TD 218 Operating Manual
Oxygen Optode 3830

AANDERAA

State-of-the-Art Scientific Products

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3rd Edition	09	July	2002	*Sensor diameter corrected, was Ø31mm now Ø36mm*
4th Edition	08	September	2002	*Specifications revised*
5th Edition	09	September	2002	*CHAPTER 5 Software - After approximately 20seconds …*

CONTENTS

INTRODUCTION

Purpose and scope

This document is intended to give the reader knowledge of how to operate, calibrate and maintain the Aanderaa Oxygen Optode 3830. It also aims to give insight in how the sensor works.

Since oxygen is involved in most of the biological and chemical processes in aquatic environments, it is the single most important parameter needing to be measured. Oxygen can also be used as a tracer in oceanographic studies.

For environmental reasons it is critical to monitor oxygen in areas where the supply of oxygen is limited compared to demand e.g.:

- In shallow coastal areas with significant algae blooms
- In Fjords or other areas with limited exchange of water
- Around fish farms
- In areas interesting for dumping of mine or dredging waste

Document Overview

The document starts by giving a short description of the physical principle behind the Oxygen Optode.

Subsequently a description of the optical, electronic and software design are presented.

An overview of the mechanical design follows, followed by a description of the test and calibration procedures and finally maintenance and an appendix of useful information.

Applicable Documents

V-8278	Assembly Drawing
V-8699	Sensor Cable 3854
V-8700	Sensor Cable 3855
Form 620	Test & Specification Sheet, Oxygen Optode
Form 621	Calibration Certificate, O^2 Sensing Foil 3853
Form 622	Calibration Certificate, Oxygen Optode 3830
D335	Data sheet

References

[1] Garcia and Gordon, Limnology & Oceanography 37(6), 1992,1307-1312

[2] TMS320LF/LC240xA DSP Controllers Reference Guide System and Peripherals, Texas Instruments, Literature Number: SPRU357A

[3] Kautsky, H. Quenching of luminescence by oxygen. Transactions of the Faraday Society 35, 1939, 216-219.

[4] Klimant, I., Meyer V. and Kühl M. Fiber-optic oxygen microsensors, a new tool in aquatic biology, Limnology & Oceanography 40, 1995,1159-1165.

Abbreviations

O_2	Oxygen molecule
LED	Light Emitting Diode
ADC	Analog to Digital Converter
DSP	Digital Signal Processor
EPROM	Erasable Programmable Read Only Memory
ASCII	American Standard Code for Information Interchange
MSB	Most significant bit
UART	Universal Asynchronous Transmitter and Receiver
RTC	Real Time Clock

Fig. 0.01 Oxygen Optode 3830 mounted on an RCM 9 MkII

CHAPTER 1 Short Description and Specifications

Description

Since oxygen is involved in most of the biological and chemical processes in aquatic environments, it is the single most important parameter needing to be measured. Oxygen can also be used as a tracer in oceanographic studies.

For environmental reasons it is critical to monitor oxygen in areas where the supply of oxygen is limited compared to demand e.g.:
- In shallow coastal areas with significant algae blooms
- In Fjords or other areas with limited exchange of water
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- In areas interesting for dumping of mine or dredging waste

The Oxygen Optode 3830 is based on the ability of selected substances to act as dynamic fluorescence quenchers. The fluorescent indicator is a special platinum porphyrin complex embedded in a gas permeable foil that is exposed to the surrounding water. A black optical isolation coating protects the complex from sunlight and fluorescent particles in the water.

This sensing foil is attached to a sapphire window providing optical access for the measuring system from inside a watertight titanium housing.

The foil is excited by modulated blue light, and the phase of a returned red light is measured (see illustration overleaf). By linearizing and temperature compensating, with an incorporated temperature sensor, the absolute O2 concentration can be determined.

The Optode outputs data in both RS-232C and Aanderaa SR10 format. On the RS-232C output both the absolute oxygen content in micro molar (µM) and the relative air saturation in % are available. The SR10 output can be configured to present oxygen content in µM or air saturation by connecting the sensor to a PC.

The lifetime-based luminescence quenching principle offers the following advantages over electrochemical sensors:

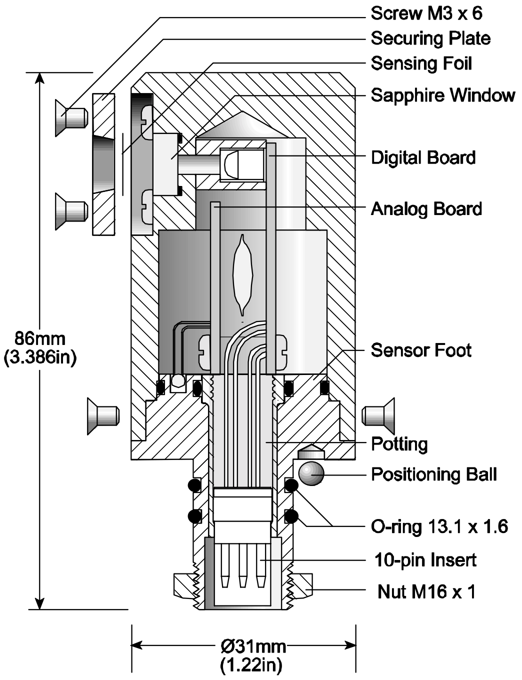
- Not stirring sensitive (it consumes no oxygen)
- Less affected by fouling
- Measures absolute oxygen concentrations without repeated calibrations
- Better long-term stability
- Less affected by pressure
- Pressure behavior is predictable
- Faster response time.

The sensor is designed to operate down to 6000 meters. It fits directly on to the top end-plate of Recording Current Meters RCM 9, RCM 11 and other Aanderaa instruments.

Specifications

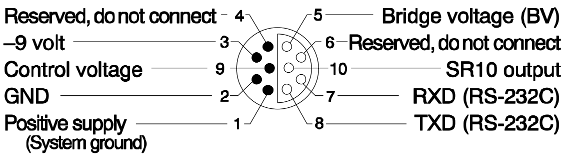
SPECIFICATIONS FOR OXYGEN OPTODE 3830

Preliminary



PIN CONFIGURATION

Receptacle, exterior view; pin = ●; bushing = ○



The sensor can be mounted directly on the top end-plate of the Aanderaa RCM 9 or RCM 11 and connected to the Main Control Board (Electronic Board) with a short cable, Sensor Cable 3854.

The Oxygen Optode can also be incorporated into other Aanderaa assemblages such as buoys, handheld profiling systems or hydrological monitoring. For such use a sensor version model 3930 is available ensuring straightforward connection to a PC.

For access to the RS-232C output the 10-pin receptacle in the sensor foot mates with Aanderaa Plug 3216A. An additional USB plug is used for providing power to the sensor.

The distance from the PC can be extended to 15 meters by using a Cable Coupler 3472 and a standard Connecting Cable 3282 with watertight titanium plugs.

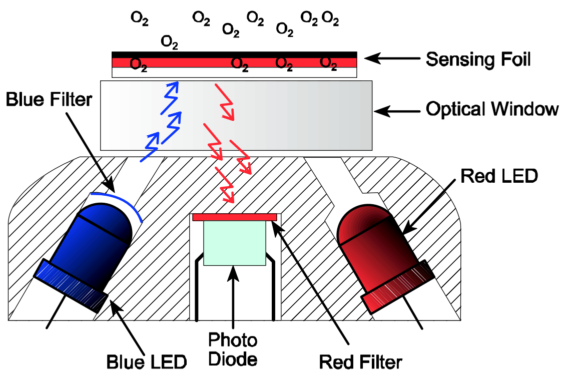
	Output Setting:	
	O_2-Concentration	Air Saturation
Measuring Range:	0-500 µM [1]	0 - 120%
Resolution:	< 1 µM	< 0.4%
Accuracy:	< 8 µM or 5%[2] which ever is greater	< 5%[2]
Settling Time (63%):	< 20 seconds	
Operating Temperature:	0 - 40°C (32 - 104°F)	
Operating Depth:	0 - 6000m (19,690ft)	
Sampling Interval:		
SR10 Operation:	SR10 controlled by Datalogger	
RS-232C Operation:	From 2 seconds to 255 minutes	
Output Formats:	RS-232C (9600 baud, 8 data bits, 1 stop bit, No parity, Xon/Xoff Handshake and Aanderaa SR10	
Electrical Connection:	10-pin receptacle mating plug 3216A	
Current Consumption:		
SR10 Operation:	13 mA/T where T is recording interval in minutes	
RS-232C Operation:	13 mA/T +5mA where T is recording interval in minutes	
Supply Voltage:		
SR10 Operation:	- 6 to -14 Vdc	
RS-232C Operation:	+5 to +14Vdc	
Dimensions:	Ø36 x 86 mm (Ø1.42 x 3.386in)	
Weight:	0.230kg (8.113oz)	
Materials:	Titanium, Hostaform(POM)	
Warranty:	Two years against faulty material and workmanship	
Accessories included:	Sensor Cable 3854	
(not included):	Sensor Cable 3855 to PC Foil Service Kit 3853 MPST1	

[1] O_2 concentration in micro Molar = µ molar/l
To obtain mg/l divide by 31.25.

[2] Valid for 0 to 2000m (6562ft) depth, salinity 33-37ppt

Specifications Subject to change without prior notice

The Optical System



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CHAPTER 2 Theory of Operation

The Oxygen Optode is based on a principle called dynamic luminescence quenching.

This phenomenon is the ability of certain molecules to influence the fluorescence of other molecules.

Dynamic Luminescence Quenching

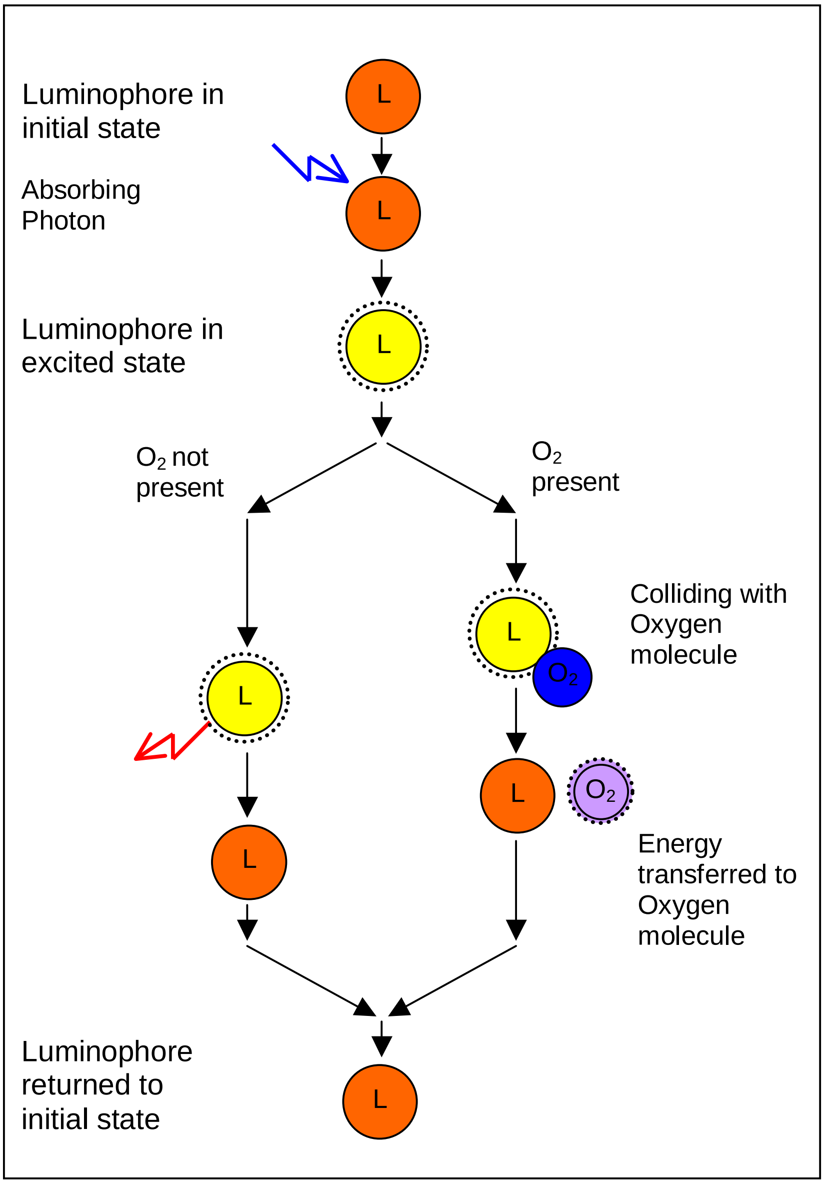


Fig. 2.01 Dynamic Luminescence Quenching

Fluorescence is the ability of a molecule to absorb light of certain energy and later emit light with lower energy.

Such a molecule, called a luminophore, will after absorbing a photon with high enough energy, enter an exited state.

After a while the luminophore will emit a photon of lower energy and return to its initial state.

Some types of luminophores might also return to the initial state when colliding with certain other molecules.

The luminophore will then transfer its excitation energy to the colliding molecule, with the result that no photon is emitted from the luminophore.

This effect is called dynamic luminescence quenching, and in the Oxygen Optode the colliding molecules is O_2.

Sensing Foil

The luminophore used in the Oxygen Optode is a special molecule called platinum porphyrine. These luminophores are embedded in a polymer layer.

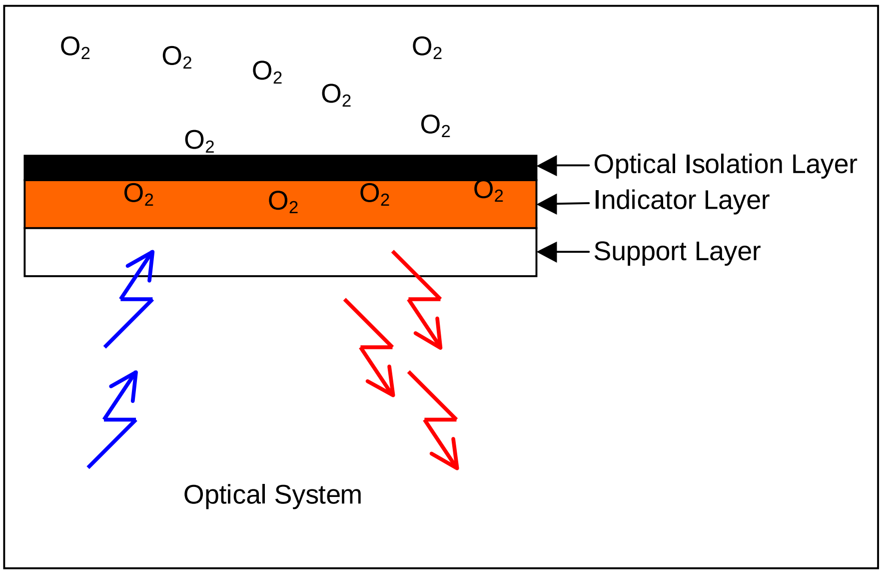


Fig. 2.02 Sensing Foil

This layer, called the indicator layer, is coated on a thin film of polyester support.

To avoid influence from fluorescent material surrounding the sensor or direct incoming sunlight when measuring in the photic zone, the foil is also equipped with gas permeable coating.

The coating gives optical isolation between the indicator layer and the surroundings.

Luminescence Decay Time

Due to its fluorescent behaviour the sensing foil will return a red light when it is excited with a blue-green light (505 nm).

If there is O_2 present this fluorescent effect will be quenched.

The amount of returned light will therefore be dependent on the concentration of O_2 in the foil.

The intensity of the returned light is however not the optimal property to measure since it is dependent on many other factors as i.e. optical coupling or bleaching of the foil.

Since the returned light is delayed with respect to the excitation light, the presence of O_2 will also influence this delay.

This property called luminescence decay time (or lifetime) will also degrease with increasing O_2 concentrations.

The relationship between the O_2 concentration and the luminescence decay time can be described by the Stern-Volmer equation:

$$[O_2] = \frac{1}{K_{sv}} \left\{ \frac{\tau_0}{\tau} - 1 \right\}$$

where: τ = decay time
τ_0 =decay time in absence of O_2
K_{sv} = Stern-Volmer constant (quenching efficiency)

In order to measure this luminescence decay time, the sensing foil is excited with a blue-green light modulated at 5 KHz.

The decay time will then be a function of the phase of the received signal.

In the Oxygen Optode the relationship between the phase and the O_2 concentration is used directly, without calculating the decay time.

The following diagram shows a typical relationship between the phase measurement and O_2 concentration:

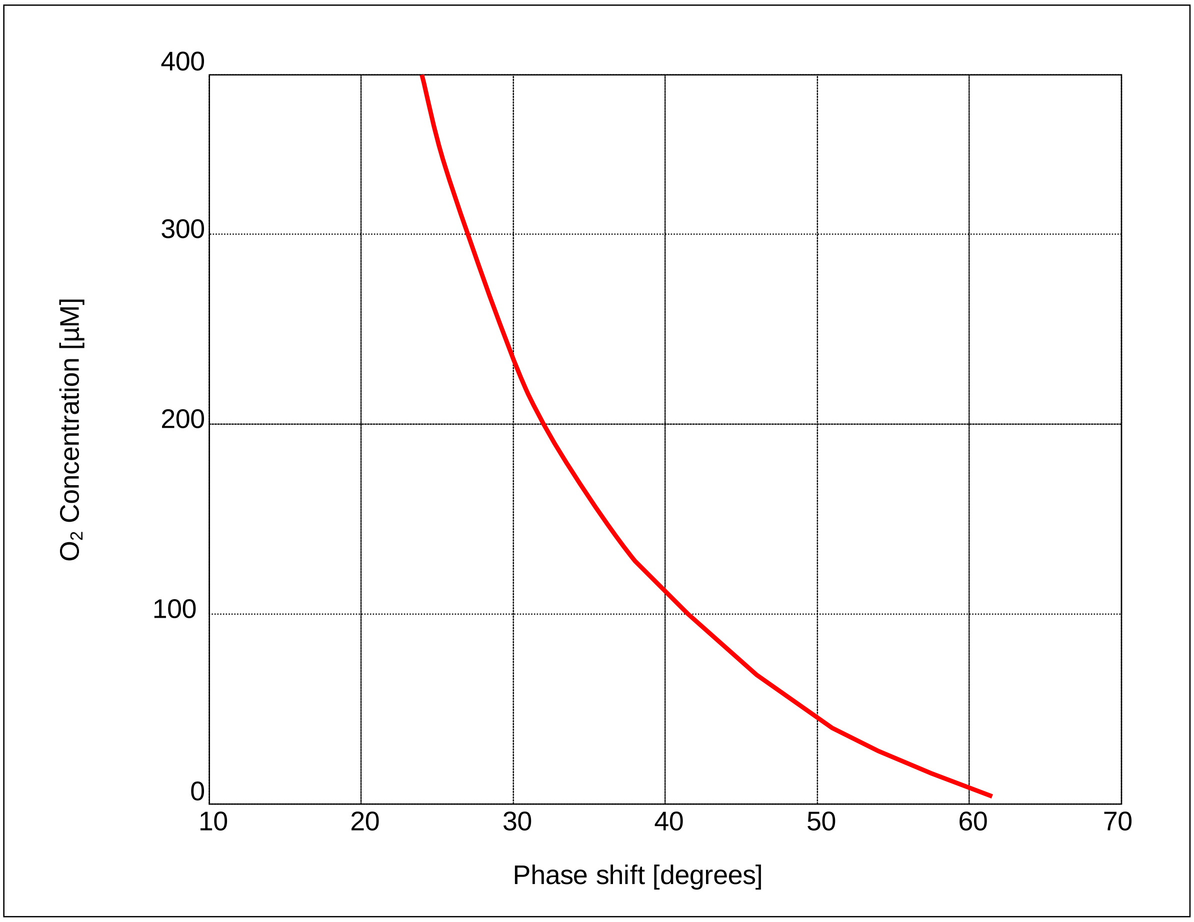


Fig. 2.03 Typical Phase/O_2 response

CHAPTER 3 Optical Design

The sensing foil is mounted outside an optical window, exposed to the surrounding water. On the inside of the window two light emitting diodes (LEDs) and a photodiode is placed. A blue-green LED is used for excitation of the foil and the photodiode is used for sensing the fluorescent light.

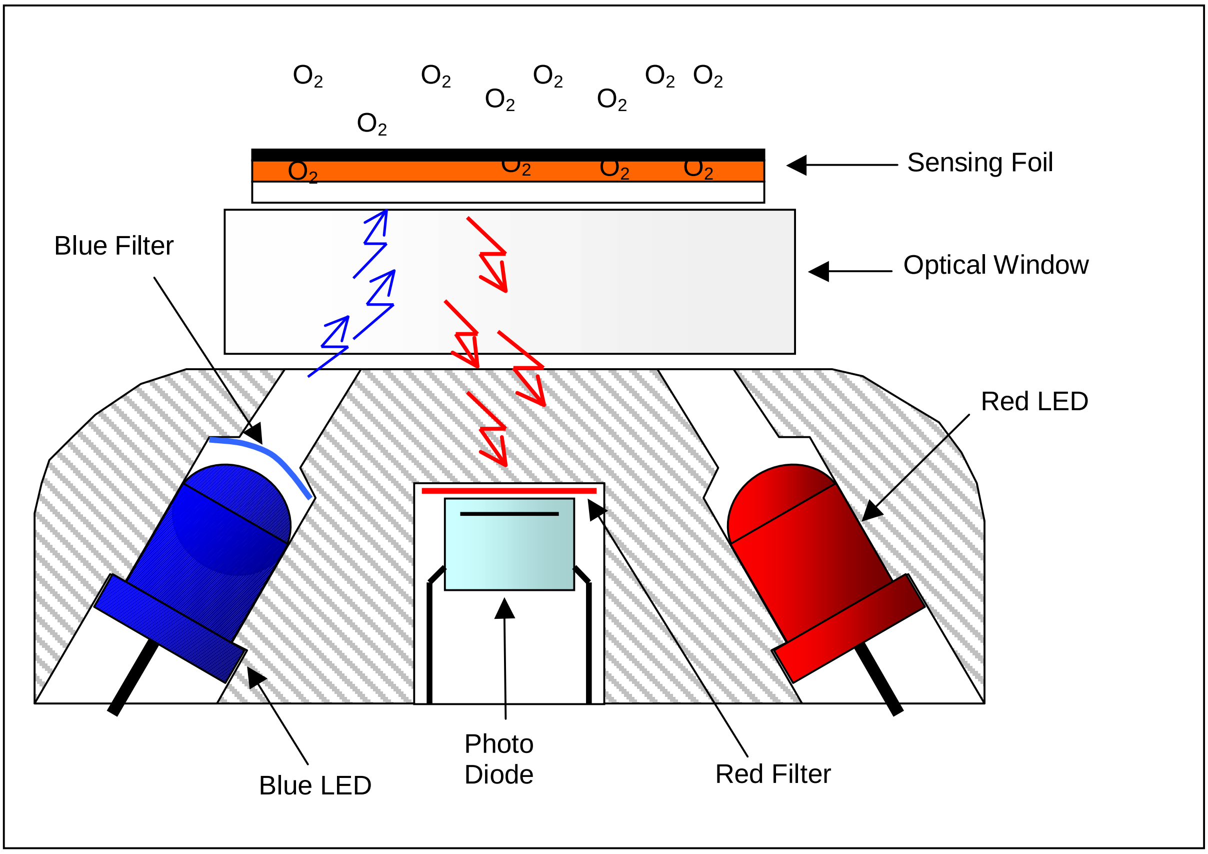


Fig. 3.01 Optical Design

Even thought the sensing foil is highly fluorescent a part of the light will be directly reflected. To minimize the influence of the reflected light the photo diode is equipped with a colour filter that stops light with short wavelengths and the blue-green LED is equipped with a filter that stops light with long wavelengths.

An additional red LED that does not make the foil emit fluorescent light is used to compensating for phase shift in the transmitter and receiver circuit.

The spectral response of the LEDs and the filter are illustrated in the following diagram.

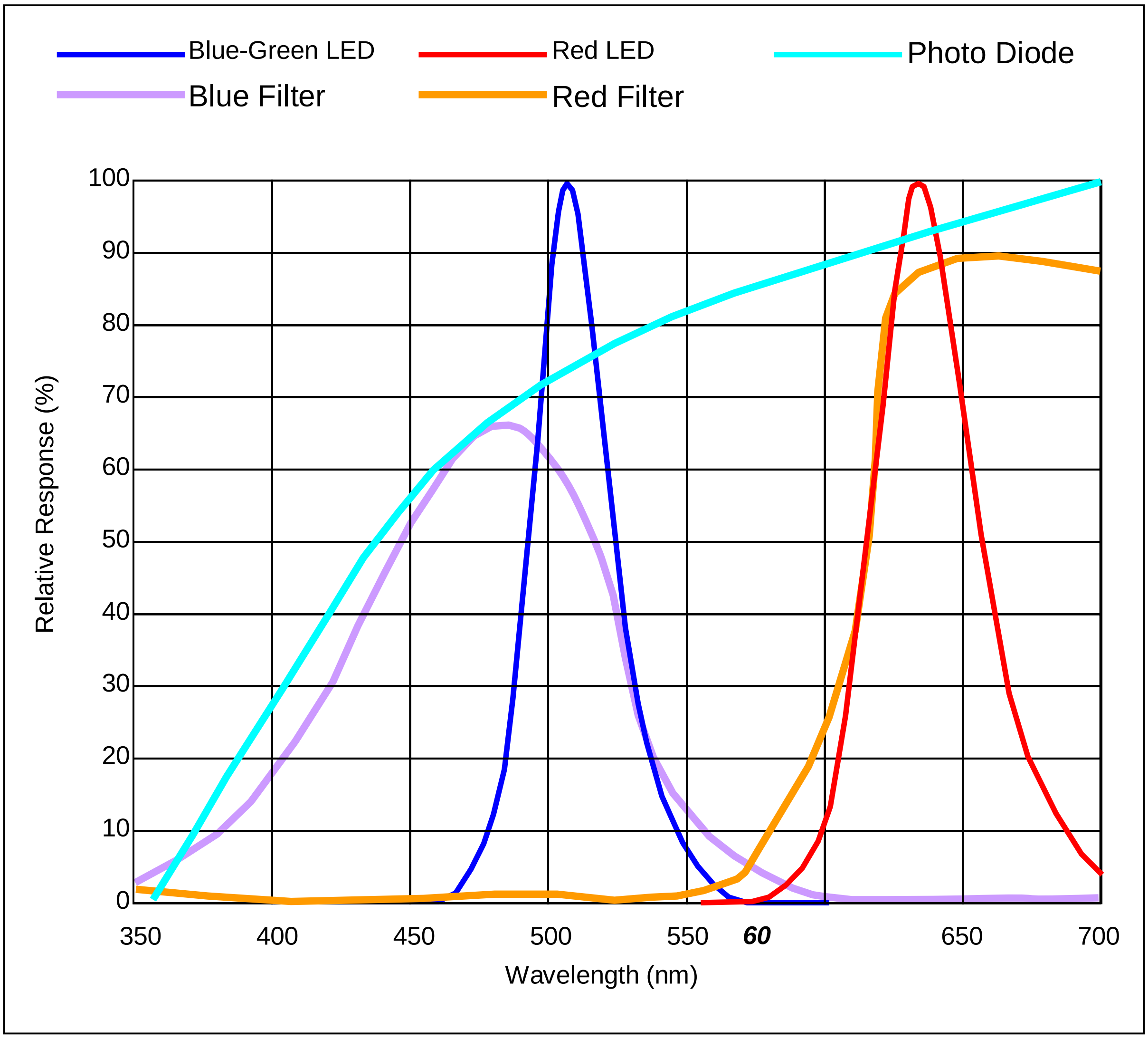


Fig. 3.02 Spectral Response

CHAPTER 4 Electronic Design

To obtain good oxygen measurement; the electronic circuit must be able to measure the phase between the excitation signal and received signal accurately and with good resolution.
The received signal is sampled with a frequency 4 times the excitation frequency. From these samples two signal components with a phase difference of 90 degrees is extracted. The phase of the received signal can then be calculated by an arcos tangents function of the two components.

Linearizing and temperature compensating the phase measurement enables calculation of the oxygen concentration. The result is presented either as an SR10 or an RS-232C output.
A thermistor thermally connected to the sensor body, provides for the temperature measurement.

The following figure illustrates the main functions of the electronics.

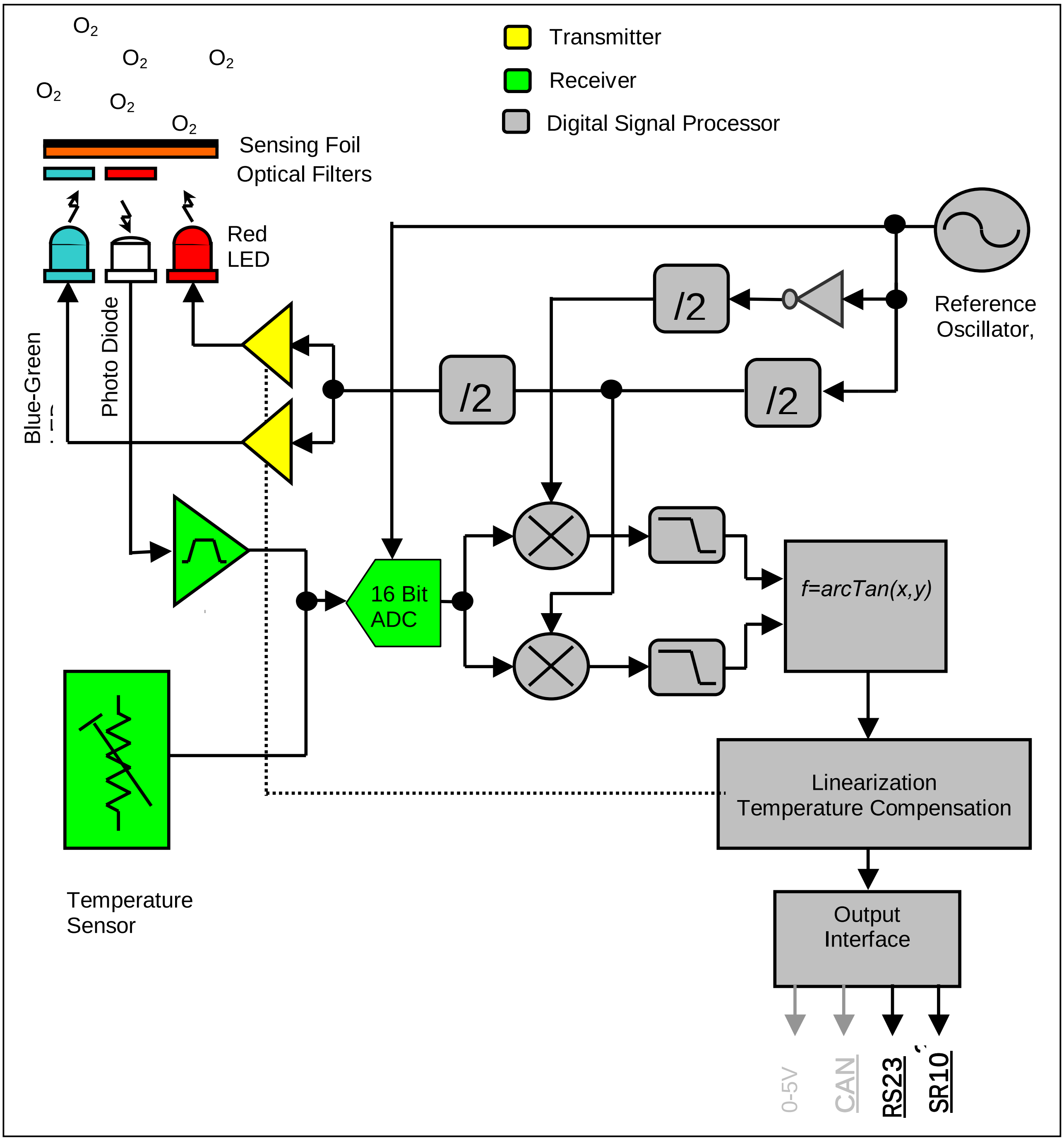


Fig. 4.01 Functional Diagram

CHAPTER 5 Software

The software's main tasks are to control the transmitter, sample the returned signal, extract the phase of this signal, and convert it into oxygen concentration.

All properties that can be changed for each individual sensor, i.e. calibration coefficients, are called sensor properties.

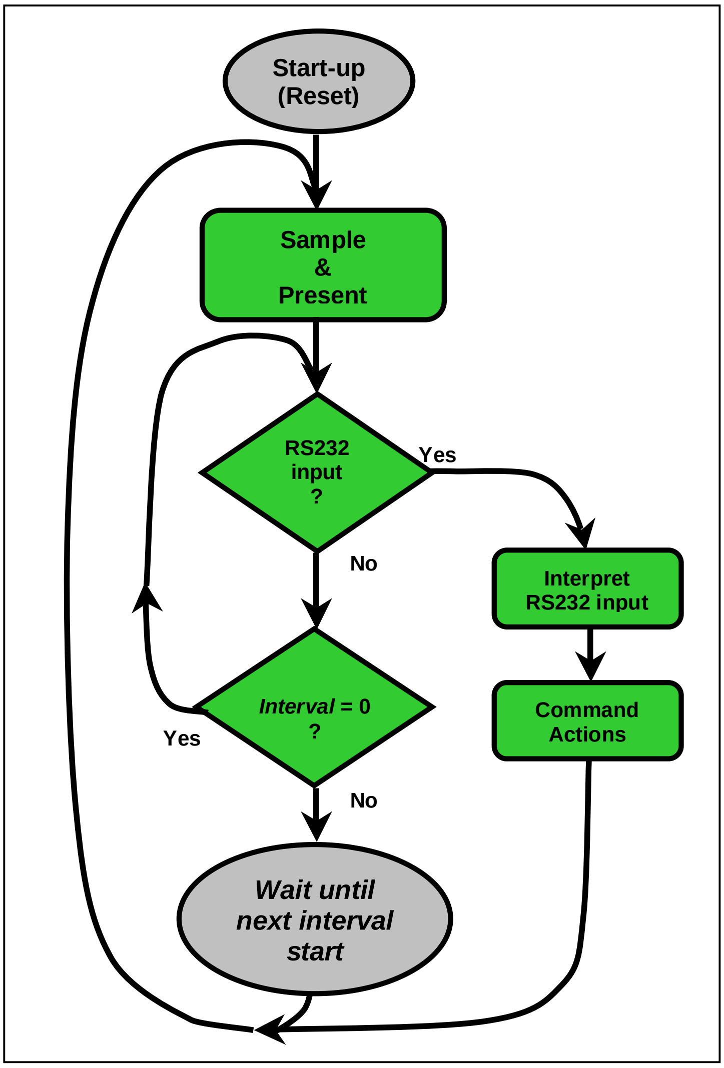


Fig. 5.01 Software, Operation Sequence

These properties can be displayed and changed using the RS-232C port (see RS-232C Protocol for how to communicate with the sensor).

When powered up; the Oxygen Optode will take an oxygen sample and present the result.

After this, and after each following sample; the RS-232C input buffer is checked for 100 milliseconds.

If the buffer contains any characters the timeout is increased to 1 second and the software starts interpreting the RS-232C input.

If the input buffer is empty the sensor will continue to sample and present data accordingly to the setting of the *Interval* property.

If the *Interval* is set to zero the user can initiate a new sample by use of a **Do_Sample** command. The following drawing illustrates the operation sequence.

After approximately 20 seconds without any valid commando inputs the sensor will enter a sleep mode until the next interval starts.

In sleep mode the sensor will not respond to RS-232C input commands.

However, before entering the sleep mode the sensor stops the host's transmission by sending out a XOFF handshake-control character.

After waking up and finishing the next sample, the host transmission is turned on again.

When this handshake method is used the host's output will be buffered until the sensor is ready to receive.

This relieves the host from the need to synchronize the communication with the sensors sampling interval.

When the Optode is connected to a RCM 9 or other Aanderaa Instrument or Logger, the power to the sensor is switched on by the Control Voltage becoming active (initiated by the RCM 9).

The sensor will then take one sample in the start of the recording interval and present this at the SR10 output.

When the logger is finished reading the SR10/VR22 sensors, the Control Voltage is turned off and the Optode sensor is powered down.

Oxygen calculation

The software calculates the engineering values (calibrated oxygen concentrations) based on the sampled raw-data and a set of stored (“flashed”) coefficients.

After converting the phase raw data to degrees, a compensated phase difference is calculated as a 3rd-degree polynomial of the difference between the phase measurement with blue light excitation and red light excitation.
The coefficients in this polynomial are called *PhaseCoef.*

The temperature in degrees Celsius (°C) is calculated by use of a similar polynomial with coefficient called *TempCoef*.

The O_2 concentration is calculated in micro Molar (µM) by use a modified Stern-Volmer function (see Chapter 2 Luminescence Decay Time).

$$[O_2] = \left\{ \frac{f_1}{\frac{P}{K_0(t)} - f_2} - 1 \right\} \cdot K_1(t)$$

where: f_1, f_2 = temperature independent coefficients

K_0, K_1 = temperature dependent coefficients

P = compensated phase difference

Each of the K_0, K_1 coefficients are calculated by use of a 3-degree polynomial with temperature as argument and the coefficients *K0Coef* and *K1Coef*.

Based on O_2 concentration, temperature and a manual salinity setting, the *Calculate* function also calculates the relative O_2 saturation.

The following formula by Garcia and Gordon [1] gives O_2 solubility (C^*) at standard air mixture and pressure (1013 hPa).

$$\ln(C^*) = A_0 + A_1 T_s + A_2 T_s^2 + A_3 T_s^3 + A_4 T_s^4 + A_5 T_s^5 + S\left(B_0 + B_1 \cdot T_s + B_2 \cdot T_s^2 + B_3 \cdot T_s^3\right) + C_0 S^2$$

where:

Ts = Scaled Temperature = $\ln\left[\frac{298.15 - t}{273.15 + t}\right]$

t = Temperature in degrees Celsius

S = Salinity (fixed setting)

A_0 = 2.00856	B_0 = -6.24097e-3	C_0 = -3.11680e-7
A_1 = 3.22400	B_1 = -6.93498e-3	
A_2 = 3.99063	B_2 = -6.90358e-3	
A_3 = 4.80299	B_3 = -4.29155e-3	

A_4 = 9.78188e-1
A_5 = 1.71069

The relative O_2 saturation in % can then be calculated as:

$$O_{2Sat} = \frac{[O_2] \cdot 2.2414}{C^*}$$

where:

$[O_2]$ = O_2 concentration in µM

C^* = Solubility in cm^3/liter

The O_2 concentration sensed by the Optode is in fact the O_2 concentration in the sensing foil. Since this foil is only permeable by gas and not water, the Optode cannot sense the effect of salt dissolved in the water. In effect this means that the Optode measures as if immersed in fresh water.

If the salinity variation on site is minor, the O_2 concentration can be corrected by setting the internal property *Salinity* to the average salinity there.

On the other hand, if salinity varies significantly and the actual salinity is available a more accurate correction may be applied externally.
The O_2 concentration in µM should then be multiplied by the following factor:

$$e^{S\left(B_0 + B_1 \cdot T_s + B_2 \cdot T_s^2 + B_3 \cdot T_s^3\right) + C_0 S}$$

where :

S = Salinity in ppt

Ts = Scaled Temperature = $\ln\left[\frac{298.15 - t}{273.15 + t}\right]$

t = Temperature in degrees Celsius

B_0 = -6.24097e-3 C_0 = -3.11680e-7
B_1 = -6.93498e-3
B_2 = -6.90358e-3
B_3 = -4.29155e-3

If the salinity setting in the Optode is set to other than zero, the O_2 concentration must also be divided by the above expression substituting S with the fixed setting.

RS-232C Protocol

For connection to a Personal computer (PC) the 1.5-meter Sensor Cable 3855 can be used.
Most terminal programs, such as the HyperTerminal by Hilgraeve Inc (included in Microsoft's operating systems), can be used for manual communication.

The following RS-232C setup should be used:

9600 Baud
8 Data bits
1 Stop bit
No Parity
Xon/Xoff Handshake

The RS-232C protocol describes how to communicate with the sensor. All inputs to the sensor are given as commands with the following format:

MainCmd_*SubCmd* or ***MainCmd_Property***(*Value*.., *Value*)

The main command (*MainCmd*) is followed by an optional subcommand (*SubCmd*) or sensor property (*Property*).
The *MainCmd* and the *SubCmd/Property* must be separated with the underscore character '_'.
When entering new settings the *Property* is followed by parentheses containing comma-separated values.
The command string is case sensitive (UPPER/lower-case) and must be terminated by a Line Feed character set (ASCII code10).
Termination with Carriage Return followed by Line Feed is also allowed.

A valid command string is acknowledged with the character '#' while the character '*' indicates an error.
Both are followed by Carriage Return/Line Feed (CRLF).
A short error message is also given subsequent to the error indication.

The following main commands are available in the Oxygen Optode:

Command	Meaning
Do_*Subcmd*	Execute *Subcmd*
Get_*Property*	Output *Property* value
Get_All	Output all property values
Set_*Property*(*Value*,..*Value*)	Set *Property* to *Value*,.. *Value*
Save	Store current settings
Load	Load stored settings
Help	Print help information

In the Oxygen Optode the following subcommands and properties are available:

Subcommand	Function	Write Protection
Sample	Execute an oxygen measurement and presents the result	
Calibrate	Execute calibration function	Yes
CalAir	Collect calibration data in air	Yes
CalZero	Collect calibration data in zero solution	Yes
Test	Execute a test function and present the result	

Properties	Type	No. of Elements	Use	Write Protection
Protect	Int	1	Protection of property read and write access	
PhaseCoef	Float	4	Curve fitting coefficients for the phase measurement	Yes
TempCoef	Float	4	Curve fitting coefficients for the temperature measurement	Yes
f1	Float	1	Coefficient in the phase to [O_2] formula	Yes
f2	Float	1	Coefficient in the phase to [O_2] formula	Yes
K0Coef	Float	4	Temperature coefficients in the phase to [O_2] formula	Yes
K1Coef	Float	4	Temperature coefficients in the phase to [O_2] formula	Yes
Salinity	Float	1	Salinity setting	
CalAirPhase	Float	1	Calibration data in air, phase	Yes
CalAirTemp	Float	1	Calibration data in air, temperature	Yes
CalAirPressure	Float	1	Calibration data in air, pressure	Yes
CalZeroPhase	Float	1	Calibration data in zero solution, phase reading	Yes
CalZeroTemp	Float	1	Calibration data in zero solution, temperature reading	
Interval	Int	1	Sampling Interval in seconds.	
Output	Char	1	Output setting	Yes

A property may contain one or more equal elements of the type Character, Integer or Float.
The Charater type is stored as an 8-bit bit word and may be signed (value –128 to 127) or unsigned (0-256).
The Integer type is stored as a 16-bit word and may be signed (value –32768 to 32767) and unsigned (0 to 65535).
The Float consists of 32-bit and has a range from 1.19209290e–38 to 3.4028235e+38.

The **Get** command is used for reading the value/values of a property.
The command name **Get,** is followed by *_Property* and returns a string on following format:

Property ProductNo SerialNo Value, ..Value

The string starts with the name of the property (*Property*), continues with the product number and serial number of the sensor, and finally the value or values of the property.
All names and numbers are separated by tabulator spacing (ASCII code 9).
The string is terminated by Carriage Return and Line Feed (ASCII code 13 & 10).

Example:

```
          Get_Salinity
Returns:  Salinity    3830    116    3.500000E+01
          #
```

A special version, **Get_All**, reads out all available properties in the sensor.

The **Set** command is used for changing a property.

Example:

```
          Set_TempCoef(-124,1.6644E-4,  3.3456E-12,0)
Returns:  #
```

Float values may be entered on normal decimal form or exponential form, either with ‘e’ or ‘E’ leading the exponent. Extra “Space” characters in front or after a value are allowed.

When one or more properties are changed, the sensor will start using the new properties.
If the **Save** command is executed the new setting will be stored in the internal EEPROM.
If a **Load** is executed instead, the previous stored setting will be reloaded.

To avoid accidental change, most of the properties are write-protected.
A special property called *Protection* must be set to 1 before changing the value of properties with this write protection.
The *Protection* property always returns to zero after power up or execution of the **Load** or **Save** command.

The **Do_Sample** command or an interval initiated measurement result in one output string containing the obtained data.

A property called *Output* controls the presentation of the measured data.

When the *Output* property is set to a negative value the SR10 output will be enabled.
Dependent on the value of the *Output* the different data are presented on the SR10 output:

Output =	Data presented on the SR10 output	Coefficients for obtaining engineering units	Unit
-1	O_2 concentration	B=0.488281	µM
-2	O_2 saturation	B=0.146484	%

When the *Output* is different from 0 a comprehensive RS-232C string containing raw data is presented:

```
MEASUREMENT   3830   104   Oxygen:      234.87 Saturation:       104.75
    Temperature:      28.78 DPhase:       7.95 BPhase:       50.37
    RPhase:      38.04  BAmp:        825   RAmp:       4678   RawTem.:   -1146
```

When the *Output* property is set to 0 a normal string with following format is transmitted:

```
MEASUREMENT   3830   104   Oxygen:      234.87 Saturation:       104.75
    Temperature:      28.78
```

The leading word, MEASUREMENT, is followed by the sensor's product number and serial number.
All words and numbers are followed by a tabulator spacing (ASCII code 9).
The string is terminated by Carriage Return and Line Feed (ASCII code 13 & 10).

CHAPTER 6 Mechanical Design

Fig. 6.01 Components
(Note! The sensor housing should not be opened)

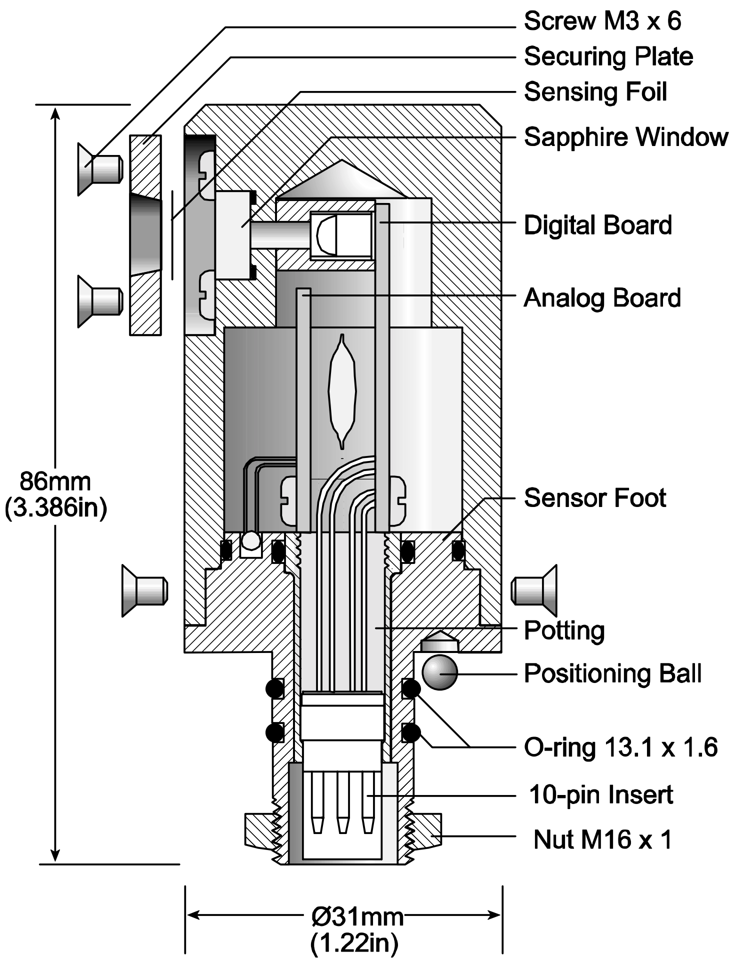


Fig. 6.02 Drawing of Sensor

A cylindrical titanium housing shields the electronics from the surrounding water and high pressure.

A 4 millimetre thick sapphire window provides for the optical connection between the optics inside the sensor and the sensing foil on the outside.

The foil is fixed to the window by securing plate and is easily replaceable.

A 10-pin receptacle in the sensor foot provides all electrical connection to the sensor.

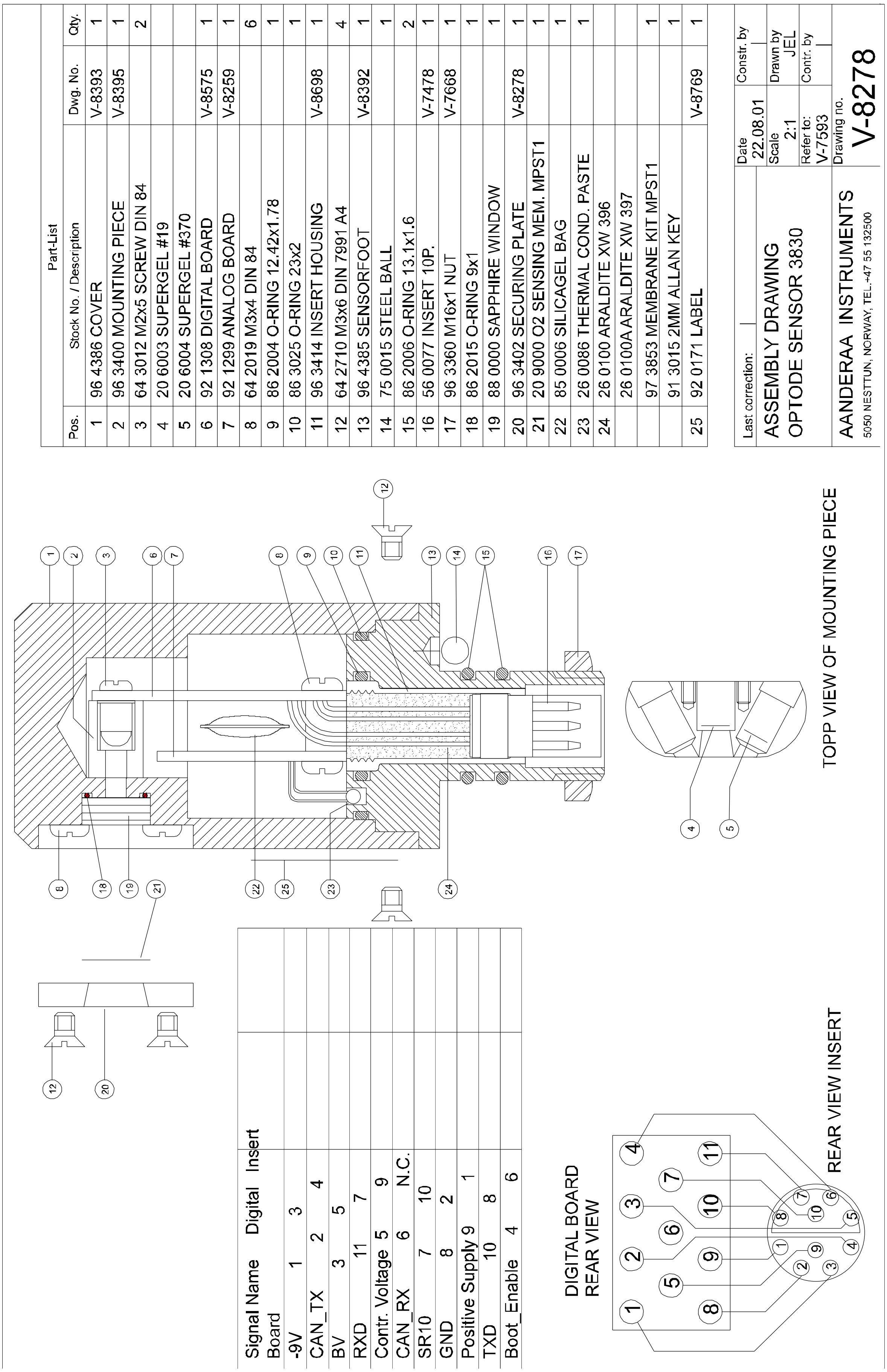
To prevent leakage from the sensor to rest of the measurement system, this receptacle is first moulded inside a receptacle housing.

The sensor can be mounted directly on the top plate of the Aanderaa RCM9 or RCM11.

A short cable called Sensor Cable 3854 is then used for connection between the sensor and the data logger.

See Maintenance for instructions concerning changing Sensing Foil.

Note! The sensor should not be opened! Opening the sensor housing could breach the warranty (see Chapter 8 Maintenance for instructions concerning changing Sensing Foil).



Part-List

Pos.	Stock No. / Description	Dwg. No.	Qty.
1	96 4386 COVER	V-8393	1
2	96 3400 MOUNTING PIECE	V-8395	1
3	64 3012 M2x5 SCREW DIN 84		2
4	20 6003 SUPERGEL #19		
5	20 6004 SUPERGEL #370		
6	92 1308 DIGITAL BOARD	V-8575	1
7	92 1299 ANALOG BOARD	V-8259	1
8	64 2019 M3x4 DIN 84		6
9	86 2004 O-RING 12.42x1.78		1
10	86 3025 O-RING 23x2		1
11	96 3414 INSERT HOUSING	V-8698	1
12	64 2710 M3x6 DIN 7991 A4		4
13	96 4385 SENSORFOOT	V-8392	1
14	75 0015 STEEL BALL		1
15	86 2006 O-RING 13.1x1.6		2
16	56 0077 INSERT 10P.	V-7478	1
17	96 3360 M16x1 NUT	V-7668	1
18	86 2015 O-RING 9x1		1
19	88 0000 SAPPHIRE WINDOW		1
20	96 3402 SECURING PLATE	V-8278	1
21	20 9000 O2 SENSING MEM. MPST1		1
22	85 0006 SILICAGEL BAG		1
23	26 0086 THERMAL COND. PASTE		1
24	26 0100 ARALDITE XW 396		
	26 0100A ARALDITE XW 397		
	97 3853 MEMBRANE KIT MPST1		1
	91 3015 2MM ALLAN KEY		1
25	92 0171 LABEL	V-8769	1

Signal Name	Digital Board	Insert
-9V	1	3
CAN_TX	2	4
BV	3	5
RXD	11	7
Contr. Voltage	5	9
CAN_RX	6	N.C.
SR10	7	10
GND	8	2
Positive Supply	9	1
TXD	10	8
Boot_Enable	4	6

Fig. 6.03 Assembly Drawing

Electrical Connections

Fig. 6.04 Sensor connected to Electronic Board

The 10-pin receptacle in the sensor foot mates with an Aanderaa 3216A plug ((Fig. 6.06).).

For connection to a Personal computer (PC) the 1.5 meter Sensor Cable 3855 can be used

This cable has a watertight 10-pin plug at the sensor end, and a 9 pin D-Sub plug at the PC-end (Fig. 6.07).

An additional USB plug is used for providing power to the sensor.

Power may also be connected to an included extension to the USB plug.

A short cable called Sensor Cable 3854 is used for connection between the sensor and Aanderaa Current meters (Fig. 6.04).

The electrical connections of the sensors are given below (Fig. 6.05).

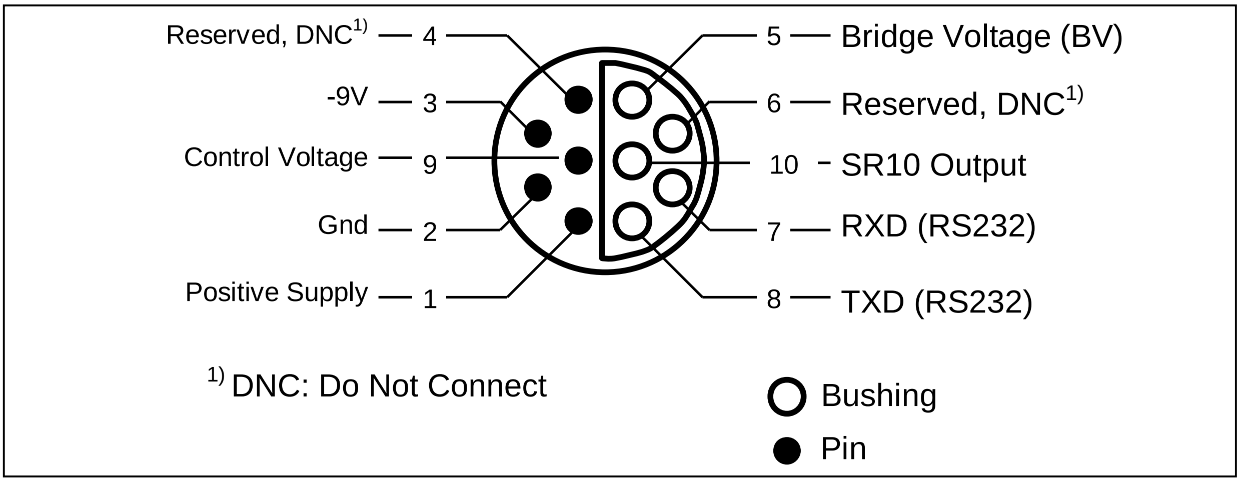


Figure 6.05 Pin Configuration

Fig. 6.06 Sensor Cable 3854

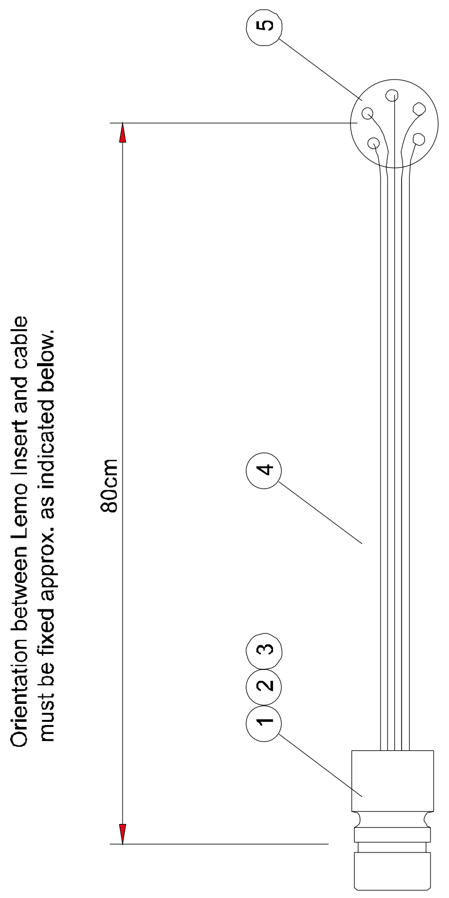
The sensor can be mounted directly on the top plate of the Aanderaa RCM9 or RCM11 and connected to the Electronic Board using Sensor Cable 3854.

Fig. 6.07 Sensor Cable 3855

A 1.5 meter cable, Sensor Cable 3855, is used for connection between the sensor and the PC. By using a Cable Coupler 3472 and a standard Connecting Cable 3282 this connection can be extended to 15 meters.

Drawings of Sensor Cables 3854 and 3855 follow:

V-8699



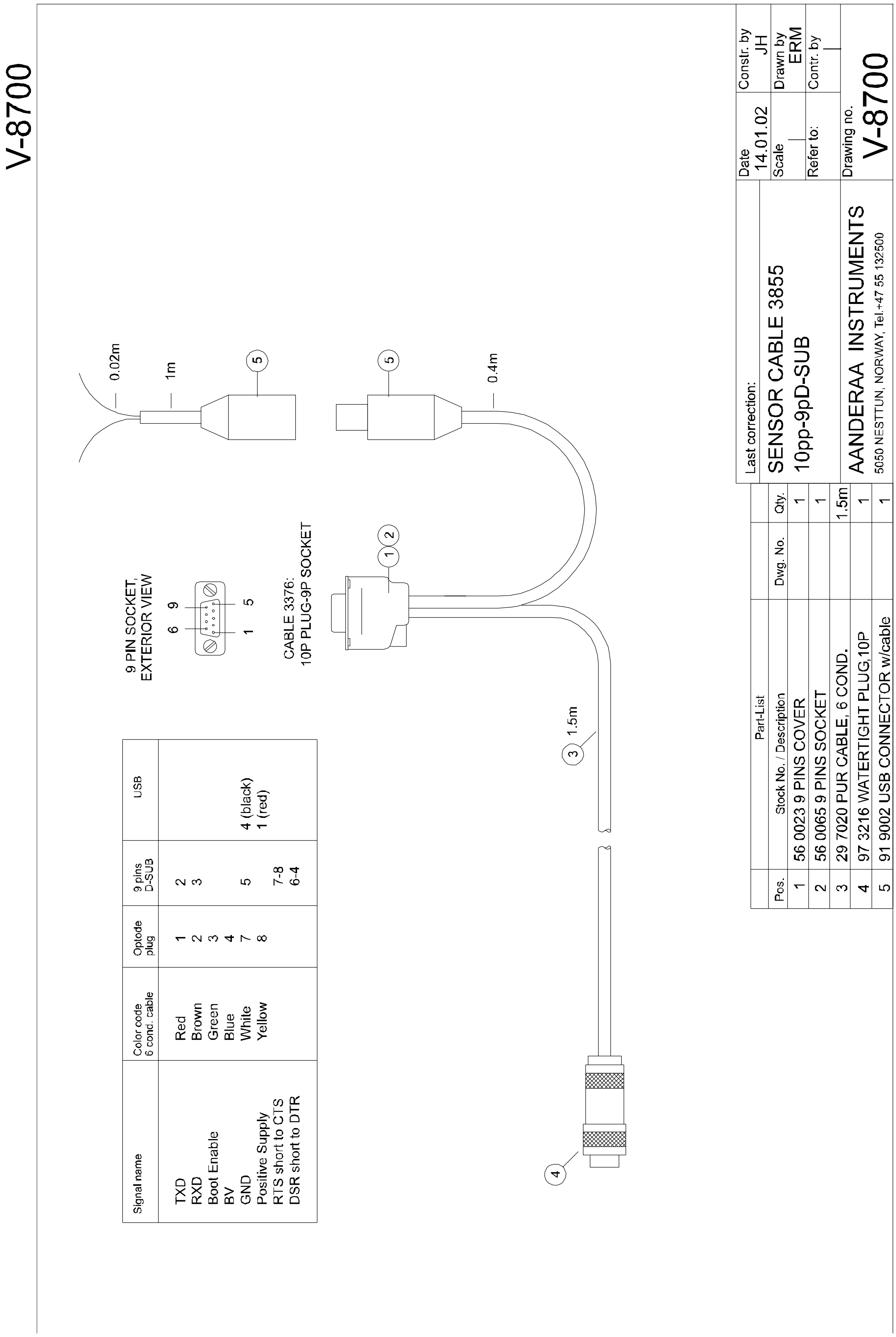
Signal name	Color	Optode Plug	Cell Plug
BV	BLUE	4	1
CONTROL VOLTAGE	VIOLET	10	2
POSITIVE SUPPLY	GREY	8	3
-9V	WHITE	6	4
SR10	BLACK	9	5

Part-List

Pos.	Stock No. / Description	Dwg. No.	Qty.
1	96 3415 PLUG HOUSING	V-8710	1
2	56 0064 LEMO INSERT		1
3	26 0044A/B SCOTCHCAST		
4	29 0008 RIBBON CABLE		1m
5	96 9021 RADIAL PLUG		1

Last correction:	Date 15.01.02	Constr. by JH
SENSOR CABLE 3854 10pp-RADIAL PLUG	Scale 1:1	Drawn by ERM
	Refer to:	Contr. by
AANDERAA INSTRUMENTS 5852 BERGEN, NORWAY, Tel.+47 55 109900	Drawing no. V-8699	

Fig. 6.08 Sensor Cable 3854



Signal name	Color code 6 cond. cable	Optode plug	9 pins D-SUB	USB
TXD	Red	1	2	
RXD	Brown	2	3	
Boot Enable	Green	3		
BV	Blue	4		
GND	White	7	5	4 (black)
Positive Supply	Yellow	8		1 (red)
RTS short to CTS			7-8	
DSR short to DTR			6-4	

Part-List

Pos.	Stock No. / Description	Dwg. No.	Qty.
1	56 0023 9 PINS COVER		1
2	56 0065 9 PINS SOCKET		1
3	29 7020 PUR CABLE, 6 COND.		1.5m
4	97 3216 WATERTIGHT PLUG,10P		1
5	91 9002 USB CONNECTOR w/cable		1

Fig. 6.09 Sensor Cable 3855

Production

Aanderaa Instruments have Proven Reliability.
With over 30 years of producing instruments for the scientific community around the world, you can count on our reputation for designing the most reliable products available.

We are guided by three underlying principles: quality, service, and commitment. We take these principles seriously, for they form the foundation upon which we provide lasting value to our customers. Our unmatched quality is based on a relentless program of continuous monitoring to maintain the highest standards of reliability.

Testing

In order to assure the quality of this sensor, critical properties are tested during production. A special form, named “Test and Specification Sheet” (see Fig. 6.10) lists the required tests and the result of these tests and checkpoints: A special test algorithm provides most of the data for the performance test in paragraph 4,5 and 6.

AANDERAA *Test & Specification Sheet*

Product: Oxygen Optode 3830
Serial No: ------

Layout No: -----, -----; Circuit Diagram No: V----- , V-8731 ; Program Version: -.-

Visual and Mechanical Checks:

1.1	O-ring surface	☒
1.2	Soldering quality	☒
1.3	Visual surface	☒
1.4	Pressure test (60 MPa)	☒
1.5	Galvanic isolation between housing and electronics	☒

Current Drain and Voltages:

2.1	Average current drain at 0.5 Hz sampling (Max.: 54 mA)	51.7	mA
2.2	Current drain in sleep (Max.: 12 mA)	2.62	mA
2.3	Quiescent current drain from –9V (Max.: 5 µA)	0	µA
2.4	DSP voltage, IC5.1 (3.3 ±0.15V)	3.3	V
2.5	Excitation driver voltage, IC1.1 (3.3 ±0.15 V)	3.29	V
2.6	Flash/RS232 driver voltage, IC7.4 (5 ±0.2 V)	5.1	V

Receiver test:

3.1	Average of Receiver readings (0±230mV)	24	mV
3.2	Standard Deviation of Receiver readings (Max.: 30mV)	14	mV

Performance Test in Air, 0°C Temperature:

		Excitation: BLUE	RED	
4.1	Amplitude measurement (Blue: 250–800 mV, Red: 350–900 mV)	365	656	mV
4.2	Phase measurement (Blue: 40±4°, Red: 0±4°)	43.0	2.59	°
4.3	Standard deviation of Phase measurement: (Max.: 0.03 °)	0.014	0.007	°
4.4	Temperature measurement: (850±180 mV)		774	mV
4.5	SR10 concentration raw data (800±150)		844	

Performance Test in Air, 20°C Temperature:

		Excitation: BLUE	RED	
5.1	Amplitude measurement (Blue: 300–600 mV, Red: 350–900 mV)	377	526.9	mV
5.2	Phase measurement (Blue: 37±4°, Red: 0±4°)	38.59	2.7	°
5.3	Standard deviation of Phase measurement: (Max.: 0.03 °)	0.012	0.007	°
5.4	Temperature measurement: (-10±180 mV)		-62	mV
5.5	SR10 concentration raw data (550±150)		573	

Performance Test in Air, 40°C Temperature:

		Excitation: BLUE	RED	
6.1	Amplitude measurement (Blue: 300–600 mV, Red: 350–900 mV)	378	471	mV
6.2	Phase measurement (Blue: 35±4°, Red: 0±4°)	36.7	2.70	°
6.3	Standard deviation of Phase measurement: (Max.: 0.03 °)	0.011	0.009	°
6.4	Temperature measurement: (-600±180 mV)		-489	mV
6.5	SR10 concentration raw data (450±150)		456	

Date: Sign.

Form No. 620
JUNE 2002

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Calibration

Each batch of sensing foils is delivered with calibration data describing the behaviour with respect to oxygen concentration and temperature. When changing the sensing foil the following coefficients must be updated:

K0Coef$_{0..3}$
K1Coef$_{0..3}$
f1
f2

These coefficients are found in the Calibration Certificate for the Sensing Foil 3853.

In addition to the above calibration, the phase measurement of individual sensors can be calibrated using the *PhaseCoef* property. This property contains coefficients for a third degree polynomial used prior to the modified Stern-Volmer equation. Even tough the *PhaseCoef* holds coefficients for a 3rd-degree polynomial; a two-point calibration is usually sufficient.

Two controlled oxygen concentrations are relatively easy to obtain, one in air, and one in a zero-oxygen solution. When measuring in vapour-saturated air the sensor will respond equal to measuring in air-saturated fresh water. The O_2 concentration will in this case be given by the following formula:

$$[O_2] = \left(\frac{p - p_v(t)}{1013}\right) \cdot \frac{100 \cdot R_{o2}}{V_m} \cdot \alpha(t)$$

where:

p = atmospheric pressure in hPa

t = temperature in degrees C

$p_v(t)$ = vapour pressure in hPa $\approx e^{\left(52.57 - \frac{6690.9}{t+273.15} - 4.681 \cdot \ln(t+273.15)\right)}$

α = Bunsen absorption coefficient

$$\approx 48.998 - 1.335t + 2.755 \cdot 10^{-2} t^2 - 3.220 \cdot 10^{-4} t^3 + 1.598 \cdot 10^{-6} t^4$$

R_{02} = volume percentage of O_2 = 20.95 %

V_m = molar volume of O_2 = 22.414 l/mol

The compensated phase measurement can be calculated by the inverse formula used for calculating the O_2 concentration:

$$P_c = \left(\frac{f_1 \cdot K_1}{[O_2] + K_1} + f_2\right) \cdot K_0$$

where:

P_c = compensated phase

f_1, f_2 = temperature independent coefficients, *f1* and *f2* property

$[O_2]$ = oxygen concentration in µM

The K_0, *K1* are temperature dependent coefficients and are calculated by the following 3rd degree polynomial:

$$K_n = A + B \cdot t + C \cdot t^2 + D \cdot t^3$$

Where *t* is the temperature measurement in Celsius, and the *A,B,C,D* coefficients are stored respectively in the $K0Coef_{0-3}$ and the $K1Coef_{0-3}$ property.

Then the first two coefficients of the *PhaseCoef* (A and B) can be calculated by ordinary linear curve fitting:

$$\mathrm{B} = \frac{P_{c1} - P_{c0}}{P_1 - P_0} \qquad \mathrm{A} = P_{co} - \left(\frac{P_{c1} - P_{c0}}{P_1 - P_0}\right) P_0$$

where:

P_0 = uncompensated phase measurement calibration at zero oxygen
P_{c0} = compensated phase measurement calibration at zero oxygen
P_1 = uncompensated phase measurement calibration in air
P_{c1} = compensated phase measurement calibration in air

In order to ease this calibration procedure, the above calculation can be performed inside the sensor. The **Do_Calibrate** command starts a function that calculates and stores the above coefficients based on the following properties:

CalAirPhase:	Uncompensated phase measurement at calibration point in air
CalAirTemp:	Temperature measurement in ºC at calibration point in air
CalAirPressure:	Air pressure in hPa at calibration point in air
CalZeroPhase:	Uncompensated phase measurement at calibration point in zero solution
CalZeroTemp:	Temperature measurement in ºC at calibration point in zero solution

These properties may be entered manually or by use of the **Do_AirCal** and the **Do_ZeroCal** commands.

When the readings are stabilized in air the **Do_AirCal** command can be entered to sample and store values in the *CalAirTemp* and *CalAirPressure* property.

Likewise, the **Do_ZeroCal** command is used for sampling and storing value to the *CalZeroPhase* and *CalZeroTemp* property after stabilization in the zero solution.

A subsequent execution of the **Do_Calibrate** command effectuates a new calibration.

Calibration Procedure

1) Prepare a suitable container with fresh water. Aerate (apply bubbling) the water using an ordinary aquarium pump together with an airstone.
2) Prepare a zero oxygen solution by dissolving 5 grams of sodium sulfite (Na_2SO_3) in 500 ml of water.
3) Connect the sensor to a Personal Computer by use of the Sensor Cable 3855.
   Start a terminal program, i.e. the HyperTerminal by Hilgraeve Inc (included in Microsoft's operating systems), with following set-up:
   9600 Baud
   8 Data bits
   1 Stop bit
   No Parity
   Xon/Xoff Handshake

4) Control and if necessary update the K0Coef, K1Coef, f1 and f2 properties accordingly to the Calibration Certificate for the sensing foil in use (see Chapter 5, RS-232C Protocol, for communicating with the sensor).

5) Submerge the sensor into the aerated water.
Set the *Interval* property to e.g. 30 seconds.
Enter the **Save** command and wait until both the temperature and and the phase measurements have stabilized.

6) Set the Protect property to 1, and enter the **Do_CalAir** command to store calibration values.

7) Set the *CalAirPressure* property to the actual air pressure in hPa at the site.
Note! For maximum accuracy do not compensate the air pressure for height above sea level.

8) Submerge the sensor in the zero solution.
Make sure that the sensing foil is free for air bobbles.
Wait until both the temperature and the phase measurements have stabilized.

9) Set the *Interval* property to zero.
Enter the *Save* command to stop the sampling, and set the Protect property to 1.
Enter the **Do_CalZero** command to store calibration values.

10) Enter the **Do_Calibrate** command to effectuate the new calibration.

AANDERAA *Calibration Certificate*

Page 31 of 39

Sensor Type: O_2 Sensing Membrane PSt3 **Batch No:** ---

Certificate No: 3767_493_64529 **Calibration Date:** 31 Jan 02

Calibration points and phase readings (degrees)

Temperature (°C)		1.65	10.38	20.34	39.95	
Pressure (hPa)		966.00	966.00	966.00	966.00	
Oxygen (%)	0.00	58.80	58.40	57.76	56.90	
	1.00	55.77	54.94	53.93	52.10	
	2.5	51.82	50.56	49.16	46.56	
	5.00	46.55	44.84	43.10	40.10	
	10.00	39.05	37.25	35.45	32.45	
	20.00	30.82	29.25	27.67	25.11	

Giving these coefficients

Index	0	1	2	3
K0 Coefficient	5.754258E+01	-5.161100E-02	-1.119012 E-03	2.193340 E-05
K1 Coefficient	2.921229 E+02	-1.179205 E+01	2.718584 E-01	-2.620612 E-03
F1	8.275762 E-01			
F2	2.002127 E-01			

Date: 24 January 2002 **Sign.** Ole Olsen
Calibration Manager

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Form 621, December 2001

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Fig. 6.11 Form 621 Calibration Sheet Sensor Foil

AANDERAA *Calibration Certificate*

Page 1 of 2

Sensor Type: Oxygen Optode 3830 **Serial No:** ---
Certificate No: 3830_118_37442 **Calibration Date:** 31-Jan-02
Sensing Foil Batch No: 0001

This is to certify that this product has been calibrated using the following instruments:

Tinsley Digital Thermometer model 5885A	Serial No.272457
Platinum Resistance Thermometer	Serial No.272457T
Calibration Bath model CB 15-45E	No.65488001E

Parameter: **Internal Temperature**

Calibration points and readings

Temperature (°C)	1.21	12.03	24.18	35.81
Reading (mV)	757.3	398.02	-50.00	-454.60

Giving these coefficients

Index	0	1	2	3
TempCoef	2.27481E+01	-2.731850E-02	2.361076E-06	-3.829331E-09

Parameter: **Oxygen**

Calibration points and readings

	Air Saturated Water	**Zero Solution (Na_2SO_3)**
Phase reading (°)	22.87	56.78
Temperature reading (°C)	19.87	20.22
Air Pressure (hPa)	1002.87	

Fig. 6.11 Form 621 Calibration Sheet Sensor Foil

Giving these coefficients

Index	**0**	**1**	**2**	**3**
PhaseCoef	6.659640E+00	8.892368E-01	0.000000E+00	0.000000E+00

Date: 24 January 2002

Sign. Ole Olsen
Calibration Manager

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Fig. 6.12 Form 622 Calibration Sheet Oxygen Optode, page 1

AANDERAA *Calibration Certificate*

Page 2 of 3

Sensor Type:	Oxygen Optode 3830	**Serial No:**	---
Certificate No:	3720_115_56739	**Calibration Date:**	**31-Jan-02**

SR10 Scaling Coefficients:

At the SR10 output the Oxygen Optode 3830 can give either absolute oxygen concentration in **µM** or air saturation in %. The setting of the internal property "Output", controls the selection of the unit. The coefficients for converting SR10 raw data to engineering units are fixed.

Output = *-1*		**Output** = *-2*
A = ***0***		A = ***0***
B = ***0.488281***		B = ***0.146484***
C = ***0***		C = ***0***
D = ***0***		D = ***0***
Oxygen (µM) = $A + BN + CN^2 + DN^3$		Oxygen (%)= $A + BN + CN^2 + DN^3$

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Fig. 6.12 Form 622 Calibration Sheet Oxygen Optode, page 2

CHAPTER 7 Maintenance

Fig. 7.01 After deployment

The Oxygen Optode requires very little maintenance.

When the foils of traditional Oxygen Sensors based on Clark cells are fouled, the ability to diffuse gas decreases. This will influence the measurement directly. Since the Optode consumes no Oxygen, the ability to diffuse gas has no influence on the measurement's accuracy.

However if the fouling is in the form of algae that produce or consume oxygen, the measurement might not reflect the oxygen concentration in the surrounding water correctly. Also the response time of the measurement might increase if the sensing foil is heavily fouled.

To avoid this the sensor should be cleaned at regular intervals from 1 month to a year depending on the required accuracy and the fouling condition at the site.

The body of the Optode can be cleaned using a brush and clean water. Carefully use a wet cloth to clean the sensing foil.

If scratched the sensing foil should be replaced (Sensing Foil Kit 3853) and the sensor recalibrated.

It is recommended that the sensor be recalibrated annually (see CHAPTER 6 Calibration Procedure).

Fig. 7-02 Screws, Securing Plate, Sensing Foil, and Hex Key

Sensing Foil Kit 3853

Consists:

5 ea. Sensing Foil packed in aluminium foil (962203)

Form No. 621 Calibration Sheet for Sensing Foil (each batch of foils is calibrated)

2 ea. Hex countersink screw 3 x 6mm Din 7991 A4 (642710)

1 ea. 2mm Hex Key (913015)

CHAPTER 8 Appendix

Oxygen Dynamics in Water

Seawater and Gases

Tabulated physical parameters of interest to people working with microsensors in marine systems.
Presented by: Unisense A/S at:
http://www.unisense.com/support/support.html)

Tables

Gas tables by Niels Ramsing & Jens Gundersen with diffusion coefficients and solubility of oxygen in seawater, density of water versus temperature and salinity and much more (PDF-file) at:
http://www.unisense.com/support/pdf/gas_tables.pdf

Note!
Use tables 1 and 2 for salinities between 0 and 40 ‰ and temperatures between 0 and 40 °C.
The formulas used to calculate these tables are only valid in these intervals.
The formula used in table 3 is less precise in these intervals, but is a good approximation at higher salinities and temperatures.

DATA-TABLE 6 *by Niels Ramsing & Jens Gundersen* **Unisense A/S - www.unisense.com**

© Unisense

Oxygen solubility at different temperatures and salinities of seawater

Units: µmol/l

Salinity (‰)	Temperature (°C) 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
0.0	456.6	444.0	431.9	420.4	409.4	398.9	388.8	379.2	369.9	361.1	352.6	344.4	336.6	329.1	321.9	314.9	308.3	301.8	295.6	289.7	283.9
1.0	453.5	441.0	429.0	417.6	406.7	396.3	386.3	376.7	367.6	358.8	350.4	342.3	334.5	327.1	319.9	313.0	306.4	300.0	293.9	287.9	282.2
2.0	450.4	438.0	426.1	414.8	404.0	393.6	383.7	374.3	365.2	356.5	348.1	340.1	332.4	325.0	317.9	311.1	304.5	298.2	292.1	286.2	280.6
3.0	447.3	435.0	423.2	412.0	401.3	391.0	381.2	371.8	362.8	354.2	345.9	338.0	330.4	323.0	316.0	309.2	302.7	296.4	290.4	284.5	278.9
4.0	444.2	432.0	420.4	409.2	398.6	388.5	378.7	369.4	360.5	351.9	343.7	335.9	328.3	321.0	314.0	307.3	300.9	294.6	288.6	282.9	277.3
5.0	441.1	429.1	417.5	406.5	396.0	385.9	376.3	367.0	358.2	349.7	341.6	333.7	326.2	319.0	312.1	305.5	299.0	292.9	286.9	281.2	275.7
6.0	438.1	426.1	414.7	403.8	393.3	383.3	373.8	364.6	355.9	347.5	339.4	331.6	324.2	317.1	310.2	303.6	297.2	291.1	285.2	279.5	274.0
7.0	435.1	423.2	411.9	401.1	390.7	380.8	371.3	362.3	353.6	345.2	337.2	329.6	322.2	315.1	308.3	301.7	295.4	289.4	283.5	277.9	272.4
8.0	432.1	420.3	409.1	398.4	388.1	378.3	368.9	359.9	351.3	343.0	335.1	327.5	320.2	313.1	306.4	299.9	293.6	287.6	281.8	276.2	270.8
9.0	429.1	417.5	406.3	395.7	385.5	375.8	366.5	357.6	349.0	340.8	333.0	325.4	318.2	311.2	304.5	298.1	291.9	285.9	280.1	274.6	269.2
10.0	426.1	414.6	403.6	393.0	383.0	373.3	364.1	355.2	346.8	338.6	330.8	323.4	316.2	309.3	302.6	296.2	290.1	284.2	278.5	273.0	267.6
11.0	423.2	411.8	400.8	390.4	380.4	370.8	361.7	352.9	344.5	336.5	328.7	321.3	314.2	307.3	300.8	294.4	288.3	282.5	276.8	271.3	266.1
12.0	420.3	409.0	398.1	387.8	377.9	368.4	359.3	350.6	342.3	334.3	326.7	319.3	312.2	305.4	298.9	292.6	286.6	280.8	275.1	269.7	264.5
13.0	417.4	406.2	395.4	385.2	375.3	366.0	357.0	348.3	340.1	332.2	324.6	317.3	310.3	303.5	297.1	290.8	284.8	279.1	273.5	268.1	262.9
14.0	414.5	403.4	392.7	382.6	372.8	363.5	354.6	346.1	337.9	330.0	322.5	315.3	308.3	301.7	295.2	289.1	283.1	277.4	271.9	266.5	261.4
15.0	411.7	400.6	390.1	380.0	370.4	361.1	352.3	343.8	335.7	327.9	320.5	313.3	306.4	299.8	293.4	287.3	281.4	275.7	270.2	265.0	259.9
16.0	408.8	397.9	387.4	377.4	367.9	358.7	350.0	341.6	333.5	325.8	318.4	311.3	304.5	297.9	291.6	285.5	279.7	274.0	268.6	263.4	258.3
17.0	406.0	395.2	384.8	374.9	365.4	356.4	347.7	339.4	331.4	323.7	316.4	309.4	302.6	296.1	289.8	283.8	278.0	272.4	267.0	261.8	256.8
18.0	403.2	392.5	382.2	372.4	363.0	354.0	345.4	337.2	329.2	321.7	314.4	307.4	300.7	294.2	288.0	282.1	276.3	270.8	265.4	260.3	255.3
19.0	400.4	389.8	379.6	369.9	360.6	351.7	343.1	335.0	327.1	319.6	312.4	305.5	298.8	292.4	286.3	280.3	274.6	269.1	263.8	258.7	253.8
20.0	397.7	387.1	377.0	367.4	358.2	349.3	340.9	332.8	325.0	317.6	310.4	303.5	296.9	290.6	284.5	278.6	273.0	267.5	262.3	257.2	252.3
21.0	394.9	384.5	374.5	364.9	355.8	347.0	338.6	330.6	322.9	315.5	308.4	301.6	295.1	288.8	282.7	276.9	271.3	265.9	260.7	255.7	250.8
22.0	392.2	381.8	371.9	362.4	353.4	344.7	336.4	328.5	320.8	313.5	306.5	299.7	293.2	287.0	281.0	275.2	269.7	264.3	259.1	254.1	249.3
23.0	389.5	379.2	369.4	360.0	351.0	342.4	334.2	326.3	318.7	311.5	304.5	297.8	291.4	285.2	279.3	273.5	268.0	262.7	257.6	252.6	247.9
24.0	386.8	376.6	366.9	357.6	348.7	340.2	332.0	324.2	316.7	309.5	302.6	295.9	289.6	283.4	277.5	271.9	266.4	261.1	256.0	251.1	246.4
25.0	384.1	374.0	364.4	355.2	346.4	337.9	329.8	322.1	314.6	307.5	300.7	294.1	287.8	281.7	275.8	270.2	264.8	259.5	254.5	249.6	244.9
26.0	381.5	371.5	361.9	352.8	344.0	335.7	327.7	320.0	312.6	305.5	298.7	292.2	285.9	279.9	274.1	268.5	263.2	258.0	253.0	248.2	243.5
27.0	378.8	368.9	359.5	350.4	341.7	333.4	325.5	317.9	310.6	303.6	296.8	290.4	284.2	278.2	272.4	266.9	261.6	256.4	251.5	246.7	242.1
28.0	376.2	366.4	357.0	348.0	339.5	331.2	323.4	315.8	308.6	301.6	294.9	288.5	282.4	276.5	270.7	265.3	260.0	254.9	250.0	245.2	240.6
29.0	373.6	363.9	354.6	345.7	337.2	329.0	321.2	313.8	306.6	299.7	293.1	286.7	280.6	274.7	269.1	263.6	258.4	253.3	248.5	243.8	239.2
30.0	371.0	361.4	352.2	343.4	334.9	326.9	319.1	311.7	304.6	297.8	291.2	284.9	278.8	273.0	267.4	262.0	256.8	251.8	247.0	242.3	237.8
31.0	368.5	358.9	349.8	341.1	332.7	324.7	317.0	309.7	302.6	295.9	289.3	283.1	277.1	271.3	265.8	260.4	255.3	250.3	245.5	240.9	236.4
32.0	365.9	356.5	347.4	338.8	330.5	322.5	314.9	307.7	300.7	294.0	287.5	281.3	275.4	269.6	264.1	258.8	253.7	248.8	244.0	239.4	235.0
33.0	363.4	354.0	345.1	336.5	328.3	320.4	312.9	305.6	298.7	292.1	285.7	279.5	273.6	268.0	262.5	257.2	252.2	247.3	242.6	238.0	233.6
34.0	360.9	351.6	342.7	334.2	326.1	318.3	310.8	303.7	296.8	290.2	283.9	277.8	271.9	266.3	260.9	255.7	250.6	245.8	241.1	236.6	232.2
35.0	358.4	349.2	340.4	332.0	323.9	316.2	308.8	301.7	294.9	288.3	282.0	276.0	270.2	264.6	259.3	254.1	249.1	244.3	239.7	235.2	230.9
36.0	355.9	346.8	338.1	329.7	321.7	314.1	306.7	299.7	293.0	286.5	280.3	274.3	268.5	263.0	257.7	252.5	247.6	242.8	238.2	233.8	229.5
37.0	353.5	344.4	335.8	327.5	319.6	312.0	304.7	297.7	291.1	284.6	278.5	272.5	266.8	261.4	256.1	251.0	246.1	241.4	236.8	232.4	228.2
38.0	351.0	342.0	333.5	325.3	317.4	309.9	302.7	295.8	289.2	282.8	276.7	270.8	265.2	259.7	254.5	249.5	244.6	239.9	235.4	231.0	226.8
39.0	348.6	339.7	331.2	323.1	315.3	307.9	300.7	293.9	287.3	281.0	274.9	269.1	263.5	258.1	252.9	247.9	243.1	238.5	234.0	229.7	225.5
40.0	346.2	337.4	329.0	320.9	313.2	305.8	298.7	292.0	285.4	279.2	273.2	267.4	261.8	256.5	251.4	246.4	241.6	237.0	232.6	228.3	224.1

DATA-TABLE 7 *by Niels Ramsing & Jens Gundersen* **Unisense A/S - www.unisense.com**

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Oxygen solubility at different temperatures and salinities of seawater

Units: µmol/l

Salinity	Temperature (°C)																				
(‰)	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0	40.0
0.0	283.9	278.3	273.0	267.8	262.8	257.9	253.2	248.7	244.3	240.0	235.9	231.9	228.0	224.2	220.5	217.0	213.5	210.1	206.7	203.5	200.4
1.0	282.2	276.7	271.4	266.3	261.3	256.5	251.8	247.3	243.0	238.7	234.6	230.6	226.8	223.0	219.4	215.8	212.3	209.0	205.7	202.5	199.3
2.0	280.6	275.1	269.8	264.7	259.8	255.0	250.4	245.9	241.6	237.4	233.3	229.4	225.6	221.8	218.2	214.7	211.2	207.9	204.6	201.4	198.3
3.0	278.9	273.5	268.3	263.2	258.3	253.6	249.0	244.6	240.3	236.1	232.1	228.1	224.3	220.6	217.0	213.5	210.1	206.8	203.6	200.4	197.3
4.0	277.3	271.9	266.7	261.7	256.8	252.1	247.6	243.2	238.9	234.8	230.8	226.9	223.1	219.5	215.9	212.4	209.0	205.7	202.5	199.4	196.3
5.0	275.7	270.3	265.2	260.2	255.4	250.7	246.2	241.8	237.6	233.5	229.5	225.7	221.9	218.3	214.7	211.3	207.9	204.6	201.4	198.3	195.3
6.0	274.0	268.7	263.6	258.7	253.9	249.3	244.8	240.5	236.3	232.2	228.3	224.4	220.7	217.1	213.6	210.2	206.8	203.6	200.4	197.3	194.3
7.0	272.4	267.2	262.1	257.2	252.5	247.9	243.4	239.1	235.0	230.9	227.0	223.2	219.5	215.9	212.4	209.0	205.7	202.5	199.4	196.3	193.3
8.0	270.8	265.6	260.6	255.7	251.0	246.5	242.1	237.8	233.7	229.7	225.8	222.0	218.3	214.8	211.3	207.9	204.7	201.5	198.3	195.3	192.3
9.0	269.2	264.1	259.1	254.2	249.6	245.1	240.7	236.5	232.4	228.4	224.5	220.8	217.2	213.6	210.2	206.8	203.6	200.4	197.3	194.3	191.3
10.0	267.6	262.5	257.6	252.8	248.2	243.7	239.4	235.2	231.1	227.1	223.3	219.6	216.0	212.5	209.1	205.7	202.5	199.4	196.3	193.3	190.3
11.0	266.1	261.0	256.1	251.3	246.7	242.3	238.0	233.8	229.8	225.9	222.1	218.4	214.8	211.3	208.0	204.7	201.4	198.3	195.3	192.3	189.4
12.0	264.5	259.5	254.6	249.9	245.3	240.9	236.7	232.5	228.5	224.6	220.9	217.2	213.7	210.2	206.8	203.6	200.4	197.3	194.2	191.3	188.4
13.0	262.9	257.9	253.1	248.4	243.9	239.6	235.3	231.2	227.3	223.4	219.7	216.0	212.5	209.1	205.7	202.5	199.3	196.2	193.2	190.3	187.4
14.0	261.4	256.4	251.6	247.0	242.5	238.2	234.0	229.9	226.0	222.2	218.5	214.9	211.4	208.0	204.6	201.4	198.3	195.2	192.2	189.3	186.5
15.0	259.9	254.9	250.2	245.6	241.1	236.8	232.7	228.6	224.7	220.9	217.3	213.7	210.2	206.8	203.6	200.4	197.2	194.2	191.2	188.3	185.5
16.0	258.3	253.4	248.7	244.2	239.8	235.5	231.4	227.4	223.5	219.7	216.1	212.5	209.1	205.7	202.5	199.3	196.2	193.2	190.2	187.4	184.6
17.0	256.8	252.0	247.3	242.8	238.4	234.2	230.1	226.1	222.2	218.5	214.9	211.4	208.0	204.6	201.4	198.2	195.2	192.2	189.3	186.4	183.6
18.0	255.3	250.5	245.9	241.4	237.0	232.8	228.8	224.8	221.0	217.3	213.7	210.2	206.8	203.5	200.3	197.2	194.1	191.2	188.3	185.4	182.7
19.0	253.8	249.0	244.4	240.0	235.7	231.5	227.5	223.6	219.8	216.1	212.5	209.1	205.7	202.4	199.2	196.1	193.1	190.2	187.3	184.5	181.7
20.0	252.3	247.6	243.0	238.6	234.3	230.2	226.2	222.3	218.6	214.9	211.4	207.9	204.6	201.3	198.2	195.1	192.1	189.2	186.3	183.5	180.8
21.0	250.8	246.1	241.6	237.2	233.0	228.9	224.9	221.1	217.3	213.7	210.2	206.8	203.5	200.3	197.1	194.1	191.1	188.2	185.4	182.6	179.9
22.0	249.3	244.7	240.2	235.8	231.7	227.6	223.6	219.8	216.1	212.5	209.1	205.7	202.4	199.2	196.1	193.0	190.1	187.2	184.4	181.6	179.0
23.0	247.9	243.2	238.8	234.5	230.3	226.3	222.4	218.6	214.9	211.4	207.9	204.6	201.3	198.1	195.0	192.0	189.1	186.2	183.4	180.7	178.0
24.0	246.4	241.8	237.4	233.1	229.0	225.0	221.1	217.4	213.7	210.2	206.8	203.4	200.2	197.1	194.0	191.0	188.1	185.2	182.5	179.8	177.1
25.0	244.9	240.4	236.0	231.8	227.7	223.7	219.9	216.2	212.5	209.0	205.6	202.3	199.1	196.0	193.0	190.0	187.1	184.3	181.5	178.8	176.2
26.0	243.5	239.0	234.7	230.5	226.4	222.5	218.6	214.9	211.4	207.9	204.5	201.2	198.0	194.9	191.9	189.0	186.1	183.3	180.6	177.9	175.3
27.0	242.1	237.6	233.3	229.1	225.1	221.2	217.4	213.7	210.2	206.7	203.4	200.1	197.0	193.9	190.9	188.0	185.1	182.4	179.6	177.0	174.4
28.0	240.6	236.2	231.9	227.8	223.8	219.9	216.2	212.5	209.0	205.6	202.3	199.0	195.9	192.9	189.9	187.0	184.2	181.4	178.7	176.1	173.5
29.0	239.2	234.8	230.6	226.5	222.5	218.7	215.0	211.4	207.9	204.5	201.2	198.0	194.8	191.8	188.9	186.0	183.2	180.5	177.8	175.2	172.6
30.0	237.8	233.5	229.3	225.2	221.3	217.4	213.7	210.2	206.7	203.3	200.1	196.9	193.8	190.8	187.9	185.0	182.2	179.5	176.9	174.3	171.7
31.0	236.4	232.1	227.9	223.9	220.0	216.2	212.5	209.0	205.5	202.2	199.0	195.8	192.7	189.8	186.9	184.0	181.3	178.6	175.9	173.4	170.9
32.0	235.0	230.7	226.6	222.6	218.7	215.0	211.3	207.8	204.4	201.1	197.9	194.7	191.7	188.7	185.9	183.0	180.3	177.6	175.0	172.5	170.0
33.0	233.6	229.4	225.3	221.3	217.5	213.8	210.1	206.7	203.3	200.0	196.8	193.7	190.7	187.7	184.9	182.1	179.4	176.7	174.1	171.6	169.1
34.0	232.2	228.0	224.0	220.0	216.2	212.5	209.0	205.5	202.1	198.9	195.7	192.6	189.6	186.7	183.9	181.1	178.4	175.8	173.2	170.7	168.2
35.0	230.9	226.7	222.7	218.8	215.0	211.3	207.8	204.3	201.0	197.8	194.6	191.6	188.6	185.7	182.9	180.1	177.5	174.9	172.3	169.8	167.4
36.0	229.5	225.4	221.4	217.5	213.8	210.1	206.6	203.2	199.9	196.7	193.6	190.5	187.6	184.7	181.9	179.2	176.5	173.9	171.4	168.9	166.5
37.0	228.2	224.1	220.1	216.2	212.5	208.9	205.4	202.1	198.8	195.6	192.5	189.5	186.6	183.7	180.9	178.2	175.6	173.0	170.5	168.1	165.7
38.0	226.8	222.7	218.8	215.0	211.3	207.7	204.3	200.9	197.7	194.5	191.4	188.5	185.6	182.7	180.0	177.3	174.7	172.1	169.6	167.2	164.8
39.0	225.5	221.4	217.5	213.8	210.1	206.6	203.1	199.8	196.6	193.4	190.4	187.4	184.5	181.7	179.0	176.3	173.8	171.2	168.7	166.3	164.0
40.0	224.1	220.1	216.3	212.5	208.9	205.4	202.0	198.7	195.5	192.4	189.3	186.4	183.5	180.8	178.1	175.4	172.8	170.3	167.9	165.5	163.1

DATA-TABLE 8 *by Niels Ramsing & Jens Gundersen* **Unisense A/S - www.unisense.com**

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Oxygen solubility at different temperatures and salinities of seawater

Units: µmol/l

Salinity (‰)	Temperature (°C) 0.0	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0
0.0	456.6	398.9	352.6	314.9	283.9	257.9	235.9	217.0	200.4	185.6	172.2	159.9	148.3	137.2	126.5	115.9	105.5	95.1	84.7	74.5	64.3
5.0	441.1	385.9	341.6	305.5	275.7	250.7	229.5	211.3	195.3	181.0	168.1	156.2	145.0	134.2	123.8	113.6	103.4	93.3	83.2	73.2	63.3
10.0	426.1	373.3	330.8	296.2	267.6	243.7	223.3	205.7	190.3	176.6	164.1	152.6	141.7	131.3	121.2	111.3	101.4	91.6	81.7	71.9	62.2
15.0	411.7	361.1	320.5	287.3	259.9	236.8	217.3	200.4	185.5	172.3	160.2	149.1	138.6	128.5	118.7	109.0	99.4	89.8	80.2	70.7	61.2
20.0	397.7	349.3	310.4	278.6	252.3	230.2	211.4	195.1	180.8	168.0	156.4	145.6	135.5	125.7	116.2	106.8	97.5	88.1	78.8	69.4	60.2
25.0	384.1	337.9	300.7	270.2	244.9	223.7	205.6	190.0	176.2	163.9	152.7	142.3	132.4	123.0	113.7	104.6	95.5	86.4	77.3	68.2	59.2
30.0	371.0	326.9	291.2	262.0	237.8	217.4	200.1	185.0	171.7	159.9	149.0	139.0	129.4	120.3	111.3	102.5	93.6	84.8	75.9	67.0	58.2
35.0	358.4	316.2	282.0	254.1	230.9	211.3	194.6	180.1	167.4	155.9	145.5	135.7	126.5	117.7	109.0	100.4	91.8	83.2	74.5	65.8	57.2
40.0	346.2	305.8	273.2	246.4	224.1	205.4	189.3	175.4	163.1	152.1	142.0	132.6	123.7	115.1	106.7	98.3	90.0	81.6	73.1	64.7	56.3
45.0	334.4	295.8	264.6	238.9	217.6	199.6	184.2	170.8	159.0	148.3	138.6	129.5	120.9	112.6	104.4	96.3	88.2	80.0	71.8	63.5	55.3
50.0	323.0	286.1	256.3	231.7	211.3	194.0	179.2	166.3	154.9	144.7	135.3	126.5	118.2	110.1	102.2	94.3	86.4	78.5	70.5	62.4	54.4
55.0	311.9	276.7	248.2	224.7	205.1	188.5	174.3	161.9	151.0	141.1	132.1	123.6	115.5	107.7	100.0	92.4	84.7	77.0	69.2	61.3	53.5
60.0	301.3	267.7	240.4	217.9	199.1	183.2	169.6	157.7	147.1	137.6	128.9	120.7	112.9	105.4	97.9	90.5	83.0	75.5	67.9	60.2	52.6
65.0	291.0	258.9	232.8	211.3	193.3	178.1	165.0	153.5	143.4	134.2	125.8	117.9	110.4	103.1	95.8	88.6	81.4	74.1	66.6	59.2	51.7
70.0	281.0	250.4	225.5	204.9	187.7	173.0	160.5	149.5	139.8	130.9	122.8	115.2	107.9	100.8	93.8	86.8	79.8	72.6	65.4	58.1	50.8
75.0	271.4	242.2	218.4	198.7	182.2	168.2	156.1	145.6	136.2	127.7	119.9	112.5	105.5	98.6	91.8	85.0	78.2	71.2	64.2	57.1	50.0
80.0	262.2	234.2	211.5	192.6	176.8	163.4	151.9	141.7	132.7	124.6	117.0	109.9	103.1	96.4	89.9	83.3	76.6	69.9	63.0	56.1	49.1
85.0	253.2	226.6	204.8	186.8	171.7	158.8	147.7	138.0	129.3	121.5	114.2	107.3	100.8	94.3	88.0	81.6	75.1	68.5	61.8	55.1	48.3
90.0	244.5	219.1	198.3	181.1	166.7	154.3	143.7	134.4	126.0	118.5	111.5	104.9	98.5	92.3	86.1	79.9	73.6	67.2	60.7	54.1	47.5
95.0	236.2	211.9	192.1	175.6	161.8	150.0	139.8	130.8	122.8	115.6	108.8	102.4	96.3	90.2	84.3	78.2	72.1	65.9	59.6	53.1	46.6
100.0	228.1	205.0	186.0	170.3	157.1	145.8	136.0	127.4	119.7	112.7	106.2	100.0	94.1	88.3	82.5	76.6	70.7	64.6	58.4	52.2	45.8
105.0	220.3	198.2	180.2	165.1	152.5	141.7	132.3	124.0	116.7	109.9	103.6	97.7	92.0	86.3	80.7	75.0	69.3	63.4	57.4	51.2	45.1
110.0	212.7	191.7	174.5	160.1	148.0	137.7	128.7	120.8	113.7	107.2	101.2	95.4	89.9	84.4	79.0	73.5	67.9	62.1	56.3	50.3	44.3
115.0	205.4	185.4	169.0	155.2	143.7	133.8	125.2	117.6	110.8	104.5	98.7	93.2	87.9	82.6	77.3	72.0	66.5	60.9	55.2	49.4	43.5
120.0	198.4	179.3	163.6	150.5	139.5	130.0	121.8	114.5	108.0	102.0	96.4	91.0	85.9	80.8	75.7	70.5	65.2	59.8	54.2	48.5	42.8
125.0	191.6	173.4	158.5	146.0	135.4	126.3	118.4	111.5	105.2	99.4	94.1	88.9	83.9	79.0	74.0	69.0	63.9	58.6	53.2	47.7	42.1
130.0	185.0	167.7	153.4	141.5	131.4	122.8	115.2	108.5	102.5	97.0	91.8	86.9	82.0	77.3	72.5	67.6	62.6	57.5	52.2	46.8	41.3
135.0	178.7	162.2	148.6	137.2	127.6	119.3	112.1	105.7	99.9	94.6	89.6	84.8	80.2	75.6	70.9	66.2	61.3	56.4	51.2	46.0	40.6
140.0	172.6	156.9	143.9	133.1	123.8	115.9	109.0	102.9	97.3	92.2	87.4	82.9	78.4	73.9	69.4	64.8	60.1	55.3	50.3	45.1	39.9
145.0	166.6	151.7	139.4	129.0	120.2	112.7	106.0	100.2	94.9	90.0	85.4	80.9	76.6	72.3	67.9	63.5	58.9	54.2	49.3	44.3	39.2
150.0	160.9	146.7	134.9	125.1	116.7	109.5	103.2	97.5	92.4	87.7	83.3	79.0	74.9	70.7	66.5	62.2	57.7	53.1	48.4	43.5	38.6
155.0	155.4	141.9	130.7	121.3	113.3	106.4	100.3	95.0	90.1	85.6	81.3	77.2	73.2	69.1	65.1	60.9	56.6	52.1	47.5	42.7	37.9
160.0	150.1	137.2	126.5	117.6	110.0	103.4	97.6	92.5	87.8	83.4	79.3	75.4	71.5	67.6	63.7	59.6	55.4	51.1	46.6	42.0	37.2
165.0	144.9	132.7	122.5	114.0	106.7	100.5	94.9	90.0	85.5	81.4	77.4	73.6	69.9	66.1	62.3	58.4	54.3	50.1	45.7	41.2	36.6
170.0	139.9	128.3	118.7	110.5	103.6	97.6	92.3	87.6	83.4	79.4	75.6	71.9	68.3	64.7	61.0	57.2	53.2	49.1	44.9	40.5	36.0
175.0	135.1	124.1	114.9	107.2	100.6	94.9	89.8	85.3	81.2	77.4	73.8	70.2	66.8	63.3	59.7	56.0	52.1	48.2	44.0	39.7	35.3
180.0	130.5	120.0	111.3	103.9	97.6	92.2	87.4	83.1	79.1	75.5	72.0	68.6	65.2	61.9	58.4	54.8	51.1	47.2	43.2	39.0	34.7
185.0	126.0	116.0	107.8	100.8	94.8	89.6	85.0	80.9	77.1	73.6	70.3	67.0	63.8	60.5	57.1	53.7	50.1	46.3	42.4	38.3	34.1
190.0	121.7	112.2	104.3	97.7	92.0	87.0	82.7	78.7	75.2	71.8	68.6	65.4	62.3	59.2	55.9	52.6	49.1	45.4	41.6	37.6	33.5
195.0	117.5	108.5	101.0	94.7	89.3	84.6	80.4	76.7	73.2	70.0	66.9	63.9	60.9	57.9	54.7	51.5	48.1	44.5	40.8	36.9	32.9
200.0	113.5	104.9	97.8	91.8	86.7	82.2	78.2	74.6	71.4	68.3	65.3	62.4	59.5	56.6	53.6	50.4	47.1	43.6	40.0	36.3	32.4