

Fiducial Reference Measurements for Satellite Ocean Colour Phase-2

Measurement Procedure Document (MPROCD) FRM4SOC2-MPROCD

Title	Measurement Procedure for operating the TRIOS/RAMSES radiometers to obtain Fiducial Reference Measurements (MPROC)
Document reference	FRM4SOC2-MPROC
Project	EUMETSAT – FRM4SOC Phase-2
Contract	EUMETSAT Contract No. EUM/CO/21/460002539/JIG
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Document Control Table

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2	1	0	09.06.2022	First complete draft	RBINS (Kevin Ruddick)
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5	3	1	24.03.2023	Footnote on temporal variability during measurements added to section 7.6.	RBINS (Kevin Ruddick)

Distribution List

Public at <https://frm4soc2.eumetsat.int>

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Acronyms and Abbreviations

Acronym	Description
AAOT	Acqua Alta Oceanographic Tower
AATSR	Advanced Along-Track Scanning Radiometer
AD	Applicable Document
ADUM	Architecture Design and User Manual document
AERONET-OC	The Ocean Color component of the Aerosol Robotic Network
AMT	Atlantic Meridional Transect
API	Application Program Interface
ARC	Assessment of In Situ Radiometric Capabilities for Coastal Water Remote Sensing Applications
BRDF	Bidirectional reflectance distribution function
Cal	Calibration
CEOS	Committee on Earth Observation Satellites
Char	Characterization
CLI	Command-Line interface
DP	Data Package
DR	Documentation-related Requirements
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FOV	Field of view
FRM	Fiducial Reference Measurements
FRM4SOC	Fiducial Reference Measurements for Satellite Ocean Colour
GEO	Group on Earth Observations
HQ	Headquarters
IOCCG	International Ocean-Colour Coordinating Group
IPR	Intellectual Property Rights
IR	Instrument-related Requirements
KO	Kick Off meeting
LUT	Look Up Table
MAVT	MERIS and Advanced Along-Track Scanning Radiometer Validation Team
MERIS	Medium Resolution Imaging Spectrometer
MVT	MERIS Validation Team
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NMI	National Metrology Institute
OC	Ocean Colour
OCDB	Ocean Colour Database
OCR	Ocean Colour Radiometer
PDF	Portable Document Format
PPE	Personal Protective Equipment
PR	Protocol-related Requirements
QA	Quality Assurance
QA4EO	Quality Assurance framework for Earth Observation
QC	Quality Control
PMP	Project Management Plan
RSP	Remote Sensing and Products Division
RD	Reference Document
S ₃	Sentinel-3
S ₃ VT-OC	Sentinel-3 Validation Team – Ocean Colour group
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SIRREX	SeaWiFS Intercalibration Round Robin Experiments
SI	International System of Units
SOW	Statement of Work
SST	Sea Surface Temperature

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Acronym	Description
TO	Tartu Observatory, University of Tartu
TR	Technical Report
TSM	Total suspended material
VAL	Validation
VIM	International Vocabulary of Metrology

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Applicable documents

Table o-1. Applicable documents

ID	Description
[AD-0]	Statement of Work for FRM4SOC phase2, EUM/RSP/SOW/19/1131157
[AD-1]	ESA's contract no 4000117454/16/I-SBo (https://frm4soc.org)
[AD-2]	D-70: Technical Report TR-2 "A Review of Commonly used Fiducial Reference Measurement (FRM) Ocean Colour Radiometers (OCR) used for Satellite OCR Validation" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-3]	'Statement of Work for Database of Ocean Colour In Situ Fiducial Reference Measurement Collections for Calibration and Validation', EUM/OPSCOPER/SOW/17/956607.
[AD-4]	IOCCG Protocol Series (2019). "Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry". Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada. (Available at https://ioccg.org/what-we-do/ioccg-publications/oceanoptics-protocols-satellite-ocean-colour-sensor-validation/)
[AD-5]	K. Ruddick et. al., "A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water", Remote Sens. 2019, 11(19), 2198; https://doi.org/10.3390/rs11192198
[AD-6]	K. Ruddick et. al., "A Review of Protocols for Fiducial Reference Measurements of Downwelling Irradiance for the Validation of Satellite Remote Sensing Data over Water", Remote Sens. 2019, 11(15), 1742; https://doi.org/10.3390/rs11151742
[AD-7]	International Network for Sensor Inter-comparison and Uncertainty assessment for Ocean Color Radiometry (INSITU-OCR), http://ioccg.org/wpcontent/uploads/2016/02/INSITU-OCR-white-paper.pdf .
[AD-8]	D-80a: Technical Report TR-3a "Protocols and Procedures to Verify the Performance of Reference Irradiance Sources used by Fiducial Reference Measurement Ocean Colour Radiometers for Satellite Validation" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-9]	D-80b Technical Report TR-3b "Protocols and Procedures to Verify the Performance of Reference Radiance Sources used by Fiducial Reference Measurement Ocean Colour Radiometers for Satellite Validation" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-10]	Bialek, A.; Douglas, S.; Kuusk, J.; Ansko, I.; Vabson, V.; Vendt, R.; Casal, A.T. Example of Monte Carlo Method Uncertainty Evaluation for Above-Water Ocean Colour Radiometry. Remote Sens. 2020, 12, 780. https://doi.org/10.3390/rs12050780
[AD-11]	TR-9 Technical Report "Results from the First FRM4SOC Field Inter-Comparison Experiment (FICE) of Ocean Colour Radiometers" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-12]	IOCCG Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation (https://ioccg.org/what-we-do/ioccg-publications/ocean-opticsprotocols-satellite-ocean-colour-sensor-validation/)

Reference documents

Table o-2. Reference documents

ID	Description
[RD-1]	ESA's contract no 4000117454/16/I-SBo (https://frm4soc.org)

	<p>EUMETSAT Contract no. EUM/CO/21/460002539/JIG Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC Phase-2)</p>	<p>Date: 24.03.2023 Page 8 (51) Ref:FRM4SOC2-MPROC Ver: 3.1</p>
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Executive Summary

This document describes a detailed Measurement Procedure for performing supervised, shipborne above-water reflectance measurements with a 3-sensor TRIOS/RAMSES system.

The measurement equipment is described in detail, including advice on how to mount equipment on a ship. A detailed packing list is provided of all hardware needed (radiometers, cables, data acquisition box RS232/USB adapter, etc.). Requirements on the measurement scientist (education, measurement training, safety training) are briefly mentioned.

Pre-cruise preparation of equipment and, especially software, is described with full details, including screenshots, provided for use of the MSDA_XE software with TRIOS/RAMSES radiometers.

Pre-departure onboard preparation of equipment and crew are described, including software testing with screenshots from MSDA_XE.

The procedure for on-station measurements is described, including the list of software operations (buttons to press), with screenshots.

Post-cruise preparation of data for processing is described with details and screenshots of the MSDA_XE data export functions. Data acquired and extracted using this Measurement Procedure should be well-formatted for ingestion into the FRM4SOC Community Processor.

Data processing, to be implemented in user or Community Processor software is described up to the level of measurement data value. Data corrections based on instrument characterisation and calculation of measurement uncertainty will be described in future FRM4SOC2 deliverables.

The use of the NIR Similarity Spectrum for Quality Control and the approach recommended for BRDF are outlined.

Finally, applicability of this Measurement Procedure to cases other than that of supervised, shipborne above-water reflectance measurements with a 3-sensor TRIOS/RAMSES system are considered and future perspectives for evolution of this Measurement Procedure and of the underlying Measurement Method are outlined.

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1. Introduction

1.1 Scope of the document

The objective of this document is the specification of a measurement procedure to operate TRIOS/RAMSES and Seabird¹/HyperOCR radiometers to obtain Fiducial Reference Measurements.

The requirements originate from [AD-0], the Statement of Work (SoW) for FRM4SOC phase-2 (Doc.No.:EUM/RSP/SOW/19/1131157, v5B, 29 April 2020). However, the original title of D-6 has been modified from “Measurement requirements and protocols when operating Fiducial Reference Measurement (FRM) Ocean Colour Radiometers (OCR) and processing data deriving Remote Sensing Reflectance for Satellite Validation – phase 2” to “**Measurement Procedure for operating the TRIOS/RAMSES radiometers to acquire Fiducial Reference Measurements**”. This document provides the users with

- A very detailed and prescriptive “recipe” to follow, ensuring that even inexperienced users – naturally having a technical background on field measurements – can unpack a new instrument of either TRIOS/RAMSES or Seabird/HyperOCR² class, and make a Fiducial Reference Measurement.
- A very detailed prescriptive set of steps that ensures that data acquisition is made in such a way that the raw data can be ingested into the HyperInSPACE [<https://github.com/nasa/HyperInSPACE>].

The quality of “procedure” of this document (see following sections on terminology) responds to the request of a critical mass of water quality scientists willing to have access to such prescriptive easy-to-follow guidelines instead of documents responding to the more abstract/generic definition of “measurement method”, hoping that it will ease the OCR users’ path to the adoption of FRM principles and thus achieve a higher endorsement rate of such principles. This request has been explicitly endorsed by the inland and coastal water communities in the Workshop on the Validation of Satellite-derived Optical and Water Quality Parameters for Coastal and Inland Waters held at the University of Wisconsin-Madison (USA) in June 2022 [31].

1.1.1 Terminology – VIM replaces “protocol”

The first clarification indicates a significant departure from previous “protocol” documents such as the NASA Ocean Optics Protocols [1] and the IOCCG protocols [2] and the FRM4SOC Protocols Reviews [3,4], which refer to the generic *Measurement Method*, as defined in the VIM [5] as the “generic description of a logical organization of operations used in a measurement”. It seems that the desired scope of D6 is more that of a *Measurement Procedure*, as defined in the VIM [5] as the “detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a measurement result”. The VIM [5] further notes that “A measurement procedure is usually documented in sufficient detail to enable an operator to perform a measurement”. In view of the significant confusion generated by the difference in terminology between the OC community, which uses the term “protocol” to cover a range of concepts from Measurement Principle through Measurement Method to Measurement Procedure, and the metrological community, which avoids entirely the term “protocol” and defines these 3 concepts differently via the VIM [5]; **it is proposed here to banish use of the ambiguous term “protocol” and adopt henceforth instead the metrological terminology for “Measurement principle”, “Measurement Method” or “Measurement Procedure” according to the VIM [5]** - see Appendix A of FRM4SOC-2 Deliverable D2 for a complete summary of proposed terminology. The proposed new title for D6 therefore uses the VIM [5] terminology for Measurement Procedure.

1.1.2 Link between D6 and HyperInSPACE Community Processor

The second clarification given above has emerged from preparatory work and discussions on the FRM4SOC-2 branch of HyperInSPACE, where it has become clear that HyperInSPACE is most easily developed if there is a very strictly formatted set of raw input data. This can be achieved if the upstream data acquisition follows strictly a single Measurement Procedure. The proposed new title for D6 therefore indicates this stricter limitation on possible Measurement Procedures, as needed for feasibility of a community processor such as HyperInSPACE. More

¹ The official company name is “Sea-Bird Scientific”, but for simplicity the name “Seabird” is used in this document, as this is common practice in this community. Some scientists refer to the HyperOCR as a “Satlantic” instrument, since the Satlantic company first produced it, but was taken over by Sea-Bird Scientific in 2011.

² The highest level of detail, down to “which button to press” and accompanying screenshots, is achieved for the TRIOS/RAMSES instrument user, although much of this document is also relevant for Seabird/HyperOCR users.

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information on the FRM4SOC2 development and use of the HyperInSpace Community Processor are given in deliverables D15-D21.

1.1.3 Measurement Procedure

Providing the user with a very detailed prescriptive set of instructions to follow and the related advantage for the CP of having to ingest raw data with a very well-defined and restricted data format clearly has, as corollary, a limitation on the measurement instruments (“measurement system” according to VIM terminology), platforms (mounting structure such as a ship, offshore platform, drifting float, etc.), water types (deep/shallow, stable/fast-varying, Case 1 or 2, etc.) and practices (supervised/automated) where this Measurement Procedure can be implemented. The FRM4SOC protocols review [3,4], focussed on uncertainty estimation, covering 4 Measurement Methods for water-leaving radiance and 3 Measurement Methods for downwelling irradiance via two peer-reviewed publications totalling 65 densely worded pages. These methods were considered in a rather generic way, with possible application to a variety of measurement instruments, including both fast multispectral and slower hyperspectral OCR, a variety of mounting structures and water types and covering both supervised and unsupervised, i.e. automated measurements.

On the other hand, a Measurement Procedure is usually defined by a single team/organisation for internal use only and is tailored to the measurements instrument, mounting structure, water type and practices that are locally available/adopted.

It is therefore unusual and rather challenging to write a (detailed and prescriptive) Measurement Procedure for external use that can be applied by many teams/organisations in diverse circumstances (and to do so in a finite number of pages). Nonetheless, this exercise is as challenging as necessary if the OC community is willing to achieve FRMs not only obtained in territories with a stable presence of scientists highly specialised in remote sensing of ocean/water colour, i.e. with deep understanding of the interaction of VIS/NIR light with natural water bodies. This preferential community of people will be likely the only one able to interpret and reduce to concrete actions (e.g. buttons in the MSDA_XE software) the generic and abstract nature of the “measurement methods”. In this sense, “measurement procedures” are complementary to “measurement methods” and are intended to be understood additionally by highly-educated technical users without the need of them being remote sensing scientists. Satellite-borne OC observations have a worldwide coverage and in turn need an in situ validation data set which is worldwide representative.

In agreement with this, the approach adopted here is to define a set of conditions (instrument, platform, water type, practice) and define a Measurement Procedure that is appropriate for that set of conditions. If the measurement scientist cannot conform to these conditions, then more expertise will be needed to assess whether Fiducial Reference Measurements can still be acquired.

The present Measurement Procedure is based on that used internally by RBINS (formerly “MUMM”) since 2000 for supervised shipborne abovewater reflectance measurements, e.g. [6], and follows the Measurement Method of [7], combining the “above-water” method for water-leaving radiance [3] with the “irradiance sensor” method for downwelling irradiance [4]. This is equivalent to Method 1 for abovewater radiometry in the NASA Ocean Optics Protocols [1], is a direct follow-up of the “MERIS abovewater reflectance” method described in the REVAMP protocols and is further discussed in Chapter 5 of the IOCCG protocols [2].

1.1.4 Scope of the Measurement Procedure

This document provides a Measurement Procedure **for supervised, shipborne, abovewater** measurement of water reflectance using **TRIOS/RAMSES radiometers**.

Unsupervised measurements are typically made by more experienced users, who have developed their own Measurement Procedure and own automated data acquisition software (not using the MSDA_XE Graphical user Interface typically needed for supervised measurements).

While the present Measurement Procedure is written for supervised shipborne measurements, much of the Procedure (equipment list, data acquisition steps, etc.) is identical for supervised measurements from fixed platforms or can obviously be transposed. Such variants are discussed in section 9.1.

1.1.5 Measurement Method

The Measurement Procedure described here is based on the Measurement Method studied for a wind-roughened sea surface by [7], used by many, many scientists, recommended by early NASA protocols [1] and the more recent IOCCG protocols document [2] and reviewed in Chapter 4 of [3].

Two radiance radiometers are deployed above water from a ship to measure a) upwelling radiance, $L_u(0^+, \theta_v, \Delta\varphi)$, for viewing nadir angle, $\theta_v = 40^\circ$, and viewing azimuth angle¹ relative to sun, $\Delta\varphi = 135^\circ$ (or without loss of generality $\Delta\varphi = 225^\circ$), and b) downward (sky) radiance, $L_d(0^+, 180^\circ - \theta_v, \Delta\varphi)$, in the “mirror” direction which reflects at the air-water interface into the water-viewing direction - see Figure 1. A third irradiance radiometer measures downwelling irradiance, E_d .

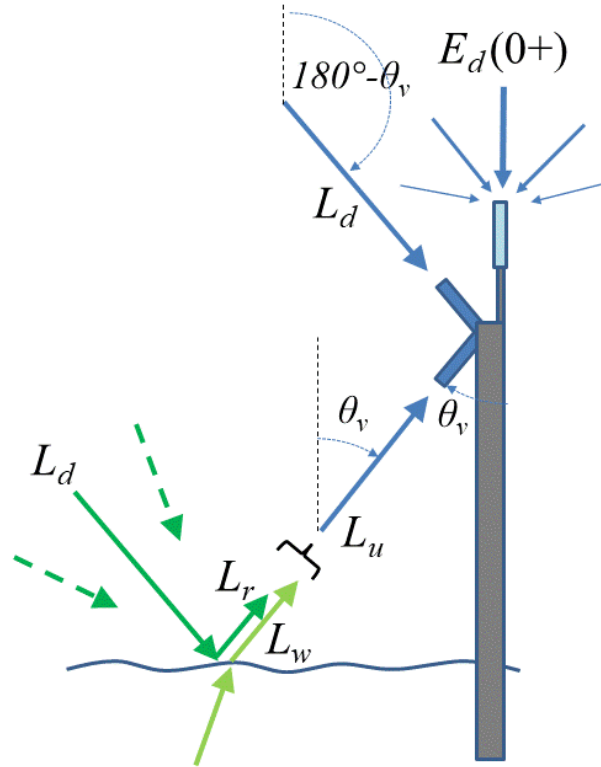


Figure 1. Schematic of above-water radiometry with measurement of sky radiance, L_d , and removal of skyglint radiance, L_r . Dashed arrows indicate that contributions to the skylight reflected at the air-water interface come from directions that are not directly measured by the L_d radiance sensor, including possible contributions from the direct sunglint direction. Reproduced from [3].

Then the water-leaving radiance in the water-viewing direction is estimated from the Measurement Equation:

$$L_w(\theta_v, \Delta\varphi) = L_u(0^+, \theta_v, \Delta\varphi) - L_r(\theta_v, \Delta\varphi) \quad (1)$$

where the skyglint radiance, L_r , which cannot be measured directly, is typically estimated as a multiple of the downwelling sky radiance, L_d , by

$$L_r(\theta_v, \Delta\varphi) = \rho_F L_d(0^+, 180^\circ - \theta_v, \Delta\varphi) \quad (2)$$

where ρ_F is a coefficient that represents the fraction of incident skylight that is reflected back towards the water-viewing sensor at the air-water interface and is the Fresnel reflectance coefficient for a flat water surface, or is called here the “effective Fresnel reflectance coefficient” for a roughened water surface. Radiative transfer simulations to estimate ρ_F for different wind speed and sun zenith angle have been performed by [7] and are tabulated at https://www.oceanopticsbook.info/packages/iws_l2h/conversion/files/rhoTable_AO1999.txt.

The shortcomings of this Measurement Method, particularly for moderate and high wind conditions, are reviewed in detail by section 4 of [3] and the references cited therein. Despite these shortcomings and in the absence of a consensus on an improved Method, this Method is used as the basis of the current document. However, the current

¹ Here the azimuth angle convention is defined as in [7,3,2] with $\Delta\varphi = 135^\circ$ pointing away from sunglint. However, care is needed to check azimuth angle convention since some references may use $\Delta\varphi = 45^\circ$ to denote pointing away from sunglint.

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Measurement Procedure (and associated FRM4SOC Common Processor) can be updated in the future to accommodate improvements provided that such improvements affect only the data processing, e.g. modelling of ρ_F , and do not require modification of the data acquisition.

1.1.6 Disclaimer

Description of a detailed and prescriptive Measurement Procedure is not possible without specification of equipment models and manufacturers. The specification of such equipment models and manufacturers does not, however, imply any endorsement by EUMETSAT or the FRM4SOC-2 consortium contractors of this equipment. The specification of particular brands associated to complementary equipment - such as connectors - or software - such as operative systems - responds to either particular choices of the TriOS/RAMSES manufacturers themselves to work with such brands or to procedures which were satisfactorily tested by the FRM4SOC2 Consortium with such equipment. The use of other complementary equipment/software is encouraged if it results equally satisfactory.

2. Measurement Equipment and pre-cruise preparations

The current section describes the equipment (hardware and software) needed for application of the present Measurement Procedure. If these conditions are not met then the measurements may still be Fiducial Reference Measurements, but further expertise and analysis will be required.

2.1 Measurement equipment - ship

This Measurement Procedure is defined for shipborne measurements and has been implemented previously for range of ships from small boats (length 5m) up to large Research Vessels (e.g. 100m).

The optimal geometry (minimum impact of ship shading/reflection on water target) for the **water-viewing radiometer** is achieved by mounting at the prow of the ship, as far forward and as high as possible – see Figure 2. The aim here is to minimise obstruction of the skydome, as seen from the water target, by the ship superstructure. This can be visualised by imagining a fish-eye camera photograph looking upwards from the point on the water surface which is at the centre of the field of view of the water-viewing radiometer. The ship should therefore be chosen to allow safe access to the fore-deck for instrument installation and cleaning preferably with a high and forward-mounted “crow’s nest” or, failing that, high guard rails or a platform at the prow.

The ship should preferably be “sharp-nosed” rather than “wide-nosed” to minimise ship shadow/reflections at the water target. In this context, small rigid inflatable boats are often suboptimal unless a forward-extending boom can be used to deploy instruments further away from the boat.

In even the best cases there will always be some optical contamination of the water-viewing measurement (since the ship, mounting structure and radiometer are not fully transparent!). While ships can be chosen and mounting structures can be designed to minimise such optical contamination, their impact on measurements will still need to be assessed in the FRM context – see section 4.2.3 of [3] for an overview and [8] and [9] for model and experimental studies of such effects for a fixed platform.

The optimal geometry for the **downwelling irradiance** sensor is above all other objects, including ship superstructure elements such as masts and any people that may be walking around or working on the ship. The sensor should also be easily and safely accessible for installation and regular cleaning, a constraint that is usually contradictory to location at the highest point of a ship (usually at the top of a mast). For most ships a compromise is adopted by mounting the irradiance sensor above normal head height typically on a temporary pole/mast structure. However, for many ships there may still be some higher structures whose impact on measurements will need to be assessed – see section 2.2.2 of [4].

There are usually no difficulties for the **sky-viewing** measurement, which can be made easily from any ship.

In addition to the abovementioned optical considerations, the ship should obviously be designed for the expected sea state and allow at least one measurement scientist to be onboard in addition to the crew. The quality of the water reflectance measurement is strongly affected by pitch (especially for the water-viewing and irradiance measurements), roll (especially for the water-viewing and irradiance measurements) and yaw (for the water-viewing measurement). Horizontal stability of the ship in expected wave conditions is therefore important, with a preference for large ships in high wave conditions. Avoidance of sea spray on optical surfaces is also important, implying a preference for high mounting location with respect to expected wind wave and ship prow wave height. See later (section 5) for use of lens caps when not measuring.

The ship will generally have a stable and uninterruptible 240V AC power supply in Europe, as needed to run the data acquisition PC and TRIOS/RAMSES and HyperOCR equipment. The latter can also be run off a 12V DC supply.

The ship should have a supply of freshwater onboard (either tap or bottled) for cleaning of instruments and cables (but not optical surfaces, for which particle-free milli-Q water is preferred).

The ship should preferably have a dynamic positioning system with bow thrusters, giving an ability to hold the required position and heading during the 10 minutes needed for data acquisition, including during adverse wind and current conditions. During these 10 minutes the ship should not be repositioned, and it may be impossible to perform other measurements simultaneously, e.g. underwater profiling measurements requiring different heading, e.g. with respect to current.



Figure 2 Good locations for installation of abovewater radiometer system on the new Research Vessel Belgica-2. The blue circle shows the optimal location (prow facing-forward) for radiance measurements to avoid optical and hydrodynamic perturbations from the ship. The red circle shows an ideal location for downwelling irradiance measurements, although for safety reasons this may be inaccessible and the blue location may be a reasonable second choice.

2.2 Measurement equipment - OCR Instrumentation

The radiometer measurement system (Figure 3 and close-up of connectors in Figure 4) is composed of:

- 1*TRIOS/RAMSES ACC-VIS hyperspectral irradiance sensor as defined via article number 40S101010 at the class level at <https://www.trios.de/en/ramses.html> with an integrated inclinometer¹ but no pressure/depth sensor.
- 2*TRIOS/RAMSES ARC-VIS hyperspectral radiance sensors as defined via article number 40S201010 at the class level at <https://www.trios.de/en/ramses.html> with no integrated inclinometer and no pressure/depth sensor.
- Tightly-fitting, hard (not soft rubber) and opaque lens caps for 1*irradiance and 2*radiance sensors.
- 3*female and 3*male SUBCONN dummy connectors for the sensors and cable ends, when sensors are disconnected and 3*M8F dummy connectors for the other cable end. The dummy connectors protect connectors when not in use and during installation, particularly in wet (rain, salt spray) conditions.
- 3*waterproof and UV-resistant TRIOS cables with SUBCONN 5-pin male and M8F connectors. A cable length of 50m is typical for shipborne operations, although 100m may be required in some

¹ It is noted that occasional (“pixel 31”) data problems have been encountered when using the RAMSES-integrate inclinometer. While these problems can be easily identified and removed during data processing a better solution in the future may be to use an inclinometer external to the TRIOS system, e.g. interface directly with the PC.

deployments according to the distance between the acquisition PC and the radiometers (allowing for any restrictions on cable runs for the ship being used).

- 1*IPS104 TRIOS power supply and data acquisition interface with mains supply power cord.
- (only if no RS232 port is available) 1*USB/RS232 adapter cable. The Hama 53325 USB 2.0 Type A adapter has been found to give good compatibility with the TRIOS/RAMSES radiometers, IPS104 box and a range of Windows-based PCs, provided the correct device driver is installed. Many USB/RS232 adapters (and associated drivers) do not work properly in this context.
- PC and USB 2.0 memory sticks or alternative medium for data storage – for more details on computer hardware see section 3.1.
- USB 2.0 GPS receiver using NMEA 0183 protocols such as the Navilock NL-602U or similar. A NMEA-compatible GPS integrated inside the PC may also perform satisfactorily, although an external GPS, e.g. attached just outside a window, is preferable if the PC is located in an internal space with poor GPS. The external GPS should be prepared as default if unsure of the GPS signal strength. A cable of sufficient length to enable deployment outdoors should be foreseen. This GPS is accessed by the TRIOS data acquisition software ensuring that the TRIOS data is time-stamped with UTC at all times.



Figure 3 Radiometer measurement system consisting of (from left to right): Multi-socket power board, IPS104 radiometer power supply and data interface box, acquisition PC, RS23/USB adapter grey cable, 3*50m SUBCON/M8F RAMSES cables, box with one irradiance and two radiance TRIOS/RAMSES sensors and dummy connectors and lens caps. No external GPS is shown here since the PC internal GPS is used.

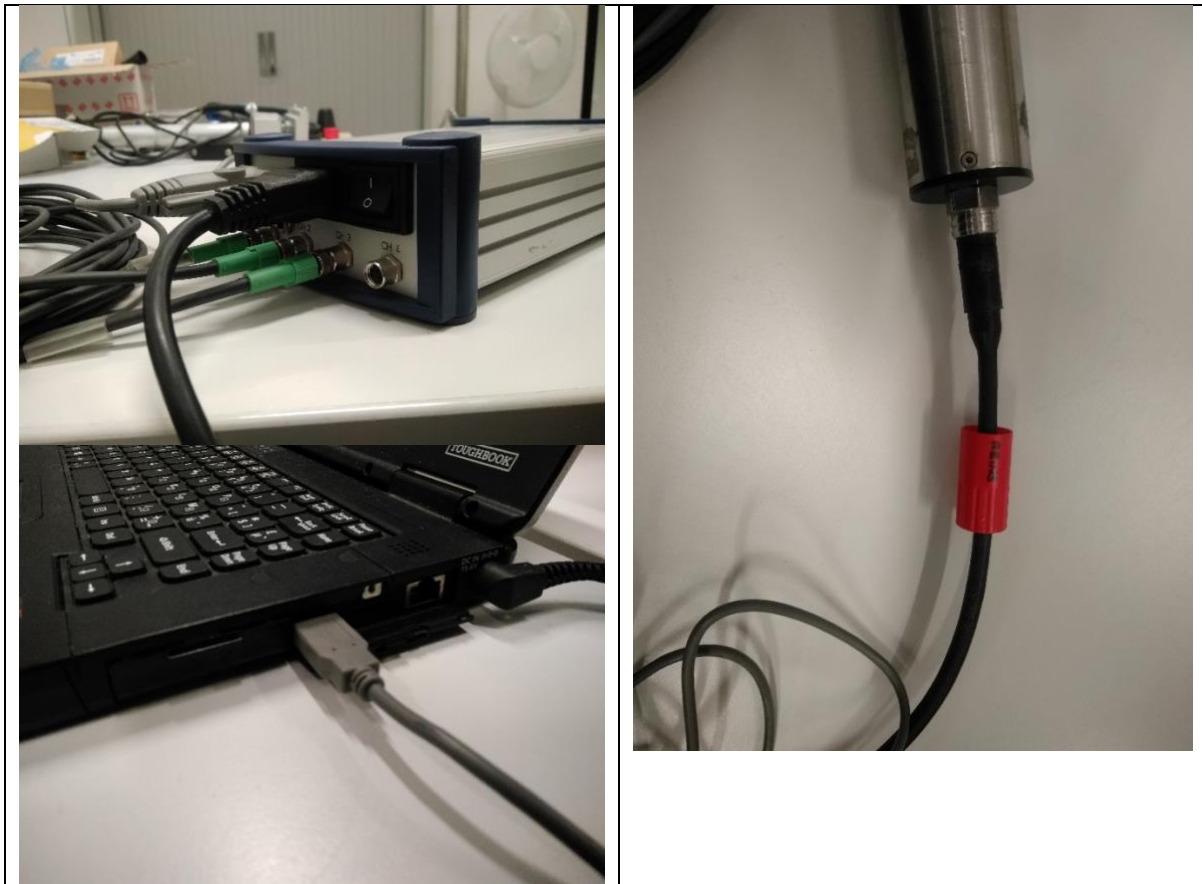


Figure 4 Close up of connections: (top-left) back of IPS104 box top-left grey cable connects to PC via RS232/USB adapter, top-middle black cable is IPS104 power cord, bottom row with green connectors go to the RAMSES sensors; (right) SUBCONN connector at base of RAMSES sensor; (bottom-left) USB connector on cable from IPS104 box.

In addition, the following auxiliary equipment is recommended:

- Optical surface cleaning equipment such as optical paper, e.g. Kimwipes, and particle- and salt-free water, e.g. milli-Q water. Lens-cleaning fluids or wet wipes leaving a surface film or papers leaving surface scratches should not be used.
- Carry cases for the abovementioned equipment, especially well-protected cases for the radiometers, which should be hand-carried whenever possible and well-protected from mechanical shock, and all electrical components which should be protected from water, including rain and seawater, and humidity.
- Digital RGB camera with both normal and fisheye lenses for equipment, water and sky photos; main and spare batteries; charger; cable or wireless PC connection for data transfer, etc.
- User manuals for TRIOS/RAMSES radiometers, MSDA_XE software, latest radiometer calibration certificates, IOCCG protocols document [2], FRM4SOC protocol review papers [3,4], and this Measurement Procedure in hardcopy or digital format.
- Cable ties and tape for safe mounting of the SUBCON/M8F cables. Gaffer tape is recommended for most applications although duct tape is preferred in presence of water (<https://www.tapejungle.com/news/gaffer-tape-vs-duct-tape-whats-the-difference/>).

Where possible spares should be embarked particularly for single point failure items such as radiometers, IPS104 box, RS232/USB adapter, cables, PC, GPS receiver.

2.3 Measurement equipment - radiometer mounting structure

The radiometers will need to be mounted in a frame, which fixes the irradiance sensors pointing at zenith and the radiance sensors at 40° nadir (water-viewing) and 40° zenith (sky-viewing), and which attaches securely

to the ship prow. In view of the different requirements for the irradiance sensor (see section 2.1, this might be mounted on a separate frame/mast higher than the prow. The radiometer frame will typically be of stainless steel for work at sea and will ideally have levelling screws to ensure a horizontal base – see Figure 5.

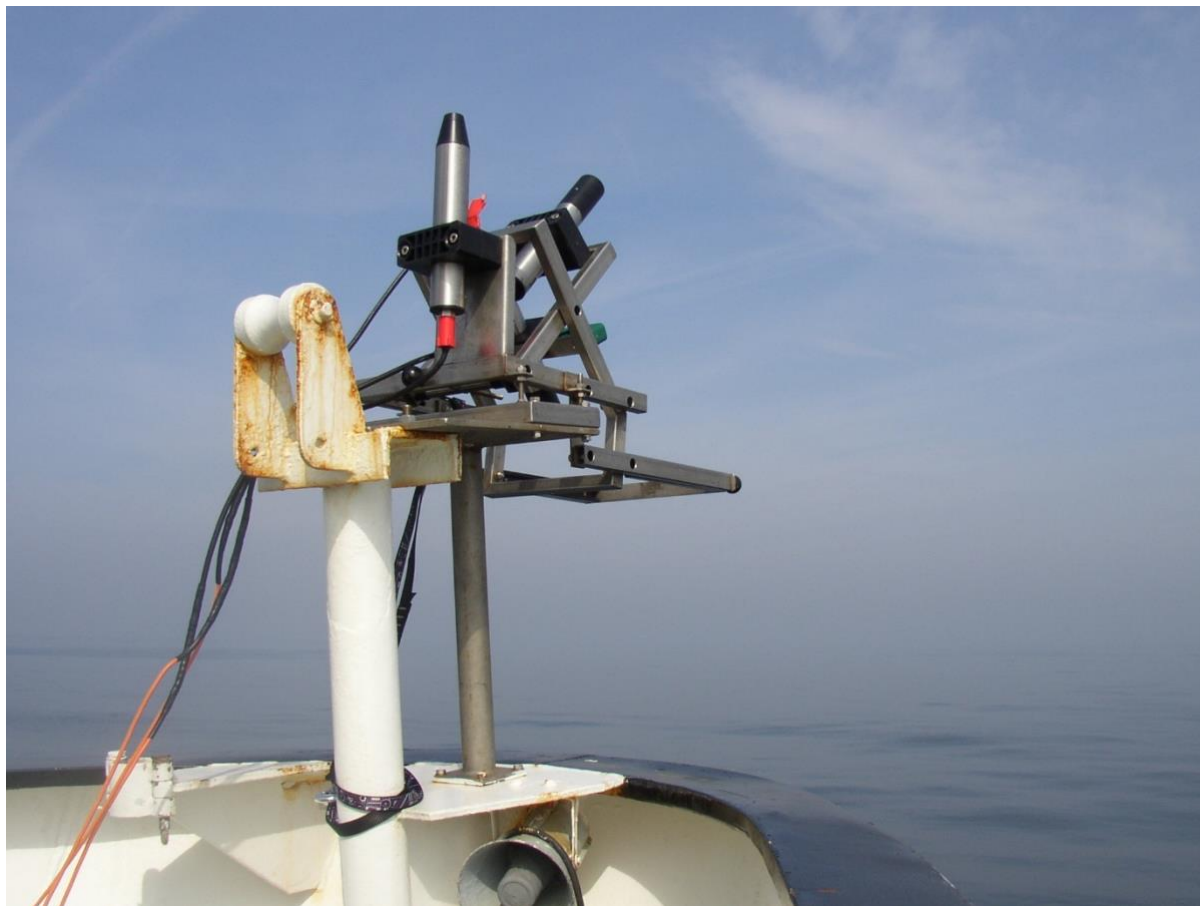


Figure 5 3-sensor abowater radiometer system mounted at prow of ship on a steel frame with levelling screws. Reproduced from [6].

The various components needed for radiometer mounting (frame, sensor clamps, nuts and bolts, spanners, digital inclinometer, spirit levels, safety rope, etc.) should be noted in a cruise-preparation checklist.

2.4 Measurement equipment - other

In addition to the equipment specifically needed for the radiometric measurements (and any other measurements not specified here), scientists should embark the normal cruise equipment and documents, including typically: Logbook, personal safety and comfort equipment, safety certificates/personal safety logbook, notes on safety procedures, cruise plan, personal emergency telephone numbers/emails, equipment technical support telephone numbers/emails, weather forecasts, satellite overpass prediction sheets, etc.

2.5 Measurement scientist

The Measurement Procedure described in the current document can be carried out by an individual measurement scientist with good general scientific/technical education, e.g. university-level. The training requirements are not covered explicitly by this deliverable, although it is expected that the measurement scientist will be previously trained by a scientist with experience in this Measurement Procedure and with the TRIOS/RAMSES radiometers.

The measurement scientist will typically have followed any safety training necessary for work onboard the ship and will be in reasonable physical condition, e.g. for attaching the radiometer frame and laying cables.

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Some equipment preparation, e.g. for attaching the radiometer frame and laying cables, may be facilitated by help from a second person, perhaps from the ship crew.

2.6 Pre-cruise preparations

All equipment should be tested in the laboratory before packing and should further be tested onboard prior to ship departure. If using a ship for the first time, the mounting structure should be tested on the ship a few days prior to cruise departure, preferably with installed OCRs and test data acquisition, to ensure a good mechanical fit, feasible cable runs, good space for the data acquisition PC and IPS104 box and no unforeseen problems.

3. Data acquisition software and pre-cruise preparations

The current section describes the software needed for application of the present Measurement Procedure. If these conditions are not met then the measurements may still be Fiducial Reference Measurements, but further expertise and analysis will be required. In particular the use of data acquisition software recommended here ensures that the acquired data is of the correct format for ingestion into the FRM4SOC2 Community Processor and use of different software is likely to lead to issues of incompatibility between the acquired data and the FRM4SCO2 Community Processor.

3.1 Data acquisition computer hardware, software and documentation

3.1.1 Data acquisition computer hardware

For data acquisition the minimum requirement is for a:

- PC – preferably ruggedized to endure shipborne conditions – with at least 2*USB 2.0 Type A socket, Windows-7 Professional operating system and power cord.

The hardware requirements for a PC are not known explicitly but are not demanding. Any recent PC (e.g. since 2012) should have no problem running the data acquisition software and performing the operations described here. In fact, provided that Internet security risks are avoided, older PCs may function more reliably than newer PCs since newer Operating Systems and Operating System updates may render data acquisition software unusable. It is quite feasible to use old PCs with a RS232 connection, since the original IPS104 hardware and software MSDA_XE software was defined pre-USB. It is common practice to use older PCs for data acquisition potentially with old Operating Systems and/or old interfaces, e.g. USB 2.0. In such a context it may be advisable to isolate the data acquisition PC from the Internet to: a) prevent upgrades, b) avoid security risks.

The MSDA_XE software probably works with other Windows Operating Systems, but compatibility is not guaranteed by the FRM4SOC2 consortium and has not been checked. The TRIOS/MSDA_XE software does not, to our knowledge, work with Linux or MAC/OS. The TRIOS company commented [Sven-Erik Krause, Private Communication, 02/12/2022] that “We had no problem with Windows-10 until now, but can only guarantee Windows-7. There is no development on the software anymore.”

If operating without Internet (e.g. because ship is outside range or because a Windows-7 PC has Internet security issues) then recommended peripherals include:

- USB 2.0 memory stick or alternative medium for daily onboard data backup.
- USB 2.0 memory stick or alternative medium with backup copies of all acquisition software and device drivers (including USB/RS232 device driver) enabling a new installation in case of major PC failure.

If operating with Internet, a simple daily (or even instantaneously synched) backup process should be implemented.

The PC should preferably be of ruggedised type for shipborne work with a high degree of mechanical shock-resistance, some waterproofing (especially sockets and keyboard) and, if the PC is installed outside, with a low glare screen. Long autonomy batteries are also relevant for fieldwork without mains grid supply (although the current document assumes a 240V AC electrical supply). The Panasonic Toughbook CF-54 PC has been found to give very satisfactory and reliable long-term performance, although many other ruggedised PCs may be quite equivalent. Ruggedised PCs are typically an order of magnitude more expensive than normal portable PCs and may be difficult to procure – the cost of a PC failure during shipborne fieldwork (including the loss of data) is, however, often more expensive than the PC itself.

While PCs are typically multi-purpose and may be used for many office functions (email, Internet, calculations, programming, etc.) other onboard functions (data acquisition for other instruments, cruise planning, etc.) as well as leisure activities, every additional usage adds risk of PC failure, which may compromise the high value data acquisition activity either temporarily (loss of time on-station) or permanently (loss of data or the ability to acquire

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data). It is highly recommended to use a dedicated standalone PC, used only for the TRIOS/RAMSES (and GPS) data acquisition and perhaps measurement log and other instrument data backup.

3.1.2 Data acquisition software

For data acquisition the following software, obtained when purchasing TRIOS/RAMSES radiometers, should be installed on the data acquisition PC:

- TRIOS MSDA_XE software version 8.9.2 (2014-04-28) and associated empty.mdb file

Other versions of this software will probably also work, although have not been tested by the FRM4SOC2 consortium and are, therefore, not guaranteed to function compatibly with the FRM4SOC2 Community Processor.

Data inspection is facilitated by:

- Microsoft Access 2000 or similar software capable of reading and manipulating .mdb files

3.1.3 Data acquisition software documentation

The user is assumed to have read the following documents, received when purchasing a TRIOS/RAMSES radiometer:

- MSDA_XE Quick Start Guide, dated 2010-12-06, 40 pages
- MSDA_XE Manual, dated 2013-06-19, 126 pages

These two documents are not limited to the RAMSES sensor but cover many other TRIOS-made sensors for which the powerful MSDA_XE software performs data acquisition and processing, e.g. sections 3-5 of the Quick Start Guide and Sections 7.2-7.7 and 8 of the Manual can be skipped.

The user is also assumed to have the following document, received when purchasing a TRIOS/RAMSES radiometer:

- MSDA_XE Advanced Manual, dated 2012-08-26, 28 pages.

although it is noted that the information and functions described in the last document are not needed for the current Measurement Procedure, except for the useful summary of files provided in section 11, p26

The current document does not repeat instructions from these three Manuals, but adds advice on how to configure and operate the instruments specifically for the purpose of making water reflectance measurements according to the Measurement Method of [7] and acquiring data that will be compatible for ingestion into the FRM4SOC2 Community Processor.

3.2 Pre-cruise hardware operations

Equipment should be fully tested before cruise start to check all hardware and software is functioning and user is fully familiar with software. Hardware is prepared as follows:

- All three radiometers should be setup, e.g. in the mounting frame or on a bench (taking care to fix radiometers and prevent rolling), and lens caps and dummy connectors removed.
- The 3 SUBCONN/M8F cables should be connected to the TRIOS radiometers (SUBCONN) and (M8F) to the IPS104 box (power off). The 3*M8F connections should be pushed into the IPS104 box and secured by twisting the ring – take care to twist just the ring and not the entire connector which will break the connector pins.
- The RS232/USB adapter cable should be screwed into the IPS104 box then connected to the PC.
- Power cords should be connected to the PC and IPS104 box, typically via a multi-socket distribution board with surge protection.
- PC and IPS104 can now be powered on

3.3 The present Pre-cruise MSDA_XE software operations

The present subsection summarises how the MSDA_XE software is configured and prepared before a cruise and should be used in conjunction with the MSDA_XE Manuals described in section 3.1.3. Operations to be carried out on the data acquisition PC, e.g. using MSDA_XE or Windows, are given in **Nyala font**, while filenames are given in **red**.

3.3.1 Copy radiometer data and software received from TRIOS

Install the MSDA_XE software, following instructions from the manufacturer.

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Create a directory for instrument data, e.g. **C:\Users\MyUserName\TRIOS\InstrumentData**

Copy to this directory the instrument data supplied by the manufacturer including:

- **Cal_MyInstrument.dat** file containing TRIOS/ASCII-formatted radiometer sensitivity data
- **Back_MyInstrument.dat** file containing TRIOS/ASCII-formatted radiometer dark pixel data
- **MyInstrument.INI** file containing important instrument data (3rd order polynomial coefficients for the spectrometer wavelength scale, and inclinometer offset and slope calibration coefficients for the irradiance sensor only), but also some MSDA_XE configuration parameters (serial port configuration, database connection, devices last connected, last size of dialog windows, further program configurations).

In the above operations “**MyInstrument**” should be replaced by the TRIOS-supplied instrument name and serial number, e.g. in the present document the sensors SAM_8068, SAM_806B and SAMIP_5042, containing irradiance radiometer SAM_8069 and inclination module IP_C071.

The combination in a single **MyInstrument.INI** file of both some instrument calibration data and currently-used software options for multiple instrument data acquisitions is unusual. Users should be careful to keep the originally-received **MyInstrument.INI** file in case the currently used **.INI** file, which is updated continuously during use of MSDA_XE, becomes corrupted. Recalibration of the inclination sensor, which is quite probable for this component during the expected lifetime of the radiometer, requires manual modification of the **MyInstrument.INI** file. Recalibration of the wavelength scale, which requires sophisticated laboratory measurements, would similarly require manual modification of the **MyInstrument.INI** file, but has never been attempted by TRIOS/RAMSES users to our knowledge.

After the first year or less of use of instruments it is probable that the user will have their instruments recalibrated, yielding a new set of CAL_* file (and possibly a new BACK_* file). In that case some extra filenames and/or subdirectory structure may be needed to distinguish between different calibration files for the same instrument, e.g. CAL_SNxxxx_20yy-mm-dd.dat, where xxxx is the instrument serial number and 20yy-mm-dd is the date of laboratory calibration (which is also included in the header of the CAL file). It is recommended that only the latest calibration data for each instrument be included in the **C:\Users\MyUserName\TRIOS\InstrumentData** directory, although older CAL files can be included in subdirectories, e.g. **C:\Users\MyUserName\TRIOS\InstrumentData\Old**. At the moment of data acquisition, the post-cruise calibration will obviously not yet be available. This is not a problem for the current document since, although the MSDA_XE software will present on-screen and archive calibrated data using the latest available pre-cruise CAL file, the raw data (digital numbers) can later be reprocessed by the FRM4SOC2 Community Processor or the user's own processor software using any desired CAL files, e.g. a linear interpolation in time between pre-cruise and post-cruise CAL files.

3.3.2 Set up the new cruise database file

Create a new database for the cruise¹:

- create directory using Windows File Explorer

C:\Users\MyUserName\TRIOS\CruiseData\ThisCruise

Open MSDA_XE, create new mdb database file and associate this file as the MSDA_XE output database:

- Open MSDA_XE
- MSDA_XE main menu>Options>Configuration>
- in “Database” tab, “Create New Database” page (Figure 11), “Create and Activate” button to create the new Access database file in the abovementioned directory and name it, e.g. **ThisCruise.mdb** file. The file as seen by Windows should have size of about 600KB.

¹ Cruise-naming convention is normally defined by the measuring team or by the cruise Chief Scientist and is not limited to the TRIOS data acquisition. A common practice for cruise-naming convention is to use the ship name and cruise start (port departure) date, e.g. Myship_2022-01-26, with the latter preferably following the ISO 8601 convention to facilitate numerical searching and chronological ordering of files.

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- Mission: Change the Mission name (Figure 12) in correspondence to the Cruise name.
- MSDA_XE main menu>Options>Professional mode (see Figure 10) providing more menu items including “Processing”
- Save Desktop As **C:\Users\MyUserName\TRIOS\CruiseData\ThisCruise\TestCruise.dsk** (type Desktop file)
- Close MSDA_XE to apply the changesSet up the TRIOS/RAMSES sensors for acquisition, including calibration data import

Ensure that Trios sensors are powered on and connected to the acquisition PC via the IPS104 box (section 3.2). The IPS104 box will show 4 lights in the lower row and 3 lights in the upper row, according to which channels are connected to radiometers. The upper row lights will flash when the radiometers are acquiring data.



Figure 6 IPS104 box showing lights when 3 radiometers are connected. Top row lights flash brighter when data is being acquired.

- Restart MSDA_XE (which should always start with the last-used desktop file)
- Open DeviceManager window and press “Scan” (Figure 13)

If MSDA does not see the connected sensors in DeviceManager, go to the Main>Options>PortManager (Figure 14). Refer to Trios manuals to configure the COM ports. It may be difficult to identify which COM ports are used by the PC internal GPS and by the IPS104 box. If necessary enable/disable until the relevant ports are located.

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If MSDA does see the connected sensors in DeviceManager and provides instructions in a pop-up window regarding importation of device files:

- Follow the instructions and
- Use Database/Devices/"Import" to load all .ini files (Figure 15) located at

C:\Users\TriOSDataAcquisition\InstrumentData
- Click "Scan" to refresh ports
- Configure the Timer: MSDA_XE main menu>Extras>Timer
- From the Timer window: "Configure">Raster: select 10sec (Figure 16)
- For each sensor in DeviceManager click on the sensor to open the sensor window and then click "Control" to edit the device (Figure 17)
- Connect/Enable (press red dot to make it green)
- For each sensor in the "General" tab (Figure 18):
 - Integration time: **Automatic**
 - [Storing]: Save to: **Database + file**; Select: **Raw + Calibrated**
 - [Automatic Measurement]: Configure: External, Chose input: Timer/Trigger.
 - Click on "Auto" (button changes from gray to green)
- For each sensor in the "Calibration" tab (Figure 19):
 - import the Cal_ and Back_ files (Figure 20)

In the "Choose dataset" window use "Import data from file" via floppy disk button in bottom row
C:\Users\TriOSDataAcquisition\InstrumentData

- and select all Back_* and Cal_* files together, this way all the files will be uploaded to the database. , (Figure 21)
- Select the corresponding files for each sensor, (Figure 22)

Configuration to **calibrate** for fixed wavelengths for **visualisation while acquiring** the data (in case not already on desktop)

- MSDA_XE main menu>Processing>Spectrum>Calibration>
- in the main Connect/Enable the "Spectrum Calibration" windows for each sensors (red to green round symbols) – Processing > Spectrum > Calibration
- Input data from **RAW** spectrum: SAMIP_5042.RAW, SAM_8068.RAW, SAM_806B.RAW
- Select (Figure 23):
 - Subtract Background
 - Calibrate amplitude
 - Physical wavelength
 - Custom (See Additional Page)
 - Save to database and file
- In the "Additional" tab:
 - select the Device (SAM_8068, SAM_806B or SAM_8069) (Figure 24)
 - Background and Calibration files should normally already be loaded

Setup inclination sensor




In DeviceManager window select SAMIP_5042, click CONTROL (Figure 25)

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- In the “General” tab:

- Integration time: **Automatic**
 - [Storing]: Save to: **Database + file**; Select: **Raw + Calibrated**
 - [Automatic Measurement]: Configure: External, Chose input: Timer/Trigger.
 - Click on “Auto” (button changes from gray to green)
- SAMIP window will show the inclination value when an acquisition is made

3.3.3 Set up window for radiometer data visualisation

- MSDA_XE main menu>View>Chart
- Open bottom panel of Chart Window
- Press button in lower left with plus sign  to open input menu
- Select first radiometer in Choose Input as open up Spectrum_Calibration>Calibrated to select ValueWLSeries input (Figure 26)
- Add an extra subchart with  button in lower left of window
- Repeat for 2nd radiometer (with appropriate Spectrum_Calibration_n datastream as input)
- Add an extra subchart with  button in lower left of window
- Repeat for 3rd radiometer

3.3.4 Make a test acquisition

- Start measurements clicking Timer “Auto” (button changes from gray to green) (Figure 27, Figure 28)
- Go to “Protocol” tab of the three radiometers and of the inclination sensor to check correct acquisition and no error messages. (Figure 29)
- Check a reasonable inclination value is shown in the SAMIP window
- Check the GPS is recording: green light and Latitude/Longitude data reasonable in main window
- Check all 3 spectra in the Chart window update and seem reasonable (Figure 30)
- Also check errors in the “Trace-List” window (if exists)
- If all functioning well, save desktop as file for future re-use.

4. Onboard installation of equipment

4.1 Hardware preparation onboard

On arrival, and after consultation of the captain and crew, where necessary, hardware should be installed as follows:

- The radiance sensor mounting frame should be securely fixed to the ship prow (and the irradiance sensor frame, if separate, should be mounted at a high point of the ship).
- The mounting frame should be levelled, e.g. using levelling screws, and horizontal of the mounting frame base should be checked to <math><0.5^\circ</math> using a calibrated digital inclinometer. This operation should be performed while the ship is at quay, preferably not under tension of tethering ropes, but will need to be repeated on departure and at any time during the cruise when major changes are made to ship balancing (e.g. change of ballast or fuel, crane deployment of equipment, etc.).
- Radiance sensors should be clamped into the prow mounting frame and irradiance sensor into its own mounting frame/pole. Viewing zenith/nadir angles of the sky- and water-viewing sensors should be checked to be $40^\circ \pm 2^\circ$ and the irradiance sensor should be checked to be vertical to $<1^\circ$ using a

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calibrated digital inclinometer¹. Radiance and irradiance sensor connectors should be protected by dummy connectors if working in a potentially wet environment.

- Check that optical surfaces for radiance and irradiance sensors are clean, repeat cleaning procedure of section 2.2, if necessary. Protect optical surfaces with lens caps until needed for measurement.
- (following advice and instructions from captain and crew) The 50m SUBCONN/M8F cables should be unfurled and passed through any bulkhead passages from prow-mounted radiance sensors and prow/pole-mounted irradiance sensor to the indoor data acquisition PC area. Care should be taken to secure cables to floor/walls with cable ties, avoiding any trip or snag hazards or any obstruction to other users of the ship, including crew. Both SUBCONN and M8F cable end connectors should be protected by dummy connectors if working in a potentially wet environment.
- When laid out, the cable should be connected to the TRIOS/RAMSES sensors.
- The data acquisition PC and IPS104 box should be set up in a dry indoor environment, preferably with good outdoor visibility to the prow and to the surrounding water and good communication with the ship navigator. The 3*M8F connections should be pushed into the IPS104 box and secured by twisting the ring – take care to twist just the ring and not the entire connector which will break the connector pins. Connect SUBCONN connectors to TRIOS/RAMSES sensors.
- The RS232/USB adapter cable should be screwed into the IPS104 box then connected to the PC.
- Power cords should be connected to the PC and IPS104 box, typically via a multi-socket distribution board with surge protection.
- PC and IPS104 can be powered on.

4.2 Crew preparation onboard

- Brief all scientists involved in this measurement procedure
- Check details of ship operations with captain (positions of cables, use of fore-deck, positioning on station, safety procedures, etc.). In particular, explain the need for achieving and maintaining during 5-10 minutes the relative azimuth angle of 135° with respect to sun – see Figure 7.
- Clarify with ship captain/navigator how to position and communicate when arriving on-station and when measuring. Communication will typically involve walky-talkies, with an agreed channel setting. The following is suggested as a typical scientist/ship communication procedure:
 - Ship captain/navigator informs scientist when 10 minutes before arrival and discusses with scientist which of the two possible azimuth angles to use (135° or 225° relative to sun, i.e. with sun on port/left or starboard/right of ship), explains any constraints due to shipping and/or wind/current and whether it is possible to hold position or is necessary to drift during measurements. Priority is always given to holding relative azimuth angle rather than position.
 - Ship captain/navigator informs scientist when arrived on position with required heading.
 - Scientist informs ship captain/navigator when acquisition started (reminding that heading must be preserved for 5-10 minutes).
 - Scientists informs ship captain/navigator when acquisition finished, allowing ship to change heading and/or proceed with other measurements on-station, if required
 - Scientists informs ship captain/navigator when lens caps replaced, allowing ship to proceed to next station.

Above-water radiometry will generally be combined on-station with other biological or optical measurements, e.g. vertical profiling of optical properties and/or collection of water samples for filtration and subsequent analysis of water constituent concentrations, such as phytoplankton pigments and/or suspended particulate matter. In such cases, the radiometer scientist should:

- discuss all on-station operations with the chief scientist and scientists from other teams, clarifying order of operations on-arrival.

Generally it is preferred to start with radiometry since many other operations may disturb the water column. If radiometry is to be used later with other bio-optical measurements, e.g. using reflectance and chlorophyll *a* concentration measurements for cal/val of chlorophyll *a* retrieval algorithms, then these measurements should be made as close together in time and space as possible. However, it is noted that on many ships and in many wind/current conditions it may not be possible to make simultaneous radiometric and bio-optical measurements

¹ If the digital inclinometer cannot be used directly with a cylindrical surface like that of the TRIOS/RAMSES body it may be necessary to construct a tool to facilitate this. Manual “post” spirit levels can be useful particularly for the irradiance sensor.

because the crucial requirement of constant heading for radiometry may be incompatible with safe winch-deployment of other equipment. E.g. in conditions of strong current, winch deployments are often made with ship parallel to current to avoid instruments being dragged under the hull.

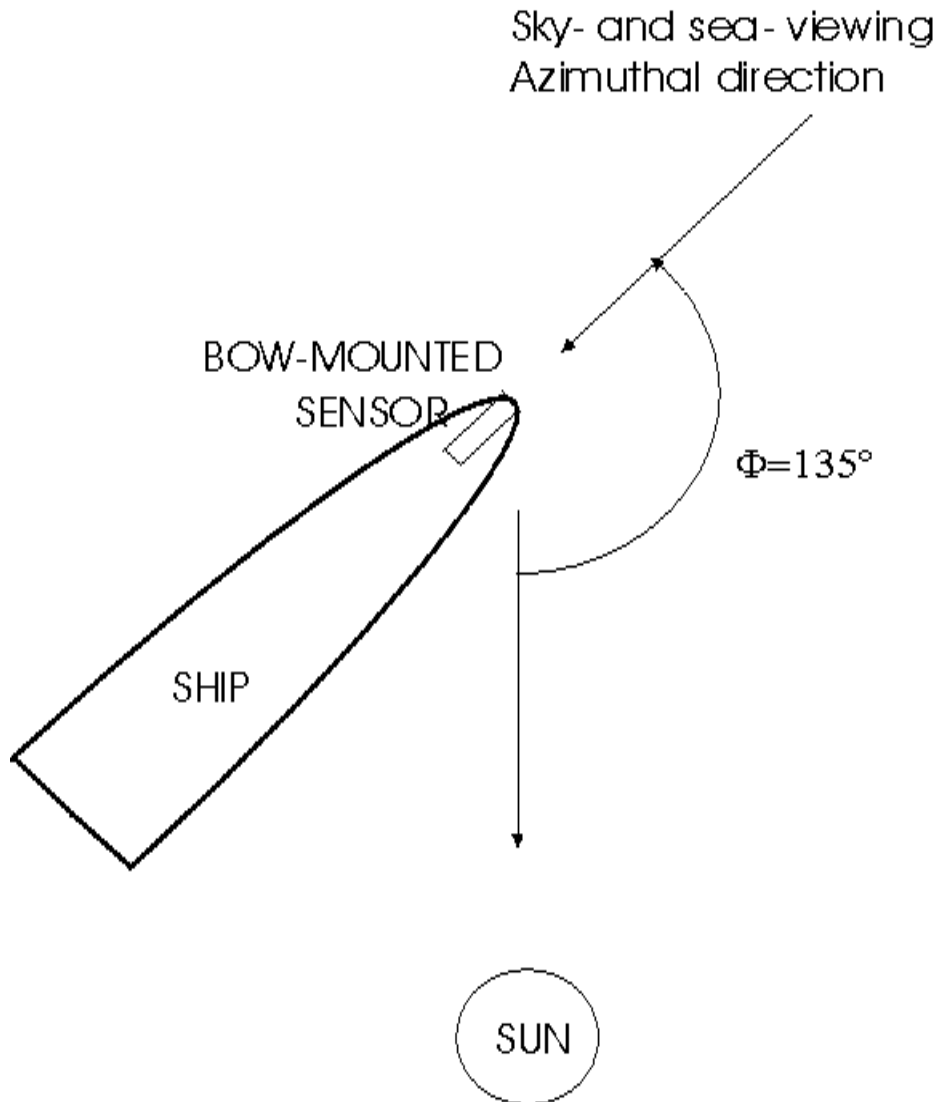


Figure 7 Orientation of ship and viewing direction of RAMSES spectroradiometers relative to sun. The relative azimuth of 225° (so with sun behind ship on port side instead of starboard side) is equally acceptable.

4.3 Software preparation onboard

Open MSDA-XE software and load previously saved desktop from section 3.3.4 (if not automatically loaded) and make a test acquisition as follows:

Start measurements clicking Timer “Auto” (button changes from gray to green)

- Go to “Protocol” tab of the three radiometers and of the inclination sensor to check correct acquisition and no error messages.

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- Check a reasonable inclination value is shown in the SAMIP window
- Check the GPS is recording: green light and Latitude/Longitude data reasonable in main window
- Check all 3 spectra in the Chart window update and seem reasonable
- Also check errors in the “Trace-List” window (if exists).

5. Procedure for an on-station measurement

Following the scientist/ship procedure agreed in start of cruise briefing (see section 4.2) scientist is typically warned 10 minutes before arrival. Then:

- Scientist estimates distance of drift from estimated drift speed * 5-10 minutes¹ and checks bathymetric charts and outdoor visual for any features (sandbanks/fronts) that would cause different optical water masses to be encountered during drift.
- Scientist prepares hardware for measurement, including donning appropriate PPE, collects measurement log and camera and walky-talky, removes radiometer lens caps (in contact with bridge/crew where necessary for safety reasons).
- Scientists prepares software for measurement, checking that PC and MSDA-XE is still running and radiometers are well-connected via IPS104 box (bottom row of orange lights should be on). Scientist enters station name and/or any comments in MSDA-XE comment function as shown below. These comments will later facilitate extraction of data by station for processing.

When informed by ship captain/navigator that ship is on station and with correct heading, scientist checks heading (e.g. outdoor rough check on sun position and any angle of any shadows on ship) and starts acquisition by MSDA-XE software, which should already be running but without active acquisitions:

- open each of the 3 radiometer tabs and inclinometer tab and add StationName in COMMENT field (Figure 31)
- Start measurement clicking Timer “Auto” (button changes from gray to green) (Figure 32)
- Go to “Protocol” tab of the three sensors to check correct acquisition and no error messages (Figure 32)
- Also check errors in the “Trace-List” window
- check that GPS is acquiring position and date/time data: green light to left of “LONGITUDE” button should be on/flashing.
- check that all 3 radiometer spectra are complete and reasonable (if very dark, then lens caps may still be on!).
- check that inclinometer data is updating and is reasonable: see SAMIP window of Figure 33. In calm seas, total inclination should be $\leq 2^\circ$ and preferably $\leq 1^\circ$.

If higher but realistic inclinations are recorded it may be that ship ballasting has changed and the radiometer system may need to be relevelled. If unrealistic inclinations are recorded it is probable that the inclinometer is broken and may need to be replaced.

- check that the mdb database is updating regularly during measurements and is increasing in size.

If satisfied that all is functioning well, a time limit for measurements of 5 minutes is set by the scientist and communicated to the ship captain/navigator. If problems are encountered, the acquisition may need to be restarted, possibly including repositioning of the ship.

¹ The procedure requires data acquisition during 5 minutes, but 10 minutes is suggested for planning of operations to allow time for problem-solving and/or restarts where necessary.

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During the 5 minutes of measurements the scientist should:

Take photos of the water and sky targets (preferably at location of radiometers), e.g. Figure 8, of the whole skydome (fish-eye) and of the radiometer system.

- Look at the water all round the ship, noting and photographing any unusual features such as fronts, foam lines, floating vegetation/objects, ship wakes that might come into the field of view of the upwelling radiance sensor or be seen in the vicinity by satellites. Check also for no shading of the downwelling irradiance sensor (people working, superstructure shading, etc.).
- Manually log the relative azimuth angles of measurements with respect to sun, including a sketch of ship, sun and radiometer pointing direction.
- Manually log hydro-meteo conditions measured by the ship systems, especially wind speed and direction (absolute, after any ship drift corrections), but also including, where available, GPS date-time-position, water depth, salinity, water temperature, atmospheric pressure.
- Manually log cloud conditions (octets), any cloud in the sun- or sky-viewing directions.
- Manually log any unusual on-board activities, e.g. crew exercises, any movements near radiometers, kitchen discharges (which should not occur during measurements), etc.
- Monitor occasionally the MSDA-XE spectra, GPS light, inclination data and mdb filesize.
- Remain in contact, e.g. by walky-talky, with the ship captain/navigator in case any special circumstances occur, e.g. need warnings regarding aquatic fronts or unusual natural features, approaching ships or need to abort measurements early.



Figure 8 Typical photos of water and sky targets during radiometric measurements.

When 5 minutes of data have been acquired, the scientist should:

- Stop measurements clicking Timer “Auto” (button changes from green to gray)

and

- manually log time of end of acquisition
- inform ship captain/navigator that heading no longer needs to be preserved.

The scientist then:

- Replaces the lens caps on the 3 radiometers and
- Informs ship captain/navigator and/or chief scientist that the station is finished as regards radiometry.

At the end of each day the scientist makes a backup copy of the cruise mdb file and saves to an Internet location, if possible, otherwise to a different PC or USB device, kept separately from the acquisition PC. Before backup it is recommended to check the mdb file visually and correct any errors made during acquisition, e.g. omission of comments. At this stage it is also possible to delete test/erroneous acquisitions, although to avoid risk of removing real data it is recommended to do this only at the post-acquisition data extraction step (section 6).

It has been recommended here to manually log observations during measurements. While it is obviously relevant to use any digital recordings of events and conditions during measurements, the act of manual logging, e.g. writing by hand or typing, is still recommended as a way of reminding the measurement scientist to observe and think

about the measurement conditions. This helps spot immediately any malfunctions or strange situations which could otherwise be missed until (during post-processing) it is too late to intervene and rectify.

6. Post-acquisition preparation of data for processing

6.1 Radiometer data extraction

The **ThisCruise.mdb** file contains all data recorded during the cruise/experiment, including test acquisitions and erroneous acquisitions. The selection of station data for subsequent processing is performed manually, to avoid any test or erroneous acquisitions. The user will generally refer to the manually recorded log and/or master cruise log to determine which station acquisitions should be extracted for further processing, first copying the overall **ThisCruise.mdb** file to **<ThisCruise_Cleaned>.mdb** and then editing this file to remove any test or erroneous or unwanted acquisitions. After this “data cleaning” the data is exported as described here.

This extraction will give a raw data file in ASCII format and containing digital counts for each of the 3 radiometers (E_d, L_d, L_w) and for each station selected for processing – see Figure 9 (top). Each data file then contains a header of typically 18 rows, starting with “%” and containing instrument serial number and other metadata (not needed for subsequent processing), one column header row, starting with “%DateTime” and “NaN” respectively and then one row of data for each acquired scan – see Figure 9 (bottom). If data was acquired every 10s during 5 minutes, then each raw datafile will contain approximately 30 rows (spectral scans of data) after the header rows.

Each row of data contains the following (meta)data values separated by spaces:

- Datetime in Julian Day with 6 decimal places (approximately 0.1s)
- Latitude in decimal degrees North (as measured by the GPS)
- Longitude in decimal degrees East (as measured by the GPS)
- Integration Time in ms
- 255 data values as digital counts (corresponding to the 255 pixel detectors of the spectrometer, of which typically the last 18 are dark pixels used for dark correction)
- 2 training text comments each starting with “%”

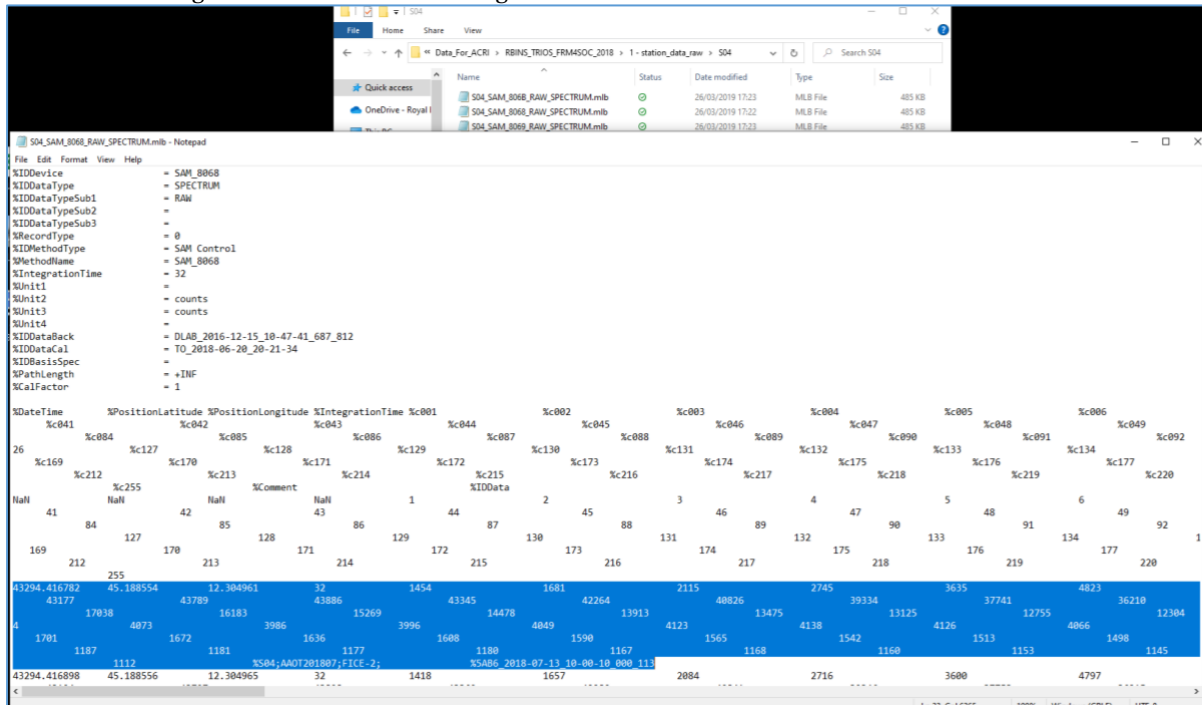


Figure 9. (top) Directory listing showing the 3 RAW data files (ASCII format, digital counts) acquired for a single station; and (bottom) typical contents of one of these files, showing header lines starting with “%”, the two column header lines starting with “%DateTime” and “NaN” and the first row of data values, highlighted in blue, starting with datetime, longitude, latitude, integration time, 255 data values (in Digital Counts) and two trailing text comments starting with “%”. Note that only part of each row is shown here since the rows are long and require left-right scrolling to see a whole row.

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To obtain these data files, data is extracted from the <ThisCruise_Cleaned>.mdb file using MSDA-XE as follows¹:

To **EXPORT RAW** files from the database (DB_Sender table obtained from Database>Data command) for each sensor separately (Figure 34)

1) Use the filters:

a) For the radiometers (Figure 35)

1. Data Type_1: RAW
2. Device (select a sensor each time): SAM_8068 then SAM_806B then SAM_8069
[adapt to actual device Serial Numbers]

b) For the inclinometer use filters:

1. Device: IPc071 [adapt to actual device Serial Number]
2. DataType: Inclination

2) Select all  and Export  using Masks (Figure 36):

Tab: **Matlab Serial Data**

Sub-tab (left): **Masks**

Directory: C:\Users\MyUserName\TRIOS\CruiseData\ThisCruise\<OutputStations>

Mask: $\${Comment0}_\${IDDevice}_\${DataType1}_\${DataType}$

In this way for each sensor one file for each station is created (Figure 37).

Example:

StationName_SAM_8068_RAW_SPECTRUM.mlb

StationName_SAM_806B_RAW_SPECTRUM.mlb

StationName_SAM_8069_RAW_SPECTRUM.mlb



It is also possible to extract calibrated radiometer data from MSDA-XE and/or data that is binned onto a regular spectral grid, e.g. 350-900nm every 2.5nm, for subsequent self-processing. However, in the FRM4SOC context this is not desirable since we need to preserve the raw digital counts on the original spectrometer wavelength scale in order to be able to perform all necessary corrections (radiometric calibration potentially using two calibration files with linear interpolation in time, non-linearity correction, straylight correction, thermal correction, etc.) and associated propagation of uncertainties.

6.2 Inclinometer data extraction

To extract one file per station of the inclinometer data:

1) Use the filters:

1. Device: IPc071 [adapt to actual device Serial Number]
2. DataType: Inclination

2) Select all  and Export  using Masks:

Tab: **Matlab Serial Data**

¹ Alternatively to using MSDA-XE for data extraction, any other suitable software can be used for extracting data from the <ThisCruise_Cleaned>.mdb file. However, a manual data selection step is still recommended to remove all test and erroneous acquisitions.

Sub-tab (left): **Masks**

Directory: C:\Users\MyUserName\TRIOS\CruiseData\ThisCruise\<OutputStations>

Mask: $\{\text{Comment0}\}_{\{\text{IDDevice}\}}_{\{\text{DataType1}\}}_{\{\text{DataType}\}}$

In this way one inclination file for each station is created.

Example:

StationName_IP_C071_Calibrated_Inclination.mlb

7. Data processing (recommended)

The scans acquired using the procedure of section 5 and extracted to ASCII files using the procedure of section 6 are now ready for radiometric calibration, quality control and the various corrections that will be applied. In this section 7, the processing recommended as best practice is defined. Possible variants are discussed in section 8.

7.1 Dark Correction and Radiometric calibration

The conversion from Digital Counts to radiometrically calibrated dark-corrected data is defined in the TRIOS Manual v1.1.01 p13-15 and [10] and is reproduced here. Notation is defined in Table 7-1

Table 7-1. Table of notation used for radiometric calibration

Notation	Units	Range	Description
n	unitless	1-237 238-255 ¹	Spectrometer detector numbers (or "pixel" numbers) used for light measurement Spectrometer detector numbers (or "pixel" numbers) used for dark correction
I_n	unitless	0-65535	Digital counts for each detector n
B_n^0	unitless	Typically 0.01- 0.02	Dark correction, constant component, for detector n obtained from 2 nd column of "background data file" BACK_SAM_xxxx.dat
B_n^1	unitless	Typically 1.0- $2.0 \cdot 10^{-5}$	Dark correction, integration time dependent component, for detector n obtained from 3 rd column of "background data file" BACK_SAM_xxxx.dat
S_n	m ² nm sr mW ⁻¹ (radiance) OR m ² nm mW ⁻¹ (irradiance)	Typically 0.01-3.0 ²	Radiometric sensitivity, for detector n obtained from "absolute calibration" file CAL_SAM_xxxx.dat
t	Ms	4-8192 ms	Integration time
t_0	ms	=8192 ms	Maximum integration time
λ_n	nm	300- 1000nm	Wavelength of detector n
L_n	mW m ⁻² nm ⁻¹ sr ⁻¹		Calibrated radiance for detector n

¹ In our experience the RAMSES radiometers have exactly 18 darkened pixels at the long wavelength end of the spectrometer. However, it is possible that different production batches have a different number of darkened pixels. This can be seen in the attributes section of the radiometer INI file, which usually gives DarkPixelStart = 237 and DarkPixelStop = 254. The latter follows a convention of detector numbering from 0 to 254, which is used in some but not all TRIOS documentation. The alternative detector numbering from 1 to 255 used in the body of the TRIOS Manual v 1.1.01 is adopted in the present FRM4SOC document.

² Obviously depends on Serial Number and will vary in time according to radiometric calibrations. Is set to zero for dark pixels and for pixels where no radiometric calibration is available.

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The digital counts I_n for all pixels are scaled to the maximum range and a background correction is made using the instrument “background correction” data.

$$C_n = \frac{I_n}{65535} - \left(B_n^0 + B_n^1 * \frac{t}{t_0} \right) \quad (3)$$

Any detectors with $I_n \geq 65535$ are saturated and the whole scan should be rejected – this should not occur since use of automatic integration time should avoid this and MSDA-XE will probably give a warning or an error message during data acquisition if this occurs.

A residual dark correction is then calculated from the dark pixels:

$$D = \frac{1}{18} \sum_{i=238}^{i=255} C_n \quad (4)$$

And radiance (or irradiance) is calculated by further removing this dark correction, dividing by calibrated sensitivity and normalising for integration time:

$$L_n = \frac{1}{S_n} (C_n - D) * \frac{t}{t_0} \quad (5)$$

7.2 Non-linear correction

The non-linearity correction for TRIOS/RAMSES sensors has been investigated by [11], [12] and [13]. The preferred method for correction and associated residual uncertainty is under discussion within the FRM4SOC-2 consortium and this section will be updated later.

7.3 Straylight correction

The straylight correction for TRIOS/RAMSES sensors has been investigated by [14]. The preferred method for straylight correction and associated residual uncertainty is under discussion within the FRM4SOC-2 consortium and this section will be updated later.

7.4 Thermal correction

The thermal sensitivity of TRIOS/RAMSES sensors has been investigated by [10]. The preferred method for correction of thermal sensitivity and associated residual uncertainty is under discussion within the FRM4SOC-2 consortium and this section will be updated later.

7.5 Polarisation correction

The polarisation sensitivity of TRIOS/RAMSES sensors has been investigated by [15]. The preferred method for correction of polarisation sensitivity and associated residual uncertainty is under discussion within the FRM4SOC-2 consortium and this section will be updated later.

7.6 Scan-level quality control tests

The following quality control tests are proposed, following [6] Web Appendix 1, to apply to each of the ~30 scans. A scan is rejected if any of the following cases occurred:

- Inclination from the vertical exceeded 5°; or
- Any of E_d , L_d or L_u at 550nm (nearest detector) differs by more than 25% from either neighbouring scan¹; or

¹ For the 3-sensor (E_d , L_d or L_u) radiometer system described here, measurements are made almost simultaneously, in contrast to automated pointing systems such as AERONET-OC/SeaPRISM [1] and PANTHYR [2], where measurements are made sequentially. The only asynchronicity comes from the

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- Incomplete or discontinuous spectra for any of E_d , L_d or L_u (occasional instrument malfunction).
 In practice, scan rejection is low or zero for calm sea and clear sky conditions but increases rapidly with increasing air-water interface roughness (typically related to increasing wind speed) and/or if cloud cover is scattered reaching up to 80% or more in the worst conditions.

The first 5 scans passing scan-level QC are then further processed to water-leaving radiance. If less than 5 scans pass scan-level QC the station is rejected and no further processing is made.

7.7 Scan-level water-leaving radiances and clear sky QC

For each of the 5 scans passing scan-level QC, the water-leaving radiance in the water-viewing direction is estimated according to the Measurement Method proposed by [7] and reviewed in detail in Chapter 4 of [3]:

$$L_w(\theta_v, \Delta\varphi) = L_u(0^+, \theta_v, \Delta\varphi) - L_r(\theta_v, \Delta\varphi) \quad (6)$$

where the skyglint radiance, L_r , which cannot be measured directly, is estimated as a multiple of the downwelling sky radiance, L_d , by

$$L_r(\theta_v, \Delta\varphi) = \rho_F L_d(0^+, 180^\circ - \theta_v, \Delta\varphi) \quad (7)$$

where ρ_F is a coefficient that represents the fraction of incident skylight that is reflected back towards the water-viewing sensor at the air-water interface. ρ_F is equal to the Fresnel reflectance coefficient for a flat water surface, or is called here the “effective Fresnel reflectance coefficient” for a roughened water surface. ρ_F is obtained as function of wind speed, sun zenith angle, and relative azimuth angle from the Look Up Table¹ of [7], provided online at https://www.oceanopticsbook.info/packages/iws_l2h/conversion/files/rhoTable_AO1999.txt.

The wind speed at 10m above water level is usually taken from measurements made on the ship itself, although may alternatively be taken from local meteorological observations or modelling.

For each of the 5 scans, water-leaving radiance is then converted to directional water-leaving radiance reflectance by:

$$\rho_w(\theta_v, \Delta\varphi) = \frac{L_w(\theta_v, \Delta\varphi)}{E_d} \quad (8)$$

To eliminate most measurements made in cloudy or partially cloudy, the QC check proposed by [6] Web Appendix 1, is applied:

- Any stations where $L_d(750nm)/E_d(750nm) > 0.05$ are rejected.

7.8 Final (directional) water-leaving radiance reflectance

The first 5 scans of directional water-leaving radiance reflectance are then mean-averaged to produce the final water-leaving radiance reflectance, $\overline{\rho_w}(\theta_v, \Delta\varphi)$ that would typically be recorded and archived for further use.

The standard deviation over the first 5 scans is a relevant quality parameter and, for example, [6] Web Appendix recommended rejection of measurements where the standard deviation of the five scans of reflectance exceeded 10% of the mean reflectance at 780 nm.

Further quality control can be applied to the $\overline{\rho_w}(\theta_v, \Delta\varphi)$ data by data users. For example, it is typical to reject from satellite validation studies all measurements taken for wind speed $> 5 \text{ m s}^{-1}$, although such thresholds could be re-

different integration times required for the 3 measurements, typically tens of ms for E_d , L_d , and a few s for L_u . There is therefore quite limited filtering of time variation during the 5 min measurement sequence here. In later processing the time variation is reflected in the standard deviation of replicates and propagated to a measurement uncertainty (see section 5.3 of D-10).

¹ Here it is noted that the quadratic wind speed formula used by [6] should not be used. The latter was developed by reproducing the simulations of [7] for a single, moderate sun zenith angle and for the single $\Delta\varphi = 135^\circ$ relative azimuth angle. Now that the full LUT from [7] with sun zenith angle and relative azimuth angle variability is publicly available, this LUT should be used instead of the quadratic approximation.

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evaluated by FRM4SOC2 or future studies if sufficient progress is made with per-measurement uncertainty estimation, particularly taking account of uncertainty (and bias) in the modelling of ρ_F . These use-specific QC restrictions should not affect the data processing to water-leaving radiance reflectance by the measurement scientist.

7.9 Propagation of uncertainty estimates

The estimation of input uncertainties and propagation of uncertainties to the final directional water-leaving radiance reflectance measurand are described in detail in FRM4SOC-2 deliverable D-10.

8. Data processing (variants)

While section 7 provides the recommended data processing procedure some acceptable variations are considered in the current section.

8.1 Near infrared similarity correction

A quality control step for water-leaving radiance reflectance measurements was proposed by [16] based on self-consistency of the reflectance spectrum with the “NIR similarity spectrum” [6]. The latter spectrum is derived from analytical assumptions that establish that the shape of the water reflectance spectrum in the near infrared (NIR: 700-900nm) is rather constant and can be approximated by the inverse of the pure water absorption spectrum. This was proposed as a method for QC of reflectance spectra, but has often been used as a correction. The QC is valid for the NIR range in clear to moderately turbid waters, but, like the similarity spectrum itself will become invalid for extremely turbid waters – for the latter see [6] Figure 4 and [17]. Use of the NIR similarity spectrum as a correction step is less reliable, particularly if extrapolated to shorter wavelengths, since the assumption of spectrally invariant sunglint/skyglint correction error, while reasonable for many sunglint-related errors, is not appropriate for skyglint-related errors.

According to [16], the wavelength-independent error on ρ_w , (after application of the skyglint correction from (6) and (7)), can be estimated from:

$$\varepsilon = \frac{\alpha_{1,2}\rho_w(\lambda_2) - \rho_w(\lambda_1)}{\alpha_{1,2} - 1} \quad (9)$$

Where λ_1 and λ_2 are two wavelengths in the NIR, chosen to correspond to quite different levels of pure water absorption, and $\alpha_{1,2} = \rho_{wn780}(\lambda_1)/\rho_{wn780}(\lambda_2)$, where $\rho_{wn780}(\lambda)$ is the (780nm-normalised) similarity spectrum tabulated in [6].

Typical choices are suggested with $(\lambda_1, \lambda_2) = (720nm, 780nm)$ giving $\alpha_{1,2} = 2.35$, or $(\lambda_1, \lambda_2) = (780nm, 870nm)$ giving $\alpha_{1,2} = 1.91$. The latter pair is definitely preferred for higher reflectance (turbid).

If used as a correction, each of the scans calculated in (8), can be corrected to give:

$$\rho_{wc}(\lambda) = \rho_w(\lambda) - \varepsilon \quad (10)$$

To give a “similarity-corrected” water-leaving radiance reflectance, $\rho_{wc}(\lambda)$.

For QC purposes both the mean value of ε calculated over replicate scans and the standard deviation are relevant. The latter provides an indication of problems associated with imperfect removal of surface wave effects – see [16] Figure 5.

It is recommended that the NIR similarity correction be made available as an option, not necessarily as the default. It may be used, as originally recommended [16], as an a posteriori estimator of skyglint correction error, based on self-consistency of the spectrum. However, it is not thought to sufficiently correct for the deficiencies of the Measurement Method at moderate to high wind speed and should certainly not be used in extremely turbid waters, where the NIR similarity spectrum is known to be inappropriate [17] unless modified to account for non-linearity of the reflectance-backscatter relationship.

8.2 Number of replicate scans used for data processing

In the recommended procedure of section 7 the number of replicate scans used for data processing (after scan-level QC) is given as 5 based on prior experience of RBINS’ shipborne measurements. 5 scans are certainly sufficient for E_d and L_d since natural variability of these measurands is low in good measurement conditions and as corollary bad measurement conditions (scattered clouds in sky-viewing direction and/or near sun) are easily identified from the standard deviation of 5 (or even 3) replicate scans.

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For the L_u measurement, which will have significant wave-induced natural variability the impact of number of replicate scans warrants further research. The variability over replicate scans will depend on sun zenith angle, viewing geometry and wave slope statistics but will also depend on radiometer instrument field of view and integration time (which is not known in advance since dependent on target brightness). Some scientists recommend processing all available scans rather than a fixed number of replicate scans.

The number of replicate scans to be used for processing may thus be adapted in the future if justified by future analysis.

8.3 Variants on scan-level filtering criteria

The HyperInSpace processor includes other variants on scan-level QC filtering. There is currently no consensus on the different scan-level QC filtering possibilities although greater convergence may be reached from ongoing analysis of the FICE data.

8.4 Bidirectional correction

Because the Measurement Method for abovewater radiometry [7] is designed to minimise sunglint contamination, data is acquired for a fixed non-nadir viewing direction with $\theta_v = 40^\circ$ and $\Delta\phi = 90^\circ$ or $\Delta\phi = 135^\circ$. For satellite validation purposes this in situ measurement will be compared to a satellite measurement acquired at a different viewing geometry ($\theta_v^{SAT}, \Delta\phi^{SAT}$). Depending on the satellite processing, the satellite measurement may be output for the acquisition geometry or may be “BRDF-corrected” to correspond to a nadir-viewing geometry, $\theta_v = 0^\circ$ and illumination by a zenith sun (with typical marine atmosphere).

There is good consensus that the modelling approach and LUT provided by [18] is appropriate for BRDF correction of Case 1 waters, where the phase function for in-water scattering can be well-estimated from Chlorophyll-a concentration. A number of studies have investigated BRDF correction for Case 2 waters [19–23], where scattering from non-algae particles is important. The IOCCG protocols recommend the [22] approach, although this remains a matter of ongoing research, including within an ongoing Copernicus-funded study [30].

Whether a BRDF correction is required or not for the in situ measurement and, if one is required, which viewing geometry is to be output (whether nadir or satellite acquisition geometry) is not known until the in situ measurement is actually used. Since it is easier to apply than to unapply a BRDF correction and in view of the expected evolution in maturity of BRDF corrections, **it is recommended that the in situ measurement be recorded without BRDF correction for the in situ acquisition geometry** ($\theta_v^{INSITU}, \Delta\phi^{INSITU}$) and for actual sun zenith and azimuth geometry, where these four geometrical parameters should be recorded in the metadata. It is then easy to apply any desired BRDF correction (or not) at the point of use, according to the user requirements and latest state of the art method.

Ideally the BRDF correction will be supplied as computer code, which can be implemented as an option, e.g. at the point of extraction of a measurement from a database.

9. Conclusions and future perspectives

9.1 Measurement Procedure applicability

This document provides a Measurement Procedure for supervised, shipborne, abovewater measurements of water reflectance using TRIOS/RAMSES radiometers. This Measurement Procedure provides the users with a very detailed and prescriptive “recipe” to follow, ensuring that even inexperienced users can unpack a new instrument and make a Fiducial Reference Measurement.

The very detailed, specific and prescriptive nature of this document ensures that data acquisition is made in such a way that the raw data can be ingested into HyperInSPACE Community Processor.

On the other hand, the very detailed and prescriptive nature of a Measurement Procedure necessarily limits the scope of when, where and how it can be applied. If the user is not in the case considered (supervised, shipborne, abovewater measurements), is not using the TRIOS/RAMSES radiometer and/or does not conform to the hardware and software requirements given here (section 3.1) then the Procedure will need to be adapted. These cases will be considered in the following subsections.

9.1.1 Different radiometers

Sections 3, 4.3, 5 and 6 have been written specifically for data acquisition by the TRIOS/RAMSES hyperspectral radiometer and must be adapted for data acquisition by other radiometers. Fundamentally, provided that the data acquisition software supplied with a radiometer is capable of outputting individual scans of raw (digital count) data

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for each photodetector element without any processing (i.e. without any dark or other correction and without any spectral processing), both for the water/sky/skydome targets and for dark readings, then it should be possible to use the present Procedure with suitable replacement of those sections. Specifically, application of this procedure with the Satlantic/Seabird HyperOCR radiometers would require adaptation of these section to use the Satcon software.

9.1.2 Fixed platforms

The current procedure has been written for shipborne measurements, although can quite easily be applied to measurements from fixed platforms, where measurements are in fact easier since there is better control of radiometer inclination and azimuth.

The requirement for installation at the ship's prow facing forwards (section 4.1), is replaced for fixed platforms by typically installing on a platform corner. This does limit the range of azimuth angles (and hence local solar times) for which data can be acquired and, because a fixed platform is generally less optically slender in plan than a ship, may increase the errors associated with optical perturbations from the platform. Moreover the limitation on azimuth angles that can be used for a fixed platform will generally lead to preference for measurements at relative azimuth of 90° to sun (rather than the 135° relative azimuth recommended by [7]). On a positive note, measurement from fixed platforms may facilitate fast measurement at both 90° and 135° relative azimuth angles at certain times of day, allowing comparison of measurements made with quite different skyglint/sunglint effects.

9.1.3 Unsupervised measurements

While unsupervised abovewater hyperspectral radiometric measurements, e.g. WATERHYPERNET/PANTHYR [24], follow a similar Measurement Method, i.e. [7], to that followed by the present Procedure, there will be major differences in detail during data acquisition.

Unsupervised measurements would not use GUI-based data acquisition software, such as the MSDA-XE software used here in sections 3, 4.3, 5 and 6, but would typically use tailor-written software executed from a command line on a computer with Linux operating system.

Unsupervised measurements made with a pointing system capable of both pan and tilt-pointing [24] can reduce hardware requirements to a irradiance radiometer and a single radiance radiometer, where the latter is used for both water- and sky-viewing radiance measurements.

9.1.4 Underway measurements

The current Procedure has been written for “on-station” shipborne measurements, where a ship holds horizontal position and orientation during the measurement and where there is a distinct start/stop to the measurement, typically lasting 5 minutes. An alternative measurement strategy is to measure “underway” from a moving ship. This is often performed opportunistically, to enable reflectance measurements to be made from research vessels without “consuming” ship-time [25–27] or even from commercial ferries with fixed routes. One advantage of underway measurements is that more “matchup” pixels can be acquired for a given satellite image, although multiple alongtrack in situ measurements may be strongly correlated.

Two additional challenges are encountered for underway measurements:

- If making underway measurements opportunistically, i.e. without being able to control ship heading, it will be necessary to rotate the radiometers automatically in azimuth to achieve the necessary azimuth with respect to sun, and it will no longer be possible to acquire data for the optimal geometry (for minimising ship perturbations) at the prow facing forwards. This can be achieved by use of hardware such as the Satlantic/Seabird Solar Tracker. For some sun azimuth/ship heading combinations (e.g. sun due South, ship heading South) it may be necessary to use 90° relative azimuth rather than 135° azimuth to avoid pointing alongside the ship.
- Measurements from the prow of a moving ship may be subject to higher inclination, particularly from ship pitching, and/or greater risk of water droplets (e.g. sea spray) contaminating the radiometer fore-optics. This can be minimised by use of a very large, stable ship and high “crow's nest” mounting of radiometers.

While the processing of underway measurements may be performed in the same way as on-station measurements, by splitting the continuous record into distinct groups of scans, which are averaged as proposed in section 7.8, the data processing would typically preserve the continuous nature of the data stream, e.g. by taking a moving average at each scan over adjacent scans. In this context it may be desirable to modify the recommended number of scans used for processing, e.g. if many scans are rejected because of high inclination.

9.2 Future perspectives for the Measurement Procedure

This Measurement Procedure was tested at the FRM4SOC-2 FICE exercise in July 2022 and feedback/improvements found there are incorporated in this update v2 of the document. The data acquired during

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the FICE July2022 exercise was successfully processed by the HyperInSpace Processor. The main difficulty encountered was to obtain a GPS fix with GPS located indoors.

The possibility of adapting this Measurement Procedure for use with the Satlantic/Seabird HyperOCR radiometer will also be considered. Aside from data format differences, the main fundamental difference between HyperOCR and RAMSES radiometers is in the dark correction, made by a shutter for HyperOCR and dark pixels for RAMSES.

The number of replicate scans proposed here for mean-averaging is given as 5, which has proven to be practical and robust but without theoretical support. Alternative numbers of replicate scans could be envisaged.

Further scan-level filtering QC tests have been proposed in the HyperInSpace processor and will be assessed in a future update of this document if consensus is reached.

The inclination threshold of 5° for QC is suggested here and has proven to be practical and robust. However, the impact of tilt on E_d measurements is clearly dependent on sun zenith angle, with minimal impact for zenith sun and very high impact at high sun zenith angle. This threshold could be considered to be more flexible if adequate estimation of tilt-related uncertainty is made.

Inclination is mentioned here without consideration of the azimuth of inclination with respect to sun. Clearly tilting in the principal plane away from or towards sun has higher impact on measurements than in the perpendicular plane. A more careful consideration of inclination effects could be made if the azimuth of inclination is recorded. This requires identification of the x/y tilt axis of the TRIOS/RAMSES inclinometer and careful alignment of this axis (e.g. x axis for ship pitch and y axis for ship roll) when the radiometer is installed on the ship.

Work in progress in the FRM4SOC2 project and prior work [10] suggests that it may be advantageous for subsequent temperature corrections to perform “lens cap” dark recordings (with no light entering the optical path) in addition to use of the spectrometer darkened pixels.

9.3 Future perspectives for the Measurement Method

As noted in the FRM4SOC-1 protocols review [3] section 4 and references cited therein, the correction of light reflected at the air-water interface is a key weakness of this Measurement Method particularly for shorter wavelengths and/or low reflectance waters and/or high wave conditions, where uncertainties (and even biases) relating to this correction may become very significant. Key problems are that:

- The light reflected into the water-viewing radiometer may include sunglint as well as skylight and is therefore not well-represented by a (spectrally-constant) multiple of the sky radiance measurement suggested by (2).
- Even in the absence of reflected sunglint, the light reflected into the water-viewing radiometer comes from different portions of the skydome, potentially with different colours (spectral composition) from the single-direction sky radiance measurement.
- Use of extraneous wind speed data for modelling of ρ_F may be a poor representation of the wave slope statistics that reflect light at the air-water interface, particularly in fetch-limited seas, including many inland waters.
- The original modelling of [7] was performed with scalar radiative transfer, although it is clear that polarisation effects at the air-water interface may be very significant [28].

Some of these problems may be reduced by better optical modelling, e.g. [29], and/or by additional data acquisitions for extra water- or sky-viewing geometries, although such ideas are the subject of research work in progress and are not yet mature and accepted enough for general usage.

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11. Appendix A – MSDA_XE screenshots

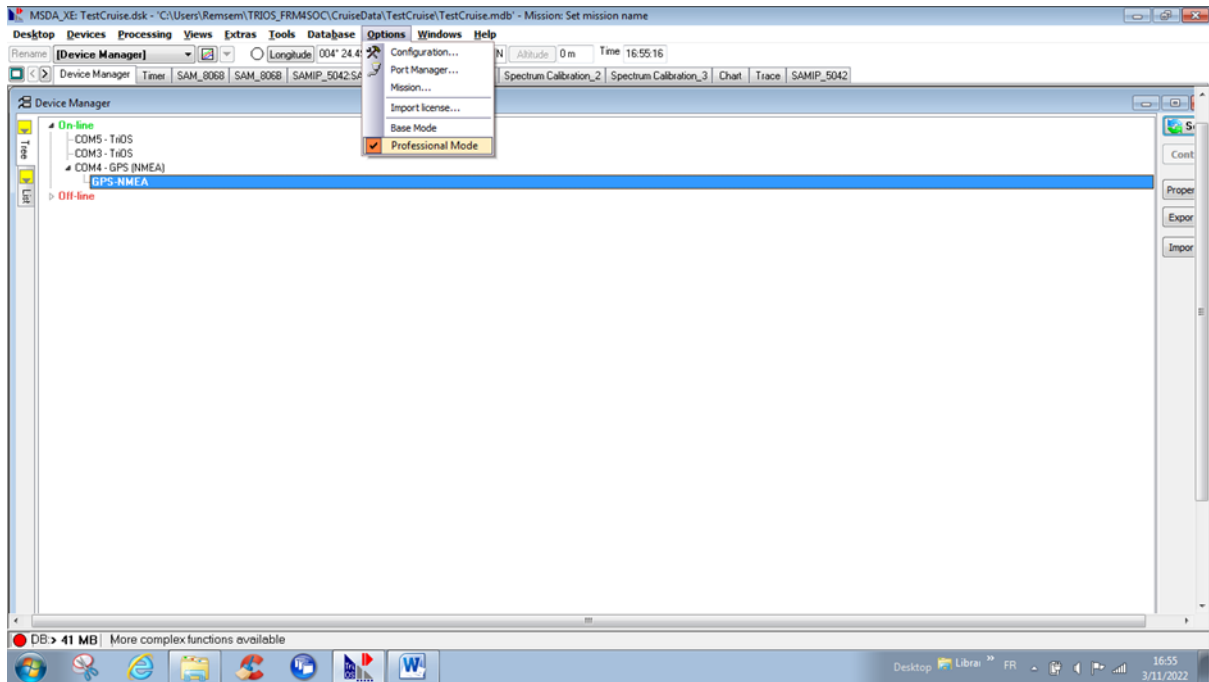


Figure 10 Screenshot to switch on professional mode showing more menu items, including “Processing”

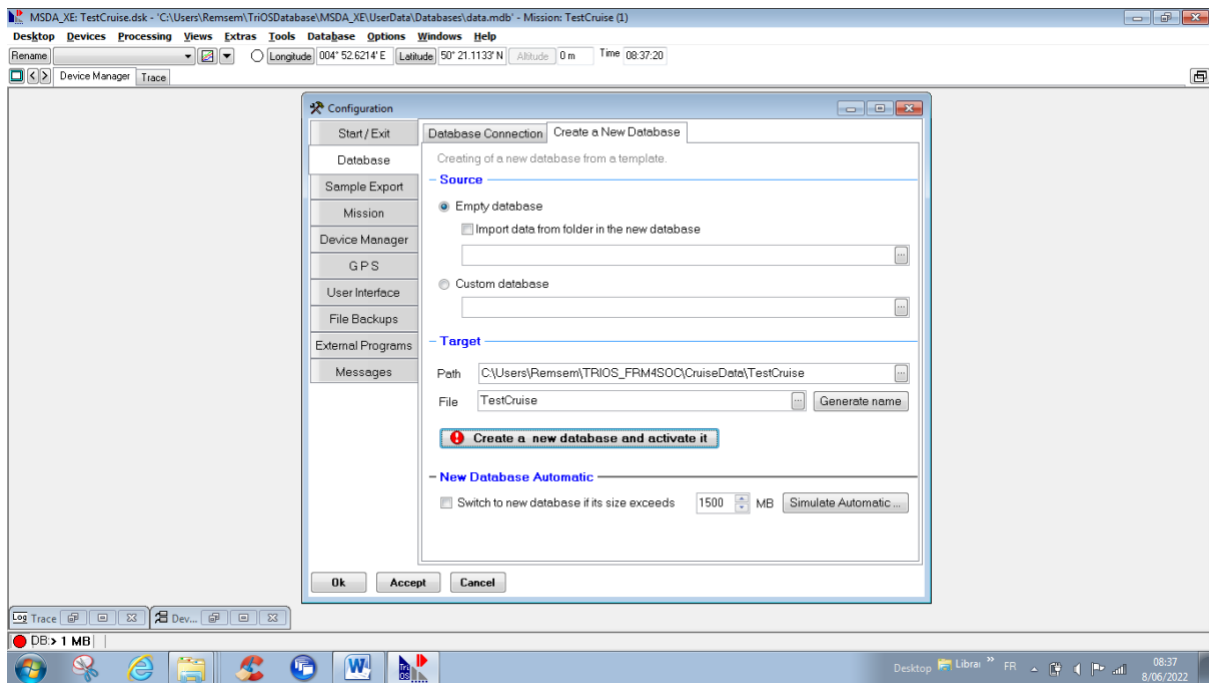


Figure 11 Screenshot when creating a new database for a new cruise.

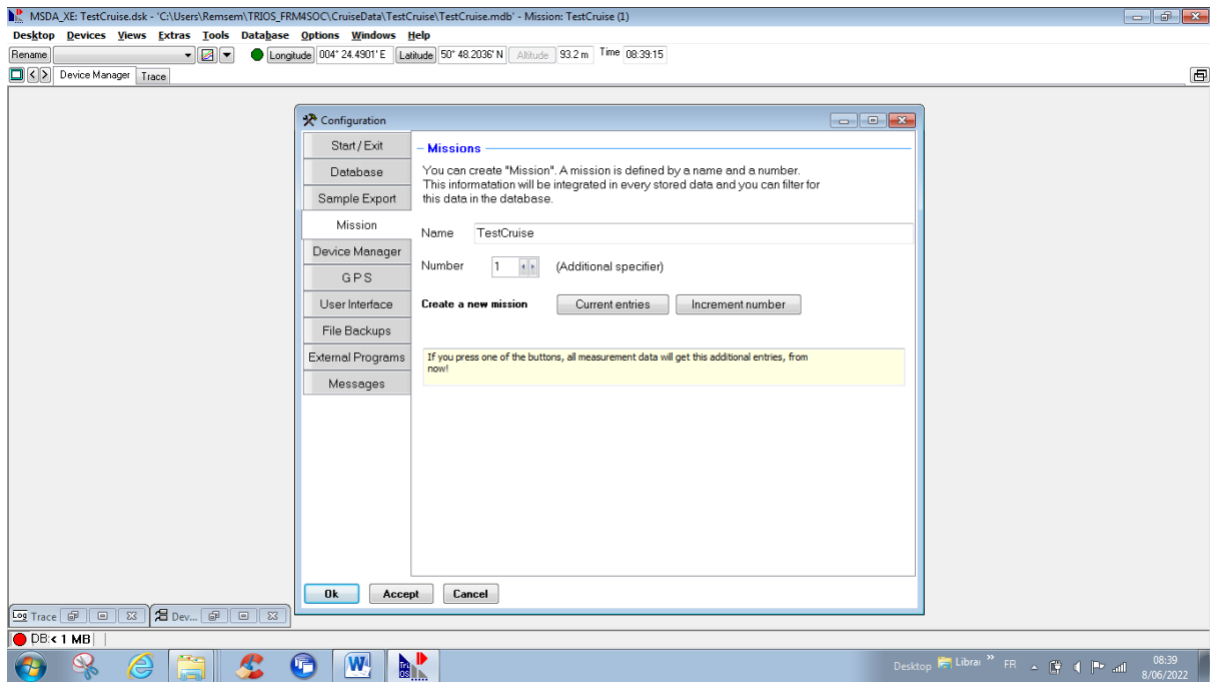


Figure 12 Screenshot when naming new mission for a new cruise.

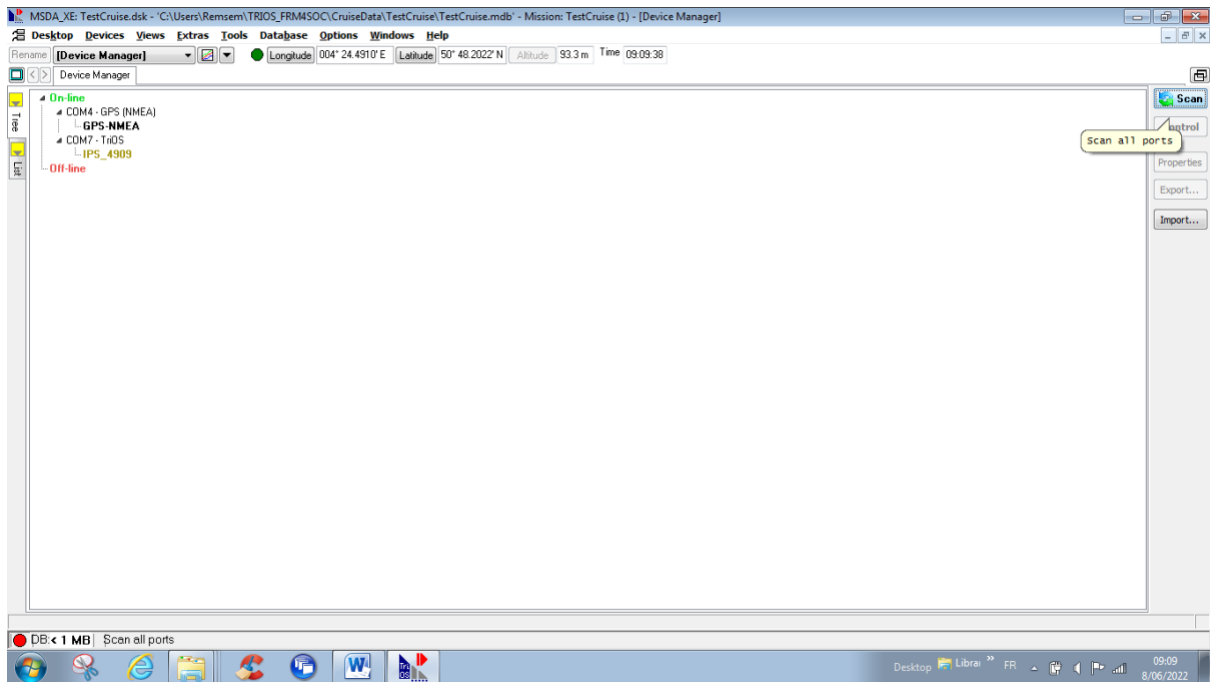


Figure 13. Screenshot after hitting scan with new sensors.

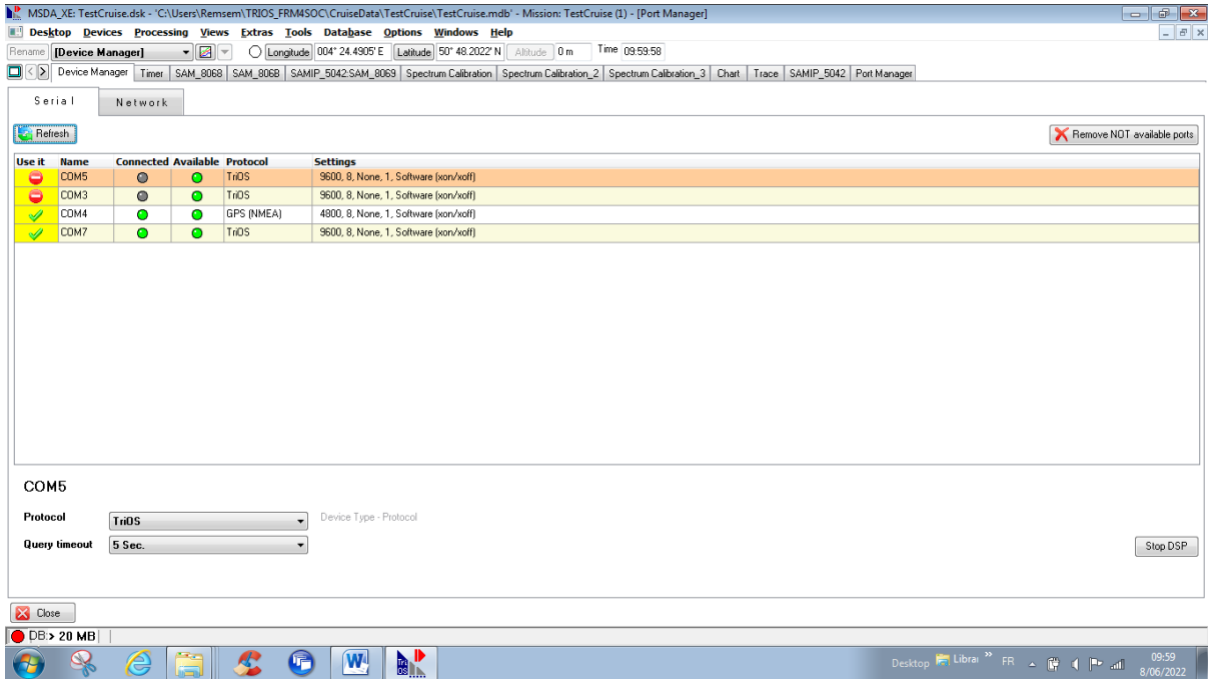


Figure 14 Screenshot showing PortManager interface with functioning GPS and IPS104 BOX.

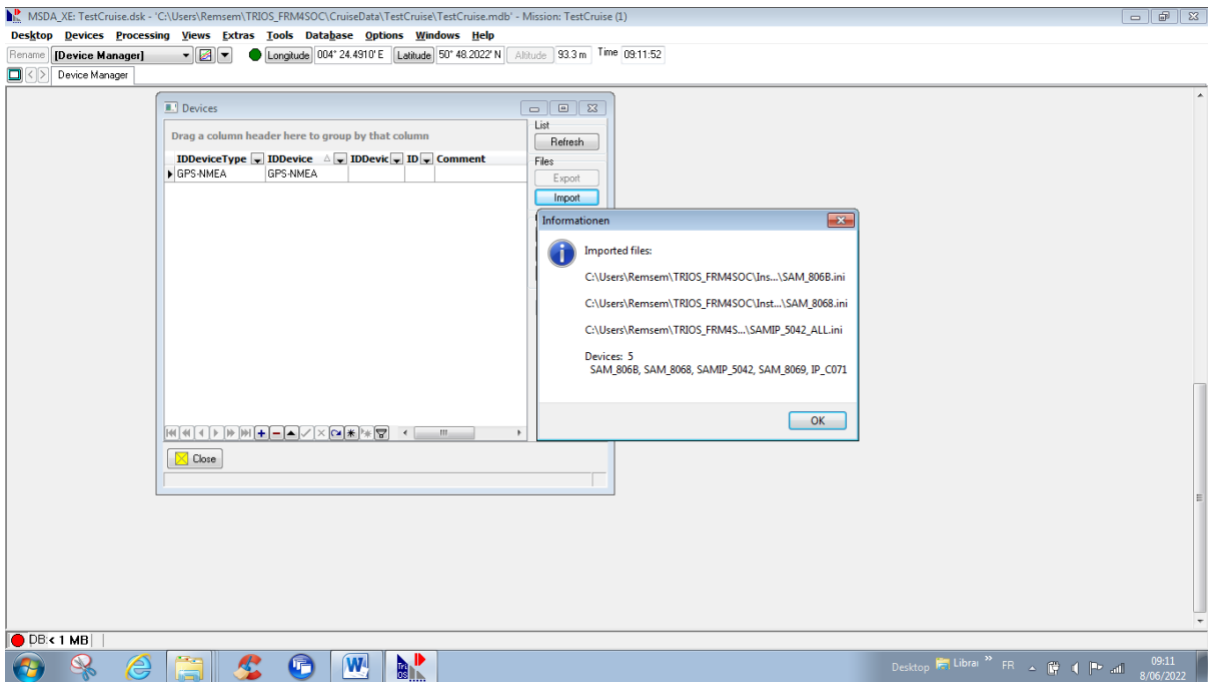


Figure 15 Screenshot while importing INI files for all new sensors.

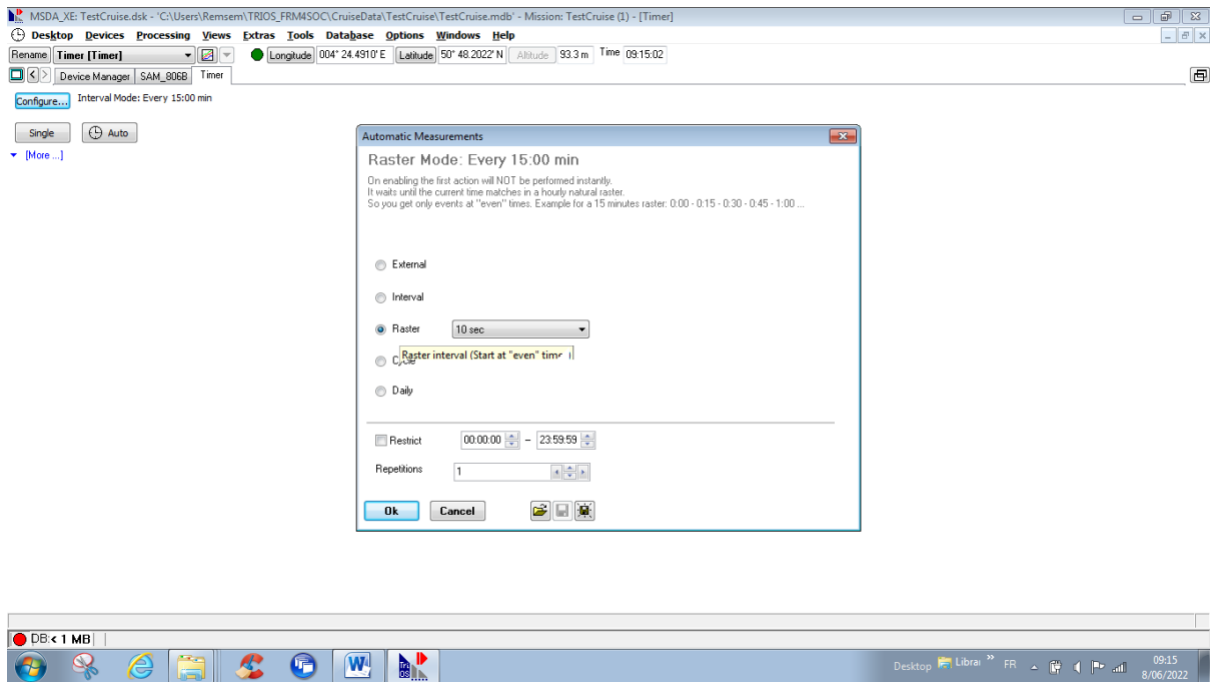


Figure 16 Screenshot setting up options for timer to trigger every 10s.

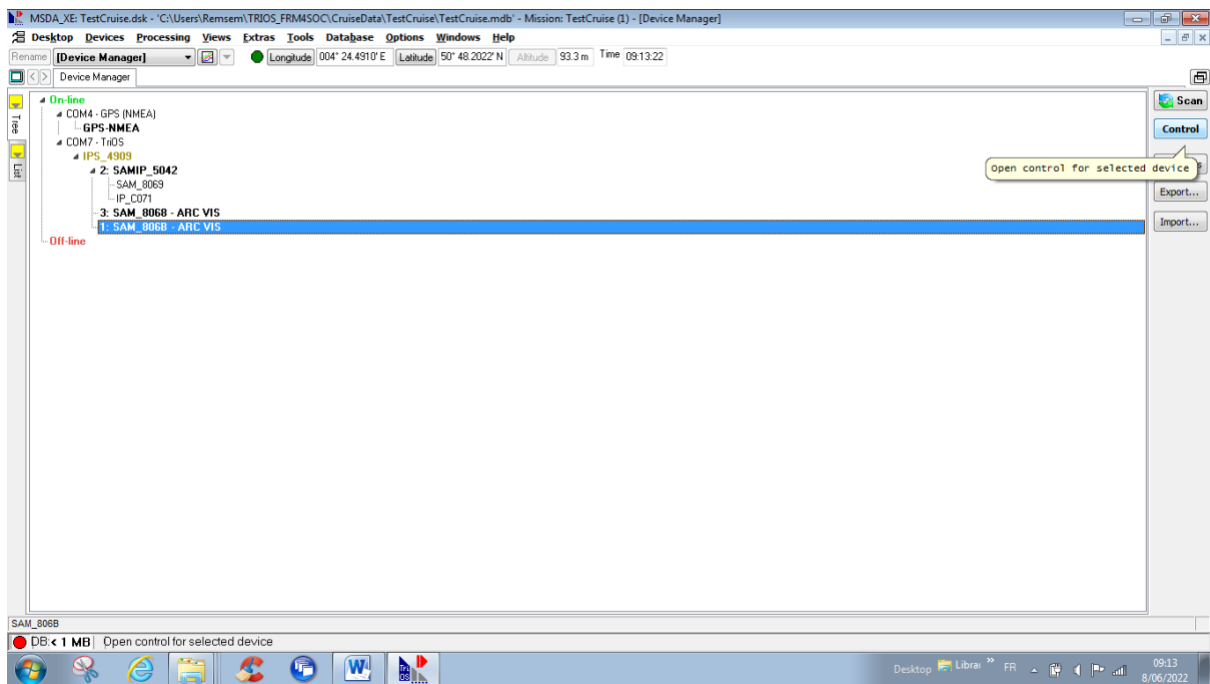


Figure 17 Screenshot opening control for new sensors before connecting with calibration data.

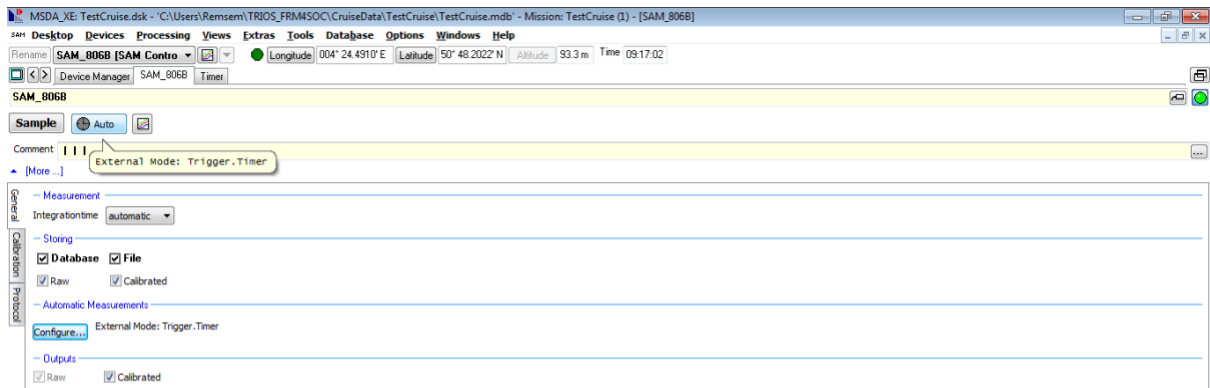


Figure 18 Screenshot to set data storage and triggering options for one radiometer.

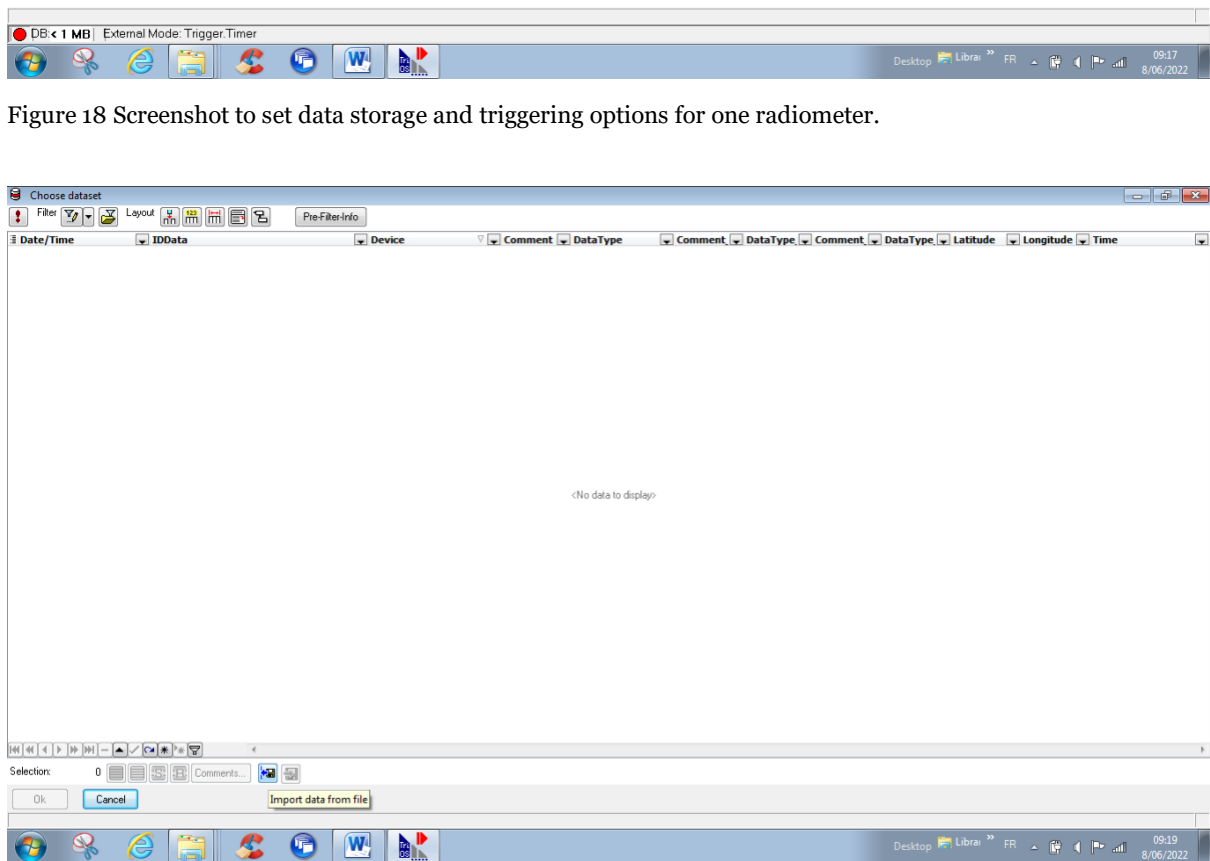


Figure 19 Screenshot just before importing calibration data for one radiometer.

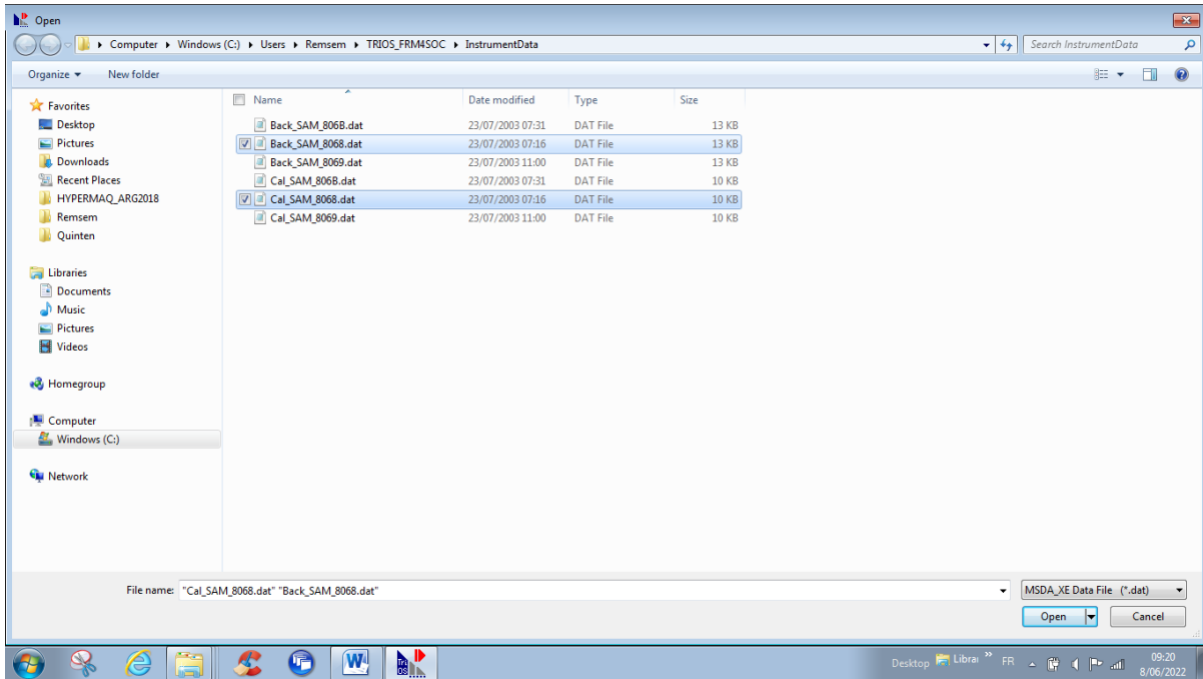


Figure 20 Screenshot while importing calibration and background data for one radiometer.

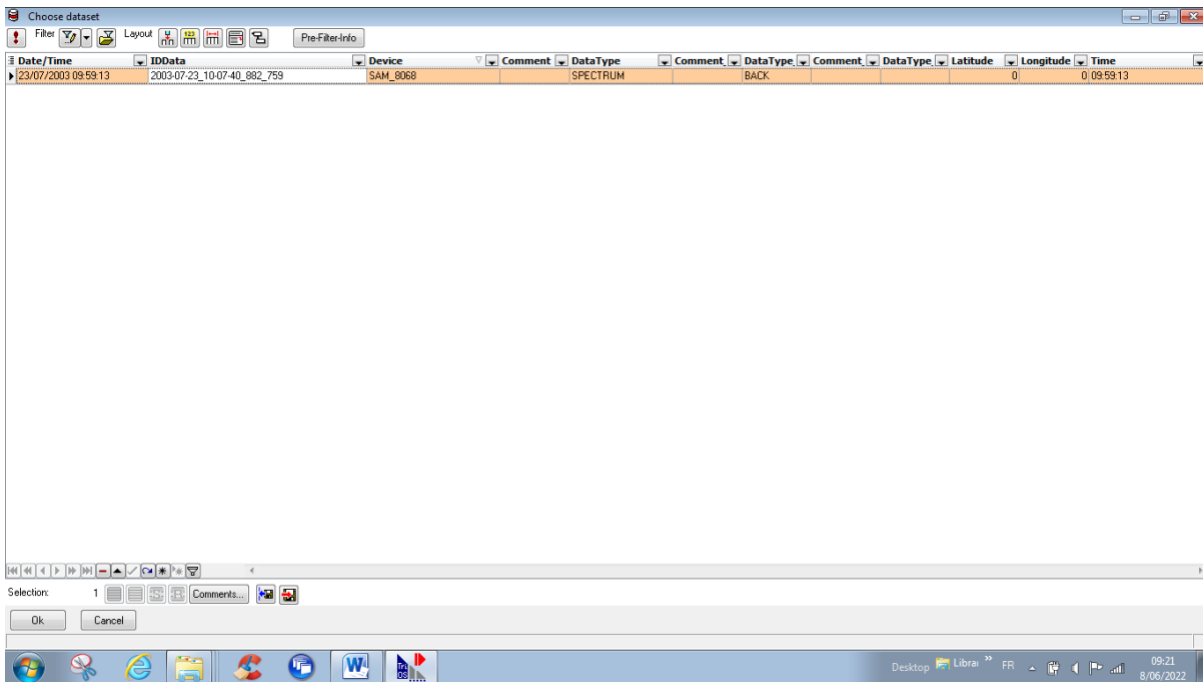


Figure 21 Screenshot selecting background data file to be used.

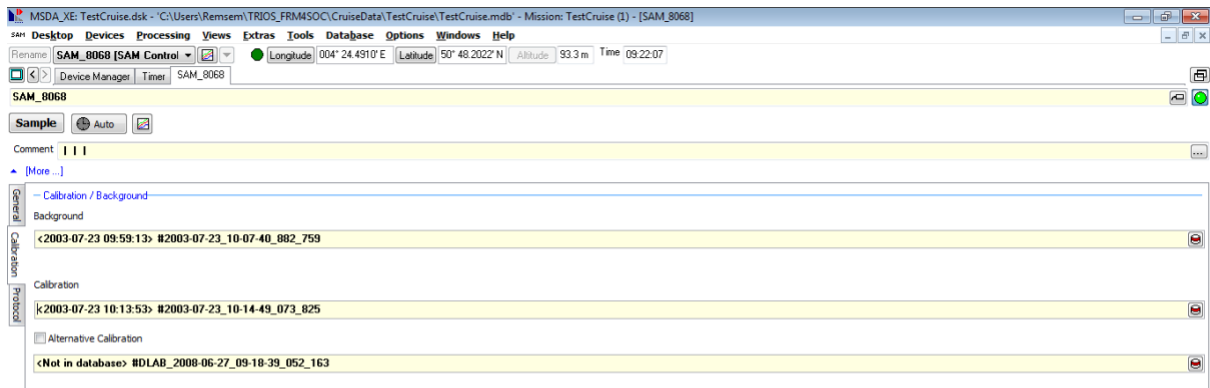


Figure 22 Screenshot after connecting calibration and background data to one radiometer.

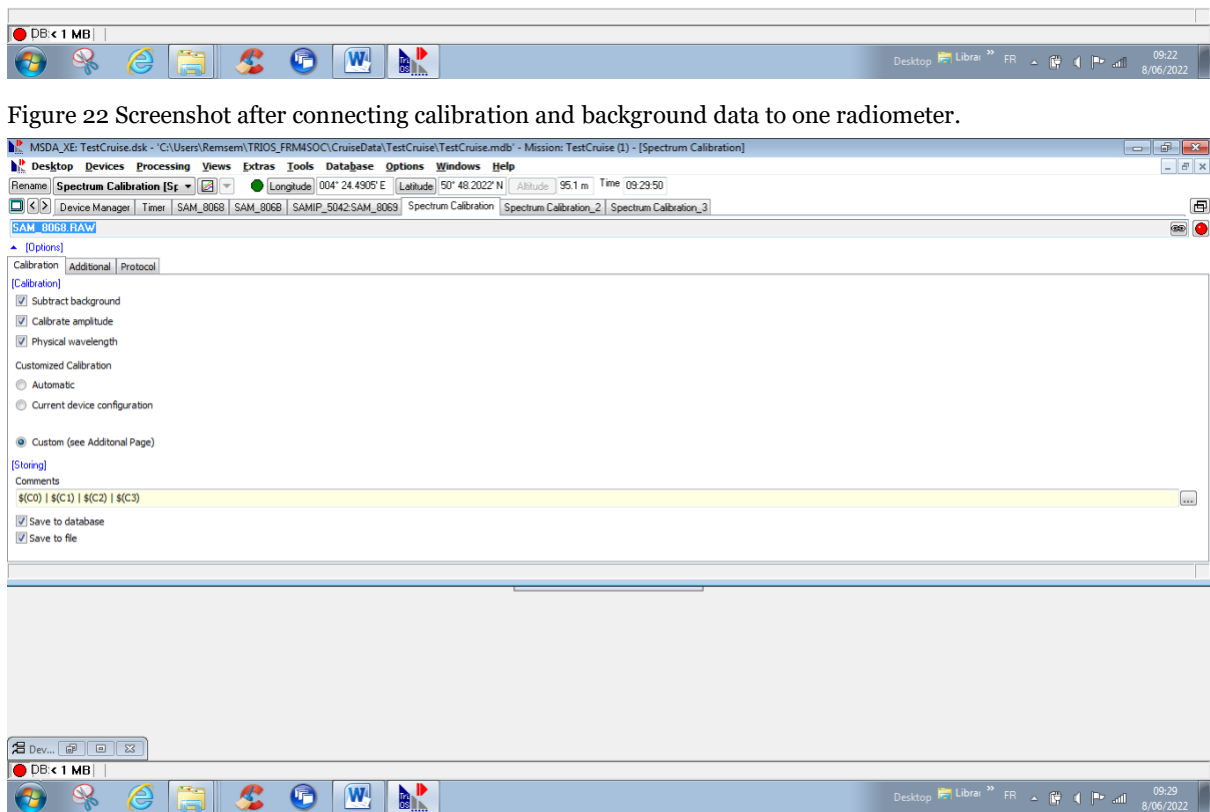


Figure 23 Screenshot setting options for spectrum calibration data (needed for visualisation only).

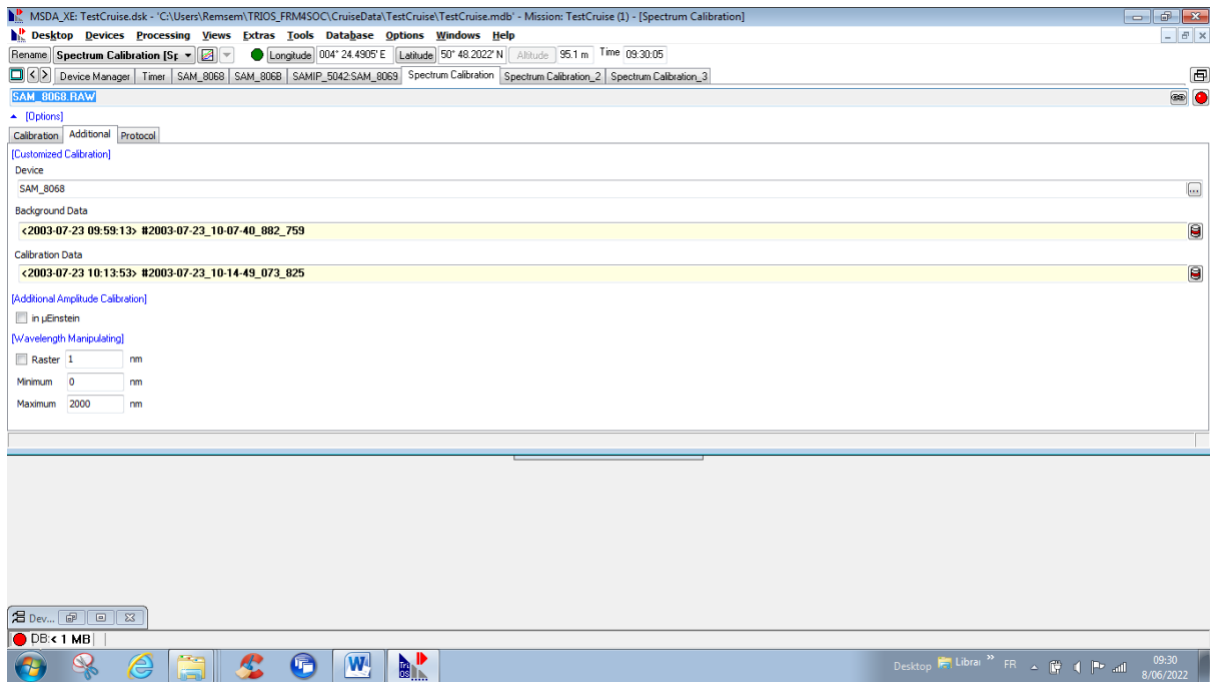


Figure 24 Screenshot selecting radiometer device and calibration and background data to be used for spectrum calibration data (needed for visualisation only).

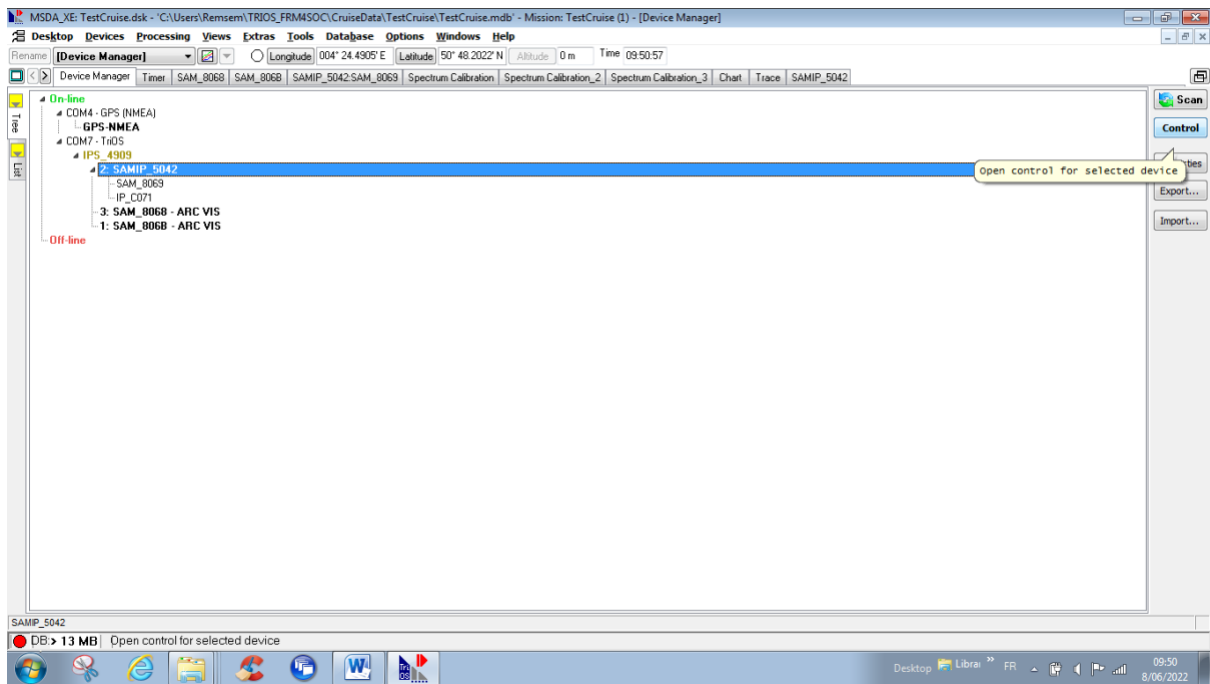


Figure 25 Screenshot selecting inclinometer for setup.

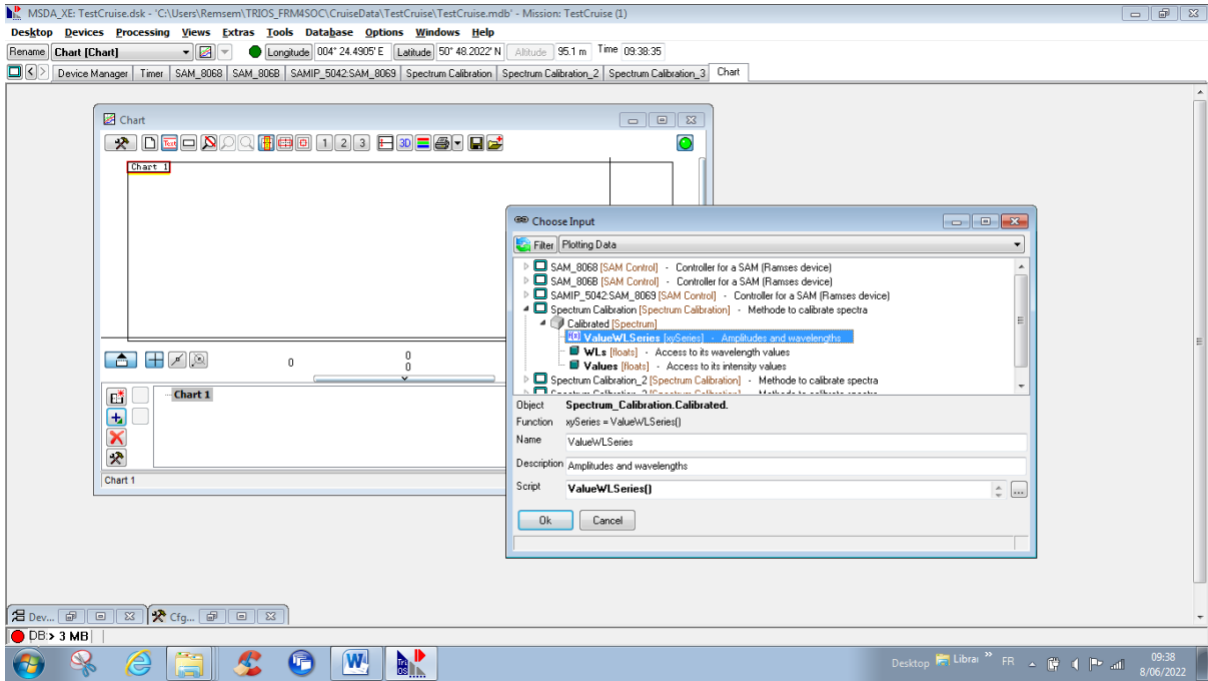


Figure 26 Screenshot selecting data from 1 radiometer for visualisation on screen during acquisition.

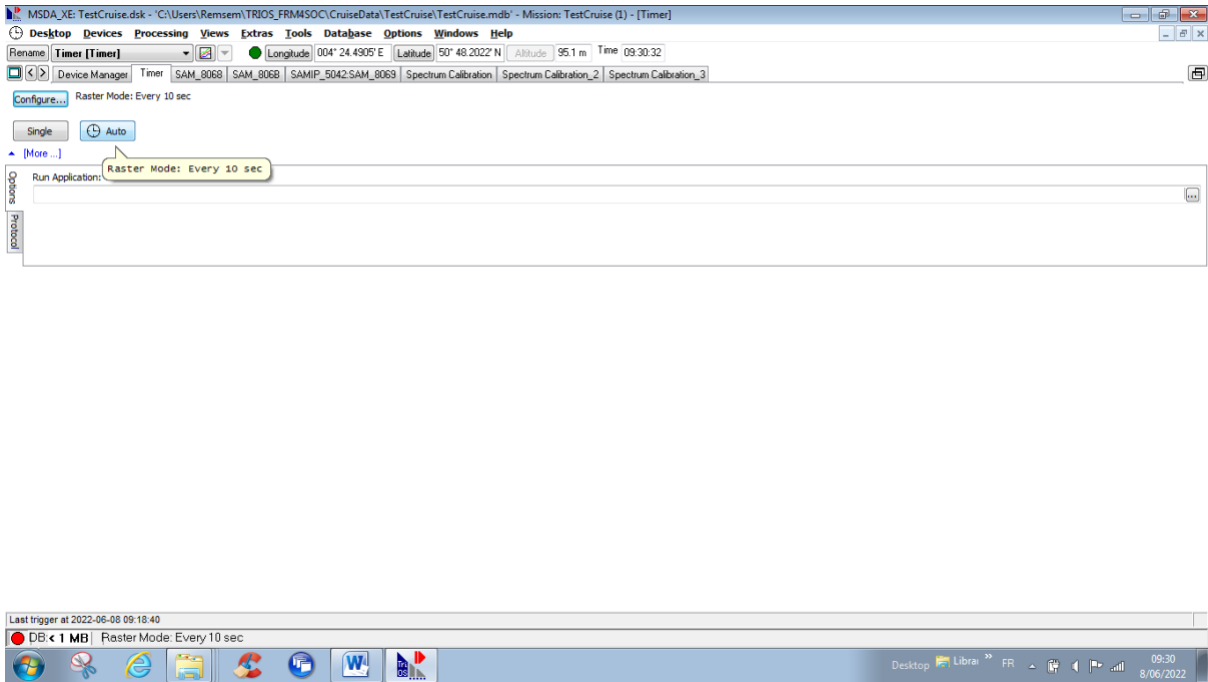


Figure 27 Screenshot before switching Timer on to AUTO.

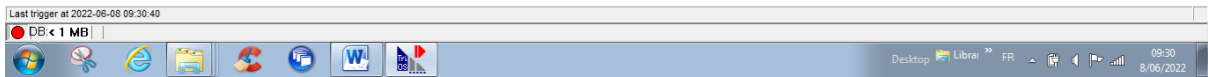
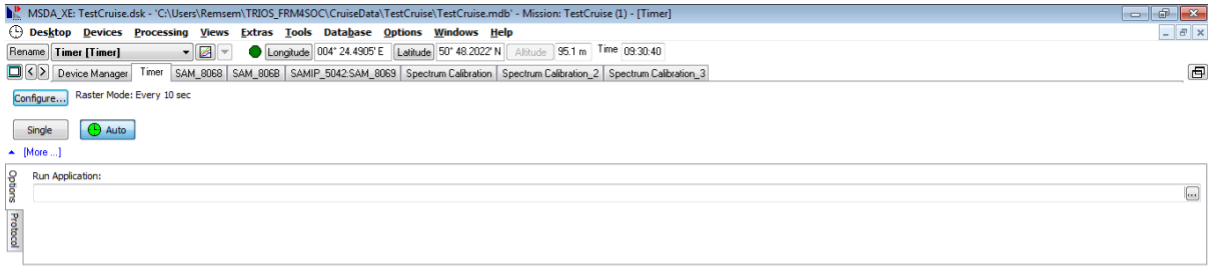


Figure 28 Screenshot before switching Timer on to AUTO.

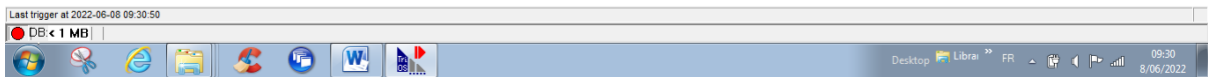
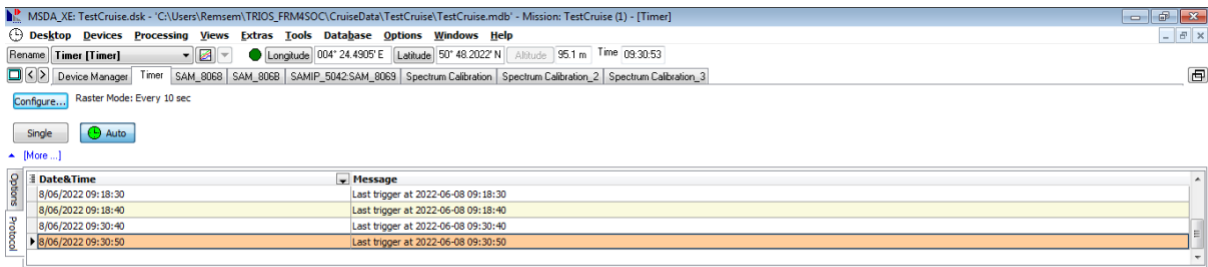


Figure 29 Screenshot checking on Protocol tab that timer is activated every 10s.

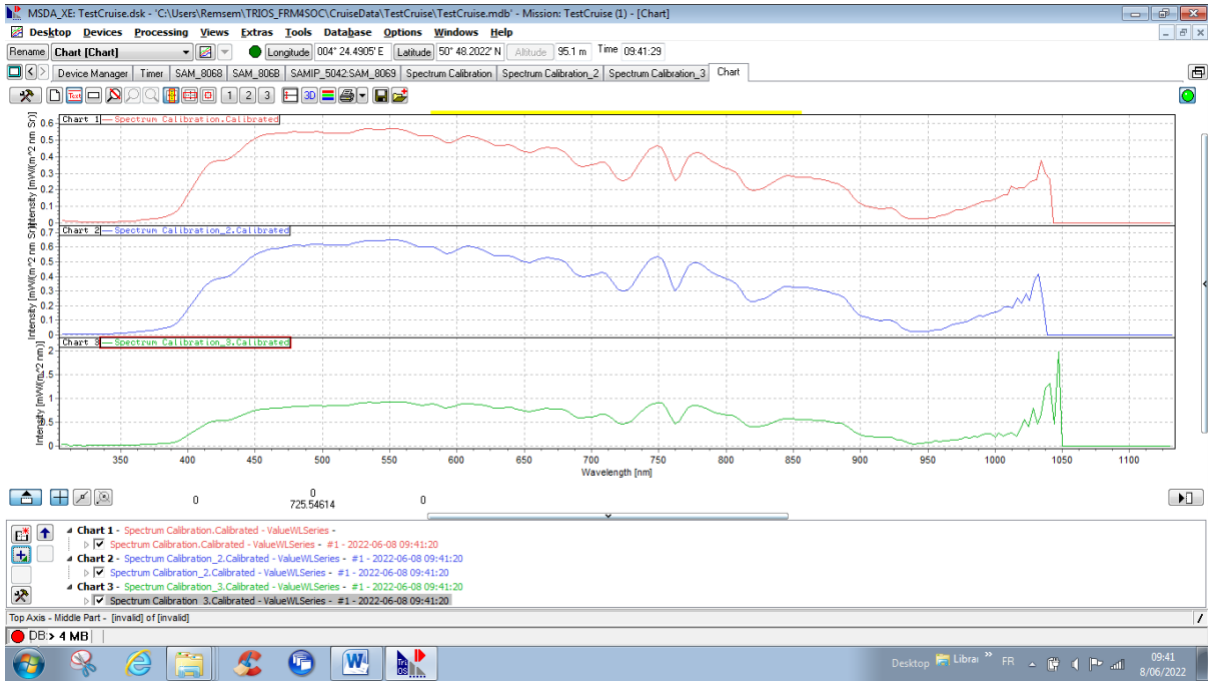


Figure 30 Screenshot showing data visualisation from 3 radiometers as spectral plots.

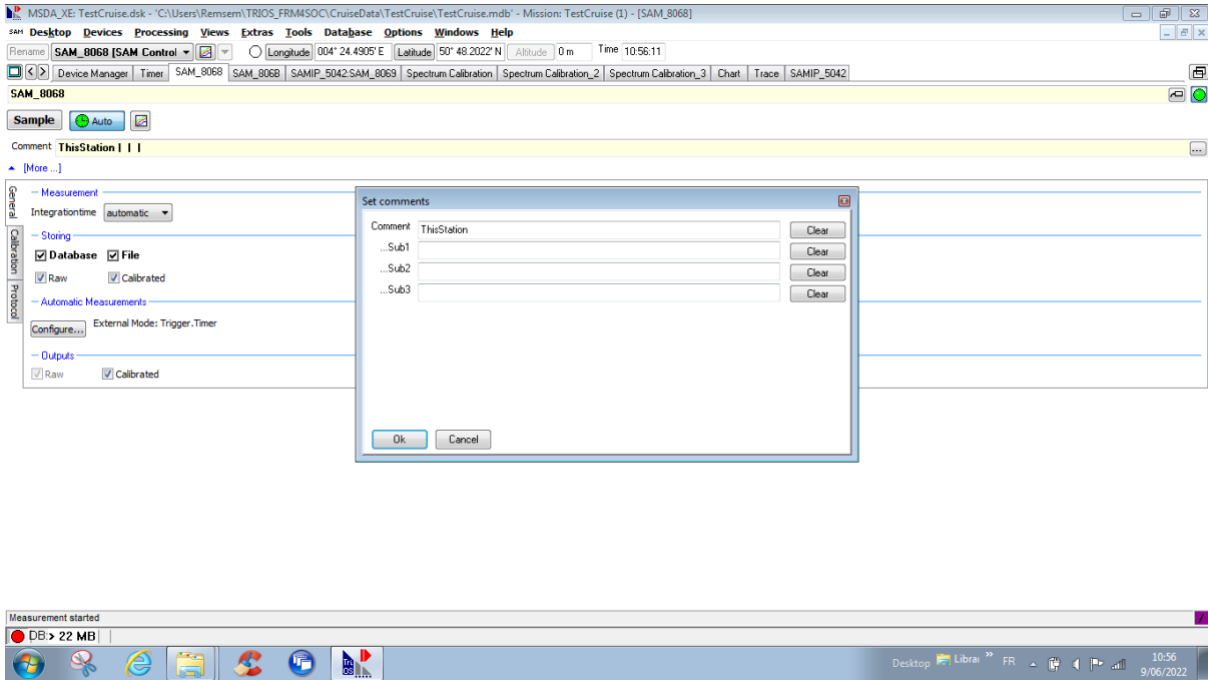


Figure 31 Screenshot adding Station name comment.

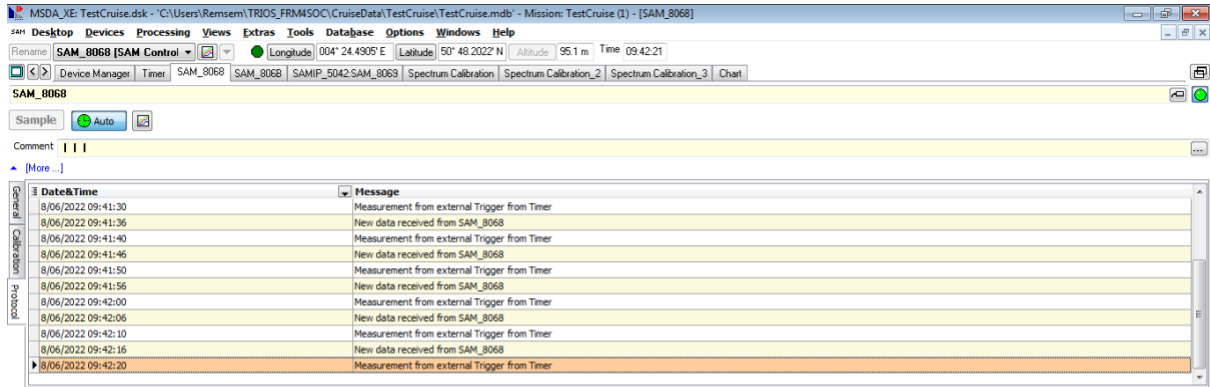


Figure 32 Screenshot checking on Protocol tab that radiometer data is acquired every 10s.

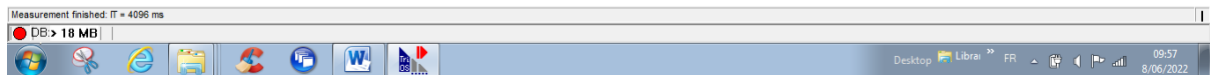
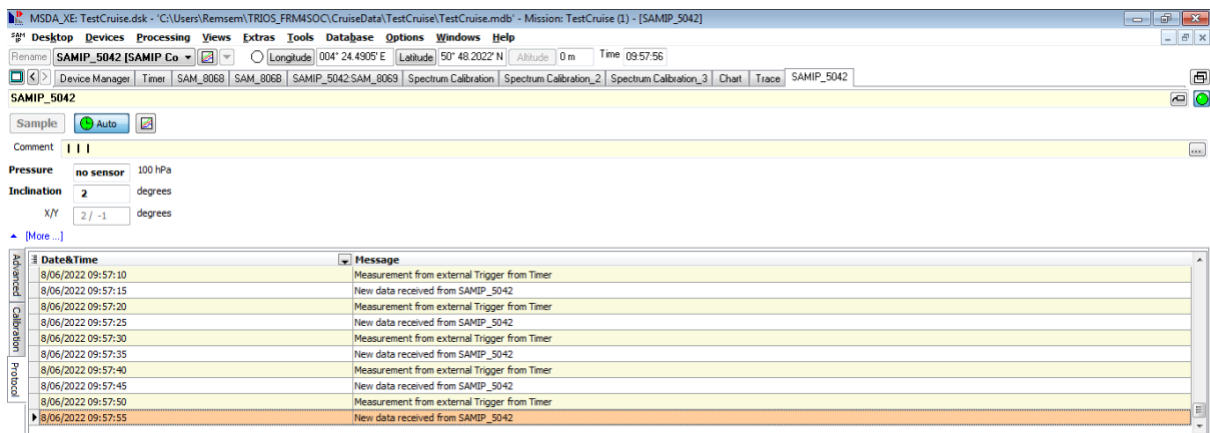
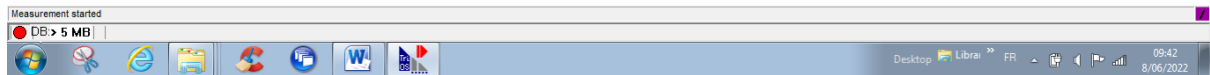


Figure 33 Screenshot after inclinometer setup, checking reasonable inclination (here 2°) and data acquisition every 10s.

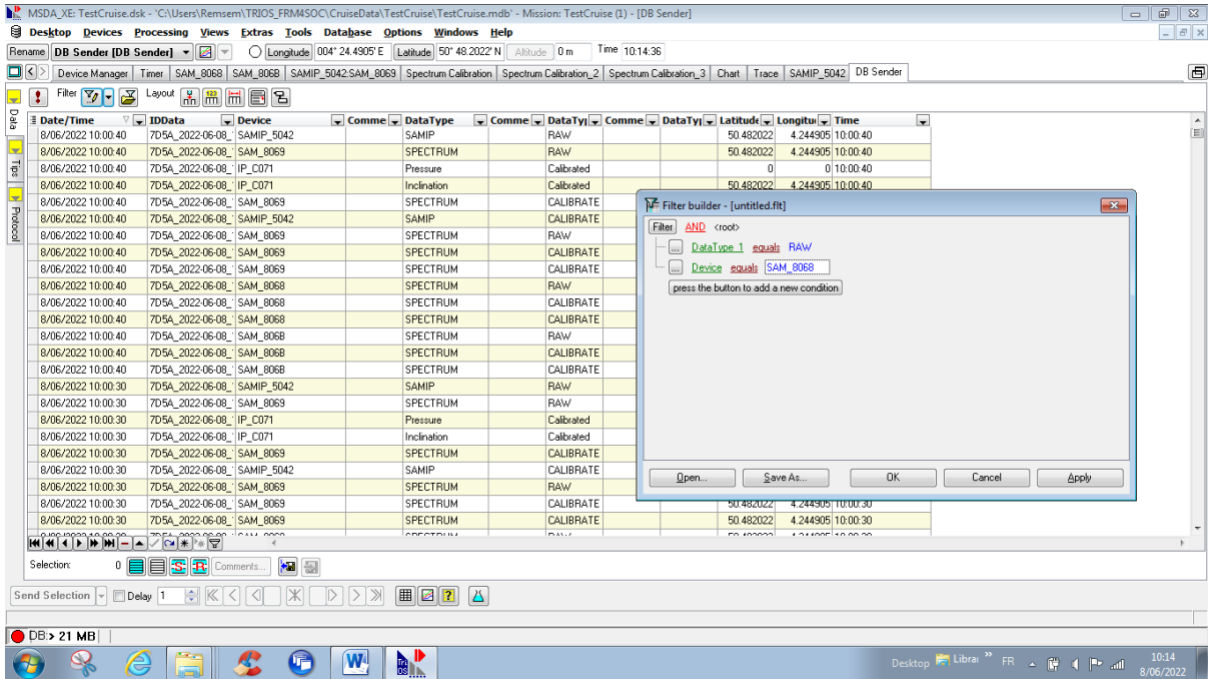


Figure 34 Screenshot preparing export of data showing data filter options for one radiometer.

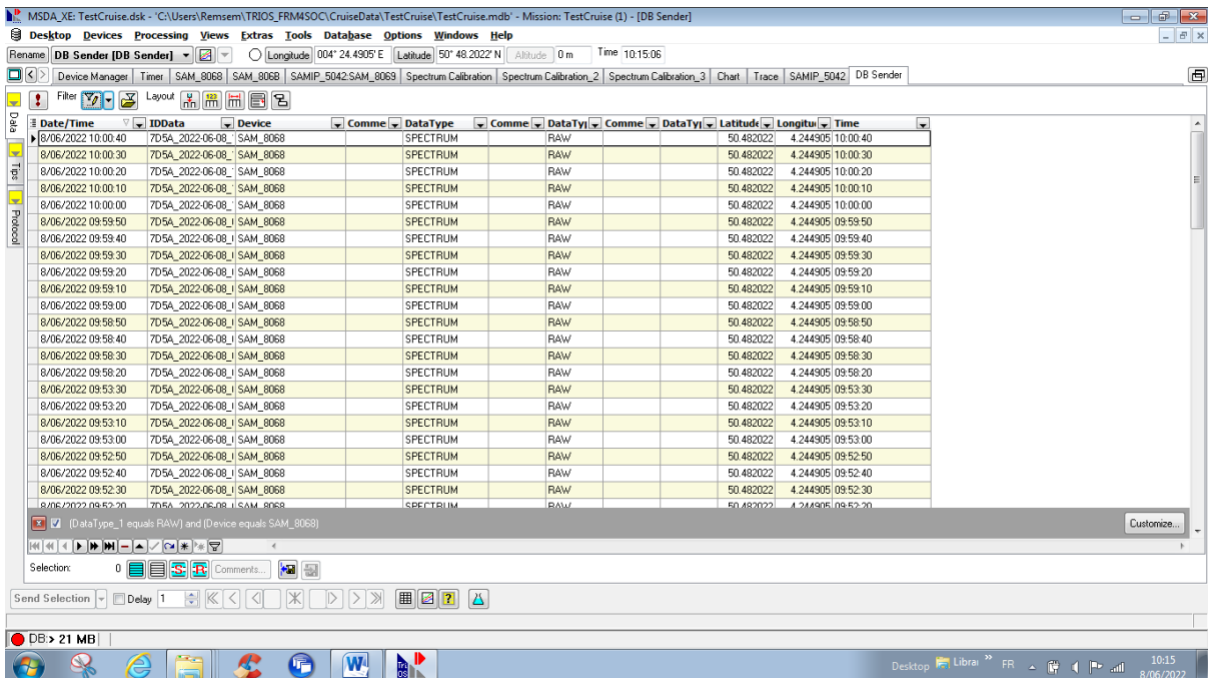


Figure 35 Screenshot after database has been filtered to only one radiometer.

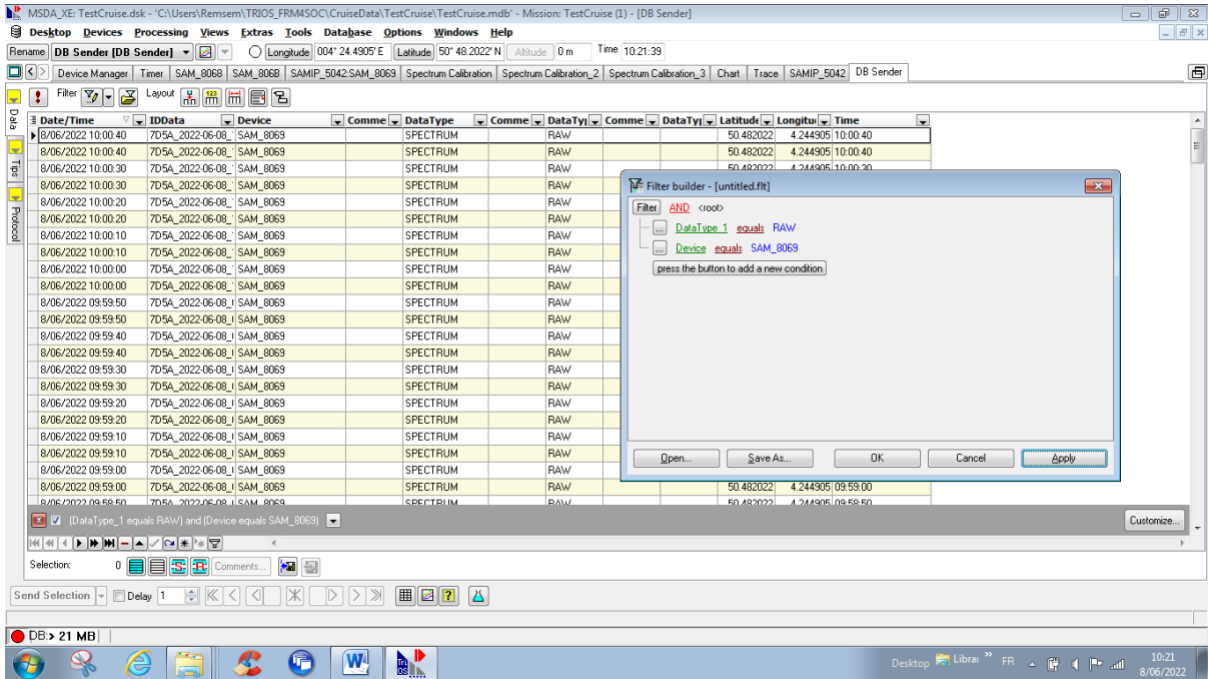


Figure 36 Screenshot preparing export of data showing data filter options for a second radiometer.

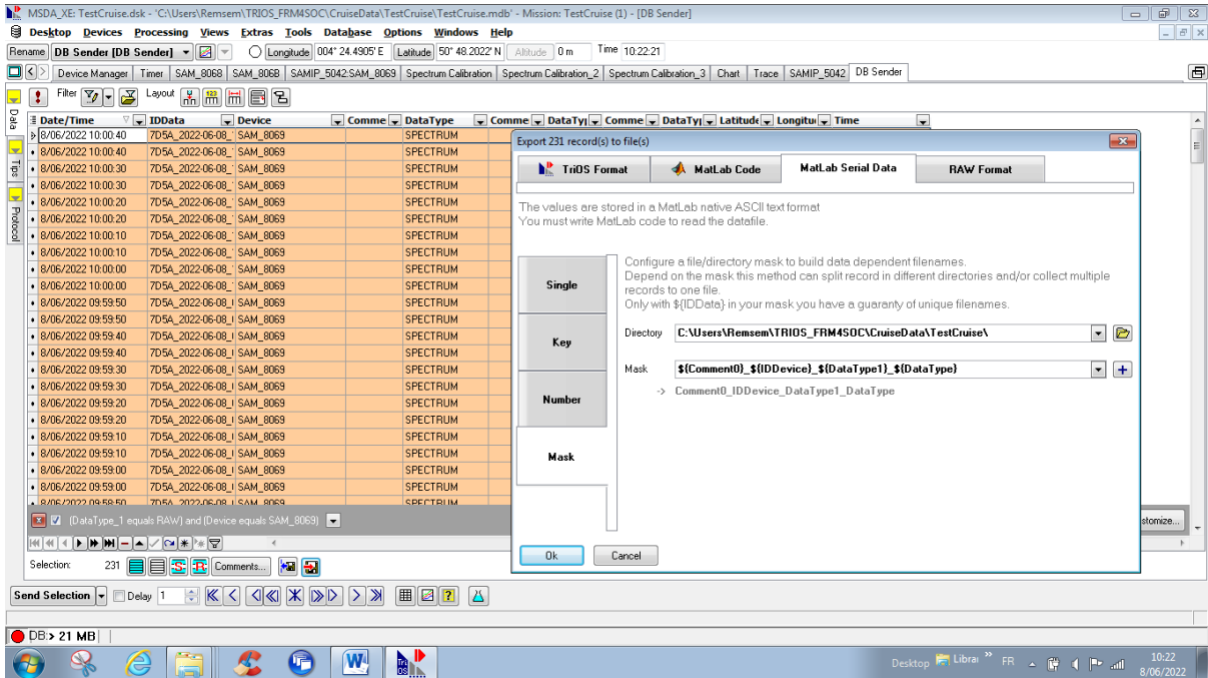


Figure 37 Screenshot while exporting data from one radiometer – showing output filename setting.