Customer	:	**DECC/Space ConneXions**	**Document Ref**	:	**ISAR-DECC-REP-14_01**
Contract No	:	**2004-03-002/CPEG 10**	**Issue Date**	:	**25 July 2014**
WP No	:	**3.5**	**Issue**	:	**1_C**

Title :

Shipborne Radiometry Network Development Plan

Abstract :

This document presents v1 of the Shipborne Radiometry Network Development Plan. It is the deliverable from Work Package 3.5 from the revised work programme for Phase 5 (2012-2014) of the "ISAR Validation of ATSR" subcontract issued by Space ConneXions Ltd. (SCL) within the overall AATSR Data Exploitation Contract (DEC) issued to SCL by the UK Department of Energy and Climate Change (DECC).

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Filename: **ISAR-DECC-REP-14_01-v1_c**

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AMENDMENT HISTORY

This document shall be amended formally by releasing a new issue of the document in its entirety. Interim changes will be reported as drafts A, B etc. of the subsequent version number. The Amendment Record Sheet below records the history and issue status of this document.

AMENDMENT RECORD SHEET

ISSUE-draft	DATE	REASON
Issue 1/A	3 Apr 2014	Initial draft of SRN Development Plan (ISR)
1 B	28 May 2014	Draft updated by WW and ISR
1 C	25 July 2014	Update with H Kelliher’s comments

1. Introduction

This document presents version 1 of the Shipborne Radiometry Network (SRN) Development Plan. It is the deliverable for Work Package 3.5 from the revised work programme for Phase 5 (2012-2014) of the "ISAR Validation of ATSR" subcontract issued by Space ConneXions Limited (SCL) within the overall Advanced Along-Track Scanning Radiometer (AATSR) Data Exploitation Contract (DEC) issued to SCL by the UK Department of Energy and Climate Change (DECC).

1.1 Purpose of this Document

This document sets out a plan for developing 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 sea surface temperature (SST) at the skin of the ocean, comparable to measurements made by satellite infrared radiometers. One of the main objectives for establishing a network is to collaborate in populating an international skin SST reference dataset that is independent of satellite data products and has sufficient accuracy and calibration traceability to make it a credible resource for the validation of global satellite-derived SST datasets used for critical climate monitoring tasks and important operational ocean forecasting roles. Other goals for the SRN are to assist in widening the geographical coverage of regular deployments of radiometers on ships of opportunity (SOO), to agree and establish international protocols, formats and standards for quality assurance of data, and to promote best practices in deploying radiometers on SOO, including activities such as side-by-side radiometer intercalibration exercises. The broad aim for the SRN is to develop a simple infrastructure for collaboration that will enable many locally-based, small-scale ship radiometer activities to contribute effectively to meeting the international challenge of accurately monitoring global SST, while retaining their individual autonomy.

In the rest of this chapter, section 1.2 outlines the background to recent developments of ship borne radiometry in relation to the growing demand for high quality *in situ* SST observations for validating global SST datasets, especially in the context of initiatives from the Group for High Resolution SST (GHRSST). Section 1.3 explains the rationale for using the proposed SRN to meet the challenge of expanding the geographical coverage and scope of shipborne radiometers deployed routinely on SOO.

Chapter 2 identifies and briefly outlines the various elements that define the objectives, activities and rules of an effective SRN.

Chapter 3 summarises the present state of shipborne infrared radiometry, with an inventory of groups who deploy ship radiometers and who are potential producers of input to the intended skin SST reference dataset. It mentions existing elements of infrastructure for supporting radiometry users in a variety of ways and identifies agencies and international organisations with which the proposed SRN will need to engage.

Chapter 4 then outlines a development plan for realising the proposals in this document.

1.2 Background

For ten years from 2002 the AATSR sensor flown on the European Space Agency's (ESA) Envisat spacecraft provided global SST measurements of the highest quality compared with other satellite-derived SST observations, in terms of accuracy and stability. AATSR is a special class of infrared sensor which provides a "dual view" of the ocean from different viewing directions in order to achieve significantly more reliable and precise atmospheric corrections than other sensor types. Although the narrow swath of AATSR dictated a fairly long sampling interval (at least 3-5 days) its spatial sampling interval of 1 km and accuracy of better than 0.2 K has led to increasing use of AATSR for ocean and climate applications. AATSR data provided the primary source for a new global SST climate dataset, ARC (ATSR Reprocessing for Climate) (Embury and Merchant, 2012; Embury *et al.*, 2012). Increasing confidence in its accuracy led to AATSR being used as a reference check for *in situ* observations (Kennedy *et al.*, 2012). As soon as AATSR data became readily accessible in the GHRSST standardised format for Level 2 SST products (Donlon *et al.*, 2007; see also section 14.4.2 in Robinson, 2010), they started to be used in operational applications around the world (Robinson *et al.*, 2012). For example they became the primary input data source for a new Met Office operational sea surface temperature analysis (OSTIA) (Donlon *et al.*, 2012), and were used routinely for providing bias adjustment for other operational SST analyses (Le Borgne *et al.*, 2012).

If the widespread use of dual-view sensors is to be justified for enhancing the absolute accuracy and stability of those SST products that combine inputs from several different types of ocean temperature sensors, following the GHRSST approach, then it is essential that the high accuracy of dual-view SST data be validated to a precision of better than 0.1 K, necessary to distinguish the enhanced accuracy of dual-view sensors from that of single view infrared or microwave sensors. This requires independent *in situ* measurements of SST with an uncertainty less than 0.1 K, which is also the level of accuracy desirable for validation of datasets used for climate monitoring.

An accuracy of 0.1 K is problematic for the conventional use of in-water temperature measurements using contact thermometers on drifting or moored buoys, smart floats, gliders or ships. These all measure the water temperature at a depth of tens of centimetres to several metres below the sea surface, whereas the satellite-derived SST corresponds to the true skin temperature of the ocean surface, within a few tens of μm of the water-air boundary. The temperature differs between these depths because the near-surface thermal structure is driven by various different physical processes depending on, for example, the wind speed, the heat flux across the air-sea boundary, and the local intensity of solar radiation (see section 7.3 in Robinson, 2004). Therefore validation of satellite SST datasets using in-water thermometry requires a model to predict the expected temperature difference between the skin and the depth of the thermometer, before meaningful comparison can be made between the satellite and the *in situ* observations. Because detailed knowledge of ambient environmental conditions is needed to constrain such models it is impossible at present to reduce the uncertainty of an individual model estimate to less than several tenths of a Kelvin. In attempts to circumvent this difficulty, model predictions based on typical environmental conditions have been used effectively for the analysis of large ensembles of satellite – thermometry comparisons for estimating the bias of climate SST datasets with an accuracy approaching 0.1 K (Embury *et al.*, 2012). However, an ensemble approach precludes a detailed analysis of satellite SST validation statistics and their variability in space and time, which calls for uncertainties less than 0.1 K for each individual *in situ* observation rather than that of the ensemble mean.

With the aim of eliminating the uncertainty associated with having to model the thermal structure of the upper ocean local to each buoy-measured temperature, the use of infrared radiometry from ships was attempted for validating the ATSR, forerunner of the AATSR (Barton *et al.*, 1995; Donlon and Robinson, 1998; Donlon *et al.*, 2002). The advent of the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) provided <0.1 K accuracy of skin SST measurement from a ship of opportunity (Minnett *et al.*, 2001), leading to the first validation of AATSR SST data products using *in situ* skin SST observations (Noyes *et al.*, 2006). Although there were few such skin measurements available at first for validation of AATSR, their superior accuracy weighted their influence in comparison with the use of much larger numbers of conventional buoy measurements (Corlett *et al.*, 2006). The development of an Infrared Sea surface temperature Autonomous Radiometer (ISAR) capable of autonomous deployments untended for several months, and with a specified accuracy of 0.1 K (Donlon *et al.*, 2008) delivered further radiometric SST measurements for AATSR validation from several individual trans-ocean deployments around the world, and also from a continuously repeated ferry line across the English Channel and Bay of Biscay (Wimmer *et al.*, 2012). The continuation of that deployment eventually yielded more than 4000 independent match-ups (coincidence within a window of 1 km and 2 h) over the last eight years of AATSR operation. It confirmed that in the limited geographical region covered, there was agreement between AATSR and the ISAR ship radiometer with a bias less than 0.1 K and a standard deviation less than 0.2 K, while no long term trend in performance could be detected.

The advantage of using ship radiometers, especially for validating high performance, dual-view radiometers, is now acknowledged within the satellite SST community, exemplified by the validation sub group (ST-VAL) of the GHRSST Science Team. Although there is presently a gap in the delivery of dual-view products following the loss of AATSR operations on the demise of Envisat in April 2012, this will be remedied following the launch of the Sea and Land Surface Temperature Radiometer (SLSTR) on ESA's Sentinel-3 satellite series, due in late 2015. The plan envisaged by ESA for calibration and validation of SLSTR has already identified a major role for shipborne radiometers to support the continuous validation of SST products over the lifetime of the Sentinel-3 series, upwards of 15 years. The initial (voluntary) membership of the Sentinel-3 Validation Team for Temperature (S3VT-T) already includes scientists from four groups engaged in ship radiometry. For the first time ever, an SST sensor is being launched by a Space Agency with some plans already in place for using ship radiometry for acquiring *in situ* skin SST for validation.

Unfortunately the geographical coverage of ship radiometry from the existing players in the S3VT-T is extremely limited. A study of the AATSR validation applicability (Kelliher *et al.*, 2007) showed that the N.E. Atlantic Ocean appears to be a region where the factors affecting atmospheric corrections of infrared radiometry are fairly benign. While this confirms that the Biscay region is ideal as a site for monitoring the ongoing stability of SST sensors, it also implies that in order to fully test how well the AATSR approach deals with unexpected stratospheric aerosols or extremes of atmospheric water vapour, there is a need to acquire *in situ* skin SST observations from a variety of other locations around the world, where atmospheric conditions are very different. It is therefore highly desirable to be able to extend the deployment of ship-borne radiometers over a much wider geographical range.

Moreover, in the current absence of any dual-view class of radiometer in orbit, skin SST from ship radiometers offers the best way of detecting how badly the SST retrievals of the other (single view) radiometers are affected in the event of a major volcanic eruption injecting high concentrations of aerosols into the stratosphere. Since such effects are likely to be zonally dependent, there is an urgent need for SOO lines carrying ship radiometers that provide north-south transects across all the major oceans.

1.3 Rationale for a SRN

From the previous paragraphs, it is evidently desirable to have a much wider spread of ship radiometer SOO lines across the world ocean by late 2015. How is this to be achieved? It is not likely to be accomplished by relying only on the present small number of ship radiometry teams, which typically are limited to servicing SOO routes which dock close to their home base. By expanding their inventory of autonomous radiometers these groups could each perhaps manage two or three more SOO lines with a modest increase in staff to service the additional instruments. But being tied to a local port, the addition of new routes is more likely to increase the density of local coverage, than to expand the geographical reach of those lines outside the major ocean on whose margin they are located. To achieve global spread requires base ports spread across all the oceans.

Since the present major push for in situ skin SST data for validation comes from ESA, which will launch the next series of dual-view class radiometers, some might expect that ESA should support a global programme of ship radiometry. However, the recognised European practice is for the sector which uses the resulting data products to bear responsibility for acquiring the *in situ* measurements needed to validate the products throughout the lifetime of a sensor's mission. In practice the role of the AATSR, as of the SLSTR which will succeed it, was such that it improved the reliability of virtually all satellite derived SST data products. In that respect, all users of global SST products around the world will benefit from effective validation of SLSTR.

From that perspective it is not fair to expect a few individual countries, or even the EU as procurer of the Sentinel satellites through its Copernicus environmental monitoring programme, to support the acquisition of global validation data. Neither is it practical for the few groups presently operating ship radiometers on SOOs to attempt by themselves to span the globe with ship radiometry lines. Instead the financial burden of doing so will be spread more equitably and sustainably if a number of teams based at locations spread across different continents are encouraged to develop their own regional programmes of ship radiometry supported by their own national or regional funding sources for ocean monitoring. However, in order to meet the exacting quality standards required by GCOS for underpinning global SST climate records in a cost-effective manner, it is very desirable that these various activities are co-ordinated within a collaborative network, to ensure that the data they acquire meet the quality threshold for ingestion into a SST Reference Dataset (currently located at the Centre for Data Archival (CEDA) at the Rutherford Appleton Laboratory (RAL) in the UK).

Co-ordination is needed:

- so that the regions covered by different teams complement each other to achieve effective global coverage;
- to ensure consistently high quality measurement standards across all participants;
- to promote best practice in the recently emerged methodology of infrared shipborne radiometry to measure skin SST;
- to facilitate intercalibration of ship radiometers;
- and to encourage operational collaboration such as teams sharing the maintenance of instruments at opposite ends of transoceanic ship routes.

There is already evidence of growing shipborne radiometry activity developing in other parts of the world, such as the Asia-Pacific rim, making it feasible to envisage collaboration as a means to expanding total coverage. It is reasonable to suppose that those starting to work with ship radiometers will be interested in the benefits of creating a network that links them to others working in the same field. There is a strong case for arguing that the establishment of a SRN is highly desirable as a means of facilitating mutual assistance amongst its members to help them to fulfil the diverse requirements which must be satisfied if measurements of SST from shipborne radiometers are to be recognised as high quality scientific data.

2. The Elements of a Shipborne Radiometry Network

The elements which are needed to make up the activity of a SRN are presented in more detail in this chapter. Most of them are essential for a SRN although some of the ideas floated could be considered as optional, depending on whether members consider them to be necessary.

2.1 Principles of the SRN

The character of the proposed SRN is that it should be based on the concept of voluntary engagement by organisations and individuals concerned with shipborne radiometry, working together on shared activities which benefit the common interests of those who participate.

Its broad aim is to promote the rapid development of the recently emerged methodology for measuring skin SST using shipborne radiometry, in order to produce reliable measurements of SST that can serve the ocean and climate science communities as independent reference temperature datasets.

Its underlying ethos is to aim for the highest standards of scientific professionalism in developing the methods and technology of ship radiometry, and in setting and monitoring standards of quality control for the retrieval of skin SST measurements from ship radiometric data.

The scope of its activity can cover 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 National Metrology Institute (NMI) reference standards,
- agreeing formats for skin SST data retrieved from ship radiometers, and
- setting procedures for quality control in order to meet agreed standards of accuracy.

The scope should also include promoting dialogue with the user communities of skin SST reference data (e.g. satellite SST validation, air-sea gas flux measurement, upper ocean hydrography etc.) although this should be by interaction with, rather than duplication of, organisations already promoting such dialogue (e.g. GHRSST, Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Ship Observations Team (SOT)).

As a collaborative organisation, the SRN should initially be structured to respond to the requirements of its members, in a bottom-up responsive approach. Nonetheless, once it has developed the methods and controls for quality control of instruments and data, it will need to adopt a more formal structure in which individuals are delegated authority to perform certain tasks.

Initially at least, no independent budget or funding requirement is envisaged for the SRN. Any costs incurred by participants must be covered by the baseline funding that supports their ship radiometry activities. This should not be a constraint for a body which intends to be a mutual support network. Activities which necessarily require specific funding, such as engaging a NMI to organise an instrument calibration intercomparison exercise, must be externally funded, just as they would if the SRN did not exist. However, it is envisaged that the formation of a coherent community for shipborne radiometry will serve to enhance the case for appropriate agencies to support such activities. The initial costs of limited staff time to spin up the SRN are already covered by work packages in the UK government funding to RAL Space and the University of Southampton for ongoing satellite SST validation work based on shipborne radiometry.

2.2 Membership and Governance

Any person or group that are active in developing, deploying or evaluating shipborne radiometers to measure SST, and those who have a requirement to use the SST data which radiometers acquire, are welcome to engage in the SRN. Individuals or groups who are considering moving into this field of work, including research students and early-career scientists and engineers, are also welcomed. Additionally, the SRN will welcome involvement by those in related organisations (e.g. GHRSST, JCOMM) with an interest in actively linking the SRN to those other groups.

For the SRN to function effectively, it will be important for a few people to be delegated responsibility to ensure that the network fulfils its purpose effectively. It is intended that the mechanism for doing this will be decided when a core membership has been established.

For the initial phase of establishing the network, up to one year, those taking the lead, with time allocated to do so, are Dr Werenfrid (Fred) Wimmer (WW) of the University of Southampton (UoS), Ocean and Earth Science (OES), based at the National Oceanography Centre, Southampton (NOCS), UK, and Dr Tim Nightingale (TN), of RAL Space, Harwell, Oxford, UK.

2.3 Developing a rational network of SOO lines

The SRN will seek to develop the capacity amongst its members to place radiometers on SOO lines which span the major oceans of the world, with the aim of regularly sampling skin SST in regions representative of diverse oceanographic conditions and different atmospheric conditions, particular covering those regions where the retrieval of SST from a dual-view sensor is likely to be sensitive to such differences. It is envisaged that this element of the SRN might develop as follows:

1. Invite radiometer users around the world to join the SRN.
2. Gather information about the typical coverage (routes and repeat frequencies) of existing ship radiometry activities, and whether such data would be available, in principle, for inclusion in a global SST reference dataset for satellite SST validation.
3. Review the initial coverage in the light of the requirements of the long term SLSTR validation programme.
4. Within the SRN, discuss the feasibility for altering SOO lines where there is duplication, or extending SOO lines to expand the coverage geographically, without needing to increase instrument numbers or staff effort.
5. Through discussion across the SRN, identify shipping companies that are supportive of hosting shipborne radiometers.
6. Identify opportunities for new routes that facilitate collaboration between network members, e.g. SOO lines between the home ports of two SRN partners, allowing the checking of each other’s radiometers when the SOO calls at the distant port.
7. Examine what further coverage would be feasible for the existing groups if more radiometers were available.
8. Identify oceanographic institutions which do not use shipborne radiometers at present but which are well placed as nodes to expand the global mesh of routes.
9. Draw up a route development plan that would provide adequate global coverage for the continuous validation of SLSTR and other satellite SST data, identifying potential SOO lines, potential additional SRN partners, and the number of new instruments needed.
10. Seek support from interested global agencies to implement the plan

2.4 Promoting best practice

More generally, since shipborne radiometry is a fairly new technology, there is a lot to be gained by sharing of experience in technical issues and best deployment practice. The approach for the SRN will follow closely the International Space Science Institute (ISSI) best-practice document entitled “Guidance for the use of radiometers in the field for the accurate measurement of skin sea-surface temperatures” (Section 3.2.3 explains the role of ISSI). The handbook covers the following areas:

1. Radiometer design
    a. Self calibration
    b. Detector design
    c. Black bodies
    d. Data Acquisition
    e. Instrument pointing
    f. Optical system and filters
    g. Environmental protection
2. Calibration
    a. Internal
    b. Laboratory tests
3. Mounting
    a. Mounting on ships
    b. Mounting on other platforms
    c. Operational considerations
4. Ancillary data collection
    a. GPS position and time
    b. Ship navigation data
    c. Metrological information
        i. Wind
        ii. Surface radiation
        iii. Subsurface temperature
        iv. Air temperature and humidity
5. Data
    a. Internal data acquisition
        i. Time stamping
        ii. Measurement sequence
        iii. Housekeeping data
    b. Data format
    c. Data processing
        i. Quality assurance
        ii. SST retrieval
        iii. Data transmission and archiving
    d. Uncertainty budget
    e. Long term archiving
        i. Field data
        ii. Calibration records

2.5 Traceability of radiometer calibration to NMI reference standards

When skin SST measurements derived from ship radiometers are to be used for validating climate data records, then quality standards set by the Global Climate Observing System (GCOS) must be met, including the need to provide traceability of a shipborne radiometer's calibration to internationally recognised infrared radiometric sources. In principle this also demands that the measurement uncertainties inherent in the radiometer's mode of operation are characterised, modelled and experimentally confirmed, by reference to standard radiometers or radiation sources held by a NMI such as the National Institute of Standards and Technology (NIST) or the National Physical Laboratory (NPL). To achieve this, intercalibration exercises for existing ship radiometers have been arranged every few years since 2000 (see section 3.2.2), most recently under the auspices of QA4EO (Quality Assurance for Earth Observations, an initiative of the Group on Earth Observations (GEO) / Committee on Earth Observation Satellites (CEOS)). Such events allow the performance quality of different radiometers to be directly compared under the scrutiny of an independent arbiter. The resultant competition has tended to stimulate subsequent quality improvements across all the radiometers involved.

It is proposed that the SRN should incorporate such exercises within its regular activities. It is inherent in the nature of calibration exercises that they must be organised by an independent body, normally a NMI, in order to ensure independence of the results. However, it would be the responsibility of the SRN to ensure that such exercises are planned regularly, and funding sought from an appropriate agency (e.g. CEOS) that has international oversight for environmental data validation. Ideally long lead-times are desirable to allow owners of radiometers to plan these events into the instrument deployment schedule. However, the SRN may also be able to develop an approach which allows portable laboratory blackbody sources to be used as secondary references to transfer traceability to those sensors which are not available to participate in a particular NMI-organised calibration event. The SRN will also maintain records of the results of NMI calibration events, and these will form a part of the traceability audit for skin SST data produced by each radiometer.

2.6 Radiometer intercomparison exercises

Side by side intercomparison exercises at sea add another component to the traceability of radiometer measurements. It is difficult to verify the ‘per SST’ measurement uncertainty budgets of radiometers at laboratory or shore-based comparisons as described in section **Error! Reference source not found.**; however a partial verification of the at-sea uncertainty budgets can be achieved by comparing two or more radiometers at sea. The SRN can organise such comparisons on existing SOO routes and thereby assess the validity of members’ uncertainty budgets.

2.7 Quality control of Radiometric SST data

The activities in 2.5 and 2.6 are concerned with validating the accuracy and evaluating the uncertainty models of individual radiometers. Activity 2.5 also confirms the traceable absolute accuracy of laboratory infrared radiance sources used for local validations before and after each radiometer is deployed at sea. These are necessary, but not sufficient, precursors for being able to provide quality control for skin SST measured by ship radiometers.

Systems need to be set in place to ensure that any data entered into an international reference database of skin SST meet particular quality standards. Such standards will refer to the calibration reports from 2.5 and 2.6, and also require adherence of radiometer deployments to operational protocols, including pre-and post-deployment validation using a properly characterised portable blackbody source. Current best practice is to characterise the uncertainty in the end-to-end derivation of skin SST from the radiometric measurements, leading to an uncertainty model which estimates the uncertainty of each individual skin SST recorded throughout a deployment. The full quality audit of data needs to combine all these factors. No formal set of protocols has yet been established, although some proposals have been drafted.

In the same way that the protocols for quality assessment of satellite SST data have been developed and standardised within the forum of GHRSST, which brings together expertise from across the satellite SST producer and user communities, there is a need for a forum for producers and users of ship radiometric SST to establish protocols and quality standards of those data. The proposed Ship Radiometry Network seems to be the appropriate body to do this, provided it clearly includes the interests of data users from climate monitoring and operational oceanography since these are the users who need to have confidence in the data.

Related to the quality control of ship radiometry data is the format for archiving the skin SST reference dataset, since it must contain the information required to establish the confidence and quality of every data point. A data format already been prototyped by Tim Nightingale and reviewed by the ISSI working group (see section 3.2.3). This provides a starting point for SRN consideration, but should be open for discussion. Similarly a set of protocols for validation of ship radiometry have been proposed by (Donlon *et.al.*, 2014) but should be open to modification when a wider group of expertise is assembled within the SRN.

2.8 Evolution of shipborne radiometer design and capability

The SRN will provide a forum for technical discussions between those involved in the design of ship radiometers and those who use them, with a view to improving the design of radiometers in relation to factors such as:

- Protection from rain and spray;
- Improved accuracy of SST retrieval;
- Improved endurance to increase deployment times for autonomous operation between servicing;
- Reducing detector noise;
- Measuring additional properties (e.g. air temperature, concentration of atmospheric CO_2);
- Reducing cost;
- Reducing size and weight.

It will be important in such discussions to create an environment that respects the intellectual ownership of particular instrument designs without constraining the creative flow of new ideas.

3. Towards a Shipborne Radiometer Network

This section identifies the activities, programmes of work (completed and ongoing), and international overseeing bodies that are relevant to the proposed SRN. The SRN will need to find the most appropriate way to engage with these activities to the mutual benefit of both.

3.1 Groups for co-operation activities already in existence

3.1.1 GHRSST

The Group for High Resolution Sea Surface Temperature is an international group, which brings together satellite SST data producers, users and scientists for the purpose of improving the quality and applicability of SST data products by adopting a complementary approach to combining data from different sources (Donlon *et al.*, 2007). The GHRSST Science Team co-ordinates the data production and related research, with special focus on diurnal variability, validation and inter-comparison of GHRSST products, as well as on improving retrieval algorithms and re-analysis[1].

A number of the potential members of the SRN already form part of the ST-VAL group which co-ordinates the GHRSST validation activities. However, while the ST-VAL group provides a forum for the validation activities, it does not coordinate the *in situ* measurements and relies on other organisations, such as JCOMM (see next section), to organise the data collection and data dissemination.

3.1.2 JCOMM

JCOMM is the umbrella organisation, sponsored jointly by the World Meteorological Organisation (WMO) and the Intergovernmental Oceanographic Commission (IOC) under which the worldwide marine meteorological and oceanographic communities work in partnership, in order to respond to interdisciplinary requirements for met/ocean observations, data management and service products. It seems sensible that the SRN should be related to JCOMM although JCOMM at present does not directly serve the

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[1] See more at: https://www.ghrsst.org

needs which SRN is intended to meet. Within JCOMM, shipborne radiometry fits within the Operations Programme Area (OPA) which oversees activities such as:

- SOT, the subgroup most relevant to ship radiometry;
- DBCP, the Data Buoy Co-operation Panel;
- JCOMMOPS, the JCOMM *in situ* Observations Programme Support; and
- Argo, the global float array.

3.2 Related research and development initiatives

3.2.1 CASOTS

“Combined action for the study of the ocean thermal skin” (CASOTS), was a Concerted Action that took place in the mid 1990s within the European Union Environment and Climate Programme to promote collaboration between research groups interested in measuring the thermal skin of the ocean.

The programme aims were: (a) to create a co-operative community of ocean skin temperature researchers and climate scientists using sea surface temperature, by co-ordinating European collaboration; (b) to increase European expertise in the measurement and climate applications of SST through meetings with selected international experts; and (c) to exchange practical experience and information on skin temperature measurements, techniques and problems, through workshops and exchange visits.

The main practical outcomes from the CASOTS project were the CASOTS blackbody (Donlon *et al.*, 1999) and the Southampton radiometer intercomparsion exercise in 1996. These outcomes led to a more standardised approach in infrared radiometer verification and traceability to SI standards. The CASOTS II blackbody (Donlon *et al.*, 2014) is an evolution of the original CASOTS blackbody now used by most ISAR operators.

3.2.2 Intercalibration exercises

In order to satisfy the traceability requirement of infrared radiometers a number of intercalibration exercises have been held, the first one taking place in 1996 at Southampton, followed by the first Miami intercomparsion workshop in 1998. Further intercomparison workshops were held in Miami in 2001 (Barton *et al.*, 2004; Rice *et al.*, 2004). and in 2009 at two locations, NPL in London and the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami (Theocharous *et al.*, 2010; Theocharous & Fox, 2010).

The two most recent workshops showed good agreement between the radiometers and the calibration blackbodies. The laboratory part of the 2001 Miami intercomparison (Rice *et al.*, 2004) compared five blackbodies (BB), the NIST water bath BB, the Miami BB, the Jet Propulsion Laboratory (JPL) BB, and the CASOTS BB from RAL and Southampton. The results showed that NIST and Miami BB agree with each other within the NIST TXR (transfer radiometer) uncertainty of 50mK. The CASOTS and the JPL BB's only agree well when the water bath temperature is around ambient temperature, when measured with the TXR. The at-sea part of the Miami 2001 intercomparison (Barton *et al.*, 2004) showed that the five radiometers used in the exercise (the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), the Scanning Infrared Sea Surface Temperature Radiometer (SISTeR), ISAR, JPL nulling radiometer, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Atmospheric Research – Model 11 (DAR011)), agree with each other within a small bias of 2-53 mK and with a standard deviation of 66 to 150 mK. However while the at-sea part of the intercomparison took place over a rather short, two day, duration and did not expose the instrument to a wide range of atmospheric condition, it did confirm that the radiometers compared are suitable for satellite validation.

Some of the shortcomings in the Miami 2001 intercomparisons, such as a short field time and not using a blind test for the BB comparison led to some changes for the 2009 intercomparison, most notably that NPL acted as the independent NMI in charge of the experiments. Again the intercomparison was split into a laboratory part and a field part, the laboratory part having a further two components, one in London and one in Miami, to show the comparability of the NIST and NPL standard. Only the SISTeR and ISAR radiometers participated in both the NPL and the NIST part. This revealed differences between the radiometer measurement and the directly measured temperature of the NPL BB, ranging from -24 mK to +126 mK (Theocharous *et al.*, 2010). The field part of the intercomparison, which was held at the pier at RSMAS, showed that M-AERI, SISTeR and ISAR measured the water temperature within 100mK of each other. The laboratory experiments at NPL showed that the CASOTS RAL BB has uncertainties of +/-15mK and the CASOTS II BB uncertainties of +/- 30mK. The BB intercomparison at Miami showed that both the Miami BB and the CASOTS II BB have similar uncertainties which lie within the combined uncertainties of the TXR.

3.2.3 ISSI working group

During 2012-14 an expert working group has been convened on four occasions under the auspices of ISSI to review the scientific and technical issues associated with how Climate

Data Records (CDRs) of SST can be produced from satellite observations to meet the quality standards required by GCOS. The group, chaired by P. Minnett of Miami, will shortly deliver an expert report on the subject. This is expected to identify satellite observations, supported by validation using ship radiometers that have calibration traceable to NMI standards, as the most promising approach. This report from an internationally recognised source is expected to provide a sound theoretical underpinning for the SRN.

3.2.4 Sentinel-3 Validation Team for Temperature

The S3VT-T subgroup gathers and coordinates expertise and validation activities for SLSTR as laid out in the Sentinel-3 Cal/Val plan.

S3VT-T define ship-borne radiometer measurements as fiducial measurements which provide traceability to SI act as an absolute standard.

3.3 Current status of shipborne radiometers capable of NMI traceable calibration

Research and development has taken place for at least 20 years to develop infrared radiometers on ships. As far as is known, there are today just three designs of instrument that continue operationally to deliver skin SST observations with an uncertainty of less than 0.1 K; M-AERI, SISTeR and ISAR.

3.3.1 M-AERI

M-AERI is a seagoing development of the Atmospheric Emitted Radiance Interferometer (AERI), and is a robust, accurate, self-calibrating, seagoing Fourier-transform interferometric infra-red spectroradiometer that is deployed on marine platforms to measure the emission spectra from the sea surface and marine atmosphere. The M-AERI performs spectral measurements in a range from 3 µm to 18 µm and uses two blackbodies, one heated and one at ambient temperature to calibrate each measurement. The instrument is traceable to NIST standards and is calibrated before and after each deployment against a NIST traceable laboratory blackbody. Figure 1 shows the M-AERI SST data collected to date. The instrument (see Figure 2) is described in detail by Minnett et al. (2001).

A M-AERI mark 2 instrument has been developed in recent years and is now operational, using the same optical components but a much more integrated version of the electronics that halves the size of the instrument. The M-AERI mark 2 development also led to a revisit of the optical components which led to an even smaller version of M-AERI, the mark 3 (Figure 3).

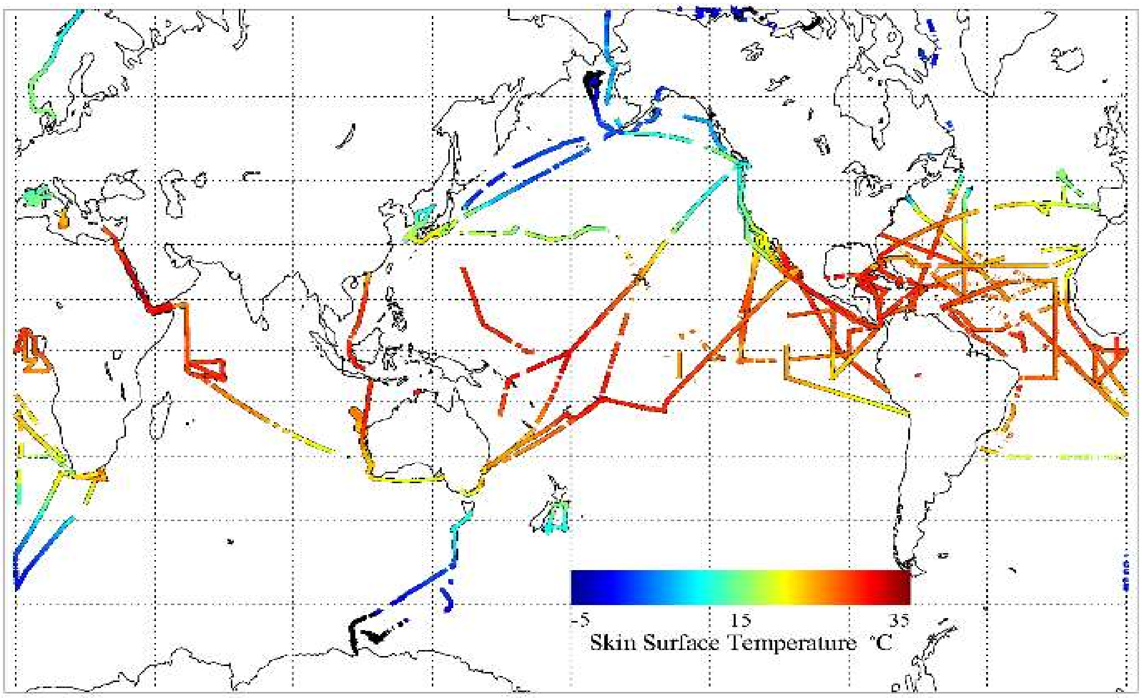

Figure 1: M-AERI data plot (1997-2013).

Figure 2: M-AERI mark 1 (left) and mark 2 (right) on the R/V Ron Brown.

Figure 3: M-AERI mark 3 in the laboratory at RSMAS.

3.3.2 SISTeR

Nightingale (2007) describes SISTeR as a compact and robust chopped self-calibrating filter radiometer. Its dimensions are approximately 20 by 20 by 40 cm and it weighs about 20 kg. The instrument is divided into three compartments containing the fore optics, scan mirror and reference blackbodies, and a small-format PC with signal processing and control electronics. SISTeR has been designed to survive in a maritime environment while maintaining its calibration over extended periods. The instrument has a DLaTGS (deuterated, L-alanine doped triglycine sulphate) pyroelectric detector with a filter wheel containing three narrow-band filters centred at 3.7 µm, 10.8 µm and 12.0 µm , matching those in the ATSR instruments. It also has a scan mirror and a ZnSe window protecting the instrument from the elements. SISTeR has two BBs fitted, one being at ambient temperature and the other at approximately 10 K above ambient temperature. Figure 4 shows the SISTeR instrument. All SISTeR measurements are traceable to NPL and NIST standards. SISTeR is currently deployed on the Cunard liner *Queen Mary 2*.

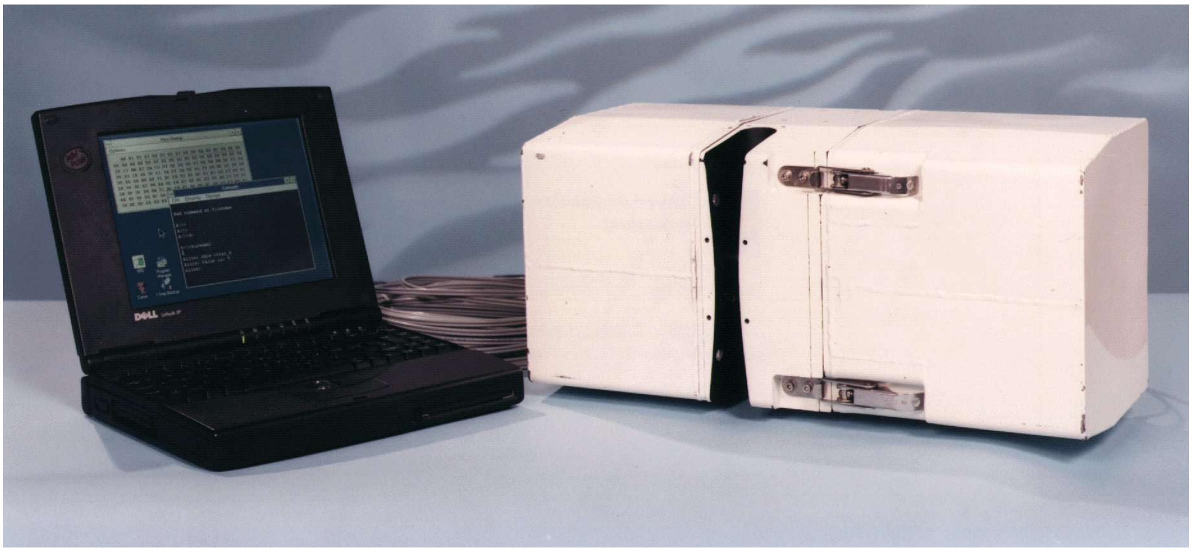

Figure 4: SISTeR with data logging computer.

3.3.3 ISAR

The Infrared Sea surface temperature Autonomous Radiometer developed at the University of Southampton (Donlon *et al.*, 2008) is a single channel (waveband, 9.6 – 11.5 µm) scanning radiometer with two internal calibration blackbodies It is normally deployed to view the sky and sea at zenith angles of 25° and 155° respectively, and the sea surface emissivity corresponding to the 25° incidence angle is taken as 0.9916.

Two radiometers are used interchangeably, being switched approximately every three months to allow inspection, servicing and replacement of any worn or optically degraded parts. The exposed optical elements of ISAR, including the scan mirror, are protected from bad weather by a shutter that closes when precipitation, spray or excessive atmospheric dust is detected by an optical rain gauge, so that ISAR can operate autonomously. Based on the experience of routine deployments for validation of AATSR (Wimmer et al , 2012) over more than 10 years, it has been demonstrated that ISAR can deliver measurements of SST with an uncertainty less than 0.1 K during untended deployments of up to 4 months.

With a view to promoting wider use of shipborne radiometers, the ISAR team at UoS have already built and sold a number of ISAR instruments to other groups around the world who wished to start their own shipborne radiometry monitoring programmes, in pursuit of a diversity of scientific or operational applications. Some of these groups continue to interact with UoS for “after-sale” advice about instrument maintenance and operating software, or for mutually beneficial discussions about improving best practice in ship radiometry. These groups form a core of potential SRN members around which it is hoped to grow the network.

The distribution of ISARs around the world, the groups that own them and approximate geographical regions covered are listed in Table 1.

Table 1: List of all ISAR instruments built by 2014.

ISAR	Operator
1	University of Miami, USA
2	University of Southampton, UK
3	University of Southampton, UK
4	University of Miami, USA
5	Ocean University, China
6	Japan Aerospace Exploration Agency (JAXA)
7	Royal Navy, UK
8	Danish Metrological Institute (DMI)
9	Woods Hole Oceanographic Institute, USA
10	CSIRO, Australia

3.4 Progress to date in developing a ship radiometer network

3.4.1 UK collaboration between RAL and UoS

Whereas between 2004 and 2012 the ISAR team at UoS and the SISTeR team at RAL worked independently to acquire skin SST data for validation of AATSR, in 2012 it was decided that they should start collaborating more closely. This has been co-ordinated by the UK government agencies that fund the two programmes separately. This provides the opportunity for the teams to operate more efficiently while allowing each group to contribute its unique strength.

Thus UoS is focusing on the ship operations, monitoring deployments of both ISAR on the Bay of Biscay ferry route and SISTeR on the *Queen Mary 2* transatlantic cruise liner. RAL is concentrating on issues such as protocols for traceable radiometer calibration, data quality control, archive formatting, and establishing a ship radiometer database which will form the foundation of the skin SST Reference Database mentioned in this document. Both groups will continue to support and maintain their different radiometers, but already they are discovering useful cross-fertilisation of technical insights.

The reason for mentioning this here is its relevance to the development of the SRN:

- The efficiency savings from collaboration have delivered the extra headroom to allow both Fred Wimmer (WW) and Tim Nightingale (TN) to devote some time to developing the SRN during 2014-15;
- Between their different experience and skills they cover most of the task elements that the SRN will address;
- Learning first-hand the benefits of collaboration between the two groups has provided insight into the potential gains available to all members of the SRN if it can achieve international co-operation that spreads capabilities across the globe;
- A side-by-side intercomparison deployment of ISAR and SISTeR on the *Queen Mary 2* is planned later in 2014, the first example of what is proposed in section 2.6.

During the current project year 2013-2014, the groundwork has been laid for establishing the SRN, with WW at UoS planning and consulting with potential participants about the operational structure of the network. In parallel, TN at RAL has been addressing the quality assessment and data management aspects of a network, preparing protocols for the data validation, intercalibration of radiometers, and defining the format for the archiving of ship radiometer observations, including uncertainty estimates. Both WW and TN have been members of the ISSI working group.

3.4.2 Other developments

A number of the potential players in a shipborne radiometer network already meet at GHRSST Science Team meetings, which provides a forum in which discussions take place while the objectives, scope of activities and the content of a formal network agreement is worked out between the participants. WW introduced the concept of the network at the 14th GHRSST Science Team meeting at Woods Hole in June 2013 and he convened a brief discussion session for potential SRN member, outside the main programme, during GHRSST-XV Science Team meeting at Cape Town in June 2014.

4. Development Plan

4.1 Strategic Approach

As indicated in section 2.1, the initial stages of establishing a new international network for voluntary co-operation must be encouraged to grow from the bottom up because a core membership needs to be established before the shape that the network needs to take to serve its members can be established. This makes it difficult to spell out a detailed implementation plan. What follows is therefore a fairly sparse outline of intentions with a timescale matched to the need to have an effective network in place by 2015, before SLSTR is launched.

4.2 Initial responsibilities

WW will lead on promoting the SRN amongst the groups engaged in deploying ship radiometers and will liaise with the JCOMM SOT. He will develop the instrument-based and deployment-focused elements of the network summarised in sections 2.3, 2.4 and 2.8.

TN will lead on developing the quality control and calibration tools (sections 2.5, 2.6 and 2.7). He will promote membership amongst the data validation and climate user communities.

4.3 Initial tasks (April - June 2014)

a) (TN & WW) Establish the network core functions.
    - Name
    - Logo
    - Web presence
b) (WW & TN) Identify potential core members.
c) (WW & TN) Plan the agenda for a meeting within GHRSST-XV ST.
d) (WW) Email open invitation to potential core members.
    - Send a copy of the SRN Development Plan;
    - Send a draft agenda for special meeting at GHRSST-XV;
    - Invite responses to specific questions, by end April;
    - Ask for suggestions of other potential members.
e) Chase and collate responses from initial mailing.
f) Tabulate information gathered from response to questions as a basis to present at GHRSST-XV special meeting.

- Numbers of people interested;
- Geographical locations;
- Coverage of their radiometer deployments (geographical, frequency of return);
- etc.

4.4 Implementation Timescale

The implementation timescale will be formalised after a user consultation at the GHRSST-XV meeting in Cape Town.

4.5 Evaluation of Progress

The evaluation of progress will be formalised after a user consultation at the GHRSST-XV meeting in Cape Town.

5. Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ARC	ATSR Reprocessing for Climate
CASOTS	Combined action for the study of the ocean thermal skin
CEDA	Centre for Data Archival
CEOS	Committee on Earth Observation Satellites
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAR-011	CSIRO Division of Atmospheric Research –Model 11
DBCP	Data Buoy Co-operation Panel
DEC	Data Exploitation Contract
DECC	Department of Energy and Climate Change
DLaTGS	deuterated, L-alanine doped triglycine sulphate
ESA	European Space Agency
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GHRSST	Group for High Resolution SST
IOC	Intergovernmental Oceanographic Commission
ISAR	Infrared Sea surface temperature Autonomous Radiometer
ISSI	International Space Science Institute
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JPL	Jet Propulsion Laboratory
M-AERI	Marine-Atmosphere Emitted Radiance Interferometer
NIST	National Institute of Standards and Technology
NMI	National Metrology Institute
NOCS	National Oceanography Centre, Southampton
NPL	National Physical Laboratory
OES	Ocean and Earth Science
OSTIA	Met Office operational sea surface temperature analysis
QA4EO	Quality Assurance for Earth Observations
RAL	Rutherford Appleton Laboratory
RSMAS	Rosenstiel School of Marine and Atmospheric Science
S3VT-T	Sentinel-3 Validation Team for Temperature

SCL	Space ConneXions Limited
SISTeR	Scanning Infrared Sea Surface Temperature Radiometer
SLSTR	Sea Land Surface Temperature Radiometer
SOO	ships of opportunity
SOT	Ship Observations Team
SRN	Shipborne Radiometry Network
SST	sea surface temperature
ST-VAL	GHRSST working group for surface temperature validation
TN	Dr Tim Nightingale
UoS	University of Southampton
WMO	World Meteorological Organisation
WW	Dr Werenfrid Wimmer

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