Ships4sst Project

Final Report: March 2019

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1. EXECUTIVE SUMMARY

This report presents the activities of the ships4sst contract. The main aim of this contract has been to validate Copernicus Sentinel-3A and Sentinel-3B SLSTR Sea Surface Temperature (SST) data products using Fiducial Reference Measurements (FRM).

In order to achieve this aim, the European Space Agency (ESA) funded the continuation, and expansion, of radiometer deployments that began during the ASD project[1]. 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* 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 availability of the *in situ* SST archive has enabled multiple organisations to add their data onto a central online open-access database (once users have registered) (see Section 2.3).

The International SST FRM Radiometer Network (ISFRN) sets 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 users of the data. To this end, the project has set up a website that allows operators to upload their own data onto a shared archive that can be accessed by registered users. The ISFRN is also regularly promoted at meetings and conferences.

The programme is being continued under a new FRM4SST ESA contract in order to support the ongoing validation of the SLSTR time series using *in situ* radiometers.

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[1] *ASD project Final Report – unpublished report (2018)*

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 IR 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 at high latitudes. The measurements help to bridge the gap between AATSR and SLSTR, tying them both to a common internationally recognised reference standard.

2.1 Bridging the gap between AATSR and SLSTR

The loss of AATSR on 8 April 2012 prior to the launch of SLSTR on 16 February 2016 raised two fundamental SST data continuity questions for the ATSR SST record. How can data from SLSTR be traced to the same internationally recognised absolute temperature reference as AATSR? And how might the data gap between AATSR and SLSTR be bridged using alternative sources of data? Both are critical questions, as scientists need to be assured that there are no biases between SST data derived from AATSR and SLSTR, and that any observed change in temperature during the data gap is real.

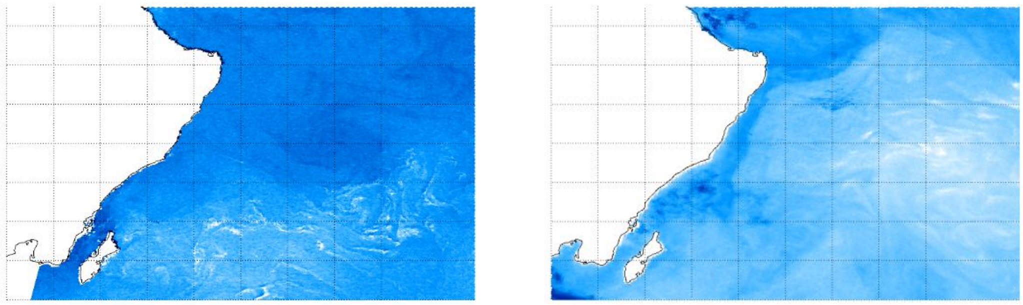

Figure 2-1 Comparison of (left) AATSR SST on 16/02/2012 and (right) SLSTR SST on 25/02/2017 in the Gulf of Oman.

The answer to both questions is to exploit all the alternative sources of data - for SST, this includes calibrated shipborne radiometers, *in situ* thermometry and alternative satellite instruments - it should then be possible to provide a baseline set of measurements against which to adequately compare the AATSR and SLSTR biases to achieve the goal of an ATSR-SLSTR Climate Data Record (CDR).

2.2 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 2-2).

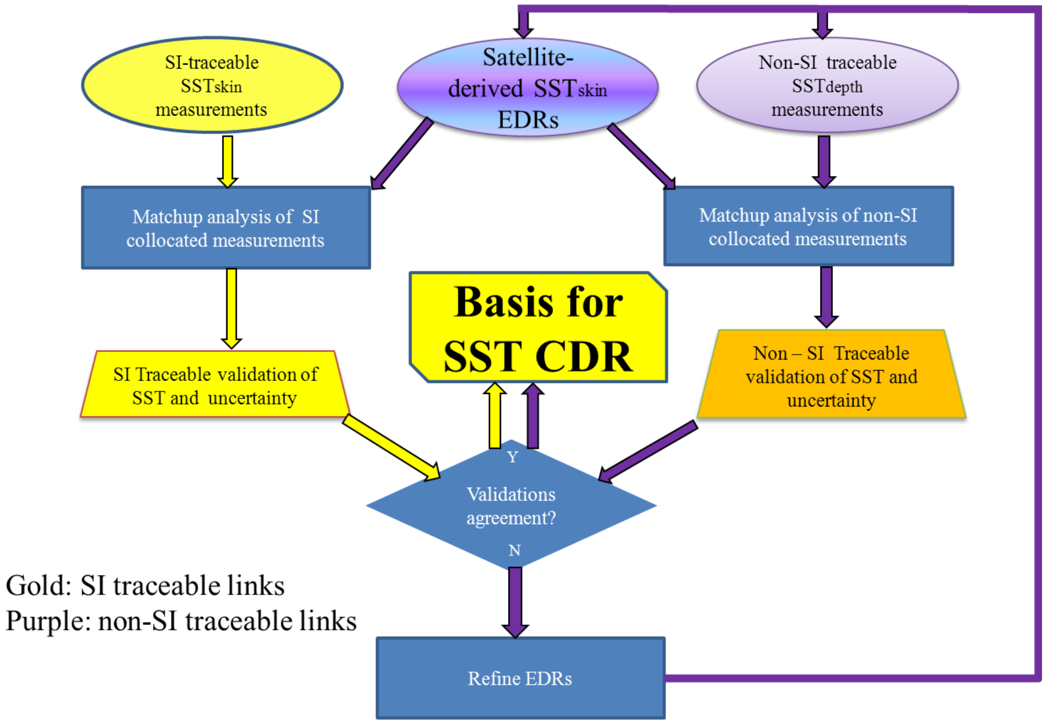

Figure 2-2 This flow diagram shows the traceability route for a SST Climate Data Record (from ISSI[2] *in situ* validation workshop). Shipborne radiometers cover the gold parts of the diagram.

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 2-3). 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.

[2] *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)*

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[3]. 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.

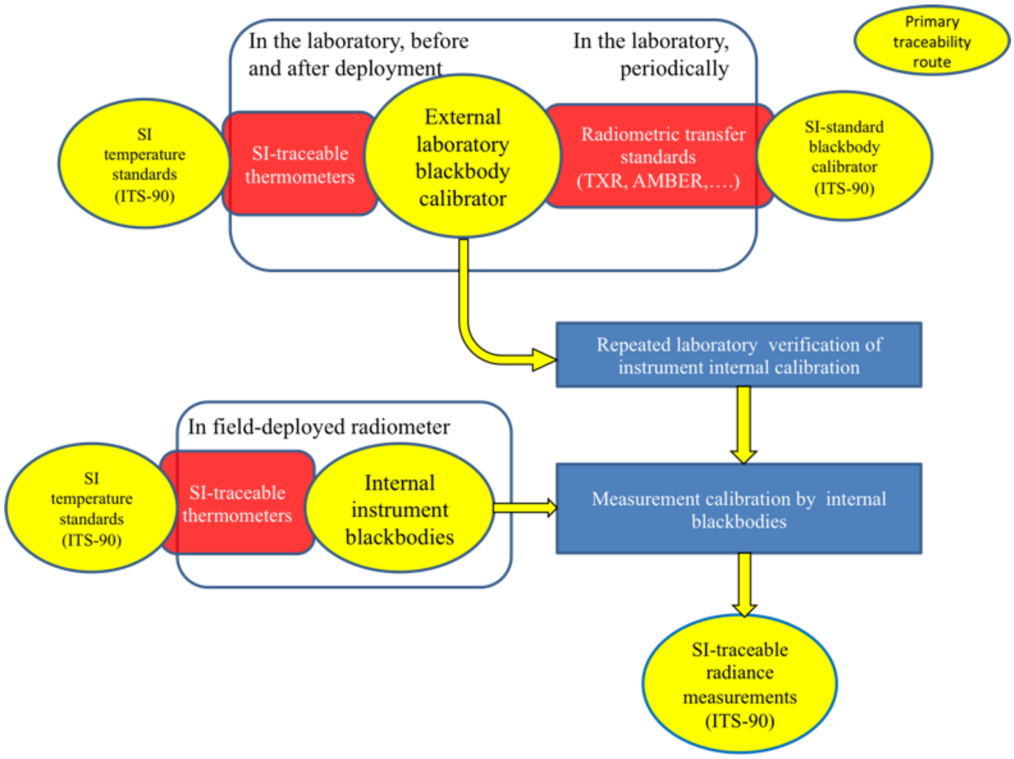

Figure 2-3 Traceability route for a shipborne radiometer (from ISSI *in situ* validation workshop).

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

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 Infrared Sea surface temperature Autonomous Radiometer and the Scanning Infrared Sea surface Temperature Radiometer 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 throughout the data gap, any geophysical changes in the SST fields during the gap will have been monitored and this will ensure that changes are not an attribute of either AATSR or SLSTR but a genuine geophysical change.

2.3 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 ESA Felyx instance which will be 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 plots and 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 ISFRN web portal.

The data archive is accessible through the ISRFN 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 ISRFN web portal, as has been done with the CSIRO and M-AERI data.

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 ~15 year period, two instruments, ISAR 002 and ISAR 003, were used to provide over 930,000 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).

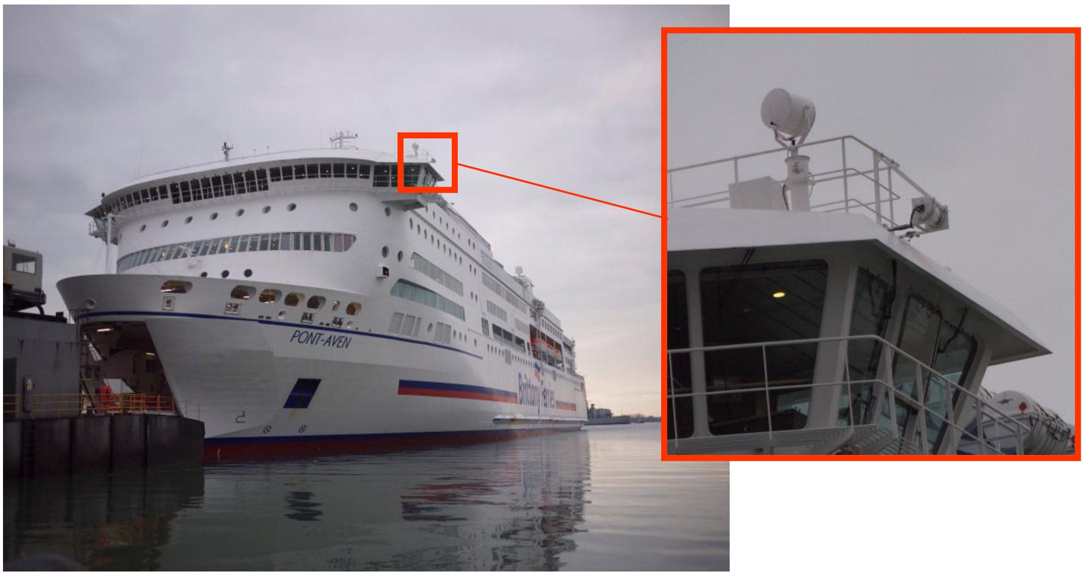

Figure 3-1 ISAR installation on the Pont Aven in October 2012. This deployment is ongoing

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 15 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.

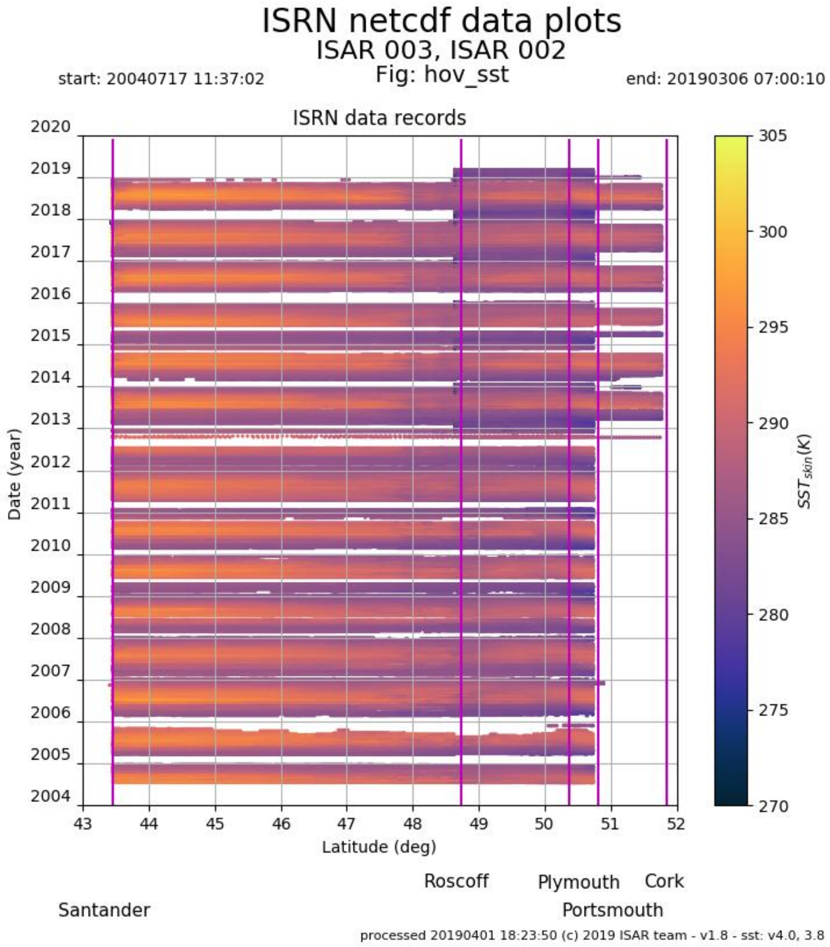

Figure 3-2 ISAR SST data from 2004 to 2019

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[4]. 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.

[4] 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.

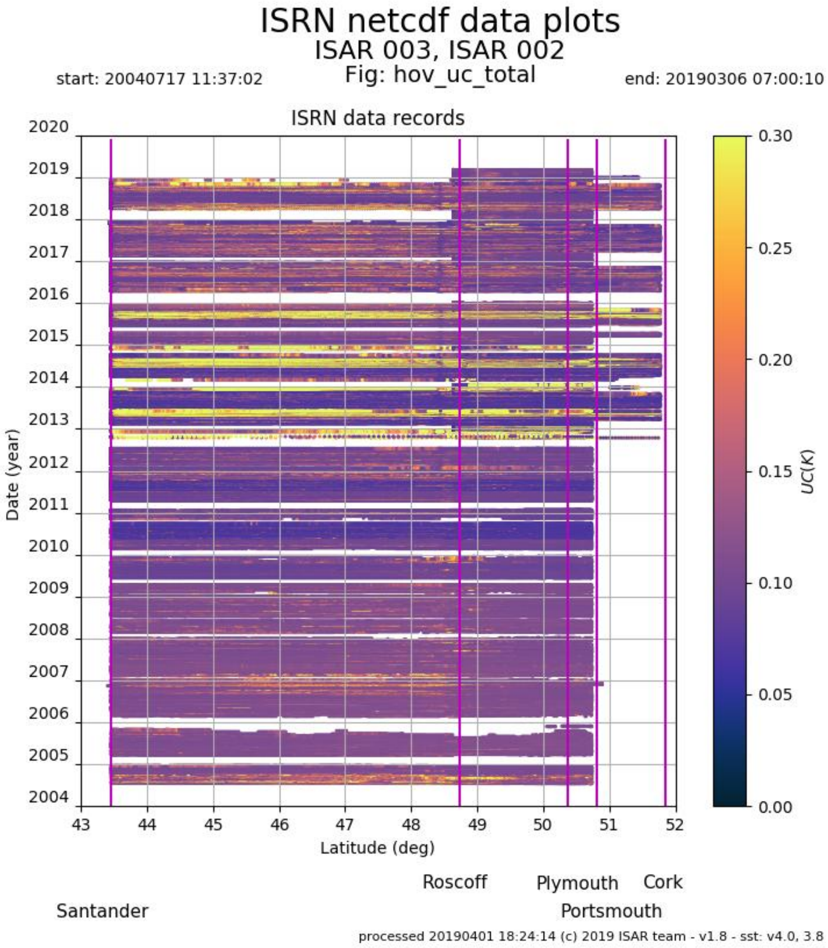

Figure 3-3 ISAR total uncertainty for all data from 2004 to 2019

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.

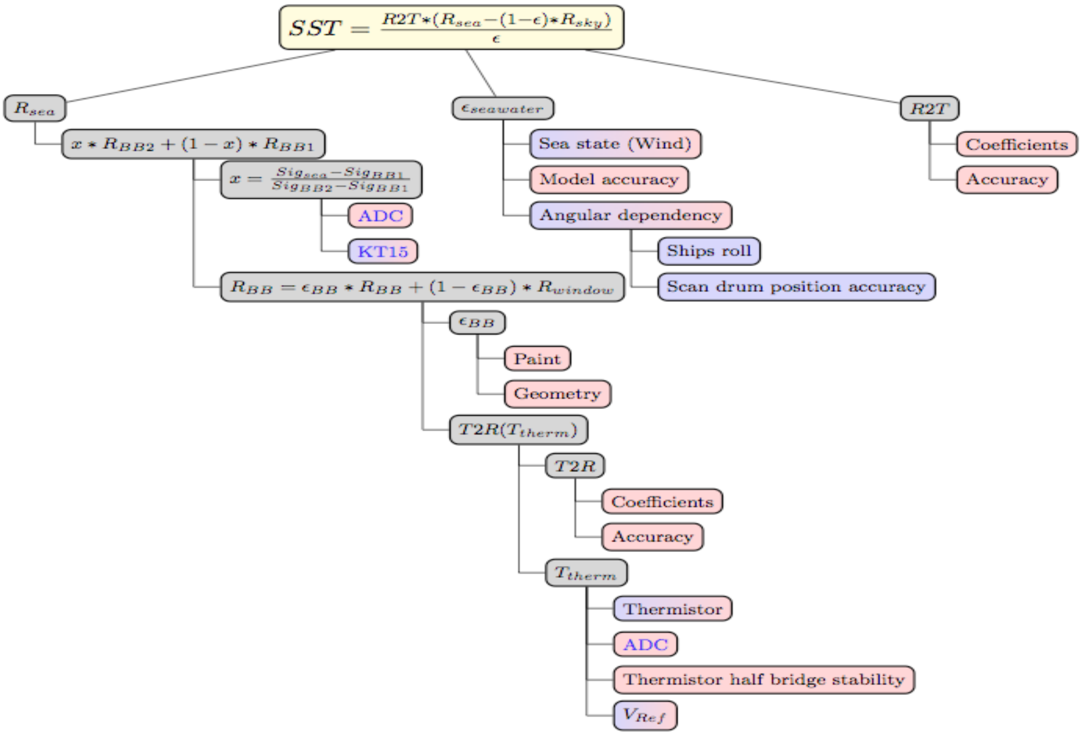

Figure 3-4: Schematic to illustrate the breakdown of the main elements of the ISAR SST processor to reveal the factors that introduce uncertainty. For clarity the R_{sky} branch has not been expanded but is essentially the same as for R_{sea} . Boxes coloured in blue represent type A uncertainties, boxes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

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:

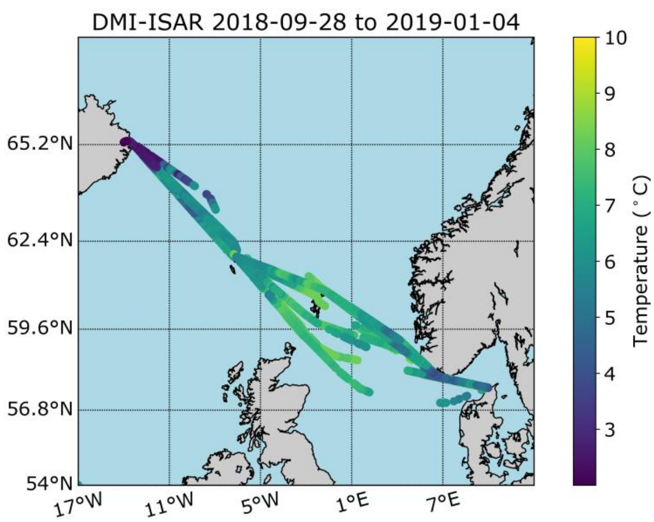

Figure 4-1: Track of the Norrøna Ferry line from Hirtshals to Faroe Islands and Iceland.

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.

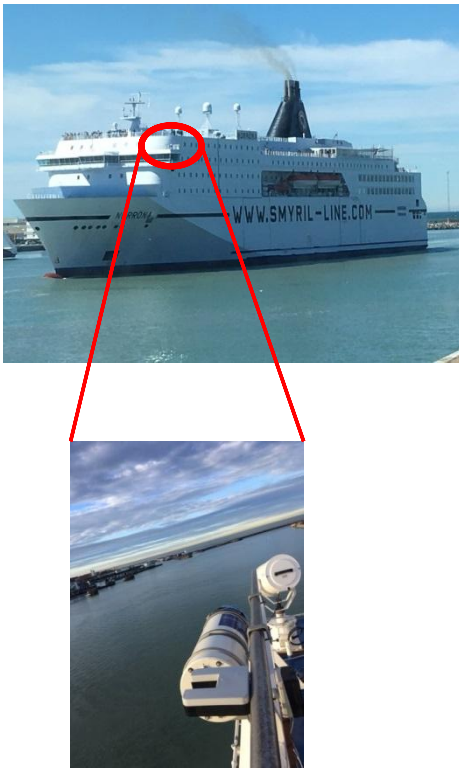

Figure 4-2: DMI-ISAR installation on board Norrøna. The first deployment was made in December 2017.

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.

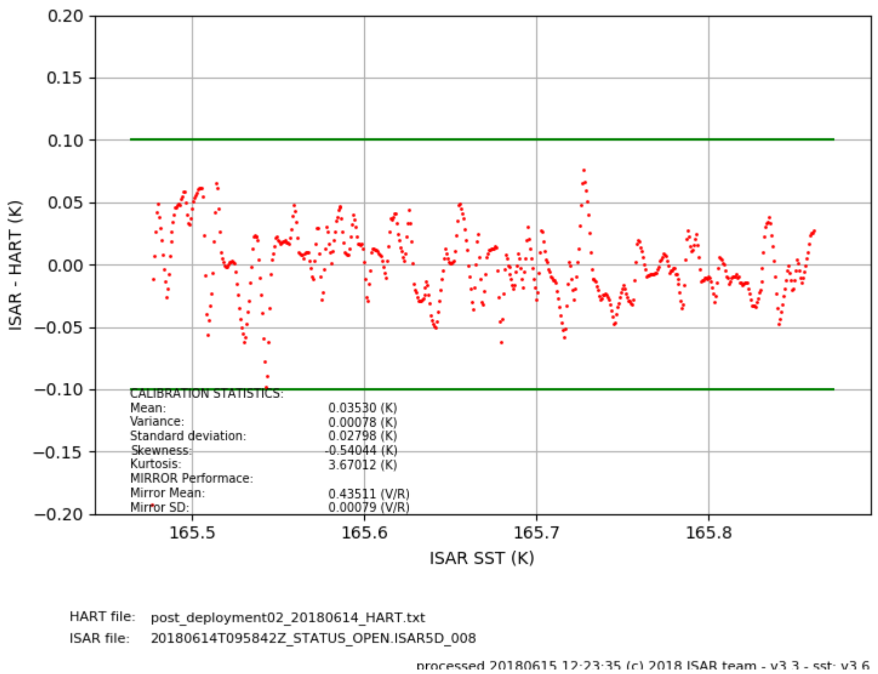

Figure 4-3**:** Calibration results from the deployment 4, pre-deployment calibration.

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.

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.

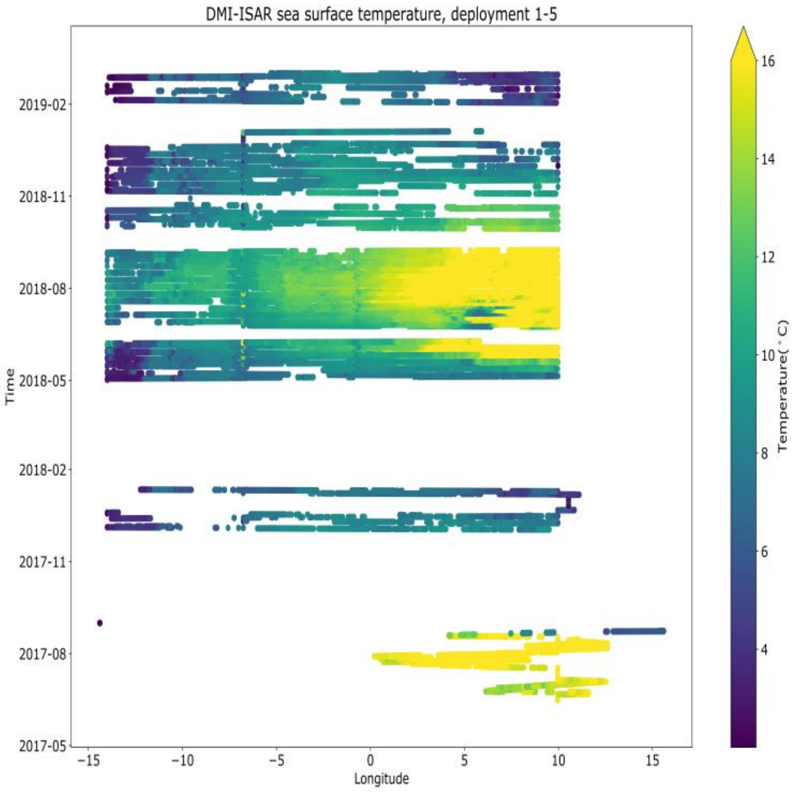

Figure 4-4**:** A longitude versus time plot of the ISAR observed SSTs during the Ships4SST contract.

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.

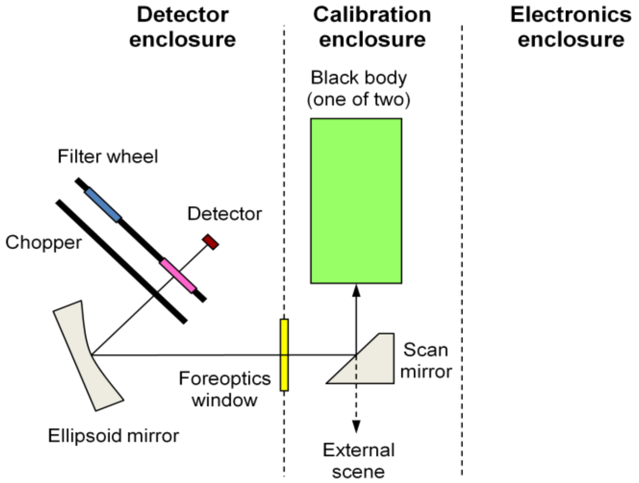

Figure 5-1: The internal configuration of the SISTeR radiometer

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 both stores the data 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.

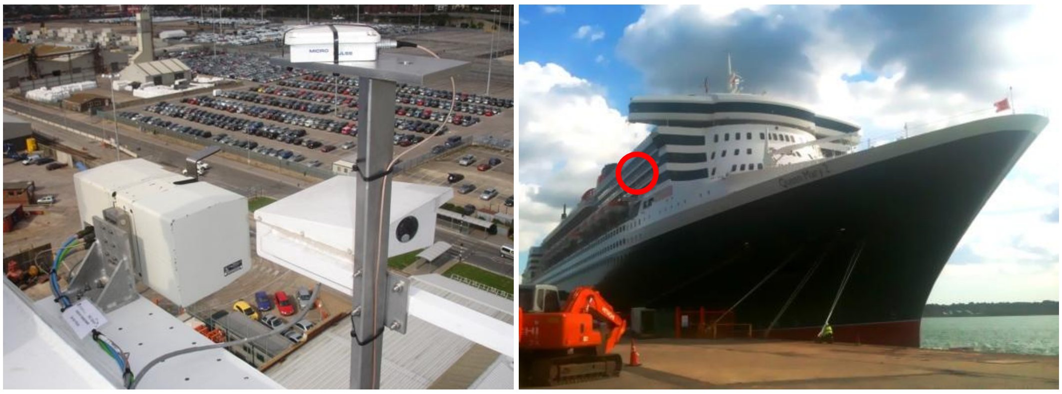

Figure 5-2: The SISTeR Instrument mounted on the *Queen Mary 2*

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.

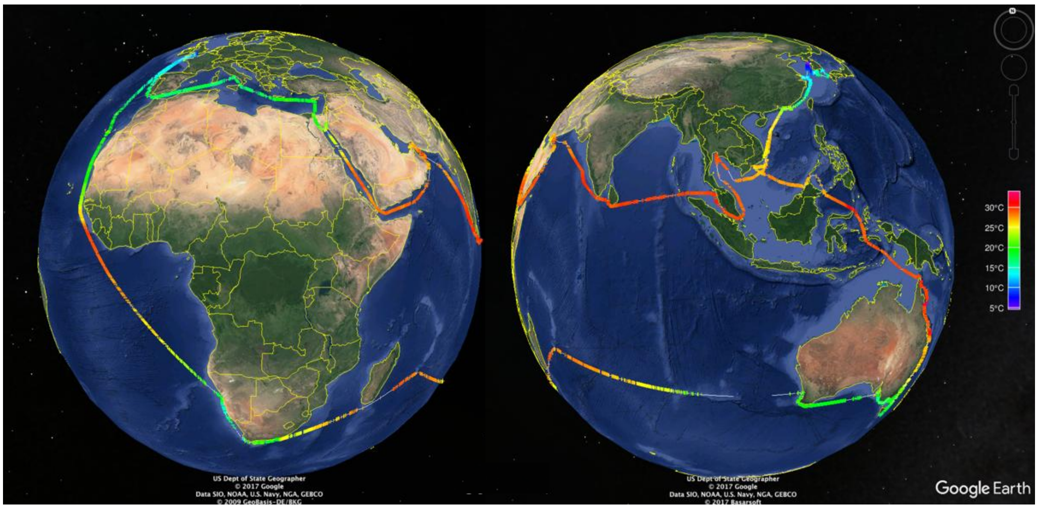

Figure 5-3 SSTs from a SISTeR “round-the-world” cruise on the *QM2*, 10/01/2017 to 08/05/2017.

SISTeR data are used to validate SLSTR using the same methods as ISAR. The combination of having ISAR on a consistent cruise pattern in a specific region 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 has recently been significantly improved as a result of the 2016 FRM4STS intercomparison 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.

6. SLSTR DATA STABILITY

6.1 Comparing SLSTR against ISAR and SISTeR data

SLSTR data was validated with ISAR and SISTeR data from August 2016 until March 2018. The validation of the SLSTR dataset shows good consistency over the period. A total of 29456 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 ISAR/SISTeR is 0.23 K for 13730 daytime match-ups from 188 different overpasses, and 0.11 K for 15685 nighttime match-ups from 180 overpasses. The Robust Standard Deviation (RSD) of the measurements is 0.5 K for day and 0.38 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 0.01 K for 2475 day time match-ups and a mean difference of -0.02 K for 804 night time match-ups. The RSD for those match-up pairs are 0.27 K for the day time and 0.25 K for the night time. The results for the DMI operated ISAR on the *Norrona* are a mean difference of 0.13 K for 32 day time matches and 0.01K for 119 night time matches. The RSD for those matches are 0.32 K for the day time and 0.46 K for the night time. Finally the results for the RAL SISTeR on the *Queen Mary 2* are a mean difference of 0.39 K for 1832 day time match-ups and a mean difference of 0.04 K for 3504 night time match-ups. The RSD for those validation data points is 0.74 K for day time match-ups and 0.2 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 very 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 6-1 shows the location of the match-ups for all ships4sst data including the RAL SISTeR data, UoS ISAR, DMI ISAR and CISRO ISAR data.

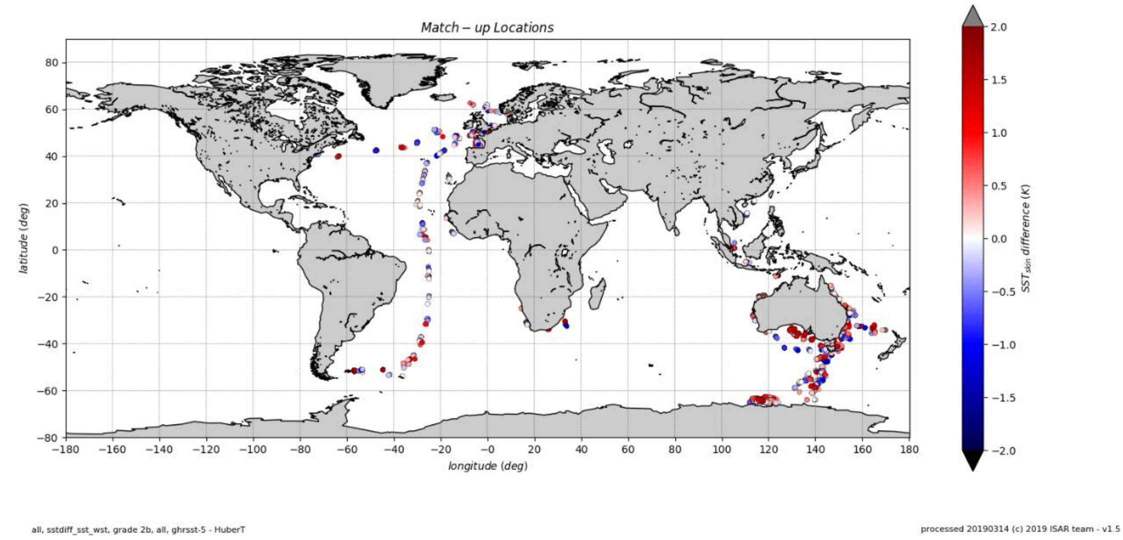

Figure 6-1 ISAR Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against ISAR/SISTeR observations between August 2016 and March 2018 .

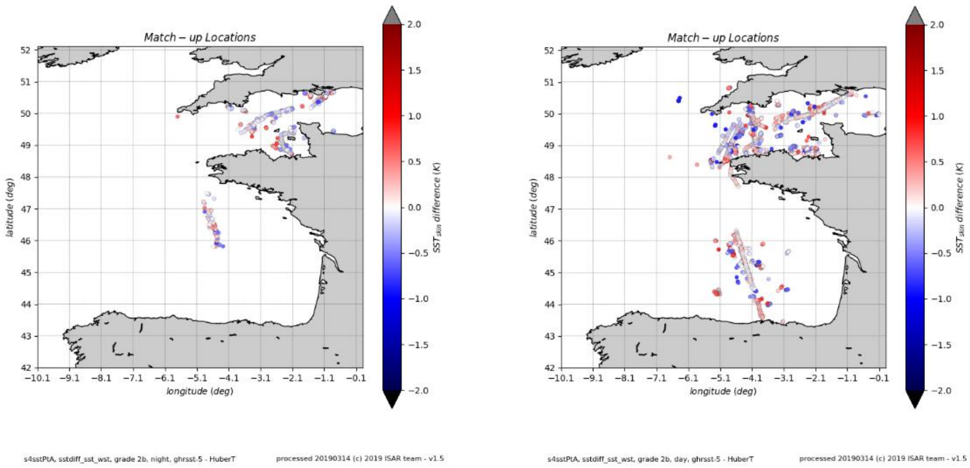

Figure 6-2: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against ISAR on the *Pont Aven* observations between August 2016 and March 2018 for night (left panel) and day (right). The stratification of the data is a side effect of the *Pont Aven's* schedule and not deliberate.

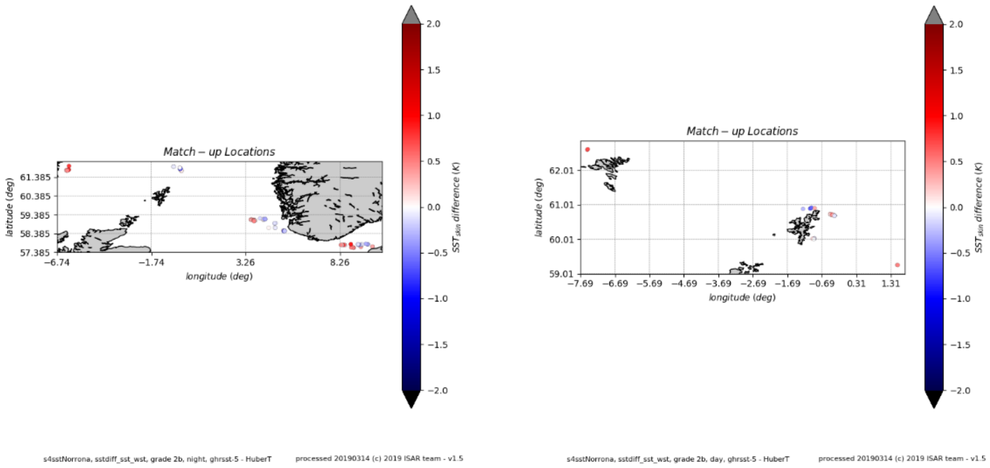

Figure 6-3: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against ISAR on the *Norrana* observations between August 2016 and March 2018 for night (left panel) and day (right). The stratification of the data is a side effect of the *Norrana's* schedule and not deliberate.

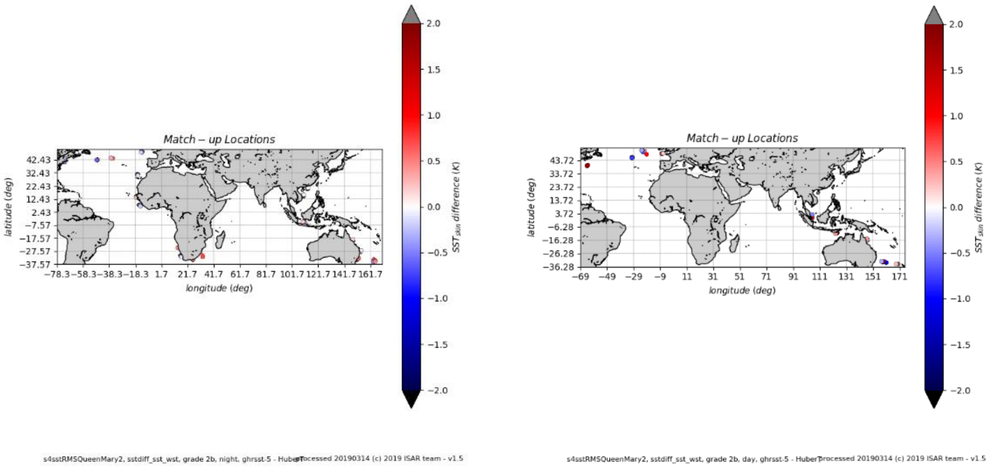

Figure 6-4: Location of the match-ups at +/- 2h and 1km coincidence for SLSTR WST dual-view SST retrievals against SISTeR on the *Queen Mary 2* observations between August 2016 and March 2018 for night (left panel) and day (right). The stratification of the data is a side effect of the *Queen Mary 2's* schedule and not deliberate.

Figure 6-5 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.

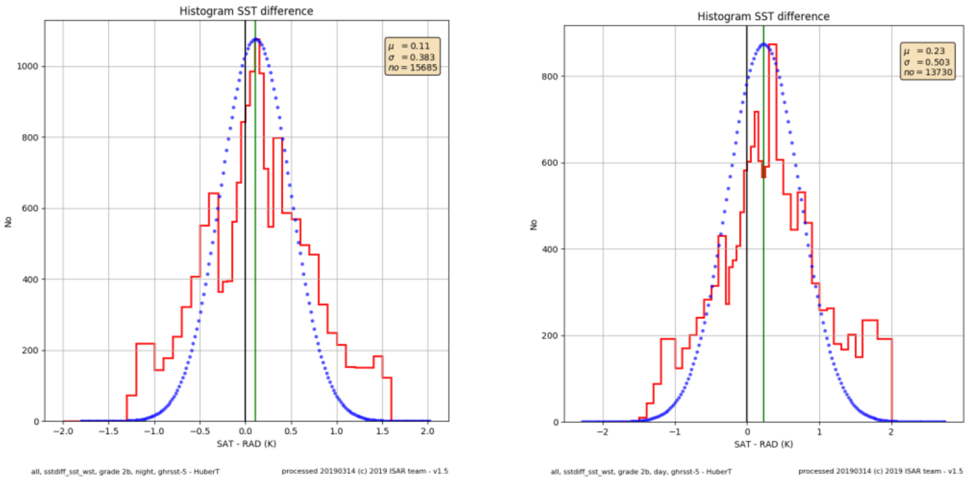

Figure 6-5**:** Histograms of Grade 2b match-up differences between SLSTR and ISAR / SISTeR SST records between August 2016 and March 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. The yellow box 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 ISAR/SISTeR of 0.11 K for nighttime data and 0.23 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.38 K for the nighttime and 0.50 K for the daytime.

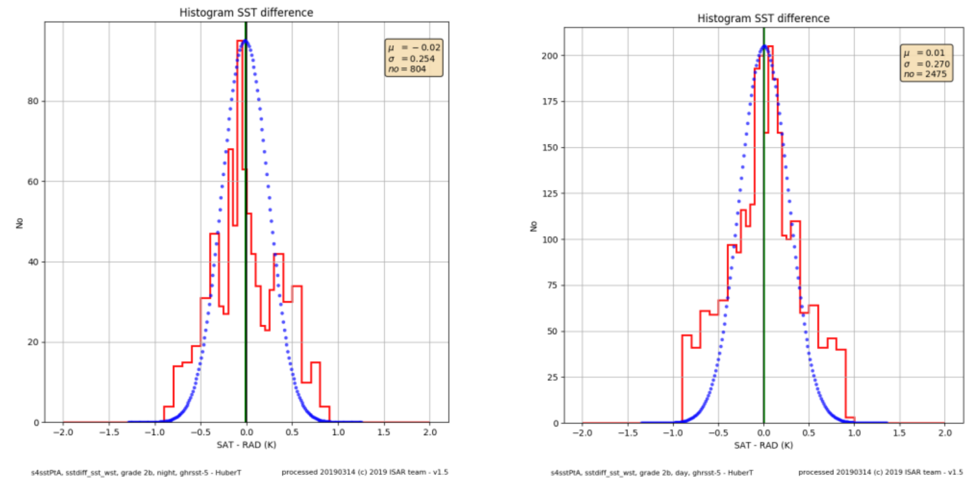

Figure 6-6: Histograms of Grade 2b match-up differences between SLSTR and ISAR SST records on the *Pont Aven* between August 2016 and March 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. The yellow 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 0.01 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.25 K for the nighttime and 0.27 K for the daytime.

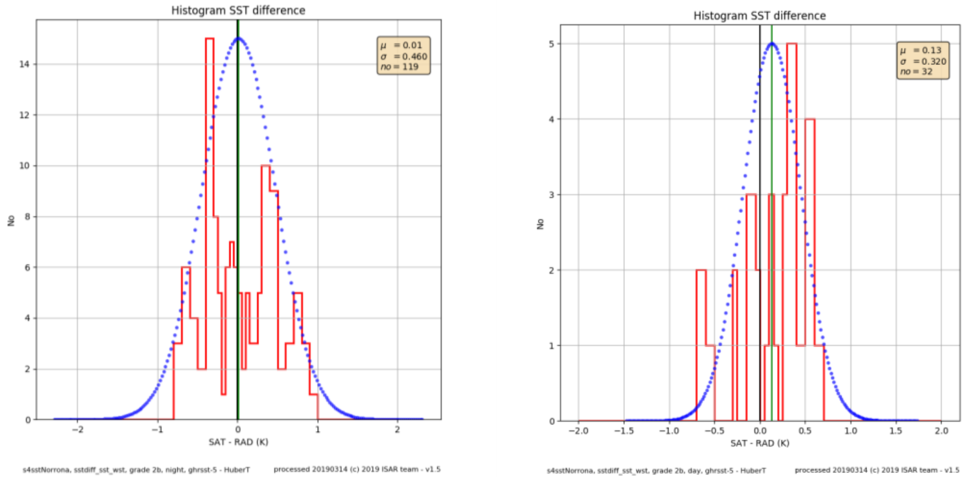

Figure 6-7**:** Histograms of Grade 2b match-up differences between SLSTR and ISAR SST records on the Norrona between August 2016 and March 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. The yellow 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 0.01 K for nighttime data and 0.13 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.46 K for the nighttime and 0.32 K for the daytime.

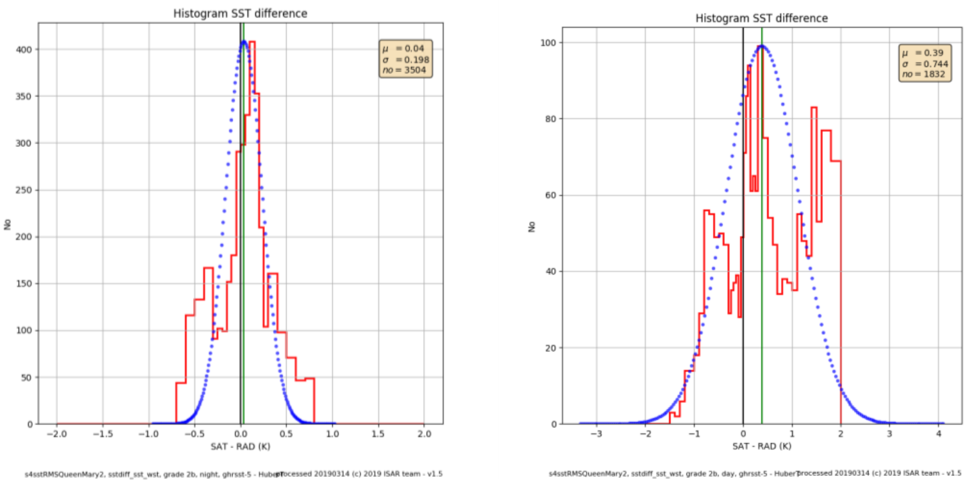

Figure 6-8**:** Histograms of Grade 2b match-up differences between SLSTR and SISTeR SST records on the *Queen Mary 2* between August 2016 and March 2018, for night (left panel) and day (right). The solid red line shows the SLSTR WST product and the dotted blue line shows a Gaussian fit to the data. 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 0.04 K for nighttime data and 0.39 K for daytime data for a match-up window of +/- 2h and 1km with an RSD of 0.20 K for the nighttime and 0.74 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. 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 have 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 a number of protocols for the deployment and operation of *in situ* radiometers, which we have distributed more widely through the International SST Fiducial Reference Measurement (FRM) Radiometer Network (ISFRN).

8. 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 is centred on a website **www.ships4sst.org** and a data archive, currently hosted by Ifremer. 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 the ships4sst project, the 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 8-1 and Figure 8-2 show the collective SST data on the ships4sst archive as of March 2019. Figure 8-1 shows the L2R files plotted as SST skin in Kelvin on a world map, whilst Figure 8-2 shows the 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.

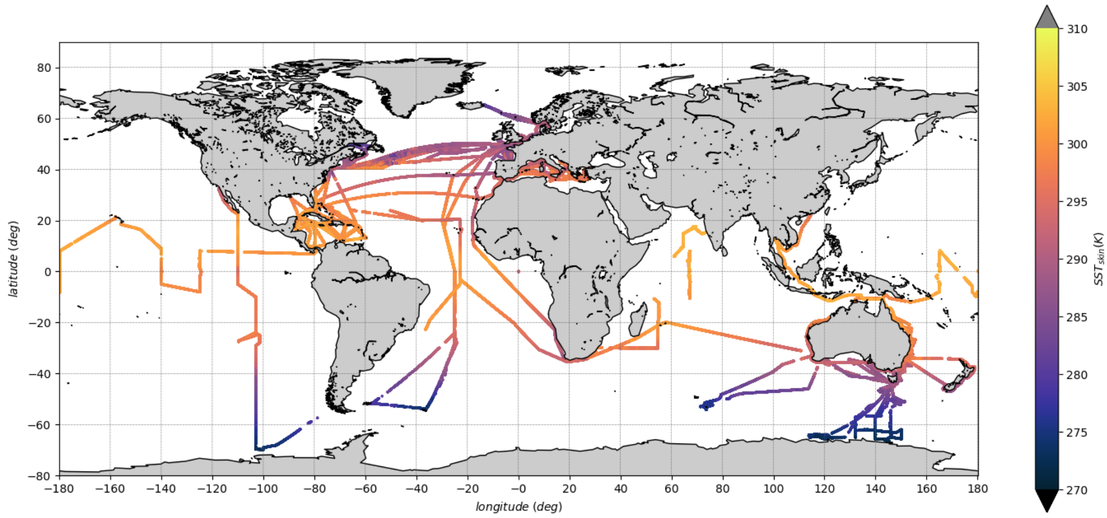

Figure 8-1: The ships4sst data archive L2R files plotted as SST on a world map.

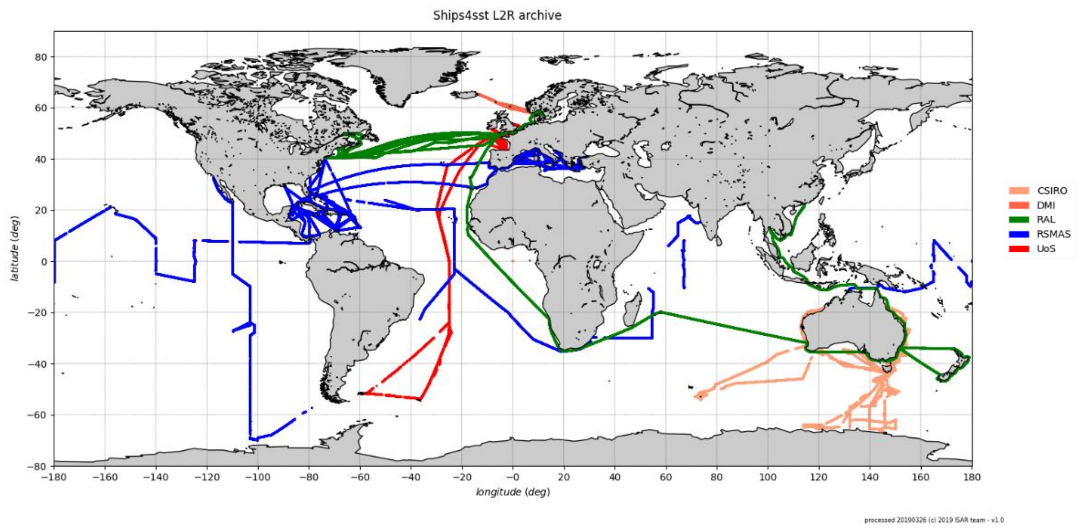

Figure 8-2: The ships4sst data archive L2R files plotted as by data provider.

9. ISFRN WORKSHOP

On the 27th February 2019 the project hosted the first international ISFRN workshop, with scientific and operational users and producers of *in situ* radiometer SST data from the UK, Denmark, America, Australia, Italy and France attending. The aim of the workshop was to present and discuss ship-borne satellite SST validation activities and results, and to share the findings of the partners in the ISFRN service.

The ESA-sponsored workshop was hosted at the National Oceanography Centre (NOC) in Southampton and consisted of two days of presentations, posters and interactive sessions, designed to review progress, results and advances in deployments, calibration and validation as well as a discussion on a service roadmap. The workshop consisted of the following sessions:

- Session 1: Experiences of Radiometer Operators
- Session 2: Developing the Radiometer Network
- Session 3: Radiometer Performance and Uncertainties
- Session 4: Validation of Satellite SST Measurements
- Session 5: Software and Tools

Following on from the final session, a group breakout commenced in which detailed discussions on the future of the service took place. Attendees discussed strategies for implementing future requirements or suggestions, and on possible impacts and difficulties that may ensue. Further information can be found in section 10 of this report.

A detailed agenda. report and presentations from the workshop are available for download at www.ships4sst.org/news/isfrn-workshop and the documents page.

Figure 9-1: Participants at the ISFRN workshop, 27-28 February 2019

The project would like to thank and acknowledge the substantial contribution of all of the participants and their funding agencies in support of this workshop.

10. 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.

The discussions identified a number of areas to target that were both High Impact and Low Difficulty, leading to a high likelihood that these suggestions will come to fruition in the near future. One of these is the need to improve openness and access to information. Strategies for implementing this included increasing the number of online documents on the ships4sst webpage, and the FRM4STS study provides an opportunity to do this. Linking the ships4sst project website to relevant sources of information was suggested several times. Whilst there are already a number of links online, it is clear that more links with more information and details are required. Again, this will be addressed in the FRM4STS study.

When specifically asked where participants would like the project to focus on, there were a number of suggestions including:

- Focussing on the operational validation of SST is important for climate studies.
- Consolidating the network and encouraging new members to contribute data and information by actively engaging with other radiometer operators.
- Maintain a network to provide data of sufficient quality to allow optimal validation.
- Looking into creating a cheaper, simplified radiometer that can go on fixed platforms. It need not be as robust as an instrument on a vessel but there could be opportunities to deploy more fixed instruments.

Looking into a cheaper and simplified radiometer has been thought of before according to several participants, but there did not seem to be a big gain, which is putting people off making them.

Plans to promote the ISFRN and actively engage with the community will continue into the FRM4STS study.

See Table 10-1 for more discussion outcomes and strategies for implementation.

Requirement / suggestion	Strategies for implementation / Comments	Impact (5 high, 1 low)	Difficulty (5 high, 1 low)	Target Date
Add more data and metadata to ISFRN database	Encourage more radiometer operators to join the network. New routes and reprocessing of existing data to L2R	5	being done routinely	ongoing
Improve information on observational methods	Write papers Publish more papers/reports/etc.	5	5 (because of time restraints)	April 2019 (2 papers by the ships4SST team)
Ensure adequacy and continuity of the observing system	Performing more intercomparison exercises will help confirm the validity of uncertainty budgets, show the validity, equivalence and traceability of the measurements. This is difficult to do in the field as there is a geophysical component we do not necessarily know.	5 - how we understand uncertainties	3 (have the knowledge, funding and time is limited)	2021
Improve openness and access to information	Increase the number of online documents on the Ships4SST webpage	5	2	2020

Requirement / suggestion	Strategies for implementation / Comments	Impact (5 high, 1 low)	Difficulty (5 high, 1 low)	Target Date
Quantified fully broken down uncertainties and sources of error in respect to SI	Source of errors might be tricky, and quantifying them, as if we can quantify them we correct for errors, otherwise they are uncertainties. Verification of uncertainty model (out at field).	5	5	ongoing
Push for more radiometers on ships of opportunities.	Radiometers can be more readily made traceable to SI than buoys Groups are starting to take up ISARS so this is increasing	5 (have better stats with more radiometers)	1	ongoing
Develop new routes	The most important areas for new route would be: 1. Reference ship tracks in frequently cloud free regions; this could be on a ship or fixed platform. This would fulfil the need for long-term consistency. 2. More radiometers going out into problem areas (arctic and islands) and the whole of the southern Ocean. 3. Aerosol regions, i.e. PIRATA North East Extension (PNE) mooring line at 24^{o}W or AEROSE (Nalli et al., 2011) – there are 6/7 cruises ready to go. Aerosols sometimes vary a lot so it is good to go to a few times.	4-5	2-3 (could use existing infrastructure)	Now
A database of information, including QA, on all radiometers to support validation	Documentation of processing versions, instrument maintenance etc. is available, but needs to be linked to reference sites, websites populated etc. A link from the ships4sst to QA3O information will be put online.	4-5	2-3	ongoing

Requirement / suggestion	Strategies for implementation / Comments	Impact (5 high, 1 low)	Difficulty (5 high, 1 low)	Target Date
Promotion of community protocols and best practises	Data submitted to the L2R archive should/must follow the ships4sst protocols. Mandatory requirement to use L2R format. There may be some more work to do on protocols and metadata as protocols are followed within the ships4sst project (therefore easier) but not always used by everyone else. Is there evidence that people follow the protocols? The FRM4STS website needs to be linked to the ships4sst site.	4	2-4	ongoing
Measurements at a range of sea depths	We can only measure at the surface (skin), so should there be a range of oceanographic regimes, or do we want to include other sensors? Many ships already measure temperature at depth so they could be combined with SST_{skin}. Merge drifter data with Radiometer data for SI link Most ships are now measuring a range of data depths. A platform in the Mediterranean would be more useful than more measurements at different depths on ships because ships do not have FRM standards. Several months' worth of data of diurnal variability on various platforms would be useful.	Unknown	5 - doable but difficult to do with ship operators	

Requirement / suggestion	Strategies for implementation / Comments	Impact (5 high, 1 low)	Difficulty (5 high, 1 low)	Target Date
Sampling of coastal variability	Is already done, but we exclude most of the data for validation. Not necessarily an issue for climate studies. Interesting for high resolution missions. Large birds could be instrumented (e.g. on albatrosses and boobies feet) – Peter Minnett commented that the data was remarkably good when birds were used.	1	1	
Where would people like to see the focus of ships4sst.	Climate focus is important – i.e. service to operational validation of SST. Getting other members to contribute so that more data records could be included Develop, consolidate and maintain a network of radiometer operators to provide data of sufficient quality to allow optimal validation. Actively engaging with other operators Telecons with international partners/operators to get them more involved. A simplified next generation radiometer that could go on fixed platforms (might not need to be as robust as those on a vessel).	Various	Various	Various

Table 10-1**:** Outcome from the Service Roadmap discussion at the ISFRN Workshop, 28 February

A more detailed report on the Service Roadmap can be found on the Ships4SST website documents page.

11. THE FUTURE

11.1 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 International Sea Surface Temperature Fiducial Reference Measurement Radiometer Network (ISFRN) and through it increasing international partnerships, including the UK, Denmark, USA, Australia and France.
- Increased web presence with the Ships4sst webpage and Twitter site.
- Continuous deployments and gathering of SST data by 3 radiometers onboard ships.
- Data from several countries is now on an easily-accessible and central data archive (Felyx) at 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 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 SISTeR matchups. There still seems to be some room for high latitude data and day time global matches.

The presentations, protocols, procedures and reports are all available on the Ships4sst website www.ships4sst.org .

11.2 A Look Ahead

The FRM4SST ESA-contract, which is due to start on the 1 April 2019, continues along the lines of 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 possible further inter-comparison exercises between the instruments. The comments and suggestions from the service roadmap will be addressed, where possible, which will result in a number of updates to the project website. Along with the continuation of deployments, the promotion of the radiometer network online, at meetings and events and the production of peer-reviewed journal articles will help expand the network and also increase the likelihood of more radiometer in situ SST data measurements joining the network and being available to users online.

12. 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
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

13. REFERENCED SCIENCE PAPERS

ASD project Final Report – unpublished report (2018)

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).

Wimmer, W. and Robinson I.S., 2016. The ISAR Instrument Uncertainty Model. *J. Atmos. Oceanic Technol.,* **33**, 2415–2433

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