FRM4SOC TECHNICAL REPORT (TR-8) ON "PROTOCOLS AND PROCEDURES FOR FIELD INTER-COMPARISONS OF FIDUCIAL REFERENCE MEASUREMENT (FRM) FIELD OCEAN COLOUR RADIOMETERS (OCR) USED FOR SATELLITE VALIDATION ON ATLANTIC MERIDIONAL TRANSECT 27".

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1-8500 SoW	1	Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) Statement of Work (SOW)

ACRONYMS AND ABBREVIATIONS

ESA	European Space Agency
FRM	Fiducial Reference Measurements
IR	Infra-Red
IOCCG	International Ocean Colour Group
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCE	Laboratory Calibration Exercise
NMI	National Metrology Institute
PML	Plymouth Marine Laboratory
OCR	Ocean Colour Radiometry
RBINS	Royal Belgian Institute Natural Science
TO	Tartu Observatory
TR	Technical Report

1 INTRODUCTION

To underpin the validation of satellite OCR, it essential that above and in water radiometers used to collect FRM's, to ascertain the accuracy of Sentinel 2 & 3 products, are inter-compared to assess data consistency and characterise uncertainties between instruments. In the absence of such inter-comparisons, the use of a wide range of instruments, methods and laboratories may only add to the uncertainty in the accuracy of Sentinel 2 & 3 products. The primary data product in satellite ocean colour used to generate biogeochemical concentrations of chlorophyll a (Chl *a*) and total suspended matter (TSM) that are widely distributed to the user community for monitoring the marine environment, is the spectral remote sensing reflectance (*Rrs*) measured from the satellite sensor as the top of atmosphere radiance. Measurements of this parameter *in situ*, are generally obtained through the deployment of in-water and above water optical measurement systems (OMS). OMS include fixed platforms, ships and tethered buoys. Within the numerous OMS that exist, the following may lead to uncertainties in measured *Rrs* that will ultimately affect the accuracy assessment of the satellite products:

1. A range of different OMS methods are deployed, including above water radiometry, underwater profiling, underwater measurements at fixed depths or combined above/underwater measurements from floating systems.
2. Different processing schemes are applied to the data from these systems.
3. A range of calibration sources and methods for the absolute radiometric calibration of field instruments are used.

Best practices on each of these steps to guide the generation of radiometric FRM's will be established in this project. Verification of these procedures will be quantified through a series of inter-comparison exercises that will be conducted in a range of different environmental conditions and biogeochemical provinces relevant to the Sentinel-2 and -3 missions. The first inter-comparison exercise will be conducted on the Atlantic Meridional Transect 27 during which PML HyperSAS SATLANTIC radiometers will be deployed alongside RBINS TRIOS radiometers. The inter-comparison will be conducted in two phases, as follows:

PHASE 1: On station radiometric inter-comparison between PML, RBINS and TO radiometers from 23rd to 29th September 2017 from the National Oceanography Centre (NOC), Southampton, UK to the Azores, Portugal.

PHASE 2: was conducted from 23rd September to 4th November 2017 from Southampton, UK to South Georgia and the Falkland Islands to compare along track measurements of *nLw* and *Rrs* between PML and TO radiometers only.

The AMT has been operated by the Plymouth Marine Laboratory (PML) in collaboration with NOC, Southampton for the past two decades. The cruise is conducted between the UK and the sparsely sampled South Atlantic during the annual passage from October to November of a NERC ship (*RRS James Clark Ross*, *RRS James Cook or RRS Discovery*). The transect covers several ocean provinces where key physical and biogeochemical variables such as chlorophyll, primary production, nutrients, temperature, salinity and oxygen are measured. The stations sampled are principally in the North and South Atlantic Gyres, but also the productive waters of the Celtic Sea, Patagonian Shelf and Equatorial upwelling zone are visited, which therefore offers a wide range of variability in which to conduct FICE for the FRM4SOC.

There are few calibration / validation sites in the blue water oligotrophic gyres of the global oceans, because of the cost of accessing and maintaining measurement platforms in such remote locations. The NOAA moored buoy MOBY (off Hawaii) has been used during the US Sea viewing Wide-Field-of-view Sensor (SeaWiFS), Moderate-resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) missions to provide vicarious calibration data to monitor and reference to satellite Level2 Reflectance (L2R) data. Both MOBY and BOUSSOLE (the CNRS, France optical moored buoy) provided this capability for MERIS, but there were few independent sites in deep blue, case 1 waters that are used for ocean colour validation. AMT therefore offers an excellent opportunity to conduct field inter-comparisons at these sites.

The AMT has an excellent heritage for ocean colour (OC) satellite calibration and validation. At IOC in 2014 and 2015, AMT was heralded as one of NASA SeaWiFS 10 greatest highlights and it was recommended this ocean observing platform be funded to provide vital calibration / validation data for future satellite missions. AMT not only provided vital FRM data for the duration of the SeaWiFS mission but also served as a developmental and inter-comparison platform for selecting the most accurate ocean colour algorithm for SeaWiFS. Many of the early AMTs in the late 1990s were financially supported by NASA for the early pre- and post-launch work on the SeaWiFS. This work included in-situ radiometric measurements to compare against the satellite derived values of water leaving radiance and coincidental measurements of chlorophyll for vicarious calibration and algorithm development. Recent AMTs have renewed the optical drive with continuous, highly accurate and well calibrated measurements of hyperspectral absorption, attenuation and backscatter (Inherent Optical Properties – IOPs) using an established optical flow-through set-up (WET Labs ECO-BB3 meter and WET Labs ACs; see Dall'Olmo et al. 2012) working from seawater from the ship's clean flow-through system. Measurements of particulate absorption are calibrated with discrete HPLC chlorophyll measurements to derive continuous along-tack estimates of chlorophyll concentration (Brewin et al. 2014). This has resulted in unprecedented numbers of data points (e.g. 400 per cruise) for use in satellite validation work (e.g. **Figure 1**). PML have opportunistically taken coincident with hyperspectral radiometer measurements of water leaving radiance (SATLANTIC HYPERSAS; see **Figure 2**).

The AMT-FICE will inter-compare the *above-water* measurements listed in **Table 2**, and the sensors and methods deployed by PML, JRC and RBINS (see **Table 1**) along a 7000 mile transect in both productive and coastal waters as well as the clearest waters in the Atlantic Ocean and under Sentinel -2 and -3 swaths additionally allowing multi-sensor comparisons at the time of satellite match-ups. Uncertainty budgets on instrument calibration, measurement platform and measurement processing will be computed to ensure measurement traceability to NIST/NPL standards based on calibrations before, during and after the cruises. This will contribute to quantification of the errors in these FRMs and also in level 2 OLCI products in open ocean Atlantic environments.

The AMT-FICE will be conducted early in the project and before the main FICE at AAOT in July 2018, so that it can be used as a guide to the scheduled activities at the FICE. The AMT-FICE will enable the consortium to develop knowledge of potential biases between measurements made by instruments under a range of operational and in water optical conditions. The AMT is costly and would be beyond the resources available to a single task and Lead within this ITT. PML will provide the ship time, personnel (both scientific, technical and ship) and additional data (CTD, biogeochemical concentrations, IOPs) at no cost to the project. Small resources are sought to cover the travel expenses of RBINS to and from the ship and for construction of a dedicated radiometer mounting to enable such an inter-comparison on *RRS Discovery*.

1.1. Campaign Aim and Objectives.

The principal aims and objectives of the AMT27 campaign are to provide high quality FRMs for the validation of marine ocean colour and sea-surface temperature products from Sentinel-3 OLCI & SLSTR and Sentinel-2 MSI products in a range of Atlantic Provinces. For ocean colour the FRMs will be used to provide a comprehensive accuracy assessment of the case 1 deep blue waters of the oligotrophic gyres, the contrasting productive eutrophic and mesotrophic shelf and upwelling zone waters and case 2 coastal regions of the UK, and Patagonia. The specific aims of AMT27 are to provide FRM for Sentinel-3A OLCI and SLSTR towards the end of its initial commission phase as well as for marine products from Sentinel 2A MSI.

1.2. Campaign management and planning approach.

PML has managed the AMT programme for 20 years and has extensive experience in campaign organization and implementation. A description of the campaign management and planning approach based on existing procedures includes the following:

- Cruise planning begins 20 months in advance of the cruise. For the AMT4SentinelFRM campaign (AMT27 – DY084) the Ship-time & Marine Equipment Application Form (SMEAF) was submitted to NERC Marine Planning in March 2017. Approval was given in August 2017. A copy of the SME will be made available to ESA if required.
- The ship time will be provided by the Natural Environment Research Council (NERC) on RRS Discovery. Marine equipment, infrastructure and technical support was provided by National Marine Facilities (NMF). A suite of core biogeochemical data (listed in Table 2.2) were also collected by PML and NOCS scientists. The core costs of the ship-time, infrastructure and technical support and the AMT core parameters, are funded through UK government NERC "National Capability".
- A provisional planning meeting with BAS and NMF will be held by teleconference in April 2017.
- A follow up meeting will be held in May 2017 with BAS ship managers and NMF marine equipment supplies to firm up logistical arrangements for the campaign.
- Diplomatic clearance requests will be submitted to BAS by June 2017.
- All cruise participants and stakeholders will be invited to a cruise planning workshop at PML in June 2017.
- COSHH, RISK and campaign execution questionnaires will be coordinated by PML prior to submission to BAS in August 2017. This is supported via an interactive web site, an example of which is provided in Fig. A1.0.
- Campaign mobilisation started in Southampton, UK on 18th September 2017, and departed Port on 23rd September and arrived in Port Stanley, The Falkland Islands on 5th November 2017.
- Table 1-1 lists the waypoints that defined the provisional cruise track..
- A cruise report will be compiled and submitted by 31st December 2017.

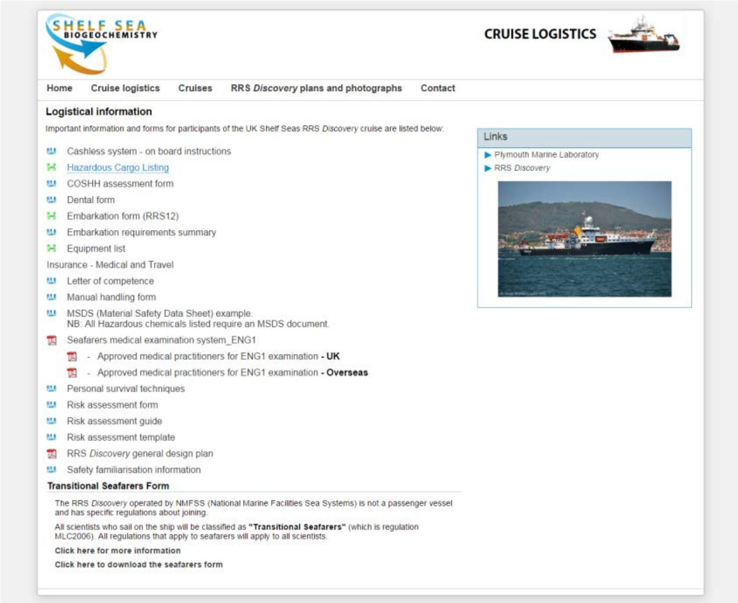

Figure 1.0. Example web site managed by PML, to plan and execute ground campaigns.

1.3. Ship track and station planning for procurement of satellite data.

The nominal way points for the AMT27 are given in Table 1.1. We will maximise ground data matchups with Sentinel-3 using two methods: 1.) a PostGIS based software that allows dynamic location of ground based stations with respect to Sentinel orbits and 2.) the deployment of an autonomous FRM system. Figures A1.1 and 1.2 illustrate the proposed AMT27 ship track with the Sentinel-3 passes assuming a cruise start date of 20th September 2017 for OCLI and SLSTR respectively. Figure 1.1 illustrates the number of coincident ground based FRMs using the autonomous, along track radiometer systems provided by PML, RBINS and TO for Sentinel-3A OLCI (Figure 1.1) and Sentinel-2 MSI (Figure 1.2).

As demonstrated in Fig. 1.1 and 1.2, the AMT trajectory would enable quantification of a variety of conditions to evaluate Sentinel-3 and -2, for a range of optical environments observed in the global ocean (coastal to open ocean); including stations at the western edge of the OLCI swath to investigate low light levels and aerosol backscattering effects. Furthermore, it may be possible (pending conditions) to dynamically adjust the trajectory of the AMT track as the ship moves to minimise stations at the eastern edge of the OLCI swath, that will be contaminated by sun glint, and maximise stations at the western edge.

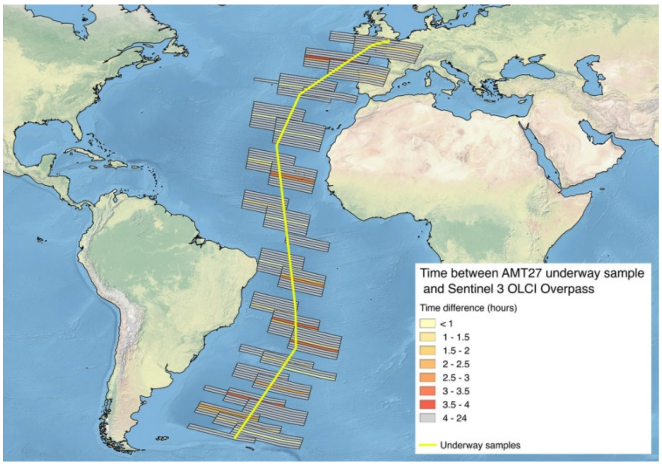

Figure 1.1. Location of AMT27 sampling locations (yellow points) with respect to Sentinel 3 OLCI overpasses (shaded areas).

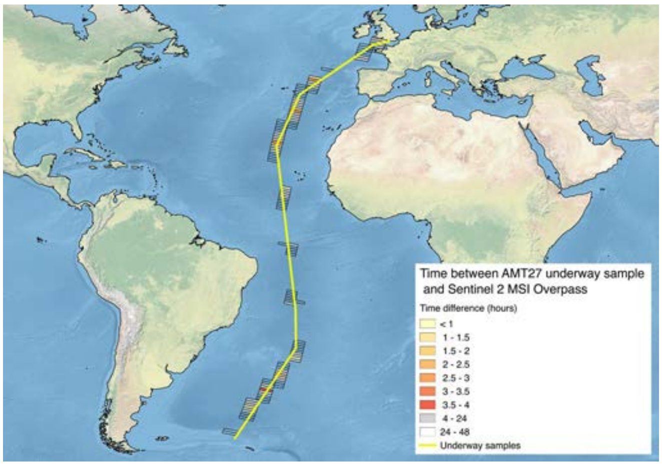

Figure 1.2. Location of AMT27 sampling locations (yellow points) with respect to Sentinel-2A MSI overpasses (shaded areas).

The AMT cruise was planned to depart on the 23rd September 2017, but delays due to upgrade of the ship's internet band width meant that the cruise did not commence until 21st September 2017.

Table 1-1. AMT27 cruise waypoints.

Waypoint number	Waypoint name	Latitude (degrees N)	Longitude (degrees W)	Cumulative distance (km)	Planned ETA
1	Southmapton	50.78	1.13	0	22/09/17 18:00
2	IoW East	50.67	1.03	14	22/09/17 18:44
3	IoW South	50.54	1.02	37	22/09/17 20:01
4	Portland	50.42	2.46	121	23/09/17 00:31
5	Start Point	50.09	3.77	222	23/09/17 06:00
6	Lizard	49.74	5.24	333	23/09/17 12:00
7	Azores	37.00	24.00	2398	29/09/17 08:46
8	NAG	23.75	30.00	3978	03/10/17 20:29
9	SAG	-18.50	25.10	8680	18/10/17 05:03
10	Southern Turn	-28.42	25.00	9732	21/10/17 04:46
11	Falkland Islands	-51.67	40.73	13515	05/11/17 22:38

Daily optics stations will be conducted at 12:00 local time, to ensure direct overlap with Sentinel-3 descending passes. Each optics station was approximately 1.0 hour duration allowing enough time for instrument operation and data acquisition. For the PHASE 1 on stations inter-comparison between PML, RBINS and TO (Southampton, UK to Azores), we made coincident measurements at 5 stations. For on station measurements between PML and TO under PHASE 2, we made 35 station measurements. In addition, the optics stations were complemented by the AMT core stations at pre-dawn (~04:00 local time) and noon (mid-day) stations during which the biogeochemical parameters listed in Table 1.2, will be measured. The optics stations will be complemented by along-track radiometry and spectrophotometry (see section 1.6.) that will be operated continuously for the duration of the cruise which will increase the number of co-located satellite and in situ observations substantially, albeit with a greater matchup time difference. In addition to acquisition of daytime FRM measurements for evaluating SLSTR during (descending) overpasses, along-track infrared radiometric measurements (complemented by pre-dawn CTD stations) will be operated at night to allow for the acquisition of FRM for evaluating SLSTR during (ascending) overpasses.

At various stages along the AMT cruise track (e.g. departing Southampton, approaching Atlantic Islands such as the Azores, South Georgia and arriving onto the Patagonian Shelf close to the Falkland Islands) there were opportunities to gather FRM to evaluate Sentinel 2 MSI performance in coastal waters. Special planned acquisitions in the open ocean will also be arranged with ESA, for use in evaluating Sentinel 2 MSI in clear waters.

Table 1.2. AMT27 Radiometric Measurements.

FRM Measurement	Sentinel-3A OLCI	Sentinel-3A OLCI/Sentinel-2A & -2B MSI
Above water Apparent Optical Properties (AOPs).	R_{rs}, nL_w from SATLANTIC HyperSAS on midday CTD stations.	R_{rs}, nL_w from SATLANTIC HyperSAS on 10:00 CTD stations.
		Along track R_{rs}, nL_w from SATLANTIC HyperSAS; maximising sampling at different parts of the OLCI swath
In water Inherent Optical Properties (IOPs) *from optical sensor profiles.*	Spectral a, b_p, c_p, b_{bp} profiles; two casts at midday.	Spectral a, b_p, c_p, b_{bp} profiles; (bulk vs. 0.2-um filtered absorption and attenuation) at 10:00.
		Along track IOPs: Spectral a, b_p, c_p, b_{bp}; maximising sampling at different parts of the OLCI swath
Discrete IOPs *from filtered water samples.*		a_{tot}, a_{ph}, a_{NAP}, a_{CDOM}, a_{CDM}, a_{ph}*, a_{NAP}*, from 10:00 CTD cast and along track. (note a_{NAP}* will nly be available for surface samples)
Sun photometry Atmospheric data.		Aerosols from Microtops II sunphotometer

HPLC pigments: *Chla*	From midday CTD cast; 2 depths x 2 replicates.	From 10:00 cast + along track.
Phytoplankton community structure	Flow Cytometry from pre-dawn and midday CTD casts	
	Chla discrete fluorometer: CTD & along track	
	CTD *Chla* fluorescence	

Table 1.3. List of in-water optical deployments made on AMT27.

STATION#	DATE	TIME (GMT)	LAT (Degrees)	LONG (Degrees)	IOP*
Optics Rig 1	24/09/2017	11:04	48.94	-7.61	Bulk
Optics Rig 3	25/09/2017	11:11	46.69	-12.00	Bulk
Optics rig 5 cancelled	26/09/2017	11:12	44.85	-14.83	Bulk
Optics Rig 6	27/09/2017	12:02	42.17	-18.80	Bulk
Optics Rig 8	28/09/2017	12:03	39.36	-22.74	Bulk
Optics Rig 10	30/09/2017	13:02	35.08	-26.34	Bulk
Optics Rig 12	01/10/2017	13:09	31.76	-27.19	Bulk
Optics Rig 14	02/10/2017	13:32	28.20	-28.07	Bulk
Optics Rig 15	03/10/2017	13:18	25.72	-28.67	Bulk
Optics Rig 17	04/10/2017	13:06	22.25	-29.48	Bulk
Optics Rig 19	05/10/2017	13:00	18.79	-29.68	Bulk
Optics Rig 21	06/10/2017	13:02	15.67	-28.85	Bulk
Optics Rig 23	07/10/2017	13:06	12.82	-28.17	Bulk
Optics Rig 25	08/10/2017	13:01	9.93	-27.44	Bulk
Optics Rig 27	09/10/2017	13:03	6.88	-26.69	Bulk
Optics Rig 29	10/10/2017	13:07	4.74	-26.16	Bulk
Optics Rig 31	11/10/2017	13:05	1.46	-25.36	Bulk
Optics Rig 33	12/10/2017	13:03	-1.78	-25.00	Bulk
Optics Rig 35	13/10/2017	13:06	-4.59	-25.02	Bulk
Optics Rig 37	14/10/2017	13:03	-7.14	-25.03	Bulk
Optics Rig 39	15/10/2017	13:03	-10.49	-25.06	Bulk

Optics Rig 41	16/10/2017	13:00	-13.73	-25.07	Bulk
Optics Rig 43	17/10/2017	13:05	-15.96	-25.05	Bulk
Optics Rig 45	19/10/2017	13:01	-21.80	-25.07	Bulk
Optics Rig 47	20/10/2017	13:02	-25.10	-25.03	Bulk
Optics Rig 49	21/10/2017	13:03	-27.86	-25.22	Bulk
Optics Rig 51	22/10/2017	13:59	-31.31	-26.19	Bulk
Optics Rig 53	23/10/2017	12:34	-33.88	-27.15	Bulk
Optics Rig 55	24/10/2017	12:36	-36.99	-28.34	Bulk
Optics Rig 57	26/10/2017	12:26	-42.13	-30.42	Bulk
Optics Rig 59	27/10/2017	12:34	-45.19	-31.73	Bulk
Optics Rig 61	28/10/2017	10:28	-47.11	-32.57	Bulk
Optics Rig 63	29/10/2017	12:40	-50.36	-34.20	Bulk
Optics Rig 65	30/10/2017	12:32	-52.94	-35.66	Bulk
Optics Rig 67	01/11/2017	10:16	-53.55	-38.64	Bulk

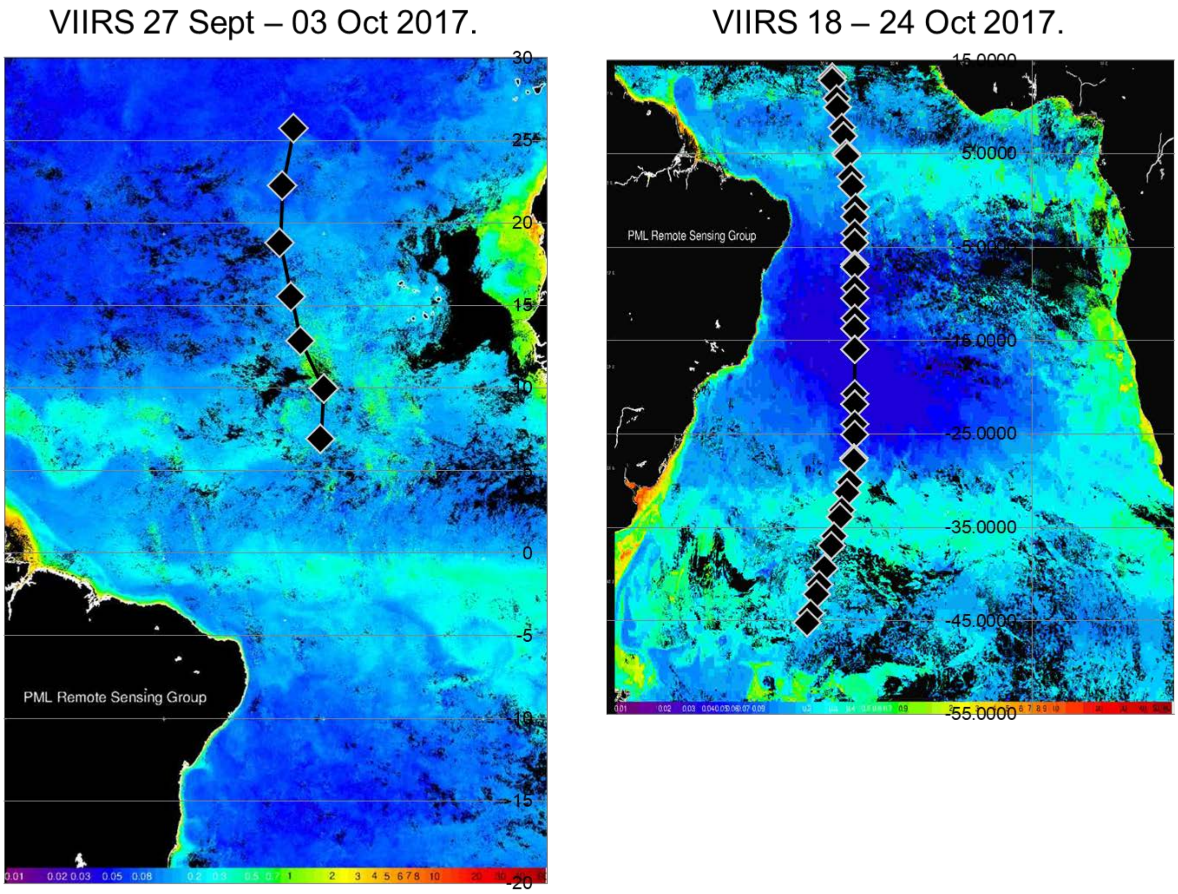

Figure 1.3. Location of AMT27 sampling locations in Northern (3-9 October 2017) and Southern (18-24 October 2017) sectors of the transect.

1.4. Technical description of FRM instrumentation.

A. <u>OCEAN COLOUR RADIOMETRY:</u>

1.4.1. Above water radiometry: The SATLANTIC HyperSAS system

For validation of Sentinal-2 and 3 visible radiometery on AMT27 PML used a series of optical instrumentation deployed along-track and at optics stations. An overview of the above radiometry (HYPERSAS) set-up is shown in Fig. 1.4. The sky (Li) and water (Lt) radiance sensors will be positioned at the front of the ship, together with the tilt and heading sensor. The sky (Li) and water (Lt) radiance sensors will be positioned at 40 and 120 degress from zenith. The downwelling irradiance sensor will be positioned on the mask at the front of the ship, to avoid any ship shadows. These instruments will be connected via a junction box and data will be transferred through a mini deck unit and onto a logging computer for processing. SatView and SatCON software, together with bespoke software developed at PML, will be used for data processing. This system has been sucessfully deployed on the past 9 AMT cruises (AMT18-26) in a variety of different weather conditions.

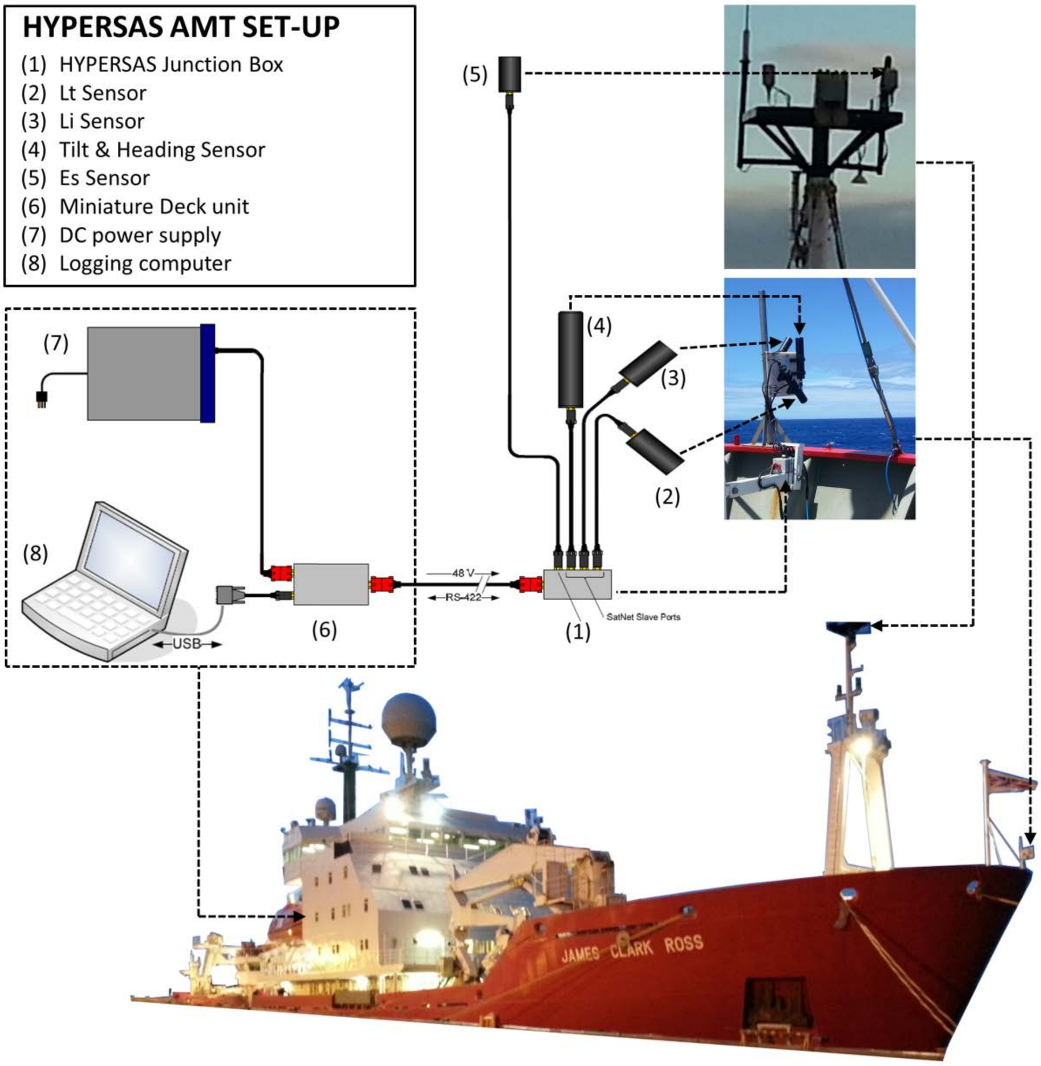

Figure 1.4: Overview of HYPERSAS set-up on AMT27.

1.4.2. In-water inherent optical properties

An optics rig set-up will also be used for vertical optical profiles of inherent optical properties (Fig. 1.6.). This will include a CTD that will measure conductivity, temperature and pressure (depth), a backscattering meter, and an absorption meter. These instruments will be connected to a data logger (DH4) powered by a battery. Instruments will be switched on prior to deployment and data will be uploaded from the data logger onto a logging computer post deployment. We will also attach a white disk to record the Secchi depth (a visual index of water clarity). This optics rig set-up has been successfully used on the past 9 AMT cruises (AMT18-26).

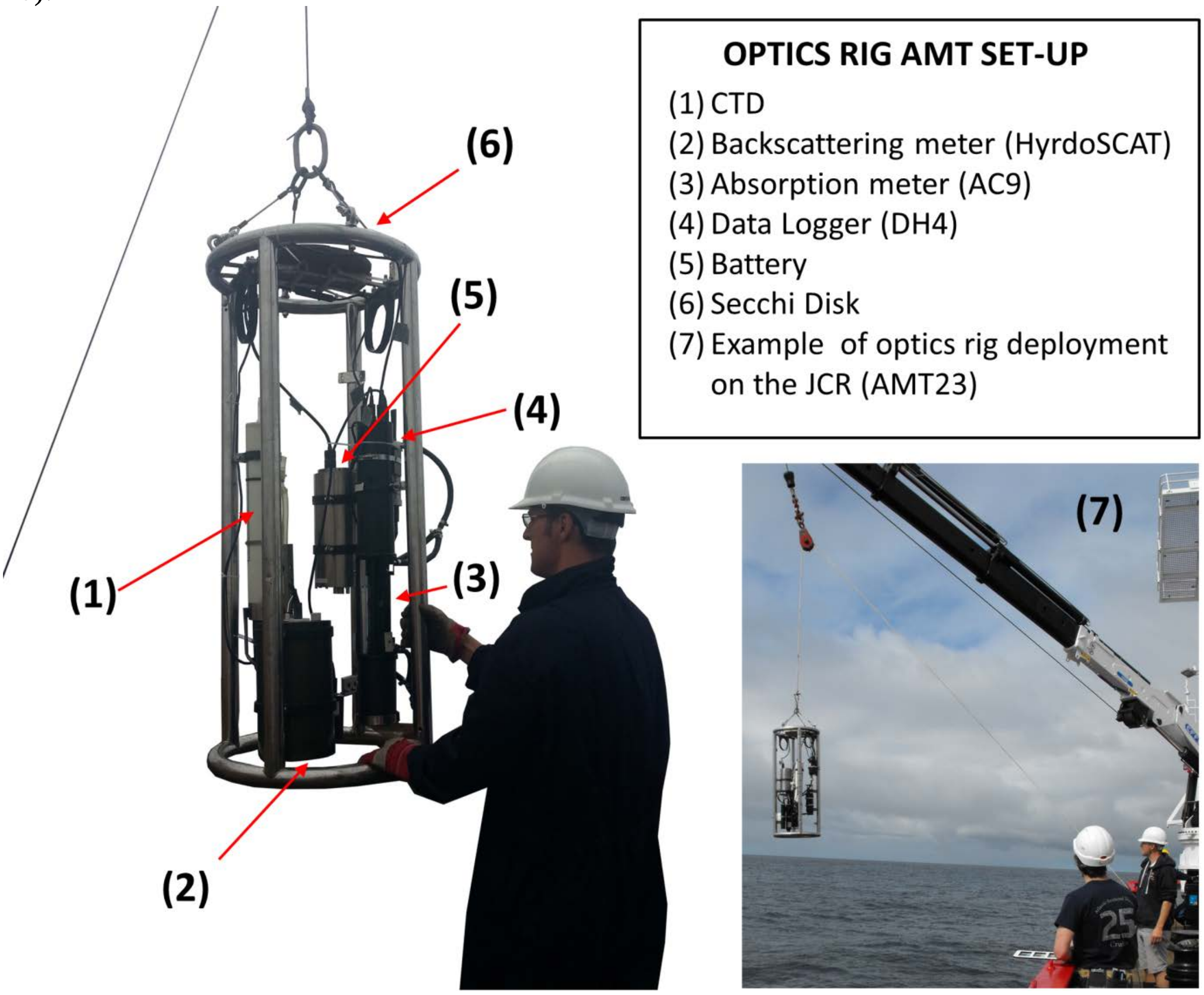

Figure 1.5. Overview of Optics Rig set-up for AMT27.

1.4.3. Under-way, continuous inherent optical properties

An underway optical system (Dall'Olmo et al. 2012) was used on AMT27 to collected continuous along-track measurements of inherent optical properties (backscattering, absorption and attenuation). The system is illustrated in Fig. 1.7. Water from the ships flow through system first passes through a Vortex debubbler, then either passes directly through the optical instruments (50 minutes for every hour) or diverted through a 0.2micron-cartridge filter (for 10 minutes every hour) prior to flowing through the optical instrument, the latter used to provide a baseline for particulate absorption measurements. Water flows through an absorption meter (typically an ACS), a transmissometer (to measure attenuation) and finally through a backscattering meter (typically a BB3), before flowing into a sink and into the outflow of the ship. This underway optics system has been successfully used on 6 recent AMT cruises (AMT19-26).

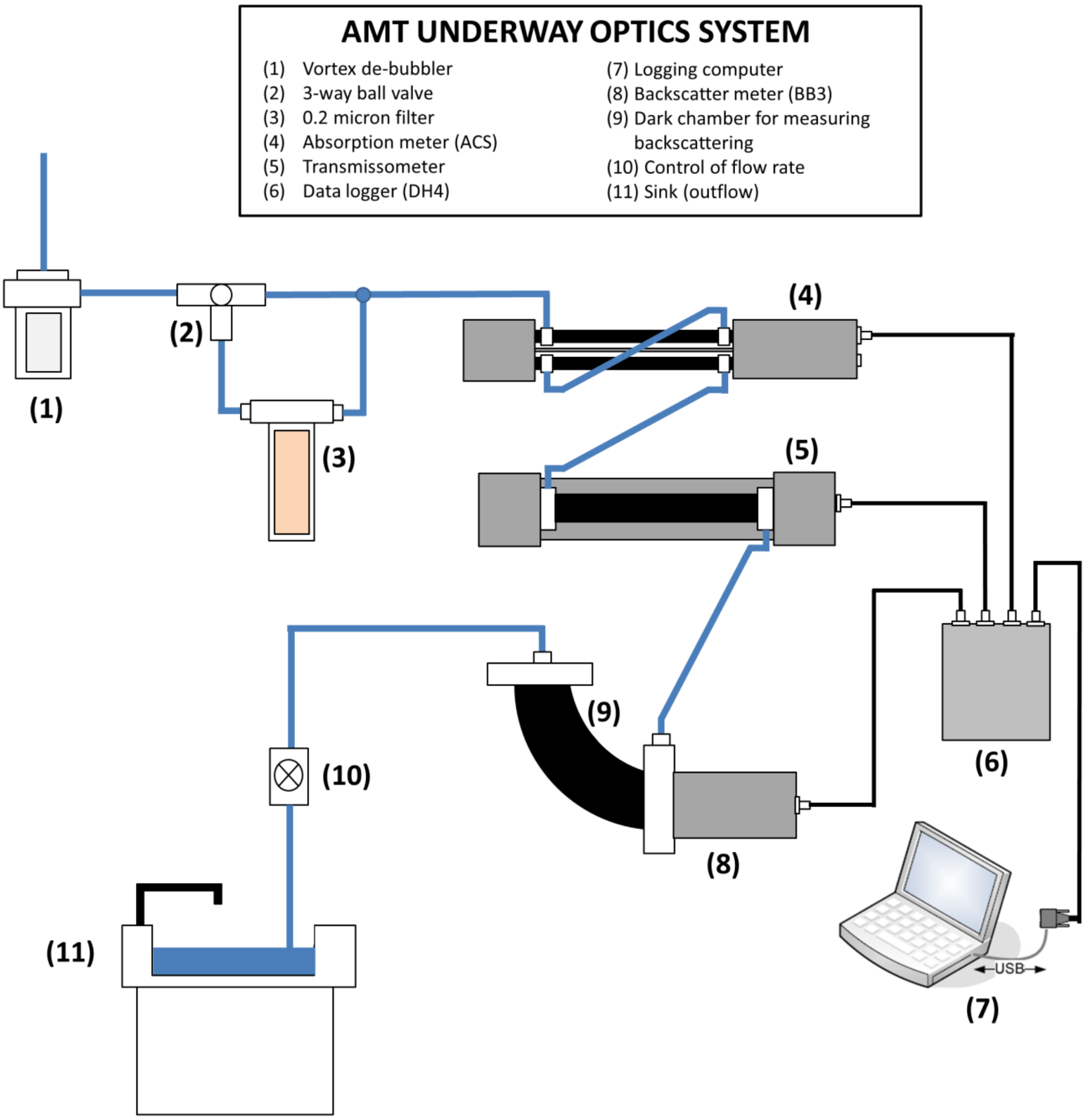

Figure 1.6. Overview of underway optical set-up for AMT27.

Having successfully operated these systems on the past 6 AMT cruises, the team (Drs. Dall'Olmo, Tilstone and Brewin) have experience dealing with issues that can arise while at sea (e.g. instrument failure). For each instrument there are contingency plans, should instruments fail including: back-up instrumentation (e.g. replacement absorption attenuation and backscattering meters), cables, data loggers and computers; good experience working with JCR deck engineers and electricians; and solid lines of communication with all instrument manufacturers while at sea. Despite contingencies, there is always a possibility of issues arising while at sea that is outside the control of the team.

1.5. Definition of best practice procedures and protocols to collect FRMs and to evaluate instrument uncertainties.

The PML ocean colour team has extensive experience in best practice and indeed generation of protocols (e.g. Tilstone et al. 2003). In addition, the scientific literature will be thoroughly monitored to identify new best practices for maintaining and verifying the calibration of all instruments to FRM quality throughout the duration of AMT27. In addition, best practices will be undertaken and protocols will be implemented for producing uncertainty budgets for all instruments and for the range of environmental conditions expected during AMT.

A. OCEAN COLOUR RADIOMETRY:

The above water radiometers operated by PML have an accurate calibration history that is maintained by frequent calibration at an SI traceable facility, which is a requirement for FRM instrumentation. Despite that fact that PML has operated the instruments on the bow of the RRS James Clark Ross for continuous periods of time over a wide range of environmental conditions (e.g., air temperature varying between -1 and 30 deg C), the radiometers have proven to be exceptionally stable over the past four years. The spectral gain has varied at most by ~4% over the last four years, and have this has been maintained at <1% over the last two years. Figure 1.12. provides the calibration history of each instrument part of the Satlantic above-water HyperSAS system deployed during the Atlantic Meridional Transect cruises. Similarly the calibration history of the underway backscatter WETLabs ECO-BB3 instrument is given in Figure 1.13. This calibration accuracy will be maintained throughout AMT27 campaign. Best practices will be undertaken and protocols will be implemented for producing uncertainty budgets for all instruments and for the range of environmental conditions expected during AMT. To this end, we will collaborate with, and aim to participate in inter-comparisons under the framework of ESA FRM4SOC. Kevin Ruddick at the Royal Belgium Institute of Natural Sciences will be involved in AMT27 to undertake an inter-comparison of radiometric measurements with the PML team.

All methodologies used to install, operate, process and quality control data from each FRM instrument, will be documented. A draft example for the on-station L_{WN} FRM is provided below:

- Scientific procedures to collect above-water FRMs of downward irradiance, upward total radiance and downward sky radiance from Satlantic HyperSAS system;
- Scientific procedures to collect in-water FRMs of upward water leaving radiance and above-water downward irradiance from tethered floating TRIOS system;
- Scientific procedures, algorithms and models needed to process the above-water measurements to obtain FRMs of L_{WN};
- Scientific procedures, algorithms and models needed to process the in-water measurements to obtain FRMs of L_{WN};
- Scientific procedures to quality control the above-water FRMs;
- Scientific procedures and algorithms to quality control the in-water FRMs;
- Scientific procedures to inter-compare the above-water and in-water FRMs of L_{WN};
- Scientific procedures to establish uncertainty budgets for above-water and in-water FRMs of L_{WN}.

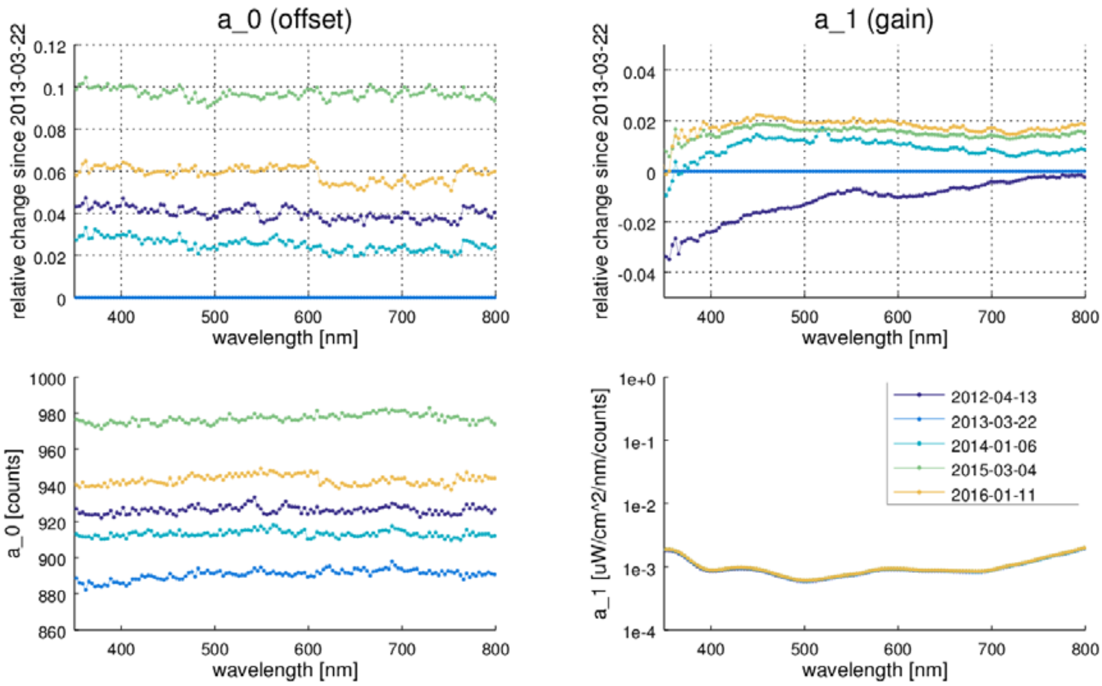

Figure 1.7. Calibration History of the PML operated Satlantic above-water radiometric system.

During AMT26, the use of the PML above water HyperSAS SATLANTIC and the JRC TRIOS radiometers enabled continuous long track inter-comparison of simultaneous measurements of reflectance. The differences observed between these measurements form a key component of estimating errors and uncertainties resulting from environmental variability, as well as instrument deployment methodology, instrument specifications and calibration. Errors from these sources can be wavelength and time dependent. Fig. 1.12 illustrates the differences between the HyperSAS SATLANTIC and TRIOS instruments over one specific day of the cruise at several wavelengths. Percentage differences between the instruments can vary by up to 60% in extreme cases. By comparing these results to ancillary data collected by the instruments, and during the cruise (with regards to environmental conditions), the sources of these differences can be established. From these results, recommendations can be made to adjust processing methodology (e.g. applying appropriate filtering thresholds), future instrument deployment methodology, and calibration processes. Furthermore, these comparisons contribute to the Type B estimates in the uncertainty budget.

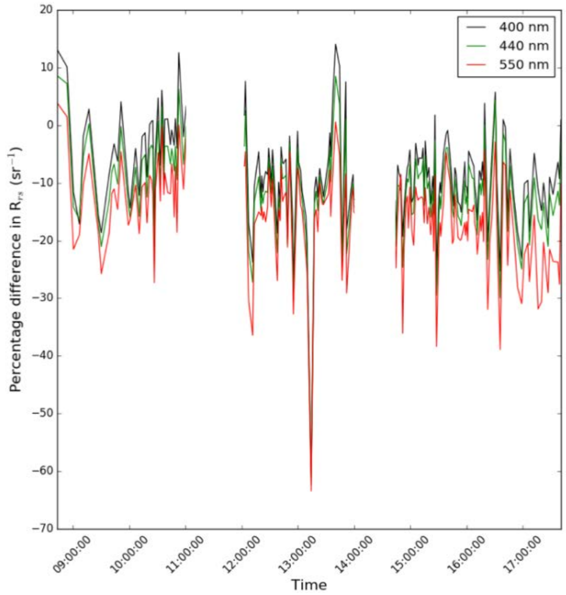

Figure A1.8. Percentage in R_{rs} between above water HyperSAS and in water TRIOS radiometers at 400, 440 and 550 nm during AMT26.

Similarly, all optical backscattering sensors have up-to-date calibration histories which will be maintained throughout the duration of AMT4SentinelFRM. An example of this calibration histories is presented in Fig. A1.9.

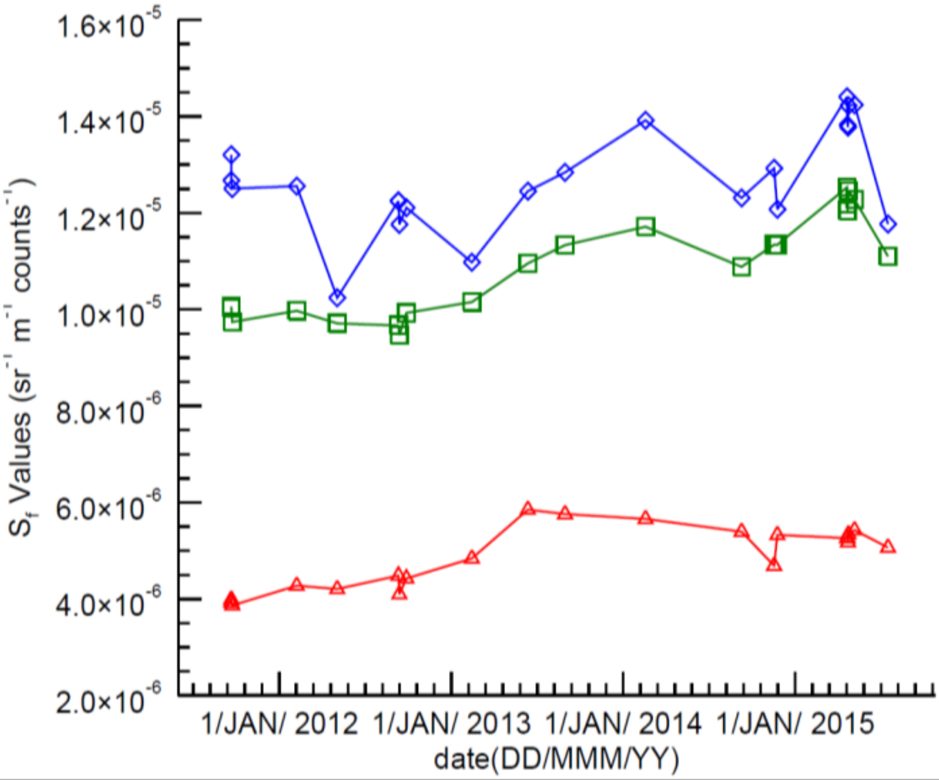

Figure 1.9. Historical variations in the scaling factors of one PML's optical backscattering WETLabs ECO-BB3 sensors (S/N 848). Colours represent the three different channels of the sensor (blue: 470 nm; green: 532 nm; red: 700 nm).

1.5.1. CALCULATION OF OCEAN COLOUR RADIOMETRY UNCERTAINTY BUDGETS.

Uncertainty budgets are required for any Fiducial Reference Measurement and will be compiled for all optical and thermal infrared measurements conducted in the framework of the AMT27. An uncertainty budget is prepared using by the following steps:

1. ***Definition of the measurement equation.*** The measurement equation is the analytical (or numerical) expression that links the measurement output (e.g., particulate optical backscattering at a given wavelength) with the input variables and parameters used to compute it (e.g., raw counts from the backscattering instrument, calibration coefficients, etc.). The measurement equation therefore also links the uncertainties in the inputs with the uncertainty of the output. A general form of the measurement equation is therefore:

$$y = f(x_1, x_2, \dots, x_n) \quad [1]$$

   where y is the measurand or the measurement output, the x_i are the input variables and f is the functional relationship linking inputs and measurand.

2. ***Identification and quantification of all potential sources of uncertainty in the input components of the measurement equation.*** This is the most critical part of the process and requires an in depth understanding of the instrumentation, of the methods used for its calibration and characterization, of the physical principles behind the measurements, as well as of any approximation employed in the measurement equation. Uncertainties in the input variables and parameters are quantified in different ways depending on the specific uncertainty, for example:

   a. by analysing existing datasets (e.g., noise in signal),
   b. by conducting additional targeted experimental measurements (e.g., field measurements of dark counts),
   c. by conducting instrument characterization exercises (e.g., wall effect),
   d. by assessing instrumental drift through pre- and post-cruise calibrations,
   e. by extracting uncertainty estimates from the literature.

   It is also important to distinguish and report which uncertainties are of “type A” and which of “type B” (BIMP & ISO, 1995). Type A uncertainties are estimates of the uncertainty that are obtained by repeated observations and therefore quantify random uncertainties. Type B uncertainties are not obtained from repeated measurements, but evaluated by scientific judgment based on any information available for the variance of the measurand, through calibration and characterisation of the instrument.

3. ***Quantify potential correlations between different sources of uncertainty.*** Input variables can be correlated and so can the uncertainties associated with these variables. When computing the combined uncertainty in the output measurement, it is critical to account for these correlations, because, as a consequence of these correlations, the combined uncertainty can either significantly decrease or increase. The identification and quantification of correlations among

input variables is achieved by analysing existing datasets and careful consideration of the measurement process.

4. ***Propagation of uncertainties.*** Each source of uncertainty then needs to be propagated through the measurement equation to quantify the "combined uncertainty", u, in the measurand due to the uncertainty in each separate input variable. This error propagation is achieved by either applying the law of propagation of uncertainty (equation 2 below; BIPM and ISO, 1995) or, if the measurement equation is numerical in nature or non-linear and input variables have relatively large uncertainties, through Monte Carlo methods. Monte Carlo methods can also be used to ensure that the uncertainty estimates obtained from the law of propagation of uncertainties have been correctly calculated.

The law of propagation of uncertainties is used to calculate the "combined variance", u_c^2, and has the following general form:

$$u_c^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j} u(x_i, x_j) \qquad [2]$$

where, $u^2(x_i)$ are the variances of the input variables, and $u(x_i, x_j)$ are the covariances between the input variables.

5. ***Calculation of the overall combined uncertainty.*** To calculate the final value of the overall combined uncertainty in the output parameter, equation 2 is then applied to all input variables to combine all sources of uncertainty and any identified correlation term.

6. ***Compilation of the uncertainty budget.*** The uncertainty budget is finally compiled by reporting each source of uncertainty and the combined uncertainty. This budget allows one to understand the relative contribution of each source of uncertainty to the final measurements and can be used as a guide to define methods to reduce the combined uncertainty in the measurand.

7. ***Presentation of results.*** All results of the above exercise are finally presented in tabular and/or graphical form. Specifically, three tables will be prepared for each measurement presenting (i) the identified sources of uncertainty, their quantified values, and their type; (ii) any correlation among input variables and their quantified values; and (iii) the uncertainty budget.

Example for particulate backscattering measurements collected during AMT19

As an example, we present the uncertainty budget that we computed for the particulate backscattering coefficient, b_{bp}, measured by the underway system during AMT19 (Dall'Olmo et al., 2012). In this study, input variables were considered not correlated. In this case the measurement equation is (wavelength dependency omitted for simplicity):

$b_{bp} = 2\pi\chi_p[S(C-D) - \beta_{sw}] - b_{b,wall}$

where:

χ_p is the ratio of particulate backscattering to the particle volume scattering function at 120°;

S is the instrument scaling factor;

C are the raw counts output from the instrument;

D are the instrument dark counts;

β_{sw} is the volume scattering function of pure sea-water;

$b_{b,wall}$ is the contribution to the signal recorded by the instrument due to reflections inside the flow-through chamber where the backscattering meter in installed.

Table 1.4. Uncertainties (their units in squared brackets) assigned to each input variable, their type and the how they were determined.

Table 2.4. Uncertainties in the input variables used to calculate $b_{bp}(526)$.

Variable, x_i	***Uncertainty, $u(x_i)$***	**Uncertainty type**	**Reference**
χ_p	2.9 [%]	B	Sullivan and Twardowski, 2009
S	10 [%]	A	Sullivan et al., 2012
C	2.5 [counts]	A	Measured
D	1.5 [counts]	A	Measured
β_{sw}	2.24 [counts]	B	Zhang et al., 2009
$b_{b,wall}$	5.2×10^{-5} [m^{-1}]	A	Measured

Table 1.5. Uncertainty budget for $b_{bp}(526)$ and demonstrates the importance of reducing the uncertainty in the scaling factor for accurately determining particulate backscattering.

Table 1.5. Uncertainty budget for $b_{bp}(526)$.

Variable, x_i	**Contribution to u_c** $\times10^{-4}$ [m^{-1}]
χ_p	0.24
S	2.19
C	0.78
D	0.47
β_{sw}	0.23
$b_{b,wall}$	0.52
Quadrature sum	**2.45×10^{-4}**

1.6. ABOVE WATER RADIOMETRY: THE TRIOS SYSTEM (RBINS).

RBINS will deploy TRIOS RAMSES radiometers on AMT27 alongside the PML HyperSAS system on the same mounting on the bow of the ship (see **Figure 1.10**).

For this system, Remote sensing reflectance, $\rho_w(\lambda)$, as defined by:

$$\rho_w = \pi \frac{L_w(\lambda)}{E_s(\lambda)}$$

is calculated from simultaneous above-water measurements of downwelling irradiance, $E_s(\lambda)$, radiance from the water surface, $L_t(\lambda)$ and sky radiance, $L_{sky}(\lambda)$. The latter two measurements are used to calculate the intermediate parameter, $L_w(\lambda)$, the water-leaving radiance (after removal of air-sea interface reflection). This method corresponds to "Method 1" of (Mueller et al. 2000). Results of the method as used for satellite Validation are presented in Ruddick et al. (2002) and Ruddick et al. (2006).

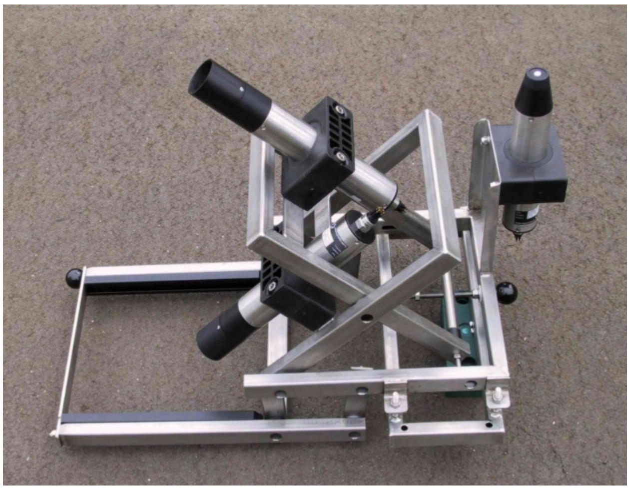

Figure 1.10. (left) System of two radiance and one irradiance sensor installed on steel frame. (right) As installed at prow of ship with irradiance sensor mounted separately to reduce optical interference from mast.

1.6.1. INSTRUMENT DESCRIPTION

The measurement system consists of three hyperspectral spectroradiometers, either TriOS-RAMSES or SATLANTIC OCR, two measuring radiance and one measuring downwelling irradiance with a cosine collector. The sensors measure over the wavelength range 350-950nm with sampling approximately every 3.3nm with spectral width of about 10nm. The sensors are based on the Carl Zeiss Monolithic Miniature Spectrometer (MMS) incorporating a 256 channel silicon photodiode array. Integration time varies from 4ms to 8s and is automatically adjusted to measured light intensity. The data stream from all three instruments is integrated by a IPS-104 power supply and interface unit and logged on a PC via a RS232 connection. The radiance sensors have a field of view of 7°. A two-axis tilt sensor is incorporated inside the downwelling irradiance sensor. The instruments are mounted on a steel frame, similar in concept to that used by (Hooker and Lazin 2000). The frame is fixed to the prow of the ship, facing forwards to minimise ship shadow and reflection and 1-8m above the water surface. Where necessary to avoid optical interference the downwelling irradiance sensor is mounted separately elsewhere on the ship.

1.6.2. INSTRUMENT CALIBRATION AND QUALITY ASSURANCE

The instruments are calibrated twice per year at NIST-traceable facilities in the framework of MERIS Validation Team workshops.

1.7. METHODOLOGY AND PROCESSING DESCRIPTION.

1.7.1. Deployment of the instrument

The instruments are mounted on a steel frame, which can be fixed to the bow of the ship. The sensors should face forward to minimize ship shadow and reflection. Before measurements the frame is levelled horizontally and the sea and sky-viewing angles are fixed at 40° with respect to zenith and viewing in the same azimuth angle. In this way the sky is viewed in the direction from which light will enter the sea-viewing sensor after reflection at a flat sea surface. The radiance sensor lenses and the irradiance sensor collector are inspected manually before each measurement and are cleaned of spray and dust when necessary. The ship is manoeuvred on station to point the radiance sensors at a relative azimuth angle of 135° with respect to sun. New platforms have been developed which automatically track the position of the sun so that continuous quality assured measurements can be taken whilst the ship is steaming (Balch et al. 2011). When the correct position and angle are achieved measurements are started and continue for 10 minutes, taking a scan of the three instruments every 10s. During measurements wind speed is recorded and sea, sun and sky state conditions are noted, especially if variable because of cloud movement or floating matter. The ship position and orientation are monitored for drift. Lens caps are used to protect all three sensors except during the 10 minute measurement sequence.

Measurements can also be made underway for a ship heading of 135° relative to sun, providing a transect of reflectance spectra. For such measurements the lenses are inspected at the end of the transect and any spray droplets are noted. During such measurements visual checks are made of the sea surface for variability such as fronts or floating material and the ship heading is monitored.

1.7.2. Description of processing techniques employed

Data is acquired with the MSDA software (v1.94 in 2001-2002) using the file recorder function and calibrated radiometrically using nominal calibration constants. Dark values are removed with the "dynamic offset" function, which uses blocked photodiode array channels. Calibrated data for $E_s(\lambda)$, $L_t(\lambda)$ and $L_{sky}(\lambda)$ is interpolated to 2.5nm intervals and exported to Excel for recalibration to the MERIS Validation Team standard and for further processing.

1.7.3. Preprocessing Quality Checks

The multitemporal dataset is screened to:

- Remove dropout (incomplete spectra)
- Avoid measurements during temporal fluctations of $E_s(\lambda)$, arising mainly from clouds or haze passing in front of the sun
- Avoid measurements during strong temporal fluctuations of $L_{sky}(\lambda)$, arising mainly from variable cloudiness in the sky-viewing direction
- Avoid outliers of $L_t(\lambda)$
- Avoid measurements with high tilt or roll (greater than five degrees)

Five scans of $E_s(\lambda), L_{sky}(\lambda)$ and $L_t(\lambda)$ are used for further processing.

1.7.4. Data Processing

The water-leaving radiance is calculated by,

$$L_w = L_t - \rho_{sky} L_{sky}$$

where ρ_{sky}, the air-sea interface reflection coefficient, is estimated for sunny conditions from Figure 9 of (Mobley 1999) as function of wind speed in m/s, W:

$$\rho_{sky} = 0.0256 + 0.00039 * W + 0.000034 * W^2$$

The reflectance, $\rho_w(\lambda)$, is then calculated for each scan and the mean and standard deviation over the five scans are calculated and plotted.

1.7.5. Postprocessing Quality Checks

Reflectance spectra are inspected subjectively to ensure:

- limited variability over scans (comparing standard deviation with mean)
- internal consistency of spectra in red and near infrared (positive reflectances with reflectance ratios given approximately by the inverse ratio of pure water absorption)

Measurements outside the range 400-900nm are not used for scientific analysis because of high uncertainty and instrument noise.

1.8. LIMITATIONS

- Measurement uncertainties associated with the air-sea interface reflection correction become significant in conditions of cloudy sun (and to a lesser extent cloudy sky in the sky-viewing direction) and high wind. Such uncertainties are relatively more important for clearer waters.
- Measurement uncertainties increase for underway measurements because of increased tilt/roll and possible contamination of lenses by spray.
- Underway measurements from small ships, e.g. Rigid Inflatable Boats, are limited to calm sea state (e.g. Bf ≤3) to avoid excessive tilt and roll.

1.9 ABOVE WATER RADIOMETRY: THE TRIOS SYSTEM (TO).

1.9.1 INSTRUMENT DESCRIPTION

Above-water TriOS systems (TriOS Mess- und Datentechnik GmbH, Germany) are composed of two RAMSES ARC hyperspectral radiometers measuring upwelling radiance *Lu(λ)* and downwelling radiance *Ld(λ)* in the same azimuthal plane, and one RAMSES ACC for downwelling irradiance *Ed(0+,λ)*. The spectral range is 350-950 nm at 3 nm step and 10 nm bandwidth. The nominal FOV of radiance sensors is 7 degrees. The data stream from all three sensors are integrated by spectrometer interface controller IPS104 and logged on a PC for further processing. The instruments are mounted on a common steel frame, alongside with the RBINS's TriOS Ramses and PML's HyperSas system as described in section 1.6.1 and 1.7.1.

1.9.2 INSTRUMENT CALIBRATION AND QUALITY ASSURANCE

The instruments are calibrated prior to the event in Tartu Observatory, Estonia.

1.10 METHODOLOGY AND PROCESSING DESCRIPTION.

1.10.1 Deployment of the instruments

TO's TriOS RAMSES radiometers will be deployed alongside with RBINS's and PML's radiometers as described in Section *1.7.1 Deployment of the instrument*. This allows to have identical zenith and viewing angles and perform measurements at the same conditions. Before each measurement series, the input windows of the radiometers are cleaned using distilled water and fibre-free wipes.

1.10.2 Description of processing techniques employed.

Data is acquired and processed with software developed in TO. All three spectra are recorded simultaneously where the time interval between the scans can be manually set. The integration time is adjusted automatically in the range of 4ms - 4s based on the scene brightness.

The remote sensing reflectance, $\rho_w(\lambda)$, is calculated with the correction coefficient of the air-sea interface reflection, ρ_{sky}, similarly as described in Section 1.7.4. In addition NIR-similarity correction and filter for clear/cloudy sky is applied after Ruddick et al. 2006.

1.11 LIMITATIONS

The considered uncertainty sources are:

- uncertainty of the absolute radiometric calibration of the *Lu*, *Ld*, and *Ed* sensors;
- uncertainty due to inherent straylight effects of the *Lu*, *Ld*, and *Ed* sensors;
- uncertainty of the NIR-similarity correction;
- effects of non-cosine response of the *Ed* sensor;
- environmental perturbations (estimated from the variation of $\rho_w(\lambda)$).

2 ABOVE WATER RADIOMETRY: THE WISP INSTRUMENT (TO).

TO will deploy two Water Insight's WISP-3 handheld spectrometers.

2.1.1 INSTRUMENT DESCRIPTION

The WISP instrument has three radiometers which are, via optical fibers, connected respectively to one cosine corrector to measure the downwelling irradiance [$E_d(\lambda)$], and two radiance sensors: the downwelling radiance from the sky [$L_{sky}(\lambda; \theta)$] in which θ = 42 deg from the zenith and the total upwelling radiance [$L_u(\lambda; \theta)$] at 42 deg from the nadir (θ = 138 deg). One instruments is using Gershun tubes for radiance sensors and the other one lenses. Otherwise, the two sensors are identical. These three radiometers and the angles are chosen according to Mobley's (1999) guidance on above-water radiometric measurements (Hommsersom et al., 2012).

2.1.2 INSTRUMENT CALIBRATION AND QUALITY ASSURANCE

The instruments are calibrated prior to the event in Tartu Observatory, Estonia.

2.2METHODOLOGY AND PROCESSING DESCRIPTION.

2.2.1 Deployment of the instrument

Devices are hand held instruments and the measurements will be taken at an azimuth angle of ~135 deg relative to the Sun. In this way the direct reflectance effects (e.g., sun glint), that occur at the surface, are avoided as much as possible (Mobley, 1999). The measurements are taken as often as the instruments allow during the 10 minute window and have to be managed by a person pressing the buttons on the instrument.

2.2.2 Data Processing

Raw measurement data is stored on the SD-card and from there, it is uploaded to the WISPWeb, where the calculation takes place and is therefore controlled by Water Insight.

2.3LIMITATIONS

Integration time is calculated on every measurement set and as one set is average of ten measurements then sometimes adapting to light together with measurements will take longer. Therefore the number of measurements during the 10 minute window is probably smaller than for other sensors. Also as it is hand held instrument, then the irradiance sensor is more affected by the ship.

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APPROACH TO DATA & AUTHORSHIP AGREEMENT.

1.6. TIMETABLE

There are four phases of the FICE, which are illustrated in Table 3. The first phase prepares for the measurements; the second phase is the measurements themselves and the third phase the analysis and report writing.

Table 3. FICE Implementation Plan Schedule

PHASE 1: PREPARATION	
Ship-time & Marine Equipment Application Form (SME)	March, 2016
UK National Marine Facilities (NMF) Approval	August, 2016
provisional planning meeting held at BAS	April, 2017
NMF & BAS ship management meeting	May, 2017
Diplomatic clearance requests	July, 2017
PHASE 2: AMT27 Inter-comparison	
Radiometer calibration	July, 2017
Participants to ship radiometers to NOC	September, 2017
FICE AMT27 dates	23 - 29 Sept, 2017
PHASE 3: AMT27 Inter-comparison	
Current dates for AMT27	23 Sept - 5 Nov, 2017
BoL's, CARs, COSHH, RA to be completed by July 2017	July 2017
Embarkation on RRS DISCOVERY	18-19 September 2017
Disembarkation in Azores	29 Sept 2017
Disembarkation in Falkland Islands	5 Nov 2017
PHASE 4: ANALYSIS AND REPORTS	
Re-Calibration of sensors	March, 2018
Participants to send raw data from AMT27 inter-comparison	May, 2018
Draft A (results circulated to participants)	May, 2018
Final draft report circulated to participants	June, 2018
Data loaded to database	July, 2018
Final Report published	August, 2018

1.7. TRAVEL ARRANGEMENTS FOR FICE

Plymouth Marine Laboratory will be arranging all travel and hotel arrangements. The point of contact for this is:

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Plymouth Marine Laboratory
Prospect Place
West Hoe
Plymouth
UK
PL1 3DH

Email: kho@pml.ac.uk
Tel: 01752 633100

PML Plymouth Marine Laboratory