OceanGliders Oxygen SOP

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CONTENTS

This GitHub repository is for the OceanGliders Oxygen Standard Operating Procedure (SOP).

Read the SOP here. If you are reading a pdf or other offline version of this SOP, please click on this link to read the most recent online version.

Continous community review

Feedback by the global glider community is possible at any time. Everyone is welcome to join the SOP.

Who is invited to review?

Constructive feedback by anyone is welcome. We encourage both experts and new gliders users who want to start observing oxygen to feedback on the document. For example: Experts are welcome to critically assess the specific methods and uncertainty ranges outlined in the SOP. New users can help to improve the SOP by providing a feedback from the user perspective. Please let us know that you use the SOP.

How to contribute

See contributer guideline here

Next steps

1. Preparation of GOOS endorsement as outline in Hermes 2020
2. Depositing of first major SOP release at the Ocean Best Practice System (OBPS) + doi by OBPS.
3. Submission of shorter version to Frontiers: Research Topic Best Practices in Ocean Observing for peer-review in spring 2022.

The main SOP document will always reside in this GitHub repository to allow updates within the OceanGliders community at any time. After major revisions regular updates are planned.

Questions?

Do you have any questions related to oxygen measurements on gliders? Or do you struggle to comment the SOP document? Just raise a question here.

License

Code of Conduct

Please read and follow our Code of Conduct.

CHAPTER

ONE

AUTHORS, DEVELOPMENT PROCESS AND CONTRIBUTIONS

1.1 Authors

1. Patricia López-García, *Ocean Technology and Engineering Group, National Oceanography Centre, Southampton, UK,* 0000-0002-4689-2775
2. Tom Hull, *Centre for Environment Fisheries and Aquaculture Science, Lowestoft, UK,* 0000-0002-1714-9317
3. Soeren Thomsen, *LOCEAN, ISPL, Sorbonne University, Paris, France,* 0000-0002-0598-8340
4. Johannes Hahn, *Federal Maritime and Hydrographic Agency (BSH), Hamburg, Germany,* 0000-0002-5638-2031
5. Bastien Y. Queste, *Department of Marine Science, University of Gothenburg, Gothenburg, Sweden,* 0000-0002-3786-2275
6. Gerd Krahmann, *GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany,* 0000-0003-0944-8795
7. Charlotte Williams, *Marine Physics and Ocean Climate Group. National Oceanography Centre, Liverpool, UK,* 0000-0001-7964-4826
8. Mun Woo, *IMOS Ocean Gliders, UWA Oceans Institute and Oceans Graduate School, The University of Western Australia, Perth, Australia*
9. Charitha Pattiaratchi, *IMOS Ocean Gliders, UWA Oceans Institute and Oceans Graduate School, The University of Western Australia, Perth, Australia*
10. Laurent Coppola, *Sorbonne Université, CNRS, Laboratoire d'Océanographie de Villefranche (LOV), 06230 Villefranche-sur-Mer, France,* 0000-0003-0473-1129
11. Tania Morales, *Plataforma Oceánica de Canarias (PLOCAN), Canary Islands, Spain,* 0000-0002-3585-8037
12. Virginie Racapé, *Institut Universitaire Européen de la mer CNRS-UMS 3113, IFREMER-coriolis, Plouzané France,* 0000-0003-0239-5125
13. Claire Gourcuff, *Euro-Argo ERIC, Brest, France* 0000-0001-6071-8389
14. John Allen, *SOCIB, Palma de Mallorca, Spain,* 0000-0001-7357-6623
15. Eva Alou-Font, *SOCIB, Palma de Mallorca, Spain,* 0000-0003-2247-3629
16. Nikolaos D. Zarokanellos, *SOCIB, Palma de Mallorca, Spain,* 0000-0002-6235-6198
17. Victor Turpin, *OceanOps, Brest, France,* 0000-0002-1662-4358
18. Catherine Schmechtig, *CNRS, Sorbonne Université, Osu Ecce Terra, Paris, France,* 0000-0002-1230-164X
19. Pierre Testor, *CNRS-Sorbonne Universités (UPMC Univ. Pierre et Marie Curie, Paris 06)-CNRS-IRD-MNHN, UMR 7159, Laboratoire d'Océanographie et de Climatologie (LOCEAN), Institut Pierre Simon Laplace (IPSL), Observatoire Ecce Terra, Paris, France,* 0000-0002-8038-9479

20. Julius Busecke, *Columbia University/Lamont-Doherty Earth Observatory, New York, USA,* 0000-0001-8571-865X
21. Evi Bourma, *Hellenic Centre for Marine Research (HCMR)/Institute of Oceanography, Athens, Greece* 0000-0001-7196-9714
22. Clark Richards, *Fisheries and Oceans Canada, Bedford Institute of Oceanography, Halifax, Canada,* 0000-0002-7833-206X
23. Stuart Pearce, *Ocean Observatories Initiative, Endurance Array, Oregon State University, Oregon, USA,* 0000-0001-8373-7152
24. Filipa Carvalho, *National Oceanography Centre, Southampton, UK,* 0000-0001-9546-4614
25. Isabelle Giddy, *Southern Ocean Carbon and Climate Observatory, CSIR | Department of Oceanography, University of Cape Town, South Africa | Department of Marine Science, University of Gothenburg, Sweden,* 0000-0002-8926-3311
26. Christian Begler, *GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany,* 0000-0002-1674-0404

1.2 SOP development process

1. Initial SOP was drafted by Patricia López-García, Tom Hull, Soeren Thomsen and Johannes Hahn.
2. Two expert sessions during OceanGliders Best Practice Workshop, May 11 - 25 2021. Additional authors joined: Bastien Y. Queste, Gerd Krahmann, Charlotte Williams, Mun Woo, Charitha Pattiaratchi, Laurent Coppola, Tania Morales, Virginie Racape, Claire Gourcuff, John Allen, Eva Alou-Font, Nikolaos D. Zarokanellos
3. First community and user feedback was provided during the OceanGliders Best Practice Workshop, May 11 - 25 2021 by attendees.
4. SOP moved to this repository by: Patricia López-García, Tom Hull, Soeren Thomsen and Julius Busecke in September 2021.
5. Additional authors joined on GitHub prior to the community review: Victor Turpin, Catherine Schmechtig, Pierre Testor, Julius Busecke.
6. 4 months community review on GitHub from October 2021 until January 31 2022
7. Additional authors joined on GitHub during the community review: Evi Bourma, Clark Richards, Stuart Pearce, Filipa Carvalho, Isabelle Giddy and Christian Begler.
8. At the moment: Preparation of submission to OBPS

1.3 Contributions

Patricia López-García drafted the initial document collating information from several SOPs, sensor manuals and articles. Main contribution to: Introduction section (producing Table 1 from information gathered from glider users and completing information for Clark electrodes sensors SBE 43/63), Pre-deployment operations and calibrations section (subsections Storage and cleaning and Pre-deployment calibrations), Post-recovery operations and calibrations section. She added some images to the document. She co-chaired two oxygen expert sessions during the OceanGliders Best Practice workshop in May 2021. She implemented discussions and comments from expert sessions. She reviewed and edited all parts of the SOP. She helps to maintain the SOP on GitHub.

Tom Hull drafted the initial document. He wrote the introduction such as the detailed description of the different Aanderaa optodes/foil types. He implemented discussions and comments from the expert sessions. Drafted and revised the Delayed Mode Quality Control section. He co-chaired one oxygen expert session during the OceanGliders Best Practice workshop in May 2021. He reviewed and edited all parts of the SOP. He helps to maintain the SOP on GitHub.

Soeren Thomsen initiated the development of the oxygen SOP in February 2021. Drafted the initial document. Coordinated the whole development process including organizing multiple meetings, e.g. two expert sessions during the OceanGliders Best Practice Workshop. He gave specific content input on the two point 0 / 100 % and Oxygen Minimum Zone calibration procedure. He reviewed and edited all parts of the SOP. He helps to maintain the SOP on GitHub.

Johannes Hahn drafted the initial document. He gave specific content input on the sections pre-deployment, operations and calibrations such as key parts like the multipoint calibration section where he provided specific values related to sensor and foil accuracy and specifications. He further provided images related to CTD calibration procedures. He joined the two expert sessions during the OceanGliders Best Practice Workshop in May 2021.

Bastien Y. Queste co-wrote the JFE Advantech RINKO and seaglider section of the introduction. He provided multiple images such as the seaglider example deployment in the Bornholm Basin. Joined the two expert sessions during the OceanGliders Best Practice Workshop in May 2021. He provided detailed feedback on the delayed mode quality control section.

Gerd Krahmann provided input to the Real Time Data Processing and Quality Control section. He provided examples of biofouling including the effect on the oxygen data. He revised the Delayed Mode Quality Control Section and provided example images of the GEOMAR time delay correction methods. He joined the two expert sessions during the OceanGliders Best Practice Workshop in May 2021.

Charlotte Williams wrote section 3.3.1.3. on Slocum sensor integration and mounting. She joined the two expert sessions during the OceanGliders Best Practice Workshop in May 2021.

Mun Woo gave specific content input to the Delayed Mode Quality Control Section. Joined the two expert sessions during the OceanGliders Best Practice Workshop in May 2021.

Charitha Pattiaratchi gave specific content input to the Delayed Mode Quality Control Section. Joined the two expert sessions during the OceanGliders Best Practice Workshop in May 2021.

Laurent Coppola gave specific content input on the sections pre-deployment, operations and calibrations such as key parts like the multipoint calibration section where he provided specific values related to sensor and foil accuracy and specifications. He co-wrote the JFE Advantech RINKO section of the introduction. He co-chaired one oxygen expert session during the OceanGliders Best Practice workshop.

Tania Morales contributed to the content of sections pre-deployment, operations and calibrations including images for the coastal deployment at PLOCAN.

Virginie Racapé co-wrote the Real Time Quality Control section.

Claire Gourcuff co-wrote the Real Time Quality Control section.

John Allen provided feedback to the overall document.

Eva Alou-Font provided feedback to the overall document.

Nikolaos D. Zarokanellos provided feedback to the overall document.

Victor Turpin wrote the parts related to the OceanGliders data management.

Catherine Schmechtig co-wrote the Real Time Quality Control section.

Pierre Testor wrote the proposals for funding the OceanGliders best practice coordination activities. He reviewed the overall document and provided feedback on the overall document.

Julius Busecke supported the moving to GitHub and jupyter books. He helped to better facilitate the community review i.e. by implementing the commenting function via utterances-bot.

Evi Bourma provided input to the SBE43 sensor section.

Clark Richards provided input to the SBE43 sensor section.

Stuart Pearce provided input to the Aanderaa optode section related to MK2 equation, SVU/Multipoint-calibration and firmwares.

Filipa Carvalho provided feedback on overall document and helped to improve the overview schematic.

Isabelle Giddy provided feedback on the pre-deployment section towards improving the procedure at very low-temperatures. Supports the technical maintanence of the SOP on GitHub.

Christian Begler provided images of an Aanderaa optode integrated on a Slocum glider.

CHAPTER

TWO

INTRODUCTION

This standard operating procedure (SOP) document for dissolved oxygen (DO) aims to guide the user through the steps necessary to collect good quality dissolved oxygen data using ocean gliders for both real time and post deployment data streams.

2.1 Overview cheat sheet

The most important actions to be taken are summarized in this simple cheat sheet below. This short summary allows the reader check under time pressure whether key points are taken into account prior to deployment. We recommend reading each chapter in detail to ensure the best quality data.

Pre-deployment/Deployment(1) Check that sensors are in good condition, and you have selected the best option for the planned mission.- BEST: Do two-point calibration (Section 4.5.1).(2) Mount the sensor(s) (Section 3).(3) Configure sensor for deployment (Section 4.2). Make sure your glider is configured to record phase with correct timings.(4) Keep sensor foil wet at least 8 hours before deployment. If it cannot be kept submerged in water, have a wet sponge covering the foil (Section 4.1).(5) Do two-point calibration shortly before deployment (Section 4.5.1).(6) In-situ reference measurements, recommended using hierarchy of decreasing quality: - BEST: Optodes attached to a CTD (Section 5.4). - BEST: multiple co-located CTD casts in well mixed waters (including Winkler samples at different depths) and in-air drift correction. - GOOD: single point Winkler sample and CTD from nearby and no drift correction (see section Section 5.3). - OK: in-air calibration only (Section 5.6.2).

Mission and Real Time data flow (Section 5)(7) Ensure data stream is set up correctly including relevant metadata is sent to allow real time data corrections (Section 6).

Recovery (Section 7)(8) Keep sensor foil wet until finish post deployment in-situ reference measurements.(9) Download data.(10) In-situ reference measurements, using hierarchy of decreasing quality as mentioned above.(11) Clean and store the sensor.

DMQC (Section 8)(12) Determine and correct optode lag.

Data sharing (Section 9)(13) Share high quality data in public open access archives.

2.2 Overview sensor glider combinations

Table 1: List of the known sensor/glider combinations. We aim to cover all combinations in this document.

Sensor / Glider	Slocum	Autosub/ ALR (NOC)	Seaglider	Deepglider	SeaExplorer	Spray	Information
Aanderaa 3835, 4330, 4330F, 4831, 4831F and 5013 optodes	X		X	X			Link
RINKO-II	X						Link
RINKO- AROD FT					X		Link
SBE 43 and 43F		X	X		X		Link
SBE 63						X	Link
RBRcoda T.ODO					X		Link
Contros Hydroflash (1)			X				Link

(1) The advanced, optical sensor is based on the principle of fluorescence quenching. Contros are no longer in operation, the sensors cannot be calibrated and are likely to become obsolete in the future.

CHAPTER

THREE

SENSORS AND INTEGRATIONS

3.1 Oxygen sensors

3.1.1 Aanderaa Optodes

Aanderaa optodes are the most widely used oxygen sensor on ocean gliders and a large body of work has now been dedicated to their characterization (e.g. (Bittig *et al.*, 2018)). These sensors are based on the oxygen luminescence quenching of a platinum porphyrin complex (fluorescent indicator) that is immobilized in a sensing foil. This offers low power consumption, good long-term stability, low fouling sensitivity while not being sensitive to H2S or freezing. Aanderaa optodes have seen several important developments since they were introduced in 2002, with various hardware and firmware revisions which we outline below (see also Fig. 3.1).

Fig. 3.1: Suit of Aanderaa smart sensors. Oxygen optodes are indicated by red arrows.

Hardware design: blue or black

While mostly cosmetic, the colour of the optode is a useful shorthand for the two main optode designs. The 3835 and 4835 optodes both feature a black housing with the temperature sensor integrated into the base of the sensor near the connector. This results in a large thermal mass and increases the response time of the temperature sensor significantly. The blue 4330 and 4831 sensors move the thermistor next to the sensing foil which results in much improved performance of the temperature sensor. With an increase in accuracy to 0.03 °C from 0.05 °C, and time-response reduction to <2 seconds rather than ~10 seconds (Data Instruments AS, 2018). All optodes other than the 4831 use a 10 pin Lemo connector, these connectors can't be connected when wet and are prone to crevice corrosion. The 4831 is therefore recommended for all applications with it's Subconn wet-pluggable connector. Older optode versions (3830) have a titanium housing in the same form factor as the 3835. Some early Slocum gliders include a 5013 optode which is identical to the 3830.

Foil type: F or standard

Most optodes use the PreSens PSt3 foil (PreSens - Precision Sensing GmbH), these have as standard a black opaque protective layer protecting the pink sensing layer. For glider applications the "F" type foils are typically preferred as these remove the opaque layer which results in much faster diffusion across the foil, and therefore faster sensor response (τ = 8 s compared to ~ 25 s (Bittig *et al.*, 2014)). However, removal of the protective layer makes the foil more susceptible to UV radiation, and is known to reduce the sensor stability, especially when exposed to strong sunlight. Newer 4330F and 4831F optodes (Since July 8th 2018) use an improved formulation of the Presens fast foil which are less sunlight sensitive and have much lower noise levels. These can be identified by their white appearance. It is recommended that older F-type instruments (with the pink foils) are upgraded with these improved foils. Otherwise, foils should typically not be replaced unless mechanically damaged (light intrusion) as older foils perform better, with less drift than new ones.

Calibration equation and firmware versions

The way optode foils are initially calibrated by Aanderaa, and how the measured values are processed by the optode varies between different optode versions. The optode illuminates the sensing foil with both a red and blue LED. Since the red light does not produce fluorescence in the foil the phase measurements are obtained from the difference between the blue (`P1`) and the red (`P2`) excitation.

```
TCphase = A(T) + (P1 - P2) · B(T)
```

Where `TCphase` is the temperature compensated phase and `T` is the measured optode temperature. A and B are temperature dependent coefficients which allow for temperature compensation of the phase measurement. However, for most 4330, 4831 and 4835 optodes these are not used, such that `A(T) = 0` and `B(T) = 1`. This can be confirmed by communicating with an optode and inspecting the `PTC0Coef` and `PTC1Coef` properties. Similarly, older optodes have their calibration (and recalibration) applied though the modification of the `PhaseCoef` coefficients. On later optodes the calibration is not applied in phase space, but on the oxygen concentration though the use of the `ConcCoef0` and `ConcCoef1` coefficients (`PhaseCoef0` and `PhaseCoef1` are set to zero and 1 respectively). Consult your optode calibration sheet and confirm which terms are being used. For older 4xxx series optodes (4330 serial numbers < 1000) the temperature compensated phase is then used to calculate `calphase` (calibrated phase). With newer optodes `TCphase` = `calphase`. For the 3830, 3835 and 5730 series optodes the calibrated phase is known as `DPhase`.

There are three different calibration equations used to convert the phase (`calphase` or `dphase`) to oxygen: The "Mk1" equation used by the older 3835 optodes uses a 5 x 4 matrix of coefficients. The "Mk2" equation is used by non-multipoint calibrated 4330(F) and 4835 optodes, and uses a 2x14 matrix (`FoilCoefA` and `FoilCoefB`) together with a 2 x 27 matrix for the polynomial degree, this second matrix is the same across all of these type optodes. Newer multipoint calibrated optodes use the Stern-Volmer (SVU) equation proposed by (Uchida *et al.*, 2008) which has 6 terms. The SVU equation was introduced with firmware version 4.4.8. As of 2019 all new Aanderaa optodes are multipoint calibrated as standard. Non-multipoint foil calibrations are based on a common characterization of a production batch. Multipoint calibrations consist of 40 calibration points across a range of concentrations and temperatures and offer improved accuracy and should be preferred when purchasing these sensors. Consult your optode foil calibration document to verify which version your optode is using. Understanding these differences in how the calculations are performed is important when recalculating oxygen from the phase readings, such as when compensating for lag.

The resultant oxygen concentration (in µmol L-1) and saturation (%) need to be corrected for salinity. Optical oxygen sensors do not measure salinity, but they can be configured to apply this salinity correction internally. We recommend to never change this from the default value of zero and to always apply a correction based on matched salinity during RTQC or DMQC. Aanderaa currently use the "combined" fit from Garcia and Gordon (1992) for this correction in their documentation. However following Bittig *et al.* (2015), this should be ideally be done using the Benson and Krause Jr. (1980) data.

Regardless of the optode version, oxygen can be recalculated from the calibrated phase (`calphase` or `dphase`) using the approach of (Uchida *et al.*, 2008). During the initial months of storage/use a Foil maturation process occurs resulting in lower readings by several %. On more than 1000 sensors, the maximum observed maturation induced drift has been 8 % for sensors with non-factory pre-matured WTW foils (model: 4835, 4531 and 5730 Steinsvik) and 6 % for sensors with factory pre-matured PSt3 foils (model: 4330, 4831, 5331 hadal). During/between field deployments there are possibilities for end users to post-adjust the sensors either by a one-point air-saturation adjustment or by taking reference samples (e.g. water samples and Winkler titration) and/or using a well-calibrated sensor in parallel. If done correctly such adjustment should result in an absolute accuracy of around 1 % for multipoint calibrated sensors (models: 4330, 4831, 5331 and 5730) and 3 % for two-point calibrated sensors (models: 4835 and 4531), see below for more information about factory calibrations. The drift will decrease over time so during the second year it is not likely to be higher than 1-2 %. After this time, it should be less than 0.5 % per year, unless the foil is mechanically damaged (Data Instruments AS, 2018).

3.1.2 RBR coda T.ODO

The RBRcoda T.ODO uses the same foils and methods as optodes 4831 and 4831F, so everything specified for the 4831 will also apply to this sensor. RBR refers to the standard optode (~30 s τ) foil as "slow" and the fast (~8 s) as "standard". Newer sensor foil design (~1 s response) is called "fast". The RBR sensor has a smaller form factor than the Aanderaa optodes, but is overall similar to a 4831 with the temperature sensor very closely located to the sensing foil. This sensor has recently been implemented in gliders, and little is known about their long-term performance.

3.1.3 JFE Advantech RINKO

AROD-FT sensor (RINKO JFE) is used for the SeaExplorer gliders (Alseamar) and for some Argo floats (small size and low power consumption) (see Fig. 3.2). These sensors use the same dynamic quenching principles as the other optical oxygen sensors (Aanderaa and RBRcoda) but made from different materials. The luminophore is coated onto the optical window rather than being embedded in a foil. They have a much faster response time (less than 1 s to 63 %) compared to foil based optical oxygen sensors while maintaining good accuracy (±2 µmol kg-1). These sensors are individually multipoint calibrated by the manufacturer (16 points with 4 temperatures and 4 DO concentrations). The DO reference standards used for these calibrations are produced by saturating the primary mixtures with DO concentrations of approximately 4 %, 10 %, 17 % and 25 % respectively (certified by the National Metrology Institute of Japan).

The DO concentration is calculated from the (Uchida H. and McTaggart, 2010) equation with 9 calibration coefficients. A second equation is used to take into account the pressure effect (a linear equation with one calibration coefficient). Finally, the salinity-compensated DO concentration is calculated by multiplying the factor of the effect of salt on the oxygen solubility (Benson and Krause Jr., 1980) and (Garcia and Gordon, 1992). This is similar to procedures used on other optodes.

Recent deployments of a SeaExplorer glider equipped with an AROD-FT sensor have shown long-term stability (low drift over time) but with a significant offset observed during sections in the Ligurian Sea (on average 10-15 μmol/kg). Deployments in the Bornholm Basin have shown good agreement across a wide range of oxygen concentrations with a nearby BOOS monitoring station (see Fig. 3.3.)

Fig. 3.2: AROD-FT sensor mounted on a SeaExplorer glider (credit: ALSEAMAR)

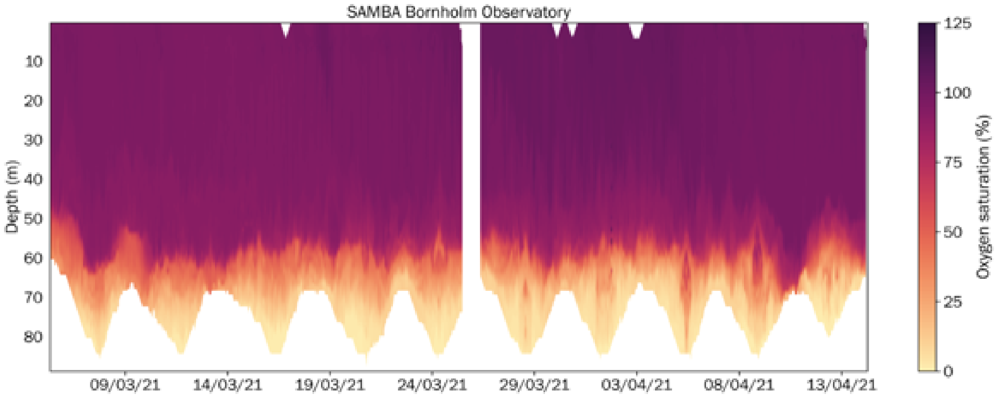

Fig. 3.3: Oxygen saturation from a Rinko AROD-FT on a SeaExplorer glider in the Bornholm Basin (credit: Voice of the Ocean Foundation and University of Gothenburg). Note that this sensor was a recent acquisition and had little opportunity to drift in storage.

3.1.4 Clark electrode polarographic sensor (SBE 43, SBE 43F and SBE 63)

The SBE 43, SBE 43F and SBE 63 are individually calibrated with a calibration drift rates of less than 0.5% over 1000 h of operation. These sensors have been used in Seagliders and Spray and also in moorings and Argo floats. Sensors are designed for use in a CTD's pumped flow path, providing optimal correlation with CTD measurements. Elapsed time between the CTD and associated oxygen measurement is easily quantified, and corrected for, in post-processing. The black plenum and plumbing's black tubing blocks light, reducing in-situ algal growth. Response time τ varies from 2-20 sec depending on the membrane thinness, ambient water temperature and flow rate. Drift thresholds for sensor performance should be established prior to data collection, to determine how often instruments should be serviced, validated, and returned to Sea-Bird for a full service and calibration. It is recommended to do validation in the lab before and after deployment/recovery and while the sensor is in the water (if possible). For this task, Winkler samples or a clean, calibrated reference sensor will be required. (Information from https://www.seabird.com) Before storing the SBE 43 sensor, it is recommended to disconnected it from the CTD if connected to it, rinse it with a syringe (avoiding high pressure of water because we can damage the membrane) and add a sponge with some sodium sulphite in order to remove all oxygen on the membrane. Some researchers are not recommending using this sensor in gliders. SBE 43 is very reliable in CTD profiling systems and moorings, but it is very sensitive and not robust enough for glider work. For example, when working in low temperature regions, you have to keep the sensor protected to avoid icing, a solution is to use an insulated cover with some handwarmers inside, but this is quite complicated when being in a boat a -10 degrees for a couple of hours. Sometimes it is impossible to do a post-deployment calibration because the membrane is broken.

3.2 Sensor integration with gliders

3.2.1 Mounting location

Spray

- input from expert needed

Seaglider

On Seagliders the oxygen sensor is normally mounted externally behind the CT sensor (see Fig. 3.4). Given this exposed location it is important to mount the optode with the sensing foil facing away from incident light to avoid unnecessary UV exposure.

Slocum

On slocum gliders the oxygen optode is typically installed aft close to the fin (Fig. 3.5).

However, this positioning is not ideal for oxygen measurements due to the optode being within a region of laminar flow (Moat *et al.*, 2016), additionally the optode response time has been observed to be dependent on the sensor orientation relative to the direction of flow (Bittig *et al.*, 2014).

An alternative mounting of the Aanderaa optode in a more prominent location fore of the glider fin has been demonstrated as being much more suitable for measuring oxygen on gliders (Fig. 3.6) (Nicholson and Feen, 2017). This mounting location means that the sensor foil faces the flow directly and therefore the diffusive boundary layer thickness at the optode membrane is minimized, reducing the optode response time. Furthermore, this mounting location also means that in-situ in-air calibrations can be performed during deployment (similar to those done with Argo floats) which are beneficial when processing the DM oxygen data (see 'in-air calibration' section).

Fig. 3.4: UEA OGIVE seaglider with 4330F optode, together with NOC LoC spectrophotometric pH, unpumped SBE CT and Fluidion potentiometric pH sensor.

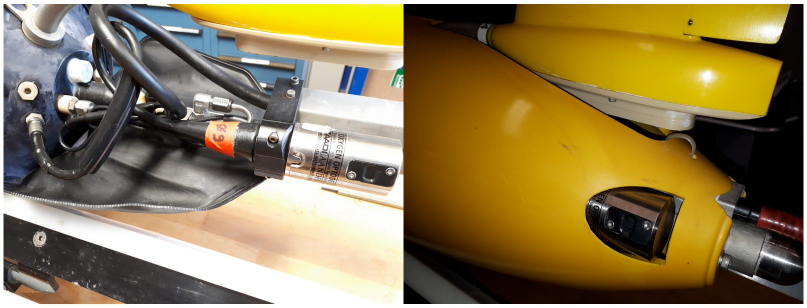

Fig. 3.5: Standard Aanderaa optode 3830 mounting under the fin of the Slocum G2.

Fig. 3.6: Slocum glider showing alternative mounting of an Aanderaa optode perpendicular to the fin.

SeaExplorer

On SeaExplorer gliders, all existing oxygen sensors are installed in the front wet payload section (called the nose cone). External mounting is also feasible using external puck mounts on the dry payload which located approximately 1/3 of the way back, but this configuration is rare and generally only used during instrument trials. The Rinko AROD-FT is generally installed on the forward starboard connector, with the sensing foil and temperature probe 15 centimetres back from the tip of the nose and lightly sheltered to avoid damage when making contact with the nose. Both the foil and temperature probe are well exposed to flow. The new RBR Coda integration is also planned to present the foil and probe slightly set back from the tip of the nose, while remaining exposed to unmodified flow. The SBE43 is found only when accompanied by a Seabird pumped CT sensor; both of these sensors are placed in the nose where the RBR Legato CT sensor can be seen in Fig. 3.7.

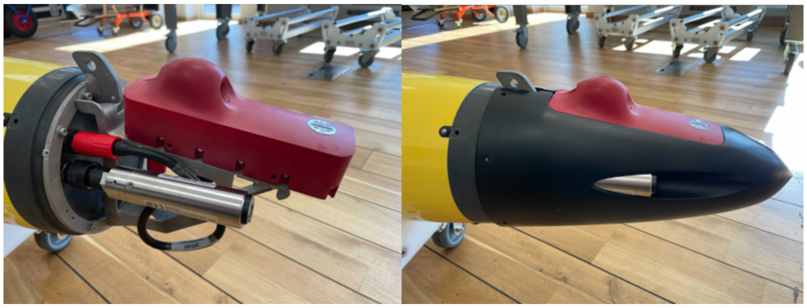

Fig. 3.7: Rinko AROD-FT in the flooded nose cone payload bay of a SeaExplorer next to an RBR Legato sensor.

CHAPTER

FOUR

PRE-DEPLOYMENT OPERATIONS AND CALIBRATIONS

4.1 Storage and cleaning

Optode foils typically drift more while in storage than while in use, the reasons for this are thought to be due to exposure to UV radiation and dry air (Bittig *et al.*, 2018), (Data Instruments AS, 2018). We recommend that all optodes should be stored away from the light (especially fluorescent lights), keep the foil wet and use the rubber caps provided with the sensor. Sensors should be cleaned before storage and stored with black caps on, including some Milli-Q or tap water, or with a piece of wet cotton taped against the foil. If sensors are stored dry the foil will dry out which could lead to 1-2 % lower readings. The sensor then needs to be placed in water to hydrate at least 24 h prior to starting field measurements again.

Fig. 4.1: Keeping sensor in small beakers before and during calibration process. Only the membrane will need to be submerged in distilled water.

After recovery the sensor has to be cleaned to remove any biofouling. The following protocol is recommended by the manufacturer:

1. If the sensor has been for too long exposed to the air, leave it overnight in a vinegar solution.
2. Next day, place the sensor in soapy water and use a soft brush to gently remove any material adhered to the surface.
3. Rinse very well with clean water and dry carefully.

NOTE: Don't change the foil unless it is physically damaged.

4.2 Sensor configuration for deployment

Salinity configuration: 0 PSU. For optode sensors: when there is a small variation in salinity (less than 1 g/kg), it can be set to the mid-value avoiding the need of salinity compensation. However, even in that case, it is a good practice to set salinity to 0 for two reasons: 1) it is usually difficult to find the salinity value defined for old deployments and 2) in case the equations change, it would be easier to recalculate oxygen values from uncompensated values. Optodes should be configured to record the intermediate parameters (`calphase` and temperature), not just oxygen concentration or saturation. Accurate time-stamps, or offsets relative to CT measurements must be recorded for performing the lag correction.

4.3 Antifouling

Materials immersed in water experience a series of biological and chemical processes, resulting in the formation of complex layers with attached organisms. This biofouling can be divided into microfouling and macrofouling (Delgado *et al.*, 2021).

In optodes sensors, biofouling can be severe enough to block oxygen molecules from entering the sensing foil. Aanderaa has different solutions that have been successfully applied, some includes:

1. Copper tape (e.g. 3M 1181) or Copper/Nickel (last much longer) are easy antifouling solutions. When applying the tape, be sure that it is not in contact with any other metal parts otherwise, the tape will lose its antifouling properties.
2. Paints / coatings - optical sensors, so these can only reduce growth nearby but not on the actual sensing foil.
3. Ongoing trials: Aanderaa is focusing on non-toxic methods like fibre/haircloth and "shark skin" film.

Mechanical wipers or UV radiation based approaches are generally unsuitable for gliders due to their increased power requirements and drag. Where optodes are mounted in such a way as to allow in-air sampling biofouling is likely reduced.

Regardless of whether efforts to prevent fouling are made, it is vital that post-recovery photographs are taken of the optode so that the impact of biofouling can be assessed during DMQC.

4.4 Air saturation quality check

Prior to deployment in-air measurements can be used as a reference to correct for drift. Aanderaa outline a method (Data Instruments AS, 2018) based on in-air calibrations on Argo floats and gliders (Bittig and Körtzinger, 2015), (Johnson *et al.*, 2015), (Bittig *et al.*, 2015), (Nicholson and Feen, 2017) and (Bittig *et al.*, 2018). It is recommended to take in-air measurements both before and after deployments. This won't be useful if sensor foil is not wet or the temperature of the foil is different from that measured with the temperature sensor. It therefore is best performed with 4330 and similar sensors where the temperature probe is next to the foil. You will need to leave the sensor logging outside in the free air for several hours before and after deployment. Remember to record the local air pressure.

NOTE: At sea level at standard air pressure (101.3 kPa = 1 Atm = 14.69 psi) the sensors should show 100 % if wet and 102 % if completely dry; at air pressure 100 kPa it should show (1.3/101.3)100 = 1.3 % lower. See also Section 4.6.

NOTE: It is highly recommended to do this protocol at night when humidity is higher and the temperature is lower and more stable.

4.5 Pre-deployment calibration

Optodes and similar instruments generally drift more while in storage than while in use. It is therefore essential that these instruments are recalibrated prior to glider deployment. This is necessary even if in-situ reference (Winkler) samples are taken during the deployment as they will not cover the full range of oxygen concentrations during the period of the mission. As the instrument drift manifests as an increasing offset from zero in addition to a reducing sensitivity, a two point calibration is required to rescale the optodes measuring range.

4.5.1 Two point calibration procedure

Two point calibration is used primarily to rescale the sensor to account for a reduction in sensitivity of the sensing foil over time. It's recommended to do it before the deployment and after recovery. NOTE: Sensor foil must be wet during all procedure steps.This procedure is suitable for the measurement of the full range of oceanic oxygen concentrations (0-400 µmol kg-1) in uncontaminated seawater.*

Some information to read before we proceed with the calibration:

- For a 100 % bubbled bath, connect an aquarium pump to a tube which has been fitted with a porous stone (bubble dispenser) at the end. This will create small air bubbles that are sufficient to equilibrate the water rapidly. To verify that optodes are in saturated water you can take them up from the water and hold them just above the surface for a few minutes. There should then be no change in the saturation readings (Aanderaa Best Practices). Avoid submerging the air-stones as this can supersaturate the solution. Use a magnetic stirrer to homogenize the water. It is important that the aquarium pump takes in air from an open atmosphere outside, not from inside the room/laboratory where O2 levels will be affected by the ongoing activities and/or the ventilation.
- For 0 % saturation solution, add 20 g sodium sulphite to approx. 1 L. A high level of precision is not required, and excess sodium sulphite is not an issue. Sodium sulphite rapidly removes the oxygen and, as long as crystals of the compound can be seen, the oxygen level in the water will stay at 0. Sodium sulphite also has the advantage of being inexpensive and the level of toxicity is low. This solution is considered irritating and wearing appropriate PPE (gloves, goggles and lab coat) is recommended. There is also an option of removing the oxygen from the water bubbling nitrogen all time. In this case you have to be sure all oxygen is removed from the solution, this will happen after 3-5 minutes bubbling (maximum volume of 100 mL approx., for bigger volume you will have to increase the time). You have to keep injecting N2 during all time of the zero calibration.
- If any residue of the sodium sulphite solution remains on the sensing surface, the 100 % measurement will be inaccurate. Therefore, 100 % DO saturation calibration should be performed first. To avoid contamination, always rinse well with distilled water.
- Always check saturation values: an outset of ± 5 % is adequate, so a value between 95 % and 105 % is correct. See {numref}(air_pressure_effects).
- While calibrating, changing air pressure and water temperature will affect the partial pressure (and apparent saturation concentration) which makes calibration difficult. Accurate air pressure readings for the room and a stable room temperature is ideal. When onboard a ship or in a lab external meteorological sensors will not represent those conditions inside and should only be used if the calibration is to be done outside. A portable barometer and air thermometer is highly recommended.
- The Winkler method can be used to determine the concentration of 100 % solution (± 0.15 µmol kg-1). We recommend following the GO-SHIP protocol described by (Langdon, 2010) and a well-trained technician to do the sampling and analysis. It can not be used for the 0 % solution and shouldn't be used for concentration below 20 µmol kg-1 (Thomsen *et al.*, 2016).

It is recommended to perform the calibration at least two different temperatures which cover the expected in-situ temperature range. There are several possibilities in order to achieve this, some examples:

1. Doing the experiments in rooms with different temperatures. Such as a walk-in fridge and a normal lab. You need to leave all materials, reagents and sensors in the room at least 8 hours (e.g. overnight) before starting the calibration.
2. Doing the experiment in a room where the temperature can be adjusted, such as with a power air-conditioning unit. You need to leave all materials, reagents and sensors in the room at least 8 hours at each temperature before starting the calibration.
3. Doing the experiment using a thermostatic bath. You need to leave the 0 and 100% solutions in the bath at least overnight before starting the calibration. It is most likely that you won't be able to use a magnetic stirrer, so you need to be sure that you place the end of the bubble tube in the bottom of the bottle/beaker.

The preferred method is with a thermostatic bath.

In situ intercomparison will be required to find the offset of the sensor in different seawater conditions. Therefore, samples should be taken in the tank during the ballasting (if this is 1-2 days before deployment, no more) and at the deployment/recovery site (ideally at different depths).

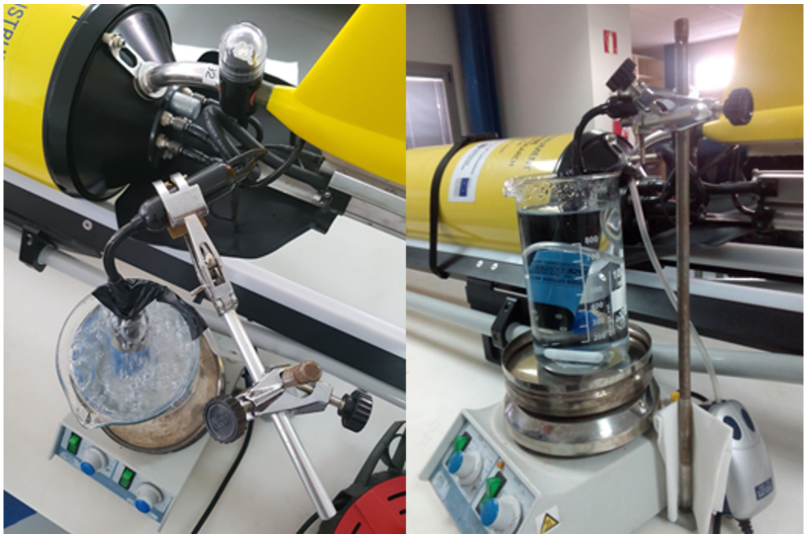

Fig. 4.2: Setup for 100% and 0% calibration.

Calibration procedure

The commands and steps needed to calibrate an oxygen sensor vary, see Section 12.1 for specific details. Here we outline the general procedure for a two point calibration.

1. Prepare a 100 % saturation water solution.
2. Immerse the sensor in the 100 % solution overnight. If this is not possible, having the sensor submerged in distilled water will be enough to keep the foil wet for the calibration.
3. Immerse the sensor(s) and ensure the sensing foils have been kept moist.
4. Prepare the 0 % solution in another container.
5. Connect to and power on your sensor, it is good practice to log the output from the terminal session to a file for reference.
6. Observe the local air-pressure and update the instrument if needed.
7. Begin taking measurements with the sensor, once temperature and oxygen concentration readings have stabilized these values are used as the saturation concentration data point.

8. Move the sensor to the 0 % solution and wait for the readings to stabilize, use these readings as the zero value.
9. Self calibrating sensors, such as optodes, can now be told to calibrate themselves, otherwise use these two data points to determine the slope and intercept needed for the sensor.
10. Rinse the sensor thoroughly to remove any sodium sulphite solution, and return the sensor back to the 100 % saturated solution to verify the calibration. The optode should read close to 100 % saturation.
11. Take paired winkler samples from the 100 % solution to confirm it is 100 % saturated.
12. Return the sensor to the configuration required for your glider.

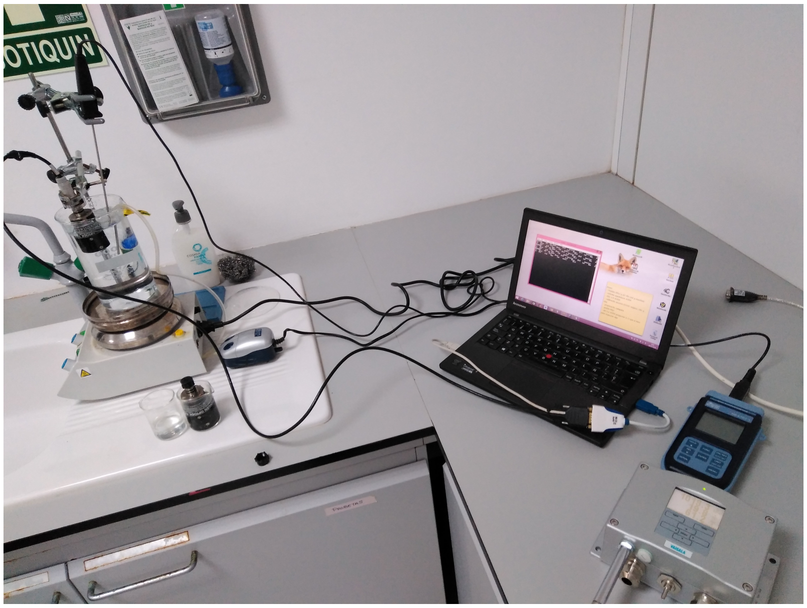

Fig. 4.3: Recording data using a terminal program.

4.5.2 In situ intercomparison in the tank during ballasting

This is an extra in situ intercomparison to carry out if access to the tank while ballasting the glider is possible and the ballasting is close in time to the deployment (no more than 1-2 days before).

Materials: Silicon tube for sampling, Winkler bottles, Winkler reagents, pipettes and tips (or a bottle-top dispenser for reagent bottles), titration material (buretes or titrator).

1. The sensor should be submerged overnight in water to ensure the foil is wet. If the sensor is already mounted in the glider, use a wet sponge or rubber lens cap. Keep the sensor in the dark.
2. Once the glider is in the ballasting tanks, place the silicon tube for sampling near the sensor.
3. Once the sensor measurements are stable (variations in the measurements are not higher than the precision/resolution of the sensor), start sampling water for Winkler analysis. Take paired samples every 5-10 minutes and record the time taken. 4 to 6 samples should be taken in total.
4. Check the outset of the sensor by comparing values measured by the Optode sensor with winkler values after measuring the bottle samples in the lab.

Fig. 4.4: Taking samples for Winkler analysis during ballasting in the glider tank at PLOCAN facilities.

4.6 Effects of atmospheric pressure during calibration

During the above procedures it is important to note that the equilibrium saturation oxygen concentration (Csat i.e. Garcia and Gordon (1992)) is expressed relative to 1 atmosphere. This solubility parametrization is described as having an RMS error of 0.3 % (± 1.01 μmol kg-1). The pressure effects can be significant, at 10 oC a change in local air pressure between 990 and 1010 hPa changes the equilibrium concentration by 5.4 μmol kg-1. The quality of the local air pressure measurements during calibration is worth considering. Ponte and Dorandeu (2003) estimated the overall uncertainty for ECMWF products to be typically less than 3 hPa over most of the ocean. This is equivalent to a 0.9-1.1 μmol kg-1 error in Csat.

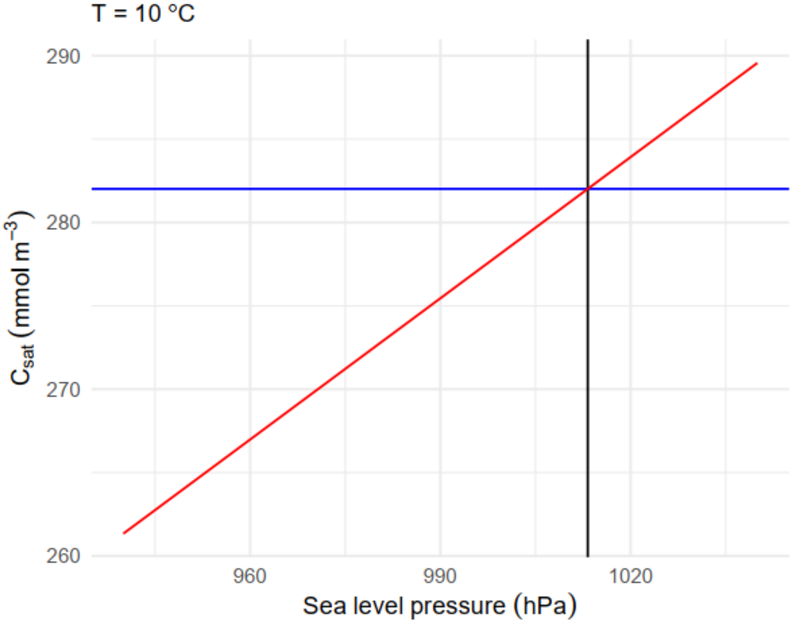

Fig. 4.5: Effect of local air pressure on the equilibrium saturation oxygen concentration (Csat) at 10 oC.

CHAPTER

FIVE

MISSIONS EXECUTION

This section covers the activities of those deploying and recovering the gliders in the field in addition to best practices for glider pilots.

5.1 Deployment

While keeping the oxygen sensor protected from sunlight and kept moist, any lens cover must be removed prior to deployment. The use of highly visible material, such as a red flag, can aid in ensuring its removal in addition to the pre-deployment checklist.

In-air measurements prior to deployment can and should be carried out together with the in-situ air pressure and relative humidity measurements to provide an additional reference for calibration. Details of this procedure can be found in the in-air calibration section.

NOTE: Remember to remove the sponge and any other material used to keep the sensor wet.

5.2 In-situ reference samples

Even with good ballasting it can require several dives for a glider to fly correctly with an ideal dive profile. In warm and dry conditions the optode foil can still partially dry out even if good care is taken. Reference data should therefore only be performed after the glider is flying well, and ideally as close to the glider's last known position as possible. Ideally multiple sets of samples should be taken unless the horizontal variability of the deployment region is very well characterized. This requires coordination between the deployment team and the glider pilot and should be part of the mission planning.

5.3 In situ intercomparison during deployment/recovery from a small boat

Materials: Silicon tube for sampling, Niskin bottles, multiparameter sonde, BOD bottles, Winkler reagents, pipettes and tips, cooling box. It is very important that the sensor has been kept wet before the deployment and after recovery. This can be done by placing a wet sponge in the sensor membrane at least 24 hours before the deployment (ensure that it doesn't get dry).

Samples should be collected with the Niskin bottle(s) for Winkler analysis during the deployment (following (Langdon, 2010) protocol). It's recommended to take between 4-6 samples on the surface (approx. 5 m) (ideally samples will be taken at different depths). After adding the Winkler reagents, samples should be kept in the dark and try to avoid high temperatures. It's also recommended to use a calibrated multiparameter sonde to do DO profiles at the deployment site while taking samples with the Niskin bottles. This will also help to record the sampling depths. When taking samples for the Winkler is not possible, values from the multiparameter sonde might be useful for in situ intercomparison. The sonde

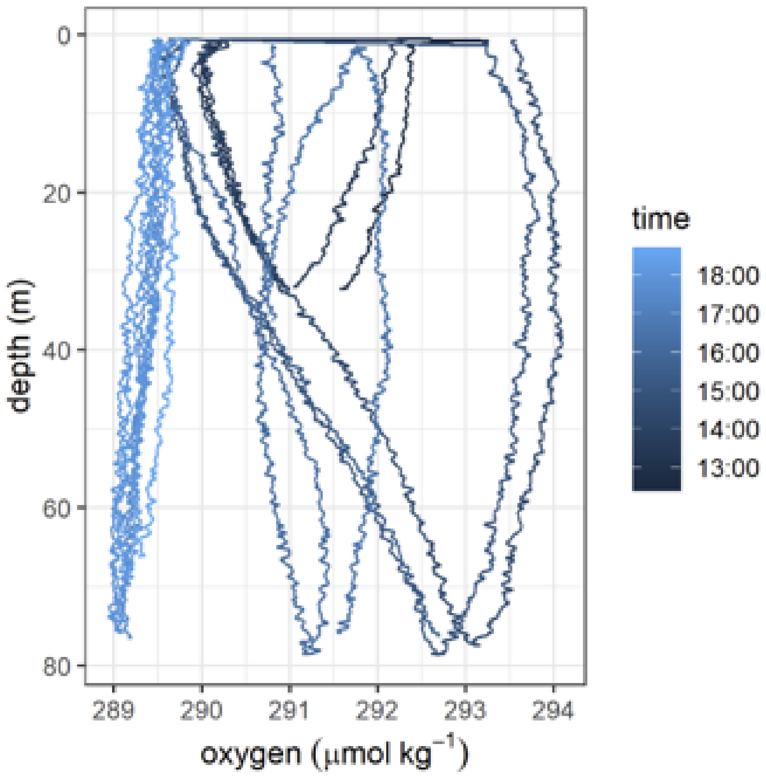

Fig. 5.1: Effect of dry foil, first dives show elevated oxygen concentrations and slow foil response times. Taken from AlterEco AE2 Slocum “Stella” using a 4330 optode (standard foil).

must be calibrated before and after the deployment/recovery (some sondes require to be calibrated the same day, please, follow manufacturer recommendations).

Fig. 5.2: Coastal deployment of a Slocum glider from a small boat (photo taken during the Glider School at PLOCAN).

5.4 Calibration during deployment/recovery from a ship with a CTD rosette equipped with a calibrated oxygen sensor

If the glider is deployed/recovered from a research vessel equipped with a CTD and a calibrated O2 sensor, the glider optode can either be connected directly to the CTD profiler if able to receive the digital (RS232) output from the Optode (Uchida H. and McTaggart, 2010), or attached via a data logger. Record down- and upcast data to allow hysteresis correction. The Optode data obtained during the bottle-firing stop for collection of water samples can be used for in situ calibration, since the difference between the downcast and upcast oxygen profiles is relatively small (1 µmol kg-1 approx., (Uchida *et al.*, 2008)). The error in the Optode can be reduced by allowing sufficient time for the sensor equilibration after the stop (minimum 2 min as recommended by (Hahn *et al.*, 2014). *NOTE: For Oxygen Minimum Zone regions follow recommendations in Section 5.5*

To summarize, the steps we recommend to follow to calibrate oxygen sensors during regular CTD/O2 casts before deployment and after recovery, are:

1. Attach the glider's O2 sensors (optodes) to the CTD rosette at the same depths where the CTD oxygen sensor pumps in the water.
2. Record down- and upcast data. Timestamps of oxygen measurements are required. In case a logger is used, ensure before the calibration cast that the internal logger time is correct (i.e. in line with the CTD time).

Fig. 5.3: Using a multiparameter sonde for in-situ intercomparison during deployments from small boats.

3. Collect calibration points against measurements with the CTD rosette oxygen sensor, which itself is calibrated against Winkler titrated water samples (Langdon, 2010).
4. Reference points for calibration are the same as the calibration stops. As for salinity, samples for Winkler titration will be collected during the upcast. When reached the selected depth, wait at least 2 min (see Fig. 5.5) to ensure an equilibrated oxygen sensor (Hahn *et al.*, 2014). Fire the bottles after this time.
5. Do 0 % and 100 % calibration after recovering the sensor at two different temperatures (warm and cold lab). If 100 % is not possible, 0 % should be done to ensure that the central temperature range at zero oxygen is covered within the calibration (Hahn *et al.*, 2014).

The combined data collected following these (CTD and lab calibration) steps will be used to evaluate the calibration coefficients (hypercast calibration).

NOTE: This calibration should be done before the deployment and after the recovery. It's important that the membrane is kept wet.

NOTE: Save all data from the profiles and calibrations before deploying the glider. As noted in Section 4.2 Always record the phase readings (Coppola et al.*, 2013).*

5.5 Deploying gliders in Oxygen Minimum Zones (OMZ)

Note that the classical Winkler titration method is not reliable at oxygen concentrations in OMZ core (Thomsen *et al.*, 2016) since the method has some limitations. There are various issues with Winkler at low oxygen concentrations that have been described in the bibliography:

- In waters with concentrations below 5 µmol kg-1, high concentration of nitrite may cause a positive oxygen bias (Langdon, 2010). In more recent articles, scientists even avoid using Winkler at concentrations below 20 µmol kg-1 (Thomsen *et al.*, 2016).
- Oxygen absorbed in the plastic of the Niskin bottles is transferred into the water sampled. This oxygen contamination increases the concentration obtained when follow Winkler method. It has been measured values of apparent concentration of 2 - 4 µmol kg-1 in the Pacific minimum zones, showing a significant positive bias (Garcia-Robledo *et al.*, 2021).

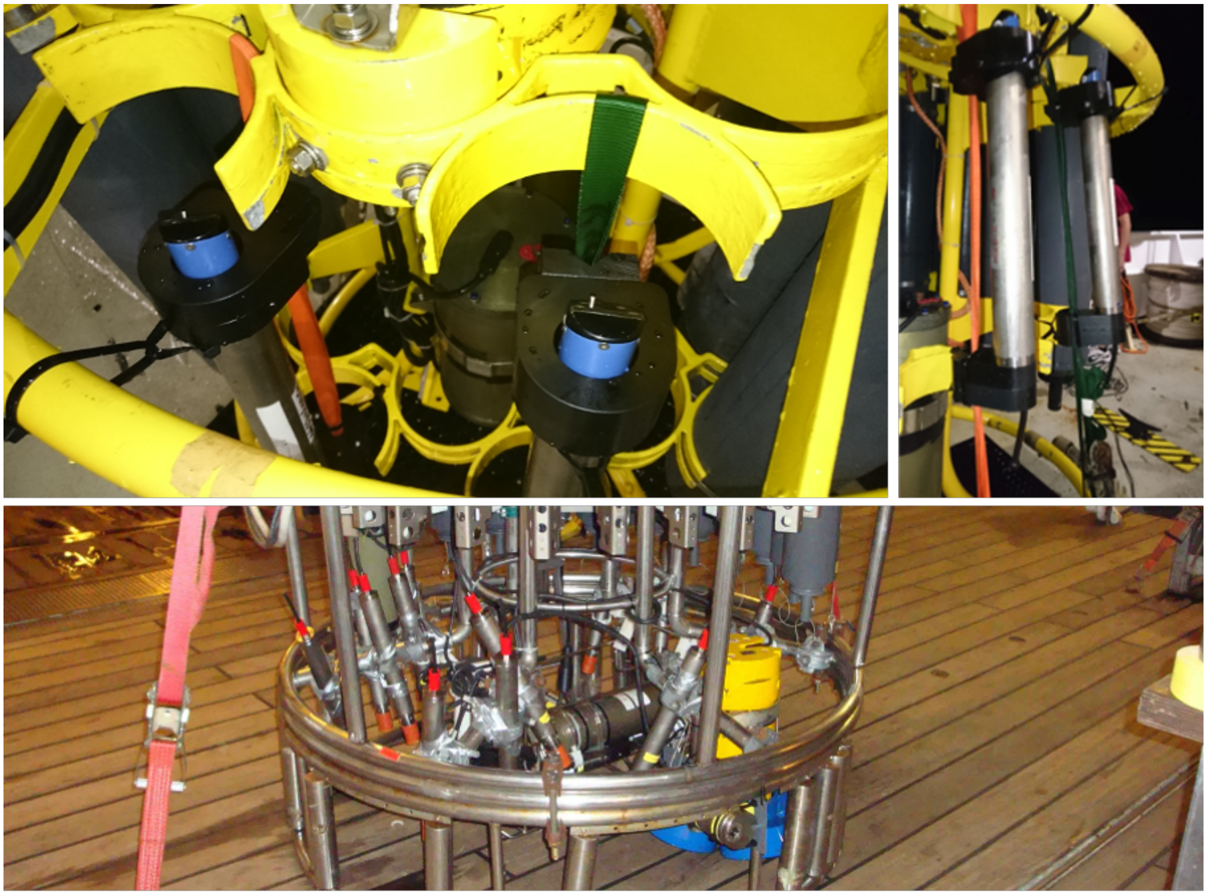

Fig. 5.4: GEOMAR oxygen data loggers (Aanderaa Optode mounted on data logger) attached to a CTD frame and prepared for in-situ calibration during a CTD cast. Panels in the upper row show fixation with straps and zip ties. Panel in the lower row shows fixation with scaffolding clamps and tape in the interior lower part of the CTD frame.

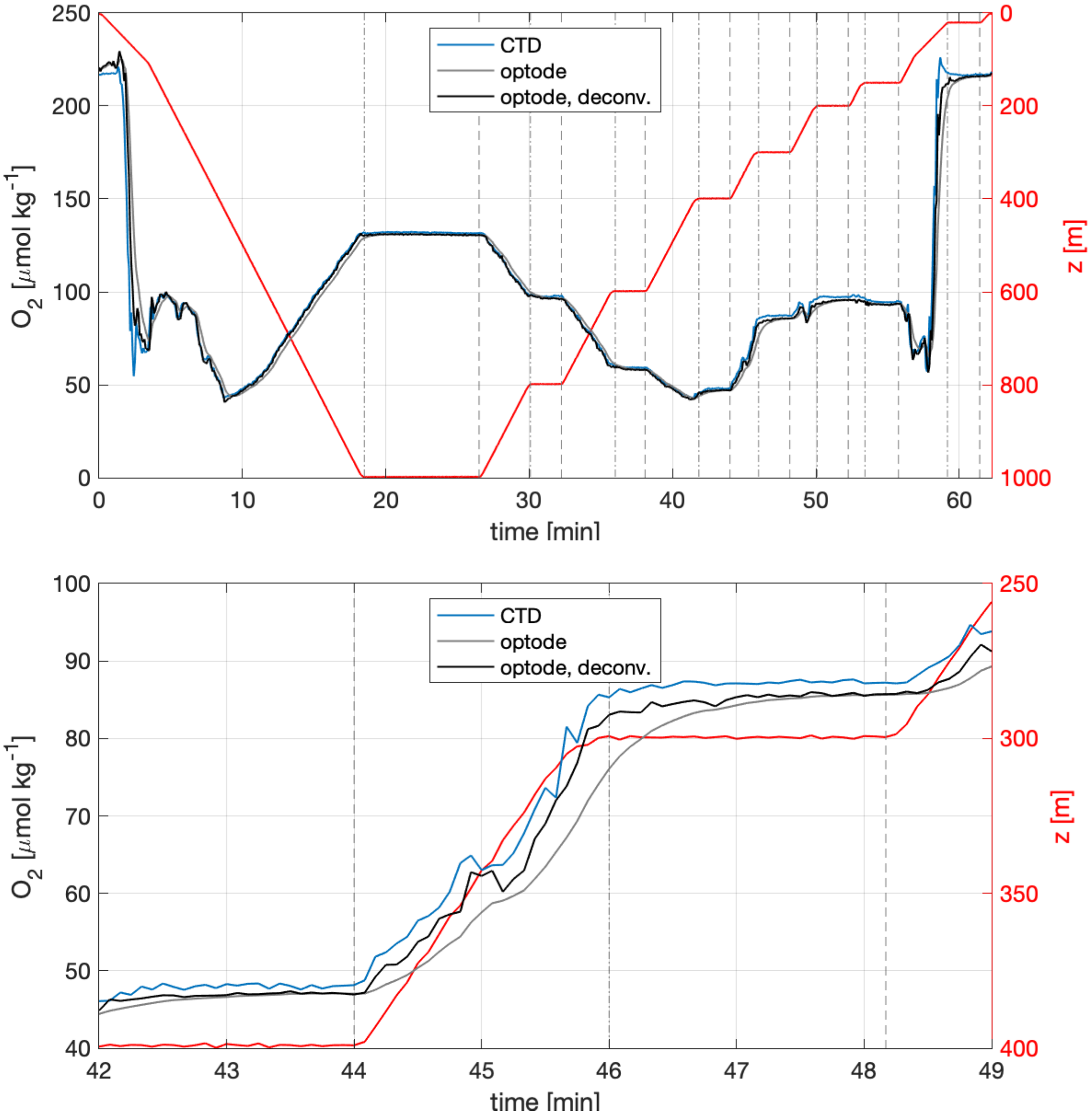

Fig. 5.5: Example oxygen time series for an in situ calibration of an optode at a CTD rosette. “deconv” means, that an inverse low pass filter was applied to the optode oxygen time series in order the correct for the response time effect.

- Presence of extremely low concentrations of oxygen concentrations (nmol levels) in areas like the core of the Peruvian oxygen minimum zones.

Thus, when working in these areas, it is recommended to do:

- In-situ approaches for 0 % calibration suggested by (Thomsen *et al.*, 2016).
- Additionally, Intercomparisons with STOX sensors attached to a shipboard CTD (Revsbech *et al.*, 2009) or new use the low-oxygen sensing foils (0-10% saturation) from Aanderaa.
- Do a 0/100 % calibration in the lab before deployment and after recovery.
- Measure Winkler in samples with concentration higher than 20 μmol kg-1, typically in the mixed layer during the deployment and/or recovery. The Winkler method is also a problem when there is a strong vertical gradient, typically found in OMZ regions. Thus, calibration points below the mixed layer are often not suitable. Look for regions with weak vertical gradients.
- Park the glider for a few hours in the OMZ core at different temperatures to get an in-situ zero calibration points.

5.6 Piloting

In this section, specific piloting requirements during the mission execution which are needed to allow quality control are mentioned. Towards the end of the mission power constraints often require the reduction in sampling frequency or even turning the oxygen sensor off. It is however essential that at least one good quality up and down cast to the maximum deployment depth is performed immediately prior to the pre-recovery samples being taken. Coordination between the recovery group and the pilots is essential.

5.6.1 Gather data to help correct for sensor response time

Regular up- and downcasts are needed to estimate and correct sensor response time. Combined up- and downcasts should be carried out at least every week and particularly at the beginning and at the end of the deployment. One to two days per week appear to be a reasonable compromise between energy saving and calibration quality. If bio-fouling is expected during the deployment it is better to collect up-down pairs earlier rather than later.

Several parameters, namely response time, profiling velocity and vertical oxygen gradient, have an impact on a feasible sampling interval and therefore on the error of the reconstructed true oxygen profile (Bittig *et al.*, 2014). (Bittig *et al.*, 2014) mentions that “the sample interval should be significantly shorter than the response time τ to resolve gradient regions and to be able to reconstruct the true oxygen profile.” Thus, a sufficient high frequency sampling, here interpreted as an order of magnitude faster, is required for a good lag correction. In particular in areas with a strong oxycline, we recommend to always sample at 5 s period. If battery lifetime is an issue, periodic up- and down dives with high frequency sampling are more useful than continuous measurement at a lower frequency.

5.6.2 Gather data to correct for sensor drift

Deep water masses or known anoxic waters

In regions with known oxygen concentrations, in-situ calibration points can be recorded, i.e. within the core of the Peruvian Oxygen Minimum Zone (OMZ) where typical oxygen concentrations are close to zero or only a few nmol kg-1 (Revsbech *et al.*, 2009), (Kalvelage *et al.*, 2013), (Thomsen *et al.*, 2016). In these regions, the glider can be parked at this depth to get a 0 calibration at the beginning and at the end of the deployment. This protocol can also be improved by adding different depth/temperature levels if the anoxic layer is thick enough to cover different temperatures. i.e. further offshore where the OMZ is several 100 m thick.

In-air calibration

In-air calibration can be carried out if optodes are attached in a way that they reach out of the water when the glider is surfacing (Nicholson and Feen, 2017) as done also for long float deployments (Bittig *et al.*, 2018) This can be valuable in particular if no 0 / 100 % lab calibration or CTD intercomparison is available as well as for long deployments. Contamination from splashing water and/or residual seawater on the sensor foil have to be considered and corrected (Nicholson and Feen, 2017). Few gliders currently have this capability.

5.6.3 Gather data for in-situ inter-comparisons

Other oxygen monitoring platforms, such as moorings can be used as an inter-comparison reference if the quality of these data is as good or better than from the glider. The mission plan should aim to pass close to these platforms, ideally multiple times across the length of the mission.

CHAPTER

SIX

REQUIRED METADATA, REAL TIME DATA PROCESSING & QUALITY CONTROL

6.1 Required Metadata and Real Time Data Processing

Configurations for the calculation of DOXY are function of the sensor model, sensor serial number, set of calibration coefficients and intermediate parameters. The recommended configurations (e.g. salinity compensation of MOLAR_DOXY, pressure correction for pressure effect on quenching, temperature compensation) and thus the required metadata are available in the Processing Argo oxygen data at the DAC level (https://archimer.ifremer.fr/doc/00287/39795).

Prior to deployment, all the required metadata should be sent ahead of the mission to the Data Assembly Center. It is important that the glider is well configured, intermediate parameters (phase measurements) should be sent in real time (RT) as well. This will allow first to check if dissolved oxygen values computed inside the glider are appropriate Fig. 6.1 and then this adds the possibility to recompute the dissolved oxygen concentration using the up to date method associated with the sensor model, intermediate parameters and calibration coefficients.

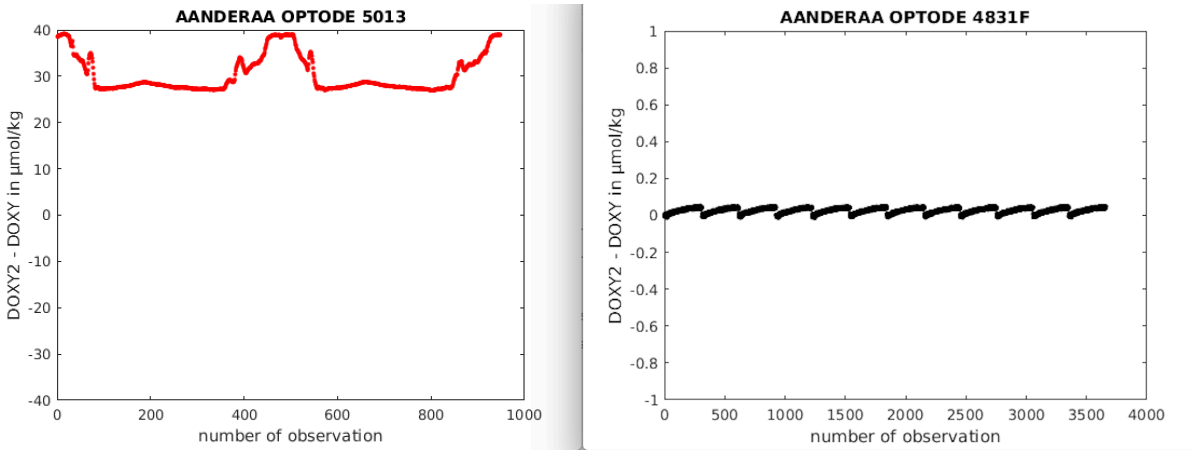

Fig. 6.1: Difference between oxygen concentration computed by the glider (DOXY) and those computed by the Data Assembly Center (DAC) from intermediate parameters and associated calibration coefficient (DOXY2).

For some optode models with large time response (e.g. 3835), it may be appropriate to apply a first time lag correction in RT, taking into account the sensor time response, using either the manufacturer value or any value defined from previous deployments with the specific sensor. A real time lag correction might improve the usability of the real time data significantly (see methods for such corrections in Section 8.3).

There is no unique procedure for Real time data and metadata sending. Protocols, format and file naming convention should be discussed with DACs before deployment. OceanOPS and DACs requirements on data and metadata are described in the OceanGliders Best Practices document in the data and metadata management section, paragraph 6 (link to be added when overview paper is in review).

6.2 Real Time Quality Control (RTQC)

Real time quality control tests applied on EGO oxygen data are extracted from the Argo quality control manual for dissolved oxygen. Details are summarized below. These tests are applied in supplement to trajectory tests. RTQC applied on the temperature measured by the oxygen sensor should follow the RTQC procedure defined for the CTD temperature.

6.2.1 Doxy QC initialization

Several oxygen sensors suffer from predeployment storage drift that can reduce accuracy by up to 20% or more (Bittig *et al.*, 2019). As a consequence and because this bias can be corrected, dissolved oxygen concentration measured in real time should be set to 3 “bad data that are potentially correctable”. To retrieve usable oxygen data, an adjustment in real time should be quickly performed.

6.2.2 Global range check

This test applies a gross filter on EGO oxygen data. If one observation is out of the global range [-5, 600] µmol kg-1, its QC flag is set up to 4 “bad data”.

6.2.3 Outlier and spike check

Outliers and spikes are difficult to detect as optodes typically smooth out spikes due to their slow response time. A simple test checking the differences between sequential measurements is nevertheless possible if i) it is applied on a specific phase (ascending or descending for example) and ii) assuming a sampling adequately reproduces changes in dissolved oxygen concentrations. In this context, if one measurement is significantly different from adjacent ones, it is a spike in both size and gradient.

Test value = | V2 - (V3 + V1)/2 | - | (V3 - V1) / 2 |

Where V2 is the measurement being tested as a spike, V1 and V3 are the values above and below.

V2 value should be flagged as 4 “bad data”, when: Test value > 50 µmol kg-1 for pressure < 500 dbar Test value > 25 µmol kg-1 for pressure >= 500 dbar

6.2.4 Stuck value test

This test looks for EGO oxygen data in the same phase (ascending or descending for example) being identical. Stuck values should be flagged as 4 “bad data”.

6.2.5 Bad P/T/S QC spreading

The test checks that the dissolved oxygen concentration in µmol kg-1 is computed from a valid pressure, temperature and salinity. Considering the pressure or temperature impact on the oxygen conversion, when pressure or temperature is marked as bad (qc = 4), oxygen concentration should be set to 4. Conversely, and as the salinity impact on the oxygen conversion is less than previous parameters, when salinity is marked as bad, oxygen concentration should be set to 3.

6.2.6 Effects of biofouling on optode measurements

Biofouling can impact the optode measurements in different ways and the real time data should be carefully checked to assess typical effects of biofouling. Two examples for the effects of biofouling on the oxygen concentrations reported by optodes are shown in Fig. 6.2. In Fig. 7.1 you can see the biofouling on the glider.

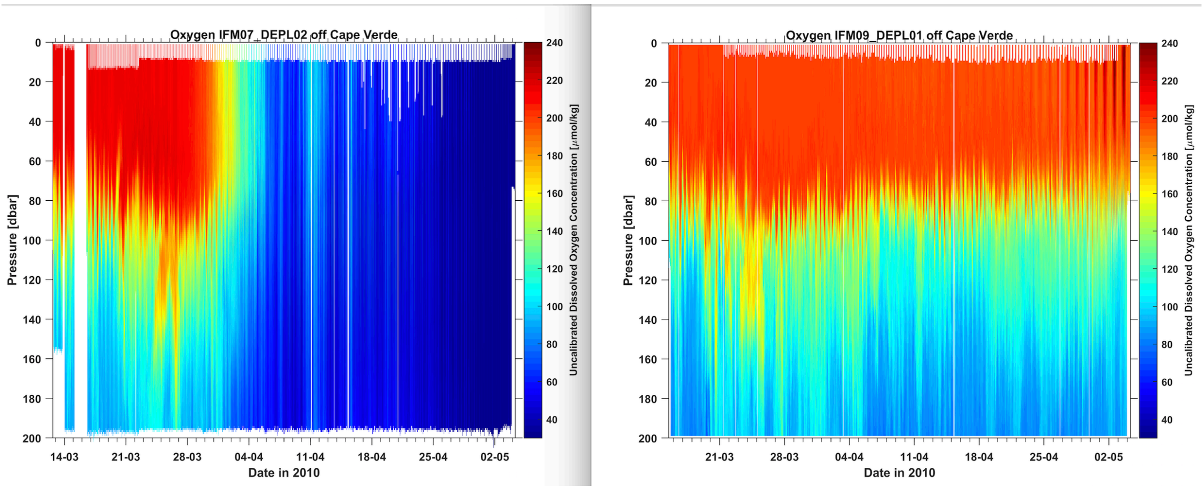

Fig. 6.2: Left: Rapidly decreasing reported oxygen concentrations caused by the growth of a gooseneck barnacle on the optode foil. At the end of the deployment the barnacle prevented all exchange of oxygen between water and foil. Right: Slow effects of algae growth on the foil. Towards the end of the deployment a diurnal cycle in the reported near-surface oxygen concentrations becomes visible. Elevated reported oxygen concentrations coincide with local daylight times and the glider being in the euphotic zone.

CHAPTER
SEVEN

POST-RECOVERY OPERATIONS AND CALIBRATIONS

At first users should report that their mission is over to support(at)oceanobs.org

7.1 Biofouling assessment

Pictures should be taken for biofuiling assessment.

Fig. 7.1: Examples of biofouling. A gooseneck barnacle is growing on the optode foil (left). Algae growth on the foil (right).

7.2 Storage and cleaning

Foil must be kept wet and protected from light after recovery until all calibrations are done. After recovery and once all caibrations are done, clean the sensor and remove any biofouling. The following protocol is recommended by the manufacturer:

1. If the sensor has been for too long exposed to the air, leave it overnight in a vinegar solution.
2. Next day, place the sensor in soapy water and use a brush gently if it is necessary to remove all material adhered to the surface.
3. Rinse very well with clean water and dry carefully.

NOTE: Don't change the foil unless it is physically damaged.

7.3 Lab calibration

When the glider is recovered, a 0% and 100% calibration at two different temperatures levels is recommended (See Section 4.5.1).

7.4 Field calibration

If you recover the glider from a small boat or a research vessel follow protocols described in Section 5.3 and Section 5.4, respectively.

CHAPTER

EIGHT

DELAYED MODE QUALITY CONTROL

8.1 Calculation of oxygen variables

Following (Bittig *et al.*, 2018).

8.2 Sensor drift correction

Aanderaa describe the in-situ drift characteristics of the 4330 and 4831 series optodes as being < 0.5 % per year, and they make no distinction between the standard or fast ("F"-type) foils (Tengberg and Hovdenes, 2014). Optodes made after 2016 undergo a "burning-in period" during manufacture and therefore have substantially less drift (Tengberg and Hovdenes, 2014). Drift is a function of UV exposure and sampling frequency. The foil becomes less sensitive and therefore drift is always towards lower oxygen concentrations. The drift is believed to be due to bleaching of the luminophore foil via ambient light; it is particularly sensitive to fluorescent lights. The bleaching effect is partly counteracted by a destabilizing effect on the luminophore. Together this manifests as a positive factor on the oxygen concentration (slope > 1) and a positive offset at zero oxygen.

(Queste *et al.*, 2018) recorded drifts of 0.0176 and 0.0109 µmol kg-1 day-1 for two Seagliders using inflections in the oxygen profiles as the glider penetrated to Arabian Sea Oxygen Minimum Zone and the sodium sulphite method, but no Winklers. (Bittig and Körtzinger, 2015) report a 10 % drift over 3 years, but this is a combination of in-situ and ex-situ drift. (Bittig *et al.*, 2018) determined the drift to be typically 0.1-0.2 % per year in-situ. A drift of 0.0004 % day-1 has been calculated based on UEA seagliders against Baltic deep water oxygen climatology (Possenti *et al.*, 2021). Values between 0.0004 and 0.0035 % d-1 have been found across 16 vehicles in-situ: slocums and seagliders with 4330F (old foil formulation), 4835 and 4831 optodes (Tom Hull personal communication).

The drift correction should be applied to the oxygen concentration, not the measured phase (Bittig *et al.*, 2018).

8.3 Sensor time response correction

In all but more important in the most homogeneous waters it is essential to correct for the slow time response of optodes (Bittig *et al.*, 2014), (Bittig and Koertzinger, 2017) (see Fig. 8.1). This is particularly critical for optodes using the "standard" black foils, and as previously mentioned Slocum gliders with the optode in the standard location near the tail of the glider (Moat *et al.*, 2016).

Correction requires the collection of optode phase, temperature and time. Therefore, the instruments and gliders should be configured to collect these variables and not just oxygen concentration or saturation. If only optode temperature and concentration are recorded, routines exist to recalculate phase, but this can introduce some inaccuracy and best to avoid it. Accurate time-stamps for these data are required to be able to perform this correction. Many data processing routines may remove these timestamps, such as to place the oxygen data on the same time-axis as the CTD, but for best results the oxygen sensor time should be used for the time response correction before interpolating to match the CTD. Users

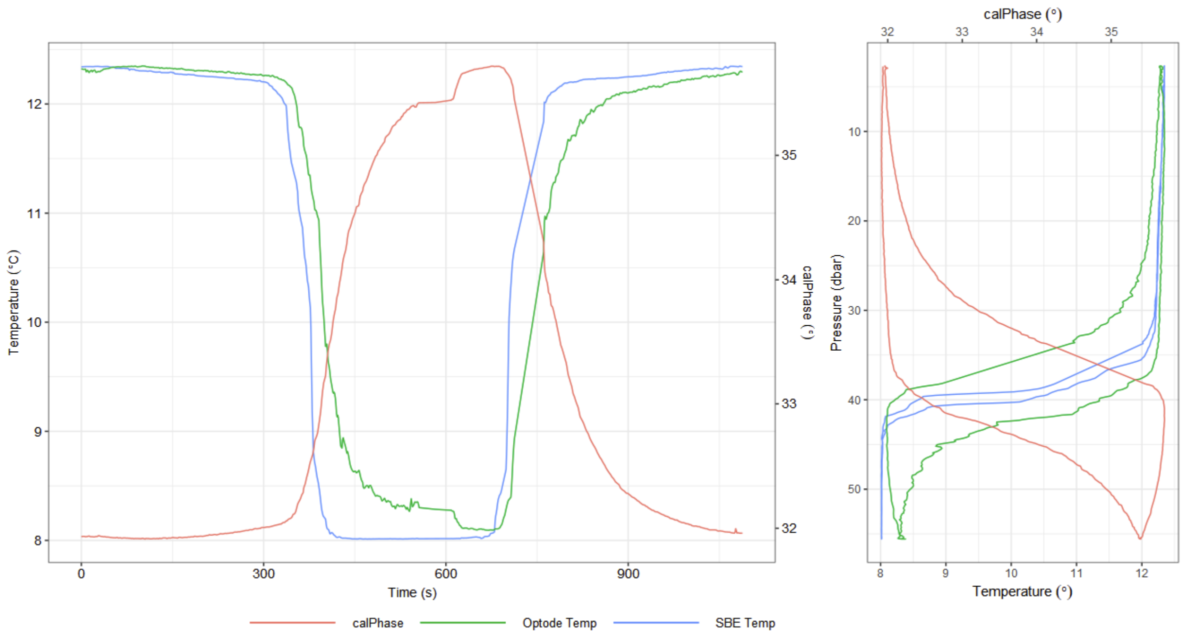

Fig. 8.1: Example uncorrected profiles from AlterEco AE5 "Kelvin" Slocum with a 4831 optode with standard foil demonstrating significant lag in both optode temperature and phase.

should be aware that many gliders have independent guidance-control computers and sensor computers and timestamps may differ between them. An important note is which temperature, be it optode or CTD, is used for the correction. The optode temperature typically has a lower accuracy and a slower response.

The lag is caused by a combination of factors, the relevance of these changes depending on the environment, optode type and glider platform. The rate of diffusion across the membrane (foil) is controlled by the water temperature and the thickness of the foil. Diffusion across the boundary layer above the membrane is also temperature dependent, but also influenced by the flow of water, which is determined by the position of the sensor and the glider speed and/or angle of attack. Lastly geometric lag is caused by a delay in water reaching the sensor due to glider geometry and the flow path of the surrounding water.

The boundary layer diffusion lag and the geometric lag will also affect the optode temperature response, which itself may have a time response due to the type of PRT used. As noted above, the type 3835 optodes have particularly slow responding temperature sensors. It is typical for users to use the CTD temperature in these instances.

The ideal correction method is still a point of discussion. We suggest users try each of these procedures and assess how well they work for their own use case.

8.3.1 Time response correction 1 - GEOMAR

Optode calibration and processing methods were developed by Johannes Hahn in collaboration with Henry Bittig for use on moored and glider-attached Aanderaa optodes. A set of routines were adapted to the particularities of optodes on gliders and to the typical conditions of GEOMAR glider deployments. This processing has now been used on nearly 100 glider deployments mostly in the Tropical Atlantic and Pacific Oceans (Krahmann *et al.*, 2021). The processing determines two delay time constants. One τ_{CTD} describes the time constant of an exponential filter which, when applied to the glider's CTD temperature, gives an estimate of the temperature of the optode foil. And the other describes the optode response time to changing oxygen concentrations. The processing so far makes no explicit correction for the "geometric" lag, that is any lag introduced by the CTD and optode being some distance from each other. This "geometric" lag should be of the order of a few seconds and thus is significantly smaller than the other two delay time constants. Implementing and correcting such a lag should however be fairly simple.

To determine the two time constants a number of steps are performed:

1. Linearly interpolate optode phase, optode temp, CTD temp, pressure and salinity variables onto 1 sec grid to avoid issues from different measurement times.
2. A set of foil temperatures is estimated by applying an exponential filter to the CTD temperature with time scales from 10 to 50 s (in steps of 5 s), thereby creating different 'virtual' foil temperatures.
3. With this set of virtual foil temperatures, oxygen concentrations are calculated using either the Aanderaa supplied or the own-calibration derived set of optode coefficients.
4. For each of the resulting oxygen concentrations a reverse exponential filter with time scales of 0 to 200 s (in steps of 20 s) is applied to create sets of oxygen concentration profiles.
5. These sets of concentration profiles are then filtered with a forward-backward filter (MATLAB `filtfilt`) to remove the noise introduced by the reverse filtering. Currently, a fixed time constant of 40 s is used for this filter. Depending on whether fast or slow foils are used, other values might deliver better results.
6. All concentrations are gridded to a 1 dbar grid (first binned and then linearly interpolated to the full dbar).
7. Differences between all up-down pairs are calculated and summed up for each of the concentration sets.
8. The one delay pair (CTD-temp delay for virtual foil temperature & Optode response delay) with the smallest difference sum is chosen and applied to the whole deployment.
9. Typically, the 'best' delays are CTD-temp: 30-100 s, optode response : 20-50 s.
10. Include into the optimization only up-down pairs that were not influenced by obvious bio-fouling.

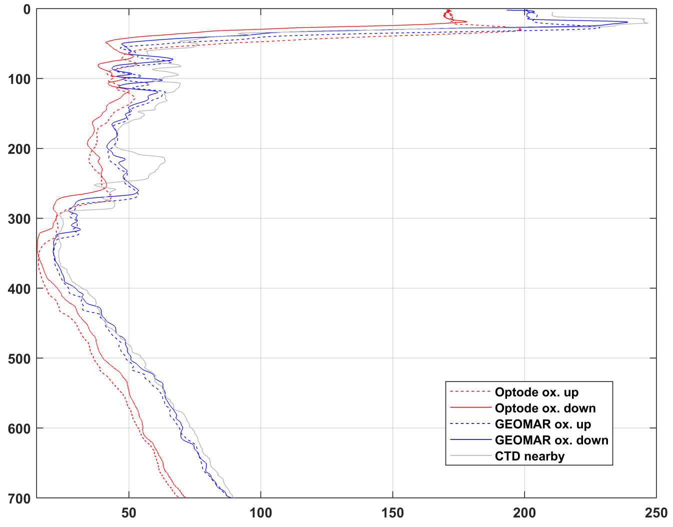

Fig. 8.2: Example of original Optode oxygen concentrations (red) and GEOMAR processed and calibrated (blue) oxygen concentrations. Shown is an up-down pair from a deployment off Angola. Solid lines are the up and dashed lines the down data. Also shown are calibrated oxygen concentrations from a nearby and contemporaneous CTD cast.

8.3.2 Time response correction 2 - IMOS

The routine developed by Mun Woo for the IMOS (Slocum) glider toolbox compares up and down casts in pressure space, but applies a time-shift rather than an exponential filter (Woo and Gourcuff, 2021). These time-shift values are determined per dive, but a rolling median is calculated to exclude dives with very high or low lag values.

The advantage of this method is that it does not amplify noise which the filter will tend to do. However, simply shifting the optode data relative to time will not remove some second order effects.

1. A τ for the geometric component of the lag is determined from the average pitch and average vertical speed for each cast.
2. These values are filtered to avoid extreme values.

1. A linear time shift using the filtered τ is then applied to align the optode phase and CTD parameters (typically 4 seconds).
2. Then, for the diffusive lag, the median RMS difference and bias between up and down cast is calculated over a range of possible τ values (0 to 40 seconds) for each dive.
3. A time shift is then applied to the optode phase with the τ which minimized the median RMS difference.
4. Oxygen concentration is then calculated using the corrected phase and CTD temperature following using the factory foil coefficients.

8.3.3 Time response correction 3 - UEA

The routine developed by Bastien Queste for the UEA Seaglider toolbox works as follows:

1. The CTD temperature is aligned based on flight speed to the optode phase using a 1-D interpolation and a flight speed dependent time-shift. (the optode and Sea-Bird temperature are close together on a Seaglider so the time-shift is small).
2. Oxygen partial pressure is calculated using the optode phase and time shifted optode temperature.
3. Up and down profiles are compared (in pressure or density space depending on environmental conditions) and either:
   1. A shoelace algorithm is used to minimize the area between the curves or
   2. The RMSD from vertically binned data is calculated
4. A minimization algorithm (`fminsearch` from MATLAB) is used to fit two lag coefficients: $\tau = \tau_0 + \tau_1(T - 20)$ as per @Hahn2014.
5. This τ is then used with an exponential inverse-filter, typically against optode phase (and oxygen recalculated) but partial pressure or concentration as per (Bittig *et al.*, 2018) has also been tested. The correction is applied on a per-dive basis.
6. Oxygen concentration is then calculated using the corrected phase and CTD temperature following using the factory foil coefficients.

8.3.4 Time response correction 4 - AlterEco

For AlterEco, many gliders were not collecting data on both up and down casts which precludes the use of the above routines. The routine implemented by Tom Hull was as follows:

1. A τ was calculated for the geometric and boundary layer diffusive lag by minimizing the difference between the CTD and optode temperatures.
2. This τ was used to then inverse-filter the optode phase and temperature.
3. A secondary lag correction based on the temperature as per the UEA toolbox and (Hahn *et al.*, 2014).
4. Oxygen concentration is then calculated using the corrected phase and optode temperature following using the factory foil coefficients.

8.4 Light intrusion

Optodes can be sensitive to light intrusion if the foil is damaged. These instruments will typically still provide good data in the absence of light. A check should be made for increased sensor noise near the surface during daylight hours and contrast this with nighttime observations.

CHAPTER
NINE

DATA SHARING

OceanGliders strongly encourages all glider operators to share their data to the public and provide open access both in real time and delayed mode. The best practices of data sharing are described in the OceanGliders data management user manual.

CHAPTER

TEN

REFERENCES

CHAPTER
ELEVEN

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EuroSea

GROOM II

GLIDERS FOR RESEARCH, OCEAN OBSERVATION &
MANAGEMENT : INFRASTRUCTURE AND INNOVATION

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CHAPTER

TWELVE

APPENDICES

12.1 Optodes commands

As discussed in Section 4.5.1 the commands required to calibrate an optode varies depending on optode firmware version. Here we present the key commands needed to perform a 0-100 calibration for all known optode variants.

NOTE: A multipoint DO calibration is necessary to obtain new foil coefficients and that can be done at the manufacturer laboratories or in any fully equipped calibration lab. These values shouldn't be changed otherwise.

The framework 3 firmware saw many changes to the output and commands from the optodes which are summarized in the optode manual Appendix 11. For optode calibration the key changes are:

- `do stop` and `do start` are now simply `stop` and `start`.
- `set interval(0)` does not switch the optode to polled mode, `enable polled mode` is now used.

Certain settings within an optode are protected, such that an unlocking command needs to be entered before the setting can be changed, these are `passkey` or `protect` depending on firmware.

It is recommended not to set the sampling rate of the optode too high during calibration to avoid self heating. We suggest a 30-second interval is appropriate.

12.1.1 Communicating with the sensor using a terminal program and a cable

When the DO sensor is disconnected from the glider connect the sensor to a PC by using the cable (Cable #3855 for 4330/4835 optodes, Cable #5335 for 4831). These cables can be purchased from Aanderaa and provide power to the optode via USB.

The following terminal configuration works for all optode types:

- 9600 baud rate
- 8 data bits
- 1 stop bit
- No parity
- Xon/Xoff flow control on
- Local echo
- CR+LF receive and transmit

12.1.2 Framework 3 (since 2013)

4835 optodes with a serial number greater than 300, 4330 optodes with a serial number greater than 1000 and all 4831 optodes are using the Framework 3 command set.

1. Immerse the optode in the 100 % solution
2. connect to the optode and open a terminal session
3. configure your terminal to log output to a file
4. `get all` - to see the current optode configuration
5. `set passkey(1000)` - to allow protected settings to be modified
6. `set enable polled mode(no)` - if the optode is set to polled mode for your glider
7. `set interval(30)` - to set the optode to collect data every 30 seconds
8. `start` - to start measuring data
9. wait for the temperature and oxygen measurements to stabilize. Variance between samples should be less than ±0.05 °C and ±0.1 µmol L-1.
10. Record the local atmospheric air pressure in hPa
11. `do collectcaldatasat` - to collect data for the 100 % data point and update the optode settings
12. `set caldataapress(XXXX.X)` - to update the local air pressure where XXXX.X is the pressure in hPa
13. immerse the optode in the 0 % solution
14. wait for the temperature and oxygen measurements have stabilized (several minutes)
15. `do collectcaldatazero` - to collect data for the 0 % data point and update the optode settings
16. `do calibrate` - to finalize the calibration and update the optode settings
17. rinse the optode very thoroughly and return it to the 100 % solution and confirm the optode is reading correctly after 10 minutes of stabilization
18. `set interval(X)` and `set enable polled mode(X)` to return the optodes back the sampling interval and mode required by your glider.

12.1.3 Older type 4835 and 4330 (pre-2013)

4835 optodes with a serial number less than 300 and 4330 optodes with a serial number less than 1000 use the following command set. These optodes can use two different levels of passkey (1 and 1000) depending on which setting needs to be changed.

1. Immerse the optode in the 100 % solution
2. connect to the optode and open a terminal session
3. configure your terminal to log output to a file
4. `get all` - to see the current optode configuration
5. `set protect(1000)` - to allow protected settings to be modified
6. `set interval(30)` - to set the optode to collect data every 30 seconds
7. `set enable polled mode(no)` - if the optode is set to polled mode for your glider
8. Wait for the temperature and oxygen measurements to stabilize. Variance between samples should be less than ±0.05 °C and ±0.1 µmol L-1 (or ±0.5 for µmol L-1 4330F)

9. record the local atmospheric air pressure in hPa
10. `do collectcaldatasat` - to collect data for the 100 % data point and update the optode settings
11. `do caldataapress(XXXX.X)` - to update the local air pressure where XXXX.X is the pressure in hPa
12. immerse the optode in the 0 % solution
13. wait for the temperature and oxygen measurements have stabilized (several minutes)
14. `set collectcaldatazero` - to collect data for the 0 % data point and update the optode settings
15. `do calibrate` - to finalize the calibration and update the optode settings
16. rinse the optode very thoroughly and return it to the 100 % solution and confirm the optode is reading correctly after 10 minutes of stabilization
17. `set interval(X)` and `set enable polled mode(X)` to return the optodes back the sampling interval and mode required by your glider.

12.1.4 Type 3830 and 3835

1. Immerse the optode in the 100 % solution
2. connect to the optode and open a terminal session
3. configure your terminal to log output to a file
4. `get_all` - to see the current optode configuration
5. `set_protect(1)` - to allow protected settings to be modified
6. `set_interval(30)` - to set the optode to collect data every 30 seconds
7. wait for the temperature and oxygen measurements to stabilize. Variance between samples should be less than ±0.1 °C and ±0.5 µmol L-1.
8. Record the local atmospheric air pressure in hPa
9. `do_calair` - to collect data for the 100 % data point and update the optode settings
10. `set_calairpressure(XXXX.X)` - to update the local air pressure where XXXX.X is the pressure in hPa
11. immerse the optode in the 0 % solution
12. wait for the temperature and oxygen measurements have stabilized (several minutes)
13. `do_calzero` - to collect data for the 0 % data point and update the optode settings
14. `do_calibrate` - to finalize the calibration and update the optode settings
15. rinse the optode very thoroughly and return it to the 100 % solution and confirm the optode is reading correctly after 10 minutes of stabilization
16. `set_protect(1)` - to allow protected settings to be modified
17. `set_interval(X)` to return the optodes back the sampling interval required by your glider. With `X` set to 0 being polled mode.

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