# FRM4SST Project

The Final Report: June 2023

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# 1. EXECUTIVE SUMMARY

This report presents the activities of Phase 2 of the FRM4SST (ships4sst) contract between 1 August 2019 and 28 April 2023. The aims of the service were to:

- validate Sentinel-3A and Sentinel-3B SLSTR SST, and other satellite data products, using Fiducial Reference Measurements (FRM) from *in situ* Thermal Infrared (TIR) radiometers,
- organise and host a CEOS International TIR Radiometer Inter-Comparison exercise at the National Physical Laboratory (NPL) and on a pier in Boscombe, UK,
- perform an inter-comparison at sea comparing microwave (MW) and thermal infrared *in situ* measurements of water temperatures,
- and promote the International SST FRM Radiometer Network (ISFRN).

To achieve these aims, the European Space Agency (ESA) has funded the continuation of ship-borne radiometer deployments that provide ESA and its partners with a long-term time series of accurate and stable *in situ* measurements of SST for climate applications across the globe. Specifically, the aims are fulfilled through the collection, processing, analysis, publication and reporting of *in situ* TIR FRM field measurements made using Infrared SST Autonomous Radiometer (ISAR) and Scanning Infrared Sea surface Temperature Radiometer (SISTeR) instruments, that are near-contemporaneous with satellite data from the Sentinel-3A and Sentinel-3B SLSTR instruments. During the course of this project, a shipborne inter-comparison with simultaneous deployment of TIR and microwave radiometers was also performed, measuring at sea cold waters for a week-long period. This inter-comparison focussed on both the differences and similarities between $SST_{skin}$ and $SST_{subskin}$ to support the integration of Infrared and microwave satellite observations and to establish links between IR and MW SST (skin vs. subskin, 1 km vs 15 km resolution) in cold waters, to maximize, for example, CIMR MW and SLSTR SST synergy.

In order to ensure that the SLSTR geophysical data products are reliable, they must be validated by comparing them with measurements from the long-term *in situ* deployment of the ISARs, and also from the SISTeR instrument; these measurements have confirmed the consistency of the SST data products (see Section 6). In order to ensure that these *in situ* SST data are generated with a consistent quality, high accuracy and reliability for the validation of all satellite SST products in open ocean and coastal waters, the CEOS TIR intercomparison exercise that took place in June 2022 has confirmed the SI-traceability of the TIR ISAR and SISTeR SST measurements (see Section 0).

Since its inception in 2018, the ISFRN has continued to provide a forum for an international network of ocean and remote sensing scientists to develop the use of shipborne infrared radiometers for measuring skin SST. The network includes operators, designers and builders of such instruments as well as the users of the data. The ships4sst website, www.ships4sst.org, hosts ISFRN information, resources and the *in situ* SST archive which has enabled multiple organisations to add their data onto a central online open-access database (once users have registered).

# 2. A BRIEF HISTORY OF THE PROJECT

The current project continues the time series of ISAR measurements in the Bay of Biscay that were used to validate Advanced Along-Track Scanning Radiometer (AATSR) and other TIR satellite SST measurements. This activity was started in 2004 with UK government funding, and then continued by ESA from 2018. The project also continues SISTeR measurements over a similar period that were funded by both the UK and ESA, and continues a time series of ISAR measurements on a wider European scale that began in the ships4sst contract. These measurements helped to bridge the gap between AATSR and SLSTR, tying them both to a common internationally recognised reference standard. Now the measurements are also used to validate satellite SST data against Système Internationale (SI)-traceable FRM. In 2018, the Danish Meterological Institute (DMI) joined the consortium with a regular ISAR deployment in the northern latitude, and the ships4sst website became the online-home of the ISFRN, with online user-registered data access to the ships4sst archive containing data from the FRM4SST team, plus the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) data from America and ISAR data from Australia.

## 2.1 Why Shipborne Radiometry?

Shipborne radiometric measurements provide the high accuracy (uncertainty <0.1 K) surface temperature measurements needed to validate high accuracy satellite SST sensors such as AATSR and SLSTR. Shipborne radiometers also provide a traceability route for satellite measurements and therefore a pathway to generate Fundamental Climate Data Records (FCDRs) from satellite SST measurements (Figure 2-1).

To achieve robust traceability to the SI temperature scale (ITS-90), shipborne radiometer calibrations derived from their internal blackbodies are regularly verified against an SI-traceable laboratory calibration target (Figure 2-2). The traceability of both the shipborne radiometers and the laboratory calibration targets are confirmed on a regular basis through inter-comparisons such as the ESA-funded Fiducial Reference Measurements (FRM) for validation of Surface Temperature from Satellites (FRM4STS) campaign, held in 2016, and the FRM4SST inter-comparison that took place during this contract, in 2022.

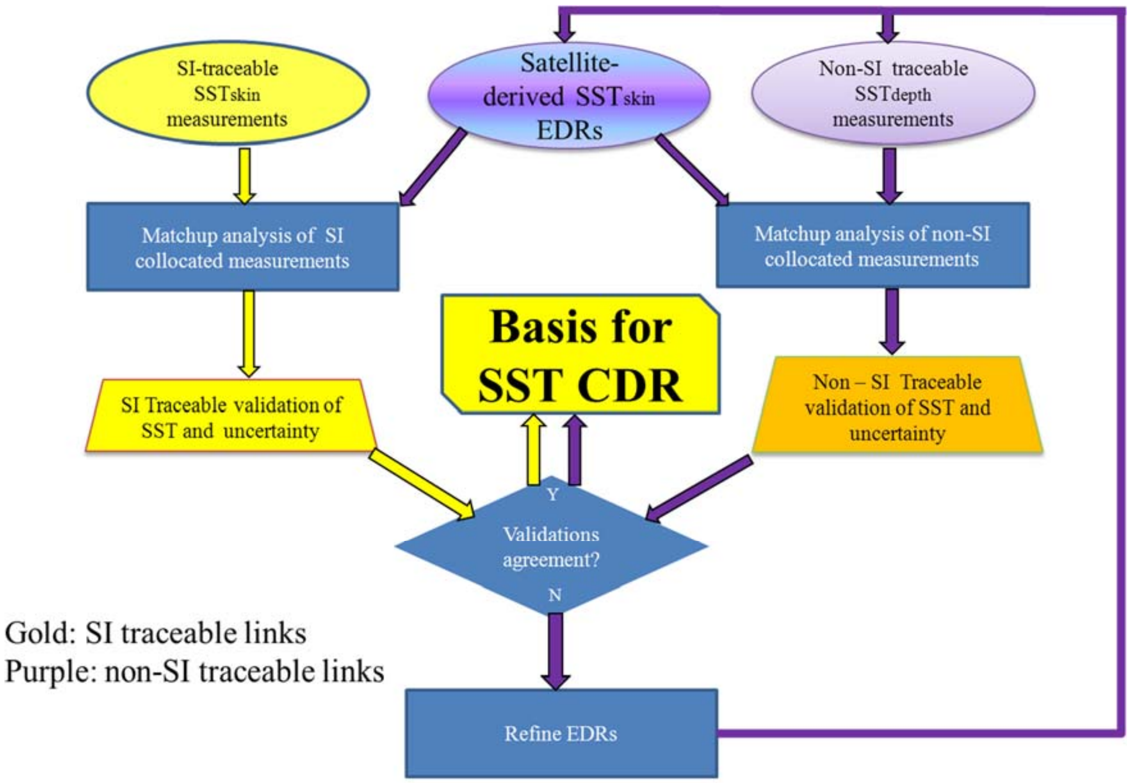



Figure 2-1: This flow diagram shows the traceability route for a SST Climate Data Record (from the ISSI[1] *in situ* validation workshop). Shipborne radiometers cover the yellow parts of the diagram.

Fiducial Reference Measurements are the suite of independent ground measurements that provide the maximum scientific utility and Return On Investment (ROI) 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 duration of the mission[2]. This means that FRM:

- Have documented evidence of SI traceability via inter-comparison of instruments under operational-like conditions (e.g. the 2016 and 2022 campaigns).
- Are independent from the satellite SST retrieval process.
- Include an uncertainty budget for all FRM instruments and ensure that derived measurements are available and maintained, traceable, where appropriate, to SI.
- Are collected using measurement protocols and community-wide management practices (measurement, processing, archive, documents etc.) that are defined and adhered to.

[1] *International Space Science Institute (ISSI) Working Group on Generation of Climate Data Records of Sea-Surface Temperature from Current and Future Satellite Radiometers – unpublished report (2014)*

[2] *Optical Radiometry for Ocean Climate Measurements, G. Zibordi, C. J. Donlon, A. C. Parr, Volume 47 (2014)*

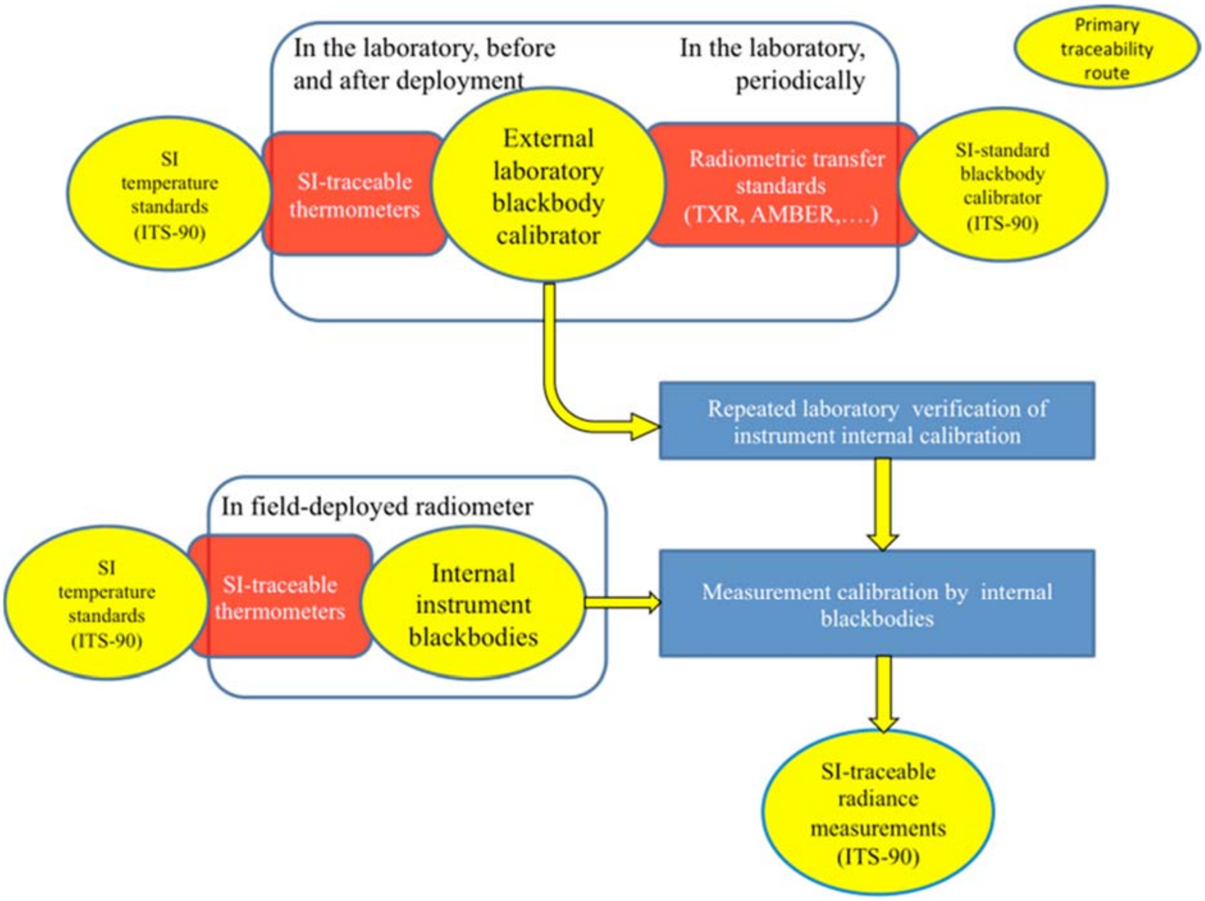



Figure 2-2: Traceability route for a shipborne radiometer (from ISSI *in situ* validation workshop).

A further advantage is that shipborne radiometers can produce per pixel uncertainties, which not only gives a degree of confidence in individual measurements, but can be validated through side-by-side inter-comparisons, such as the joint deployment of the ISAR and SISTeR instruments on the *Queen Mary 2* in 2015, or the laboratory and field-based comparison of multiple infrared radiometers that took place in June 2022.

Shipborne radiometers (including ISAR, SISTeR and M-AERI) provide an important SI-traceable link between satellite instruments, facilitating the evaluation of any offsets or trends between two instruments. This would normally be achieved by an overlap period of six months or more in the operations of the two satellite instruments; however, this cannot always occur. For example. with the sudden end of Envisat, and delays in the launch of Sentinel-3, no overlap period was possible between AATSR and SLSTR-3A. Nevertheless, because measurements were made by *in situ* instruments including shipborne radiometers throughout the data gap, any geophysical changes in the SST fields during the gap were monitored, ensuring that changes are not an attribute of either AATSR or SLSTR but a genuine geophysical change.

## 2.2 Data Archive

The ships4sst data archive is hosted at Ifremer, due to their expertise in maintaining data archives such as Coriolis (http://www.coriolis.eu.org/Data-Products/Data-Delivery). The Felyx tool at Ifremer processes and generates validation reports and satellite match-ups. This processing is now performed by EUMETSAT. All partners (UoS, RAL Space and DMI) store their ISFRN L2R data files at the archive once they become available, which is normally after the post-deployment calibration. The ISFRN L2R files are accompanied by calibration information, such as calibration factors from the pre- and post-deployment calibrations. Documentation of the traceability of all calibration equipment is also stored at the data archive, as well as on the ships4sst website.

The data archive is accessible through the ships4sst web portal and provides data to users on request. Uploading data from non-project partner groups who collect data to ISFRN standard and submit the data in ISFRN L2R format is also facilitated through the ships4sst web portal, as has been done with the CSIRO ISAR and M-AERI data. Figure 2-3 shows the combined archive $SST_{skin}$ data from the ISARs, M-AERI and SISTeR, as shown on a world map.

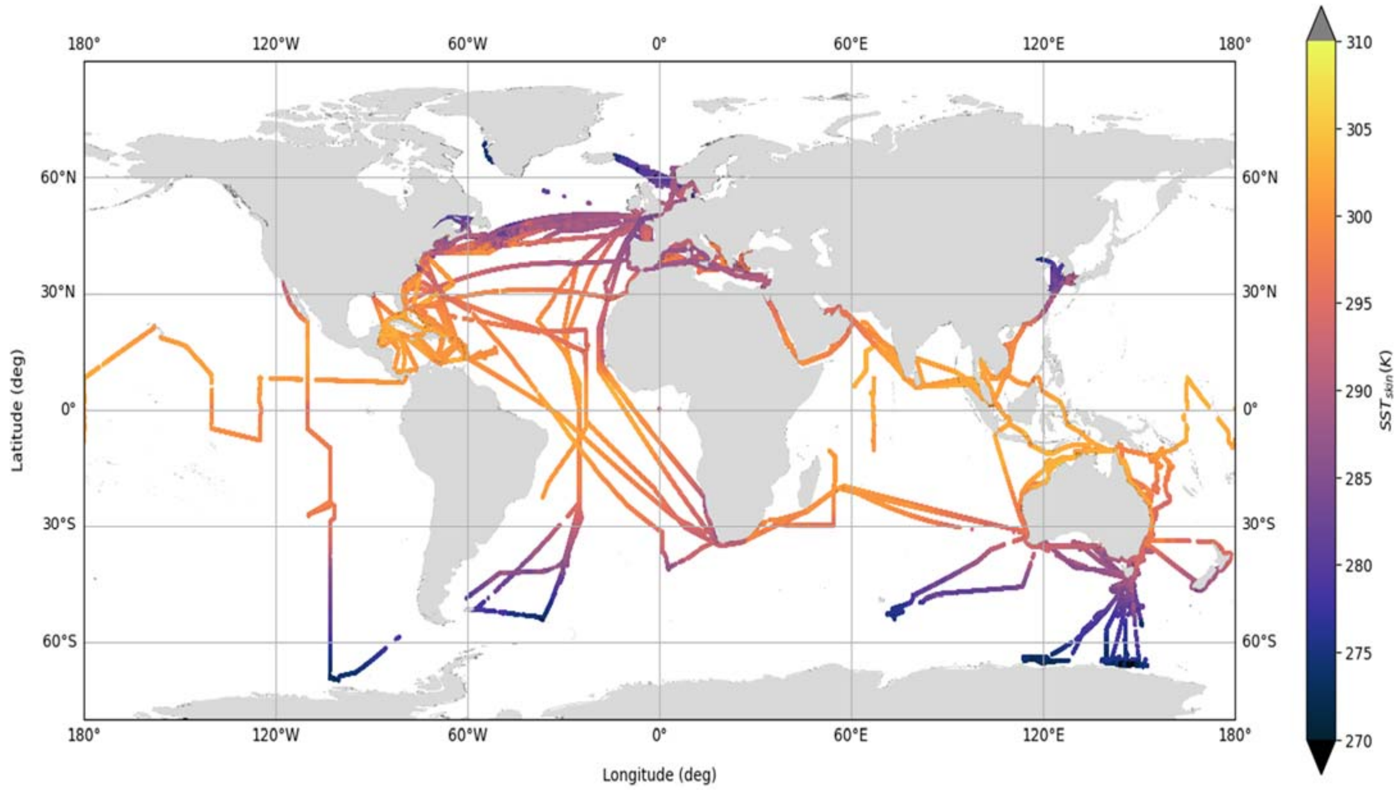



Figure 2-3: The ships4sst data archive L2R files plotted as SST on a world map, March 2023

# 3. ISAR (UOS)

ISAR has been deployed on a number of ferries in the English Channel and Bay of Biscay since spring 2004. Over the ~19-year period, two instruments, ISAR 002 and ISAR 003, have provided over 1,000,000 SSTskin measurements, with per pixel uncertainties.

## 3.1 Deployments in the Bay of Biscay

The first deployment was on the P&O *Pride of Bilbao* in March 2004 moving to the Brittany Ferries *Cap Finistere* in October 2010 and finally moving to the Brittany Ferries *Pont Aven* from October 2012 where the ISAR is currently deployed (Figure 3-1).

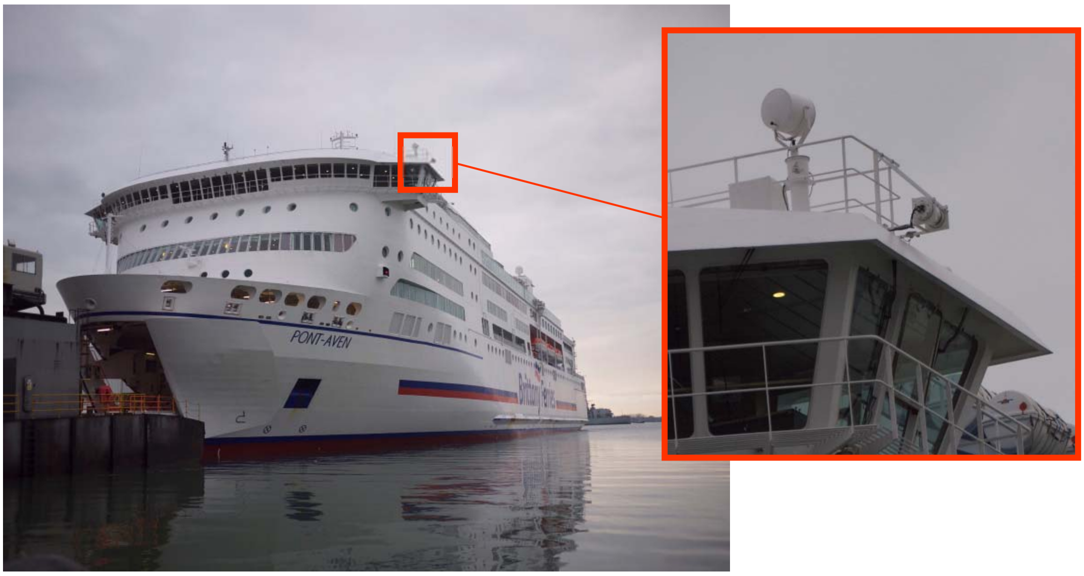



Figure 3-1: ISAR installation on the Pont Aven in October 2012. This deployment is ongoing

Figure 3-2 shows a latitude-time plot of the complete ISAR SSTskin dataset, with the main ports on the route labelled at the bottom. The figure shows the 19 years of data collection and the changes in route, for example the addition of Cork after the change to the *Pont Aven*. The figure also shows some white areas where no data was collected. This is either due to bad weather, restriction in travel during the COVID pandemic, when the ISAR shutter was closed, or times when the instrument was removed during a ferry re-fit, which was normally during the winter for a few weeks. The plot also shows the seasonal changes along the route with warmer temperatures in the summer near the Spanish coast and colder water in the English Channel in the winter.

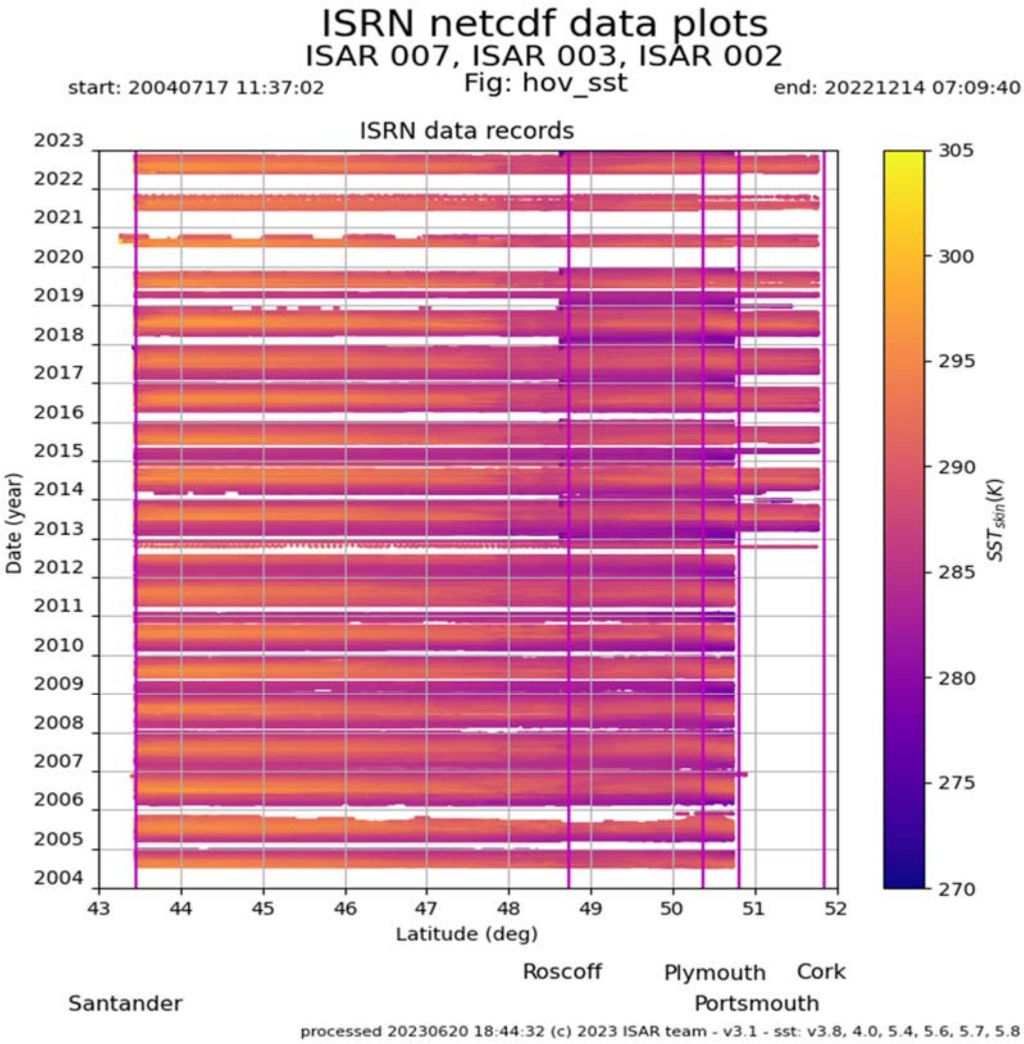



Figure 3-2: ISAR SST data from 2004 to 2022

Figure 3-3 shows the associated uncertainty for each measurement shown in Figure 3-2. Each of these uncertainty values has been derived using the ISAR uncertainty model[3]. This model analyses the components of the ISAR instrument and propagates the uncertainties through an equation to give total uncertainty for each measurement. The uncertainty shows the degree of confidence a user can have in the SST measurement.

[3] Wimmer, W. and I. Robinson, 2016: The ISAR Instrument Uncertainty Model. *J. Atmos. Oceanic Technol.,* **33**, 2415–2433, doi: 10.1175/JTECH-D-16-0096.1.

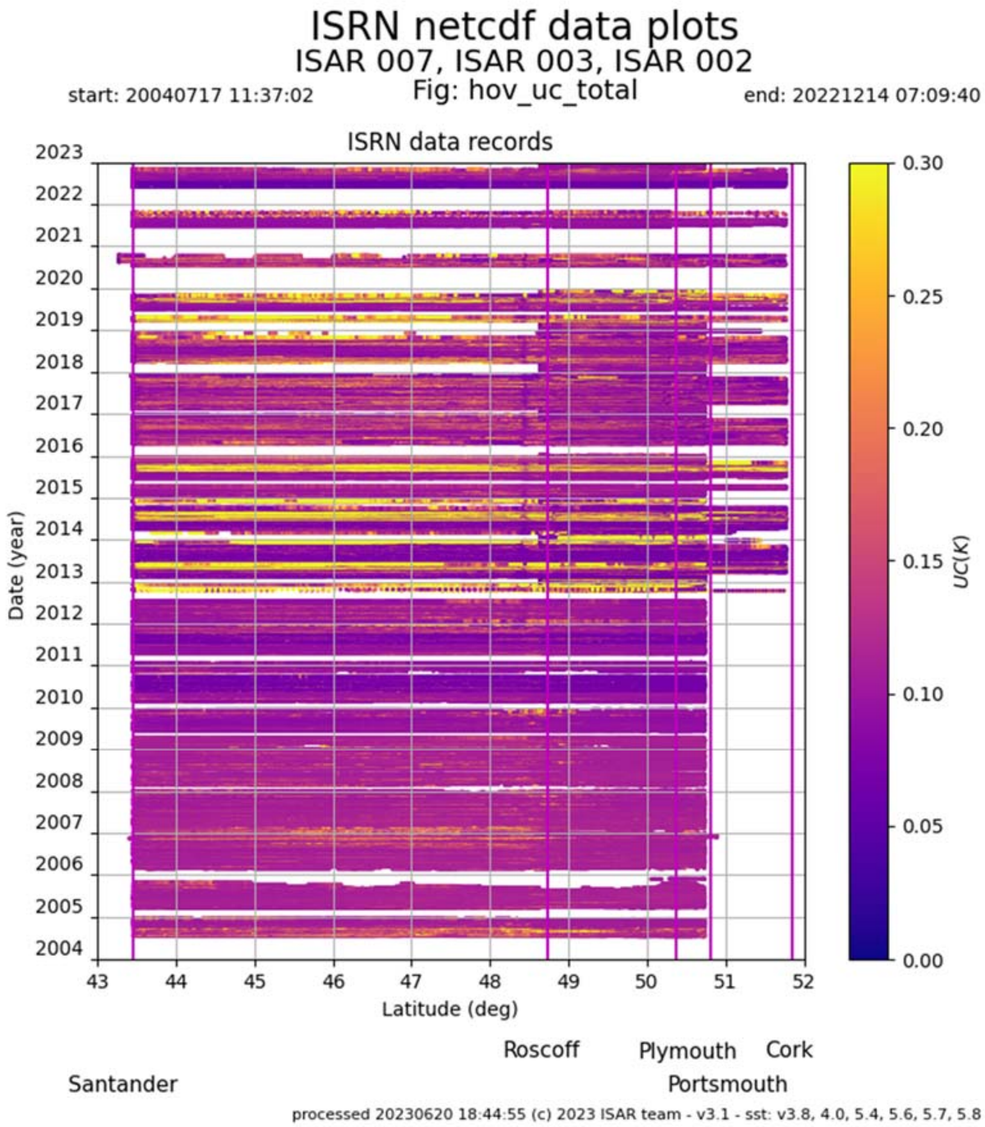



Figure 3-3: ISAR total uncertainty for all data from 2004 to 2022

## 3.2 ISAR Uncertainty Model

FRM are required to determine the on-orbit uncertainty characteristics of satellite measurements via independent validation activities. In order to be a classified 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, as shown in Figure **3-4**. 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, ε 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. The results are shown in Figure 3-2 for SST and in Figure 3-3 for the total uncertainty. A detailed description of the uncertainty model can be found in Wimmer and Robinson 2016.

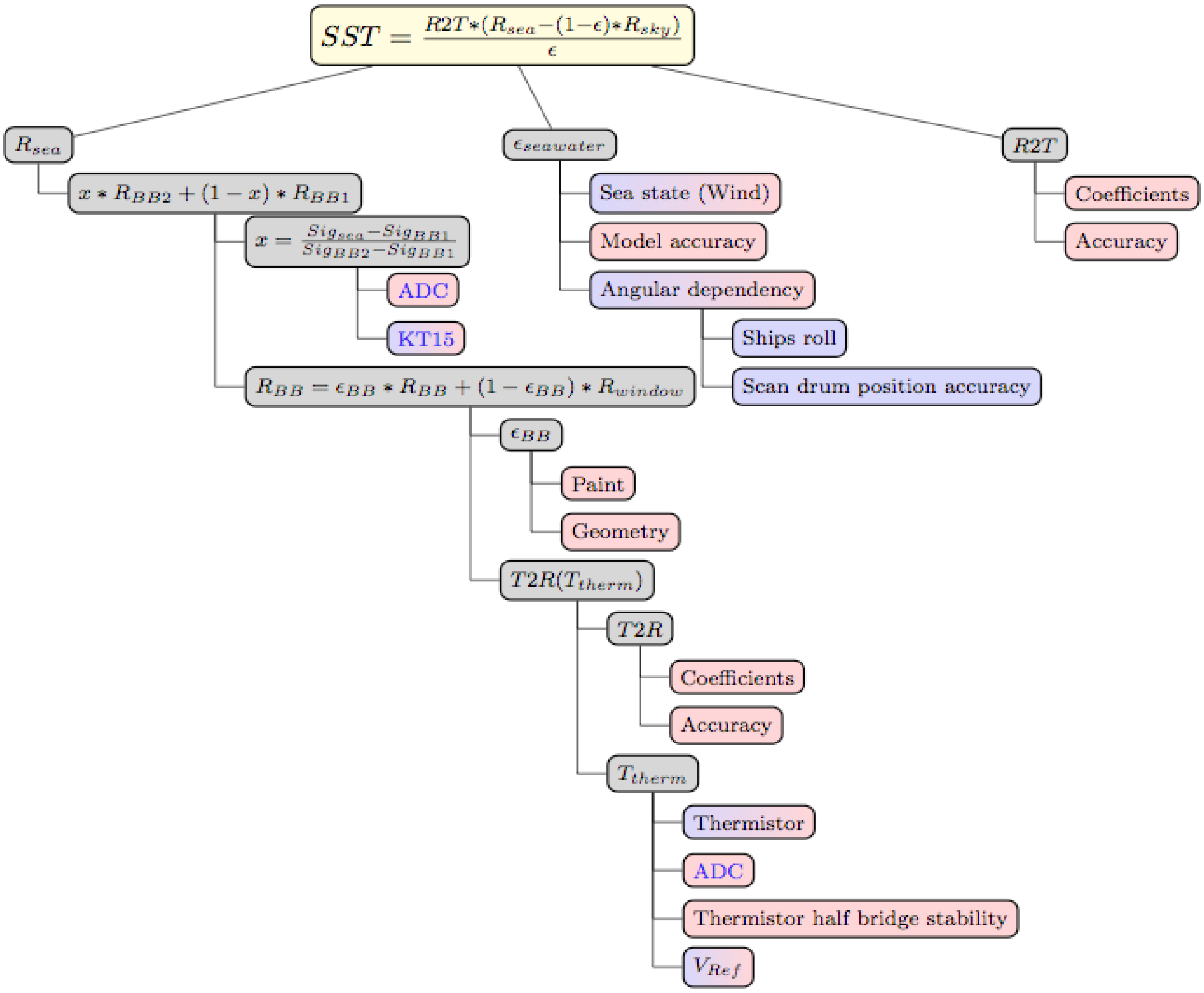



Figure 3-4: Schematic to illustrate the breakdown of the main elements of the ISAR SST processor to reveal the factors that introduce uncertainty. For clarity the $R_{sky}$ branch has not been expanded but is essentially the same as for $R_{sea}$ . Boxes coloured in blue represent type A uncertainties, boxes coloured in red show type B uncertainties, and boxes in red and blue contain both type A and type B uncertainties. From Wimmer and Robinson 2016.

# 4. ISAR (DMI)

An ISAR has been at DMI since 2017, where it previously had been used for ship of opportunity deployments on a best effort basis. These deployments included: scientific campaigns on ice breakers sailing to the North Pole, Royal Arctic Line cargo ships servicing Greenland settlements and the Danish research vessel, Dana. In 2021, two new ISARs joined the fleet which resulted in more data being acquired in the northern latitudes and a more continuous dataset.

## 4.1 High Latitude Deployments with ISAR

Since the start of the ships4SST project, the DMI ISAR has been deployed regularly on Norrøna, a ferry line that has a weekly service between Denmark (Hirtshals), Faroe Island (Tórshavn) and Iceland (Seyðisfjörður). Figure 4-1 displays all the measurements of the North Sea taken with the ISAR instrument from 2016 until the present time.

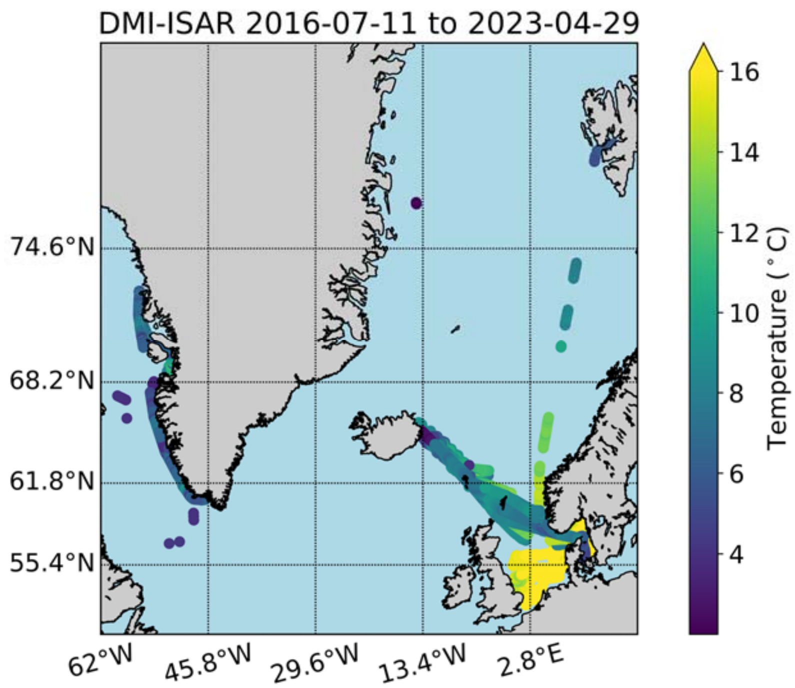



Figure 4-1: DMI's SST observations using ISAR from 2016 to 2023, including the regular track of the Norröna Ferry line from Hirtshals to Faroe Islands and Iceland.

The instrument is positioned on the front port side of the ship, above the bridge, where it measures the temperature of undisturbed waters from an elevation of approximately 20 meters above sea level.

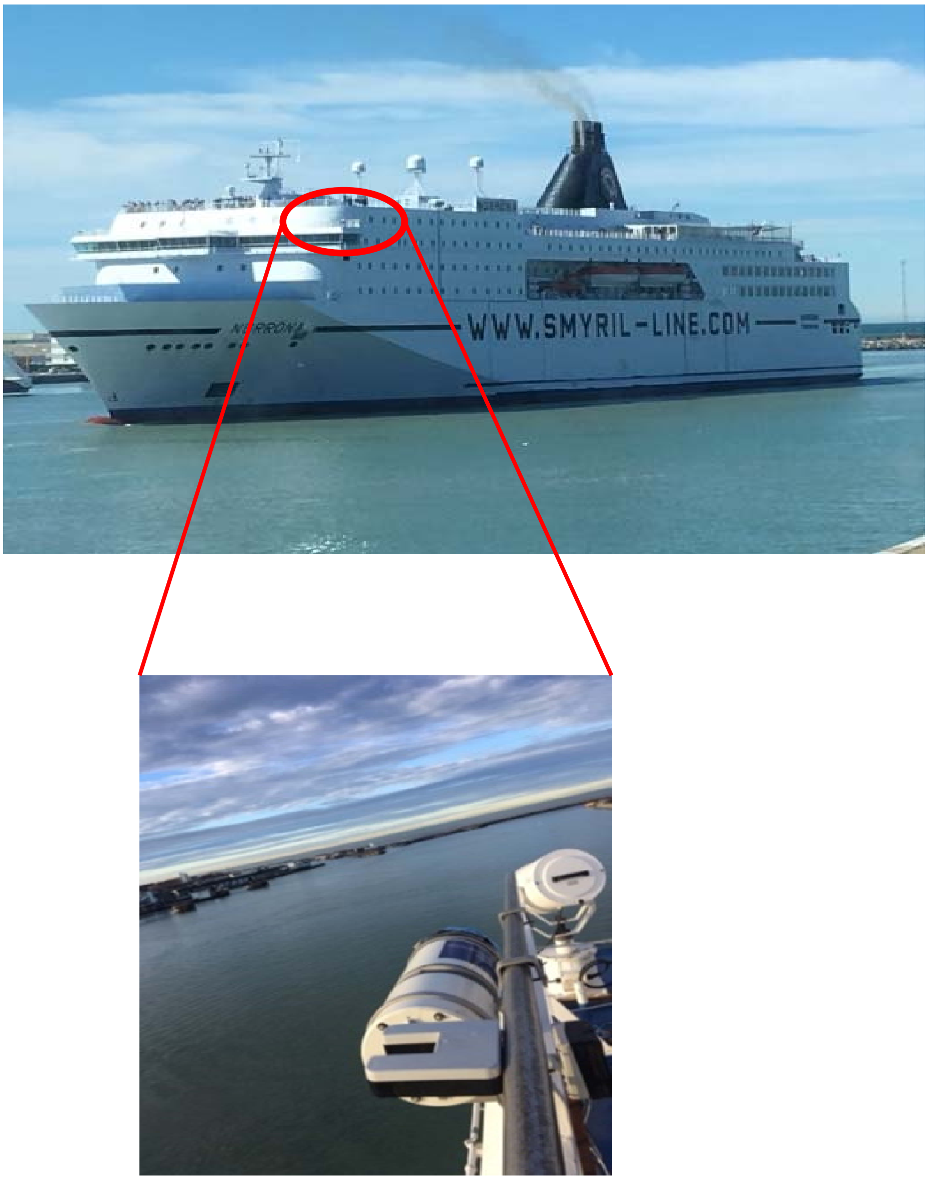



Figure 4-2: DMI-ISAR installation on board Norröna. The first deployment was made in December 2017.

Along with the ISAR, Norröna also carries additional scientific instrumentation, such as a Ferrybox system, installed by NIVA in Norway, measuring the temperature/salinity and turbidity of the ship intake. Finally, Woods Hole Oceanographic Institute have installed an Acoustic Doppler Current Profiler (ADCP) that measures the ocean currents along the cruise.

## 4.2 Calibration and Processing

As part of the operational FRM procedure, processing and calibration experiments are performed before and after each deployment to assess the performance of the DMI ISAR and to maintain traceability of the observations. The service and calibration is carried out every 2-3 months, more often in the winter time than summer time due to the harsh conditions in the Atlantic in winter. The calibrations are performed using the second-generation Concerted Action for the Study of the Ocean Thermal Skin (CASOTS-II) blackbody as a reference with a calibrated Fluke thermistor probe. An example of a pre-deployment calibration is shown in the figure 4-3 below. The mean difference between ISAR and Fluke *in situ* for this particular experiment was 0.01K (ISAR-*in situ*) with a standard deviation of the differences of 0.03K.

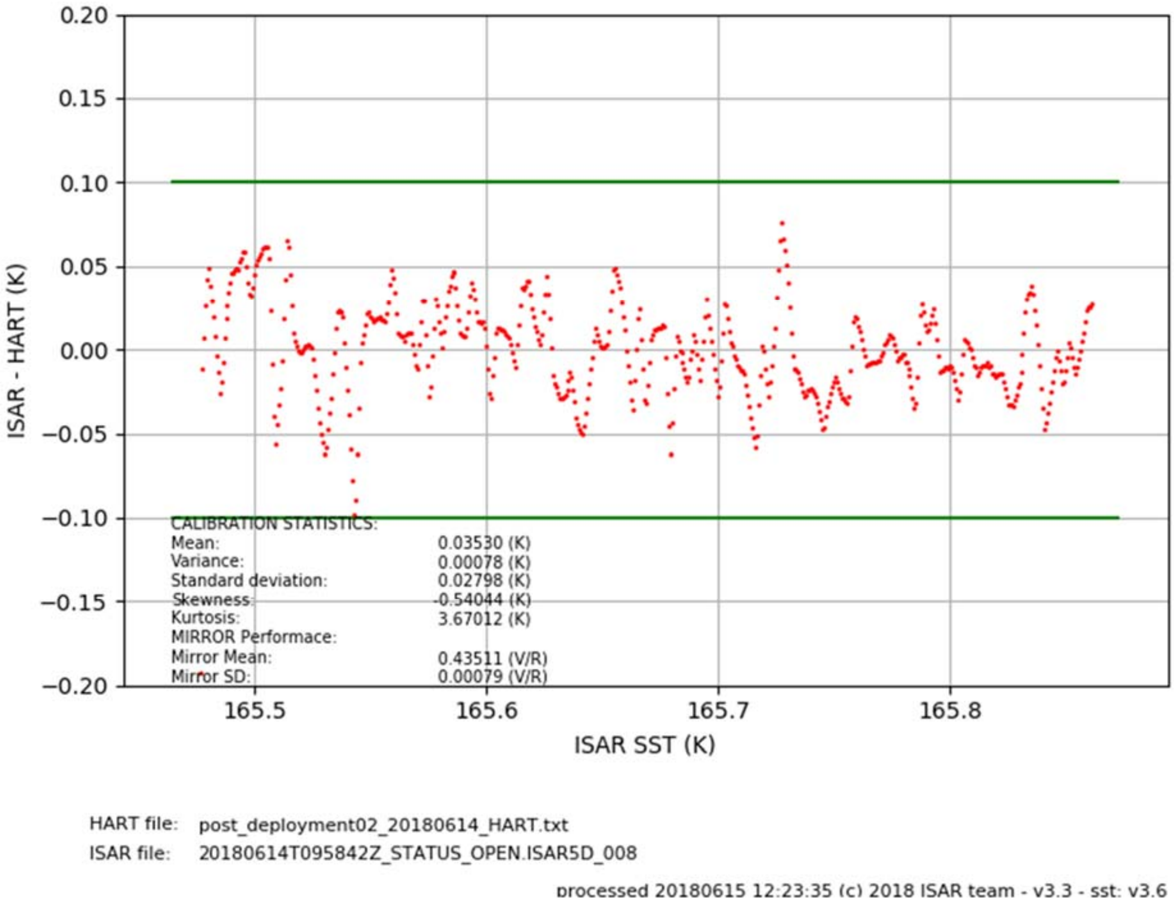



Figure 4-3: Calibration results from deployment 4, pre-deployment calibration.

## 4.3 An important transect to monitor

The regularly observed track between Denmark and Iceland is not only a valid region for the use of radiometer data for satellite SST validation. The ship line transects the inflow of warm waters to the Nordic Seas, which is an important part of the Atlantic Meridional Overflow Circulation (AMOC). Variability in the AMOC has been linked to fluctuations in the global climate and it is therefore crucial to monitor changes in the temperature of the inflow waters. Figure 4-4 shows the FRM SSTs along the deployments between 2017 and 2023.

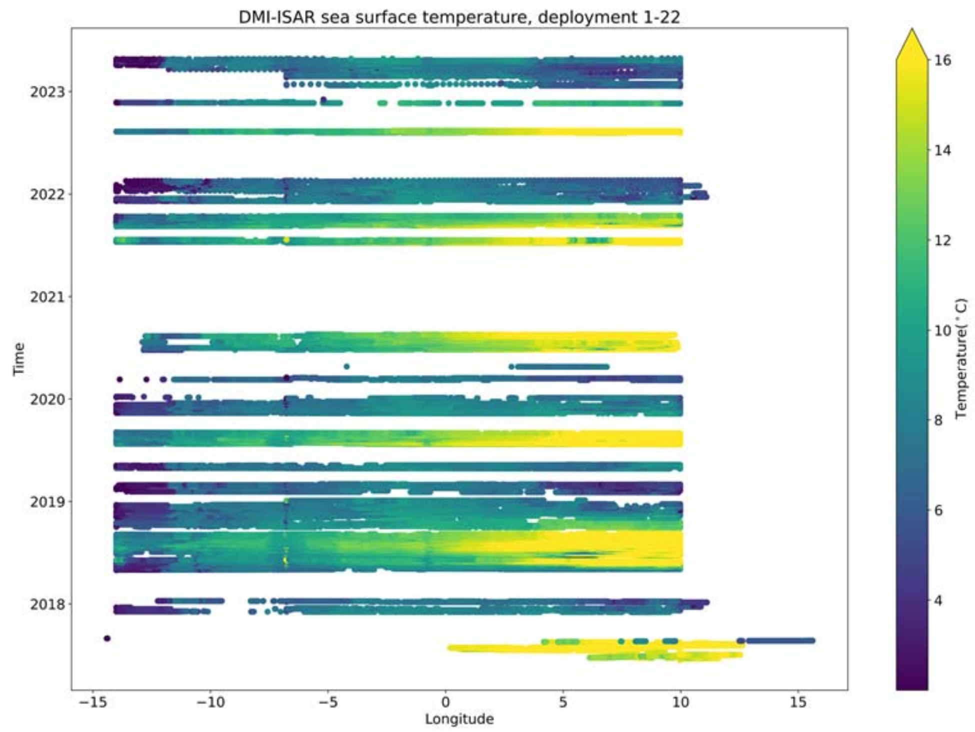



Figure 4-4**:** A longitude versus time plot of the ISAR observed SSTs during 2017 - 2023.

# 5. SISTER

SISTeR is a chopped, self-calibrating filter radiometer. Designed and operated by RAL Space, the SISTeR instrument makes highly accurate and traceable measurements of the sea surface skin temperature using the same techniques as ISAR. The instrument can protect itself against bad weather and can operate unattended for extended periods. SISTeR has been deployed since 1997 on a range of research ships and passenger vessels, most recently on the Cunard Line *Queen Mary 2 (QM2)* ocean liner.

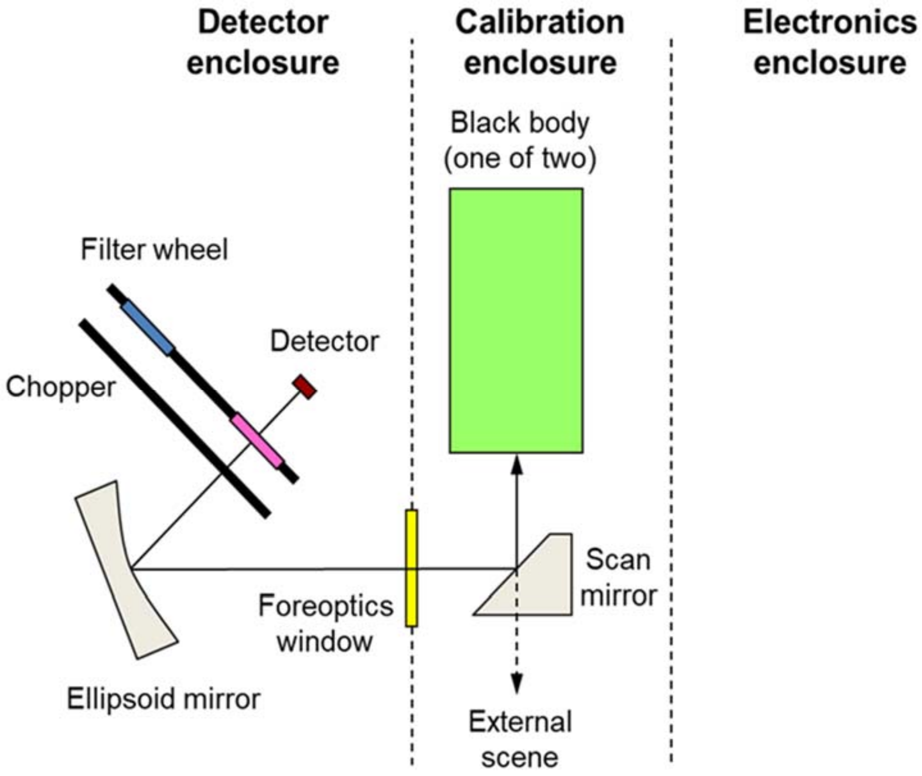



Figure 5-1: The internal configuration of the SISTeR radiometer

## 5.1 Deployments on the QM2

Since 2010, the SISTeR instrument has been mounted above the *QM2's* starboard bridge wing (Figure 5-2). SISTeR is programmed to take a repeating pattern of radiometric measurements of the sea surface, the sky, and two internal calibration sources. These data, along with "housekeeping" measurements of the instrument state, are transmitted over a serial data link to a data logging computer. The computer stores the data both locally and sends them daily via the ship's satellite Internet link to an email address at RAL Space, where it is checked, calibrated and processed to sea surface temperatures.

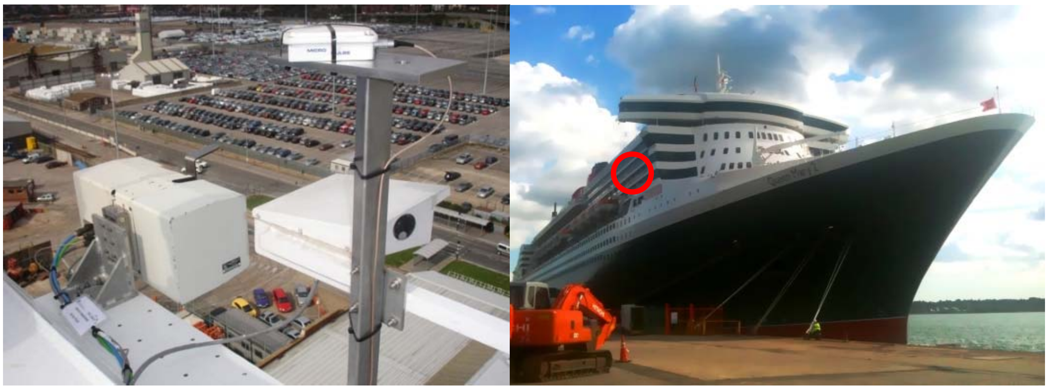


Figure 5-2: The SISTeR Instrument mounted on the *Queen Mary 2*

From January to May each year, the *QM2* undertakes a “round-the-world” cruise (Figure 5-3), crossing the Atlantic, Indian and Pacific oceans. For the remainder of the year, the liner makes regular crossings of the North Atlantic between Southampton and New York, with occasional trips to other destinations, including Newfoundland and Scandinavia.

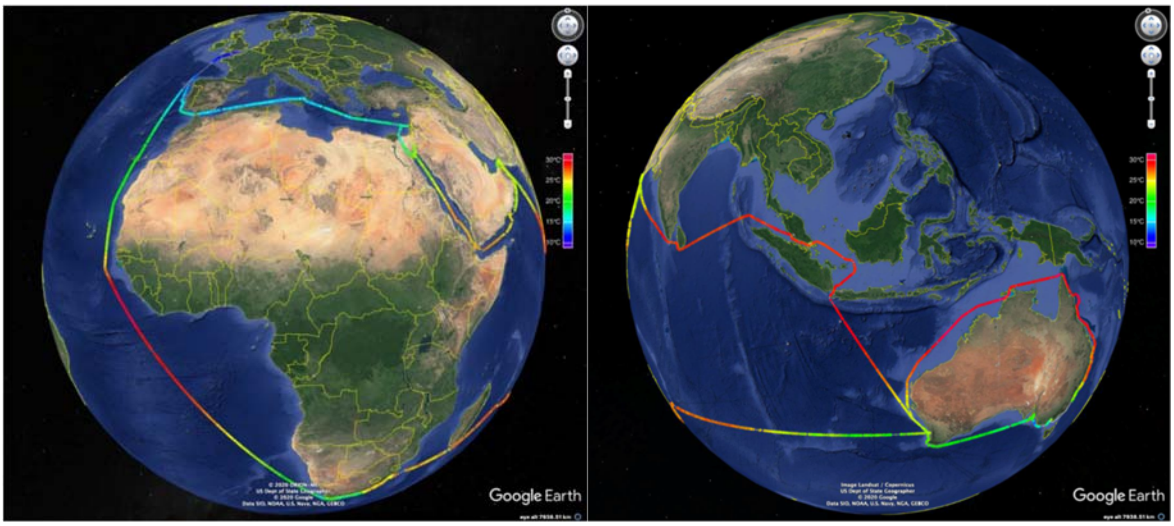



Figure 5-3 SSTs from a SISTeR “round-the-world” cruise on the *QM2*, 10/01/2020 to 18/04/2020.

SISTeR data are used to validate SLSTR using the same methods as ISAR. The combination of having the ISARs on a consistent cruise pattern in specific regions and SISTeR’s more global coverage is extremely beneficial, especially during the data gap between AATSR and SLSTR.

## 5.2 SISTeR Processing

The SISTeR processor was significantly improved in 2019 as a result of the 2016 FRM4STS inter-comparison campaign. This includes the verification of dates on past data and a development of the uncertainty model, which has been incorporated into the L2R format in the form of a quality flag.

The data collected during the contract period have been uploaded and made available to the community. Earlier data will be processed and uploaded in the near future and future data will be processed and uploaded as it becomes available.

Due to COVID-19 world-wide travel restrictions during 2020, RAL Space was unable to deploy SISTeR since the world cruise during the first quarter of 2020 which has resulted in less data from the SISTeR instrument in 2020 and 2021 than in previous years. SISTeR deployments resumed on the QM2 in March 2022 and at time of writing this report, the SISTeR instrument is on its first 'normal' world cruise since 2020.

# 6. SLSTR DATA STABILITY

## 6.1 Comparing SLSTR A and B against ships4sst FRM data

SLSTR data was validated with ISAR and SISTeR data from January 2019 until December 2019. The validation of the SLSTR A and B dataset shows good consistency over the period. A total of 10074 match-up pairs were evaluated for a match-up window of +/- 2h and within 1 km off the overpass of SLSTR A and B. For SLSTR A, 4968 match-up pairs were collected, showing a mean difference compared to ships4sst of -0.01 K for 2083 daytime match-ups from 119 different overpasses, and 0.00 K for 2885 nighttime match-ups from 162 overpasses. The Robust Standard Deviation (RSD) of the measurements is 0.33 K for daytime and 0.18 K for nighttime SLSTR A data. For SLSTR B, 5106 match-up pairs were collected, showing a mean difference compared to ships4sst of 0.09 K for 2027 daytime match-ups from 108 different overpasses, and 0.01 K for 3079 nighttime match-ups from 149 overpasses. The RSD of the measurements is 0.36 K for daytime and 0.20 K for nighttime SLSTR B data. Both SLSTR A and B show excellent results when compared with ships4sst data, with SLSTR A showing slightly less mean difference and slightly smaller RSD than SLSTR B.

When broken down for the three main areas covered by this project, the results for the Bay of Biscay and English Channel operated by the UoS ISAR's on the *Pont Aven* are a mean difference of 0.05 K for 509 day time match-ups and a mean difference of -0.04 K for 888 night time match-ups for SLSTR A data. The RSD for those match-up pairs are 0.23 K for the day time and 0.18 K for the night time for SLSTR A. For SLSTR B a mean difference of -0.03 K for 383 day time match-ups and a mean difference of -0.02 K for 880 night time match-ups is recorded. The RSD for those match-up pairs are 0.23 K for the day time and 0.19 K for the night time for SLSTR B data.

The results for the DMI operated ISAR on the *Norrona* show a mean difference of -0.07 K for 247 day time matches and 0.08 K for 248 night time matches for SLSTR A data. The RSD for those matches are 0.39 K for the day time and 0.20 K for the night time for SLSTR A. For SLSTR B a mean difference of -0.03 K for 213 day time match-ups and a mean difference of 0.18 K for 215 night time match-ups is recorded. The RSD for those match-up pairs are 0.28 K for the day time and 0.28 K for the night time for SLSTR B data.

Finally the results for the RAL SISTeR on the *Queen Mary 2* show a mean difference of 0.02 K for 74 day time match-ups and a mean difference of 0.24 K for 140 night time match-ups for SLSTR A data. The RSD for those validation data points is 0.11 K for day time match-ups and 0.10 K for night time match-ups for SLSTR A. For SLSTR B, a mean difference of 0.16 K for 248 day time match-ups and a mean difference of 0.09 K for 306 night time match-ups is recorded. The RSD for those match-up pairs are 0.15 K for the day time and 0.20 K for the night time for SLSTR B data.

The comparison with AATSR data in the Bay of Biscay and English Channel shows that SLSTR's performance is very similar to AATSR in that area, with a higher number of matches compared to AATSR. The high latitude results on *Norrona* have produced few matches but the area is challenging for SST skin measurements and the matches show a good agreement with SLSTR. The SISTeR matches produced a good number of matches with results for the night time match-ups being very similar to the Bay of Biscay and English Channel results, however the day time match-ups produce for SLSTR B and the night time match ups for SLSTR A produced a slightly larger mean difference than expected. Figure 6-1 shows the location of the SLSTR A match-ups for all ships4sst data including the University of Miami M-AERI data, RAL SISTeR data, UoS ISAR, DMI ISAR and CISRO ISAR data. Figure **6**-2 shows the location of the SLSTR B match-ups for all ships4sst data including the University of Miami M-AERI data, RAL SISTeR data, UoS ISAR, DMI ISAR and CISRO ISAR data.

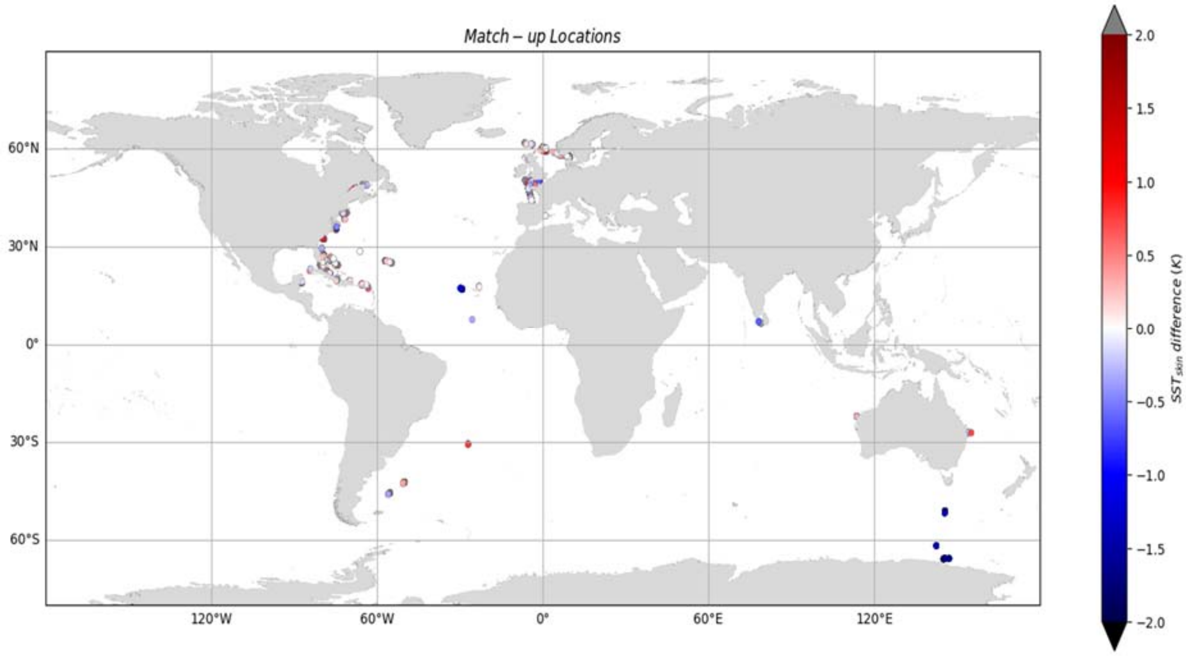



Figure 6-1 Location of the match-ups at +/- 2h and 1km coincidence for SLSTR A WST dual-view SST retrievals against ships4sst observations between January 2019 and December 2019.

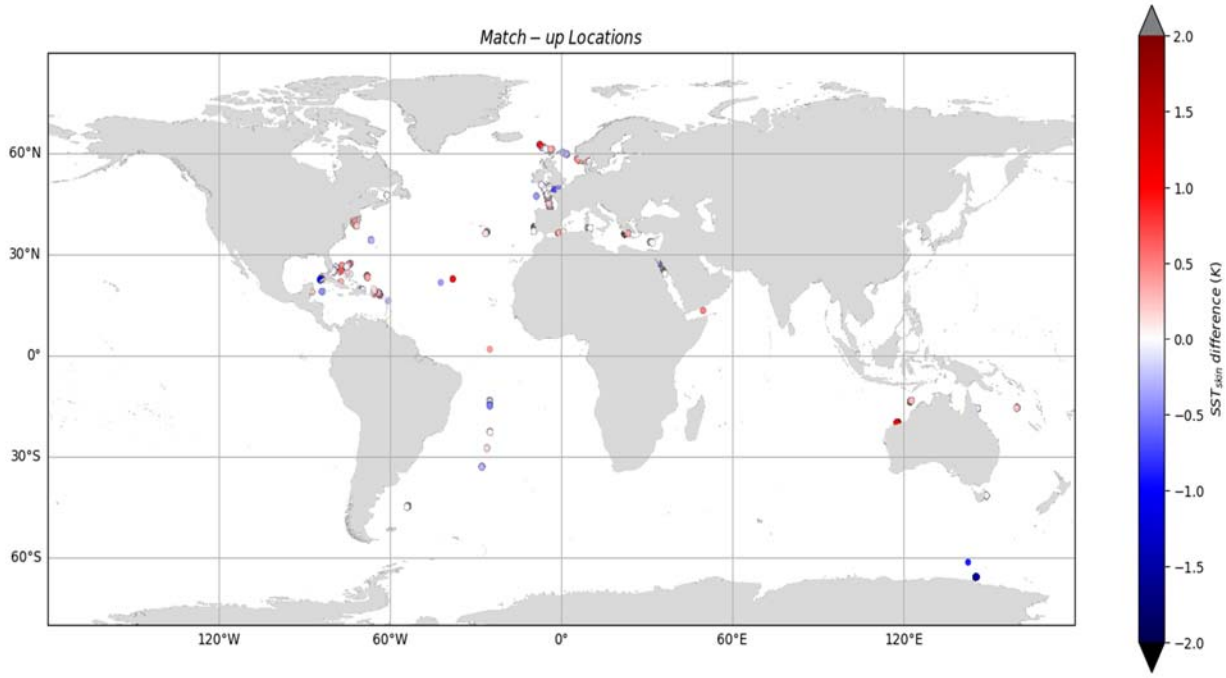



Figure 6-2 Location of the match-ups at +/- 2h and 1km coincidence for SLSTR B WST dual-view SST retrievals against ships4sst observations between January 2019 and December 2019.

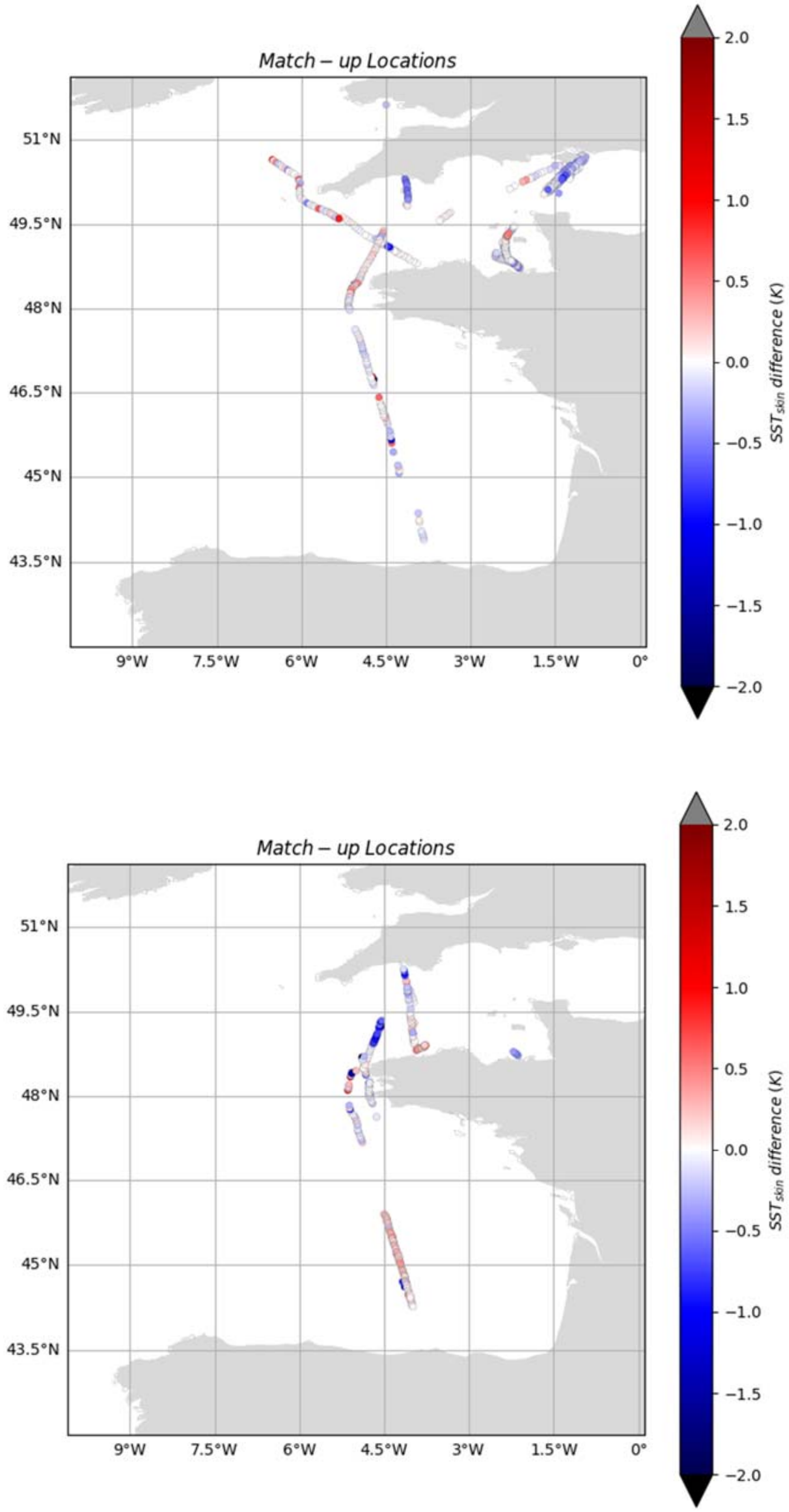



Figure 6-3: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR A WST dual-view SST retrievals against ISAR on the *Pont Aven* observations between January 2019 and December 2019 for night (left panel) and day (right). The stratification of the data is a side effect of the *Pont Aven's* schedule and not deliberate.

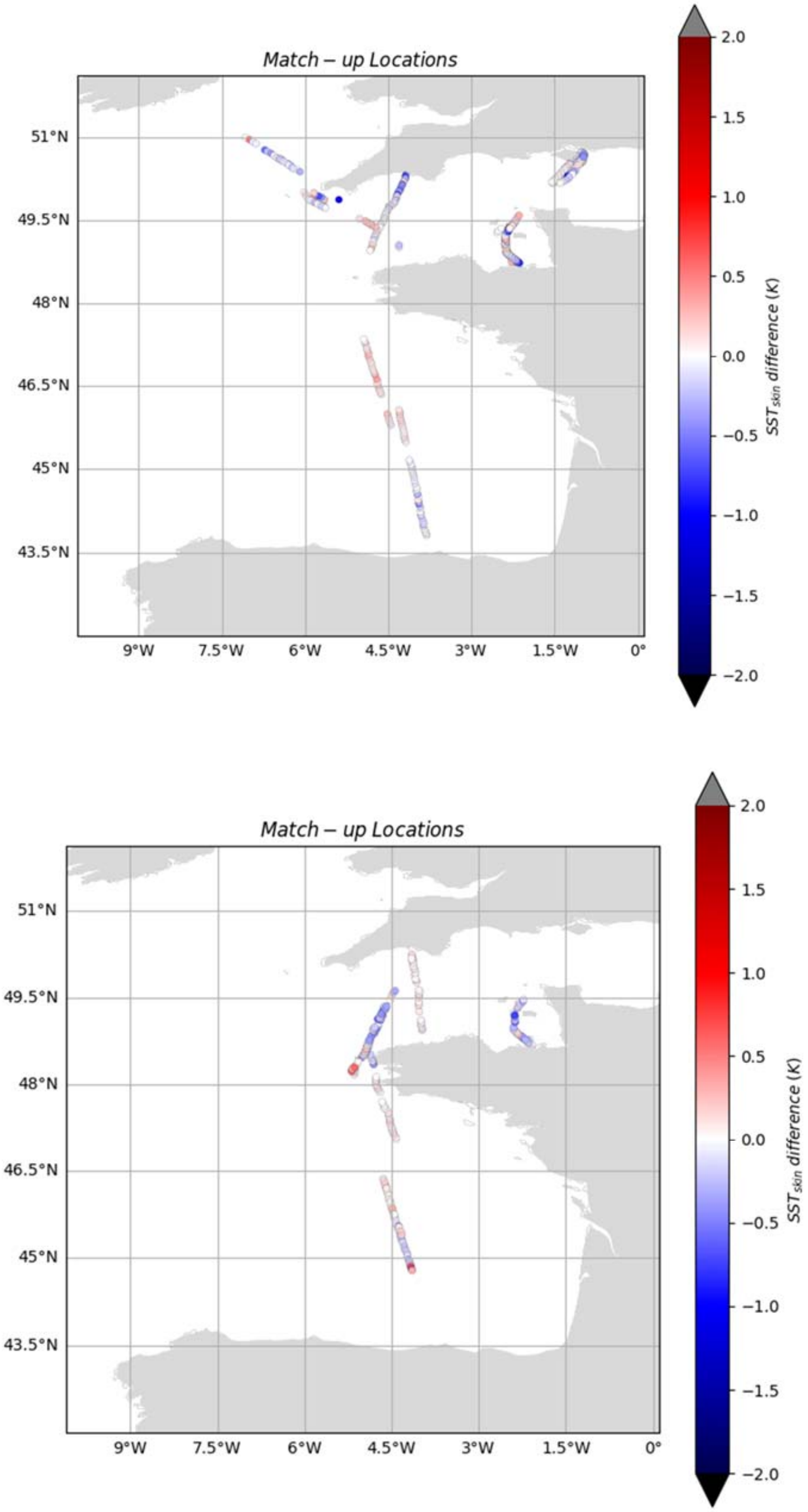



Figure 6-4: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR B WST dual-view SST retrievals against ISAR on the *Pont Aven* observations between January 2019 and December 2019 for night (left panel) and day (right). The stratification of the data is a side effect of the *Pont Aven's* schedule and not deliberate.

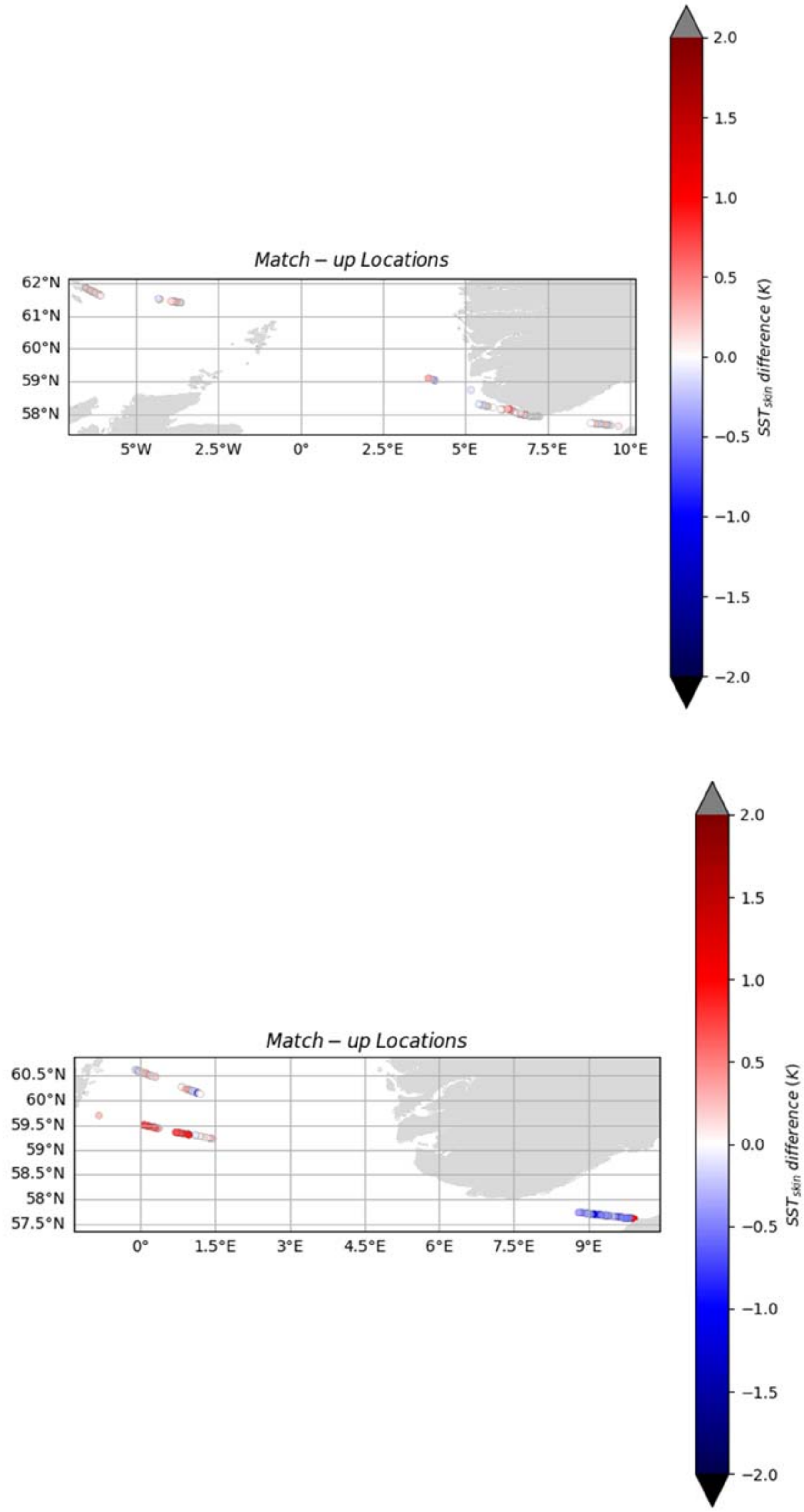
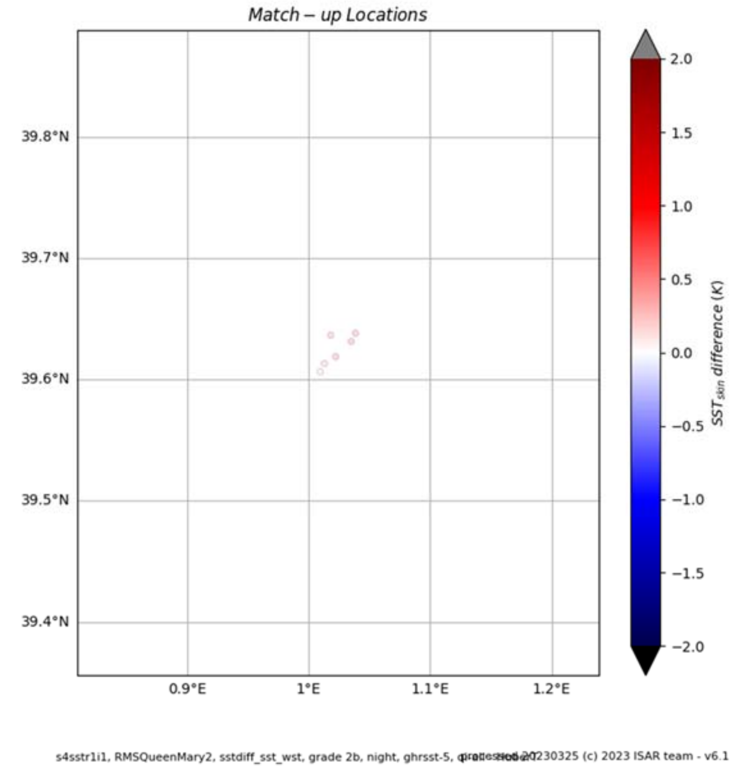



Figure 6-5: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR A WST dual-view SST retrievals against ISAR on the *Norrana* observations between January 2019 and December 2019 for night (left panel) and day (right). The stratification of the data is a side effect of the *Norrana's* schedule and not deliberate.



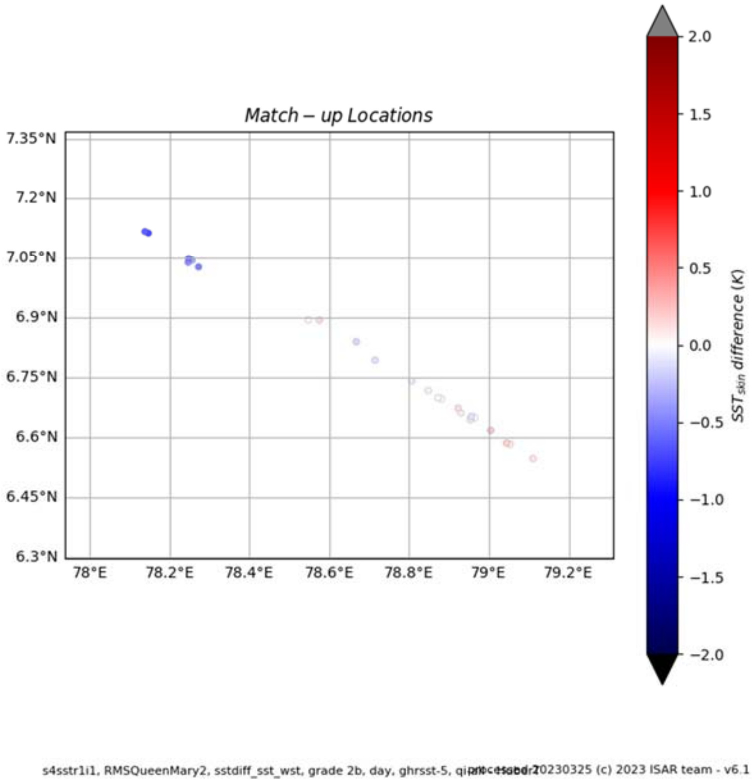




Figure 6-6: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR A WST dual-view SST retrievals against SISTeR on the *Queen Mary 2* observations between January 2019 and December 2019 for night (left panel) and day (right). The stratification of the data is a side effect of the *Queen Mary 2's* schedule and not deliberate.

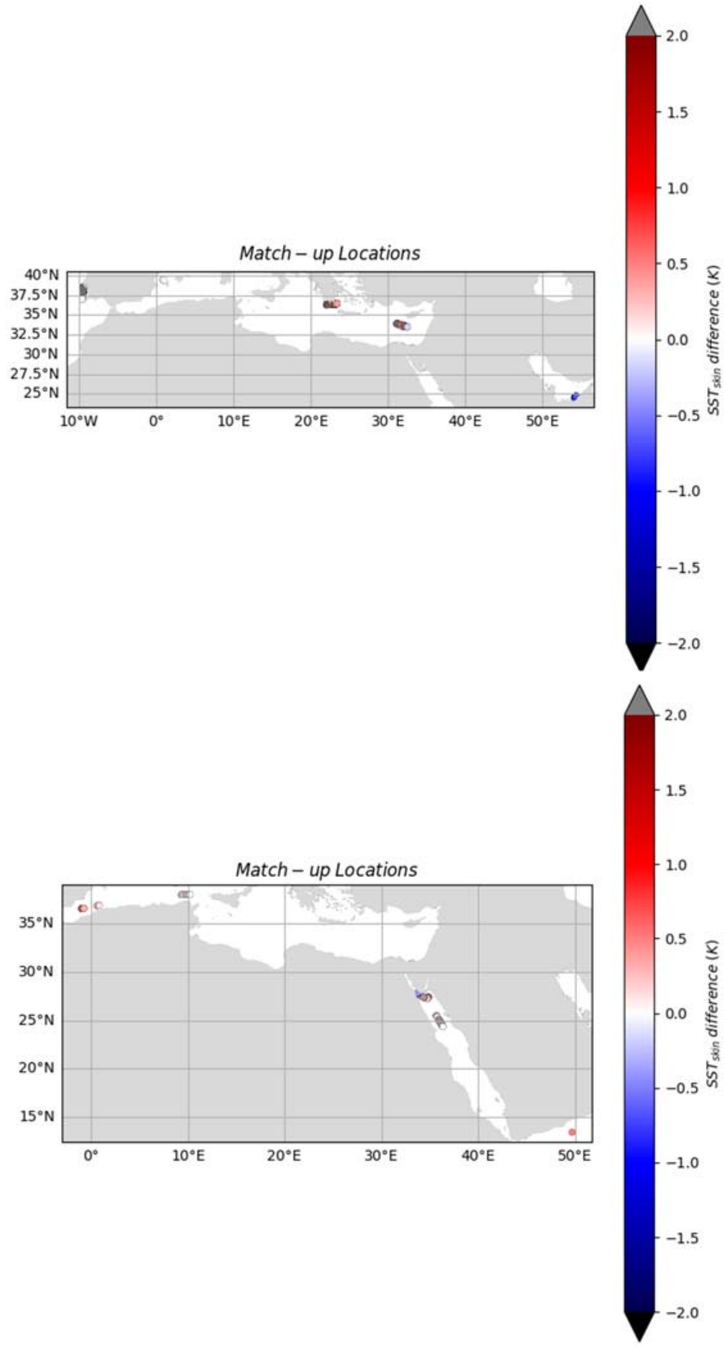



Figure 6-7: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR B WST dual-view SST retrievals against SISTeR on the *Queen Mary 2* observations between January 2019 and December 2019 for night (left panel) and day (right). The stratification of the data is a side effect of the *Queen Mary 2's* schedule and not deliberate.

Figure 6- shows the histograms for the SLSTR-ISAR/SISTeR match-ups, with nighttime match-ups on the left and day- time match-ups on the right-hand side of the plot. The temperature range validated is from 0 °C to 35.4 °C.

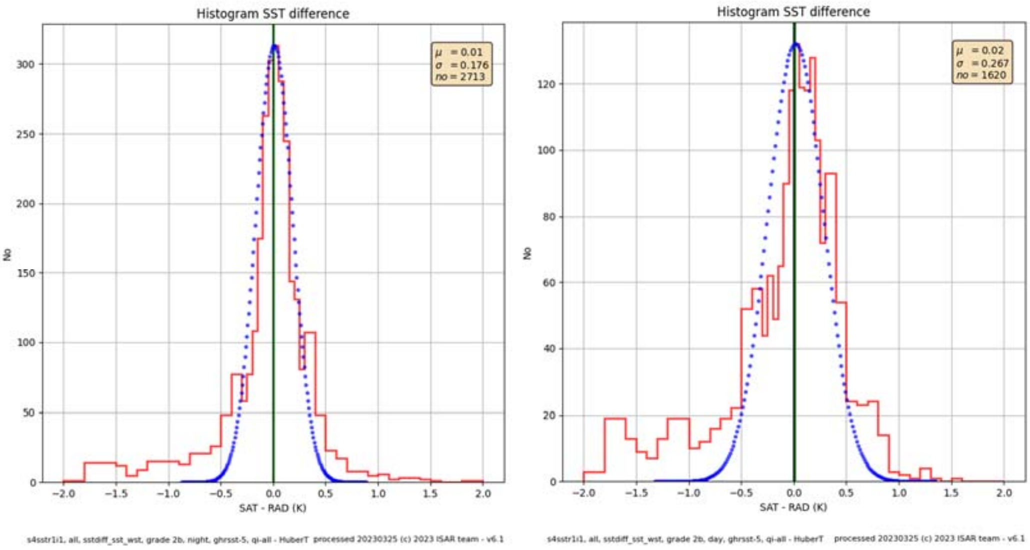



Figure 6-8**:** Histograms of Grade 2b match-up differences between SLSTR A and ships4sst SST records between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR A WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR A match-ups with a difference between SLSTR A and ships4sst of 0.01 K for nighttime data and 0.02 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.183 K for the nighttime and 0.27 K for the daytime.

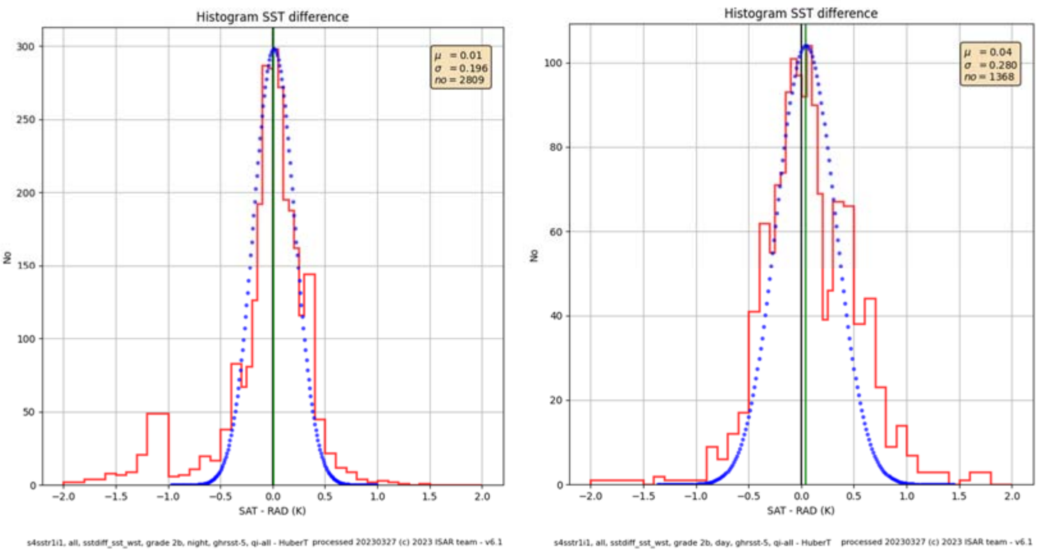



Figure 6-9**:** Histograms of Grade 2b match-up differences between SLSTR B and ships4sst SST records between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR B WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR B match-ups with a difference between SLSTR B and ships4sst of 0.01 K for nighttime data and 0.04 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.20 K for the nighttime and 0.28 K for the daytime.

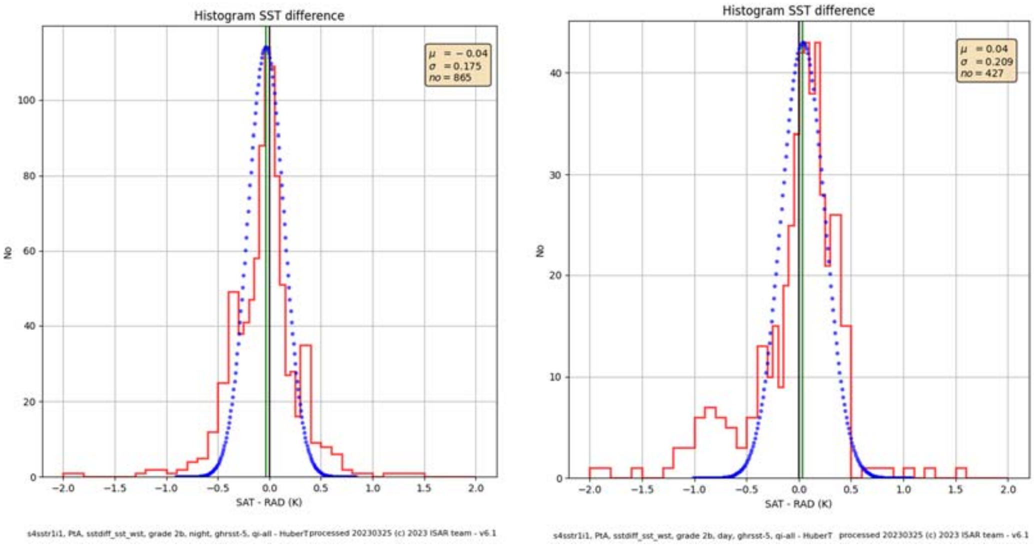



Figure 6-10: Histograms of Grade 2b match-up differences between SLSTR A and ISAR SST records on the *Pont Aven* between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR A WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR A match-ups from the *Pont Aven* with a difference between SLSTR A and ISAR of -0.04 K for nighttime data and 0.04 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.18 K for the nighttime and 0.21 K for the daytime.

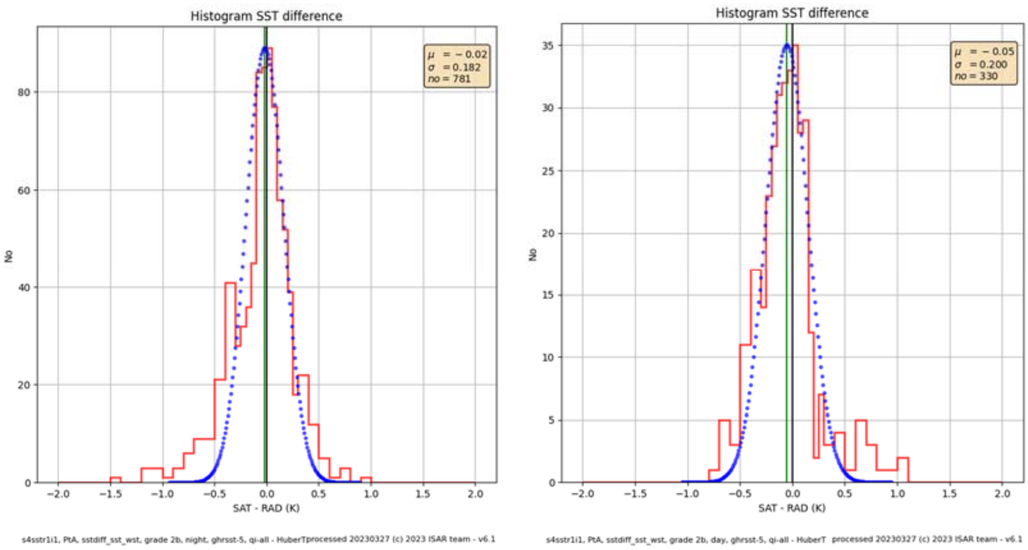



Figure 6-11: Histograms of Grade 2b match-up differences between SLSTR B and ISAR SST records on the *Pont Aven* between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR B WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR B match-ups from the *Pont Aven* with a difference between SLSTR B and ISAR of -0.02 K for nighttime data and -0.05 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.18 K for the nighttime and 0.20 K for the daytime.

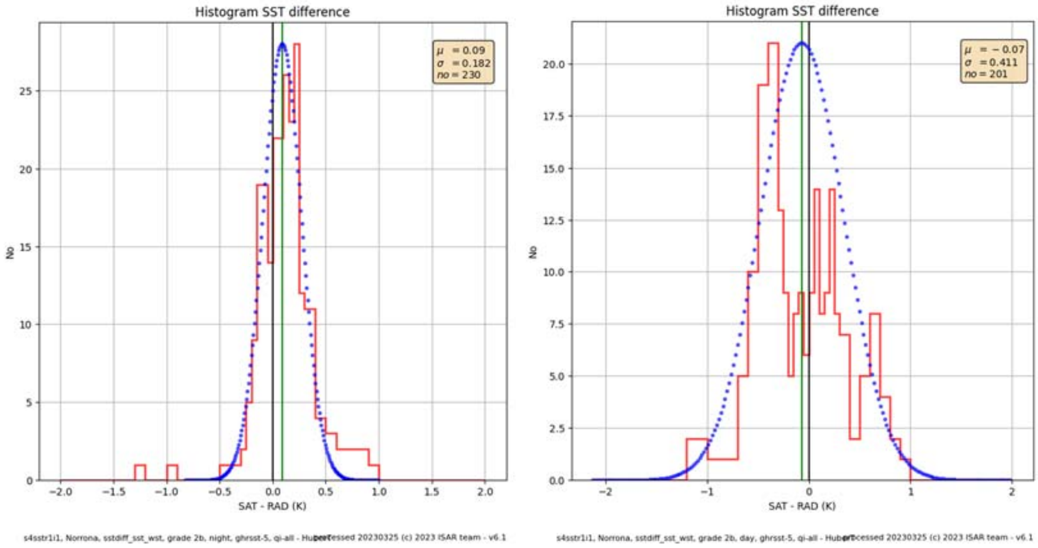



Figure 6-12**:** Histograms of Grade 2b match-up differences between SLSTR A and ISAR SST records on the Norrona between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR A WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR A match-ups from the *Norrona* with a difference between SLSTR A and ISAR of 0.09 K for nighttime data and -0.07 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.18 K for the nighttime and 0.41K for the daytime.

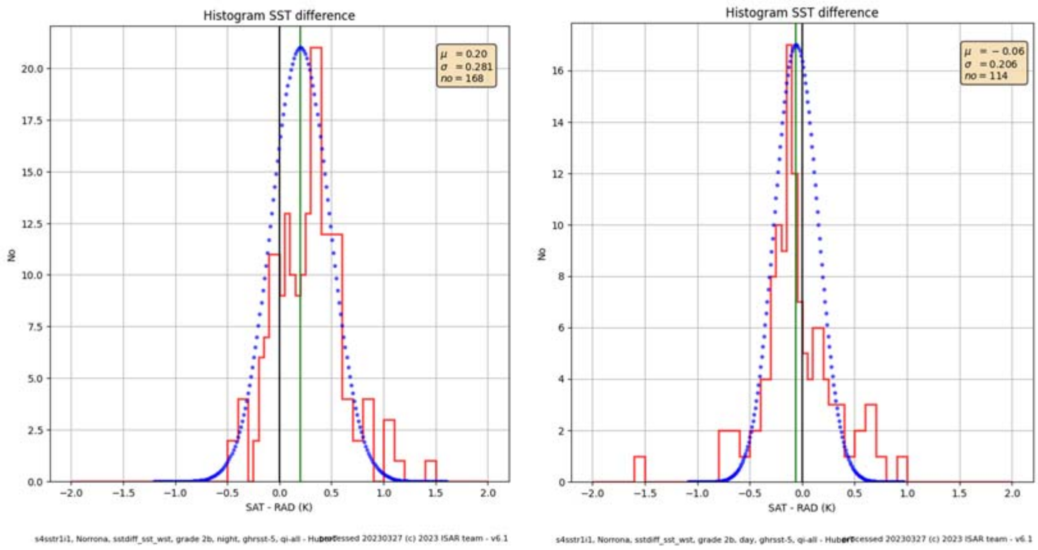



Figure 6-13**:** Histograms of Grade 2b match-up differences between SLSTR B and ISAR SST records on the Norrona between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR B WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR B match-ups from the *Norrona* with a difference between SLSTR B and ISAR of 0.20 K for nighttime data and --0.06 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.20 K for the nighttime and 0.21K for the daytime.

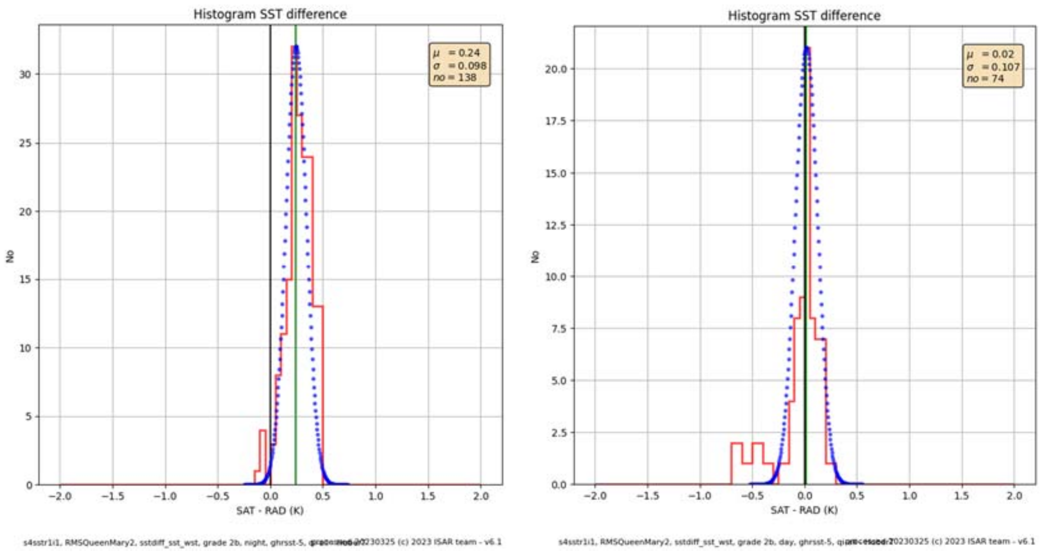



Figure 6-14**:** Histograms of Grade 2b match-up differences between SLSTR A and SISTeR SST records on the *Queen Mary 2* between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR A WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR A match-ups on the *Queen Mary 2* with a difference between SLSTR A and SISTeR of 0.24 K for nighttime data and 0.02 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.10 K for the nighttime and 0.11 K for the daytime.

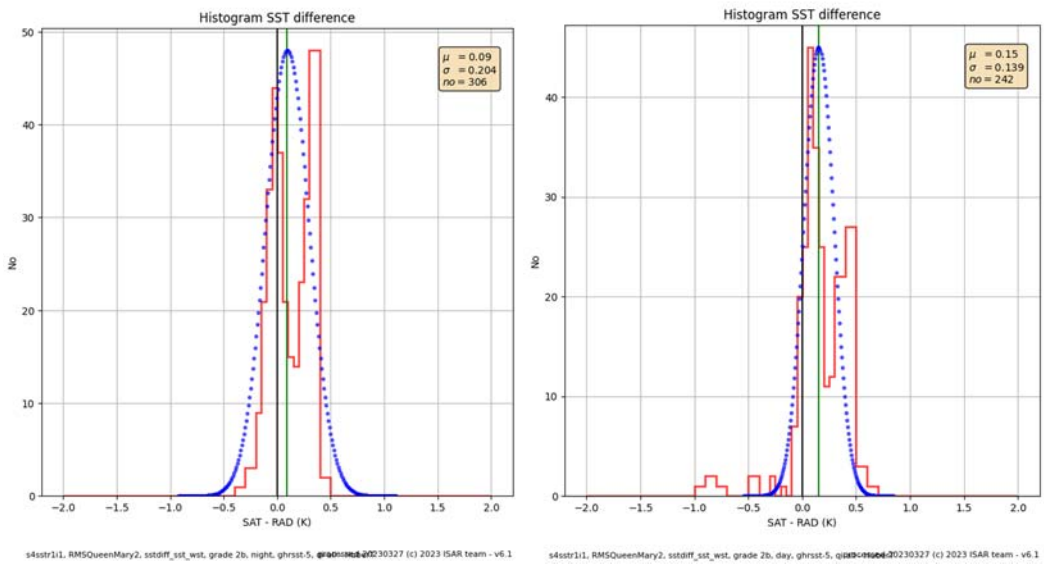



Figure 6-15**:** Histograms of Grade 2b match-up differences between SLSTR B and SISTeR SST records on the *Queen Mary 2* between January 2019 and December 2019, for night (left panel) and day (right). The solid red line shows the SLSTR B WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR B match-ups on the *Queen Mary 2* with a difference between SLSTR B and SISTeR of 0.09 K for nighttime data and 0.15 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.20 K for the nighttime and 0.14 K for the daytime.

Overall SLSTR A and B showed excellent performance over the analysed years when compared to ISAR and SISTeR data, exceeding its design specification of an accuracy of 0.3 K, shown by the global ships4sst data. In the project's regions, both SLSTR A and B perform excellently with some small mean difference issues in high latitude day time data. Overall, both SLSTR A and B exceed the data quality achieved by AATSR, however there is still some room for improvement in high latitude matches and day time matches.

# 7. CEOS TIR RADIOMETER INTER-COMPARISON EXERCISE

To verify the accuracy of shipborne IR radiometers and continue the reliable validation of SST measurements from space to FRM SI units, the Committee on Earth Observation Satellites (CEOS) and Working Group on Calibration & validation (WGCV) has been conducting comparisons of SSTskin measuring radiometers every 6-7 years. During such comparisons, radiometers are gathered from around the world and compared with reference standards as well as amongst themselves.

In June 2022 the project held one such CEOS WGCV international TIR radiometer inter-comparison exercise, organised and hosted by NPL in the UK. Participants from UoS, RAL, DMI, CSIRO, Karlsruhe Institute of Technology (KIT) and the University of Valencia (UoV) brought together their respective radiometers, firstly to NPL for a laboratory comparison, and then to the south coast of England for a field comparison in which the sea surface was measured.

The laboratory exercise involved a comparison of participants' radiometers, in which two NPL standard variable blackbodies (BB) were used to provide the reference value. A comparison of the participants' blackbodies that were used to calibrate the radiometers was also performed and the NPL standard radiometer AMBER provided the reference value. The measurand in both cases was the radiance temperature on the International Scale of 1990 (ITS-90)[4] at a wavelength of 10µm.

The results from the BB comparison are shown below in Figure 7- and Figure 7-. ISAR and SISTeR contain specialised BBs (i.e. CASOTS and CASOTS-II) that have a BB cavity that is immersed in stirred water bath and has a substantially smaller associated uncertainty. Temperature readings show good agreement with the reference value.

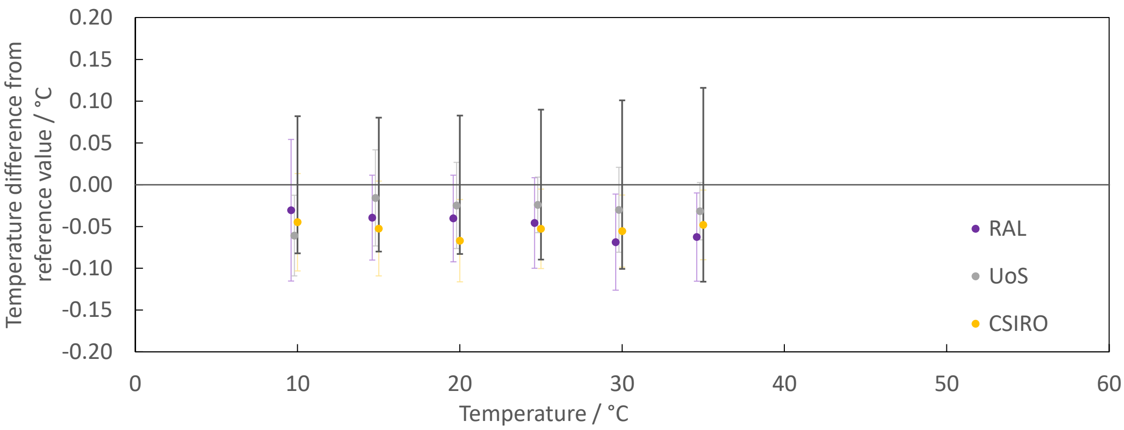



Figure 7-1: Laboratory comparison results showing the temperature difference from reference value for the specialised BBs (CASOTS and CASOTS-II). Error bars denote k = 2 uncertainties.

[4] http://lef.mec.puc-rio.br/wp-content/uploads/2015/05/The_International_Temperature_Scale_1990.pdf

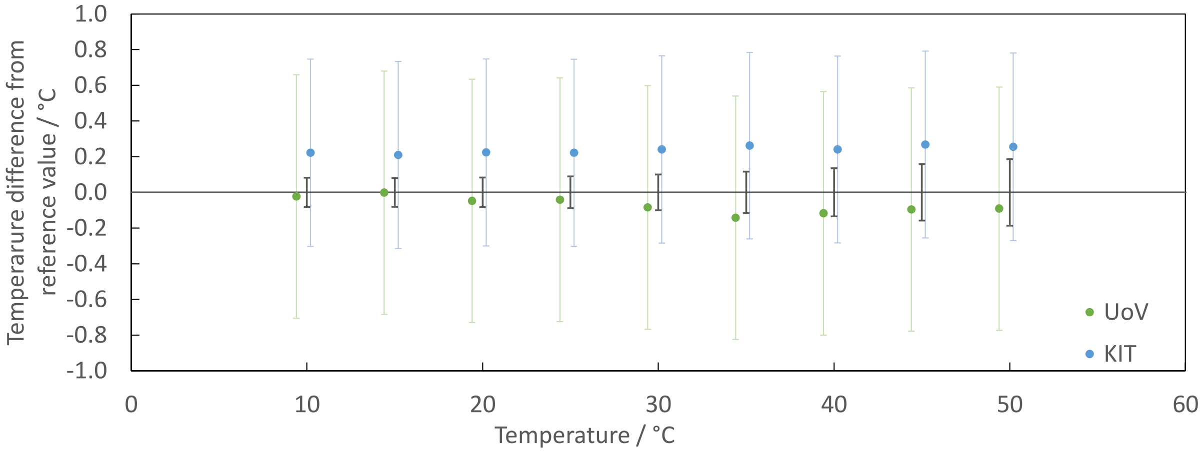



Figure 7-2: Laboratory comparison results showing the temperature difference from reference value for the commercial BBs (Landcal P80P). Error bars denote k = 2 uncertainties.

The results from the radiometer comparison are shown below in Figure 7- and Figure 7-. Temperature readings show that at zero and sub-zero degrees, the uncertainty estimation should be enlarged for all radiometers (although practically, the sea does not go this cold).

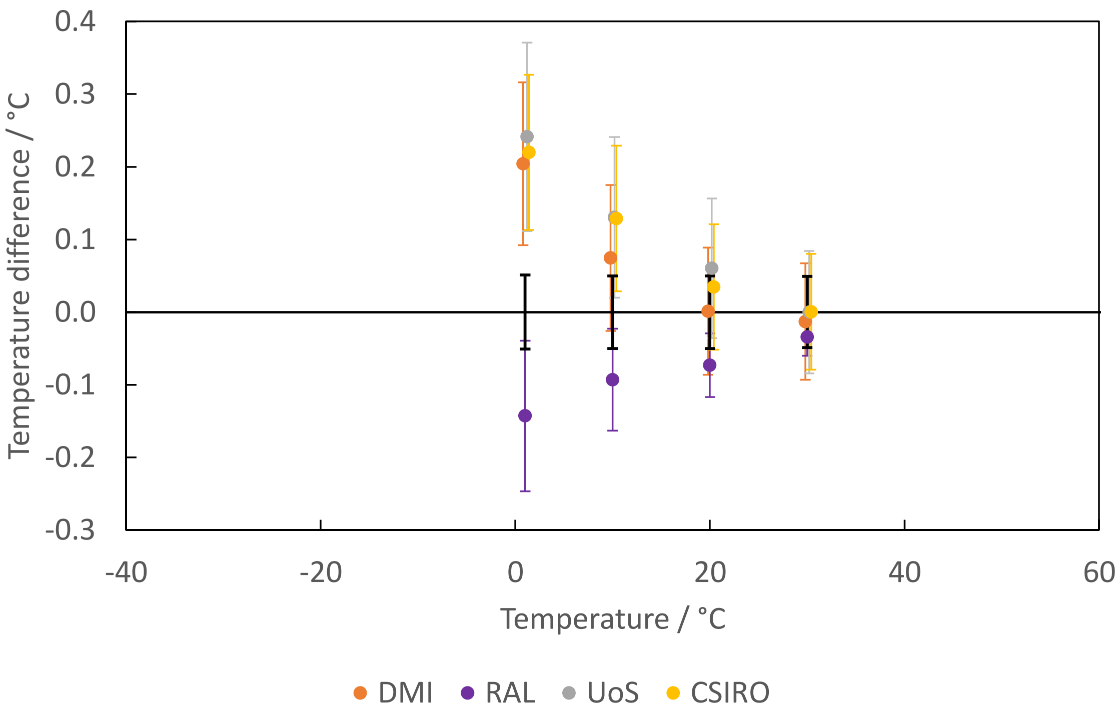



Figure 7-3: Radiometer comparison results showing the temperature difference from reference value (a stirred liquid bath BB) for the ISAR and SISTeR instruments. Error bars denote k = 2 uncertainties.

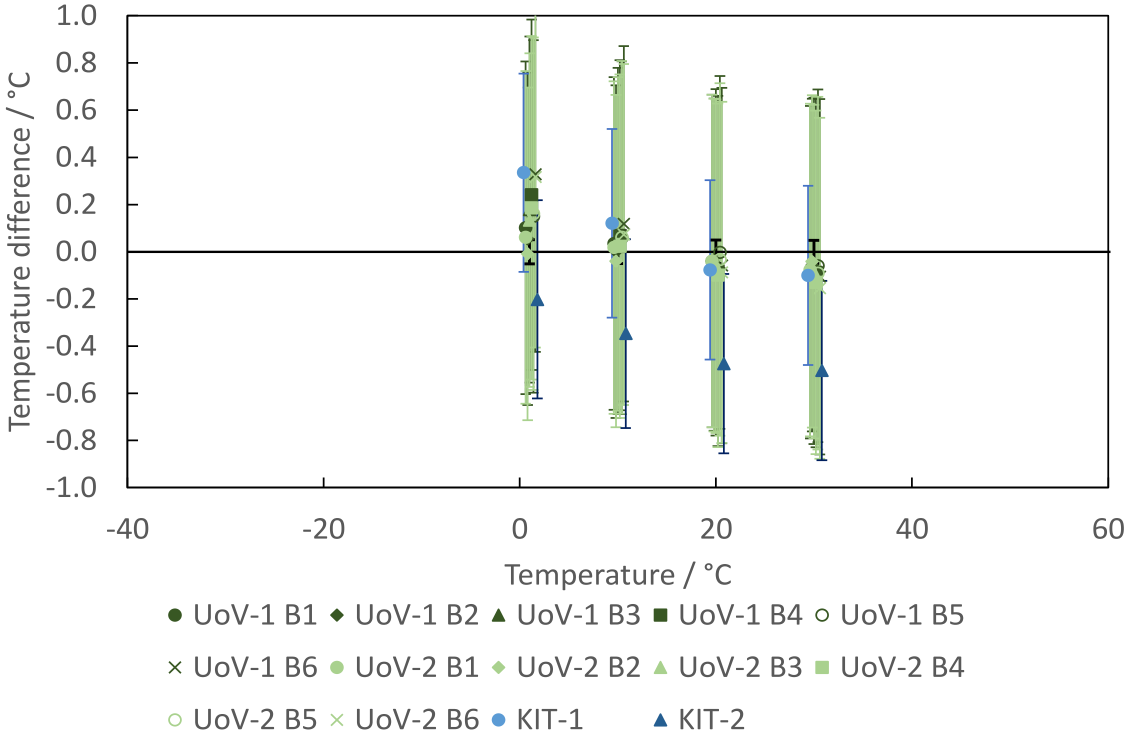



Figure 7-4: Radiometer comparison results showing the temperature difference from reference value (a stirred liquid bath BB) for commercial instruments. Error bars denote k = 2 uncertainties.

The field comparison took place at the end of a south-facing Pier in Boscombe, Bournemouth. All the radiometers were positioned so that they viewed the same area of sea. Continuous measurements were taken of the sea radiance as well as the sky background radiance and corrections were applied for the reflection and the emissivity to derive the SST. The measurand in this case was the SST and the reference value was the mean of the participants' reported SST values (excluding outliers from one of the instruments, which were possibly due to a contamination of the optics 2 days in to the field exercise).

The results from the field comparison are shown in Figure 7-5: Field comparison results showing the temperature difference for all instruments, averaged over 20 minutes. Error bars denote k = 2 uncertainties.Figure 7-5. There was a two times improvement in agreement compared to the 2016 comparison (in terms of mean of the difference from reference value). An abrupt shift of KIT's SST data readings can be seen after the 22/06/22, however this was not discovered until after the experiment. This result shows the importance of using internal reference BB for internal calibration (as in ISAR and SISTeR). All radiometer readings agreed with the uncertainties for all temperature ranges of interest, and the averaged SST values over 20 minute durations show very good agreement.

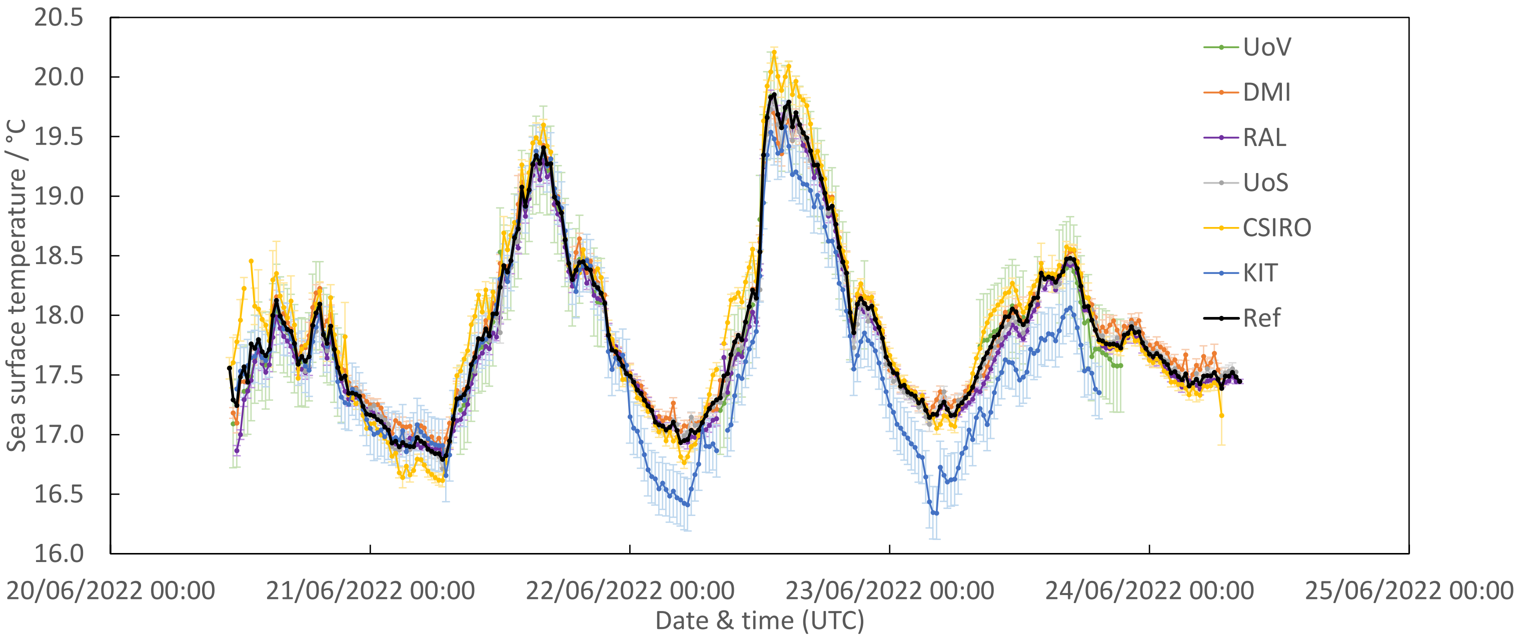



Figure 7-5: Field comparison results showing the temperature difference for all instruments, averaged over 20 minutes. Error bars denote k = 2 uncertainties.

The results of this work package can be found in more detail in the WP-40 Reports on the ships4sst website, and will also be published in two (as yet, unpublished) journal papers: Yamada, et al., "CEOS International Thermal Infrared Radiometer Comparison: Part I: Laboratory Comparison of Radiometers and Blackbodies", and Yamada, et al., "CEOS International Thermal Infrared Radiometer Comparison: Part II: Field Comparison of Radiometers".

# 8. MICROWAVE/THERMAL INFRA-RED EXPERIMENTS

DMI and the Danish Technical University (DTU) collaborated on an intercomparison study of passive microwave (PMW) and IR observations, with the objective of obtaining simultaneous data to enhance our understanding of SST at both the subskin and skin levels. The aim of this study was to support the integration of IR and MW satellite observations.

DTU's radiometer setup consisted of C-band (7.025–7.075 GHz) and X-band (10.59-10.79 GHz) measurements in both vertical (V) and horizontal (H) polarizations. These instruments were specifically refurbished for this purpose.

As a preparation for the subsequent shipborne intercomparison campaign, a one-day "static" experiment was conducted on a bridge in Copenhagen, Denmark, on January 13, 2021. During this static experiment, the IR (ISAR-19) and MW instruments were installed side by side to simulate ocean observations. Analysis of the data collected during the static experiment revealed the stability of the X-band observations, while the C-band H-pol measurements exhibited a consistently noisy signal throughout most of the deployment, possibly due to radio frequency interference (RFI). Further details about the results of this experiment and the MW radiometers can be found in Høyer et al. (2021).

From May 29$^{th}$ to June 4$^{th}$ 2021, a shipborne campaign took place, with the same instruments installed side by side onboard Norröna for the transect between Denmark and Iceland (both ways), including a stopover in the Faroe Islands. The acquired data on brightness temperature variability and characteristics were analysed, and SST were retrieved from MW brightness temperatures. To better understand the MW data and its geophysical implications, forward model simulations have been incorporated. This novel approach will enhance our conclusions regarding the relationship between $SST_{skin}$ and $SST_{subskin}$. The outcomes of this work package are expected to be submitted before the upcoming summer break to the Remote Sensing Journal, titled "Shipborne Comparison of Infrared and Passive Microwave Radiometers for Sea Surface Temperature Observations."

# 9. STUDY FOR A NEXT GENERATION RADIOMETER

The majority of the current *in situ* radiometer fleet are first- and second-generation instruments with origins in the 1990's. While they have been very successful and now operate routinely with high accuracy and good reliability, their designs are now more than twenty years old, have obsolescence issues and could, with the benefit of operational experience, be better optimised. Drawing on the ISFRNs extensive experience with *in situ* infrared radiometers, as well as the familiarity with other measurement approaches, including microwave radiometry and infrared spectro-radiometry, the project team has written a case study for a next generation radiometer.

The study for the next generation radiometer began in Phase 1 of the FRM4SST project and recently, the results of the case study have been used as a basis to generate a requirements specification for a next-generation radiometer to be built using UK funding. The focus of the case study was to produce a design capable of high-quality traceable SST measurements for the validation of current and future satellite instruments which can easily be scaled to multiple models at a viable cost and used and maintained by an operator with basic technical competence.

The proposed next generation instrument is an evolution of its predecessors, rather than a radical redevelopment. It will maintain their general scales and configurations, including a moderately divergent optical system with a small exit aperture, a 45º scan mirror, two compact blackbodies and (from SISTeR) a chopper, filter wheel and uncooled detector.

The quality of radiometry from the ISAR and SISTeR instruments is already high (Theocharous et al, 2010 and 2019). There may be some scope to make incremental improvements to the blackbody thermometry, control of light in the optical system and the robustness of the scan mirror optical coating, but it is unlikely that a new instrument will have markedly lower brightness temperature and SST uncertainties.

The most significant areas for improvement in a new instrument are reliability, manufacturability, maintainability and the user interface.

The most frequent reliability issues in the existing designs have been failures of the scan mirror coatings and the weather doors. Recent iterations of the mirror coatings have been significantly more durable, but the weather door design requires further study. Other vulnerabilities include electrolytic corrosion at dissimilar metal interfaces, connectors, switches and limit sensors. In most cases these can be mitigated or designed out of the new instrument. Other reliability enhancements should include a limitation, so far as possible, on the size of the wiring loom and the number of interconnections, and the inclusion of passive protections against water ingress.

The key to manufacturability and maintainability is simplified assembly. The new instrument should have modular "plug-and-play" subsystems to aid assembly and replacement. These subsystems should have self-aligning mechanical interfaces or a designed-in process for alignment where possible. Subsystems which impact the instrument calibration should have unique identifiers and, where appropriate, should hold this information electronically, including calibration coefficients and a calibration history. Subsystems such as the blackbodies and mechanisms should, if possible, have self-contained control and read-out electronics and a standard power and serial bus interface.

In its broadest sense, the user interface covers any user interaction with the instrument, including maintenance activities, deployments, software, and data management. It is essential that a full suite of hardware and software tools are available; that instrument activities, tools and processes are thoroughly documented; that training, and support is provided and that standards are followed where applicable. The ISAR project has pioneered many of these aspects and this experience should be extended for the new instrument.

A next generation SST instrument, with its high-quality radiometry, extended capabilities and improved operability, could open up *in situ* radiometry to a larger range of marine scientists and other operators and significantly extend the validation SST record.

The case study for a next generation radiometer[5] can be found on the ships4sst website.

[5] *Case Study report for Next Generation Radiometer, Nightingale, T., Lee, A., Wimmer, W. FRM4SST report: FRM4SST-SR-RAL-001*

# 10. THE INTERNATIONAL NETWORK

The ISFRN aims to develop and promote an international network of ocean and remote sensing scientists who share an interest in using shipborne infrared radiometers to measure skin SST at the surface of the ocean, to be used to validate measurements made by satellite infrared radiometers. This includes operators, designers and builders of such instruments as well as users of the data.

The scope of the ISFRN activity covers all aspects of the science and technology of shipborne radiometers used to measure SST. This includes

- exchange of operating advice and information that promote best practice for radiometer deployments,
- establishing protocols for shipborne radiometry including the validation of observations traceable to NMI reference standards,
- agreeing formats for skin SST data retrieved from ship radiometers,
- setting procedures for quality control in order to meet agreed standards of accuracy,
- supporting satellite radiometer operators in the long-term validation of satellite products,
- informing the wider community about the network's activities, and
- providing a single access point of the data collected around the world.

The ISFRN aims to provide a single point of access for *in situ* SST data, documentation and information about the validation activities of the ISFRN members.

Over the last few years, the ships4sst website has been updated and expanded to include more information that is relevant and useful to the radiometer network. The network has been promoted at meetings and events, including the project's own annual ISFRN Workshop. Data have been regularly added to the archive since the beginning of the project and at the time of writing, ISAR data from three countries (the UK, Denmark and Australia), SISTeR data from the UK and M-AERI data from America are all online and accessible via the project website.

Figure 10-1 shows the collective SST L2R files by data provider plotted on the world map where pink is CSIRO, light red is DMI, green is RAL, blue is RSMAS and deep red is UoS.

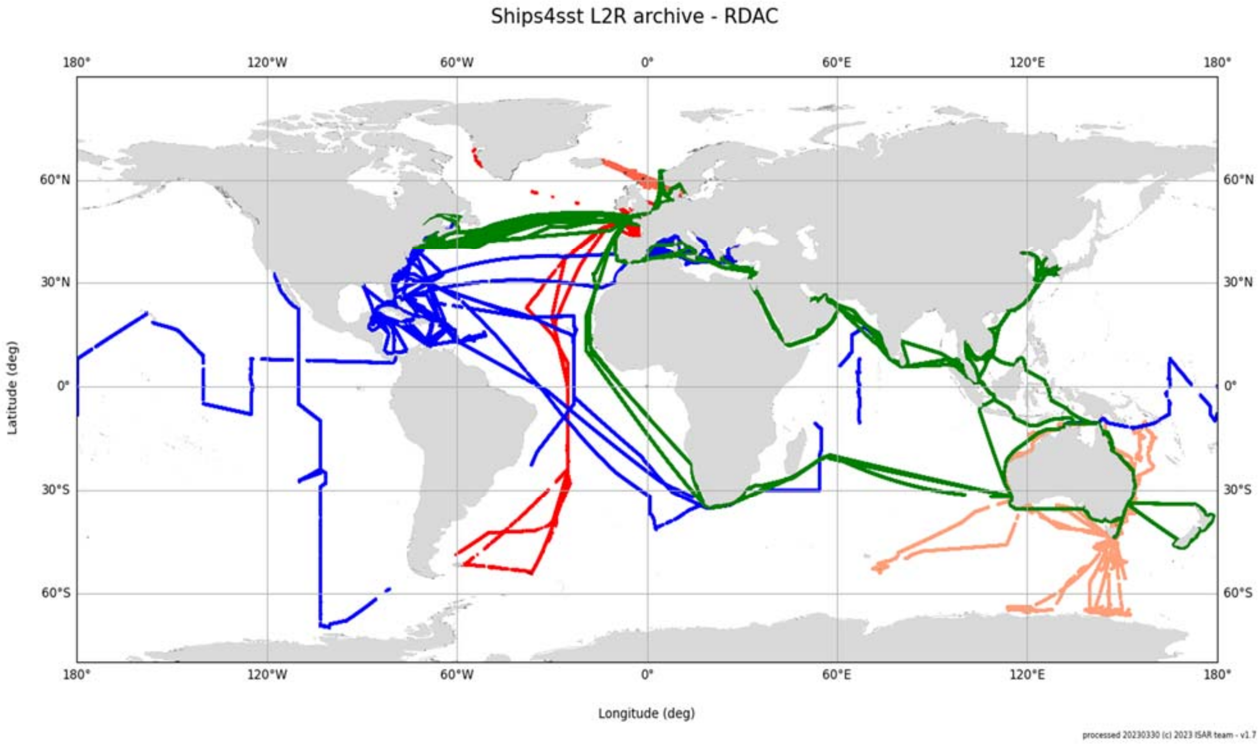



Figure 10-1: The ships4sst data archive L2R files plotted as by data provider, March 2023

## 10.1 Radiometer Standards and Protocols

Standards and protocols help us to ensure the accessibility and reliability of SST reference measurements for validation. Standards systemise and document the organisation of the measurement data, while protocols systemise and document good practice for data collection. As the collection of *in situ* radiometric SST measurements is a relatively recent activity in scientific terms (about thirty years of measurements to date), data collectors are often still working with *ad hoc* data formats and procedures evolved from their early experiences.

With the support of the international *in situ* radiometry community, we developed a "universal" data format for *in situ* SST data, called L2R. Now, anyone who wants to use the *in situ* data knows that all of the information they need will be included in the product, and that they only need to develop a single reading tool for *in situ* SST measurements, regardless of the data provider. The SISTeR and ISAR instrument teams have adopted the L2R format for their measurements and it is now being taken up more widely by other radiometer groups.

This format extends the principle of unified access to *in situ* data in the form of a specification for an *in situ* level 2 radiometric SST data format (L2R) optimised for data collection at a single geographic point or along a trajectory. Although it has been designed with radiometric data in mind, it can also be used for other single-source *in situ* SST measurements, including those from buoys and profilers. The L2R specification adopts the standard GHRSST Data Specification header and contains descriptions of mandatory, optional and user-defined data fields applicable to *in situ* measurements. In particular, the product contains estimates of SST measurement uncertainties.

In support of good practice, we have documented and updated a number of protocols for the deployment and operation of *in situ* radiometers over the years. This document is distributed via the ships4sst website.

## 10.2 Third ISFRN Workshop

On the 8 – 9 September 2023 the project hosted the third international ISFRN workshop, with scientific and operational users and producers of *in situ* radiometer SST data from 13 different countries attending. The aim of the workshop was to share the findings of the partners in the ISFRN service and to understand the network's progress against its objectives as listed in section 10.

The ESA-sponsored workshop was hosted online by Space Connexions Limited and in person at NOCS, UK, and 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

The ISFRN Workshop brought experts in the radiometry field together 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 is being used to research ocean dynamics. It is clear from the presentations and discussions, 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 such as SLSTR, and helping scientists understand ocean dynamics and the impacts of climate change. It is encouraging to see the developments within and outside the ISFRN and the international collaborations that have developed over the years.

A detailed workshop report[6] and the presentations from the workshop are available for download at https://ships4sst.org/documents/frm4sst-phase-2-2021-2023 .

[6] *ISFRN Workshop Report, Wilson, R. FRM4SST report: FRM4SST-WR-SCL-002*

# 11. SERVICE ROADMAP

The ISFRN workshop has proved to be a very useful forum to enable broad international discussions about the status and influence of the service, radiometer instruments, data uses and validation activities. A service roadmap[7] was developed for the FRM4SST project based on these discussions and within this section, the results of the roadmap that was developed at the start of the current phase are analysed within Table 1.

Notably, a number of the high impact-rated suggestions / requirements have been addressed within this service. These are:

- *the request for a next-generation radiometer*. Thanks largely to the case study for a next generation radiometer that was written during this project, the funding that is required to build a next generation radiometer has been provided by the UK Government. The aim is for 3 next generation IR radiometers to be built by 2025, to be used for both SST and land surface temperature (LST).
- *to perform another CEOS Radiometer Inter-comparison* exercise and to *re-visit measurements made in extreme weather (or sub-zero) environments*. The NPL-led CEOS Intercomparison in June 2022 had a laboratory temperature range of -30°C to 30°C. See section 7 for more details.
- to *include Microwave (MW) data with infrared (IR)*. DMI have performed several MW and TIR side-by-side comparisons and are reporting their results in a journal paper. See section 8 for more details.
- *Improve the radiometer uncertainly model*. The uncertainty model used for the ISAR instrument has been updated twice to version 3 during the service. An out-at-field and a laboratory comparison have also taken place in which it was suggested that the uncertainties increase at zero and sub-zero temperatures (see WP40 results on ships4sst website for more detail).
- *Push for more radiometers on ships of opportunity* and *add more data and metadata to the ships4sst database*. A further 4 ISARs were manufactured during the contract period and are now used by the respective teams, in turn adding more data to the ships4sst database. For example, DMI use their additional radiometers on their existing deployment, which enables continuous deployment of an ISAR on the *MS Norröna*.

Table 1 shows an analysis of all the suggested areas for improvement that were made at the start of the service, and information on how some areas can continue to be addressed or improved upon in the next phase of the service.

[7] *Service Roadmap, Wilson, R. FRM4SST report: FRM4SST-SR-SCL-001*

**Table 1: FRM4SST Service Roadmap for current and next phase**

| Area | Requirement / suggestion | Strategies for implementation / Comments | Impact (5 high, 1 low) | Difficulty (5 high, 1 low) | Target Date | 2023 Analysis |
|---|---|---|---|---|---|---|
| **Data and data archive** | Add more data and metadata to the ships4sst database | Encourage more radiometer operators to join the network e.g. saildrone data. | 5 | being done routinely | ongoing | See ISFRN Workshop Report for development of saildrone data. More ISAR deployments have been made in the last 2 years and some new routes and reprocessing of existing data to L2R. |
| | Simplify the ships4sst archive | Consolidation of instrument processor data version numbers. This is difficult to do as each operator has their own processor version history. | 3 | 4 | 2021 | Discussions are ongoing between ISFRN members. |
| **Adequacy and continuity of the observing system** | Perform another CEOS Radiometer Inter-comparison exercise | Performing more inter-comparison exercises will help confirm the validity, equivalence and traceability of the measurements. | 5 | 3 | spring 2022 | The CEOS intercomparison took place in June 2022, led by NPL. See section 7 for further information. |
| | Improve the radiometer uncertainly model | Verification of uncertainty model (out at field).<br>Performing more bi-lateral exercises between radiometers out on voyages will help confirm and improve the validity of uncertainty budgets and enable a re-visit into the effect of surface emissivity on $SST_{skin}$ measurements. | 5 | 4 (requires funding and time) | 2022 | Uncertainty Model Versions 2 and 3 have been released between 2020 and 2023, and the following intercomparisons took place between 2020 and 2023:<br>• ISAR 03 – KIT, M/V Friedrichshafen, 01.09 – 23.09.2020<br>• CEOS Intercomparison led by NPL (June 2022) |

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|---|---|---|---|---|---|---|
| | | | | | | The uncertainty model continues to be improved upon using results from these exercises. |
| | Quantified fully broken down uncertainties and sources of error in respect to SI | The quantification of uncertainness relies on component manufacturer documentation and laboratory experiments (e.g. component testing, emissivity experiments). Depending on required detail this can be very time consuming and expensive. | 4 | 5 | ongoing | This is always ongoing.<br>A breakdown of the uncertainties of the next generation radiometer will be made during its build (the manufacture of the radiometer is not in this contract) which could help increase the level of detail of the uncertainties of the current radiometers too. |
| **Instrumentation** | Push for more radiometers on ships of opportunities. | Radiometers can be more readily made traceable to SI than buoys and an increase in numbers means better stats. | 5 | 2 | ongoing | 4 ISARs were delivered between 2020 and 2022 to Australia, Norway and Denmark. More are planned during the next 3 years.<br>Three 'next generation radiometers' based on the case study written in this project will also be manufactured by 2025 (not in this project). |
| | A next generation radiometer | A next generation radiometer that could go on fixed platforms as well as ships. | 5 | 4 | 2022 | Thanks to the case study report, a next generation radiometer is now being funded by the UK and designed and built by RAL and UoS. |

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|---|---|---|---|---|---|---|
| **Outreach and documentation** | A database of information, including QA, on all radiometers to support validation | Documentation of processing versions, instrument maintenance etc. is online and just needs to be revisited to check for latest updates. | 4-5 | 2-3 | ongoing | A link from the ships4sst to QA4EO information has been put online.<br>The ships4sst website will be updated in the next phase (2023 – 2026) to improve upon the information users receive from the project. |
| | Improve information on observational methods | Write and publish more papers and reports. | 5 | 3 | ongoing | Several papers will be published in 2023.<br>The ships4sst website will be updated in the next phase to improve upon the information users receive from the project. |
| | Promotion of community protocols and best practises | Data submitted to the L2R archive must follow the ships4sst protocols and documentation is provided to help the data providers. | 4 | 2-4 | ongoing | This is a continuous activity which has been followed through the length of the project.<br>The ships4sst website will be updated in the next phase (2023 – 2026) to improve upon the information users receive from the project. |
| | Improve information for radiometer instrument handlers | A specification of what is expected if a radiometer is taken into different environments, particularly in sub-zero climates, was requested at the 2019 workshop. This could come in the form of a one page document with some requirements for a future generation radiometer based on | 4 | 2 | 2022 | Not yet addressed. However, at the CEOS intercomparison exercise in June 2022, the temperature range was increased to the between -30°C to 30°C. Analysis of results is ongoing. |

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| | | the expected issues of instruments in different climates.<br>A suggestion was made to revisit instrument user manuals; there were a few noted occasions where an instrument was not able to work during part or all of a voyage. | | | | |
| **Measurements** | Measurements at a range of sea depths | The impact on science is large. Several months' worth of data of diurnal variability on various platforms would be useful, e.g. there is a platform being used for scientific experiments in the Mediterranean Sea. | 3 | 5 | 2022 | Not yet addressed as this is difficult to do with ship operators. |
| | Include Microwave (MW) data with infrared (IR) | A FRM TIR/MW inter-comparison is planned for 2021. It requires refurbishment of a pre-existing MW radiometer. | 4 | 3 | 2021 | DMI have performed this comparison and are finalising a paper on it. See section 8 for more details. |
| | Re-visiting measurements made in extreme weather (or sub-zero) environments. | The last FRM TIR/MW field campaign for IST experiments was done in 2017. Community members feel that another campaign within the next few years would be useful. | 4 | 5 (requires funding) | 2023 | The recent NPL-led inter-comparison performed measurements at extreme temperatures (down to -30ºC). |

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|---|---|---|---|---|---|---|
| | Develop new routes | The most important areas for new routes would be:<br>1. Reference ship tracks in cloud free regions; this could be on a ship or fixed platform. This would fulfil the need for long-term consistency.<br>2. More radiometers going out into problem areas (Arctic and islands) and the whole of the southern area.<br>3. Aerosol regions, e.g. (P&E) 24° west. Aerosols vary a lot so it is good to go to these regions a few times. | 4-5 | 3 (could use existing infra-structure) | 2021 | This is ongoing and requires agreement with ship operators.<br>Existing infrastructure could be used; for example, a presentation made during the ISFRN workshop spoke of a platform in the Mediterranean Sea that could be effective, easy and cheap to install and use scientific equipment on.<br>This is also something to keep in mind when the decision for where to deploy any new radiometers manufactured over the next few years, including the next generation radiometers (circa 2025). |

## 11.1 Achievements of Service

In addition to the activities highlighted within the service roadmap, the *in situ* radiometers have had great success in achieving accurate measurements and the processing of the data from the three instruments has produced an accurate match-up database of SST data needed for validation of the SLSTR instrument. Specific achievements of this contract include:

- The promotion and expansion of the ISFRN, thereby maintaining and increasing international partnerships, including the UK, Denmark, USA, Australia, China and France.
- Increased web presence with the ships4sst webpage and Twitter site.
- The continuation of data from several countries being uploaded to the ships4sst project website – this is a growing database with increasing number of match-ups and wide geographical coverage of *in situ* SST data.
- Promotion of standards and protocols and a common data format used by all radiometer operators within the ISFRN.
- A large number of data match-ups that are used in the validation of SLSTR SST data.
- Validation analyses of SLSTR A and B against the ISARs and SISTeR shows that overall, SLSTR showed excellent performance over the analysed three years, exceeding its design specification of an accuracy of 0.3 K in the region of the English Channel and the Bay of Biscay and for night time match-ups. There still seems to be some room for improvement in high latitude matches and day time global matches.
- A case study for a next generation radiometer has led to the manufacture of the instrument, with an expected completion date in quarter 1, 2025. See section 9 for more information.
- A static and at-sea inter-comparison of a MW and TIR radiometer has been achieved, the results summarised in Section 8.
- The 2022 International TIR inter-comparison took place in June 2022 and the results have been written up in reports and papers. See Section 0 for more information.

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

In summary, the FRM4SST service has been a major driver of shipborne radiometry and *in situ* SST measurement that are consistent, stable, SI-traceable and essential for validating satellite data from instruments such as SLSTR. This is helping scientists understand ocean dynamics and the impacts of climate change, and supports the production and maintenance of a Fundamental Climate Data Record (FCDR) for SST.

# 12. THE FUTURE

The next phase of the FRM4SST ESA-contract is currently under discussion with ESA. It will continue along the same lines as the current service to ensure that the SST FRM data collections are sustained. Continuous deployment of the ISARs at UoS and DMI, and SISTeR at RAL, will continue, along with the data processing, archiving and validation work. So far, validation of SLSTR (S3A and S3B) with shipborne FRM data show very good results for SLSTR; this validation work will continue as more recent data becomes available from Eumetsat. The network will continue to be promoted with the continuation of deployments, the promotion of the ships4sst website and social media account, at meetings and events including an annual 2-day online ISFRN meeting, and via the production of science reports and peer-reviewed journal articles. We continue to see an increased awareness of the ISFRN as well as appreciation for the usefulness of the quality and FRM-standard of shipborne radiometer data.

There will be a strong focus on the outreach and publication of project results during the next phase of the contract. The ships4sst website will be updated with a user-orientated focus and the latest data will be added monthly to the website under a new “Results” page.

The suggestions made in the project service roadmap that are ongoing will also continue to be addressed.

# 13. ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AATSR | Advanced Along-Track Scanning Radiometer |
| ATSR | Along-Track Scanning Radiometer |
| AVHRR | Advanced Very High Resolution Radiometer |
| BB | Blackbody |
| CDR | Climate Data Record |
| CCI | Climate Change Initiative |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DMI | Danish Meteorological Institute |
| DTU | Danish Technical University |
| ECV | Essential Climate Variable |
| EDS | Engineering Data System |
| EGSE | Electrical Ground Support Equipment |
| EO | Earth Observation |
| ESA | European Space Agency |
| ESL | Expert Support Laboratory |
| ESOC | European Space Operations Centre |
| EU | European Union |
| FPA | Focal Plane Assembly |
| FRM | Fiducial Reference Measurements |
| FRM4STS | Fiducial Reference Measurements for validation of Surface Temperature from Satellites |
| FTP | File Transfer Protocol |
| GHRSST | Group for High Resolution SST |
| GTMBA | Global Tropical Moored Buoy Array |
| HTTP | HyperText Transfer Protocol |
| IPCC | Intergovernmental Panel on Climate Change |
| IR | Infra-Red |
| ISAR | Infrared SST Autonomous Radiometer |
| ISFRN | International SST FRM Radiometer Network |

| | |
|---|---|
| ISSI | International Space Science Institute |
| KIT | Karlsruhe Institute of Technology |
| L0 | Level 0 |
| L1 | Level 1 |
| L2 | Level 2 |
| LST | Land Surface Temperature |
| M-AERI | Marine-Atmospheric Emitted Radiance Interferometer |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NOCS | National Oceanography Centre, Southampton |
| OP | Operational Processor |
| RAL | Rutherford Appleton Laboratory |
| RP | Reference Processor |
| RSD | Robust Standard Deviation |
| SCL | Space ConneXions Limited |
| SISTeR | Scanning Infrared Sea surface Temperature Radiometer |
| SLSTR | Sea and Land Surface Temperature Radiometer |
| SST | Sea Surface Temperature |
| ST | Surface Temperature |
| STFC | Science and Technology Facilities Council |
| TIR | Thermal Infra-Red |
| UoV | University of Valencia |