grow rapidly. This has driven the need for ever more complex satellites to ensure global coverage and the provision of data on demand. Over the last four decades satellites have moved from the provision of useful imagery to time series of quantitative geo spatially mapped information. The latter, critical to enable scientists to derive small signals from backgrounds of natural variability and noise, often requiring decades to achieve the necessary sensitivity. The signals together with appropriate models enables them to provide policy makers with the evidence needed to take informed decisions. The criticality of this data and derived information to policy makers and society as a whole is reflected in the commitment of funding agencies such as EU Copernicus programme to support a long-time series of overlapping missions, the Sentinels with the aim of operationally providing the same type of data for at least the next two decades. However, a single agency or geographical region does not have the resources to collect all the necessary global data to meet the operational needs of society. The global meteorological agencies collaborate to ensure that data is automatically shared from the geo-stationary and polar orbiting platforms to facilitate improved weather forecasting. The needs of climate and other applications are becoming equally important requiring an interoperable global earth observing system.

A key role of the Committee on Earth Observation Satellites (CEOS) is to coordinate activities and infrastructure of its member agencies to maximise benefit and minimise unnecessary duplication of effort and resources whilst seeking to ensure all of societies observational needs are met. This includes discussions on deployment of satellites and fundamentally underpinning this, the means to ensure interoperability of their delivered data. The latter, requiring as a minimum, the means to identify and account for any biases between sensor products. A major step forward was the development and endorsement by CEOS of the Quality Assurance Framework for Earth Observation (QA4EO) http://QA4EO.org in the early part of this decade. QA4EO provided a set of key principles together with supporting guidance documentation to encourage and facilitate ascribing 'quality indicators' to EO data products based on evidence of traceability to international standards.

CEOS through its Working Group on Calibration and Validation (WGCV) supported by efforts of individual member agencies has subsequently committed significant effort to developing harmonised methods and infrastructure for coordinated post-launch Cal/Val of satellite L1 and L2 products. This has involved dedicated campaigns, networks of test sites and fundamentally, international comparisons of both satellites and terrestrial based instrumentation. In the context of this document, ESA has established a set of projects with the title precursor 'Fiducial Reference Measurements for…..' (FRM4…) to develop and encourage best practise in post-launch Cal/Val and evaluate international consistency through comparisons. As this generic part of their titles infers these projects all relate to establishing the concept of FRM's for particular measurements.

Although the terminology for FRM's is becoming widespread it is probably worthwhile stating the definition here for completeness as it provides the principle context for the rest of this document and resultant strategy.

FRMs are: '*the suite of independent ground measurements that provide the maximum return on investment for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission'*

An FRM must:

- Have documented evidence of its degree of consistency for its traceability to SI through the results of round robin inter-comparisons and calibrations using formal metrology standards
- Be independent from the satellite geophysical retrieval process
- Have a detailed uncertainty budget for the instrumentation and measurement process for the range of conditions it is used over and be at a level that is appropriate for the application
- Adhere to community agreed measurement protocols and management practises.

It is thus considered essential that regular comparisons be carried out amongst peers and ideally involving metrology institutes to some level to ensure an assessment of the evidence of SI traceability can be determined. Such comparisons need to span the range of conditions of the satellite measurements and be organised to facilitate inclusivity of the international community.

In the context of surface temperature measurements CEOS has been active for some time. The relative maturity and importance of ocean temperature measurements has already resulted in series of international comparison over the last two decades. These have been organised on an approximately 5 yearly basis with ever increasing sophistication and completeness. The first three took place at, or had some part of the comparison take place at the University of Miami and consequently became known as the 'Miami comparisons'. All had some participation from at least one national metrology institute (NMI), NIST and/or NPL The last of these took place in 2010 at both university of Miami and NPL in the UK and included an increased number of radiometers designed primarily for land applications. (REFS).

In 2015, CEOS decided it was time to organise the next comparison and with it to expand the scope to include more applications (Land/Ice) not only in the laboratory but also in the field to evaluate potential environmental effects. ESA responded to the request from CEOS and established the FRM4STS project to organise the various comparisons which again included two NMIs, NPL and PTB to ensure robust linkage to SI.

5 SCIENCE REQUIREMENTS FOR LST, IST AND SST APPLICATIONS: CLIMATE, METEOROLOGY AND OCEANOGRAPHY

5.1 INTRODUCTION

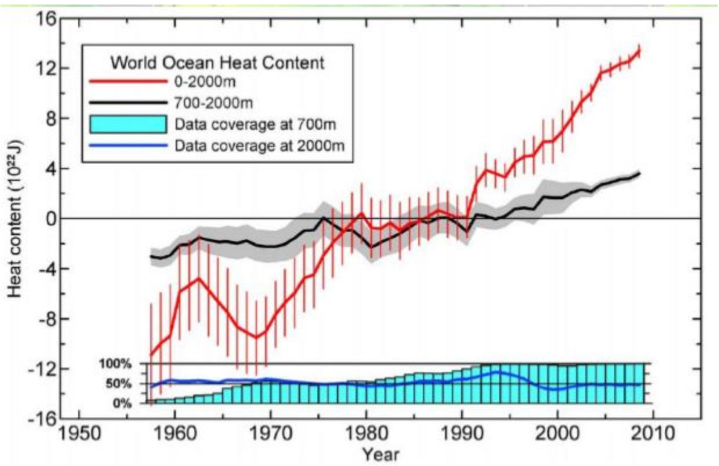
The first session consisted a series of expert presentations to scope the principle science drivers of surface temperature measurements and the adequacy of the current observing system. This was complimented by interactive discussions both during the session and throughout the meeting as a whole. A summary of the key elements are presented below structured by domain.

5.2 OCEAN DOMAIN

Although there are many applications requiring good quality, consistent, water (particularly ocean) temperatures for example meteorology, the driver from an uncertainty perspective is climate with the following requirements derived from GCOS (stability referring to decadal). Given the large thermal mass of the oceans and its surface area in relation to the globe consistent long term change in its temperature is recognised as a good indicator of global climatic temperature change, with predictions, based on current models and anthropogenic influences suggesting it might rise by around 0.2K per decade. This is challenging to detect and requires multi-decadal time series to have sufficient accuracy to unequivocally attribute.

Table 1:

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
SST	10km	N/A	Daily	0.1K over 100km scales	Less than 0.03K over 100km scales



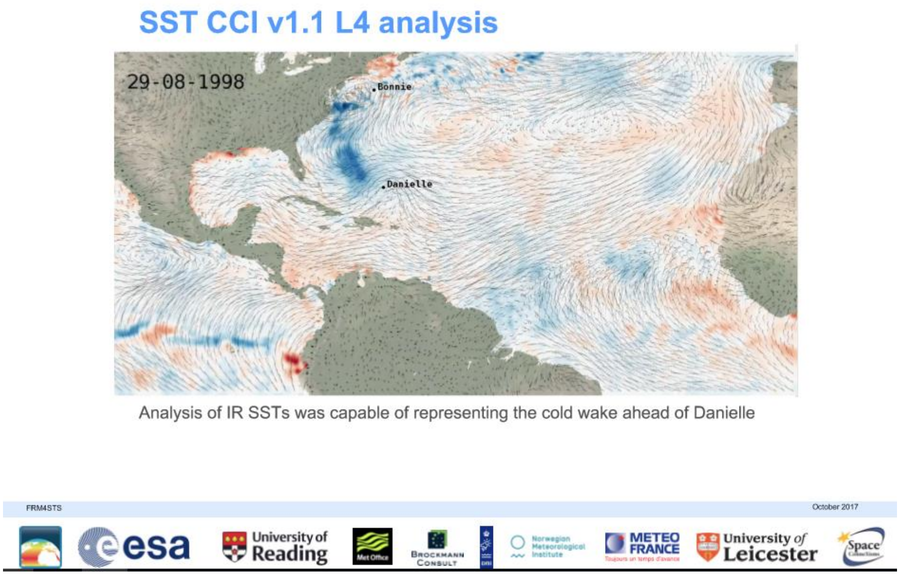
The heat content of the World Ocean for the 0–2000 m layer increased by 24.0 ± 1.9 10^{22} J (± 2 S.E.) corresponding to a rate of 0.39 Wm^{-2}.

A mean increase of temperature of 0.09°C.

Figure 1: Time series of ocean heat content : (1022 J) for the 0-2000 m (red) and 700-2000 m (black) layers based on running pentadal (five-year) analyses. Reference period is 1955-2006. Red bars and grey-shading represent ±2 standard errors. The blue bar chart represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used in their computation at 700 m depth. Blue line is the same as for the bar chart but for 2000 m depth. (Levitus, S. Et al (2012). *World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010*. Geophysical Research Letters 39, L10603. 10.1029/2012GL051106). Figure 1 is taken from the workshop presentation by Minnett regarding the increase in heat stored in the Oceans.

The meeting noted how there has been significant progress in recent times, led by activities such as GHRSST and the ESA CCI program on evaluating sources and types of error and uncertainty, including the nature of their correlations from all types of observation systems. It also noted how the observing system has matured over time from wooden buckets to an increasing number of well-calibrated buoys. This has led to greater consistency in reported values and the means to establish long time series as Climate Data Records (CDRs) derived from harmonisation of various satellite sensors e.g. ATSR+ series and AVHRR with uncertainties close to the 0.1K level but with validation limited to around 0.15-0.2K due to the performance of the currently widely available drifting buoy networks. The objective of the ESA CCI programme is to reach a point where the satellite derived SST CDR can be solely derived from a physical understanding of all the processes (sensor, radiative transfer code and inter satellite harmonisation through comparison) at an uncertainty level commensurate with need.

Review of historical satellite observations has shown they have the capability to robustly detect small relatively rapid changes in surface temperature preceding and indicating the path of tropical storms/hurricanes. However, there remain challenges on the validation of their data across the full range of conditions of the oceans due to performance, spatial distribution, and representativeness of the terrestrial observations. Buoys do not sample the skin temperature, are not evenly distributed across the oceans (currents, ship lanes, deployments ….) and with a few exceptions (increasing in number) do not have the uncertainty requirement needed nor the traceability or ability to detect calibration change once deployed. Whilst radiometers have the necessary performance and sample skin temperature they are relatively few in number and thus not representative of global conditions or have many opportunities for satellite co-location measurements.



SST CCI v1.1 L4 analysis

Analysis of IR SSTs was capable of representing the cold wake ahead of Danielle

Figure 2: Taken from workshop presentation by Merchant shows the cold wake ahead of Hurricane Danielle.

Ocean science conclusions/recommendations.

A recent review by Kent et al (2017) BAMS https://doi.org/10.1175/BAMS-D-15-00251.1 proposed the following recommendations to reduce biases in SST observations:

- Add more data and metadata to ICOADS
- Reprocess existing ICOADS records
- Improve information on observational methods.
- Improve physical models of SST bias.
- Improve statistical models of SST bias.
- Maintain and extend the range of different estimates of SST bias

- Expand data sources for validation and extend use of measures of internal consistency in validation.
- Ensure adequacy and continuity of the observing system.
- Improve openness and access to information.

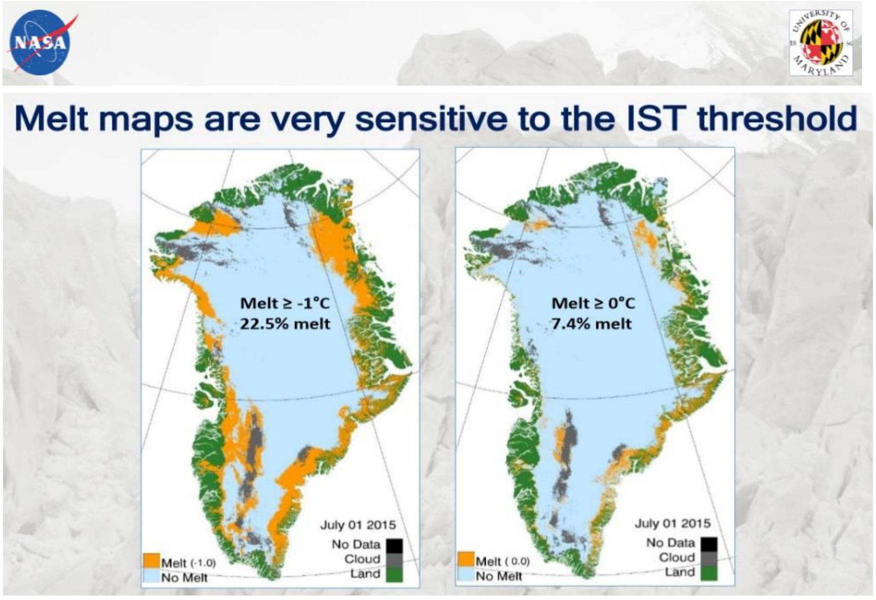
Complementing this, experts indicate that whilst it is clearly highly desirable to have high accuracy, densely sampled over wide spatial and geographical scales, in the ‘interim’ it was important to be able to trust and readily understand the data that was available:

- Quantified fully broken down uncertainties and sources of error in respect to SI (traceability)
  - With validated detail on their STD deviations. Correlations, distributions, stabilities
- The means to propagate information (including uncertainties) to all spatial and temporal scales (particularly from point samples to satellite pixels)
- Documented statement of limitations of use/analysis

The meeting emphasised the need for further studies on quantifying the temperature profile and its relationship to the skin temperature as a function of depth and sea state and fundamentally the need for wide geographical scale, regular high accuracy validation of satellites using FRM (ideally both radiometers and buoys with <0.05 °C during operations). The FRM not only to validate the existing satellite observing system, and/or to establish its own independent CDR but also to provide the means to help maintain/recover from a potential break in the satellite FCDR through catastrophic failure of a critical sensor before sufficient harmonisation with a follow-on.

5.3 ICE DOMAIN

Measurement of Ice/snow temperature compared to ocean and land is relatively immature, but with the cryosphere playing a potentially significant role in magnifying the impacts of global temperature rise through non-linear feedback processes it is of increasing importance. In particular the melt, runoff and surface mass balance of snow, is impacted by surface and consequential internal temperatures. Albedo, and of course its consequential feedback on the melt can also be related to surface temperature and also energy balance both in terms of reflectance and emittance. Melt is very sensitive to temperature change as illustrated below:



Melt maps are very sensitive to the IST threshold

Figure 3: Taken from workshop presentation of Hall showing the sensitivity of melt to temperature.

The ice surface temperature is highly complementary and in many cases a key pre-requisite to studies on ice thickness, glaciers etc and thus missions such as Cryostat.

Large areas of permafrost are thought to be latent sources of prehistoric hydrocarbons which could be released uncontrollably to the atmosphere as an additional Greenhouse gas flux if temperatures rise above a critical temperature. Careful monitoring and associated modelling is needed to provide the community with guidance on the potential impact of this threat.

Another area of importance is the marginal zone, usually coastal where Land Ice, Water Ice and Water are all mixing together in terms of the satellite observations.

To date CDRs have been created, centered around MODIS extended back with AVHRR and now moving forwards with VIIRS, with Greenland providing a principle location for validation efforts for both US and European teams. However, it is relatively rare at this time for the validation instrumentation to be traceably calibrated and/or consistent methodologies to be deployed. In some cases air temperature is used but its relationship to the ice is not well defined, similarly snow can be very different and not representative.

One of the biggest challenges for Ice temperature measurement from satellites is discrimination from cloud and fog, which is a challenge for all domains but particularly acute in this domain.

Conclusions/recommendations

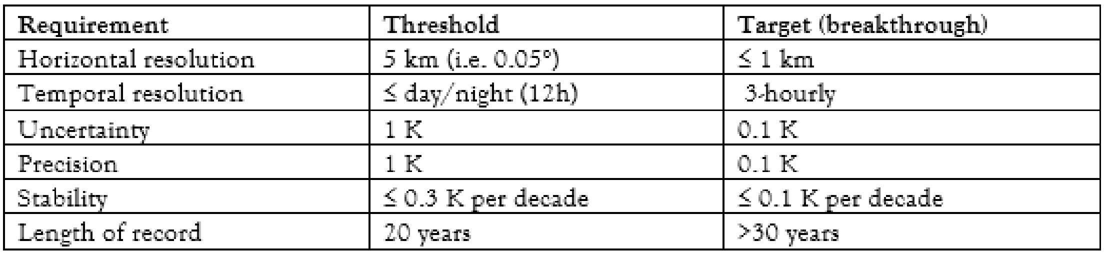
- For Ice there is a need to consider and compare retrieval algorithms to evaluate variances and assess uncertainty.
- Accuracies of < 1°C and ideally 0.5°C are required particularly around ambient to address the onset of melt
- Need for synergy and increased coordinated observations from passive and active microwave, solar reflective and TIR sensors.

5.4 LAND DOMAIN

Land surface temperature (LST) has recently been designated as an Essential Climate Variable (ECV) By UN GCOS and is a key parameter impacting the energy balance and meteorology at interface to atmosphere. The recently published CEOS LST product validation best practice guide (https://lpvs.gsfc.nasa.gov/PDF/CEOS_LST_PROTOCOL_Oct2017_v1.0.0.pdf) provides amongst other things a good overview of the science drivers and the introductory paragraph is reproduced here as an extract. LST is a fundamental variable in the physics of land surface processes from local to global scales and is closely linked to radiative, latent and sensible heat fluxes at the surface atmosphere interface. Thus, understanding and monitoring the dynamics of LST and its links to human induced changes is critical for modeling and predicting environmental changes due to climate variability as well as for many other applications such as geology, hydrology and vegetation monitoring. From a climate perspective, LST is important for evaluating land surface and land-atmosphere exchange processes, constraining surface energy budgets and model parameters, and providing observations of surface temperature change both globally and in key regions.

The climate requirements are summarized below:

Table 2: LST product requirements for climate related studies



Requirement	Threshold	Target (breakthrough)
Horizontal resolution	5 km (i.e. 0.05°)	≤ 1 km
Temporal resolution	≤ day/night (12h)	3-hourly
Uncertainty	1 K	0.1 K
Precision	1 K	0.1 K
Stability	≤ 0.3 K per decade	≤ 0.1 K per decade
Length of record	20 years	>30 years

Many of the challenges facing this domain are similar to those of the other two in terms of greater sampling, scaling, cloud removal and retrievals. However, for Land, one of the most significant challenges, stems from the large surface heterogeneity, even at relatively small scales, coupled with the associated variance in emissivity between different surface types and how to treat this, particularly in the context of global satellite retrieved products.

Conclusions/recommendations

From a science perspective establishing a global CDR to meet the GCOS requirements is the driver and the key elements to achieve this are:

- Greater density of traceable validation sites (not necessarily all fully FRM in themselves but linked to). For air temperature, it is estimated that 170 well distributed sites are needed!
  - Spanning different land types and terrain e.g. mountains, urban
  - Co-locate into ‘super sites’ with other non-thermal parameters
- Methods to deal with anisotropy of surfaces (at satellite sub-pixel scale) particularly related to emissivity
- Need for standardized protocols for validation and cloud screening

6 RETRIEVING SURFACE TEMPERATURES FROM SPACE

For most domains (Ocean, Land, Ice) the key challenges relating to retrieving surface temperature are similar and relate to:

- the need for better radiative transfer codes (and associated inputs) for atmospheric correction,
- identification and removal of the effects of cloud

In particular, discussion focussed on the need to consider RT simulations to explore potential sources of error and their uncertainties and in particular how to deal with atmospheric correction when often the sensor measuring T has limited spectral channels for aerosol detection. It is also uncertain if RT codes are using the latest data for atmosphere characteristics (scattering absorption cross-sections etc).

For all applications Cloud detection – screening, shadowing particularly at night was a big challenge (the Night Day band of VIIRS provides some help for this sensor can could be considered for others).

For Land and to some extent ice heterogeneity of surface and in particular emissivity made it hard to have confidence in retrievals over anything other than ideal sites. However, in all cases improved validation, with rigorous uncertainties over a range of scene types was considered essential to help constrain retrieval algorithms. Such FRM sites should have the capacity to measure ancilliary data such as ground view of cloud, column aerosol and water vapour as well as Temperature (surface and air). It was noted that for VIIRS biases (measures warmer) of around 3-5 0C to air temperature are observed.

New methods to simultaneously retrieve surface T and emissivity using for example a Kalman filter approach using Seviri were discussed and shown to be consistent with validation results for land and ocean within the estimated Uc of 0.2K. Similarly, approaches prototyped using hyperspectral aircraft based sensors by King’s College London and ONERA France were also reported.

Summary/Recommendations

- Carry out simulations/comparisons of Retrieval algorithms using standardised data sets including cloud simulations
- Develop research to compare and improve cloud detection and its effects for different sensors and between sensors

- Evaluate means to correct residual biases and associated uncertainties associated with representativeness of the measured surface (point scale) (validation/Truth) and that observed by the sensor and its pixel size and geo-location accuracy.
- Encourage FRM sites to have additional measurands potentially as part of super sites, a good example would be a cloud camera.

6.1 VALIDATION METHODS AND ARCHITECTURE

For other than the oceans, validation takes a similar pattern: a few specific well-characterised test sites complimented with designated campaigns. The test- sites are usually characterised by IR measuring radiometers, usually transported across a site by hand or vehicle of some form or by air, in the case of an initial characterisation or time-limited campaign. There are in some cases, particularly on Ice, of some measurements being made with contact thermometers directly measuring surface and/or air. In both cases, these need to be correlated and corrected to the surface temperature that would be observed by satellite. For example, over ice the air temperature can have around 5 K bias to that measured by satellite, and insulation of snow can mean that true temperatures are hard to define.

Figure 4: Examples of land and Ice surface temperature validation methods: tower at Gobabeb, FRM4STS comparison campaign in Gobabeb and buoys for ice temperature in Greenland.

For both Land and Ice, emissivity variation, over usually heterogeneous sites at the scale of a satellite pixel, play a significant role in determining uncertainty of co-located satellite match-ups. In both these cases and indeed the oceans too, the relative lack and geographical distribution of such validation measurements is a significant problem in trying to determine a reliable CDR representative of the globe.

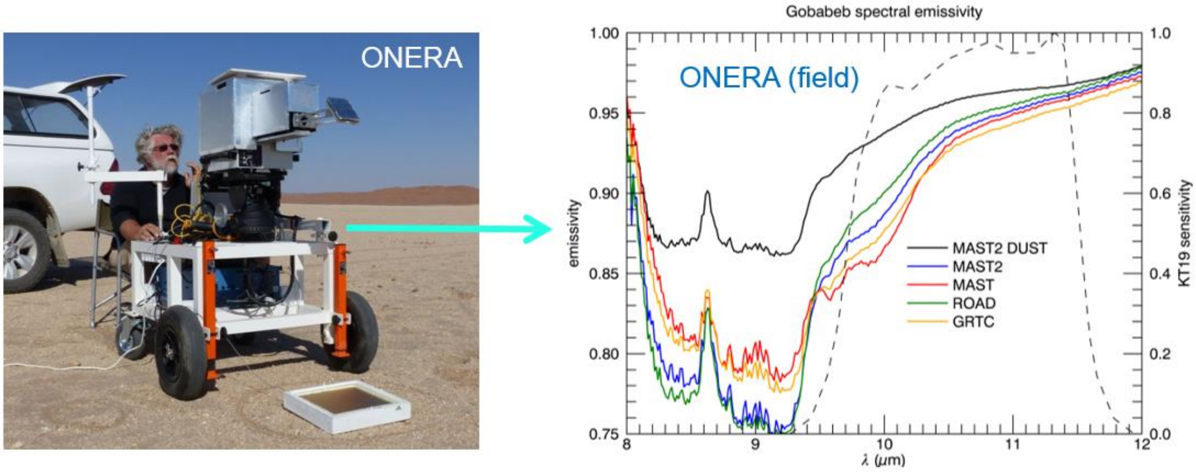
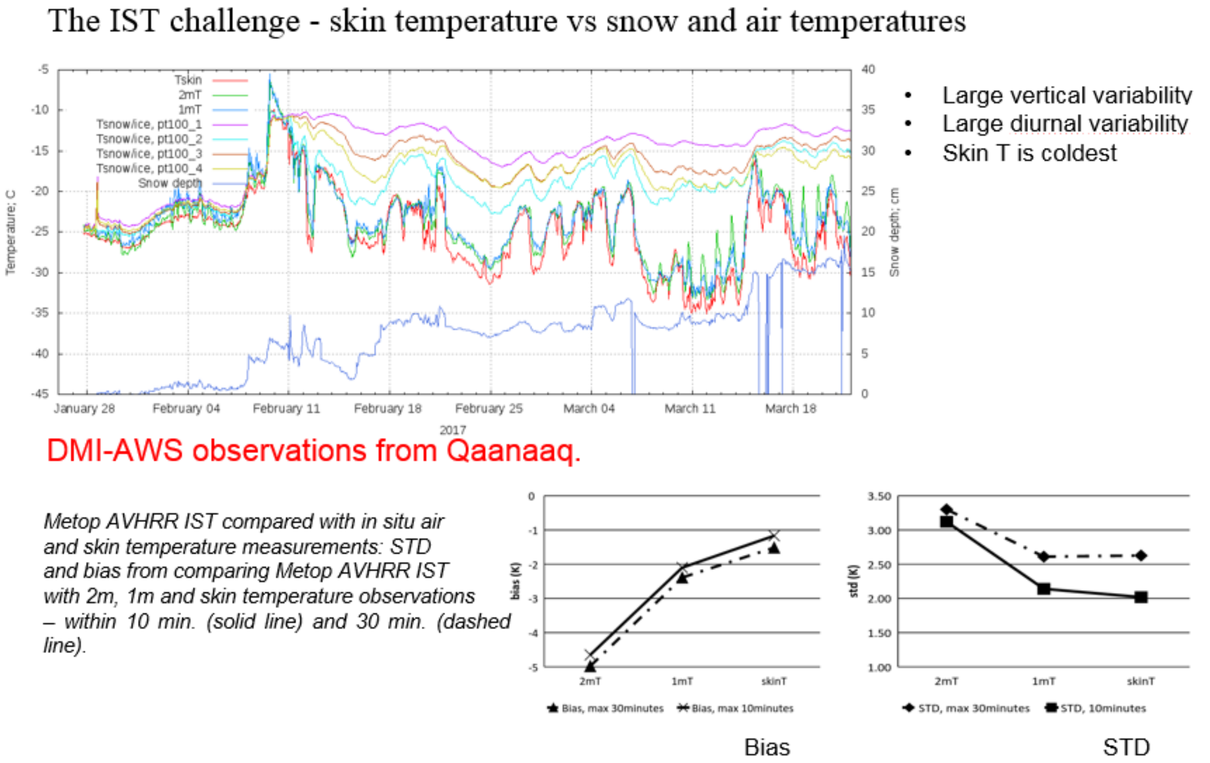


Figure 5: Mobile emissivity measurements of Gobabeb by ONERA

In a similar vein, until recently, lack of community agreed protocols for taking such validation measurements and their use for satellite validation is a concern expressed by many. For Land, CEOS has recently established a best practise, in part taking input from the FRM4STS project, which has also laid the basis of one for Ice. Any best practise explicitly requires that the FRM principles are met and that evidence from round-robin or similar comparisons is regularly obtained and published. The latter have till now been rarely undertaken and particularly not with the formality needed for them to be considered FRM.


The IST challenge - skin temperature vs snow and air temperatures

- Large vertical variability
- Large diurnal variability
- Skin T is coldest

DMI-AWS observations from Qaanaaq.

Metop AVHRR IST compared with in situ air and skin temperature measurements: STD and bias from comparing Metop AVHRR IST with 2m, 1m and skin temperature observations – within 10 min. (solid line) and 30 min. (dashed line).

Bias

STD

Figure 6: From workshop presentation by Dybkyjaer showing differences in air, ice skin and snow temperatures

For the Oceans, although significantly more mature, and not suffering as much from emissivity variations, although sea state, is still a potential issue at the uncertainty levels sought, the challenges remain as significant. The vastness of the Earth's oceans and intervening atmosphere and the more demanding uncertainty requirements, makes it equally important to validate satellites across the globe.

This geographical coverage can only be obtained from the network of free roaming ocean buoys, but these tend to cluster around ocean currents and sea lanes, limiting representativeness. Of course in general, in the context of FRM and the needs of climate validation they also suffer from lack of traceability and in most cases accuracy due to their lack of recoverability and specification for their primary purpose (Meteorology).

Figure 7: Taken from presentation of Minnett, showing state of ocean Buoy after a year at sea!

As can be seen from Fig 7, once the buoy has been launched it is virtually impossible to know what its condition is and how well its reported temperature represents that of the ocean and since this is not a skin measurement, how well this can be correlated with a satellite.

Work is in progress at university of Miami to evaluate, under real ocean conditions, the long term stability of typical buoys. Similarly, effort is being made by a number of agencies not least EUMETSAT, to deploy buoys with improved, traceable pre-deployment calibration, rather than type or batch testing.

The Argo network is also an example of improved calibrated buoys but relatively few in number. Studies, particularly in the context of GHRSST but also CCI and others have shown that with a sufficient number to allow a reasonable degree of statistical robustness an ensemble of Buoys can provide validation accuracies close to around 0.2 K plot of Merchant, Fig 8.

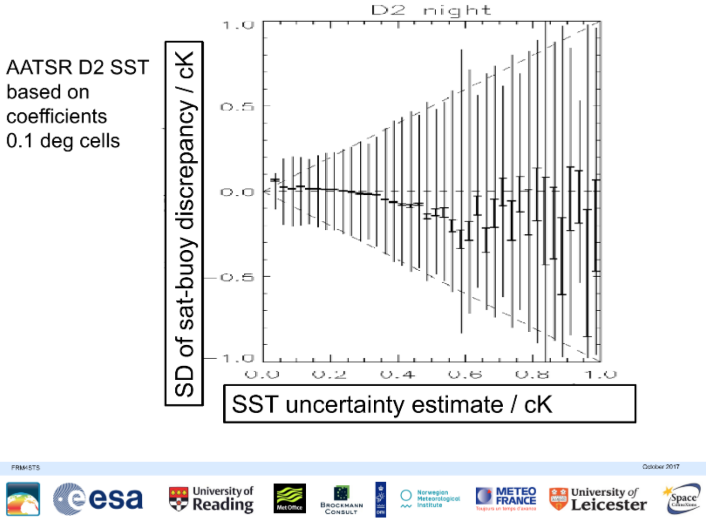


Figure 8: Taken from presentation of Merchant showing comparison of Buoys to AATSR

Recommendations from GHRSST to Buoy Data Co-operation Panel (DBCP) formed by WMO and UNESCO for a high performance Buoy, High Resolution Sea Surface Temperature (HRSST) , 0.05K accuracy and 0.01K resolution were reported to have been adopted and initiatives in place to work towards the adoption of a version 2 with specially designed and individually characterised sensor, (currently 1200 deployed of which 70 are the V2) with EUMETSAT committing to the purchase of around 100 to support the validation of SLSTR and to evaluate the benefit of the added complexity and cost of the V2. Similarly, a new database providing access to information including QA on all the buoys is under development and will be available to the community to support validation. Discussions on how to improve their traceability was the subject of discussion and will form part of a future report.

IR radiometers, as for land and Ice, providing they are well-calibrated, probably provide the most accurate means to validate the satellites, at least from on a point to point basis, since their measurand is the same as that of the satellite, skin brightness temperature, and often in a very similar spectral band. However, although in principle they can be deployed anywhere on the globe they are relatively few in number, and rely on ships of opportunity to make measurements. Thus, there are significantly fewer match-ups with satellites and in relatively limited transects of the oceans.

Radiometers in contrast to Buoys can be more readily made traceable to SI and considered FRM providing they are appropriately calibrated before and after a deployment.

There are several independent designs of IR radiometer, not only to suit the domain of interest, Land, Ocean but also within each domain. In principle, radiometers designed for one application can be used for another, although sometimes the environmental conditions can place operational constraints. Evidence to demonstrate the performance and traceability of the different instruments requires comparison. Fortunately, this community has for some time recognised the importance of this and the 2016 CEOS comparison was the forth in a series carried out at approximately 5 yearly intervals.

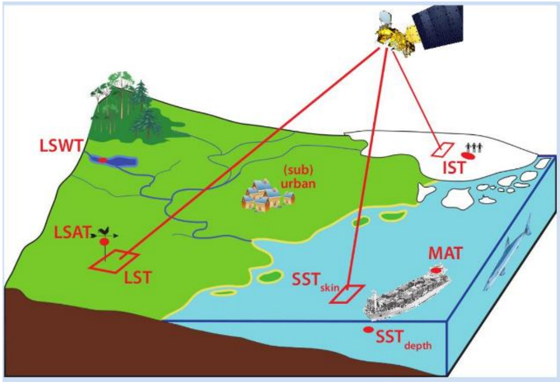
The ideal architecture for validating the oceans would be a combination of buoys and ship borne radiometers, both traceably calibrated as FRM. In the case of the buoys, investment in improved calibration of at least a sub-set of buoys <0.05 K and potentially increased number of redundant thermometers on each buoy to three to aid confidence attributed to their reported values.

In addition to validation from surface measurements, satellite to satellite cross-comparison and in some cases recalibration is also a key element for any strategy. In the absence of any alternative SI traceable reference in space, JAXA are making use of coefficients from other satellites e.g. IASI, as a WMO GSICS reference, to update its pre-flight calibration coefficients for the geo stationary platform Himawari-8 . Similarly, ESA CCI has made use of the well-calibrated nature of the ATSR series of satellites and SNO overpasses to provide a robust harmonised FCDR across all three sensors and also bias coefficients to enable the AVHRR series to be incorporated. Similar comparisons between Modis and VIIRS and others has and continues to take place. Such comparisons should ideally be organised to follow robust protocols in a similar manner to surface FRM to remove ambiguity and/or bias due to choice of any reference sensor.

Summary/Recommendations

- Significantly greater number of match-ups in a range of waters, particularly in polar regions, mountainous zones and water bodies is needed using traceable high accuracy FRM quality buoys and radiometers. This should include fixed long term deployment of radiometers on a number of fixed locations, ice and land.
- Community protocols and best practises to be developed and widely promoted
- Research on the means to improve traceability and trust in measurements from floating buoys whilst maintaining relatively low costs.
- Make measurements at a range of sea depths: skin to around 70 cm to overlap with Argo
- Evaluate T as a function of depth for snow/ice
- Regular comparisons of radiometers under a variety of conditions (laboratory to operational) particularly in the Ice and Ice/coast regions.
- Encourage the development of networks of super sites with a range of measurands, not only surface T, but also air T, reflectance, atmosphere, wind etc. Some networks for a number of parameters, particularly those of WMO already exist and could be added to.

- The concept of FRMs and that regular calibration and assessment of uncertainties in the validation instrumentation should be seen as a pre-requisite for any measurements used by a space agency in support of a satellite mission.
- Where possible satellite to satellite and in-situ co-locations should be encouraged and results reported. Observed differences, including retrieval algorithms should be explored with urgency and openly reported.
- Funding agencies should look to cooperate internationally to ensure that the necessary long term Validation infrastructure remains in place and consistent beyond the life on any one mission to enable interoperability and the creation of FCDRs and CDRs.
- Use of Drones and aircraft to evaluate effects of heterogeneity for land and Ice should be encouraged also potential use of thermal imaging cameras for relative measurements.
- Consider potential of adding PV powered motors to enable some buoys to be recovered and more controlled sampling/drifting.



Left: *from Merchant et al., 2013*: *http://www.geosci-instrum-method-data-syst.net/2/305/2013/gi-2-305-2013.html*

There is a need for a global network of in situ reference sites where relationships between different types of surface temperature can be characterised over land, ocean, ice and lakes.

Oceanic and desert regions, ice-covered surfaces, high elevation and high latitudes generally are currently poorly represented.

Figure 9: Taken from Merchant, illustration of nature of validation sites

7 METROLOGICAL FRAMEWORK: TRACEABILITY AND UNCERTAINTY

One of the overarching requirements that stems from not only the science requirements but also from the cal/val community is the need to establish and ensure SI traceability, and with it an appropriate uncertainty budget. The workshop discussed the underpinning concepts of metrology as practiced by international NMI community which are centered around the use of rigorous uncertainty analysis evidenced by comparisons. The interpretation of this for the EO community was illustrated from case studies and concepts developed within the EU FIDUCEO project. (http:www.Fiduceo.eu). Here the establishment of a measurement equation and its dissection into its constituent parts and sub-equations and the associated derivation and propagation of uncertainties through it was discussed as a framework for how this can be considered as ‘best practice’ for the future. RAL-Space presented an example of the application of this philosophy and the presentation style using SLSTR.

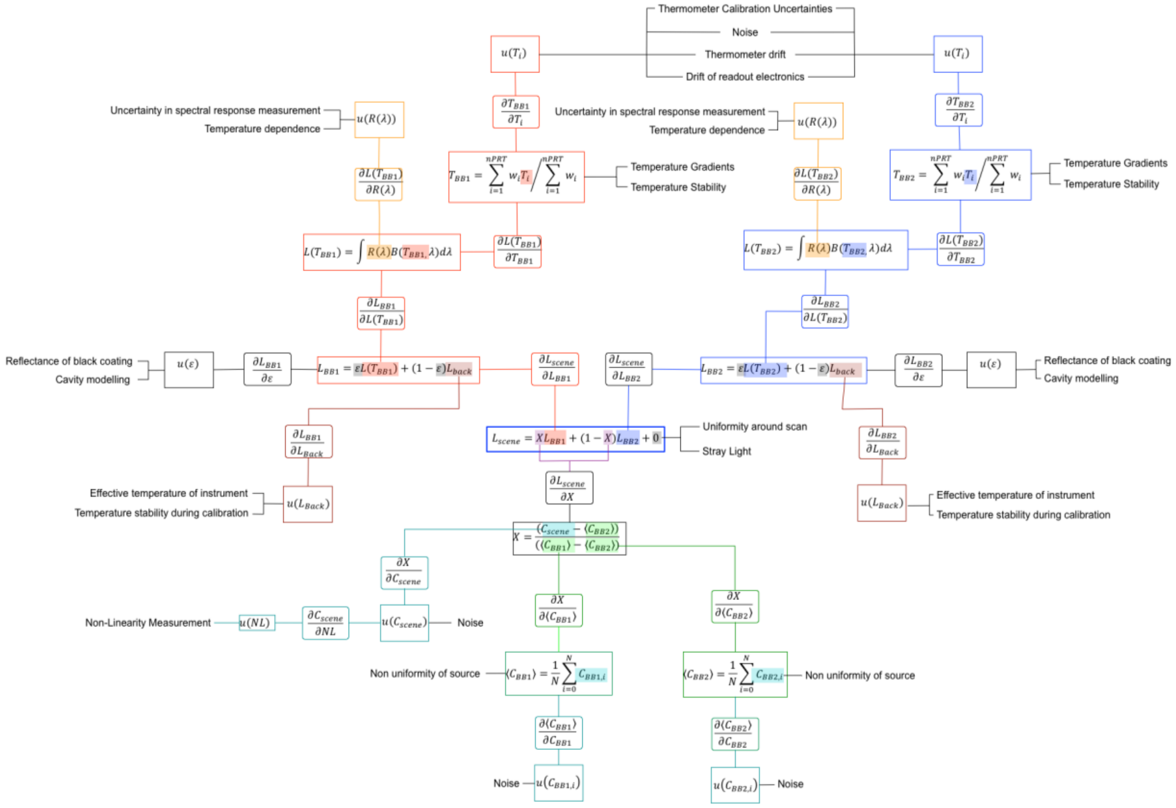


Figure 10: Taken from workshop presentation of Smith, SLSTR traceability tree following method of FIDUCEO

Recognising the importance of comparisons, lessons learnt from the NMI community were summarized and the guidance documents that they have produced were used as a basis for the CEOS comparisons performed under the FRM4STS project. A key aspect of this is the development of formal protocols, agreed by all participants before the start of any comparison. These protocols need to contain an outline of the logistical and technical aspects of the comparison activities, how the results will be analysed, and a baseline template for presenting the results and the uncertainties for each participant.

The protocols, results and uncertainties for each of the comparisons carried out under the project FRM4STS are available on this projects websites; www.FRM4STS.org and so will not be repeated here, we simply summarise below the range of comparisons carried out. It should be noted that this project was explicitly established to evaluate the state of the art in terms of FRM for ocean, land and ice surface temperature measurements and to undertake activities to encourage their global development and deployment. The project thus had the following objectives:

1 Designing and implementing a laboratory-based comparison of the calibration processes for FRM TIR radiometers (SST, LST, IST and others);

2 Designing and implementing a laboratory-based comparison to verify TIR blackbody sources used to maintain calibration of FRM TIR radiometers;

3 Designing and implementing field inter-comparisons using pairs of FRM TIR radiometers to build a database of knowledge over several years;

4 Conducting field-campaigns for TIR FRM in collaboration with CEOS and the international community;

5 Conducting a full data analysis, derivation and specification of uncertainties;

6 Studying SI Traceability for SST, LST and IST measurements collected using instruments other than FRM TIR radiometers.

The rigorous validation of satellite derived surface temperature measurements through FRM test-sites[1] enables:

1 Quantification of the performance and validity of the atmospheric correction algorithm used in satellite geophysical parameter retrieval;
2 Monitoring of any specific satellite instrument performance over the mission lifetime;
3 Establishment of independent reference data to bridge the gap between different satellite missions;
4 Development and improvement of satellite retrieval algorithms;
5 Identification of potential means to harmonise observations from different satellites and conceptually different technologies;
6 Further understanding of the air-sea-land-ice interaction and electromagnetic energy emitted from the Earth’s surface.

and in conclusion the project has delivered:

Key deliverables

1 Laboratory-based comparison of calibration processes for FRM TIR radiometers (SST, LST, IST);
2 Laboratory-based comparison to verify TIR blackbody sources;
3 Field inter-comparisons of SST using pairs of FRM TIR radiometers on board ships;
4 Field-campaigns for FRM TIR of LST and as a pilot IST;
5 Best practice protocols for the calibration, operation and performance of FRM of surface temperatures;
6 Full data analysis, derivation and specification of uncertainties, following agreed NMI protocols on all data collected as part of FRM4-CEOS;
7 All outcomes published to promote benefits of Cal/Val;
8 Results of a study of means to establish traceability and potential benefits to satellites validation and CDRs of high accuracy ocean temperature using non-recoverable sensors.

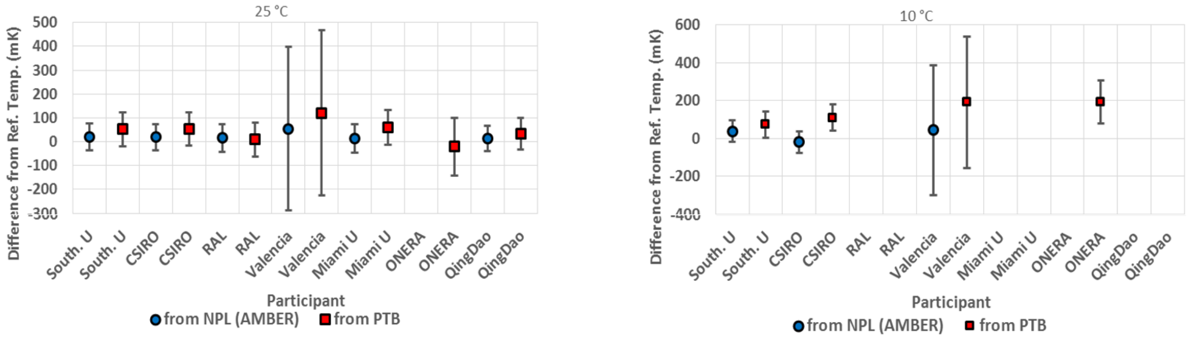
The results of the laboratory comparisons highlighted how well the community has progressed in terms of the core instrumentation. All reference blackbodies were consistent with each other and SI within their stated uncertainties for the full range of Temperatures. Similarly for the most common range of temperatures (around 10 to 30 °C) radiometers were also consistent. However, as temperatures deviated significantly from the nominal and in particular the observed temperatures had large deviations compared to laboratory ambient biases started to develop. Although in some cases these biases may be due to closeness of the radiometers field of view to that of the observed reference black body. However, non-linearity due to non-normally large differences between the radiometer internal ‘ambient temperature’ reference black body may be the principle cause.

---

[1] well-calibrated, SI traceable surface based measurement sites

Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 25 ºC.

Difference between the mean of the values reported by participating blackbodies from the values measured by AMBER (shown in blue) and PTB (shown in red) for a nominal blackbody temperature of 10 ºC.



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 20°C.

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.

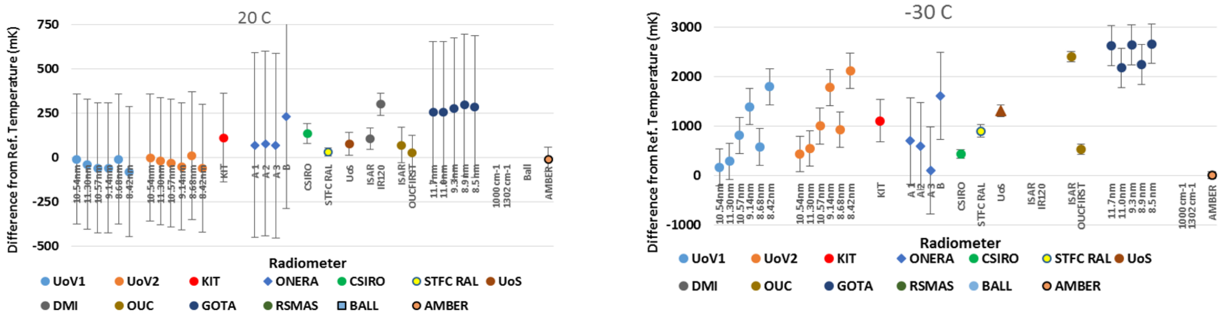


Figure 11: Taken from Fox example results of FRM4STS laboratory comparison, top; blackbodies and bottom radiometers.

One participant, University of Miami, made use of the wide range of Temperatures and the observed discrepancies to evaluate uncertainty and establish a correction to the emissivity of the radiometers internal reference black body. This demonstrated the additional benefit that can be obtained from the result of rigorous well-planned comparisons.

Summary/Recommendations

- More education and case studies to explain how to identify, quantify and propagate uncertainties at specific activity level and end to end.
- Creation of a thesaurus on terminology
- How to treat sampling and scaling issues?
- Regular comparisons, ideally tailored to reflect as near as possible operational conditions e.g. ambient temperature in addition to ideal conditions using them not only to identify potential biases but also to understand their causes.
- Funding bodies should oblige participation in comparisons to demonstrate evidence of uncertainties (FRM compliance) before using data.

8 COMMUNITY PRIORITIES: TOWARDS A ROADMAP FOR THE FUTURE

Taking account of the discussions and recommendations from the various sessions the community developed the following set of priorities grouped by domain area in the following tables.

Table 3: 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 4: 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 5: 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	7	8	2-3 years Takes a lot of planning

	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			

8.1 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.

The earlier sections in this report provide more detailed technical recommendations.

8.2 CONCLUSION

This report provides a summary of the discussion of a 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 societies science goals, driven by climate, are able to be met. The presentations, comparison results, protocols and draft best practises are all available on the FRM4STS web site (www.FRM4STS.org).

8.3 APPENDIX A: WORKSHOP ATTENDEES

Ali Hussain	RAL Space
Andrew Banks	National Physical Laboratory
Andrew Brown	National Physical Laboratory
Anke Duguay-Tetzlaff	MeteoSwiss
Anne O'Carroll	EUMETSAT
Calin Ciufudean	"Stefan cel Mare" University
César Coll	University of Valencia
Christopher Merchant	University of Reading
Christopher Tsamalis	Met Office Hadley Centre
Craig Donlon	ESA
Dave Smith	Science and Technology Facilities Council
David Meldrum	SAMS
DooChun Seo	Korea Aerospace Research Institute
Dorothy Hall	NASA
Eleanor Barber	Science and Technology Facilities Council
Emma Woolliams	National Physical Laboratory

Eunghyun Kim	Korea Aerospace Research Institute
Frank-Michael Göttsche	Karlsruhe Institute of Technology
Garry Hensey	National Physical Laboratory
Gary Corlett	The University of Leicester
Guido Masiello	University of Basilicata
Isabel Trigo	Instituto Português do Mar e da Atmosfera
Jacob Høyer	Danish Meteorological Institute
John Kennedy	Met Office Hadley Centre
Jon Mittaz	National Physical Laboratory
Jose Sobrino	University of Valencia
Katharine Hurst	CGI
Kiran Fatima	Shaheed Zulfikar Ali Bhutto Institute of Science & Technology
Laurent Poutier	ONERA
Lei Guan	Ocean University of China
Lilian Osei bonsu	University of Ghana
Liqin Qu	Ocean University of China
Manuel Arbelo	Universidad de La Laguna
Mark Tschudi	CCAR, University of Colorado
Martin Wooster	King's College London
Mary Langsdale	King's College London
Misako Kachi	JAXA
Nick Rayner	Met Office Hadley Centre
Nigel Fox	National Physical Laboratory
Olutayo Victor Olayeni	University of Ibadan
Peter Minnett	University of Miami
Peter Thorne	Maynooth University Department of Geography
Saad Ul Haque	Institute of Space Technology
Theo Theocharous	National Physical Laboratory
Tim Nightingale	Science and Technology Facilities Council
Yamen Alsayed Omar	Cranfield University
Yuhan Rao	University of Maryland - Department of Geographical Sciences

8.4 APPENDIX B: WORKSHOP SCIENTIFIC COMMITTEE

Anne O'Caroll	EUMETSAT / GHRSST / Sentinel-3
Changyong Cao	NOAA
Craig Donlon	ESA
Helen Beggs	CSIRO (Australasia)
Nigel Fox	NPL/CEOS WGCV IVOS/FRM4STS
Phillipe Goryl	ESA
Simon Hook	JPL CEOS WGCV LPV (LST co-lead)
Chris Merchant	University of Reading, GHRSST / ESA CCI SST
David Meldrum	DBCP
Jose Sobrino	University of Valencia CEOS WGCV LPV (LST co-lead)
Kurtis Thome	NASA (CEOS WGCV Chair)
Lei Guan	Ocean University of China
Peter Minnett	RSMAS (SST)
William Emery	University of Colorado

8.5 APPENDIX C: WORKSHOP AGENDA

An international workshop was held at NPL, 16-18 October 2017. The objective of the ESA sponsored workshop was to bring together the worlds' expertise in Earth surface (Land, Water, Ice) temperature measurements under the auspices of Committee on Earth Observation Satellites (CEOS) to review the current state of the art in measurement accuracy for satellite validation. The workshop considered the outputs and results from the recent CEOS comparison of fiducial reference measurements/instruments and concluded with looking to develop an internationally coordinated strategy to ensure that the global reference measurement infrastructure is adequate to meet the future needs and aspirations of all users.

	Programme: Day 1, Monday 16 October	**Presented by**
0900 – 0930	Registration	
0930 – 1000	Introduction to the Workshop	Craig Donlon (ESA) & Nigel Fox (CEOS)
1000 – 1300	**Session 1; *Science requirements for LST, IST and SST applications: Climate, Meteorology and Oceanography***	Chaired by Peter Minnett (University of Miami)
1000	*Presentation details still to be confirmed*	Chris Merchant (University of Reading)
1020	*Making long-term sea-surface temperature data sets for climate*	John Kennedy (Met Office - Hadley Centre)
1040	**Coffee break**	

1120	*Influence of Surface Temperature on Cryospheric Processes: Developing the Case for Long-Term, Accurate Records*	Dorothy Hall (NASA)
1140	*What role could a putative global surface reference network play?*	Peter Thorne (Maynooth University)
1200	Discussion	All
1300 – 1400	**Lunch**	
1400 – 1540	**Session 2; *Retrieving Surface Temperatures from Space* *Keynote Ocean, Keynote Land, Keynote Ice***	Chaired by Chris Merchant (University of Reading)
1400	*Progress in Establishing a Satellite-derived Climate Data Record for Sea-Surface Temperature*	Peter Minnett (University of Miami)
1450	*Creating, calibrating, and validating a satellite-based sea ice surface temperature product*	Mark Tschudi (CCAR, University of Colorado)
1515	FIDUCEO Principles for Satellite retrieval	Jon Mittaz (NPL)
1540	**Coffee break**	
1600	Discussion	
1630 – 1730	**Session 3; *FRM4STS Overview***	Chaired by Craig Donlon (ESA)
1630	Overview of FRM4STS Project including laboratory results	Nigel Fox (CEOS)
1700	Discussion & presentation of key questions to be addressed	All
1730	Interactive Presentations & Icebreaker • *Simultaneous measurement of land surface temperature and emissivity using ground multiband radiometers* • *Needs for Fiducial Reference Temperature Measurements in the EUSTACE project* • *The NPL Absolute Measurement of a Blackbody Emitted Radiance (AMBER) Facility* • *The NPL Infrared Spectral Responsivity Measurement Facility* Provided by E. Theocharous, NPL • *FRM4SOC - project to establish and maintain SI traceability of Fiducial Reference Measurements (FRM) for satellite Ocean Colour Radiometry (OCR) with accompanying uncertainty budgets.*	All César Coll, et al. (University of Valencia) Nick A. Rayner, et al. (Met Office Hadley Centre) Theo Theocharous (NPL) Theo Theocharous (NPL) Andrew Banks (NPL)

1900	Close of Day 1	
	Programme: Day 2, Tuesday 17 October	
0900 - 1300	**Session 4; *Metrological framework: Traceability and uncertainty, sampling and scaling, representativeness***	Chaired by Nigel Fox (CEOS)
0900	*Metrology principles for Earth Observation: the NMI view*	Emma Woolliams (NPL)
0930	*Protocols of the 2016 FRM4STS NPL comparisons*	Theo Theocharous (NPL)
1000	*Land Surface Temperature Field Inter-Comparison Experiment at Gobabeb, Namibia*	Frank Göttsche (Karlsruhe Institute of Technology)
1030	*Water Surface Temperature intercomparisons at Wraysbury reservoir and in the North Atlantic*	Tim Nightingale (STFC RAL Space)
1100	**Coffee break**	
1130	*Towards traceability when validating ice surface temperature observations from satellite observations*	Jacob Høyer (Danish Meteorological Institute)
1200	*Towards improved drifter SST: a collaboration between the satellite community and the Data Buoy Co-operation Panel*	David Meldrum (Scottish Marine Institute)
1230	Discussion / endorsement of approaches	All
1300 - 1400	**Lunch**	
1400 - 1730	**Session 5; *Protocols for Post-launch validation of surface temperature measurements from Space***	*Chair to be confirmed*
1400	*JAXA SST Products and Validation Activities - GCOM-W, GCOM-C and Himawari-8*	Misako Kachi (JAXA)
1420	*Land surface temperature products validation for GOES-R and JPSS missions: status and challenge*	Yuhan Rao (University of Maryland)
1440	*Kalman Filter Retrieval of Skin Temperature From Seviri: Improved Forward Modelling And Inter-Comparison Case Studies*	Guido Masiello (University of Basilicata)
1500	*An uncertainty budget for validating satellite derived sea surface temperature measurements*	Gary Corlett (University of Leicester)
1520	**Coffee break**	
1550	*ONERA methodology for the in-flight vicarious calibration of airborne and space borne thermal infrared instruments.*	Laurent Poutier (ONERA)
1610	*Land Surface Temperature and Surface Spectral Emissivity from thermal infrared hyperspectral data: application to OWL and implications for satellite validation*	Mary Langsdale (King's College London)

1630	*Validation of sea ice surface temperature products from the AVHRR and IASI instruments on Metop_A*	Gorm Dybkjær (Danish Meteorological Institute)
1650	Discussion	All
1730	**End of Day 2**	
1900 - 2200	Event Dinner The Wharf Restaurant & Bar, 22 Manor Road, Teddington	
	Programme: Day 3, Wednesday 18 October	
0900 - 1200	**Session 6; *Post-launch validation: Buoys***	Chaired by David Meldrum (Scottish Marine Institute)
0900	*Evaluation of Suomi NPP VIIRS Sea Surface Temperature Using Shipboard Measurements in the Northwest Pacific*	Lei Guan (Ocean University of China)
0930	*Towards Fiducial Reference Measurements from drifting buoys for Copernicus satellite validation*	Anne O'Carroll (EUMETSAT)
1000	*The quality of Sea Surface Temperature observations from drifting buoys and the role of the natural variability*	Christoforos Tsamalis (Met Office - Hadley Centre)
1030	**Coffee break**	
1100	*Calibration and In-Flight Performance of the Sentinel-3 Sea and Land Surface Temperature Radiometer*	Dave Smith (RAL Space)
1130	Discussion	All
1200 - 1300	**Lunch**	
1300 - 1500	**Session 7; *Establishing a sustainable framework of measurements to ensure fit for purpose data to meet the needs of society***	*Chair to be confirmed*
1300	Introductory presentation	Nigel Fox (CEOS)
1330	Roadmap Development discussion	All
1500	Workshop close	
	End of Workshop	

-END OF DOCUMENT-