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| **Customer** | **:** | **ESTEC** | **Document Ref** | **:** | **FRM4SST-WR-SCL-002** |
| **Contract No** | **:** | **3-15990/19/NL/IA** | **Issue Date** | **:** | **13 March 2023** |
| **WP No** | **:** | **11** | **Issue** | **:** | **1** |

**Project** : **FRM4SST (ships4sst)**

**Title** : **ISFRN Workshop Report**

**Abstract** : This document contains the proceedings of the ISFRN workshop which took place on 8 – 9 September 2022.

RWilson

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# AMENDMENT RECORD

This document shall be amended by releasing a new edition of the document in its entirety. The Amendment Record Sheet below records the history and issue status of this document.

## AMENDMENT RECORD SHEET

| ISSUE | DATE | REASON FOR CHANGE |
|---|---|---|
| A | 28/10/2022 | Draft for first internal review |
| B | 09/01/2023 | Draft issued to presenters for review |
| C | 16/02/2023 | Updated draft issued to FRM4SST team for comment |
| 1 | 13/03/2023 | Issued to ESA following comments |

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# Executive Summary

The latest in a long series of UK and ESA-funded contracts to support the Infrared Sea Surface Temperature Autonomous Radiometer (ISAR) and Scanning Infrared SST Radiometer (SISTeR) deployments is known as FRM4SST or “ships4SST”. The aim of the ships4sst service is to validate satellite SST such as the Sentinel-3A and Sentinel-3B SLSTR SST data products and to promote and evolve the International SST FRM Radiometer Network (ISFRN or “Network”). To this end, an ISFRN workshop was held at the National Oceanography Centre (NOC) in Southampton and virtually on the 8 – 9 September 2022. The aim of the workshop was to bring together scientific and operational users and producers of in situ radiometer SST data from around the world to review progress, achievements and potential developments within the radiometer community, with several presentations given by world experts in several fields, including radiometer operators, data users and validation scientists.

In this workshop report we summarise the key points from the presentations and use participant feedback to comment on the current and future state of the shipborne radiometer network in assessing the accuracy of satellite-derived $SST_{skin}$ and encouraging best practise in the collection, formatting and validation of $SST_{skin}$ data.

We would like to thank and acknowledge the important contribution of all the participants and presenters in support of this workshop.

# Acronyms and Definitions

| | |
|---|---|
| ISFRN | International SST FRM Radiometer Network |
| FRM4SST | Fiducial Reference Measurements for Sea Surface Temperature |
| CDR | Climate Data Record |
| SST | Sea Surface Temperature |
| ISAR | Infrared Sea Surface Temperature Autonomous Radiometer |
| TIR | Thermal InfraRed |
| SISTeR | Scanning Infrared SST Radiometer |
| M-AERI | Marine-Atmospheric Emitted Radiance Interferometer |
| RSMAS | Rosenstiel School of Marine and Atmospheric Science |
| SUSTAIN | Surge-Structure-Atmosphere Interaction |
| CEOS | Committee on Earth Observation Satellites |
| GSICS | Global Space-based Inter-Calibration System |
| GHRSST | Group for High Resolution SST |
| CIMR | Copernicus Imaging Microwave Radiometer |
| NRT | Near Real Time |
| WST | The best SST at each SLSTR location in GHRSST L2P format. |
| L2P | The L2P product contains only the best available SST for each pixel according to a set of rules as defined in the SLSTR Level 2 SST ATBD. |

# 1. Introduction

## 1.1 Background

Satellite remote sensing of the Earth has become an essential tool in increasing our understanding of the climate, weather patterns and the impact of climate change. It continues to assist scientists in their analysis of the Earth's climate and policy makers in the formation of policies to adapt to or mitigate the effects of climate change. For this reason, remote sensing data must be as accurate as possible as well as long-term; i.e. they must be suitable for contributing to a reliable data series of linked satellite sensors, which requires that they be validated by comparison to common reference standards. To this end, *in situ* Thermal Infrared (TIR) radiometers are deployed on vessels across the globe to collect $\text{SST}_{\text{skin}}$ data, which are then used to validate and verify the $\text{SST}_{\text{skin}}$ data derived from the measurements of satellite radiometers. Ensuring the accuracies needed for climate research sets very stringent accuracy requirements[1].

Shipborne radiometric measurements provide the high accuracy surface temperature measurements (standard uncertainty <0.1 K) necessary to validate high accuracy satellite SST sensors such as the Sea and Land Surface Temperature Radiometer (SLSTR). Shipborne radiometers also provide a traceability route to SI (International System of Units) standards for satellite measurements and therefore a pathway to generate Climate Data Records (CDRs) from satellite $\text{SST}_{\text{skin}}$ retrievals[2].

To achieve robust traceability to the SI temperature scale (ITS-90), the real-time calibration of shipborne radiometers derived from their internal blackbodies is regularly verified against SI-traceable laboratory calibration targets. The traceability of both the shipborne radiometers and the laboratory calibration targets are confirmed on a regular basis through inter-comparison exercises such as the ESA-funded Fiducial Reference Measurements for SST (FRM4STS) campaign[3] held in 2016 and the recent FRM4SST campaign in June 2022 (see section 6.3).

Whilst the protocols and procedures for maintaining robust traceability to SI standards are now well established within the Network, it is important to keep regular contact and have regular feedback from scientists and data users who share a common interest in the $\text{SST}_{\text{skin}}$ data and satellite data validation results. This is the purpose of the ISFRN and the annual ISFRN workshop.

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[1] Ohring, G., B. Wielicki, R. Spencer, B. Emery, and R. Datla, 2005: Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop. *Bull. Amer. Meteor. Soc.*, **86**, 1303–1314, https://doi.org/10.1175/BAMS-86-9-1303.

[2] Minnett, P. J., & Corlett, G. K. (2012). A pathway to generating Climate Data Records of sea-surface temperature from satellite measurements. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *77-80*, 44-51. https://doi.org/10.1016/j.dsr2.2012.04.003

[3] Theocharous, E., and Coauthors, 2019: The 2016 CEOS Infrared Radiometer Comparison: Part II: Laboratory Comparison of Radiation Thermometers. *J. Atmos. Oceanic Technol.*, **36**, 1079–1092, https://doi.org/10.1175/JTECH-D-18-0032.1.

The ISFRN was set up to develop and support a community of in situ radiometer builders, operators and data users and to:

- Promote good practice in the construction and operation of *in situ* radiometers
- Agree and establish protocols, formats and standards for quality assurance of data
- Provide a single access point for the collection and dissemination of radiometer data
- Support satellite radiometer operators in the long-term validation of satellite products
- Share knowledge and coordinate activities between Network members
- Inform the wider community about the Network's activities

The aim of the annual workshop is, amongst other things, to understand the Network's progress against these objectives.

## 1.2 Workshop Structure

The ESA-sponsored workshop was held at the National Oceanography Centre (NOC) in Southampton, UK, and virtually over two days. The workshop consisted of online presentations, designed to review progress, results and advances in deployments, calibration and validation as well as to look at how the data from shipborne radiometers are used in practice. Time was also allowed for discussions between participants. The workshop consisted of the following sessions spread over two days:

- Session 1: Experiences of Radiometer Operators
- Session 2: Datasets and Fiducial Reference Measurements (FRM)
- Session 3: Validation of Satellite SST and in situ SST Measurements
- Session 4: The ISFRN Network
- Session 5: SST Data in Practice
- Session 6: Radiometer Performance and Uncertainties

This sequence of topics also forms the framework of this report. A detailed agenda is included in the Appendix and can also be viewed, along with presentations from the two sessions, at www.ships4sst.org.

# 2. Experiences of Radiometer Operators

## 2.1 ISAR UK

### *Presenter: Werenfrid Wimmer*

The Infrared Sea Surface Temperature Autonomous Radiometer (ISAR) is a single channel (9.5 – 11.5µm) radiometer with a multi-angle sky and sea scan mirror, which produces high quality SSTskin data to FRM (fiducial reference measurement) standards. Routine deployments on the *Pride of Bilboa* began in 2004, after which it was moved onto the *Cap Finistere* between 2010-2012, before it was installed onto the current ship, the *Pont Aven*. There has been 16 years of near continuous operations and between these deployments, approximately 1 million SST measurements have been made, making it one of the longest SST skin data records to date. See Figure 1 for the full record of deployments. The ISAR has also been deployed on ad hoc cruises over the past few years for additional experiments including oceanic, land, lake and ice side by side comparisons with other ISARs and SISTeR, 4 AMT (Atlantic Meridonal Transect) cruises, and two FRM intercomparisons in the lab and in the field, in 2016 and 2022. ISAR manufacture is ongoing with 11 customers from various countries around the world now using the instrument. Covid protocols have caused some deployments not to take place or instruments to be inaccessible at times over the last two years, however, this is becoming a more infrequent issue.

The instrument is autonomous and works in most environments; however careful maintenance is needed to keep the ISAR working well. Design changes and improved maintenance and pre-deployment checks have helped reduce failures on deployments, and protocols, user, and procedure manuals are available for users via the ships4sst website.

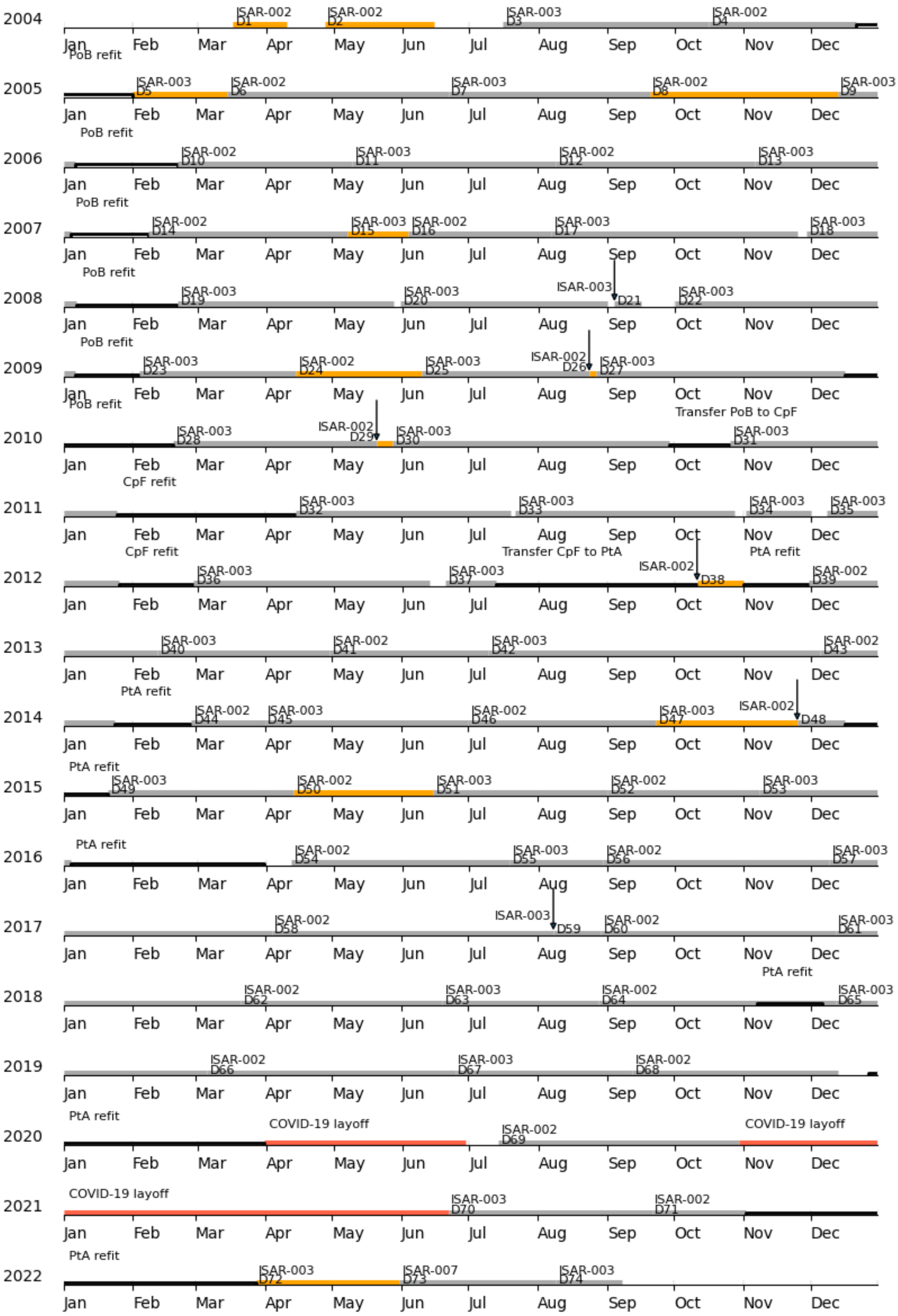

Figure 1: Bay of Biscay and English Channel deployments between 2004 – 2022. There are 74 deployments, approximately 5,000 days at sea and 200 SST$_{skin}$ measurements a day. The orange parts show failures during deployments and red shows the break during COVID-19 lockdowns.

## 2.2 M-AERI & Heitronics Radiometers on Saildrones

### *Presenter: Peter Minnett*

The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) is a very well-calibrated and stable sea-going Fourier transform infrared (IR) interferometer. It is calibrated before and after each deployment and contains two internal blackbodies, with thermometers with NIST-traceable calibration, for at-sea calibration. It can also be run autonomously with daily checks so can be deployed for months without maintenance. Deployments first began in 1996, and 3 Mk2 M-AERI are usually deployed on Royal Caribbean Group ships since 2000. However, COVID-19 has caused a hiatus since 2020 so deployment of one Mk2 is currently on the NOAA ship *Ronald H Brown* whilst the Mk3 has been involved in laboratory measurements in the SUSTAIN (Surge-Structure-Atmosphere Interaction) at RSMAS.

M-AERI data between 2013 – 2020, over 3427 days' worth of SST data, are available on the ships4sst website and at https://doi.org/10.17604/bswq-0119.

Saildrones are long-endurance Autonomous Surface Vehicles (ASVs) that carry a set of meteorological and oceanographic sensors. They use wind for propulsion and solar panels for power, and sail between waypoints sent via satellite link. The waypoints are adaptive and can be updated as required to achieve scientific measurement objectives. Two Saildrones were deployed in 2019 using pairs of Heitronics radiometers in a 'unicorn' configuration, up- and down-looking at 50° angles to derive $SST_{skin}$, in the Pacific Sector of the Arctic as part of the NASA/NOPP 3rd Multi-Sensor Improved SST (MISST-3) project. $SST_{skin}$ can be derived to useful accuracy using this method, as long as measurements from a limited range of accurately measured attitude angles are used due to the pitch and roll of the Saildrone changing the sky incidence angle, and periods of spray and precipitation are rejected. A comparison of $SST_{skin}$ from two Saildrones sailing less than 10 km apart shows good accuracies, with a mean or ~7 mK and a robust standard deviation of 0.126 K. Taking out diurnal heating and comparing with the Donlon et al (2002) formula, the asymptotic values at high winds differ by 0.01K, which is very encouraging. See https://doi.org/10.1109/TGRS.2022.3231519 for the derivation of $SST_{skin}$ from saildrone measurements.

## 2.3 Skin Temperature Measurements for USVs and Buoys: Use of an Optimal Spectral Band

### *Presenter: Andy Jessup*

There are some challenges that limit the $T_{skin}$ measurements to ships, these break down to; a need for in situ two-point calibration using precision blackbodies, a separate sky measurement to correct for reflected downwelling radiance, and emissivity uncertainty which depends on incidence angle and roughness.

The improved stability of commercial radiometers over the past few decades now allows for simplified 1-pt calibration, and by using a filter radiometer with the optimal spectral band approach, this may eliminate the need for the sky measurement, via modelling using air temperature and Relative Humidity, and reduce the emissivity effects.

AJ et al have been working on a simplified calibration (combining laboratory characterising with a 1 point ambient temperature in situ calibration) with separate sky measurements using separate up and down IR sensors. This has been tested using ship measurements by deploying two ROSRs as reference measurements (shown as very well correlated) and then comparing with the IRISS prototypes with the 1-pt calibration (showing accuracy comparable to the ROSR) and adding uplooking IR sensors to the existing units on saildrones and then shadowing with the ship.

The 7.5 - 7.8 µm band was chosen to reduce the influence of clear skies causing a big variation in sky and air temperature, using the commercially available radiometer KT19.45. Preliminary results from the Optimal Band radiometer show promise; there is little deviation due to clear sky radiation and a RMS of 0.15°C with 'light' quality control on IRISS and ROSR Tskin data. The next steps are to determine whether we can use this optimal band technique to eliminate the need for a sky measurement, by modelling sky radiance based on Tair and relative humidity and continuing deployments of radiosondes and radiometers.

## 2.4 ISAR Denmark – High Latitude Radiometer Activities at DMI

### *Presenter: Jacob Høyer*

DMI now has 3 ISARs and has deployed an ISAR on the *MS Norröna* ferry, which travels between Denmark, the Faroe Islands and Iceland, since December 2017. Deployments also continued all throughout the covid-19 pandemic. It has an incidence angle of 25° and is deployed on round trips of 1 week. ISAR gets serviced and calibrated every 2-3 months due to the harsh weather in the North Atlantic. It also undergoes routine pre- and post- deployment calibration as an FRM and the internal calibration BB can be used to help correct performance e.g. correction when the mirror gets dirty. A 2-way communication box has recently been developed and is already installed.

In 2021, DMI performed the first inter-comparison between microwave (MW) and thermal infra-red (TIR) SST radiometers using an ISAR and the DTU EMIRAD (microwave radiometer in C and X band) to assess the IR (skin) and MW (subskin) SST relationship, in preparation for CIMR (Copernicus Imaging Microwave Radiometer). The first campaign saw a static deployment of ISAR and EMIRAD side by side on a bridge overlooking salty waters in Copenhagen. It consisted of a 1-day deployment in cold and calm waters, and results showed very good agreement between the two instruments. Detailed results are documented in the Characterisation report found on the ships4sst website. A 2nd campaign took place over 10 days during a deployment on the *MS Norröna* ferry and consisted of 2 ISARs (at 25° incidence angle), the EMIRAD X and C bands (at 55° incidence angle) and a TIR camera. The weather was very good so lots of data were acquired. Currently, the ISAR and EMIRAD observations are being collocated and auxiliary information (SST (L4), TCLW, TCWV, wind speed and direction, Salinity and simulated surface emissivity) have been added to the match-ups, to form one dataset that is to be analysed in detail. This will include a comparison of the MW BTs and IR TBs with simulated BTs and to determine spatial and temporal scales of both MW and IR TBs in order to help understand the MW and IR variability. Further sea ice activities on the ISAR are also planned for March/April 2023.

## 2.5 ISAR Australia

### *Presenter: Helen Beggs on behalf of Nicole Morgan*

CSIRO (Nicole Morgan) is responsible for the calibration, maintenance and repairs of the ISAR on the *RV Investigator* vessel, a blue-water sea research ship. The Australian Bureau of Meteorology (BOM, Helen Beggs, Janice Sisson and Haifeng Zhang) are the primary data users of the ISAR data and the Australian Antarctic Division (AAD, Dominic Weller) is responsible for the new ISAR.

Data from the *RSV Nuyina* (AAD) and the *RV Investigator* (CSIRO) cruises using ISAR 10, 13 (tbd) and 16 is sent to BOM where the data is processed, quality controlled and accessed in real time. In delayed mode, after a cruise, the ISARs are re-calibrated and reprocessed with Werenfrid Wimmer's reprocessing code to calculate the uncertainties and then the data is transformed to BOM format and transferred and merged with the real time data at BOM. The processed data is stored at marlin, thredds and AAD and so far there are 23 completed voyages with v3.1 processing code, 14 completed voyages with v3.8 and 5 completed voyages with v5.6. The plan is to reprocess all past voyages in v5.6 reprocessing code by the end of the year, so that all the data is consistent, and within 12 months of a voyage. The amount of data obtained on cruises has improved since 2014 as known instrument problems have been fixed, leading to data obtained from every cruise in 2022 (to date).

*RV Investigator* is funded for 300 days at sea a year and carries a number of scientific instruments including a weather radar, barometer and ISAR. ISAR-10 was installed on the *RV Investigator* in 2014 and has completed 55 voyages to date and provided 1131 days of data. ISAR 16 took part in the FRM4SST CEOS intercomparison in June 2022 and the new ISAR at the AAD was installed and integrated recently after one summer season in 2021/2022. ISAR 10 and ISAR 16 are due to go on a comparison cruise post-CEOS intercomparison workshop in June 2022, in order to check the effect reducing the samples per angle for ISAR 16 on data quality.

A new environmental test chamber arrived in 2021 and is now used for calibration the ISARs, showing good results.

## 2.6 SISTeR

### *Presenter: Tim Nightingale*

SISTeR (Scanning Infrared SST Radiometer) is a chopped, autonomous, self-calibrating infrared filter radiometer that can measure IR brightness temperatures to high accuracy (~30mK). It is split into three compartments, the inner being the calibration enclosure which hosts two blackbodies and a rotating scan mirror. SISTeR measures the upwelling radiance from the sea surface and corrects for the reflected sky component with measurements of the downwelling sky radiance. The blackbody thermometer calibrations are traceable to ITS-90. SISTeR generates level 0 data and a dedicated processor unpacks this data. The SISTeR processor is coded in IDL and all higher level products are encoded in netCDF. Level 2 and level 3 SST products follow the L2R in situ radiometer data format.

SISTeR was first deployed in 1997 and since 2010 has been deployed on the Cunard *Queen Mary 2* (*QM2*) liner (usually sailing between Southampton and New York between May - January and annual world cruise between January - May) where it is mounted on a dedicated platform above the starboard bridge wing. A data logger laptop is connected to the ship’s Ethernet network and emails daily level 0 products back to the UK. COVID-19 restrictions caused a gap in deployments between 2020 and 2022, but deployments resumed in March 2020 and is now on the *QM2* on its 24th cruise. A full set of SSTs was received on the 23rd cruise and a fine yellow dust was discovered on the scan drum (suspect pollen or dust). SISTeR also participates periodically in radiometer inter-comparisons.

# 3. Datasets and Fiducial Reference Measurements

## 3.1 Felyx

### *Presenter: Jean Francois Poille*

Felyx is a generic open-source tool for extracting Earth Observation data over static or moving locations particularly for the production of Match-up Databases. Initially developed under ESA funding, a new version has now been created by the Ifremer team, with new requirements defined by EUMETSAT and funded by Copernicus. There are 2 extraction modes; dynamic, where satellite passes are subsetted over trajectories (time and location) which usually correspond to trajectories of buoys and ships, and static, systematic extraction of satellite passes over predefined areas (e.g. calibration sites) respectively. The extracted match-ups are then assembled in to NetCDF files containing multiple match-ups and is then joined with in situ data attached to the dynamic sites. There is a lot of flexibility with the output format of the MMDB so that many variables can be configured, e.g. periodicity, combining datasets, dividing into subcontracts. An end-to-end command allows all steps to be processed (from input SST files to MMDB output) in one go.

A new version of Felyx has been developed to support the reprocessing of Sentinel-3 / radiometer MMDB. The main improvement for v2 of Felyx, is the creation of a lighter system, i.e. reduced dependencies on third party tools, entirely file based (YAML) configuration, easier installation, Apache/parquet format for storage of in situ data. Complementary framework is provided for distributed processing (jobard) and comes with additional tools and packages for graphical reporting and alerting (felyx-report). Visit https://felyx.ifremer.fr for more information including documentation and installation guidance. The public release of Felyx v2 is planned for September 2022.

## 3.2 Metrology in the TRUSTED Project

### *Presenter: Marc Lucas*

The TRUSTED project was set up by Copernicus and is overseen by Eumetsat to get high quality in situ data for the calibration/validation of the Sentinel-3 radiometers. Higher quality data is needed to enable finer scientific investigations. The TRUSTED project uses a SVP-BRST buoy design with an added sensor to measure high-resolution SST and hydrostatic pressure data, so the depth of the buoy correlating to the SST data measurement is known. The MoSens sensor has a rapid response time so measurements can be taken every second if need be, and can be removed from the buoy so that calibration of the sensor is quick and easy. A big part of the TRUSTED project was the calibration and quantification of the uncertainties. This was done in two steps: every MoSens sensor deployed underwent a calibration and then the uncertainty budget for the MoSens was looked at. Once the MoSens was inserted into the buoy, 1 out of 10 buoys deployed was then verified with a final uncertainty budget also. Post deployment calibration was also performed on the first deployment of the buoys where 3 were recovered. The target uncertainty is 5mK/year and the quantification of the temperature sensor’s drift showed a ~4mK/year, so this was well within the target uncertainty.

Instrument comparisons were performed on the AMT29 cruise and showed good preliminary results, i.e. there was very little difference between the 2 MoSens sensor measurements that were deployed and the reference instrument measurements.

152 buoys were deployed globally in the first phase of the project, with the longest deployment being 720 days and a maximum of 70 at sea at any one time. Currently, a FRM standard for the TRUSTED project is being worked on. A traceability diagram for the origin of buoy measurement uncertainties have been drawn up to help achieve this goal. Getting a high number of usable metadata archived within the ocean op database system is also being worked on.

There are plans to deploy ice temperature buoys in the high northern and southern latitudes; this is in the early stages, and snow and ice conditions tend to be quite different between the Arctic and Antarctic, so validation data is needed in these regions.

# 4. Validation of Satellite SST Measurements

## 4.1 M-AERI validation of SLSTR, MODIS, VIIRS, ABI, and Reanalysis $SST_{skin}$

### *Presenter: Peter Minnett*

Target accuracies and decadal stability requirements are demanding and challenging to verify. Both buoys and radiometers are traditionally used to validate satellite $SST_{skin}$ data, each having their pros and cons. For example, buoys are numerous, started in the early 1980s and so have a long time series, whilst radiometers are fewer in number with a shorter time series, but they have very good calibration and are a comparison of like-with-like with satellite IR radiometers. Comparison with shipborne radiometers ensures that satellite $SST_{skin}$ retrievals have an SI-traceable reference and enable $SST_{skin}$ CDRs to be generated.

MODIS on Terra (launched 1999) and Aqua (launched 2002), were both in nominal operations as of 8 September 2022 but with end-of-life procedures expected to start late 2022/early 2023. A standard atmospheric correction algorithm is a modified NLSST for day and night. The entire mission was reprocessed at the end of 2019 and all of the match-up databases now use the R2019 algorithms. Major changes include using CMC (Canadian Metrological Centre) fields as the reference, a new cloud screening algorithm using alternative decision trees[4] and night-time aerosol correction[5]. Comparing MODIS to M-AERI shows a very good night time SST4 median (-0.047 K) and a 0.324 K robust standard deviation (based on 22,000 match-ups).

VIIRS on Suomi-NPP (launched 2011) is currently in nominal operations as of 8 September 2022. It has fewer channels than MODIS (no SST4 pair), but the NASA VIIRS $SST_{skin}$ atmospheric correction algorithm is comparable to MODIS NLSST. Comparing against M-AERI SSTskin shows that the $SST_{triple}$ night is comparable to SLSTR.

ABI (Advance Baseline Imager) on GOES-16 (operational in 2017) are comparable to MODIS and VIIRS in terms of number of channels, noise level, calibration and quality of instruments. The $SST_{skin}$ is derived using an NOAA ACSPO algorithm. 44448 match-ups with M-AERI within 30 minutes and 5 km between January 2018 and May 2019 show that the current generation of geostationary visible and IR imagers are much improved on the previous generation and that the data are good enough to be used for many scientific applications.

Overall, SLSTR, MODIS, VIIRS and ABI are producing very good $SST_{skin}$. SLSTR on Sentinel-3a shows (an impressive) median $SST_{skin}$ difference of 8 mK when compared with M-AERI data.

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[4] https://doi.org/10.1175/JTECH-D-18-0103.1
[5] https://doi.org/10.1016/j.rse.2019.01.009

The ERA5 $SST_{skin}$ is derived by model simulations with data from satellite-derived SSTs, based on the foundation temperature from the OSTIA analysis. The $SST_{skin}$ from ERA is good, but there is room for improvement through better modelling of aerosol effects, diurnal heating and the skin layer.

## 4.2 Sampling and Measurement Error Models for ICOADS Ships SSTs, based on the ESA CCI SST Analysis

***Presenter: Alexey Kaplan***

The International Comprehensive Ocean-Atmospheric Data Set (ICOADS) aim to collect all in situ Ocean surface data. However, this data is sparse over the global oceans which presents a problem in estimating the data error. The standard approach to estimate the error is using binned summaries (means and nobs). This approach can be more rigorously tested using the ESA CCI SST satellite data set which is independent from in situ data. ESA CCI SST Analysis product (v1.0) from 1992-2010 was used to validate an error model for monthly 1°x1° averages of ship data from ICOADS R.3.0; this model allows for climatological biases and treats the remaining errors as random. For 1°x1° monthly bins with more than a single observation, errors are within 20% of the model in more than 66% of all locations with temporal coverage exceeding 50%. Another advantage made possible by using the analysis product in this study, is the ability to split total random error estimates into the sampling and measurement error components. Seasonal variations in the error magnitude were traced to the sampling error component, i.e. to the seasonality of true SST intrabin variability; the seasonality of measurement error was not significant. Measurement error estimates, including those obtained by ERI and buckets, agree well with those by Kent and Challenor (2006). Estimates for hull measurement types and for electronic sensors (appearing to be the most accurate) were also obtained.

## 4.3 Using ships4sst data to validate SLSTR data

***Presenter: Werenfrid Wimmer***

SLSTR NRT data from 2019, FRM radiometer data from ships4sst and MDB files produced by Felyx are used within the validation. SLSTR L1b and L2 data are used within 400x400 pixels of the match-ups and the L2R is within 6 hours of match-up. These MDB files are then reprocessed to allow multiple matches per match-up location. The WST, D3, D2, N3, N2 and all GHRSST CV level (0, 3,4, 5) are validated using the Wimmer et al. 2012 approach. Most data are around the Atlantic and around Australia, as this is where most of the in situ radiometer data are measured.

The WST validation results from SLSTR on both S-3A and S-3B show a robust standard deviation that is lower at night than daytime and almost no mean difference. The validation results for CV5, D3 and N3 on S3A show an outlier in the D2 and N2 daytime results which will be investigated further. The CV5, D3 and N3 S3B results do not have the same outlier result that can be seen in the S3A histograms.

Overall, the validation of SLSTR with FRM data shows very good results for SLSTR with virtually no mean difference at night and only a small difference at daytime. The robust standard deviation is comparable to AATSR. Further investigation will be made on the QI results.

The NRT results for 2018 are available, along with the results for GHRSST CV 3 and 4, dependence plots for WST, D3, D2, N3 and N2 and the QI methodology on D3, D2, N3 and N2. The regional results for each route, split by ship's name with the same set of statistic and plots as that done for the global results, are also available.

## 4.4 Validation of ENVISAT-AATSR SST retrievals for the study of trends associated with climate change in the Mediterranean Sea

*Presenter: Ludovico Buizza*

The primary objective of this project is to evaluate a split window algorithm to accurately retrieve SST data with equal to or (ideally) less than 0.3 K uncertainty from ENVISAT-AATSR and analyse SST trends associated with climate change. The aim is to generate monthly SST maps for the Mediterranean Sea between 2003 – 2011 and assess the spatio-temporal trends over this period. The validation in the Mediterranean Sea is done using buoys (Poseidon) based in the Aegean Sea which measure SST at 1m depth, so the bulk-skin effect is accounted for when comparing against AATSR SST skin data. At wind speeds >6m/s, 7 out of 10 buoys have uncertainties equal or lower than the target of 0.3K, and SSTs retrieved from nadir-view AATSR data using a split-window algorithm achieve the accuracy of 0.3k also. Temporal resolution of AATSR over the Mediterranean Sea is 4-5 swaths per day, resulting in full coverage in 3-4 days. A five-step procedure has been used to generate monthly SST maps from the satellite data during 2003 – 2011 and discern trends; for example, a trend of 0.086 +- 0.005°C/yr was detected, showing a clear warming in the Mediterranean Sea during this time period.

Future plans include extending the validation area within the Mediterranean Sea using other in situ measurements and extending the time period in both directions using data from additional satellites, such as that from the ATSR and SLSTR series of instruments.

# 5. The ISFRN Network

## 5.1 Status of the ISFRN data archive

### *Presenter: Werenfrid Wimmer*

The ships4sst data archive is managed by Ifremer and can be logged into via the members pages on the ships4sst website. The archive contains a good amount of data and has good geographical coverage for IR data. L2R $SST_{skin}$ data on the archive covers 07/2004 to 02/2022 over 5 different datasets from UoS, DMI, CSIRO, RAL and RSMAS. The upload frequency of the data is provider-dependant.

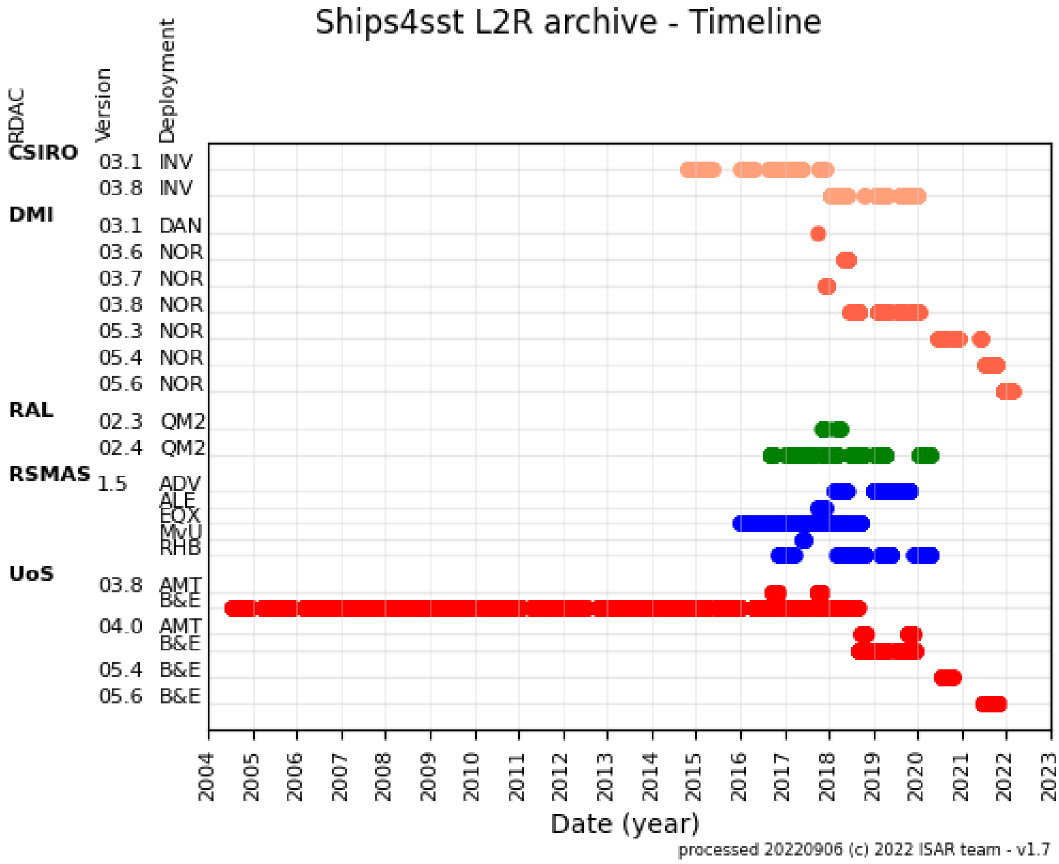

Figure 2: Archive data on the ships4sst archive split by instrument and version number

Issues with data files on the archive can include; wrong file name convention, missing compulsory data fields, new data not matching old data file number on replacement files provided and folder names generation if non alphanumeric characters in instrument name, removing bad quality data and data duplication. In most cases, an email is sent to users to help resolve any problems. There is also an FAQ document on the ships4sst website (user page) to help with the most common problems that users can encounter.

## 5.2 Status of the ISFRN

### *Presenter: Werenfrid Wimmer*

The ISFRN is an international network of ocean and remote sensing scientists who share a particular interest in promoting and improving the use of shipborne infrared radiometers for measuring $SST_{skin}$ at the surface of the ocean, comparable to the retrievals made by satellite infrared radiometers. Objectives of the ISFRN are to:

- OBJ-1: Validate satellite SST products to FRM standards
- OBJ-2: Maintain and evolve the International SST FRM Radiometer Network (ships4sst) and deploy on a continuous basis Thermal Infrared Radiometers (TIR) and necessary supporting instrumentation to validate SST products.
- OBJ-3: Process, archive and quality control ships4sst data following documented FRM procedures that approve their use for FRM satellite validation.
- OBJ-4: Deliver approved ships4sst data sets and uncertainty budgets to users.
- OBJ-5: Prepare and submit peer-reviewed journal articles.
- OBJ-6: Conduct communications and outreach material promoting ISFRN activity.

The ships4sst project, which leads the ISFRN, has a number of tasks including:

Task 1 International collaboration: this covers all international developments and partnerships including the ISAR training (e.g. Korea, China and South Africa), L2R data upload to the website (e.g. from ISARs, SISTeR and M-AERI), potential collaborations through instrument building and loans and outreach on the webpage, Twitter (@ships4sst) and at conferences. An international intercomparison took place in the UK in June 2022, and a number of papers are being written that should be published in 2023.

Task 2 covers data collection and archive. To date, the UoS have delivered data covering 12 deployments, DMI and RAL have 8 deployments. The COVID-19 pandemic has impacted some deployments, with ships being moored, particularly between 2020-2021 and no access to some instruments. This has become less of an issue in more recent times, however. The data archive is located at ftp/ifremer.fr and can be accessed via the ships4sst website.

Task 3 covers data processing and validation. The Felyx MDB (Taberner et al, 2013) generation is done at Ifremer/EUMETSAT and processes SLSTR L1b and L2 data within 400 x 400 pixels of a match-up, and L2R in situ data within 6hrs of a match-up. The MDB analysis tool uses the approach as stated in

Wimmer et al. 2012[6] and has been upgraded to Python 3. Reprocessed SST fields from 2016, 2017 and 2018 have been used whilst WST 2019 data is currently being worked on.

Overall, there has been good progress on international collaboration over the past few years and good results have been obtained in the validation of SLSTR against the shipborne radiometers. The amount of global $\mathrm{SST_{skin}}$ data on the ships4sst archive is also consistently increasing. See Validation talk (section 4.3) for more information on the most recent validation results.

## 5.3 Next Generation *In Situ* Radiometer

### *Presenter: Tim Nightingale*

Most of the in-situ radiometers currently in service are from the first generation of effective, reliable instruments. However, there is now a desire for greater flexibility and obsolescence is increasingly an issue. The next generation of satellite radiometers are currently under development (CIMR, ASLSTR, LSTM, etc.) so there is an opportunity to revisit the design choices made 20+years ago. This is being addressed in an ESA-funded Case Study report being written by RAL Space, within the FRM4SST project.

After a user consultation in October 2020, the key drivers and design choices were:

1. That SST validation is the primary activity, so the main requirement is for traceable SSTs with total uncertainties of 100mK or better.
2. Other applications and measurements are of interest too so the ability to contribute to air-sea fluxes, skin vertical temperature profiles, air temperature, humidity, ice surface temperature (etc.) measurements is desirable.
3. A moderate priced instrument with some flexibility, measuring in thermal infrared.
4. A non-imaging filter radiometer that is easy to maintain and deploy.

Several design choices have been investigated including spectral selection, calibration schemes and imaging vs non-imaging instrumentation. The chosen baseline design is a self-calibrating thermal infrared filter radiometer that will be an advancement of the current ISAR and SISTeR designs, rather than a radical change. There will be an emphasis on ease of manufacture and use. Multiple spectral bands are possible using a filter wheel, which is simple to install and to update band selection, although measurements cannot be made simultaneously in different bands. A dichroic beamsplitter could be used to measure different bands simultaneously; however it is more complex to install, requires multiple detector chains and it would be difficult to update the bands.

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[6] Wimmer, W. et al (2012). Long-term validation of AATSR SST data products using shipborne radiometry in the Bay of Biscay and English Channel. Remote Sensing of Environment, 116, 17-31. DOI: 10.1016/j.rse.2011.03.022

# 6. SST Data in Practice

## 6.1 Application of the RV Investigator ISAR data

### *Presenter: Haifeng Zhang*

Part 1: The skin SSTs from ISAR on board the R/V Investigator have been used to investigate the night-time cool skin effect along the Australian coastal transects, with a small portion of data coming from cruises through the Southern Ocean to Antarctica. A total of 103 days spanning two years between January 2016 – February 2018 of match-ups were used and the heat fluxes were calculated following version 3.6 of the TOGA COARE bulk parameterisations. The physical cool skin model used was Fairall et al. The nighttime cool skin signals obtained from concurrent ISAR and SBE38 SSTs show expected features and statistics. Calmer winds typically lead to cooler SST skins and real warm skin signals are directly observed in nature.

Part 2: Validation of BoM Himawari-8 (H08) skin SST. A number of quality checks were conducted on the ISAR and satellite SST datasets to ensure the best data was used, with a final temporal coverage of January 2016 to December 2019. Preliminary results show that BoM H08 AHI skin SST with high temporal resolution (10 mins) has reasonable sensitivity to skin diurnal warming signals, which is in good agreement with Yang et al 2020 and that the L2P SST data is of very good quality under nearly all available conditions in this study when compared with ISAR skin SSTs. There is no obvious dependence of $\Delta T$ on local time and wind speed observed, although there does appear to be a warming trend of H08 under very warm SST conditions (>27°C).

In general, with proper quality control, the reprocessed ISAR skin SST data from RV Investigator are of good quality and can be used for scientific research purposes. More information can be found in the paper: https://doi.org/10.1175/JTECH-D-19-0161.1

## 6.2 The Importance of SST and in situ observations for improving global air/sea $CO_2$ flux estimates

### *Presenter: Tom Bell*

It is important to understand the global carbon cycle and how it can change in the future, to do this we have to measure parameters like the air-sea $CO_2$ flux. Estimates of $CO_2$ flux are done using indirect measurements of oceanic/atmospheric variables, e.g. the gas transfer velocity (K) and the concentration difference in $CO_2$ between the ocean and the atmosphere, which takes into account the solubility of the $CO_2$ at the sea skin (interface) and thermal boundary layers (the solubility is highly dependent on temperature). A correction algorithm is used on the $CO_2$ within seawater that is measured during at-sea measurements, as a typical ship's intake is at 1 – 10m depth.

Part of the temperature correction is the cool skin effect. This is estimated using the Fairall96 model, which takes into account the wind dependence. The overall temperature correction adjusts the global ocean $CO_2$ uptake estimate to be more in agreement with the independent ocean carbon inventory estimate (2.1 +- 0.4 $PgCyr^{-1}$). The temperature correction is an important term in the estimation of global ocean uptake as there is a 30% reduction in carbon uptake without it (see Dong et al., 2022).

The gas transfer velocity is dependent on wind speed and, among other things, surfactants (biologically-derived matter on the surface of the ocean), see Yang et al, Frontier 2022 and Nature Sci Rep 2021 for more detail. Eddy covariance is a technique that measures the vertical flux of $CO_2$, and has been deployed autonomously during cruises in the Atlantic Ocean along with measurements of sea surface scattering by satellites (e.g. METOP). Data collected during the AMT 28 and 29 cruises show flux into the ocean at higher latitudes and flux out at lower latitudes, as expected. A strong correlation between polarised wave scattering and K is found, with a similar strength relationship to K vs wind speed. Cross polarisation (VH) and 50° angle are optimal. More in situ observations are needed for future work, which includes an investigation into the potential for satellite cross polarisation.

# 7. Radiometer Performance and Uncertainties

## 7.1 Radiometer Uncertainty Models

### *Presenter: Werenfrid Wimmer*

FRM are required to determine the on-orbit uncertainty characteristics of satellite measurements via independent validation activities. To be classified as an FRM, not only are pre- and post-deployment calibrations required, but also a per-measurement uncertainty model. For ISAR, the model was developed on a first principle basis by analysing the components of the measurement equation (Figure 3), where the measurement equation is shown in yellow. R2T stands for radiation to temperature transformation, $R_{sea}$ is the radiation from the sea, $R_{sky}$ the radiation from the sky, $\varepsilon$ the seawater emissivity, $R_{BB1,2}$ the radiation from the two on-board blackbodies, $Sig_{Sea}$, $Sig_{Sky}$, $Sig_{BB1,2}$ are the signals from the detector when viewing the sea, sky of the two blackbodies. The ISAR post processor, which was implemented following this model, produces an uncertainty value for each $SST_{skin}$. A detailed description of the uncertainty model can be found in Wimmer and Robinson (2016) [7].

Uncertainty results are produced for each element of the uncertainty equation, but the biggest uncertainty for the self-calibrating chopped radiometers is emissivity. Common models are used with knowledge of the view angle which ranges between 25º and 55º. As the ship moves, the viewing angle varies and there is also a wind dependence. The emissivity effect on SST is also larger when there is clear sky.

Uncertainty validation is carried out during inter-comparisons; four side by side comparisons (with ISAR, SISTeR and KIT) have taken place since 2015 and recently (June 2020) during the CEOS intercomparison exercise at NPL. More inter-comparisons are needed to continue the validation and improvement of the uncertainty model as data is sparse, especially for higher uncertainties.

Uncertainty results from an Atlantic Meridional Transect (AMT) 28 and 29 cruises showed that the uncertainty was generally being overestimated, due to the roll dependence of emissivity. Two ISARs were used on these cruises to compare results and the overestimated uncertainty was confirmed. The measurements were filtered and produce better results.

A version 2 of the uncertainty model was recently released, which addresses the roll dependence and associated change in emissivity measurement. A Hanning filter is applied and averaging over the sea and sky signal for the uncertainty, which gives a more realistic result for lower uncertainties. An additional update (v3) addresses the high uncertainties by estimating geophysical indicator as an extra uncertainty. Results so far show an improvement in the uncertainties but there are more improvements that can still to be made.

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[7] Wimmer, Werenfrid & Robinson, Ian. (2016). The ISAR instrument uncertainty model. Journal of Atmospheric and Oceanic Technology. 33. 10.1175/JTECH-D-16-0096.1.

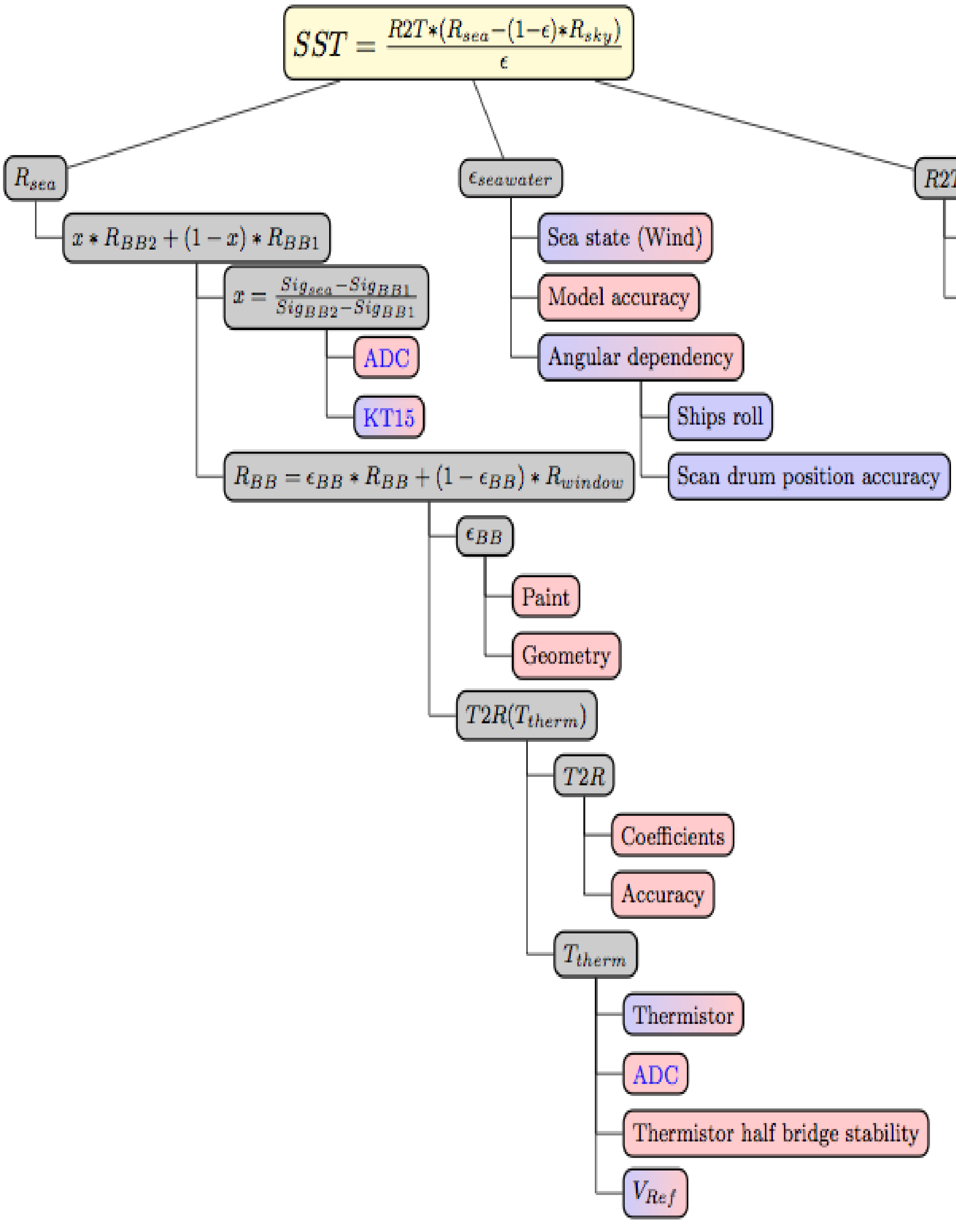

Figure 3: Schematic to illustrate the breakdown of the main elements of the ISAR $SST_{skin}$ processor to reveal the factors that introduce uncertainty. For clarity the $R_{sky}$ branch has not been expanded but is essentially the same as for $R_{sea}$. Boxes coloured in blue represent type A uncertainties, boxes coloured in red show type B uncertainties, and boxes in red and blue contain both type A and type B uncertainties.

## 7.2 Comparison (of shipborne radiometers) with other *in situ* measurements

### *Presenter: Gary Corlett*

When making comparisons of in situ and satellite datasets, there are many variables that need to be taken into account, including match-ups within predefined spatial and temporal limits and $\mathrm{SST}_{\mathrm{skin}}$ (satellites) vs $\mathrm{SST}_{\mathrm{depth}}$ (in situ). So, the way we consider validation now is in the form of an uncertainty budget which is currently made up of 5 components; the satellite, reference, geophysical (surface), geophysical (depth) and geophysical (temporal).

The assessment of the uncertainty of satellite measurements involves comparison to a reference dataset, such as $\mathrm{SST}_{\mathrm{skin}}$ from shipborne radiometers (FRM), subsurface temperatures from drifting buoys, near-surface measurements from Argo profiling floats (close to FRM), and from the Global Tropical Moored Buoy Array (GTMBA). These reference measurements have pros and cons, for example the drifting buoys have good global coverage but measure at $\mathrm{SST}_{\mathrm{depth}}$ (~20 cm) and are not FRM (although are moving towards FRM with the TRUSTED buoys), whilst shipborne radiometers in the ISFRN are very high accuracy and SI-traceable, but with limited global coverage.

Validating satellite SST retrievals using reference datasets has sources of error that cannot easily be corrected. These sources of error can, however, be minimised using knowledge of the variability in the atmosphere and upper ocean, and comparing $\mathrm{SST}_{\mathrm{skin}}$ from IR radiometers with reference data at different depths, as well as applying the law of large numbers. However, for example when comparing both Argo SST measurements at 4 m depth and drifter SST measurements at 20 cm depth with AATSR $\mathrm{SST}_{\mathrm{skin}}$, a minimum geophysical uncertainty component of 0.1 K (1 km; +/- 2 hours) was calculated.

To use drifting buoys to validate satellite SSTs, an estimate of drifter $\mathrm{SST}_{\mathrm{skin}}$ at the time of the satellite overpass is made. This is done using a 3-step approach; 1. Raw drifter measurement at depth is taken. 2. It is adjusted to $\mathrm{SST}_{\mathrm{skin}}$ using model of skin effect (Fairall et all, 1996) and diurnal stratification (Kantha and Clayson, 1994). 3. Which is then adjusted to $\mathrm{SST}_{\mathrm{skin}}$ at satellite measurement time using the same combination model (referred to as FKC). Similar methods are used for other reference datasets depending on their depth.

SLSTR uses a dual view 3 channel retrieval to provide its highest quality $\mathrm{SST}_{\mathrm{skin}}$ and is validated using match-ups between satellite and in situ data (including data from the ISFRN). Overall, the results from the match-up model look good. Comparing to independent skin measurements you do see, for example, a daytime dependence in the NWP wind speed and diurnal warming in the data; however, when you apply the FKC time adjustment to the results the wind speed results improve, and little if any residual dependence is seen. Note that currently all the radiometer data needs to be used together to be statistically significant. This independent validation using data from multiple in situ sources/depths show that satellite radiometers such as SLSTR can provide $\mathrm{SST}_{\mathrm{skin}}$ to an accuracy better than 0.1 K.

The continuity of $SST_{skin}$ FRM is essential to maintain long-term SST records and so a new generation of in situ (FRM) are required to support $SST_{skin}$ validation (to identify geophysical effects from retrieval effects).

## 7.3 A Metrological approach to FRMs: Uncertainty and Traceability in the QA4EO Framework

### *Presenter: Emma Woolliams*

Endorsed by CEOS in 2010 and adopted by GSICS, the QA4EO Principle states: 'It is critical that data and derived products are easily accessible in an open manner and have an associated indicator of quality traceable to reference standards (preferably SI) so users can assess suitability for their applications; i.e., 'fitness for purpose'.' The core principles of metrology; stability (century scale), interoperability (equivalence worldwide) and coherence (by combining different measurements), are achieved through traceability, uncertainty and comparison.

Environmental data have long value chains, from upstream (e.g. space segment, ground segment and data acquisition, data processing, etc.) to downstream applications (e.g. value added services and end users) and a number of different communities at each step in the chain. The sharing of information is therefore very important to ensure the core principles of metrology are maintained. Another issue is that the science in Earth Observation happens at very different spatial and temporal scales, and so the relative importance of error sources varies depending on the scale being addressed. Finally, the data sets used in Earth observation are large and have complicated covariance structures (e.g. spatial, temporal, spectral, instrument type, etc.), so we also have to think about how these error structures are propagated and used. The establishment of the terms FDR (fundamental data record), TDP (thematic data product) and FRM (fiducial reference measurements) has occurred over the last decade and are now being used by many data communities.

There are 5 main steps to an FDR/TDP or FRM uncertainty budget. These are:

1. Define the measurand and measurement function
2. Establish the traceability with a diagram
3. Evaluate each source of uncertainty and fill out an effects table
4. Calculate the product and its uncertainty
5. Store relevant information for future users

The QA4EO website (www.qa4eo.org) has guidelines on how to implement these steps and links to training materials. Additionally, open-Source tools have been developed to enable easy handling and processing of dataset error-covariance information, for example the CoMet Toolkit. (www.comet-toolkit.org).

## 7.4 Radiometer inter-comparison exercise, June 2022

### *Presenter: Yoshiro Yamada*

The 5th CEOS TIR radiometer intercomparison took place in June 2022 as a laboratory comparison at the National Physical Laboratory (UK) and a field comparison at Boscombe Pier (UK). The main objectives are to establish a degree of equivalence of radiometric scales between field deployed ship-borne TIR radiometers and ensure robust traceability to SI.

The laboratory-based exercise compared TIR radiometers and their blackbodies against the SI via an NPL reference radiometer (AMBER as a reference standard radiometer and the Heitronics TRT-IV.82 as the transfer standard radiometer) and reference blackbodies (an ammonia heatpipe blackbody and a stirred liquid bath blackbody). For this inter-comparison, a transfer radiometer was introduced to measure participants blackbodies to increase flexibility, and a second variable temperature blackbody with a large aperture was introduced so that two measurements could be done in parallel.

The TIR radiometers were compared against each other with a view of the ocean and open sky during the field-comparison. Seven radiometers took part in the campaign.

Currently, data analysis is in progress and reports are planned to be submitted to CEOS WGCV and published in early-to-mid 2023.

# 8. Conclusion

There is a clear need for reliable and accurate $SST_{skin}$ measurements for referencing and validating satellite SST retrievals to FRM standards, whether for gap bridging between satellite deployments, validating satellite data or to be used in understanding the state of our oceans, for example, in calculating flux in the air-sea boundary and/or modelling the global carbon sink and its effects all over the globe. Work is taking place to gather SST measurements to FRM standards all over the globe, and recent results show the high quality of the data obtained from shipborne IR radiometers. The COVID-19 pandemic has taken a toll on the amount of shipborne radiometer data gathered in 2020, but deployments are now fully underway again.

The in-situ SST measurement field is at a stage of exciting technological progression. Saildrone measurements have continued to become increasingly more common over the last few years with ongoing improvements in measurements and designs. More sophisticated buoys containing MoSens sensors are being used and tested on the TRUSTED project and an FRM standard is also being worked on. The case for a next generation shipborne radiometer has been presented as a case study report within the FRM4SST project and a UK-funded design and manufacture of a next-generation IR radiometer that uses this study as a basis for its design has recently been funded.

Establishing and maintaining FRM standards, uncertainty budgets and traceability, as highlighted in Emma Woolliams presentation, has become increasingly understood in its importance over the past decade, and is now used by many data communities. For example, results from Werenfrid Wimmer's Uncertainty model presentation show how the ISAR uncertainty budget is calculated, continuously improved upon and is able to contribute to the FRM classification of the SST data. Members of the ISFRN who deploy shipboard radiometers have established protocols, best practices and a recommended data format that is now used by three instruments types (the M-AERI, ISAR and SISTeR). As shipborne radiometers provide a traceability route for satellite $SST_{skin}$ retrievals they are a reference for generating CDRs from satellite SST measurements. The ISFRN continues to help to develop and take these practices forward.

There are a number of areas that have been identified or recommended for further work within the ISFRN community. This includes:

- More high quality (i.e. SI-traceable) in situ observations on a global scale. More in situ SST data to FRM standards was notably requested by many of the presenters at today's workshop.
- A 'next-generation' IR radiometer is desired, as the current models are based on designs that were made circa 20 years ago.
- Improvement in the uncertainty models across all instruments including shipborne radiometers. More bi-lateral experiments would help further understand these uncertainties.
- Additional instrument data inputs such as saildrone data.

- Continued field campaigns investigating FRM TIR/MW for IST, in high northern and southern latitudes.
- Further understanding of the difference between the TIR $SST_{skin}$ and $SST_{subskin}$ and how waves impact the dynamic temperature of the $SST_{skin}$, particularly with respect to the flux and ocean carbon sink.
- Further improvement of the modelling of aerosol effects, diurnal heating and the skin layer during $SST_{skin}$ validation.

With the changing climate and the impact our oceans have on the outcome of these changes, it is more important than ever to have reliable and accurate FRM to SI standards. Although there are still advances to be made, shipborne radiometers are able to provide the level of accuracy required for a CDR.

The ISFRN Workshop brought together a number of experts in the radiometry field to present and discuss the latest results in shipborne radiometry and other in situ methods such as saildrone and buoys. The latest satellite SST validation activities were discussed and scientists showed how in situ $SST_{skin}$ data was being used to research into ocean dynamics. It is encouraging to see the continued developments within and outside the ISFRN and the international collaborations that have developed over the years. Whilst this report has only summarised the key information from the workshop presentations and discussions, it is clear that shipborne radiometry and in situ SST measurement instruments in general are gaining strength and recognition for the consistency, stability and usefulness of the measurements in validating satellite data from instruments including AATSR and SLSTR, and helping scientists understand ocean dynamics and the impacts of climate change.

The presentations, protocols, procedures and reports are all available on the ships4sst website at www.ships4sst.org/documents.

# 9. Acknowledgements

The FRM4SST project would like to thank and acknowledge the substantial contribution of all the participants and their funding agencies in support of the ISFRN workshop and this review document. In particular, the European Space Agency (ESA), whose funding made the ISFRN workshop possible, and the University of Southampton and Space Connexions Limited, for hosting the workshop both in Southampton and via WebEx. The participation of the group at RSMAS, University of Miami, is supported by funding from the NASA Physical Oceanography Program and the NASA Participating Investigators Program.

The author acknowledges the work and information provided by all the presenters at the ISFRN workshop, whose data, figures and information have been included in this paper. The author would also like to thank all who attended for their insights and contributions to the ISFRN Workshop.

# Appendix

## Agenda

**Thursday 8th September 2022 (1330 – 1730 (UK), 0830 – 1230 (US EDT))**

| | | |
|---|---|---|
| 1330 – 1340 | Welcome addresses | Craig Donlon, ESA |
| 1340 – 1500 | ***Experiences of radiometer operators*** | |
| | ISAR UK | Werenfrid Wimmer, UoS, UK |
| | M-AERI | Peter Minnett, University of Miami, USA |
| | Skin Temperature Measurements using an Optimal Spectral Band | Andy Jessup, University of Washington, USA |
| | ISAR Denmark | Jacob Høyer, DMI, Denmark |
| 1500 - 1540 | ***Datasets and FRM*** | |
| | Felyx | Jean-Francois Piolle, Ifremer, France |
| | The TRUSTED Project | Marc Lucas and Marc Le Menn, EUMETSAT, Germany |
| Coffee break (10 min) | | |
| 1550 - 1630 | ***Validation of satellite SST and in situ SST measurements*** | |
| | Using M-AERI to validate MODIS and SLSTR SSTs | Peter Minnett, University of Miami, USA |
| | Sampling and Measurement Error Models for ICOADS Ship SSTs, based on the ESA CCI SST Analysis | Alexey Kaplan, LDEO of Columbia University, USA |
| 1630 – 1730 | ***The ISFRN Network*** | |
| | Status of the ISFRN data archive | Werenfrid Wimmer, UoS, UK |
| | Status of the ISFRN | Werenfrid Wimmer, UoS, UK |
| | Next generation In-situ radiometer | Tim Nightingale, STFC, UK |
| 1730 | Closing remarks | Craig Donlon, ESA |
| **1730** | **Close of meeting** | |

**Friday 9th September (0800 – 1215 (UK), 1500 – 1915 (Beijing), 1700 – 2115 (Melbourne))**

| | | |
|---|---|---|
| 0800 – 0810 | Welcome Address | Craig Donlon, ESA |
| 0810 – 0910 | ***Experiences of radiometer operators*** | |
| | ISAR Australia | Nicole Morgan, CSIRO, Australia |
| | SISTeR | Tim Nightingale, STFC, UK |
| 0910 – 0950 | ***Validation of satellite SST measurements*** | |
| | Using ISAR to validate SLSTR data | Werenfrid Wimmer, UoS, UK |
| | Validation of ENVISAT-AATSR SST retrievals for the study of trends associated with climate change in the Mediterranean Sea | Raquel Niclos / Ludovico Buizza, University of Valencia, Spain |
| Coffee break (10 min) | | |
| 1000 – 1040 | ***SST Data in Practice*** | |
| | Applications of the RV Investigator ISAR data | Haifeng Zhang, BOM, Australia |
| | *In situ* observations of air/sea CO2 fluxes | Thomas Bell, PML, UK |
| 1040 – 1200 | ***Radiometer performance and uncertainties*** | |
| | Radiometer uncertainty models | Werenfrid Wimmer, UoS, UK |
| | Comparison with other *in situ* instruments | Gary Corlett, Eumetsat, Germany |
| | A metrological approach to FRMs: Uncertainty and Traceability in the QA4EO framework | Emma Woolliams, NPL, UK |
| | Radiometer intercomparison exercise, June 2022 | Yoshiro Yamada, NPL, UK |
| 1200 – 1210 | Closing remarks | Craig Donlon, ESA |
| **1215** | **Close of meeting** | |

## Workshop Participants

| Name | Organisation | Country |
|---|---|---|
| Ruth Wilson | Space ConneXions Ltd | UK |
| Hugh Kelliher | Space ConneXions Ltd | UK |
| Werenfrid Wimmer | UoS | UK |
| Craig Donlon | ESA | Netherlands |
| Tim Nightingale | STFC RAL | UK |
| Jacob Hoyer | DMI | Denmark |
| Arrow Lee | STFC RAL | UK |
| Peter Minnett | University of Miami | USA |
| Andy Jessup | University of Washington | USA |
| Anne O’Carroll | Eumetsat | Germany |
| Gary Corlett | Eumetsat | Germany |
| Thomas Bell | University of Exeter | UK |
| Helen Beggs | BOM | Australia |
| Rory Scarrott | University of Cork | Ireland |
| Yoshiro Yamada | NPL | UK |
| Guisella Gacitua | DMI | Denmark |
| Alexey Kaplan | LDEO of Columbia University, NY | USA |
| Janice Sisson | BOM | Australia |
| Igor Tomazic | EUMETSAT | Germany |
| Claudia Fanelli | CNR | Italy |
| Haifeng Zhang | BOM | Australia |
| Emma Woolliams | NPL | UK |
| Gianluigi Liberti | CNR | Italy |
| Jean-François Piolle | Ifremer | France |
| Daniele Ciani | CNR | Italy |
| Christo Whittle | CSIR | South Africa |
| Mohamed Hosny Hassan Abdelkader | SWERI | Egypt |
| Chunying Liu | NOAA | USA |
| Marc Lucas | EUMETSAT | Germany |
| Raquel Niclos | University of Valencia | Spain |
| Ludovico Buizza | University of Valencia | Spain |
| Dom Weller | AWE | Australia |
| Cristina González Haro | CSIC | Spain |
| Luis Escudero Herrera | Instituto del Mar del Perú | Peru |