Protocols to maintain the SI traceability of shipborne radiometers

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Acronyms

AD	Applicable Document
ACDD	Attribute Convention for Data Discovery
CEDA	Centre for Environmental Data Analysis
CF	Climate Forecast
GPS	Global Positioning System
HDF5	Hierarchical Data Format
HF	High Frequency (radio)
Ifremer	Institut français de recherche pour l'exploitation de la mer
ISO	International Organization for Standardization
JCGM	Joint Committee for Guides in Metrology
L2R	Level 2 Radiometer format
NetCDF	Network Common Data Form
QA4EO	Quality Assurance for Earth Observation
RAL	Rutherford Appleton Laboratory
RD	Reference Document
RF	Radio Frequency
SD	Secure Digital
SI	Système international d'unités
SISTeR	Scanning Infrared Sea surface Temperature Radiometer
SST	Sea Surface Temperature
SSTskin	Sea Surface Skin Temperature
USB	Universal Serial Bus
UTC	Coordinated Universal Time / Temps Universel Coordonné

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1 Introduction

A number of groups around the world have been measuring SST with thermal infrared radiometers since the 1990s (Jessup et al. [1], Minnett et al. [2], Nightingale [3], Donlon et al. [4]). The Protocols used by these groups for the measurements of SST are all similar and have been evaluated against each other at TIR inter-comparisons (Barton, et al. [5]). However, a more formal version of these protocols was only recently published by Minnett, et al. [6] and Donlon et al. [7][8].

Donlon et al. [7][8] define a set of 9 protocols intended to guide any group collecting shipborne infrared radiometer data for use in satellite SST validation activities towards a “common sense” best practice that will improve the quality and reduce the uncertainty in the satellite SST validation process. Each individual deployment of a ship-borne radiometer is highly specific and the protocols summarised below are considered as a minimum requirement for an *in situ* radiometer.

The following sections reproduce the methodology of Donlon et al. [8] and discuss some practical considerations for the implementation of the protocols.

2 Protocols to maintain the SI traceability of shipborne radiometers

2.1 Definition of measurement methodology

The exact methodology used to measure SSTskin using a ship-borne radiometer shall be fully documented. This shall include:

- A full technical description of the radiometer instrument (e.g. spectral characteristics, sampling characteristics, measurement technique, a description of the instrument internal calibration approach).
- The spectral characteristics of the measurement system (i.e. instrument band-pass).
- The value used for seawater emissivity.
- How the component of “sky radiance” reflected at the sea surface into the radiometer field of view is properly addressed (Donlon and Nightingale [9]).
- A description of the radiometer mounting arrangements and the geometric configuration of the radiometer with all measurement angles accurately documented.
- A description of steps taken to ensure that measurements are free of ship effects (e.g. ship’s bow wave, significant emission from the ship superstructure, emissions from ship exhaust plumes etc).
- On-board instrument software used (e.g. version, release date)
- Data post processing software (e.g. version, release date)
- Any other aspect considered relevant to better understanding the quality of the measurements obtained.

2.2 Definition of laboratory calibration and verification methodology and procedures

Infrared radiometers typically used for satellite validation work are calibrated using on-board calibration reference radiance sources (black bodies). The purpose of performing pre-and post-deployment verification using external reference blackbodies is to assess the accuracy of the internal calibration system, and to provide a link in an unbroken chain of comparisons linking the shipborne radiometer to an SI reference. The exact methodology and procedures used to perform a laboratory calibration and verification of a radiometer shall be defined and documented (Theocharous and Fox [10], Theocharous et al. [11])

2.3 Pre-deployment calibration verification

Following the defined methodology and procedures developed in Section 2.2, the calibration performance of a ship borne radiometer used for satellite product validation shall be verified prior to deployment using an external reference radiance source that is traceable to SI standards over the full range of sea surface temperatures expected for a deployment at sea. Ideally, the verification measurements should be repeated over a range of ambient temperatures representative of the instrument operating conditions.

The radiometer hardware, on-board configuration, on-board processing software, and data post processing software shall not be modified in any physical way between the calibration and the sea deployment (with the exception of dismounting and transporting the instrument to the calibration laboratory).

2.4 Post-deployment calibration verification

Following the defined methodology and procedures developed in Sections 2.2 and 2.3, the calibration performance of a ship borne radiometer used for satellite product validation shall be verified after deployment.

2.5 Uncertainty budgets

Ship-borne radiometer calibration and verification data shall be linked to uncertainty budgets determined in agreement with defined National Standards Laboratory protocols (JCGM [12]) accounting for a comprehensive range of uncertainty sources (e.g. contributions from instruments, processing, deployment restrictions, and environmental conditions etc.). An uncertainty budget for the end-to-end SSTskin measurement shall be provided.

2.6 Improving traceability of calibration and verification measurements

Efforts should be made where possible to define community consensus schemes and measurement protocols for calibration and verification. Well-documented data processing schemes and quality assurance criteria shall be established to ensure consistency and traceability to SI standards of in situ radiometer measurements used for satellite validation. Ship-borne radiometer users must participate regularly in inter-comparison “round-robin” tests and comparison with international standards to establish SI traceability for their data. International radiometer and reference blackbody inter-calibration experiments (Kannenberg [13], Rice et al. [14], Theocharous and Fox [10], Theocharous et al. [11]) are essential under this protocol and the need for regular activities of this type is obvious.

Radiometer intercomparisons should follow QA4EO principles and guidelines (Fox and Greening [15]) and should include the following components:

- A laboratory-based comparison of the calibration processes for radiometers and verification of blackbody sources used to maintain calibration of radiometers and provide traceability to SI,
- Field inter-comparisons using pairs of radiometers to build a database of knowledge over a several years.

The benefits of radiometer inter-comparison work include:

- Establishment and documentation of protocols and best practice for radiometer and reference blackbody inter-comparisons for future use,
- Establishment of community best practices for radiometer deployments,
- Evaluation and documentation of differences in IR radiometry primary calibrations and performances under a range of simulated environmental conditions,
- Establishment and documentation of formal SI-traceability and uncertainty budgets for participant blackbodies and radiometers,
- Evaluation and documentation of protocols and best practice to characterise differences between radiometer measurements made in field (land, ocean, ice) operational conditions.

2.7 Accessibility to documentation

Documentation describing ship-borne radiometer calibration and verification process shall be made available to the user community to promote peer review and ensure appropriate promulgation of knowledge on ship borne radiometer calibration and verification.

2.8 Archiving of data

Ship-borne radiometer calibration and verification data should be archived following good data stewardship practices providing access to records by research teams on request. Laboratory calibration and verification data shall be published in a format that is freely and openly available to users of the data.

2.9 Periodic consolidation and update of calibration and verification procedures

Ship-borne radiometer calibration and verification measurement procedures should be consolidated as a result of a critical review of those currently documented in peer-review literature or already included in compilations produced by former programs and "lessons learned" from deployments aboard ships and in the laboratory. Consolidated protocols should be maintained and published.

3 Practical considerations

This section discusses some of the practical considerations when implementing the shipborne radiometer protocols.

3.1 Field deployments

3.1.1 General

The following considerations are valid for ship or fixed platform installations:

- Work safely. Can the mounting position be accessed safely? What extra measures are required to ensure safe working? Have you carried out a risk assessment? There is usually a legal requirement to ensure safe working and this is in any case good practice. There may be a number of unfamiliar hazards when working on ships, including: working at height, falling objects (on others below as well as on yourself), sudden movement, strong winds, slippery surfaces and difficulty communicating or attracting attention when in isolated positions.
- How much power does the instrument need? Can this power be provided by the platform (ship or fixed)?
- What wiring is needed for the instrument? Can the instrument access existing infrastructure or does specialized wiring need to be installed? If specialized wiring is needed, the platform operator may require that this be installed by their preferred contractor, which can increase lead times for the installation.
- Does the instrument need a dedicated data logging system and does the logging system need be close to the instrument?
- If near real time data transmission to shore is needed to monitor the instrument status, the installation of a dedicated system (e.g. an Iridium modem) may be required. In some cases, this can be achieved using the platform's existing internet infrastructure.
- Ensure that your instrument and any ancillary equipment are properly maintained. Inspect and test them before each deployment, and clean, refurbish or replace parts as required.
- Recalibrate components essential to your traceability chain (e.g. black body thermometers, external reference thermometers) on a regular basis.
- Validate the instrument calibration immediately before and after every deployment. Do not alter the instrument in any way between the validation and deployment measurements.
- With increasing angles from nadir, the emissivity of sea water decreases and its rate of change with angle increases. Choose sea viewing angle that is small enough to control sensitivity to knowledge of emissivity and large enough to avoid reflections from the platform structure. Common choices of viewing angle are between 15° and 55° from nadir.
- Ensure that the instrument is mounted so that it has unobstructed views to undisturbed seawater, and to the sky at the complementary angle. Confirm and record the mounting orientation.
- Avoid contamination of the measurements by exhaust and other effluents, such as hot air outlets.
- Mounting the instrument on the platform will, in general, require a specialized instrument frame or adaptor. Consider the ease of instrument installation and removal in the mounting

design. If the instrument needs alignment in a frame, include alignment marks. Alternatively, use a self-aligning mount.

- When deploying, make sufficient functional tests of the instrument and ancillary equipment to ensure that data is being recorded and that at the least, any functions essential for instrument safety are operating correctly (e.g. weather protection, uninterruptable power supply). If not, remove the instrument, repair and redeploy.
- Be aware of other factors that may affect your deployment and the quality of your data (e.g. RF interference from HF radio antennas and RADAR, window washing sprays, engine exhaust, stray light from navigation lights and searchlights)
- Consider collecting additional contextual measurements, including SST at depth (hull or inlet sensors), air temperature, humidity, wind speed and direction, longwave downwelling radiation.

3.1.2 Mounting on ships

For a ship-mounted radiometer the following points should be considered:

- The instrument should be mounted so that the sea view is of undisturbed water forward of the bow wave and the sky view is clear of obstructions (i.e. superstructure). This normally means a mounting position as far forward on the ship as practicable. Such a position should also avoid views of heated engine cooling water, which is usually discharged behind the bow wave.
- To avoid sea spray and, in difficult conditions, green water, the instrument should be mounted as high as practicable. This could be a forward instrument mast (e.g. research vessel) or the bridge roof on a vessel with a bridge near to the bow of the ship (e.g. cruise ship, passenger ferry).
- On research ships that hold station for instrument deployments or for sampling, bow thrusters can disrupt the thermal skin. In windy conditions, the ship is often oriented with the working deck or winch to windward, so that the wind does not push the ship onto the wire. As the ship is pushed downwind, water in the radiometer field of view may have passed under the hull and become mixed.
- Consider how the ship’s roll may modulate the emissivity of the sea surface and the pointing of the sky view (Donlon and Nightingale [9]).
- If possible, install the instrument on a part of a passenger ship where passengers do not have access.
- Other installation considerations include: predominant wind direction, sun angle, possible superstructure shielding from wind, spray and the sun and the potential effects on the measurement.

3.1.3 Mounting on other platforms

Additional considerations for installations other than ships:

- The power supply might be difficult to sustain if the platform is powered by solar cells and batteries. How can the instrument be made safe if power is interrupted?
- Tidal effects should be considered before installing the instrument in coastal regions.
- Sun angle might have a bigger effect than on ships as the instrument will have the same relative position to the sun every day.

- Water may move round or under a platform, driven by tides or prevailing winds. This may disrupt its temperature structure.

3.2 Data

- In addition to high level products (e.g. geolocated SSTs), always record data at the lowest level that is available (e.g. detector counts), so that it can be reprocessed if required. Where possible, record the complete state of the instrument, including internal temperatures, mechanism positions and other housekeeping data.
- In all products, always include a reliable UTC timestamp (GPS receivers are a good source), and include geolocation data or ensure that external geolocation data are available.
- Where available, use agreed data standards (e.g. netCDF, HDF5), metadata standards (e.g. CF convention, ACDD, ISO 8601) and product formats (e.g. L2R).
- Ensure that all data are recorded securely. If possible, make local secondary copies during measurement campaigns on independent media. A USB stick or SD card may be suitable.
- Assure the quality of your data. Check the format. Check any flags. Check that the data is realistic.
- Plan for the long-term archival and maintenance of your data and any associated documentation (Section 3.3). National data centres (e.g. CEDA, UK; Ifremer, France) may be appropriate.

3.3 Documentation

Document the instrument, data format, data processing methods and deployment, including:

- The spectral characteristics of the instrument,
- The value used for seawater emissivity,
- Any calibration coefficients, including those for on-board thermometers,
- The SST algorithm,
- A description of the radiometer mounting arrangements and the geometric configuration of the radiometer with all measurement angles accurately documented,
- The steps taken to ensure that measurements are free of ship effects (bow wave, radiative emission from the ship superstructure, emissions from ship exhaust plumes),
- On-board instrument software used (version, release date),
- Data post-processing software (version, release date),
- Any other aspect considered relevant to better understanding the quality of the measurements obtained.

Make the documentation publicly available and reference it in the data products.

3.4 Calibration sources and performance verification

- The calibration target should be capable of being operated at fixed temperatures or at a temperature that changes very slowly compared with an instrument calibration cycle (no more than a few kelvin per hour).

- The thermometric temperature of the target must be an accurate representation of its brightness temperature, or alternatively, the brightness temperature must be derived from the thermometric temperature(s) using a calibration target mathematical model with an accuracy sufficient for the calibration verification.
- The calibration target brightness temperature uncertainty must, at the most, be equal to the required verification uncertainty and preferably should be significantly smaller.
- The calibration target aperture must be sufficiently large and its cavity design such that the target aperture does not vignette the instrument beam, and the instrument field of view falls completely on the intended surfaces of the target cavity.
- Where possible, the instrument should be operated in the orientation and with the viewing geometry used for sea surface observations.
- All calibration measurements must be securely archived (Section 3.2).

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