ships4sst
shipborne radiometers for sea surface temperature

FRM4SST Project

Final Report: December 2020

RAL Space

University of Southampton

DMI
Vejr, klima og hav

Space ConneXions

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1. EXECUTIVE SUMMARY

This report presents the activities of the FRM4SST (ships4sst) contract. The main aim of the service is to validate satellite SST such as the Sentinel-3A and Sentinel-3B SLSTR SST data products using Fiducial Reference Measurements (FRM) from *in situ* Thermal Infrared (TIR) radiometers and to promote and evolve the International SST FRM Radiometer Network (ISFRN).

In order to achieve this aim, the European Space Agency (ESA) has funded the continuation, and expansion, of radiometer deployments firstly within the ships4sst contract, and then FRM4SST. These deployments 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 aim is 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.

In order to ensure that the SLSTR geophysical data products are reliable, they must be validated by comparing them with *in situ* measurements. Measurements from the long-term *in situ* deployment of the ISARs, and also from the SISTeR instrument, have confirmed the consistency of the SST data products (see Section 6).

The ISFRN has developed and promoted 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 skin SST at the surface of the ocean, comparable to measurements made by satellite infrared radiometers, since its set up in 2019. This includes operators, designers and builders of such instruments as well as the users of the data. The ISFRN is also regularly promoted at meetings and conferences. 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) (see section 2.2).

2. A BRIEF HISTORY OF THE PROJECT

The current project continues the time series of ISAR measurements in the Bay of Biscay that were started in 2004 with UK government funding and that were used to validate AATSR and other TIR satellite SST measurements. The project also continues SISTeR measurements over a similar period that were funded by both the UK and ESA, and starts a time series of ISAR measurements on a more global scale. These measurements helped to bridge the gap between AATSR and SLSTR, tying them both to a common internationally recognised reference standard. Since 2019, the Danish Meterological Institute (DMI) has joined the consortium and deployed another ISAR instrument regularly in the northern latitude.

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 Climate Data Records from satellite SST measurements (Figure 2-1).

To achieve robust traceability to the Système Internationale (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 planned for 2022.

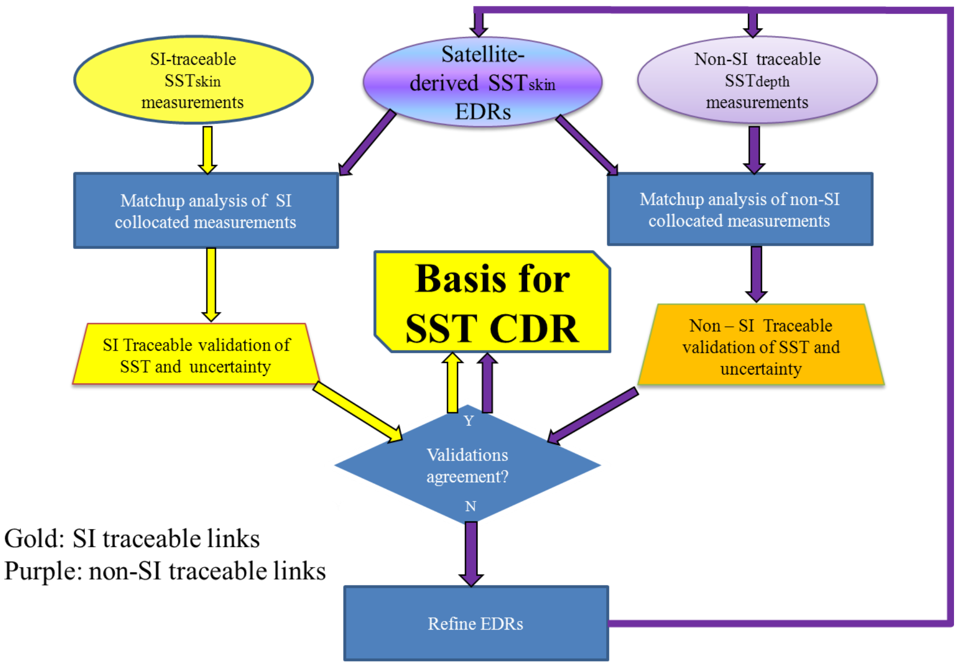

Figure 2-1 This flow diagram shows the traceability route for a SST Climate Data Record (from ISSI[1] *in situ* validation workshop). Shipborne radiometers cover the gold parts of the diagram.

Fiducial Reference Measurements are the suite of independent ground measurements that provide the maximum Scientific Utility and Return On Investment for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the 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 campaign).
- Are independent from the satellite SST retrieval process.
- Include an uncertainty budget for all FRM instruments and 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.

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[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)*

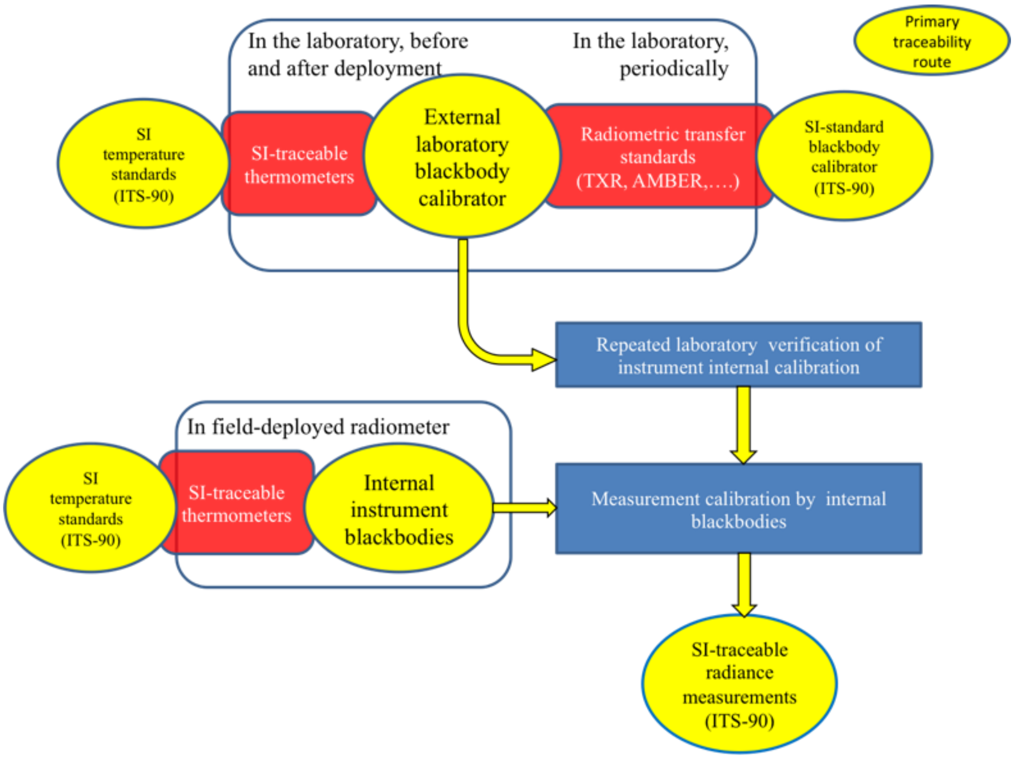

Figure 2-2 Traceability route for a shipborne radiometer (from ISSI *in situ* validation workshop).

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.

Shipborne radiometers (ISAR, SISTeR, and the US Marine-Atmospheric Emitted Radiance Interferometer, M-AERI) provide an important SI-traceable link between AATSR and SLSTR, facilitating the evaluation of any offsets or trends between the two instruments. This would normally be achieved by an overlap period of six months or more of the two satellite instruments. However, with the sudden end of Envisat, and delays in the launch of Sentinel-3, no overlap period was possible. 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 and this ensures 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 for data archives such as Coriolis (http://www.coriolis.eu.org/Data-Products/Data-Delivery) and the closeness to the Felyx instance which is used to provide the satellite match-ups. 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 are also stored at the data archive, as well as the ships4sst web portal.

The data archive is accessible through the ships4sst web portal and provides data to users on request through the web portal. 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 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.

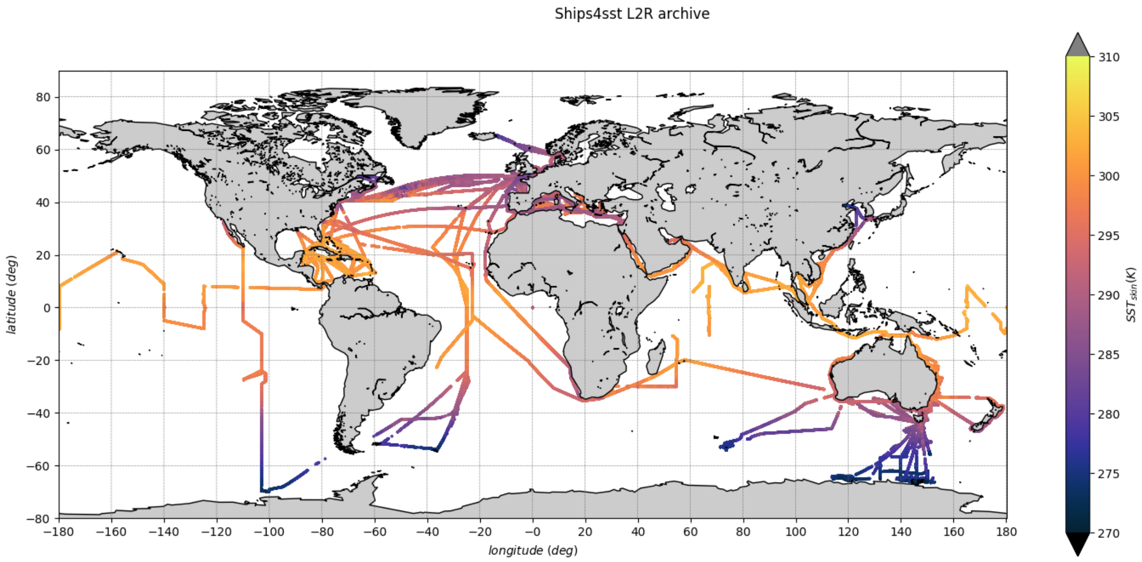

Figure 2-3 The ships4sst data archive L2R files plotted as SST on a world map, October 2020

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 ~16 year period, two instruments, ISAR 002 and ISAR 003, have provided over 960,000 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).

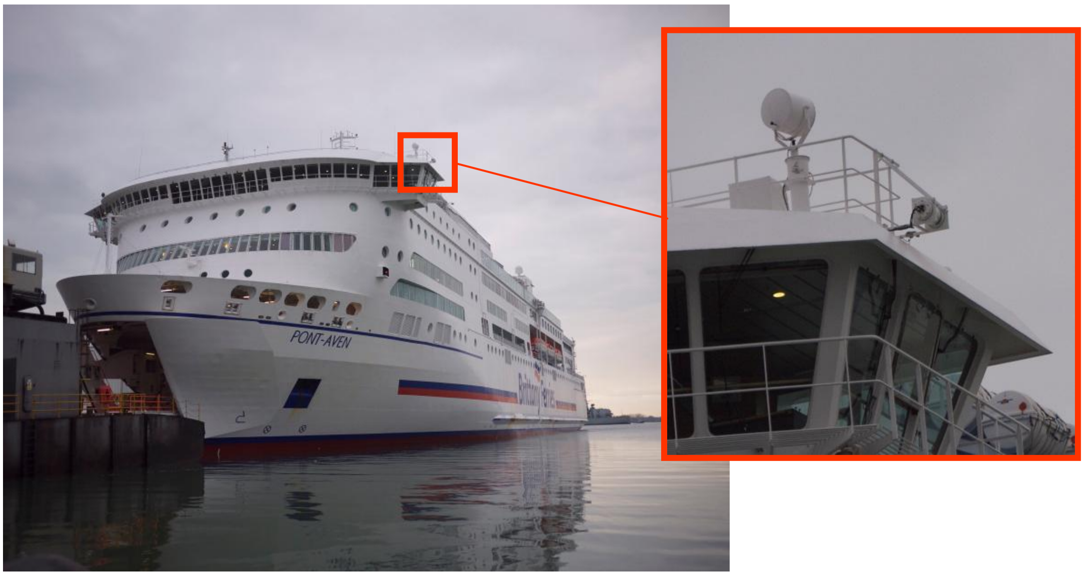

Figure 3-1 ISAR installation on the Pont Aven in October 2012. This deployment is ongoing

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 16 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, 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.

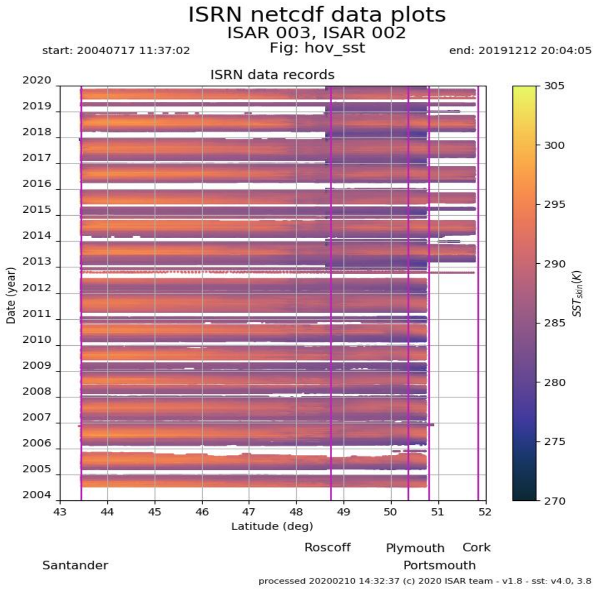

Figure 3-2 ISAR SST data from 2004 to 2020

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.

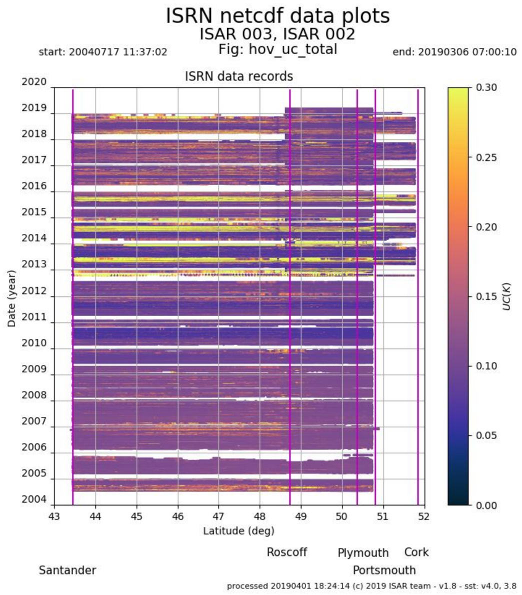

Figure 3-3 ISAR total uncertainty for all data from 2004 to 2019

[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.

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 bases 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 black bodies, Sig_{Sea}, Sig_{Sky}, $Sig_{BB1,2}$ are the signal from the detector when viewing the sea, sky of the two black bodies. 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.

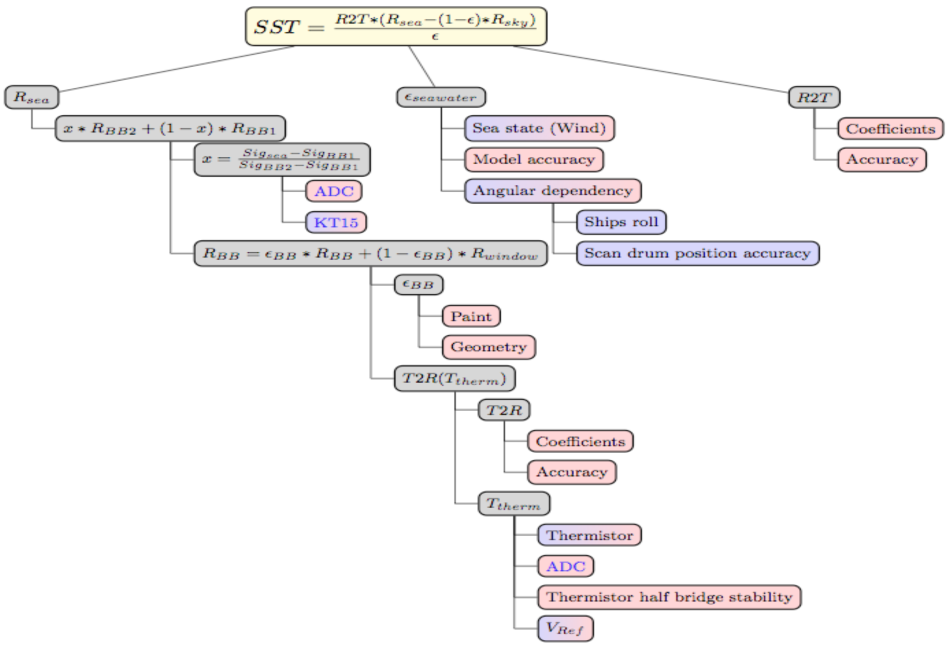

Figure 3-4: Schematic to illustrate the breakdown of the main elements of the ISAR SST processor to reveal the factors that introduce uncertainty. For clarity the R_{sky} branch has not been expanded but is essentially the same as for R_{sea} . Boxes coloured in blue represent type A uncertainties, boxes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

The ISAR has been at DMI since 2012, where it previously has been used for ship of opportunity deployment on a best effort basis. These deployments include: 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 are due to join the fleet which will result in more data 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). The track of the ship is shown in figure 4-1 below:

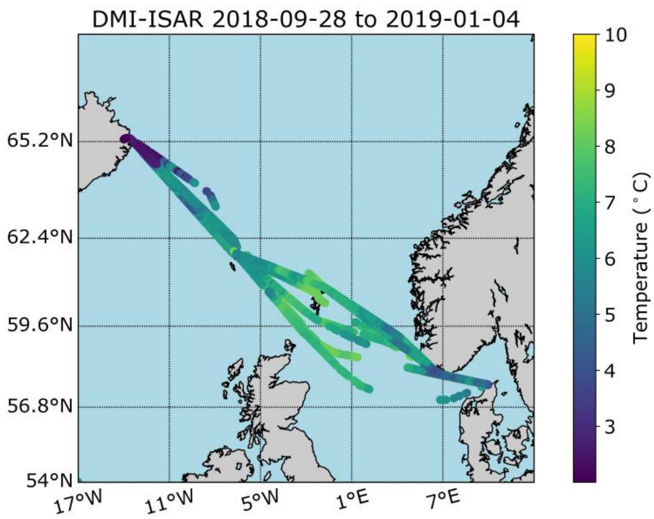

Figure 4-1**:** Track of the Norrøna Ferry line from Hirtshals to Faroe Islands and Iceland.

The instrument is deployed on the port side of the ship above the bridge in the front of the ship and measures the temperature of the undisturbed waters at a height of about 20 meters above sea level.

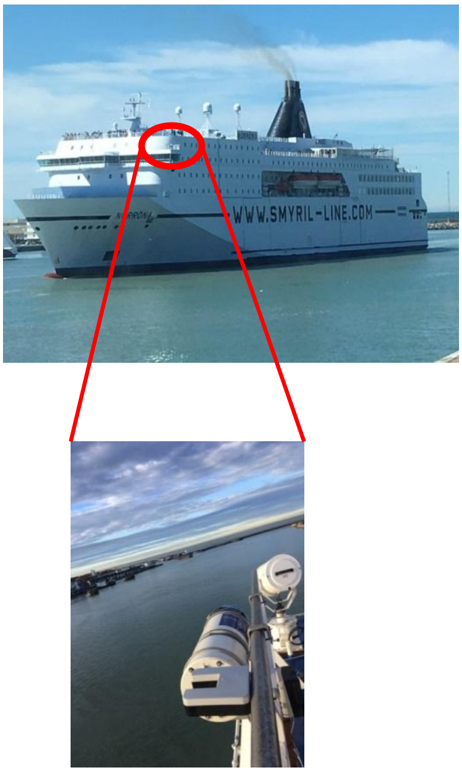

Figure 4-2: DMI-ISAR installation on board Norrøna. The first deployment was made in December 2017.

Along with the ISAR, Norrøna 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 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* was for this particular experiment 0.01K (ISAR-*in situ*) with a standard deviation of the differences of 0.03K.

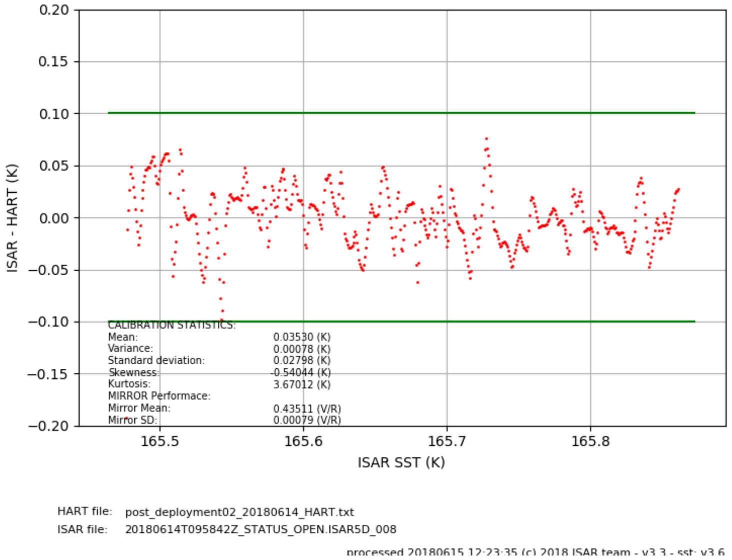

Figure 4-3**:** Calibration results from the deployment 4, pre-deployment calibration.

4.3 An important transect to monitor

The observed track between Denmark and Iceland is not only a valid region for the use 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 deployment 4.

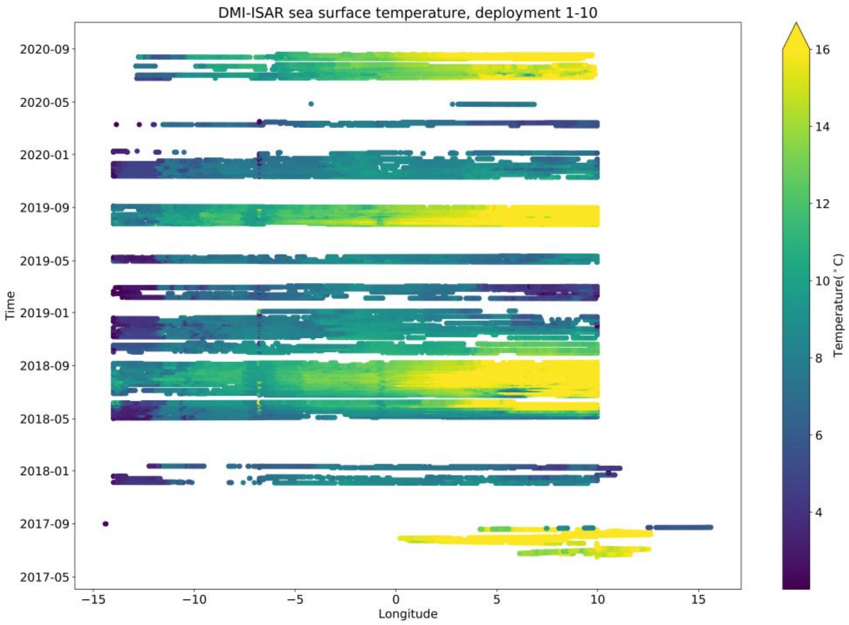

Figure 4-4**:** A longitude versus time plot of the ISAR observed SSTs during 2017 - 2020.

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.

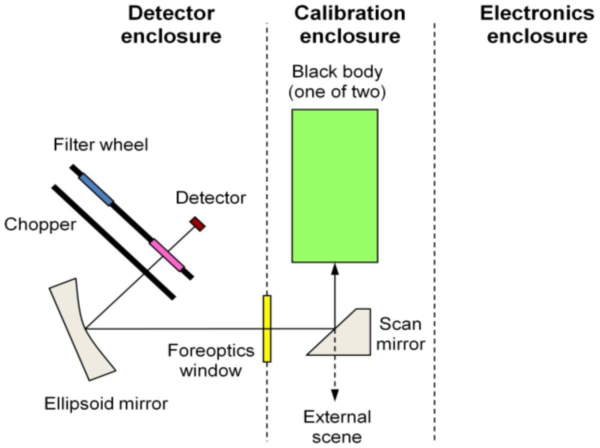

Figure 5-1: The internal configuration of the SISTeR radiometer

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.

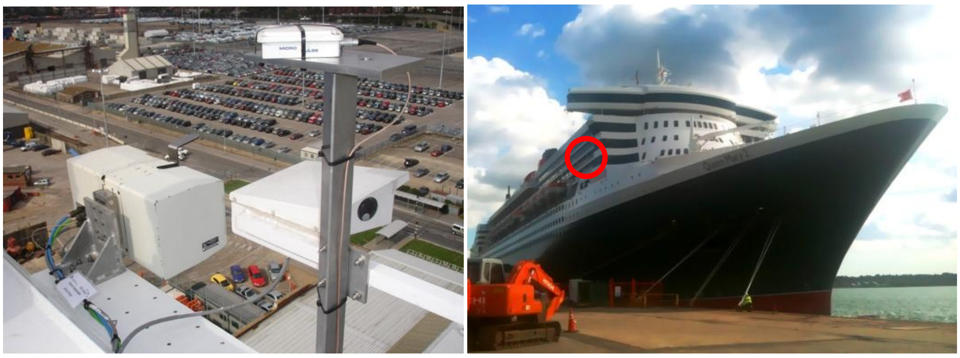

Figure 5-2: The SISTeR Instrument mounted on the *Queen Mary 2*

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.

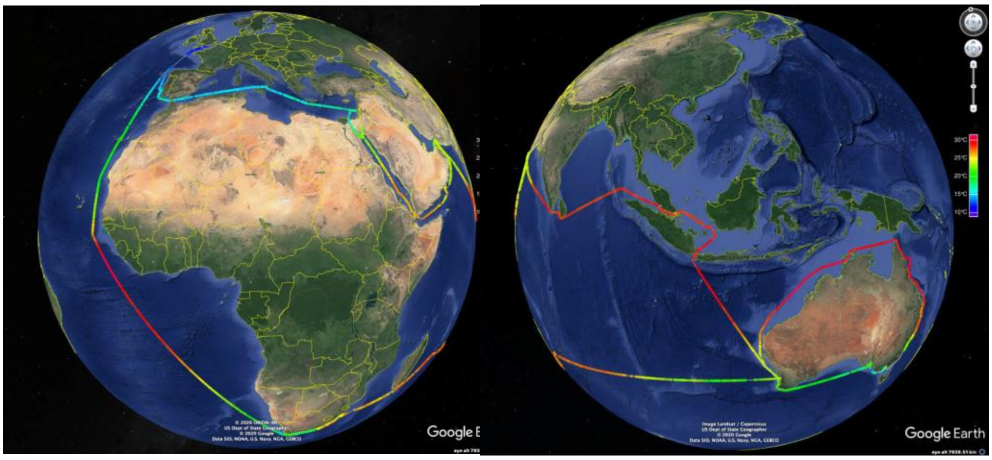

Figure 5-3 SSTs from a SISTeR “round-the-world” cruise on the *QM2*, 10/01/2020 to 18/04/2020.

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.

With the progression of COVID-19 world-wide during 2020, RAL Space has been 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 than in previous years.

6. SLSTR DATA STABILITY

6.1 Comparing SLSTR against ISAR and SISTeR data

SLSTR data was validated with ISAR and SISTeR data from April 2018 until December 2018. The validation of the SLSTR dataset shows good consistency over the period. A total of 9294 match-up pairs were evaluated for a match-up window of +/- 2h and within 1 km off the overpass of SLSTR. The mean estimated difference compared to ships4sst is 0.12 K for 3965 daytime match-ups from 187 different overpasses, and 0.02 K for 5329 nighttime match-ups from 229 overpasses. The Robust Standard Deviation (RSD) of the measurements is 0.37 K for day and 0.26 K for night data. 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 0.12 K for 977 day time match-ups and a mean difference of 0.02 K for 1225 night time match-ups. The RSD for those match-up pairs are 0.30 K for the day time and 0.24 K for the night time. The results for the DMI operated ISAR on the *Norrona* are a mean difference of 0.22 K for 588 day time matches and 0.24K for 592 night time matches. The RSD for those matches are 0.18 K for the day time and 0.22 K for the night time. Finally the results for the RAL SISTeR on the *Queen Mary 2* are a mean difference of 0.01 K for 323 day time match-ups and a mean difference of -0.02 K for 1242 night time match-ups. The RSD for those validation data points is 0.22 K for day time match-ups and 0.21 K for night time match-ups.

The comparison with AATSR data in the Bay of Biscay and English Channel shows the SLSTR performs very similar to AATSR in that area with a higher amount 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 large 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 not only a larger mean difference but also a large RSD. Figure 6-4 shows the location of the 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.

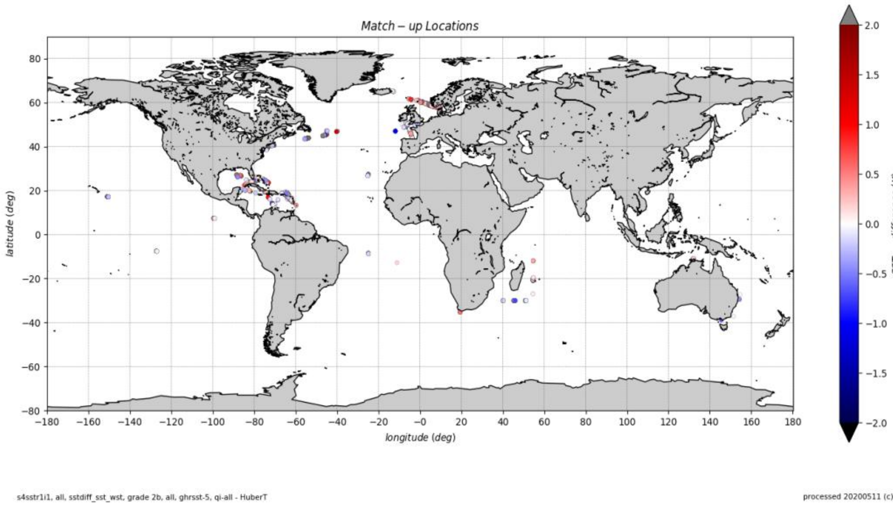

Figure 6-4 ISAR Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against ships4sst observations between April 2018 and December 2018.

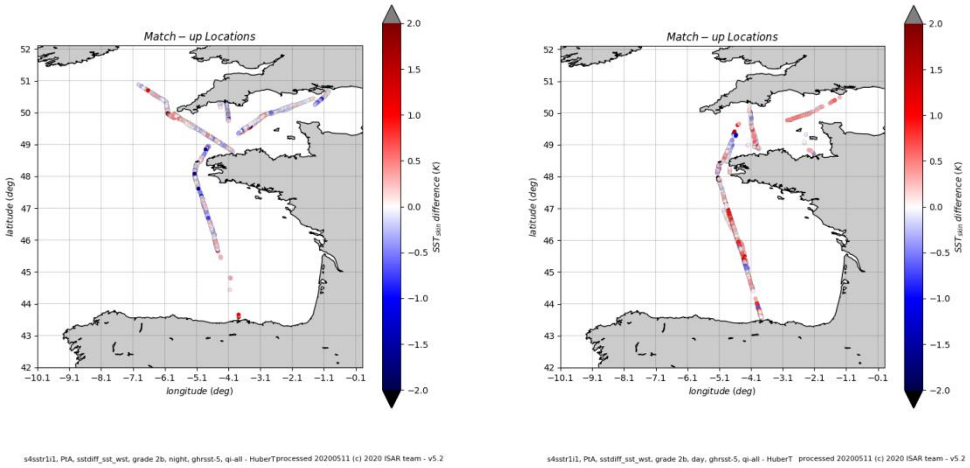

Figure 6-5: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against ISAR on the *Pont Aven* observations between April 2018 and December 2018 for night (left panel) and day (right). The stratification of the data is a side effect of the *Pont Aven's* schedule and not deliberate.

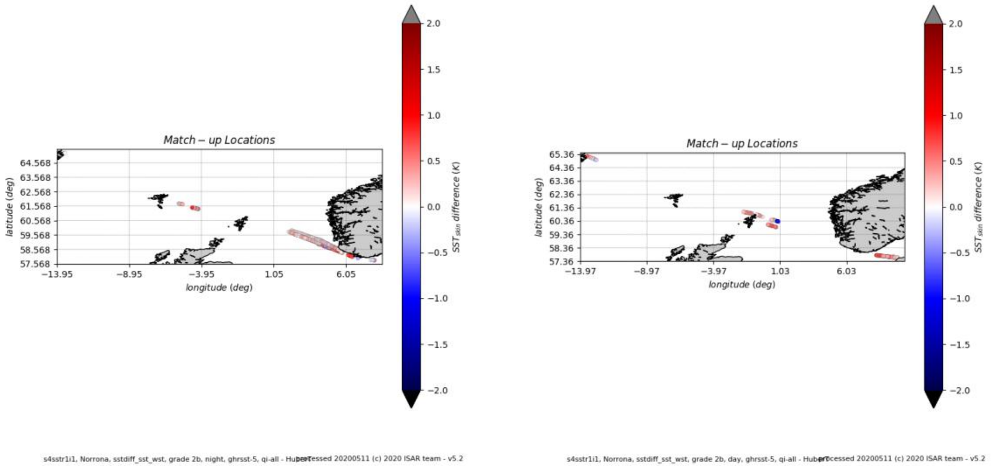

Figure 6-6: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against ISAR on the *Norrana* observations between April 2018 and December 2018 for night (left panel) and day (right). The stratification of the data is a side effect of the *Norrana's* schedule and not deliberate.

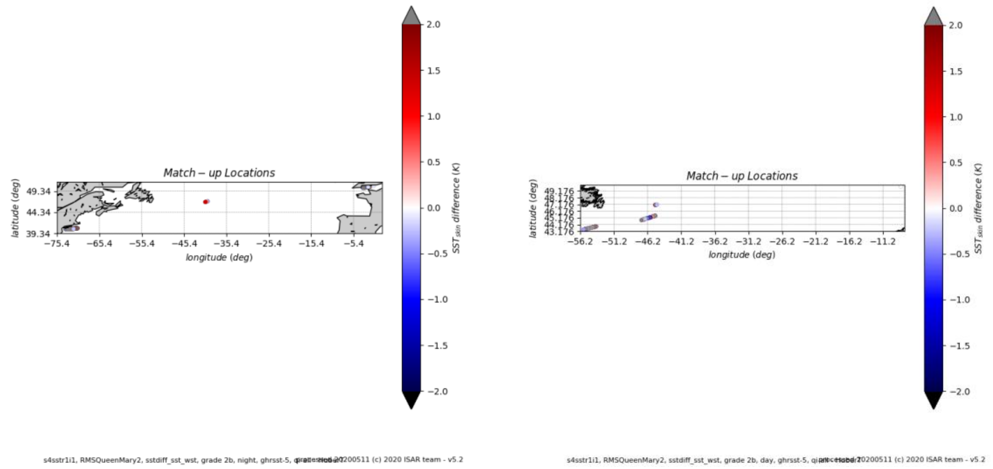

Figure 6-7: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against SISTeR on the *Queen Mary 2* observations between April 2018 and December 2018 for night (left panel) and day (right). The stratification of the data is a side effect of the *Queen Mary 2's* schedule and not deliberate.

Figure 6-8 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.

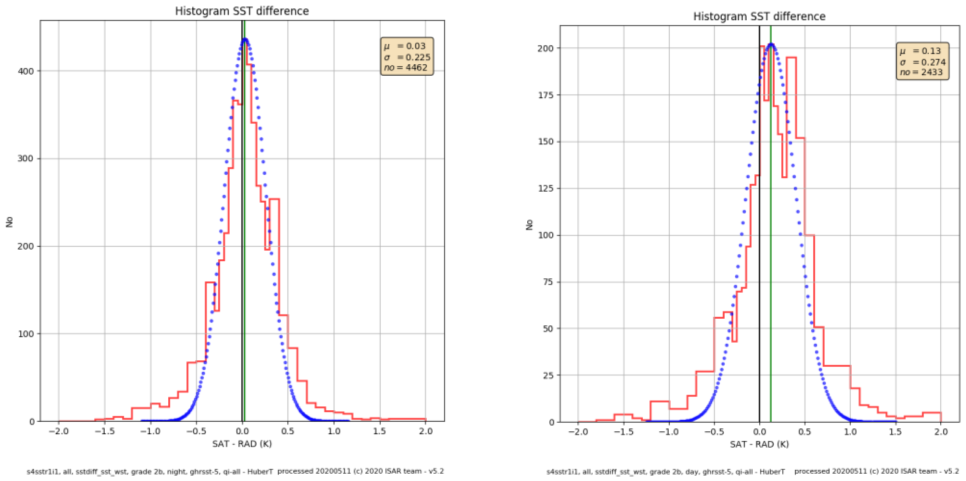

Figure 6-8**:** Histograms of Grade 2b match-up differences between SLSTR and Iships4sst SST records between April 2018 and December 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box in the right hand top corner shows the median (μ), the robust standard deviation (σ) and the number of matches (no) showing the SLSTR match-ups with a difference between SLSTR and ships4sst of 0.03 K for nighttime data and 0.13 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.23 K for the nighttime and 0.27 K for the daytime.

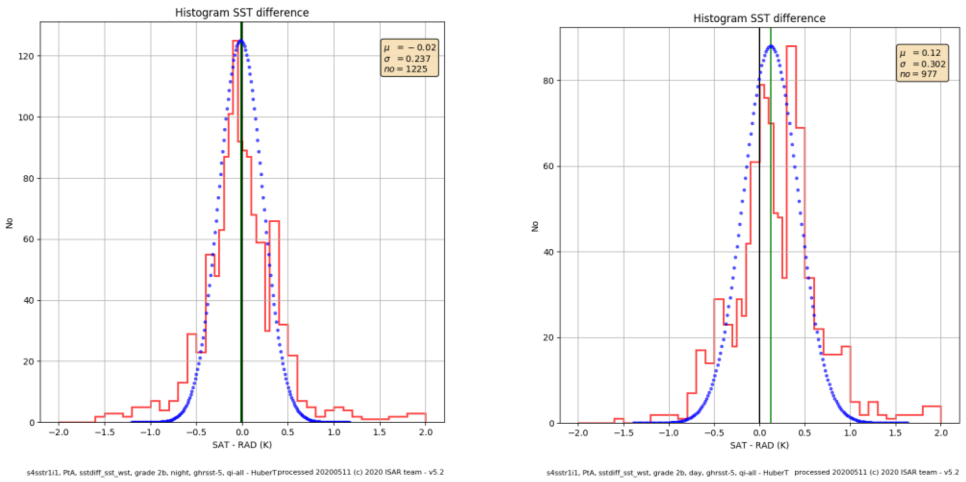

Figure 6-9: Histograms of Grade 2b match-up differences between SLSTR and ISAR SST records on the *Pont Aven* between April 2018 and December 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. The yellow 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 match-ups from the *Pont Aven* with a difference between SLSTR and ISAR of -0.02 K for nighttime data and 0.12 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.24 K for the nighttime and 0.30 K for the daytime.

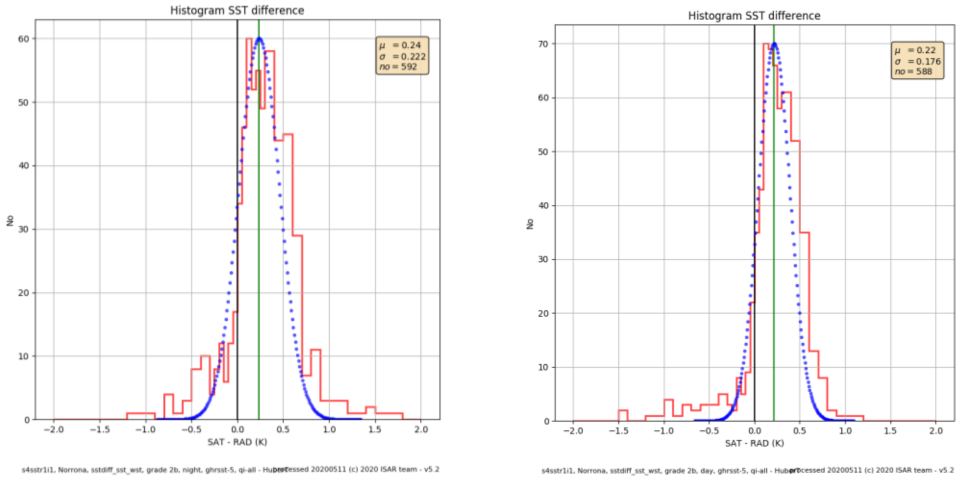

Figure 6-10**:**Histograms of Grade 2b match-up differences between SLSTR and ISAR SST records on the Norrona between April 2018 and December 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. The yellow 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 match-ups from the *Norrona* with a difference between SLSTR and ISAR of 0.24 K for nighttime data and 0.22 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.22 K for the nighttime and 0.18 K for the daytime.

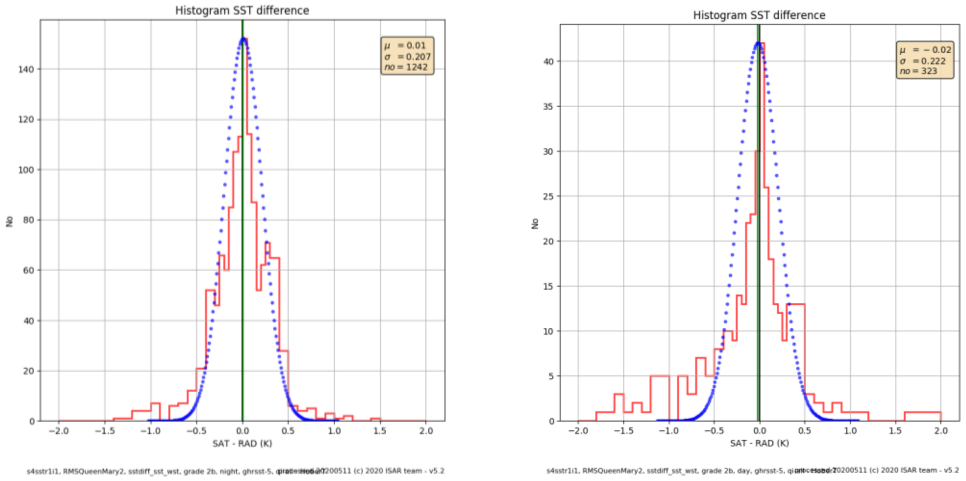

Figure 6-11**:**Histograms of Grade 2b match-up differences between SLSTR and SISTeR SST records on the *Queen Mary 2* between April 2018 and December 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. 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 match-ups on the *Queen Mary 2* with a difference between SLSTR and SISTeR of 0.01 K for nighttime data and -0.029 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.21 K for the nighttime and 0.22 K for the daytime.

Overall SLSTR 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 in the region of the English Channel and the Bay of Biscay and for night time SISTeR matchups. There still seems to be some room for high latitude data and day time global matches.

7. PLAN A CEOS INTERNATIONAL TIR INTER-COMPARISON EXERCISE

In July 2020 the project was tasked with planning a CEOS international TIR inter-comparison exercise. This exercise will build on the 2016 inter-comparisons performed at the National Physical Laboratory (NPL) and at Wraysbury in the UK. The first stage to the planning was to analyse the lessons learnt from the previous inter-comparison and discuss any additional criteria with potential participants. This was done both during the 2020 ISFRN workshop and during a targeted telecon with international partners of the ISFRN. From this, and through reviewing the protocols as described in Theocharous, et al (2017) for the blackbody inter-comparison, Barker-Snook et al (2017a) for the radiometer inter-comparison and Barker-Snook et al (2017b) for the radiometer SST field inter-comparison, an updated version of the protocols will be produced prior to the next inter-comparison.

Discussions have also been underway with NPL, who will be organising, hosting and producing the reports in the form of papers for the laboratory-based radiometer inter-comparison. The field-based SST inter-comparison will be organised by UoS although NPL will be in charge of the experiment to ensure impartiality and consistency as during the 2016 inter-comparison.

The agreed provisional date is Spring 2022, to allow time for participants to sort out travel and funding arrangements. The final date is dependent on when NPL and UoS can arrange the laboratory based and the field activities so that they are held back to back.

The results of this work package can be found in more detail in the Inter-comparison Preparation Report.

8. PREPARATION OF MICROWAVE/THERMAL INFRA-RED EXPERIMENTS

Since July 2020 the Danish Technical University (DTU) has been working on the refurbishment of a passive microwave (PMW) radiometer in preparation for a short land-based demonstration of simultaneous deployment of thermal infrared and microwave radiometers. During this time, the DTU C-band (~6.9 GHz) and X-band (10.59-10.79 GHz) radiometers have been renovated in order to obtain fiducial reference measurements during deployment. The renovated instruments consist of a fully characterized C-band radiometer, measuring in V and H polarization using a multiplexer. Both instruments fully live up to expectations, and they are now considered ready for measurement campaigns. Possibilities for future further development exist, and new components have been chosen, so that they can be used in further upgraded systems, e.g. systems with enhanced bandwidth and upgraded digital subsystems.

During the demonstration, one ISAR was deployed alongside two radiometers for C-band and X-band measurements. The demonstration took place on a small bridge that lies over brackish waters in Copenhagen, Denmark, on 13 January 2021 and initial results show good agreement between the IR and PMW observed SSTs, as seen in Figure 8-12. An increased noise on the C-band MW radiometer was observed, possibly due to external factors like RFI. However, the best agreement is obtained with information from the X-band observations. This was not expected due to the lower sensitivity of the X-band observations for cold waters, compared to the C-band sensitivity. Detailed investigations are ongoing to assess the sources of the observed C-band variability and it is recommended to repeat the static experiment at another site, to rule out possible RFI effects. In addition, a repeated experiment could also increase the temporal sampling of the sky measurements to determine the sky variability over time in C-band and X-band.

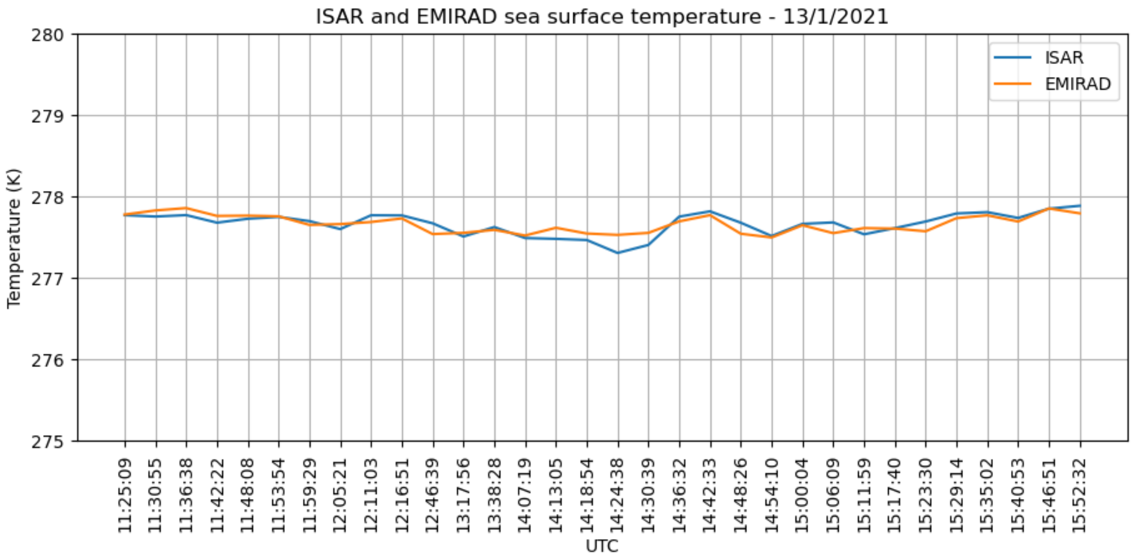

Figure 8-12: Temperature comparison between ISAR and EMIRAD.

This demonstration is a precursor for a later possible shipborne inter-comparison experiment between Denmark and Iceland with simultaneous deployment of thermal Infrared and microwave radiometers, measuring on cold waters. The campaign could focus upon the differences and similarities between SST_{skin} and $SST_{subskin}$ to support the integration of Infrared and microwave satellite observations.

The results of this work package can be found in more detail in the characterisation report for C-band radimoeter and a revised protocols document for radiometer deployments.

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, an opportunity to review the progress in instrument development and to consider the design drivers for a new generation of *in situ* radiometers took place this year. 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 includes:

- A survey of the applications for in-situ radiometers and consolidation of the requirements associated with these applications.
- A consideration of both the basic environmental regimes (sea, ice and land) and the applications within these regimes.
- Validation activities are the main consideration but other topics such as heat and gas exchange and frontal studies are considered.
- The relative strengths of different measurement approaches, particularly infrared broadband and spectro-radiometry and microwave radiometry and their suitability for the different applications are considered, including the achievable accuracies and noise performances, traceability, spectral and spatial resolutions and the density of measurements.
- Experience with existing instruments, particularly SISTeR and ISAR, are reviewed and areas of the designs that have been particularly successful or that could be improved significantly are identified.
- Both the radiometric performance of the instrument and the practical requirements for extended operations at sea and elsewhere are considered. This includes how any new instrument capabilities could be incorporated into the design and whether there would be any impact on the baseline instrument performance.

An outline design for a new instrument that best addresses the requirements that have been identified is proposed within the case study. Along with a summary of the instrument architecture and major subsystems and an indication of the areas that will need the most extensive development work.

The results of this work package can be found in more detail in the Case study for a next generation radiometer.

10. THE INTERNATIONAL NETWORK

The International Sea Surface Temperature (SST) Fiducial Reference Measurement (FRM) Radiometer Network (ISFRN) set out to develop and promote 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 skin SST at the surface of the ocean, comparable to measurements made by satellite infrared radiometers. This includes operators, designers and builders of such instruments as well as the user 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 provides a focus for UK and overseas *in situ* radiometer operators with the aim to provide a single point of access for *in situ* SST data, documentation and validation activities.

During this contract, the ships4sst website has been updated and expanded to include more information relevant and useful to the radiometer network. The network has been promoted at meetings and events, including the project's own ISFRN Workshop. Data has 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 plotted on the world map as per data provider where pink is CSIRO, light red is DMI, green is RAL, blue is RSMAS and deep red is UoS.

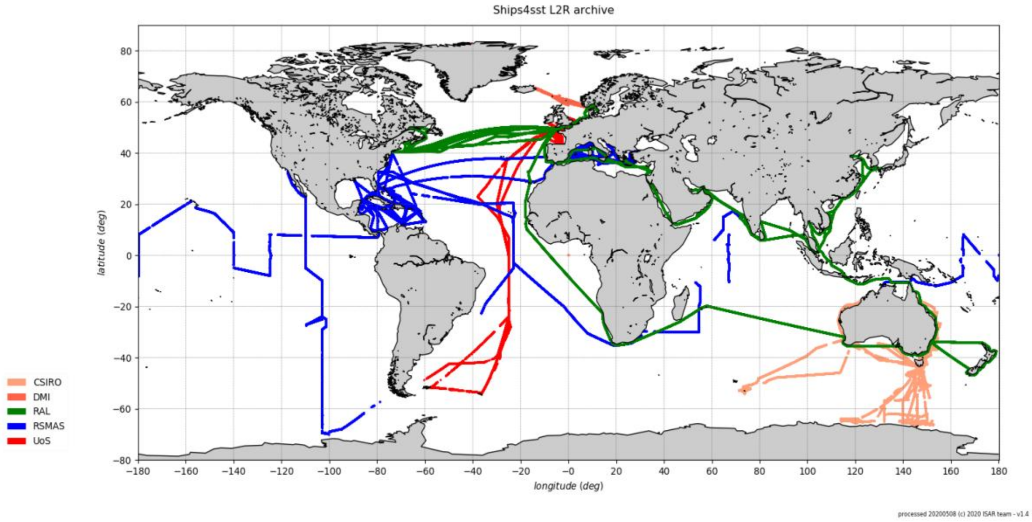

Figure 10-1: The ships4sst data archive L2R files plotted as by data provider, May 2020

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 this year. This document is distributed via the ships4sst website.

10.2 ISFRN Workshop

On the 17 – 18 September 2020 the project hosted the first virtual international ISFRN workshop, with scientific and operational users and producers of *in situ* radiometer SST data from 16 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 consisted of online presentations and a poster, 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: Validation of Satellite SST Measurements
- Session 3: SST Data in Practice
- Session 4: The ISFRN Network
- Session 5: Radiometer Performance and Uncertainties

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 developments within and outside the ISFRN and the international collaborations that have developed over the years.

A detailed workshop report and the presentations from the workshop are available for download at www.ships4sst.org/documents/2020.

11. SERVICE ROADMAP

The collective wealth of experience of project members and attendees at the ISFRN workshop enabled a roadmap of the future to be developed. Although the workshop had to be changed to a virtual meeting due to the COVID-19 pandemic, a positive result was that more international participants and presenters from all over the globe were able to attend, giving rise to broad international discussions about the status and influence of the service, radiometer instruments, data uses and validation activities. This builds on and adds another dimension to the 2019 roadmap which, with limited participation from America and Australia, was mostly constructed using feedback from European-based participants.

Discussions throughout the service and during the ISFRN workshop identified a number of areas with a high impact on the service. Generally, these come with a high difficulty rating, often due to the need for additional funding or time but there are a number of suggestions with high impact and low-medium difficulty which could take high priority within the next 2 years of work. These are:

- Add more data and metadata to the ships4sst database.
    - It is clear from presentations made during the recent ISFRN workshop that there are a number of saildrones now producing SST skin data around the globe and the possibility of adding saildrone data to the ships4sst archive was discussed. This can be further explored using the contacts made during the workshop.
    - 6 ISARs has been delivered over the last 2 years. More data will most likely be obtained once all these ISARs are deployed and operating in their respective countries.
- Perform another CEOS Radiometer Inter-comparison exercise.
    - Plans are underway to perform an inter-comparison exercise in 2022.
- Push for more radiometers on ships of opportunity
    - As mentioned previously, a number of ISARs are planned for delivery in 2020/2021. One will provide DMI with a second radiometer on their existing deployment, which will enable continuous deployment of an ISAR on the *MS Norröna*. Other radiometers may be deployed on new ships of opportunity.
    - COVID-19 has affected the cruise industry in 2020, some ships have been hit harder than others, and so one variable that may be considered for future radiometer ships of opportunity is their resilience during a global pandemic. Experience this year has taught is that the ships that operate due to necessity (e.g. cargo ships) are more likely to resume deployments sooner after a pandemic.

- All suggestions within the outreach and documentation section were deemed high impact and low-medium difficulty. This includes checking and updating website and data archive documentation, and publishing reports and papers. These are updated routinely and this will continue in phase 2 of the FRM4SST contract. The information provided to radiometer instrument operators could be revisited in 2021; it was noted during the workshop that there were a couple of times when the operator could not get the instrument to work for part of or all of a voyage. A revisit could establish whether updates need to be made to the documents to clarify answers to the FAQs.
- Develop new routes
  - Three areas for new routes have been identified; reference ship tracks in cloud-free regions, 'problem areas' such as the Arctic, around islands and in the southern oceans, and lastly aerosol regions. The southern oceans may be addressed when CSIRO receive their new ISAR in 2021. Existing infrastructure could be used; for example, a presentation made during the ISFRN workshop spoke of a platform in the Mediterranean Sea that is effective, easy and cheap to install and use scientific equipment on. This could be explored in 2021.

Whilst it does have a high difficulty rating, further work on radiometer uncertainty was brought up a number of times during the workshop and a verification of the uncertainty model out at sea is noted to have a high impact. The effect of surface emissivity on the SST_{skin} measurements can also be investigated at the same time. The difficulty arises as, depending on the detail required, this can be a very time consuming and expensive endeavour.

Another suggestion with high impact and difficulty ratings is the request for a next-generation radiometer. It has been a number of years since a radiometer was last designed and with the advancement of technologies and satellite measurements over the years it now appears to be the right time to revisit the design. A case study for a next generation radiometer has been written and discussed within the ISFRN community, and there is enthusiasm for not only a TIR shipborne radiometer but also one which includes microwave measurements, to validate satellite instruments such as CIMR. The high difficulty rating is due to the funding that is required to build a next generation radiometer.

The detailed Service Roadmap can be found on the project website at www.ships4sst.org/documents/2020 .

12. THE FUTURE

12.1 Achievements of Service

As we have seen, 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 acquired for validation of the SLSTR instrument. Specific achievements of this contract include:

- The promotion and expansion of the ISFRN and 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. There was talk at the ISFRN workshop of adding saildrone data to the database also.
- Promotion of standards and protocols and a common data format used by most, if not all, radiometer operators.
- A large number of data match-ups that are and can be used in the validation of SLSTR SST data.
- Validation analyses of SLSTR 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 high latitude data and day time global matches.
- A case study for a next generation radiometer has been investigated and produced
- A static inter-comparison of a MW and TIR radiometer has been achieved, the results summarised in the work package report.
- The plans for a 2022 International TIR inter-comparison consisting of around 10 participants have been produced. The last inter-comparison took place in 2016 and there is a large desire for another one.

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

Whilst this report is only a high level summary of the FRM4SST service, it has been clear over the last 2 years 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.

12.2 A Look Ahead

Phase 2 of the FRM4SST ESA-contract, which is due to start in 2021, is currently under discussion with ESA. It will continue along the same lines as the current service in order to ensure that the SST FRM data collections are sustained. Continuous deployment of the ISARs and SISTeR is expected, with the data processing, archiving and validation work and with possible further inter-comparison exercises between the instruments. An International CEOS TIR Inter-comparison will take place in 2022. The comments and suggestions from the service roadmap will be addressed, where possible. 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 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.

13. ACRONYMS AND ABBREVIATIONS

AATSR	Advanced Along-Track Scanning Radiometer
ASD	ATSR Satellite Dataset
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BB	Blackbody
BEIS	Business, Energy and Industrial Strategy
CDR	Climate Data Record
CCI	Climate Change Initiative
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEC	Data Exploitation Contract
DECC	Department of Energy and Climate Change
DMI	Danish Meteorological Institute
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
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
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
UKSA	UK Space Agency
VISCAL	Visible Calibration
VS	Validation Scientist

14. REFERENCED SCIENCE PAPERS

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