GROOM

Gliders for Research, Ocean Observation and Management

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Sensors for gliders: existing, under development, and future sensors

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I. INTRODUCTION

I.A. Objectives

The marine environment is punctuated by seasonal, inter-annual and inter-decadal variability, underlying anthropogenic effects of change. The spatial and temporal scales of the different phenomena that characterize the marine environment necessitate the use of various platforms and approaches that span these scales (Dickey 2003). The establishment and expansion of the Global Ocean Observing System (GOOS) has significantly contributed to charting the marine environment. In particular, mobile, low-power platforms such as floats and gliders have greatly expanded the space and frequency with which several important parameters are documented throughout the year (Testor et al. 2010).

The cost-efficient nature of autonomous platforms has led to their higher visibility and popularity as oceanographic tools. The FP7-funded project GROOM (Gliders for Research, Ocean Observation and Management, http://www.groom-fp7.eu) has been funded to help coordinate the glider infrastructure in Europe, in collaboration with other similar infrastructures elsewhere. The goals of GROOM include, among others, the standardization of the use of current sensors on gliders through calibration, intercomparison, and quality control/quality assessment (QC/QA) protocols, the testing and introduction of new sensors to gliders, and the determination of future needs for glider sensors by the present users.

In this report, we catalogue existing mission-tested sensors, prototypes currently under testing, sensors that are readily adaptable for gliders (typically used on other autonomous platforms), as well as parameters/sensors which may well be developed within 5-10 years. We list sensor characteristics, especially those that impact glider payload, i.e., power requirements, weight, and size (dimensions), relying on published documentation, as well as the surveying of the glider community at-large including users and industry partners. Sensor performance is included in this report only to the extent where payload considerations apply. Quality control/assurance issues, as well as calibration, intercalibration and intercomparison topics are discussed in GROOM deliverable D5.3. Information on desired sensors for biogeochemical and ecological parameters is further elaborated in GROOM deliverable D3.5.

I.B. General overview

The JERICO project (Joint European Research Infrastructure network for Coastal Observatories, http://www.jerico-fp7.eu), also funded by FP7, conducted a thorough study of the status of the European glider fleet, and the results were summarized in JERICO deliverable D3.2 (Tintoré et al. 2013). The main points of relevance to this report are summarized as follows:

(a) As of May 2013, the European glider fleet consisted of 82 gliders, of which 29 are deep Slocum gliders, 26 are Seagliders, and 21 are coastal Slocum gliders (*Figure 1*a). It is noted that a European institution first purchased a glider in 2004 (it was a Slocum glider);

(b) As of May 2013, there were plans to add 22 gliders to the European fleet, of which 11 will be Slocum gliders, and 6 will be Seagliders;

(c) Unpumped CTDs outnumber pumped CTDs by 67 to 13 (*Figure 1*b), all of which are made by Sea-Bird (see section II.A);

(d) Back-scatter sensors (70) are widely used, mostly due to the incorporation (practically by default) of the WetLabs ECO Puck models onto gliders (*Figure 1*b). The other ECO Puck sensors, Chl *a* fluorometers (54) and CDOM fluorometers (27), are also widely operated (see sections II.C, II.E and II.F);

(e) A total of 55 oxygen sensors are in operation on gliders, most of which (85 %) are manufactured by AADI/Aanderaa, and the rest made by Sea-Bird (see section II.B);

(f) Single items of numerous other types of sensors (for irradiance, turbulence/velocity, nitrate, PAR, etc.) are owned by various groups according to their needs and goals. While there are 286 CTDs, back-scatter, fluorometer and oxygen sensors operated on gliders as of May 2013 (mentioned above), there are only 19 "rare" sensors currently in use.

Our report catalogues the specifications of not only the sensors alluded to in JERICO deliverable 3.2, but also other sensors in use on gliders internationally, regardless of their commonality or rarity.

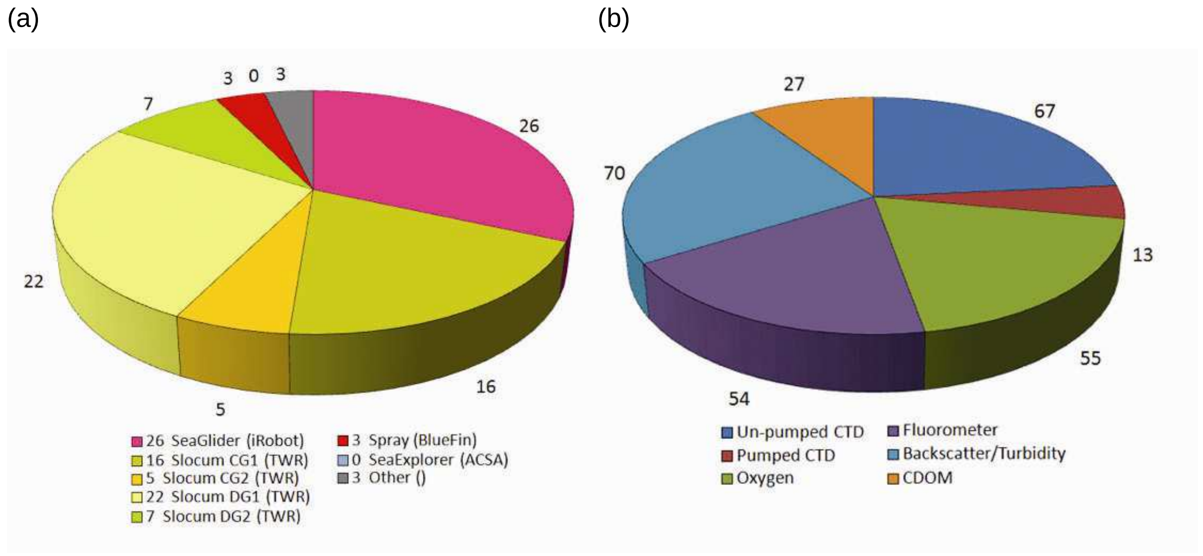

Figure 1 Figures adapted from JERICO deliverable D3.2 (Tintoré et al. 2013): (a) European glider fleet composition by manufacturer and model as of May 2013 (total = 82 gliders); (b) Most common sensors used in the European glider fleet as of May 2013 (total = 286 sensors).

I.C. Sensor readiness

For the purposes of this paper, we define a sensor as to include not only a detector but also any related circuitry that may accompany it. We opt for this definition, which by VIM (Vocabulaire International de Métrologie) standards is referred to as a transducer (Waldmann et al. 2010), because the industry typically produces, tests, and markets sensors as such. Table 1 lists all sensors discussed in this report.

We group the parameters for which glider sensors have been used to readiness or development levels, based on two intuitive classification schemes: (a) The Technology Readiness Levels (TRL), as these were adapted by Waldmann et al. (2010) for Ocean Sciences sensors (OS-TRL), and (b) development status, as defined by Johnson et al. (2000) during the OCTET study (Table 2). Typically, sensors that are listed in glider industry literature as "accommodated", "previously integrated", and available, are classified at OS-TRL 4 (9. Mission proved) or status I (Bluefin Robotics 2010, iRobot 2012, Teledyne Webb Research 2010). Unique prototypes that have been experimentally deployed are classified at OS-TRL 2-3 (Research prototype or system prototype deployment in a suitable environment) or status II-III. Sensors which have been succesfully deployed on other autonomous platforms and consequently are deemed readily adaptable for low power applications, such as on gliders, are classified as OS-TRL 2 (4. Validation in a laboratory environment) and status IV (Bench-top prototype in operation). Information on sensors at other stages of development was obtained from publicly available documents as well as from personal communications with the glider user community, including users and industry partners (Table 1).

Table 1 Overview of sensors developed and/or under development for glider usage.

Parameter(s)	Sensor type	Manufacturer	Model(s)	Glider type(s)	Representative sources
Developed, mission-proved, commercially available sensors for gliders					
Pressure, Conductivity, Temperature	CTD	Sea-Bird Electronics	CT-Sail, GPCTD, Slocum GPCTD	Slocum, Seaglider	Sea-Bird (2007, 2010, 2012a, b), Eriksen et al. (2001)
		WHOI	Fin-cell GCTD	Slocum	Schmitt and Petitt (2006)
Oxygen (O_2)	DO optode	Aanderaa (AADI)	3880, 4831F	Slocum, Seaglider	AADI (2012a)
	DO sensor	Sea-Bird Electronics	SBE-43F	Seaglider	Sea-Bird (2012c)
	DO sensor	JFE ALEC Co. Ltd (RINKO)	RINKO III Fast DO	Slocum	JFE ALEC Co. (2010)
Chl *a* fluorescence	ECO Puck	WETLabs	FL designation	Slocum, Seaglider	WETLabs (2009a)
	Fluorometer	Seapoint Sensors	Chl. fluorometer	Spray	Seapoint Sensors (2013a)
Phycobilins (phycocyanin, phycoerythrin)	ECO Puck	WETLabs	FL designation	Slocum, Seaglider	WETLabs (2011a)
Turbidity backscatter	ECO Puck	WETLabs	BB designation	Slocum, Seaglider	WETLabs (2009a, 2011a)
	Beam Attenuation meter	WETLabs	BAM	Slocum	WETLabs (2009b)
	Turbidity meter	Seapoint Sensors	Turbidity meter	Spray	Seapoint Sensors Inc. (2013b)
Chromophoric Dissolved Organic Matter (CDOM) fluorescence	ECO Puck	WETLabs	FL designation	Slocum, Seaglider	WETLabs (2009a, 2011a)
Current	ADCP	Nortek	AD2CP	Seaglider, Spray	Siegel and Rusello (2013)
	ADCP	Nortek	Aquadopp	Slocum, Spray	Nortek (2013)

	DVL	Teledyne RDI	Explorer DVL	Slocum	Teledyne RD Instruments (2011)
	ADCP	Teledyne RDI	Explorer ADCP	Slocum	Teledyne RD Instruments (2013)
Radiance, irradiance and PAR	Irradiance sensor	Satlantic	AUV Micro 4 channel	Slocum	Satlantic (2013a)
	Radiance sensor	Satlantic	AUV Micro 4 channel	Slocum	Satlantic (2013a)
	PAR sensor	Biospherical Instruments	QSP-2000 series	Seaglider	Biospherical Instruments (2011)
	PAR sensor	Satlantic	Log AUV PAR sensor	Slocum	Satlantic (2012)
Animal biomass and presence	Echosounder	Imagenex	853 (120 kHz)	Seaglider, Slocum	Imagenex (2013)
	Transceiver	VEMCO	VMT	Slocum	Oliver et al. (2013)
	ADP	SonTek	760 kHz	Slocum	Davis et al. (2008)
Marine mammal detection	Hydrophone	High Tech Inc.	HTI-99-HF	Seaglider	Klinck et al. (2012)
	Hydrophone	WHOI	DMON	Seaglider, Slocum	Hurst et al. (2012)
Turbulence	Turbulence profiler	Rockland Scientific	MicroRider-1000	Slocum	Rockland Scientific (2013a)
	ADCP	Nortek	Aquadopp HR ADCP	Spray	Rusello et al. (2011)
Wind	Acoustic recorder	Greeneridge Sciences Inc.	Acousonde	Slocum, Seaglider	Greeneridge Sciences Inc. (2012)
Nitrate (NO_3^-)	Nitrate sensor	Satlantic	SUNA v2	Slocum	Satlantic (2013b)
Prototypes and sensors in development for gliders					
Radioactivity	NaI Scintillation Probe	Amptek	Gamma-Rad	Slocum	Jones et al. (2011)

Video imagery	Digital camera	-	-	Slocum	Glenn and Schofield (2009)
Multiple optical properties	Optical sensors	Turner	Cyclops	Slocum	Jones et al. (2011)
Readily adaptable sensors for glider use					
Nutrients	Microfluidics analyzers	SubChem Systems	APNA	-	SubChem (2011a)
			ChemFIN^{TM}	-	SubChem (2011b)
			MarChem	-	SubChem (2009)
Nitrate	UV sensor	NOC/Valeport Ltd.	SUV-6	-	Pidcock et al. (2010)
Unexploded ordinance	Ordinance immunosensor	US NRL/SubChem	-	-	Adams et al. (2011, 2013), Charles et al. (2011)
Harmful algal bloom (HAB) toxins	Microfluidics analyzer	SubChem	MarChem		Hanson and Kusterbeck (2010, 2011)
Methane (CH_4)	IR spectrometer	CONTROS	HydroC™ CH_4	-	CONTROS (2011a)
Carbon dioxide (pCO_2)	IR spectrometer	CONTROS	HydroC™ CO_2	-	CONTROS (2011b)
Hydrocarbons	Fluorometer	CONTROS	HydroC™ PAH	-	CONTROS (2011c)
	ECO Puck	WETLabs	FL designation	Slocum, Seaglider	WETLabs (2013)
	Fluorometer	TriOS Optical Sensors	EnviroFlu-HC	-	Tedetti et al. (2010), TriOS Optical Sensors (2013)
	Fluorometer	CNRS/MIO	MiniFluo-UV	SeaExplorer, Slocum	Tedetti and Goutx (2012), Tedetti et al. (2013)
Bioluminescence	Luminometer	WETLabs	UBAT	-	WETLabs (2010)

Table 2 Ocean Sciences Technology Readiness Levels (OS-TRL), as defined by Waldmann et al. (2010), matched by development status as described by Johnson et al. (2000). The nine TRL definitions originate from NASA (Mankins 1995). Parameters covered by existing glider sensors, as identified by this review (Table 1), are categorized in the last column.

TRL	**TRL description (Waldmann et al. 2010)**	**Status of development (Johnson et al. 2000)**	**Glider sensor parameters**
OS-TRL 1: Proof-of-concept/development			
1	Basic principles observed and reported		
2	Technology concept and/or application formulated		
3	Analytical and experimental critical function and/or characteristic proof-of concept		
OS-TRL 2: Research prototyping		**IV** Bench-top prototype in operation	Nutrients, NO_3^-, Unexploded ordinance, HAB toxins, $p\mathrm{CO}_2$, CH_4, Hydrocarbons, Bioluminescence
4	Component and/or breadboard validation in laboratory environment		
5	Component and/or breadboard validation in relevant environment	**III** Early stage of development with successful short-term deployments in the marine environment	Radioactivity, Video imagery
6	System/subsystem model or prototype demonstration in a relevant environment		
OS-TRL 3: Commercial product			
7	System prototype demonstration in a space/ocean environment		
8	Actual systems completed and “mission qualified” through test and demonstration	**II** Successfully deployed in the marine environment for extended periods (>1 month) with oceanographically consistent results but not commercially available	
OS-TRL 4: Mission proved		**I** Currently operational and available commercially	Pressure, Conductivity, Temperature, O_2, Chl *a* fluorescence, Phycobilins, Turbidity backscatter, CDOM fluorescence, Current, Radiance, Irradiance, Animal biomass, Marine mammals, Turbulence, Wind, NO_3^-
9	Actual system proven through successful mission operations		

II. MISSION-PROVED, COMMERCIALLY AVAILABLE SENSORS FOR GLIDERS

II.A. Pressure, conductivity and temperature

II.A.1. Sea-Bird Glider Payload CTDs

The predominant CTD sensors used on gliders in Europe are the Sea-Bird CTDs, previously the CT Sail and more recently the Seaglider and Slocum GPCTDs (*Figure 2*). Their specifications are listed in Table 3 (pressure), Table 4 (conductivity), and Table 5 (temperature).

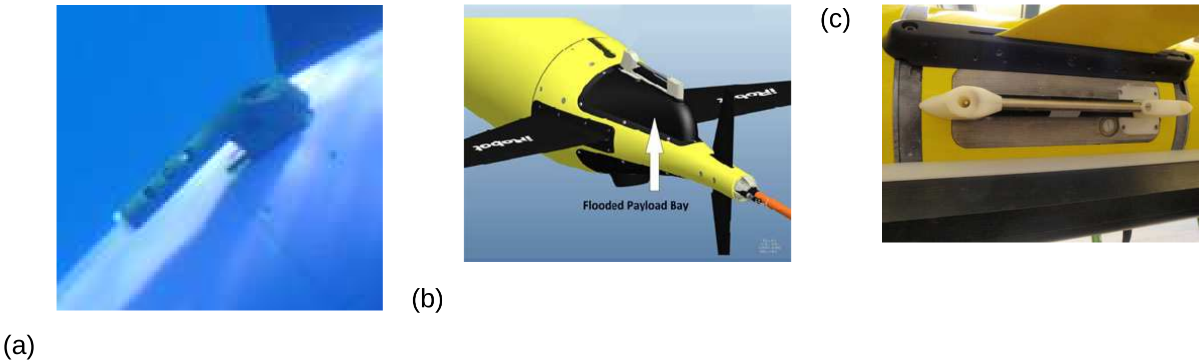

Figure 2 (a) Sea-Bird CT Sail CTD on a Seaglider (courtesy Angelos Hannides), (b) Sea-Bird Glider Payload CTD for Seagliders (Janzen and Creed 2011) (c) Sea-Bird Slocum Glider Payload CTD mounted on a Slocum glider (courtesy Lucas Merckelbach).

Based the questionnaire findings reported in JERICO deliverable D3.2 (Tintoré et al. 2013), it is evident that 5 in 6 CTDs used on gliders in the European fleet are the original flow-though or unpumped CTDs. This design ensures lower power consumption by removing the need to pump water through the measurement system, but simultaneously introduces an uncertainty as to the intensity and stability of the flow rate. The unknown and variable flow rate, which depends on the flight dynamics of the glider (speed and angle of attack), hampers a reliable correction for the thermal lag error (Garau et al. 2011).

In contrast, the newer design for glider payload CTDs uses a low power pumping system, which, at the expense of perhaps a small power consumption increase, generates a steady flush rate through the conductivity cell approximately equal to 10 mL s^{-1} (Janzen 2011). The high and steady flow rate improves the performance of thermal lag correction methods, and also reduces the magnitude of the thermal lag error.

II.A.2. Fin-cell GCTD

Schmitt and Petitt (2006) developed a fast-response four-electrode CTD, dubbed the fin-cell GCTD (*Figure 3*), designed to be free flushing, with low drag, low thermal mass, and low fouling potential. The GCTD sampled more frequently and precisely than a Sea-Bird CTD during testing on a Slocum glider. It is powered at 12 VDC (±10%) and draws 35 mA. The electronics board (15.36 cm × 4.74 cm × 1.92 cm) is mounted to the internal chassis of the glider, and is connected to the external CT sensor. More information is provided in Table 4 (conductivity) and Table 5 (temperature).

Figure 3 (above right) The fin-cell GCTD mounted onto a Slocum glider (Schmitt and Petitt 2006).

Table 3 Specifications for pressure sensors for gliders.

Manufacturer and model	***Sea-Bird CT Sail (Paine 211-75-710-05)***	***Sea-Bird Glider Payload CTD (GPCTD)***	***Sea-Bird Slocum Glider Payload CTD***
Glider platform	Seaglider, Slocum	Seaglider	Slocum
Weight (kg)	Air: 0.18	350 m version: Air: 1.0, Water: 0.2 1500 m version: Air: 1.2, Water: 0.4	Air: 2.0, Water: 0.4
Dimensions (cm)		25.6 × 11.6 × 6.2	
Power supply (VDC)		8-20	8-20
Current (mA)		30	
Wattage (mW)		175-190 (continuous)	241 (continuous)
Depth rating (m)	3000	350, 1500	
Range (dbar)	0-1500	0-100, 0-350 0-1000, 0-2000	0-100, 0-350 0-1000, 0-2000
Accuracy (%)	± 0.25% (full Scale)	± 0.1	± 0.1
Resolution (%)		± 0.002	± 0.002
Stability (% y^{-1})		0.05	
Reference	Eriksen et al. (2001)	Sea-Bird (2012a)	Sea-Bird (2010)

Table 4 Specifications of conductivity sensors for gliders.

Manufacturer and model	***Sea-Bird CT Sail SBE 4***	***Sea-Bird Glider Payload CTD***		***Sea-Bird Slocum Glider Payload CTD***		***Fin-cell GCTD***
Glider platform	Seaglider, Slocum	Seaglider		Slocum		Slocum
Weight (kg)	Air: 0.7, Water: 0.34	350 m version: Air: 1.0, Water: 0.2 1500 m version: Air: 1.2, Water: 0.4		Air: 2.0, Water: 0.4		Air: 0.225 (without internally mounted board)
Dimensions (cm)	25×7.7×4.8	25.6×11.6×6.2				
Power supply (VDC)	6-24	8-20		8-20		12 (± 10 %)
Current (mA)	18	30				35
Wattage (mW)		175-190 (continuous)		241 (continuous)		
Depth rating (m)	3400	350	1500	350	1500	
Range ($S\ m^{-1}$)	0-7	0-9	0-9	0-9	0-9	0-6
Accuracy ($S\ m^{-1}$)	± 0.0003	± 0.0003	± 0.003	± 0.0003	± 0.003	± 0.001
Resolution ($S\ m^{-1}$)	± 0.0003	± 0.00001	± 0.0001	± 0.00001	± 0.0001	± 0.00001
Stability ($S\ m^{-1}\ mo^{-1}$)	± 0.00004	0.0003	0.003	-	-	-
Reference	Sea-Bird (2012b)	Sea-Bird (2012a)		Sea-Bird (2010)		NBOSI (2013)

Table 5 Specifications of temperature sensors for gliders.

Manufacturer and model	***Sea-Bird CT Sail SBE 3plus***	***Sea-Bird Glider Payload CTD***	***Sea-Bird Slocum Glider Payload CTD***	***Fin-cell GCTD***
Glider platform	Seaglider, Slocum	Seaglider	Slocum	Slocum
Weight (kg)	Air: 0.63, Water: 0.28	350 m version: Air: 1.0, Water: 0.2 1500 m version: Air: 1.2, Water: 0.4	Air: 2.0, Water: 0.4	Air: 0.225 (without internally mounted board)
Dimensions (cm)	3.6 (∅) × 27	25.6 × 11.6 × 6.2		
Power supply (VDC)	11-16	8-20	8-20	12 (± 10 %)
Current (mA)	25	30		35
Wattage (mW)		175-190 (continuous)	241 (continuous)	
Depth rating (m)	6800	350, 1500		
Range (^{o}C)	-5 - 35	-5 - 42	-5 - 42	0-30
Accuracy (^{o}C)	± 0.001	± 0.0002	± 0.0002	± 0.005
Resolution (^{o}C)	± 0.0003	± 0.001	± 0.001	± 0.0001
Stability (^{o}C mo^{-1})	< 0.00017	0.0002	-	
Reference	Sea-Bird (2007)	Sea-Bird (2012a)	Sea-Bird (2010)	NBOSI (2013)

II.B. Dissolved Oxygen (DO)

There are two predominant sensors for the detection of DO on gliders in the European fleet. According to the JERICO survey (JERICO Deliverable 3.2; Tintoré et al. 2013), the vast majority (85 %) of DO instruments are Aanderaa DO optodes, and the remainder are Sea-Bird’s DO sensors. A third sensor, the RINKO III Fast DO sensor, is listed in the Slocum G2 Glider product catalogue (Teledyne Webb Research 2013) for incorporation into the Slocum payload bay. Specifications of all three sensors are shown in Table 6.

II.B.1. Aanderaa DO optode (3880, 4831F)

The most popular DO sensor on European fleet gliders is the AADI/Aanderaa DO optode. Two major models are in operation, the older 3880 and the more recent 4831F (AADI 2012a, b). The DO optodes operate on the lifetime-based luminescence quenching principle. Specifically, a platinum-porphyrin complex embedded in a gas-permeable foil that is in contact with the surrounding seawater, is excited by blue light emitted by an LED source and emits red light, which is detected by a sensor (Tengberg et al. 2003). The complex reacts with oxygen present in the seawater, and consequently the emitted light is quenched in proportion to the oxygen concentration. In lifetime quenching, the optode measures the time it takes (lifetime) for the light returning to the instrument to disappear. The superiority of DO optodes over Clark-type sensors is mainly due to the sensitivity of the latter to various measurement conditions, including flow rates (see below).

II.B.2. Sea-Bird DO sensor (SBE-43F)

The Sea-Bird SBE-43F DO sensor (Sea-Bird 2012c) is a polarographic membrane Clark-type sensor (Clark Jr. et al. 1953). A gold cathode and a silver anode are immersed in an ionic solution which is separated from surrounding seawater by a gas-permeable membrane. The current which flows between the polarized cathode and the non-polarized anode is proportional to the DO in the ionic solution, which is equilibrated with surrounding seawater with respect to DO.

One concern with polarographic (Clark-type) sensors is that DO is actually consumed during detection and consequently its signal is negatively affected by reduced flow rates and consequently slower equilibration. Since the Sea-Bird DO sensor is commonly connected to an unpumped CTD (based on the user surveys conducted for JERICO and GROOM), the resulting signal may often be an underestimation of the actual concentration.

II.B.3. RINKO III Fast DO sensor

A third sensor, listed in the Slocum G2 Glider product catalogue (Teledyne Webb Research 2013) is a polarographic fast DO sensor manufactured by JFE ALEC and distributed by Rockland SI (JFE ALEC Co. 2010). There is no information on the extent of use of this DO sensor.

Figure 4 DO sensors used on gliders: (a) Exposed Aanderaa DO optode on a coastal Slocum glider (NCCOOS 2012), (b) Inflow and outflow of a Sea-Bird 43F DO sensor on a Seaglider (courtesy Angelos Hannides), (c) The RINKO III DO sensor for Slocum gliders (JFE ALEC Co. 2010).

Table 6 Specifications of dissolved oxygen sensors used on gliders.

Manufacturer and model	***Aanderaa optode 3880, 4831F***	***Seabird SBE-43F***	***JFE ALEC RINKO III Fast DO sensor***
Glider platform	Slocum, Seaglider	Seaglider	Slocum
Weight in water (kg)	0.21	0.1 (plastic), 0.2 (Ti)	0.9
Dimensions (cm)	3.6 (∅) × 8.6	3.9 (∅) × 14.2	
Depth rating (m)	≤ 6000	600 (plastic), 7000 (Titanium)	7000
Range (µmol L^{-1}, %)	0-500, 0-120	-, 0-120	0-20 mg/L, 0-200
Accuracy (µmol L^{-1}, %)	8, 5	-, 2	-, 2
Resolution (µmol L^{-1}, %)	1, 0.4		0.01 to0.4% (2to8 µg/L)
Stability (% y^{-1})			1% (24 hours), 5% (1 month)
Response time			0.4 sec (63%), 0.9 sec (90%)
Current	80 mA s^{-1} (recording interval)		110 mA (during measurement)
Wattage (W)		0.045	
Reference	AADI (2012a)	Sea-Bird (2012c)	JFE ALEC Co. (2010)

II.C. Chlorophyll *a* fluorescence

The predominant sensor used to detect Chlorophyll *a* (Chl *a*) fluorescence by gliders is the WETLabs ECO Puck (WETLabs 2009a), which comes under different parameter configurations. The inclusion of a Chl *a* fluorescence module is designated with the letters FL in the ECO Puck and Triplet model names.

Questionnaire responses indicated that, even though Chl *a* fluorescence is routinely collected by gliders in the European fleet, the resulting data remains underused due to the questions surrounding the relationship between Chl *a* concentration and fluorescence, as this is measured using a multitude of sensors on various platforms (e.g., ship-deployed packages, moored buoys, floats, AUVs, gliders, etc.). Chl *a* fluorescence is commonly defined as the intensity of radiation at 695 nm, or emission wavelength (this value may be different, but always in the range of 650-700 nm) that is detected after the sample has been irradiated at 470 nm, or excitation wavelength (Earp et al. 2011). This intensity is thought to be proportional to the amount of Chl *a* present in the sample, but the actual relationship is affected by numerous parameters (e.g., nutritional status, species composition, recent light history, etc.) that introduce variability of up to an order of magnitude (Holm-Hansen et al. 2000, Jolliff et al. 2012). Therefore, significant effort is invested in comparing sensor Chl *a* fluorescence readings with Chl *a* concentrations from bottle samples (e.g., Bagniewski et al. 2011, D’Asaro 2009) or with satellite observations (Lavigne et al. 2012, Mignot et al. 2011).

II.C.1. WETLabs ECO Puck (models including FL designation)

As previously mentioned, the WETLabs ECO Puck (*Figure* 5a) and Triplet (*Figure* 6a) sensors can be purchased in various configurations that may include a Chl *a* module, and in that case the model name includes the designation FL. In the case of the ECO Pucks, the excitation and emission wavelengths are 470 nm and 695 nm, respectively. Specifications for the ECO Puck are shown in Table 7.

II.C.2. Seapoint Chlorophyll Fluorometer

Seapoint has produced a Chlorophyll fluorometer (Seapoint Sensors Inc. 2013a), which has been repeatedly deployed by one group on Spray gliders (Davis et al. 2008, Todd et al. 2011). Excitation and emission wavelengths are 470 nm and 685 nm, respectively. Specifications for the Seapoint Chlorophyll fluorometer (*Figure* 5b) are shown in Table 7.

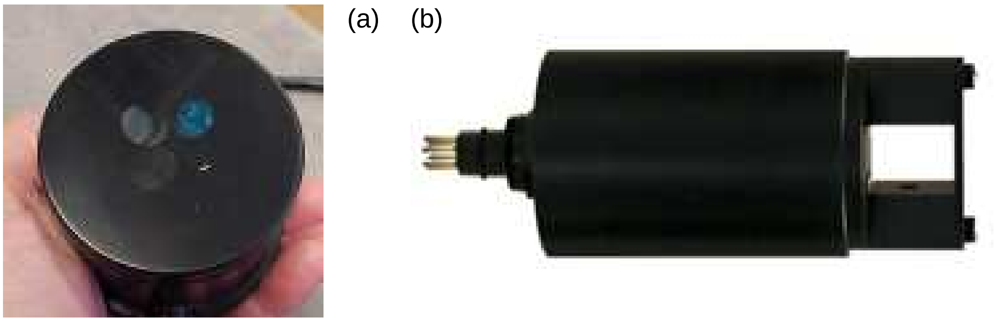

Figure 5 Chlorophyll a sensors used on gliders: (a) The WETLabs ECO Puck (WETLabs 2009a), (b) the Seapoint Chlorophyll fluorometer (Seapoint Sensors Inc. 2013a)

Table 7 Specifications of chlorophyll *a* fluorescence sensors used on gliders.

Manufacturer and model	***Wetlabs ECO Puck (models including FL)***	***Seapoint Chlorophyll Fluorometer***
Glider platform	Slocum, Seaglider	Spray
Weight (kg)	Air: 0.28/0.4* Water: 0.02	Air: 0.85
Dimensions (cm)	6.3 (∅) × 5/12.7*	6.4 (∅) × 16.8
Excitation/Emission λ (nm)	470/695	470/685
Range (counts)	4200	
Resolution (counts)	1-2	
Voltage (VDC)	7-15	8-20
Current (mA)	80/60*	15 (aver.), 27 (peak)
Reference	WETLabs (2009a)	Seapoint Sensors Inc. (2013a)

* ECO Triplet

II.D. Phycobilins (phycocyanin, phycoerythrin)

II.D.1. WETLabs ECO Puck (models including FL designation)

The WETLabs ECO Puck (*Figure* 5a) and Triplet (*Figure* 6a) sensors can be customized to optically detect phycocyanin and phycoerythrin (WETLabs 2011b). These two phycobilins act as light-harvesting antennae for photosystem II, which only occurs in cyanobacteria, therefore they are considered reliable proxies for cyanobacterial abundances (Poryvkina et al. 1994). Excitation and emission wavelengths are 630/680 nm and 540/570 nm for phycocyanin and phycoerythrin, respectively, with a sensitivity of 0.09 ppb over a range of 0–175 ppb (WETLabs 2011a). Design and payload specifications for the ECO Puck and Triplet are listed in Table 7.

II.E. Turbidity backscatter

The degree of light scattering at various wavelengths in the visible spectrum is considered to be a reliable proxy of particle concentrations, even though absolute correlation between scattering and concentration may require extensive intercomparison (e.g., Glenn et al. 2008). Below, we list the optical sensors that have been used to measure this proxy.

It should be noted that, in principle, scattering could be representative of not just sediment grains, but also plankton and detritus. As for sediment, such applications for backscatter remain to be explored through intercomparison. Apart from the effect of particles on optical properties, acoustic sensors such as ADPs can be also be used (e.g., Davis et al. 2008), even though acoustics are more commonly used for the detection of animals, both plankton and nekton (see Section II.I).

II.E.1. WETLabs ECO Puck (models including BB designation)

The WETLabs ECO Puck (*Figure 5*a) and Triplet (*Figure 6*a) sensors can be selected to measure scattering at four different wavelengths: 470, 532, 650, and 700 nm. The relevant specifications are shown in Table 8.

II.E.2. WETLabs Beam Attenuation Meter

According to the product catalogue (Teledyne Webb Research 2013), the Slocum glider can be configured to accommodate a WETLabs Beam Attenuation Meter (*Figure 6*b), originally configured for AUVs (WETLabs 2009b). The BAM can be configured to measure at 470, 532, or 650 nm. Other specifications for this sensor are shown in Table 8.

II.E.3. Seapoint Turbidity Meter

Seapoint has produced a turbidity meter (Seapoint Sensors Inc. 2013b), that is reportedly being used on a Spray glider owned and operated by PLOCAN (2013). The source wavelength is 880 nm and the sensing distance is < 5 cm. Specifications for the Seapoint Turbidity Meter (*Figure 6*c) are shown in Table 8.

Figure 6 Turbidity backscatter sensors used on gliders: (a) the WETLabs ECO Triplet (WETLabs 2011a), (b) the WETLabs Beam Attenuation Meter, mounted in a Slocum glider (Teledyne Webb Research 2013), (c) the Seapoint Turbidity Meter (Seapoint Sensors Inc. 2013b).

Table 8 Specifications for optical turbidity back-scatter sensors.

Manufacturer and model	***WETLabs ECO Puck***	***WETLabs BAM***	***Seapoint Turbidity Meter***
Glider platform	Slocum, Seaglider	Slocum	Only reported on Spray
Weight (kg)	Air: 0.28/0.4* Water: 0.02	Air: 3.28 Water: 2.06	Air: 0.086
Dimensions (cm)	6.3 (∅) × 5/12.7*	19.56 × 12.45 × 6.35	2.5 (∅) × 12
Materials	Acetal copolymer		ABS plastic, epoxy
Depth rating (m)	600	1000	6000
Power requirements (VDC)	7-15	7.5-15	7-20 VDC
Current (mA)	80/60*	35	3.5 (aver), 6 (peak)
Source λ (nm)	470, 532, 650, 700	470, 532, 650	880
Range	0-5 m^{-1}		25, 125, 500 counts
Resolution		0.003 m^{-1}	< 2 %
Sensitivity	0.003 m^{-1}		
Sensing distance (cm)	1-2	Path length: 10 cm	< 5
Reference	WETLabs (2009a, 2011a)	WETLabs (2009b)	Seapoint Sensors Inc. (2013b)

* ECO Triplet

II.F. Chromophoric dissolved organic matter (CDOM) fluorescence

The optical properties of chromophoric dissolved organic matter (CDOM) in seawater have been studied for more than 80 years, and work to better correlate these properties with the chemical composition of CDOM is ongoing (Nelson and Siegel 2002). The optical property that is relevant to CDOM sensors such as those used on gliders is that CDOM fluoresces blue when irradiated with UV light. Because seawater is characterized by fairly featureless excitation and emission spectra, excitation wavelengths of 300-360 nm and emission wavelengths of 400-500 nm can be representative of the whole spectrum (Chen and Bada 1992). Therefore, an excitation-emission pair can be used to measure CDOM fluorescence.

II.F.1. *WETLabs ECO Puck (models including FL designation)*

The WETLabs ECO Puck (*Figure* 5a) and Triplet (*Figure* 6a) sensors can be selected to measure CDOM fluorescence at excitation and emission wavelengths of 370 nm and 460 nm, respectively. The relevant specifications are shown in Table 9.

Table 9 Specifications of the WETLabs ECO Puck sensor used for CDOM fluorescence measurements on gliders.

Manufacturer and model	***WETLabs ECO Puck***
Glider platform	Slocum, Seaglider
Weight (kg)	Air: 0.28/0.4* Water: 0.02
Dimensions (cm)	6.3 (∅) × 5/12.7*
Materials	Acetal copolymer
Depth rating (m)	600
Power requirements (VDC)	7-15
Current (mA)	80/60*
Excitation/Emission λ (nm)	370/460
Range	0-375 ppb
Sensitivity	0.28 ppb
Sensing distance (cm)	1-2
Reference	WETLabs (2009a, 2011a)

* ECO Triplet

II.G. Current

Velocity observations by gliders are mostly derived by dead-reckoning between profiles. The position of the glider upon surfacing from GPS fixes is compared to the expected position based on dead reckoning calculations from a hydrodynamic model of vehicle speed (Eriksen et al. 2001). The difference between the positions in time and space is assumed to be due to an average velocity of the water during the vehicle dive. It should be noted that other navigation errors can contaminate these calculations, such as an improperly calibrated or poorly functioning compass (Merckelbach et al. 2008), or a poorly-configured hydrodynamic model for the vehicle velocity. These depth-average velocities are essential to the control of gliders, as well as being valuable data. If the depth-average velocities can be considered as reliable currents, then they can be used to provide an absolute reference to the geostrophic current shear calculated from adjacent density profiles. Because this calculation only provides the component of current perpendicular to the line connecting the stations, only this component can be referenced. In effect, this allows the verification of the ‘level of no motion’ assumption typically made.

To achieve absolute current profiles with this method, it is important to plan a glider mission to cross currents in a transverse fashion, since the along-track component of the depth-average velocity cannot be supplemented by density-based geostrophic shear calculations. The ongoing deployment of Acoustic Doppler Current Profilers (ADCPs) on gliders will provide direct observations of depth-dependent velocity profiles, making possible the calculation of fluxes of other observed parameters, such as heat, salinity, nutrients, etc. However, other technical problems appear with ADCP use. In particular, unless bottom-tracking is available, there is no simple, proven method to reference the currents relative to the glider, as measured by the ADCP.

II.G.1. Nortek AD2CP

In 2012, Nortek AS (Oslo, Norway) released the AD2CP-Glider. Nortek AD2CP have now been successfully deployed on Seagliders and Sprays (Rusello 2012, Siegel and Rusello 2013). Technical specifications are listed in Table 10. AD2CPs are self-contained physically, and only require power supply and a control connection.

II.G.2. Nortek Aquadopp

The Nortek Aquadopp profiler is a well established acoustic Doppler current profiler for use on multiple platforms (Nortek 2013). It has been deployed on a Slocum glider (*Figure 7*b) by Woods and Fratantoni (2011) in the Great South Channel, North Atlantic, with considerable success. The specifications of the Nortek Aquadopp are listed in Table 10.

II.G.3. Teledyne RDI Explorer Doppler Velocity Log (DVL)

The Explorer Doppler Velocity Log (DVL) by Teledyne RDI (Teledyne RD Instruments 2011) has been deployed succesfully on a Slocum glider (Jones et al. 2011).

Figure 7 (a) A Nortek AD2CP integrated on a Seaglider (Nortek 2011), (b) A Nortek Aquadopp on a Slocum glider (Rusello 2012), (c) A Teledyne RD Instruments Explorer DVL mounted on a Slocum glider (Jones et al. 2011).

II.G.4. Teledyne RDI 600 kHz Explorer ADCP

In March 2012, Teledyne RD Instruments (RDI) announced that engineering and field work is underway to test a fully integrated ADCP with bottom tracking capability that will be used to collect high resolution current profiling data from a glider platform (Teledyne RD Instruments 2012). This year, Teledyne RDI announced that a 600 kHz Explorer ADCP has now been successfully mounted and operated on Slocum gliders (Teledyne RD Instruments 2013; Margo Newcombe, personal communication). According to Jerry Mullison (personal communication), Teledyne RDI has established the accuracy of the bottom track solution for an Explorer ADCP mounted to a Slocum glider when oriented for level flight or for descent (the results will be presented at Oceans 2013 in San Diego in September 2013. Moreover, work is continuing on Lowered ADCP techniques with results expected within 2013, while noting independent efforts in the research community on the same front (Ordonez 2012). At this point, Teledyne RDI has delivered 20 of 24 units to be integrated to Slocum gliders destined for the Ocean Observatories Initiative (Alan Kenny, personal communication).

Table 10 Acoustic Doppler current profilers (ADCPs) used as current meters on gliders.

Manufacturer and model	***Nortek AD2CP***	***Nortek Aquadopp***	***Teledyne RDI Explorer DVL***
Glider platform	Seaglider, Spray	Slocum	Slocum
Weight (kg)	Water: 0.9	Air: 2.2, Water: 0.2 (1 MHz)	Air: 4.3, Water: 0.8
Dimensions (cm)	13.5 (∅) × 12.2	8.2 (∅) × 57.3 (1 MHz)	12.5 (∅) × 32.9
Depth rating (m)	1000	Varies	1000
Materials	Titanium	Titanium, Delrin	
Power requirements (VDC)	18-26	9-15	12-24
Current (A)		3 (peak)	
Wattage (W)	0.2-0.9	0.2-1.5 (max), $3\text{x}10^{-7}$ (quiesc.-RS232)	12 (peak), 2 (aver.), 1.1 (quiesc.)
Acoustic frequency (MHz)	1	1	0.6144
Max profiling Range (m)	30	20	35
Cell Size (m)	1 (typical)	0.3-4.0	
Maximum Sampling (Hz)	1	1	12
Reference	Siegel and Rusello (2013)	Nortek (2013)	Teledyne RD Instruments (2011)

II.H. Radiance, irradiance and PAR

Light penetration into the surface ocean drives many critical processes, most importantly heating, photosynthesis, and animal behavior. Sensors have been developed to measure various parameters related to light penetration: (a) irradiance, defined as power per unit area (e.g., W m^{-2}), (b) radiance, defined as power per solid angle per unit area (e.g., W sr^{-1} m^{-2}), and (c) Photosynthetically Active Radiation (PAR), defined as the number of photons per unit area per unit time (µmol m^{-2} s^{-1}). While radiance/irradiance sensors are used in physiological studies and in satellite sensor calibration, PAR sensors are generally used to determine the zone in which light levels favor primary production.

Various options are now listed as commercially available for deployment on gliders, and are briefly described below.

II.H.1. Satlantic AUV Irradiance sensor (OCR504-ICSW)

Satlantic produces a series of multispectral radiometers. One of these, the OCR504 (*Figure 8*a), can be configured as a 4-channel Irradiance sensor (Satlantic 2013a). The sensor can be mounted onto a Slocum glider with a 10-inch cable. Specifications are listed in Table 11.

II.H.2. Satlantic AUV Radiance sensor (OCR504-R10W)

Satlantic’s OCR504 (*Figure 8*a) can also be configured as a 4-channel Irradiance sensor, also for mounting onto a Slocum glider (Satlantic 2013a). Specifications are listed in Table 11.

II.H.3. Biospherical Instruments PAR sensor (QSP 2000 series)

A Biospherical Instruments PAR sensor (*Figure 8*b) (Biospherical Instruments 2011) was deployed on a Seaglider operated by the University of East Anglia (Jan Kaiser, personal communication). Specifications are listed in Table 11.

II.H.4. Satlantic PAR sensor

According to the product catalogue (Teledyne Webb Research 2013), the Slocum glider can be configured to accommodate a Satlantic Logarithmic AUV PAR sensor (*Figure 8*c) (Satlantic 2012). Specifications are listed in Table 11.

Figure 8 Radiance and irradiance sensors deployable on gliders: (a) the Satlantic Irradiance/Radiance sensor OCR504 (Satlantic 2013c), (b) the Biospherical Instruments PAR sensor, QSP 2000 series, (c) the Satlantic PAR sensor (Satlantic 2013c).

Table 11 Radiance and irradiance sensors available for operation on gliders.

Manufacturer and model	***Satlantic AUV Irradiance sensor (OCR504-ICSW)***	***Satlantic AUV Radiance sensor (OCR504-R10W)***	***Biospherical Instruments PAR sensor (QSP-2000 series)***	***Satlantic PAR sensor***
Glider platform	Slocum		Seaglider	Slocum
Weight (kg)	Air: 0.2 Water: 0.04		Air: 1.1	Air: 0.127
Dimensions (cm)	4.6 (∅) × 9.8		5 (∅) × 15	3 (∅) × 7.6
Materials	Anodized aluminum		PTFE sphere on aluminum housing	Plastic
Power supply (VDC)	6-22			6-30
Current (mA)				5 (anal) 15 (digi)
Depth rating (m)	2000 m			600
Effective λ (nm)	400-700 (customizable)		400-700	400-700
PAR dynamic range	-		1.4×10^{-5} - 0.5 µE·cm^{-2}·sec^{-1}	0 - 5000 µE·m^{-2}·sec^{-1}
Reference	Satlantic (2013a)		Biospherical Instruments (2011)	Satlantic (2012)

II.I. Animal biomass and presence

While microbial biomass (i.e., bacteria, archaea, and small phytoplankton and zooplankton) can potentially be detected using turbidity backscatter (see Section II.E), larger animals can be passively detected by echosounding using acoustic sensors. Animal detection is not limited to echosounding, however. Underwater mammal detection, for instance, is mostly achieved by recording audible communications using hydrophones. Moreover, where individuals of species don’t communicate audibly, they can be fitted with transmitters, and their signals detected by appropriately tuned receivers. Gliders can now be fitted with sensors employing echosounding, sound recording and telemetry to serve these needs. These sensors are briefly described below.

II.I.1. Imagenex 853 Echosounder

Imagenex, at the request of the University of East Anglia, developed a 120 kHz echosounder with a data logger, the Imagenex 853 Echosounder (*Figure 9*a), to be mounted on a Seaglider in order to detect zooplankton abundance (Imagenex 2013). The echosounder was used in early 2012 in the Weddell Sea, and its performance was tested using known targets such as krill swarms (Guihen et al. 2012). A serial interface allows transmission of the collected data during surfacing via satellite. According to Imagenex (Steve Curnew, personal communication), Teledyne Webb has also purchased and integrated this sensor on Slocum gliders. Specifications for the Echosounder are shown in Table 12.

II.I.2. VEMCO Mobile Transceiver (VMT)

During a study in late 2011, a VEMCO (2013) Mobile Transceiver (VMT) mounted on a Slocum glider (*Figure 9*) was used to detect telemetered (transmitter-fitted) Atlantic sturgeon (Oliver et al. 2013). Since 2012, a Slocum-integrated VMT has been used to detect telemetered tiger sharks (Oliver 2012). According to preliminary information provided by VEMCO (Denise King, personal communication), the Slocum-integrated instrument is based on a customized cabled receiver, the VR2C (*Figure 9*b and c), and is now listed in the Slocum G2 Glider product catalogue (Teledyne Webb Research 2013).

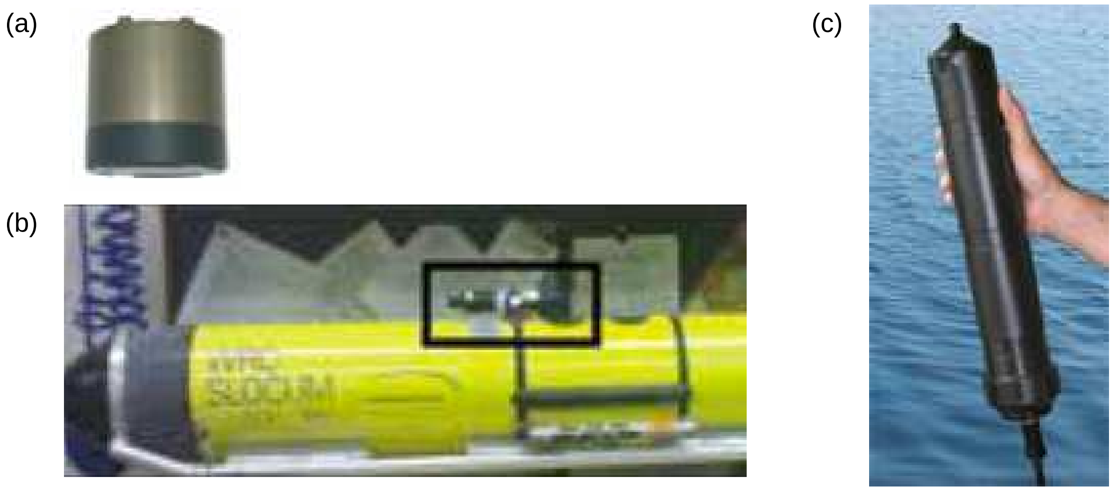

Figure 9 (a) The Imagenex 853 Echosounder (Imagenex 2013), (b) A VEMCO Mobile Transceiver (VMT) mounted on a Slocum glider (Oliver et al. 2013), (c) The VEMCO cabled receiver VR2C (Denise King, personal communication).

Table 12 Specifications for the Imagenex 853 Echosounder (Imagenex 2013).

Manufacturer and model	***Imagenex 853 Echosounder***
Glider platform	Seaglider, Slocum
Weight (kg)	Air: 1, Water: 0.55
Dimensions (cm)	8.3(∅) × 7.9
Materials	6061-T6 Aluminum, PVC
Power supply (VDC)	9-32
Wattage (W)	< 0.25
Depth rating (m)	1000
Min-max detectable range (m)	0.5-100
Frequency (kHz)	120
Beam width	10 °
Source level (nominal)	210 dB re 1 μPa at 1 m
Pulse length (μs)	100
Receive sensitivity (nominal)	-180 dB re 1 V/μPa
Receive bandwidth (kHz)	10
Reference	Imagenex (2013)

II.I.3. SonTek 760 kHz ADP

Davis et al. (2008) used the backscatter strength from a SonTek ADP on a Spray glider as an indicator of zooplankton biomass. According to the company, this product was only produced for this research group and is now discontinued (Joel Edelman, personal communication).

II.J. Marine mammal detection

II.J.1. High Tech Inc. HTI-99-HF hydrophone (PAAM system)

Klinck et al. (2012) have reported the incorporation of High Tech Inc. HTI-99-HF hydrophones on Seagliders as part of a passive autonomous acoustic monitoring (PAAM) system for the detection of marine mammals. PAAM involves the recording of signals, their compression, screening for mammal calls using a detection algorithm, and reporting of detection events when surfacing. The design and testing of PAAM research was funded by ONR and involved experimentation with multiple hydrophones at various configurations (*Figure 10*a).

II.J.2. WHOI Digital Acoustic Monitoring Device (DMON)

Another alternative is a new self-contained, low-power digital acoustic monitoring device (DMON; *Figure 10*b and c), manufactured by the Woods Hole Oceanographic Institution (WHOI) specifically for passive acoustic detection for both Slocum gliders and Seagliders (Hurst et al. 2012). DMON has the necessary broadband and low-noise signal acquisition capabilities necessary for mammal sound detection. It records sound to solid-state memory either continuously or when a detection is made, and consequently offers low power consumption (longer deployment lifetime).

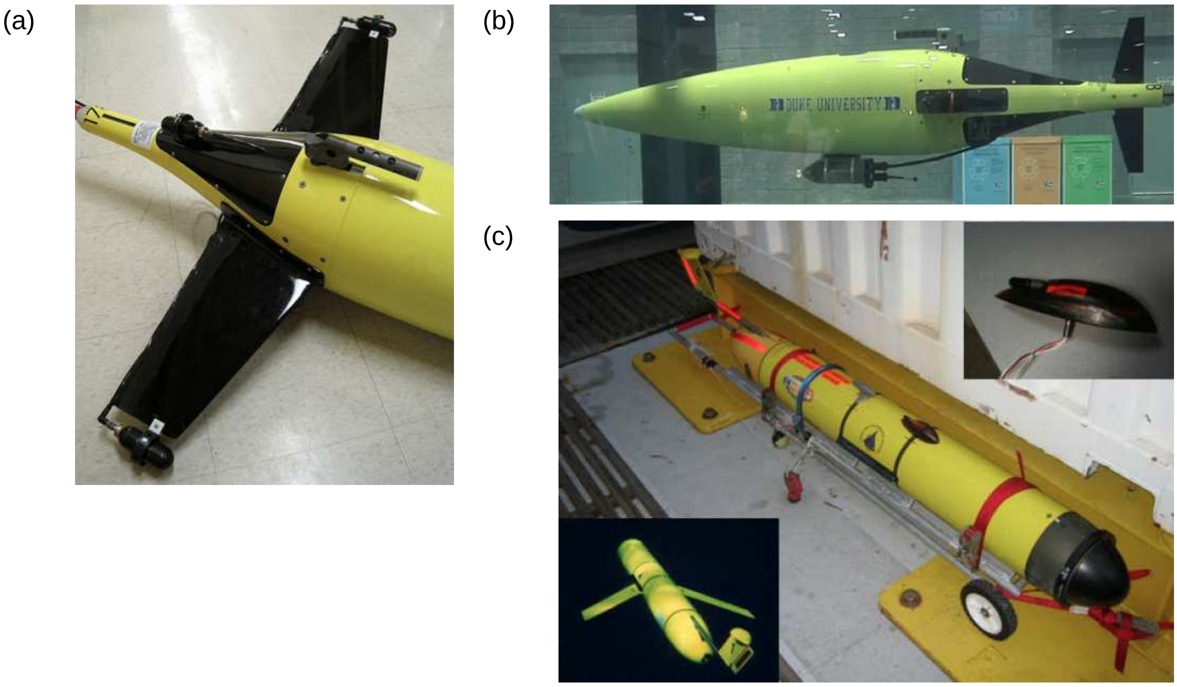

Figure 10 (a) Three High Tech Inc. HTI-99-HF hydrophones mounted on a Seaglider as part of a PAAM system (Bogue and Luby 2011); A WHOI DMON integrated with (b) a Seaglider, and (c) a Slocum glider (Hurst et al. 2012).

II.K. Turbulence

II.K.1. Rockland SI MicroRider-1000 (MR-1000-6)

Rockland Scientific Instruments produces a turbulence profiler, the MicroRider-1000 (*Figure 11*), a modular multi-instrument package carrying velocity shear probes, thermistors, a micro-conductivity probe, a high-resolution pressure sensor and acceleration sensors, and a tilt sensor (Rockland Scientific 2013a). The MicroRider is currently used on Slocum gliders operated by the GEOMAR glider fleet (Gerd Krahmann, personal communication). Furthermore UIB has interfaced one of its Slocum gliders with a MicroRider that is provided by a separate project (Ilker Fer, PI, personal commmunication). The deployments in the Faroe Bank Channel using the UIB Slocum equipped with the MicroRider suggest that a glider is a suitable platform for turbulence measurements both using shear probes (Fer et al. 2013) and fast response thermistors (Peterson and Fer 2013).Technical specifications of the MicroRider are shown in Table 13.

Figure 11 (a) The Rockland SI MicroRider-1000 (Rockland Scientific 2013a), mounted on (b) a Slocum glider (Rockland Scientific 2013a), and (c) a Spray glider (Rockland Scientific 2013b).

II.K.2. Nortek Aquadopp HR ADCP

The Nortek Aquadopp that appears in section II.G.2 above can be configured in “HR” mode (Nortek 2013); “HR” stands for “High Resolution” which is synonymous for pulse-coherent processing. In HR mode (different firmware, same transducers/electronic boards as a 3000 m Aquadopp in the case of a glider application), the sensor can measure very near-field velocities using the measurement of phase shifts rather than frequency shifts. For the 1 MHz (2 MHz) model, bin size is as low as 2.0 cm (0.7 cm). Maximum range is 6 m (3 m). This has been shown sufficient for measuring turbulence from a profiling body as well as mean horizontal currents (Rusello et al. 2011).

Table 13 Technical specifications of the MicroRider turbulence profiler (Rockland Scientific 2013a).

Manufacturer and model	***Rockland SI MicroRider-1000***
Glider platform	Slocum, Spray
Weight (kg)	Air: 5.5, Water: 0
Dimensions (cm)	10 (∅) × 1.02
Materials	6061-T6 Aluminum, PVC
Power supply (VDC)	9-18
Wattage (W)	1
Depth rating (m)	1000
Velocity shear range, accuracy, resolution	$3 \times 10^{-10} – 10^{-4}$ W kg^{-1}, 5 %, 2.5×10^{-3} s^{-1}
Water temperature range, accuracy, resolution	-5 – 35 ^{o}C, 1×10^{-3} ^{o}C, 1×10^{-4} ^{o}C
Microtemperature range, resolution	-5 – 35 ^{o}C, 1×10^{-5} ^{o}C
Conductivity range, accuracy, resolution	0 – 7 S m^{-1}, 0.0003 S m^{-1}, 0.00004 S m^{-1}
Microconductivity range	0 – 7 S m^{-1}
Pressure range, accuracy, resolution	0 – 1000 dbar, 0.1 %, 0.0005 dbar
Accelerometer range, accuracy, resolution	±2 g, 0.5 %, 3×10^{-5} g
Tilt sensor range, accuracy, resolution	Dual axis ± 90^{o}, 0.1^{o}, 0.025^{o}
Reference	Rockland Scientific (2013a)

II.L. Wind

II.L.1. Greeneridge Sciences Inc. Acousonde

Acousonde (*Figure 12*) is a miniature, self-contained, autonomous acoustic/ultrasonic recorder designed for underwater applications, produced by Greeneridge Sciences Inc., and distributed by Cetacean Research Technologies (Greeneridge Sciences Inc. 2012). Cauchy et al. (2013) have used it as an external autonomous device on Slocum and Seaglider gliders to record underwater sounds (from 2kHz to 40kHz). An external battery housing for lithium batteries was especially developed to increase the device's autonomy (Burgess 2012). By post processing the data using the methods described in Ma et al. (2005), Cauchy et al. (2013) have been able to successfully estimate wind speeds at sea surface. Rainfall rate estimation is still pending (Pierre Cauchy, personal communication). It is noteable that wind direction, which cannot be obtained from the acoustic device, can be determined when using a Slocum glider by taking advantage of the fact that it heads towards the wind when at the surface. The specifications for the Acousonde are listed in Table 14.

Figure 12 An Acousonde recorded mounted externally on a Slocum glider (courtesy Pierre Cauchy).

Table 14 Technical specifications of the Acousonde recorder (Greeneridge Sciences Inc. 2012).

Manufacturer and model	***Acousonde***	
Weight in water (kg)	0.086	
Dimensions (cm)	3.2 (∅) × 22.1	
Power supply (VDC)	4.5	
Depth	500/1000/2000/3000 m	
Lifetime	6-14 days (maximum if sampling < 26kH)*	
Max sampling rate	232 kHz	
Acoustic sampling resolution	16 bits	
	low-power channel	**high-frequency channel**
***Unamplified sensitivity, re 1 V/µPa* (db)**	-201	-204
***Saturation at 0-db gain, re 1 µPa* zero peak (db)**	187	172
Anti-alias filter	8-pole elliptic, adjustable to 9.2 kHz	6-pole linear phase, fixed
3-db anti-alias cutoff (kHz)	9.2	42
22-db anti-alias cutoff (kHz)	11.1	100
3-db high-pass cutoff (kHz)	22	10
Reference	Greeneridge Sciences Inc. (2012)	

* 2 months if recording for 1 min every 10 min (Pierre Cauchy, personal communication).

II.M. Nitrate (NO_3^-)

II.M.1. Satlantic SUNA v2

Johnson and Coletti (2002) developed an optical sensor for the detection of nitrate (NO_3^-), which exhibits a distinct absorbance peak at 216-220 nm, i.e., in the ultra-violet (UV). The sensor, then dubbed ISUS (In Situ Ultraviolet Spectrophotometer), was able to measure spectra in the UV (< 280 nm) with high resolution, approx. 1 nm, and using a least-squares-fitting algorithm, allowed the deconvolution of the effects of other interfering chemical species, primarily bromide, bisulfide and CDOM. The ISUS is now marketed for glider (and other) uses as SUNA v2 by Satlantic (2013b). Technical specifications are listed in Table 15. The SUNA v2 is composed of a straight-through quartz sample chamber of a path length of 1 cm (*Figure 13*a) and a microcontroller used for data processing. The optical sensing system is designed to measure absorption spectra at 1 nm resolution. The resulting spectra are de-convoluted into contributing species concentrations, so that NO_3^- concentrations can be reported at a rate of 1 Hz.

Satlantic already provides a Slocum glider mounting package (*Figure 13*b) for the deep version of SUNA v2 that consists of a plastic nose cone and connector end-cap attachments that have 1/4”- 20 threaded mounting points (Satlantic 2013b). The mounting package is designed in such a way so that the sensor is mounted on the top side of the glider and oriented in such a manner as to prevent air bubbles and sediment from becoming trapped in the sample chamber. Jones et al. (2011) report the deployment of the SUNA sensor on a Slocum glider. However, there appear to be unresolved issues with its operation, e.g., pre-mission calibration, on-board concentration computations, etc., necessitating further work on this sensor before it is declared mission-proved.

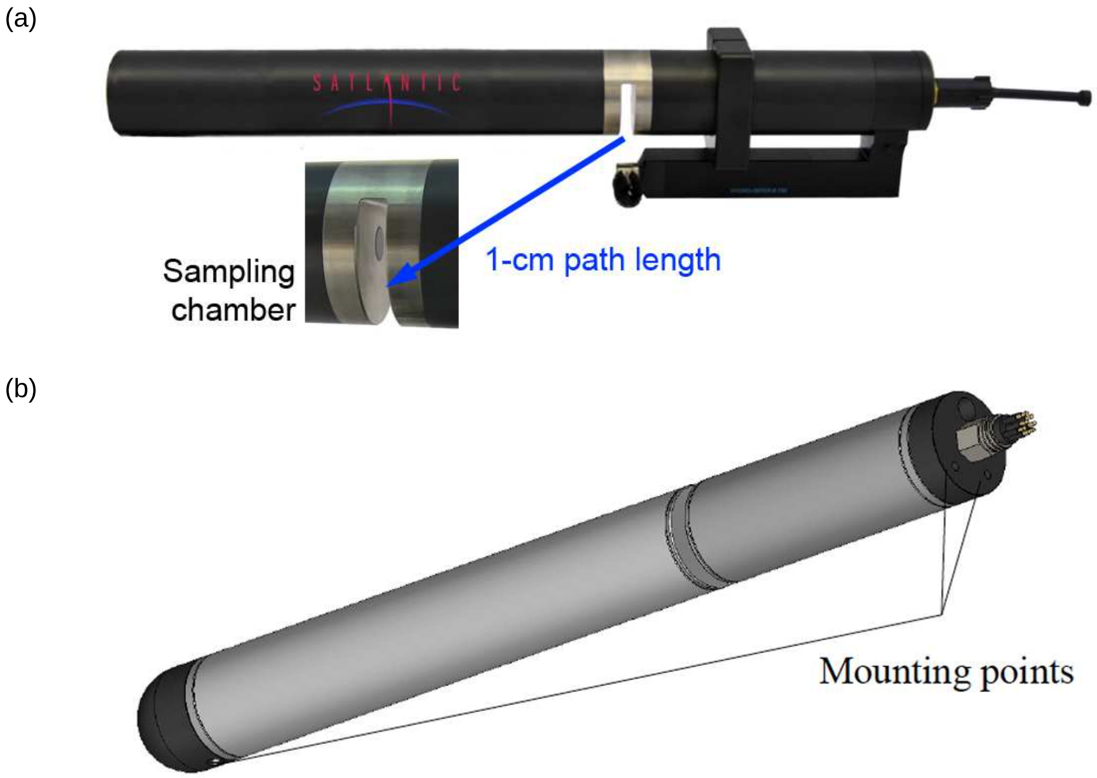

Figure 13 The Satlantic SUNA v2: (a) the sensor with close-up of the sampling chamber and circular quartz window (Satlantic 2013c), (b) Mounting package for deployment on a Slocum glider (Satlantic 2013b).

Table 15 Technical specifications of the Satlantic SUNA v2 sensor, deep version for mounting onto Slocum gliders (Satlantic 2013b).

Manufacturer and model	***Satlantic SUNA v2***
Weight (kg)	1.8
Dimensions (cm)	5.7 (∅) × 55.5
Power supply (VDC)	5-18
Wattage (W)	7.5
Current (mA)	625 mA at 12 V (nominal), 20 mA at 12 V (standby)
Depth	2000 m
Material	Anodized aluminum
Lifetime	900 h (2-4 weeks)
Spectral range (nm)	190-370
Concentration range (μM)	0 to 1000, 2000, 3000, and 4000
Accuracy	± 2 μmol L^{-1} or ± 10% of reading, whichever is greater
Precision	± 2.4 μmol L^{-1} (in seawater, 0-40 psu)
Limit of detection	2.4 μmol L^{-1} (in seawater, 0-40 psu)
Internal Memory	2 GB
Telemetry	Real time
Reference	Satlantic (2013b)

III. PROTOTYPES AND SENSORS IN DEVELOPMENT FOR GLIDERS

In this section, we catalogue sensors that are or were explicitly being developed for or have been tested already on gliders. Brief statements in the published literature or in the public domain have been supplemented with information from companies and individuals to obtain a general sense of the stage of development and/or testing a sensor is in and to, consequently, determine its readiness level as well as its availability to others than the original users.

III.A. Radioactivity

III.A.1. Amptek Gamma-Rad NaI Scintillation Probe

Jones et al. (2011) first reported the integration of an Amptek Gamma-Rad NaI Scintillation Probe into a dual science payload bay of a Slocum glider. Two probes have been flight-tested since, but not routinely operated for longer time periods (Clayton Jones, personal communication). At this point, no more information is available on the success of the deployment and the data obtained.

III.B. Video imagery

III.B.1. Mounted digital video cameras

Glenn and Schofield (2009) reported that video imagery instruments were carried by Slocum gliders. To this effect, a video camera science bay was built to carry an internally mounted digital camera looking out a window (Oscar Schofield, personal communication). Images were successfully obtained throughout the deployment, but this was a one-time test, and no further deployments or use have taken place.

III.C. Multiple optical properties

III.C.1. Turner Designs Cyclops sensors

Jones et al. (2011) reported the integration of a Turner Cyclops sensor onto a Slocum glider. Tests with the Turner Cyclops are still underway and undergoing a comparison study (Clayton Jones, personal communication), after which it will be available soon as a full product line. According to Turner Designs (2013), the Cyclops is available for numerous parameters, including chlorophyll, turbidity, CDOM/FDOM, phycocyanin, phycoerythrin, and oil.

IV. READILY ADAPTABLE SENSORS FOR GLIDER USE

IV.A. Overview

Glider sensors share a set of attributes that, when combined, create unique design restrictions:

- Compact size and light weight (payload limited to 2-5 kg), and consequent miniaturization of components, and modification to limit interference with navigation,
- Low energy consumption to extend glider endurance,
- On-board data-processing capacity, and
- Real-time or near-real-time data transmission requirements.

It is evident how these attributes, in isolation or in combination with one another, may also apply in the case of other platforms, most notably autonomous underwater vehicles (AUVs) as well as Argo floats. It is, therefore, natural that sensors already employed in the cases of AUVs and floats are much more readily adaptable for use on gliders than tethered or moored instruments.

Consequently, the section that follows draws heavily from advances in sensor technologies already used on small mobile platforms. It should be noted that most industry partners are ready and willing to work on integrating such sensors onto gliders, but usually the cost for developing an integrated prototype is a burden that the routine expenses of a glider facility cannot overcome.

Please note that prospective biogeochemical parameters and sensors are addressed in GROOM deliverable D3.5. Please consult that deliverable for more information and details.

IV.B. Nutrients

SubChem Systems Inc. (2013) produces three “wet-chemistry” sensors that, with the use of microfluidics, allow the colorimetric (spectrophotometric and fluorometric) analysis of small-volume seawater samples for any compound for which colorimetric methods exist. These three sensors, the APNA, ChemFIN, and MARCHEM, have been especially designed for low-power, minimal payload platforms, and have all been used on AUVs for a variety of applications, but most notably for nutrient (NO_3^-, NO_2^-, PO_4^{3-}, $Si(OH)_4$, NH_4^+) analysis, as well as unexploded ordinance (see Section IV.C) and toxins released during harmful algal blooms (see Section IV.D).

IV.B.1. SubChem APNA

The Autonomous Profiling Nutrient Analyzer (APNA, *Figure 14*a) is an autonomous, multi-channel submersible chemical analyzer utilizing spectrophotometric and fluorometric analytical methods for continuous or intermittent in situ measurements of nutrients, trace metals and other chemicals. Its minimal payload features allow deployments on shipboard profiling systems and also on autonomous platforms (Hanson et al. 2006). APNA can be configured for 3, 4 or 5 channels for either continuous operation (i.e., 1 Hz when profiling) or intermittent measurements (10-15 minutes per measurement cycle). A Sensor Integration Module (SSIM) allows real-time data acquisition/transmission. APNA’s main specifications are listed in Table 17.

IV.B.2. SubChem ChemFIN

ChemFIN is a 1-2 channel analyzer configured for the detection of nutrients in seawater (SubChem Systems Inc. 2011b). It is a small independent sensor payload, which has successfully been mounted onto AUVs (*Figure 14*b). A ChemFIN design review meeting (San Diego, January 2007) led to an improved specification for the best means of integrating the ChemFIN single channel analyzer on to gliders. It was determined the best interface to a glider would be the wing interface to the hull (Alberto Alvarez, personal communication). A new wing interface was also designed to allow the ChemFIN housing to be clamped to the port or starboard side along the centerline of the glider. SubChem Systems Inc.’s partners also determined the best electronic interface to the glider would be a new multi-cable termination at the aft end of the vehicle that would have another cable running forward to the ChemFINTM housing end cap. Table 16 summarizes ChemFIN’s main specifications.

IV.B.3. SubChem MarChem

A third SubChem Systems Inc. compact, low power submersible chemical analyzer payload for deployment on AUVs (originally for the Konesburg/Hydroid REMUS 100 AUV) is the Micro AUV Ready Chemical Analyzer (MarChem). The MarChem (SubChem Systems Inc. 2009) is a two-channel sensor capable of performing real-time, rapid response measurements of nutrients in trace concentrations in marine waters while mounted on AUVs (*Figure 14*c). The technical specifications for the MarChem are identical to the ChemFIN Analyzer (Table 16), except that the MarChem is mechanically configured (housing shape and size) to adapt it to the Autonomous Under Water Vehicle (AUV) or glider hull section of choice (Alfred K. Hanson, personal communication).

IV.B.4. SUV-6 nitrate sensor

The National Oceanography Centre (UK), in collaboration with Valeport Ltd., developed an ultraviolet nitrate (NO_3^-) sensor, the SUV-6, with an improved accuracy, twice that of other similar sensors, which improves the utility of UV NO_3^- detection in open-ocean, nutrient-poor settings (Pidcock et al. 2010). The basic principles of this detection method have already been described in this deliverable (see section II.M.1). The SUV-6 measures absorption at 205, 220, 235, 250, 265, and 280 nm, and corrections based in the readings at these wavelengths may be applied to normalize absorption at 220 nm, which correlates with NO_3^- concentration. Technical specifications for this sensor are listed in Table 16.

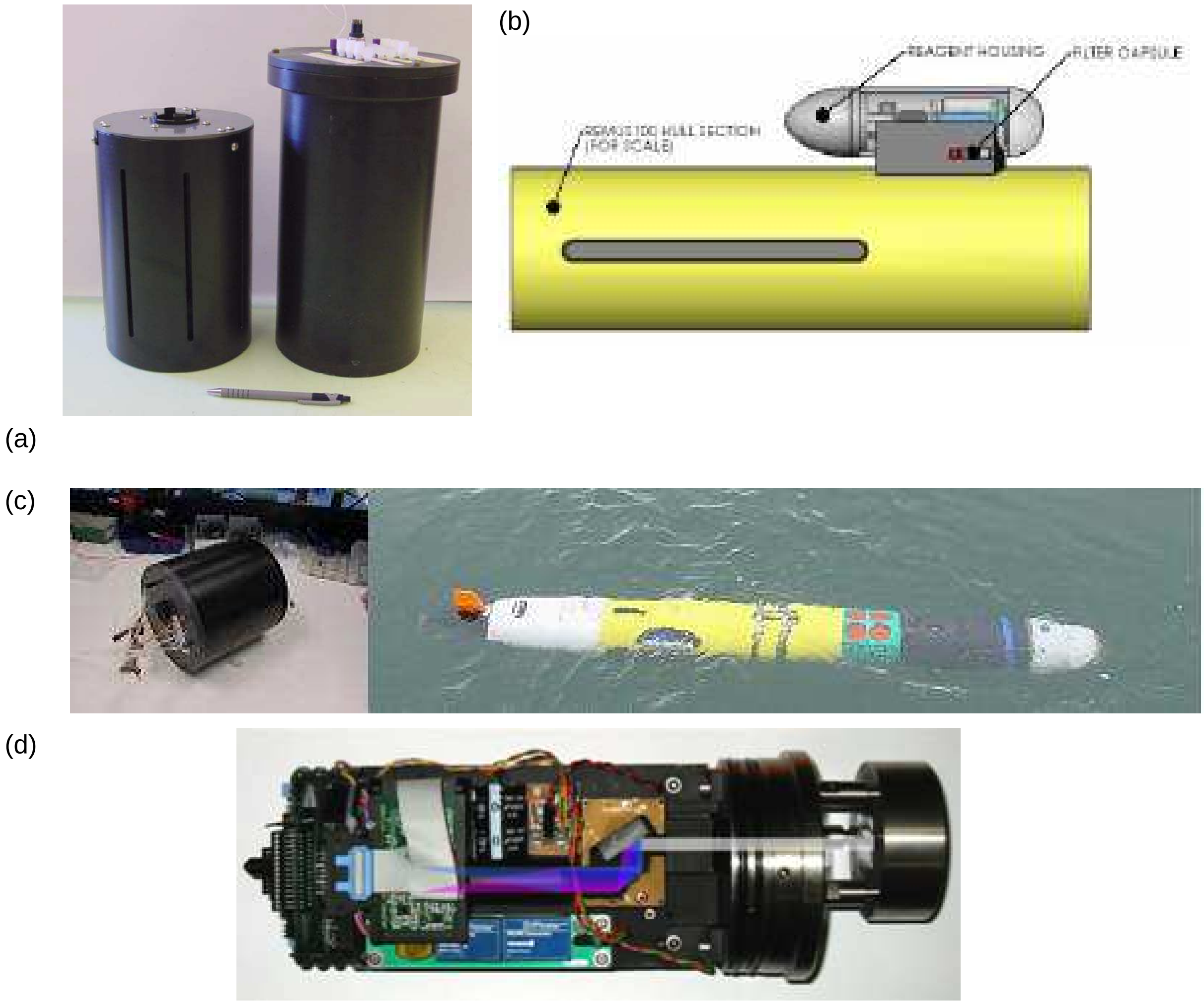

Figure 14 “Wet-chemistry” analyzers for autonomous platforms manufactured by SubChem Systems Inc: (a) APNA reagent reservoir (left) and the analyzer (right) (SubChem Systems Inc. 2011a), (b) The ChemFIN sensor externally mounted onto a Remus AUV (Hanson and Kusterbeck 2009), (c) Integration of MarChem analyzer (left) into a Remus 100 AUV(SubChem Systems Inc. 2013), (d) The SUV-6 nitrate sensor developed by the National Oceanography Centre (UK) and Valeport Ltd. (NOC 2013).

Table 16 Technical characteristics of two multi-nutrient (NO_3^-, NO_2^-, PO_4^{3-}, $Si(OH)_4$, NH_4^+) sensors developed by SubChem for use with AUVs, and a UV NO_3^- sensor, SUV-6, deployed on a SeaSoar towed vehicle.

Manufacturer and model	***SubChem APNA***	***SubChem ChemFIN***	***SUV-6***
Weight (kg)	Air: 8.8, Water: 1.4	Water: 2.9	
Dimensions (cm)	16.8 (∅) × 32.6	10 (∅) × 33	11.3 (∅) × 40
Displacement (cm^3)		2700	
Materials	Peek, PVC, Nylon, Aluminum, Delrin, AcetalGP	Non metallic, Acetal	Aluminium alloy
Input Voltage (VDC)	12	12-15	
Wattage (W)	28 (Analysis)	3 (Analysis)	1 (at 8 Hz)
Depth rating (m)	200	600	5000
Lamp Lifetime	7 d (continuous) 2-3 mo (intermittent, ~2000 measurements)	500 h	2500 h
Wavelength Range (nm)	370 – 820	370 – 820	205-280
Detection Range (µmol L^{-1})	0.02 – 170		0-100
Accuracy	± 1 – 3 %	± 2 %	± 0.2 µmol L$^-$
Internal Memory (GB)	1-8	8	
Telemetry	Real time	Real time (Acoustic, RF, cellular, Wi-Fi, Iridium, LAN)	
Reference	SubChem (2011a)	SubChem (2011b)	Finch et al. (1998), Pidcock et al. (2010)

IV.C. Unexploded ordinance

IV.C.1. NRL/SubChem Systems ordinance immunosensor

The U.S. Naval Research Laboratory (NRL), in collaboration with SubChem Systems Inc., have developed an in-situ seawater chemical analyzer (Adams et al. 2011, Charles et al. 2011) for the detection of small nitroaromatic molecules, such as 2,4,6-Trinitrotoluene (TNT). The sensor employs monoclonal antibodies specific for TNT, which are immobilized on the microchannel walls of the microfluidic device, and whose binding regions are occupied by a fluorescent analog of TNT (*Figure 15*a). When actual TNT is present in the sample, it displaces the fluorescent analogue, which then enters the detection stream thus increasing the fluorescent signal detected by the sensor.

The sensor has been successfully deployed and operated on a Hydroid REMUS 100 AUV (Adams et al. 2013). The nosecone of the AUV housed the sample intake, which extended beyond the nose of the AUV within the free flow boundary layer (*Figure 15*b), while the microfluidic system was placed on the forward bulkhead of the immunosensor, referred to as the coupon interface (*Figure 15*c), thus rendering it easily replaceable when spent. Moreover, this coupon can be customized for the detection of other compounds depending on the antibodies used. While sampling, the power draw is on the order of less than 3 W, while on standby mode it is <120 μW. The sensor is designed to be a 12 VDC nominal device. *Figure 16* shows a prototype sensor deployed on a REMUS 100 AUV.

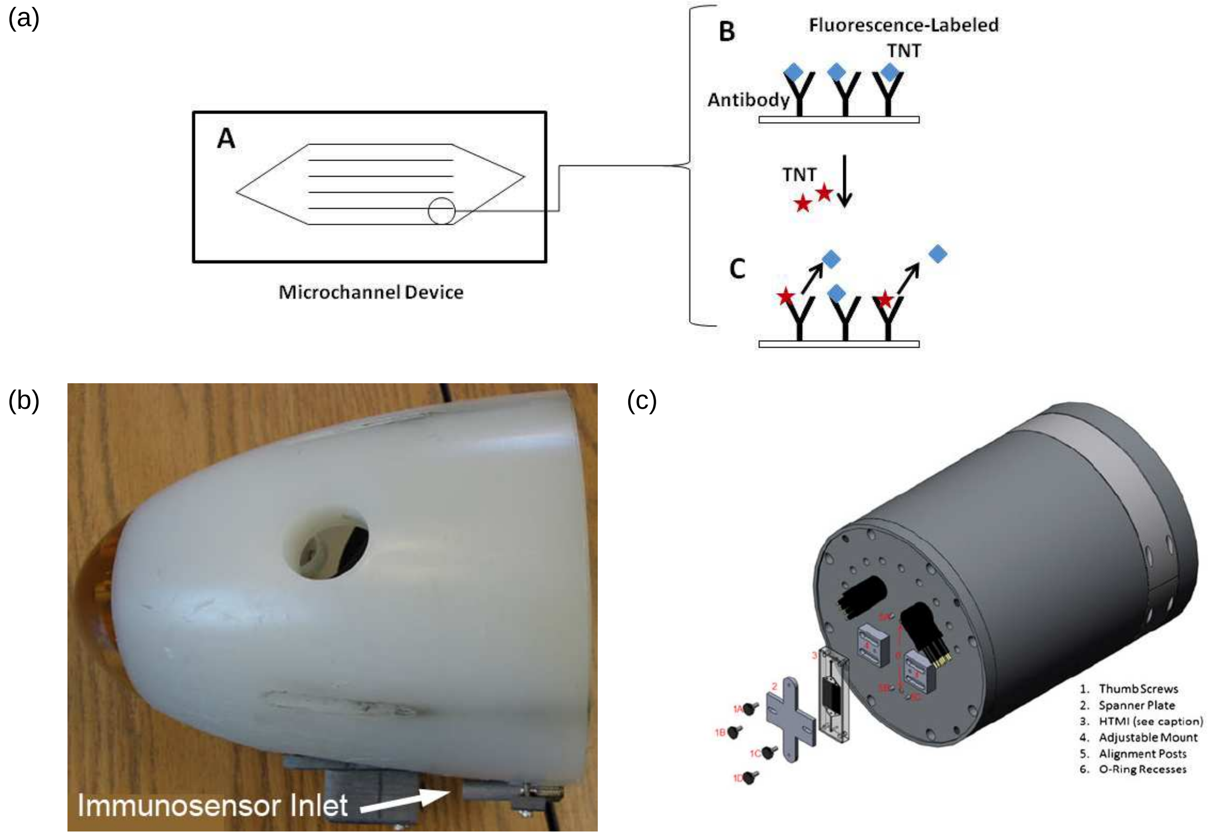

Figure 15 (a) Schematic illustrating the process employed by the immunosensor for TNT detection: TNT in the sample displaces the fluorescent TNT analogue immobilized on TNT-specific monoclonal antibodies; as the fluorescent analogue enters the stream, it increases the fluorescent signal detected by the sensor (Charles et al. 2011), (b) Location of the immunosensor inlet on the nosecone of the REMUS 100 AUV (modified from Adams et al. 2013), (c) The microfluidic device is mounted on the forward bulkhead, also known as the coupon, of the immunosensor (modified from Adams et al. 2013).

IV.D. Harmful algal bloom (HAB) toxins

IV.D.1. SubChem MarChem

The Naval Research Laboratory (NRL, USA), in collaboration with SubChem, has demonstrated that MarChem can be used to detect saxitoxin and domoic acid (Hanson and Kusterbeck 2010, 2011), two toxins released by marine algae, which occasionally accumulate to abundances high enough to create harmful algal blooms (HABs).

As described previously in this report (see section IV.C.1), the SubChem sensors allow the easy configuration of the microfluidic system, also called the coupon, according to the desired analysis. In 2010, the principles of testing for a toxin, in this case domoic acid, were tested using the MarChem sensor (Hanson and Kusterbeck 2010), followed by a successful deployment of the sensor on a REMUS 100 AUV in parallel with ongoing work on an immunosensor (*Figure 16*).

In 2011, a coupon for saxitoxin was prepared using mouse monoclonal antibodies and fluorescently labeled saxitoxin (Hanson and Kusterbeck 2011). Samples were excited at 632 nm and the emission at 665 nm was monitored, yielding a linear relationship between saxitoxin concentration and sensor response, thus demonstrating the potential utility of such a sensor on an AUV.

Figure 16 A prototype MarChem sensor (configured for use as an NRL/SubChem Systems ordinance immunosensor) deployed on a REMUS 100 AUV (Hanson and Kusterbeck 2010).

IV.E. Carbon dioxide (pCO_2)

IV.E.1. *Contros HydroC™ CO_2*

The Contros HydroC^{TM} CO_2 sensor is an underwater CO_2 sensor that employs non-dispersive infrared spectrometry (NDIR), by allowing the seawater sample to equilibrate with the gas in an internal gas circuit where NDIR takes place (CONTROS 2011b). Its effectiveness and promise as a sensor on an autonomous platform has been demonstrated by Fiedler et al. (2013), who successfully deployed it on Argo floats during four missions lasting 14-56 days each in 2010-2011. Its small size and weight (*Figure 17*a) recommend it for integration into gliders (technical specifications are listed in Table 17).

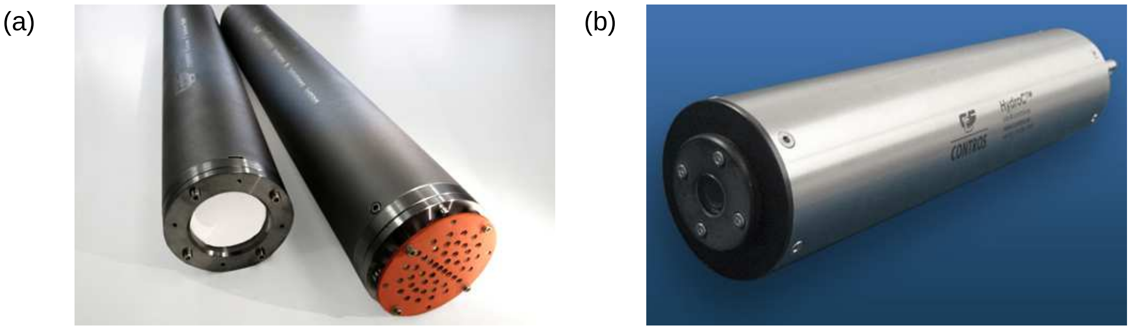

Figure 17 (a) CONTROS titanium housings for the HydroC^{TM} CO_2 and CH_4 sensors; the housing on the right carries the optional copper biofouling protector, (b) CONTROS HydroC^{TM} PAH sensor in a titanium housing (both images from CONTROS 2013).

IV.F. Methane (CH_4)

IV.F.1. *CONTROS HydroC™ CH_4*

CONTROS also manufactures an underwater CH_4 sensor, the HydroC™ CH_4 (*Figure 17*a). The dissolved CH_4 is measured using the same principle and procedures as CO_2, using NDIR (CONTROS 2011a). The specifications for the sensor are shown in Table 17.

IV.G. Hydrocarbons

IV.G.1. *CONTROS HydroC™ PAH*

The CONTROS HydroC™ PAH fluorometer (*Figure 17*b) detects hydrocarbons by illuminating the sample at 254 nm and detects emitted radiation at 360 nm (CONTROS 2011c). The housing design is representative of the HydroC™ sensors, and therefore is eminently suited for integration into minimal payload platforms such as gliders. The specifications of the sensor can be seen in Table 17.

IV.G.2. *WETLabs Eco Puck (models including FL designation)*

WETLabs has explored the potential of their CDOM fluorometers (see Section II.C.1) as detectors of oil in seawater during the Deep Water Horizon oil spill, and has assembled the relevant documentation on its web-site (WETLabs 2013). While initial indications from this application are promising (Joint Analysis Group for the Deepwater Horizon Oil Spill 2011), more work must be done to render the optical specifications of the sensor more definitive to the presence of oil.

Table 17 Technical characteristics of HydroC^{TM} sensors for CO_2, CH_4 and PAH.

Model	***HydroC™ CH_4***	***HydroC™ CO_2***	***HydroC™ PAH***
Chemical parameters	CH_4	CO_2	PAH, Diesel, Crude Oil, Marine Diesel (MDO), Marine Gas Oil (MGO), Fuel Oil
Weight (kg)	Air: 4.7, Water: 2.2		Air: 4.4, Water: 2.7
Dimensions (cm)	9 (∅) × 37.6		7.5 (∅) × 32
Depth rating (m)	2000/4000/6000		6000
Materials	Titanium		
Current (mA)	300		
Wattage (W)	7.5		3 (max)
Range	100 nmol L^{-1} – 50 µmol L^{-1}	200 – 1000 ppm	0 – 500 µg L^{-1}
Resolution	10 nmol L^{-1}	< 1 [ppm]	0.1 ppb
Accuracy	± 3 %	± 1 %	
Software	Software DETECT™ included (real time data visualization, setting of sensor parameters, download data from internal data logger)		
Internal memory			Option internal SmartDI datalogger with 2 GB CompactFlash Memory
Reference	CONTROS (2011a)	CONTROS (2011b)	CONTROS (2011c)

IV.G.3. TriOS Optical Sensors EnviroFlu-HC

The EnviroFlu-HC fluorometer (*Figure 18*) is designed to measure PAH fluorescence at excitation and emission wavelengths of 254 nm and 360 nm, respectively (TriOS Optical Sensors 2013). The relevant specifications are shown in Table 18.

Figure 18 The TriOS EnviroFlu-HC fluorometer (TriOS Optical Sensors 2013).

Table 18 Specifications of the TriOS Optical Sensors EnviroFlu-HC sensor used for PAH fluorescence measurements.

Manufacturer and model	***TriOS Optical Sensors EnviroFlu-HC***
Glider platform	-
Weight (kg)	In air: 1.85 (titanium), 2.7 (stainless steel)
Dimensions (cm)	6.8 (∅) × 31.1
Materials	Titanium or stainless steel
Depth rating (m)	300 or 6000
Power requirements (VDC)	0-5
Current (mA)	4-20
Excitation/Emission λ (nm)	254/360
Range	0-50, 0-500 or 0-5000 ppb phenanthrene
Sensitivity	0.1 ppb phenanthrene
Sensing distance (cm)	0.5
Reference	Tedetti et al. (2010), TriOS Optical Sensors (2013)

IV.G.4. CNRS/MIO MiniFluo-UV fluorometer

Recently, the Mediterranean Institute of Oceanography (MIO, Marseille) has developed an original submersible fluorometer in Puck^{TM} format (*Figure 19*) to simultaneously measure phenanthrene and tryptophan compounds in the marine environment (Tedetti and Goutx 2012, Tedetti et al. 2013). Phenanthrene fluorescence is measured at excitation and emission wavelengths of 255 nm and 360 nm, respectively, while tryptophan fluorescence is measured at excitation and emission wavelengths of 280 nm and 340 nm, respectively. The MiniFluo-UV, which has been deployed at sea on CTD profilers, is currently being mounted on the SeaExplorer glider. Its specifications are listed in Table 19.

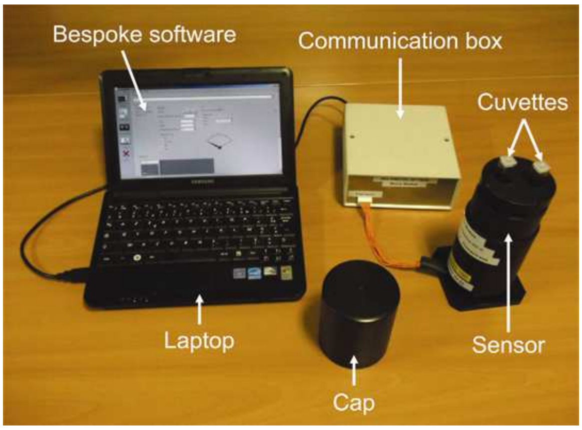

Figure 19 The Puck-format CNRS/MIO MiniFluo-UV fluorometer, labeled “sensor” on the right of the photograph (Tedetti et al. 2013).

Table 19 Specifications of the CNRS / MIO MiniFluo-UV sensor used for PAH and tryptophan fluorescence measurements.

Manufacturer and model	***CNRS / MIO MiniFluo-UV***
Glider platform	SeaExplorer, Slocum
Weight (kg)	0.5 (in air)
Dimensions (cm)	6.5 (∅) × 6 + cap
Materials	Aluminum, quartz
Depth rating (m)	500 (validation at 1000 m in progress)
Power requirements (VDC)	12
Current (mA)	50
Excitation/Emission λ (nm)	255/360 and 280/340
Range	0-100 ppb phenanthrene, 0-100 ppb tryptophan
Sensitivity	0.1 ppb phenanthrene, 0.4 ppb tryptophan
Sensing distance (cm)	0.5
Reference	Tedetti and Goutx (2012), Tedetti et al. (2013)

IV.H. Bioluminescence

IV.H.1. Underwater Bioluminescence Assessment Tool (UBAT)

The Underwater Bioluminescence Assessment Tool (UBAT) was designed by WETLabs to be deployed on a variety of platforms in order to provide measurements of mechanically stimulated bioluminescence (BL) potential. The UBAT is based on the Multipurpose Bioluminescence Bathyphotometer (MBBP), a compact, self-contained bathyphotometer (Herren et al. 2005). The MBBP demonstrated that turbulence generated by pumping in a sample chamber of approximate volume of 0.5 L generated ample shear force resulting in the generation of bioluminescence by bioluminescent organisms in the sample.

The UBAT (WETLabs 2010) is designed to optimize the mechanical stimulation that is needed to obtain the maximum bioluminescent potential from bioluminescent organisms in the sample, while preventing pre-stimulation. Pre-stimulation is prevented by entraining the sample into an S-shaped intake. A regulated pump impeller provides the mechanical stimulation needed for bioluminescence immediately before the sample enters the 0.440 L detection chamber, where the generated turbulent flow results in multiple stimulation events. The main specifications of the UBAT are listed in Table 20.

UBAT (external view):
1. Front—intake section with internal S-shaped light baffle
2. Midsection—mounting platform
3. Back—6-pin and 3-socket MCBH connectors
4. Back—exhaust

UBAT (internal view):
5. calibration/validation port
6. detection chamber interior
7. guide pins
8. jack screw
9. flow impeller (pump impeller not shown)
10. exhaust, showing the front of the 3-turn helical light baffle
11. 6-pin MCBH connector
12. clear PMT faceplate, with arrow to the PMT baffle
13. electronics housing

Figure 20 The UBAT components (WETLabs 2010).

Table 20 Technical characteristics of the UBAT sensor.

Manufacturer and model	***WETLabs UBAT***
Weight (kg)	Air: 5.10, Water: 1.64
Dimensions (cm)	34.93 × 10.80 × 16.83
Power supply (VDC)	9-18
Current (mA)	600
Depth rating (m)	600
Materials	Acetyl copolymer plastic (chamber: Titanium dioxide and polyurethane)
Spectral Range (nm)	430-700
Detection Range	1.50×10^{7} – 6.7×10^{13} photons s^{-1}
Accuracy/Sample rate	60 Hz with 1 Hz data output rate
Internal Memory	None
Telemetry	Real time
Reference	WETLabs (2010)

IV.I. Marine mammal detection

IV.I.1. SIO High-frequency Acoustic Recording Package (HARP)

In addition to the acoustic systems described previously (see section II.J), several autonomous packages for mammal detection have the potential of being miniaturized for possible mounting on gliders. One of the most capable autonomous systems currently available for glider is a miniaturization of the High-frequency Acoustic Recording Package (HARP, *Figure 21*) from Scripps Institute of Oceanography (SIO), an autonomous data logging system optimized for long-term, broad-band marine mammal monitoring. The HARP system includes low-power electronics, high-speed data sampling, large capacity data storage, and batteries for self-contained power (Wiggins and Hildebrand 2007).

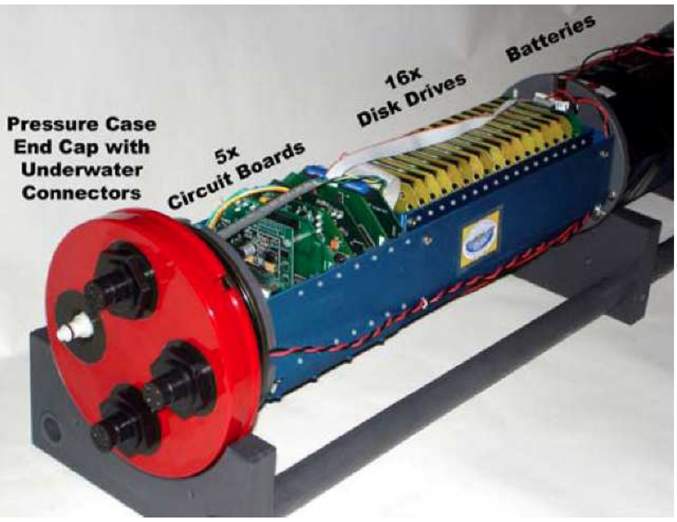

Figure 21 An open HARP logger for deployment as part of a seafloor package (Wiggins and Hildebrand 2007). The end-cap measures 7 in (almost 18 cm) in diameter.

V. DESIRED SENSORS

In this section, we elaborate on sensors that the GROOM consortium desires to be developed and which have not been covered in previous sections. There are two main drivers that can instigate the development and operation of new sensors: research needs and public policy needs. Recent EU legislation, such as the Water Framework-Directive (2000/60/EC, EC 2000) and the Marine Strategy Framework-Directive (2008/56/EC, EC 2008), and research policies are increasingly harmonizing policy goals and needs with research objectives, thus bringing the two drivers closer. This is by no means a definitive or exhaustive list, but it constitutes a consensus view at the time of the release of this deliverable.

V.A. Metals

Metals are of interest as environmental contaminants, due to their adverse impacts on several biochemical processes when in high concentrations, as well as nutrients when in trace amounts, and are therefore of interest in both coastal and offshore settings. Major metal contaminants, e.g., Cd, Pb, Ni, etc., can be detected with spectrophotometric methods, therefore the aforementioned multi-channel chemical analyzers made by SubChem (see section IV.B) or any other microfluidic analyzers can be adapted to test for such metals colorimetrically. Voltammetric electrodes constitute another option for metal detection that may be ultimately applicable on autonomous platforms.

V.B. Organic pollutants

Another major group of pollutants of interest are organic compounds such as polyaromatic hydrocarbons (PAHs), polybrominated biphenyls (PBBs), pesticides etc. Many of these organic compounds impart optical properties and, therefore, are candidates for detection by optical sensors. The example of petroleum detection after an oil spill using the WETLabs ECO Puck and the concomitant difficulties of connecting signal and compound have already been discussed (see section IV.G.2).

V.C. Particle and plankton size distributions

A comprehensive understanding of the distribution, abundance, and dynamics of particulate matter and organisms in pelagic environments is crucial to predicting the export and sequestration of biogenic carbon (Stemmann and Boss 2012). Several imaging systems of varying processing capacities have already been developed and successfully deployed from vessels (Benfield et al. 2007), along with suitable quality control procedures (e.g., Picheral et al. 2010). These systems have yet to be miniaturized enough to be mounted on or integrated with gliders. A description of what such an incorporation entails, as well as a short review of the topic are included in GROOM deliverable D3.5.

V.D. Underwater noise

Noise pollution, especially from shipping or underwater mining activities, is now recognized as an important factor that should be monitored, and is mentioned in the Marine Strategy Framework-Directive as one of the two major energy pollution types (the other being heat). Hydrophones have already been successfully used for the recording of marine mammal songs (see section II.J). Applications for these or other hydrophones to detect both continuous low-frequency noise (63-125 Hz) as well as low-frequency and middle-frequency (10 Hz to 10 kHz) impulsive sounds (EC 2010) would fill a major knowledge gap in the European seas.

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