The eddy correlation (EC) technique in aquatic systems is becoming a more commonly applied method for determining $O_2$ fluxes at boundary-layer interfaces. The advantage of the EC technique is that it noninvasively resolves constituent fluxes in high-temporal resolution and can do so at study sites where it is not feasible to deploy benthic chambers or microprofilers (e.g., coral reefs or rocky bottoms). Furthermore, the EC measurements document the natural hydrodynamics, and thus shed new light on the highly intermittent nature of benthic fluxes. The technique has since been applied by various researchers in lakes (Brand et al. 2008), rivers (McGinnis et al. 2008; Lorrai et al. 2010), shallow coastal regions (Berg et al. 2003; Kuwae et al. 2006; Berg and Huettel 2008), deep-ocean sediments (Berg et al. 2009), hard-bottom substrates (Glud et al. 2010), sea grass beds (Hume et al. 2011), and has now been extended to measure $H_2S$ fluxes in the Baltic Sea (this work). Whereas the EC technique has a great potential for a wide range of applications, the number of users is still relatively limited. One of the largest challenges is acquiring reliable EC equipment.

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two parameters—the vertical velocity and the dissolved constituent (from here on referred to as $O_2$ unless otherwise specified) in the same measurement location (measurement volume; Fig. 1A). The determined fluxes are derived from the signals arising from seafloor exchange in an upstream area of $\sim$10-100 m$^2$ (Berg et al. 2007). The $O_2$ concentration must be measured with fast responding microelectrodes (<0.2 to 0.3 s) and a fast, robust picoamplifier (Berg et al. 2003; McGinnis et al. 2008; Lorrai et al. 2010).

Whereas the $O_2$ EC technique is gradually becoming a standard flux measurement approach, there still exists a deficit of reliable, affordable ‘off-the-shelf’ EC equipment. At the time of this publication only two commercial manufacturers provide complete $O_2$ EC systems, however, neither of these systems have a proven track record. Therefore, we developed a simple, robust amplifier in an open-source effort between various researchers with the goal that the amplifier design is available for free to interested users. Our amplifier is highly customizable for both varying microelectrode ranges and can be used with different amperometric electrodes. The amplifier itself is a single component and can be easily adapted to existing ADVs with an analog input. The functional circuitry is galvanically isolated and features very low noise which is necessary for indoor flumes subject to 50/60Hz electrical noise contamination. The amplifier can be easily built in-house by personnel with qualified electronics training or by outside manufacturers and will increase the availability of EC systems for the scientific community.

The main technical features of the amplifier include the following: Adjustable sensor polarization, gain, and voltage-offsets—can use any type of amperometric microelectrode with polarization potentials within ±1.2 V; ability to measure in burst or continuous mode; clean, unfiltered acquisition of sensor data; cutoff filtering and response time of signal well above the frequency range of contributing eddies; galvanic isolation; self-contained, plug-and-play design adaptable to existing ADVs with analog inputs.

In this article, we describe the amplifier concept and design, test the response time, present (briefly) the sensor mounting and housing, and perform a sensitivity analysis evaluating potential loss of flux due to limitations in sensor ranges and analog-to-digital conversion. Finally, results are shown from field tests in a local river ($O_2$) and the Baltic Sea ($H_2S$).

**Materials and procedures**

The complete EC system consists of an ADV (Fig. 1A), amplifier and housing, sensors and mount, a deployment frame, and associated battery housings, cables, etc. Several configurations exist and most of these details are published (see references above). We focus here on the picoamplifier.

**Electronics**

Fig. 2A shows the top and bottom photo of the amplifier and the schematic overview (Fig. 2B – See Web Appendix for complete schematics). The components are mounted on a 3 x 7 cm board using high-quality components. The amplifier can operate between 9 to 18 V input power, but other voltages can be adapted. The average power consumption is 50 mA at 12 V. The output voltage is ±14 V, which offers a wide range of applications. The galvanic isolation separates the measurement current from the output current and therefore avoids feedback and reduces noise contamination of the signal.

**Fig. 1.** A) Eddy correlation system shown on an ROV-deployable frame. 1) frame, 2) measurement volume, 3) sensor and sensor holder and 4) amplifier housing and connector. B) Dual $O_2$ sensor deployed on the same ADV.
Adjustable gain

As the pA output of every microelectrode is different (e.g., in a test batch of 10 microelectrodes the output values for 0% O2 saturation ranged from 3-20 pA while 100% ranged from 54-220 pA), the amplifier is equipped with an adjustable range (gain) setting. This allows the ‘tuning’ of the system to optimize the measurement voltage output. Furthermore, the voltage output can also be specially adjusted for the system in which measurements will take place, for example in a system with very low oxygen concentration the range can be enlarged to increase measurement resolution.

Adjustable polarization

The amplifier is designed to be used with any sensors with polarization potentials between ± 1.2 V, however currently only O2 and H2S sensors are fast enough for EC application. These sensors require different polarization voltages for O2 (-0.78 V) and H2S (+0.08 V) (Revsbech, 1989; Kuhl et al. 1998).

Offset

The offset setting allows the user to adjust the lower voltage output that corresponds to the 0 µmol L⁻¹ input signal. This helps to prevent potential off-scale reading in the event of sensor drift.

Laboratory testing

The response of the amplifier to input signals ranging from 1 to 100 Hz was tested using a DC square wave generator. This essentially tests the amplifier’s ability to resolve realistically sized fluctuations. The generated signal was recorded through two separate channels: one was connected directly to an oscilloscope (reference signal), whereas the other one was first sent through the amplifier. The amplifier signal was then compared with the reference signal to determine response time and signal loss/cutoff.

Amplifier housing

The amplifier is housed within a stainless steel casing (Fig. 3) with a pressure rating of 6000 m. The system described below utilizes impulse connectors between the sensor and the amplifier with a silicon oil-filled sensor holder for pressure compensation (plans available upon request). The impulse connector is pressure rated to 3500 m; however sensor holders using Kemlon connectors (rated for 6000 m) have been used and are available (plans available upon request).

EC system

The analog output from the amplifier is connected to the ADV analog input with a shielded cable and a 5-pin impulse connector. Different types and qualities of connectors and cables exist with a trade-off between availability, price, and signal quality that goes beyond this study. The Vector used in this study is equipped with a Nortek-supplied end-bell with two analog inputs (5-pin each) and an 8-pin external power/RS-422 connection. The system allows a maximum of two sensors to be simultaneously deployed (Fig. 1). Power for the ADV is supplied by batteries installed in the ADV housing or with an external battery canister, and power for the amplifiers is supplied by a separate, external battery source (Fig. 1A). With the 4GB memory available on the Nortek ADV, this configuration allows over 10 d of continuous data collection at 64 Hz (assuming six 13.5V 50 Wh batteries for the ADV). With 20 D cell batteries, a single amplifier can be
operated from 7 to 9 d. For further details on deployment, see Berg et al. (2003), Berg and Huettel (2008), and McGinnis et al. (2008). The EC equipment can be mounted on various frames optimized for different environmental conditions (Fig. 4) including the IFM-GEOMAR frame for ROV deployments (Fig. 1A).

Flux analysis

The constituent (C) fluxes (F) are expressed as \( F = V_Z C \) (mass area\(^{-1}\) time\(^{-1}\)), where the vertical velocity \( V_Z \) and constituents can be broken up into their mean and turbulent fluctuation \( V_Z = \bar{V}_Z + V'_Z \) and \( C = \bar{C} + C' \) (Berg et al. 2003; Lee et al. 2004). The fluxes are calculated from raw velocity and dissolved constituent data using a self-developed software program (McGinnis unpubl. data). For simplicity, the mean and fluctuation are defined and extracted using linear detrending (see Lee et al. 2004) over generally 2 to 2.5 min windows. This time window is selected as it includes all contributing eddies (up to \( \sim 100 \) s) while excluding larger scale, non-turbulent contributions (McGinnis et al. 2008; Lorrai et al. 2010). Due to the turbulent nature of the fluxes (i.e., the large degree of flux variability), they are averaged into 15 min time windows (Berg et al. 2009).

Sensitivity to lower grade AD converter

The following procedure is used to investigate potential flux signal loss due to the 16-bit AD converter. We developed an EC simulation program that models the \( O_2 \) measurement from the tip of the electrode through the amplifier and finally the 16-bit converter in the Vector. The assumption is that the \( O_2 \) concentrations in the original data set are those that will be actually measured in the water column by the modeled EC. This analysis extends to the sensitivity of potentially limited ranges of microelectrodes.
Procedure:
1. $O_2$ measured is converted to pA (0–300) with a linear relation.
2. pA range is converted to voltage (0–5) where 4 V is 100% $O_2$ saturation.
3. Volts are converted to bits (digitized).
4. Bits are converted to an integer, which is now a step function of voltage.
5. $O_2$ ‘processed’ is calculated from bits (linear relation).
6. Fluxes are extracted from ‘processed’ $O_2$ data.

**Freshwater $O_2$ tests**

Two field tests were conducted in the Schwentine River in Kiel, Germany (Fig. 4A). This is a shallow (~70 cm) dammed river. The EC devices were positioned near the spillway where the water velocity was relatively constant. The first test was in 19 June 2009 in which two sensors were deployed simultaneously with a single ADV. The second test was conducted in November 2009, however one of the sensors failed.

**Baltic Sea $H_2S$ test**

The $H_2S$ field test was conducted in the anoxic deepwater of the Baltic Sea in June 2010 aboard RV Alkor during cruise AL355 (Fig. 4B). The system was deployed in the Eastern Gotland Basin at 192 m depth and collected data for nearly 24 h (15 Jun 16:48 – 16 Jun 16:28). The deployment was approximately 50 km west of Ventspils, Latvia (57°18.71¢ 20°32.95¢). Two $H_2S$ microelectrodes were attached on the EC equipment; however one of them malfunctioned as the system was deployed.

**Assessment**

**Amplifier frequency range**

While the size distribution and time scales of the vertical eddies depend on local hydrodynamics (see Lorrain et al. 2010), for field applications the frequency of the flux contributing eddies are generally in the range of 0.01 – 1 Hz (1 – 100 s) (Berg et al. 2003; McGinnis et al. 2008). The fastest eddies we should ever have to resolve are slower than about 3-5 Hz (Kuwae et al. 2006; Lorrain et al. 2010). Therefore, it is crucial that the amplifier can resolve the smallest eddy with no signal loss due to cutoff or response time. It was found that nearly independent of input frequency, the amplifier generally had a response time of < 0.1 ms. There is no signal loss due to the cutoff frequency (50 Hz) from low frequencies up to 20 Hz. Therefore, the amplifier is fully capable of resolving the complete spectrum of flux contributing eddies.

**Noise analyses**

Noise in the amplifier is due to external/internal electrical issues, sensor imperfections, and perhaps loose or moist connections. This noise is random (white) and cancels out in the flux calculations. However, it is obviously desirable to minimize the noise in the measurement system, especially in oligotrophic systems where fluxes can be below 1 mmol m$^{-2}$ d$^{-1}$.

The noise analysis is simply defined as the difference of neighboring data points $C_{i+1} - C_i$ and is performed on the unfiltered, raw 64 Hz data—much faster than the fastest eddies. The data are plotted in a normalized histogram (Fig. 5). The left 3 panels (Fig. 5A-C) are from the EC systems shown in Fig. 4A in the Schwentine River. These have surprising low noise considering the environment where they are deployed (near electrical cables and not completely submerged). The $H_2S$ EC deployed in the Baltic Sea also shows very low noise in the data. Furthermore, the noise is approximately evenly distributed (Gaussian) reflecting “white noise,” which does not interfere with the flux values.

**n-bit analog to digital conversion and sensor range**

The Nortek Vector utilizes a 16-bit AD converter. Obviously, there is a risk that loss of the constituent fluctuations in the analog-to-digital conversion will affect the flux calculations. Therefore, we evaluate this process by using a computer simulation to step down the bits and recalculate the fluxes to determine when and how much of the flux signal may be lost (Table 1, Fig. 6).

Two data sets were used in the analyses covering the broad range of fluxes and conditions that can be encountered: the Schwentine River data ($O_2$avg = 212 µmol L$^{-1}$, $V$avg = 5.4 cm s$^{-1}$, Fluxavg = 30.4 mmol m$^{-2}$ d$^{-1}$) and the deep-sea data from Berg et al. (2009) ($O_2$avg = 59 µmol L$^{-1}$, $V$avg = 1.7 cm s$^{-1}$, Fluxavg = –2.05 mmol m$^{-2}$ d$^{-1}$). Table 1 lists the results of this analysis, as well as the corresponding converter and $O_2$ resolution assuming 0–250 µmol L$^{-1}$ over the full scale (all available stored integers). Fig. 6A shows the dramatic reduction in resolution of measured $O_2$ as a function of AD converter bits; however, for both data sets no significant change was detectable in the fluxes down to 14 bits (Table 1; Fig. 6C). Surprisingly, for the Schwentine River data, only very small (<1%) errors were observed for bit conversions from 13 to 9. However, as expected for environments with low absolute $O_2$ exchange rates, the higher bit AD conversion is more critical. The EC data from a deep-sea site with low fluxes of 2.05 mmol m$^{-2}$ d$^{-1}$ (Berg et al. 2009) reveals a 2% error with the 13-bit converter, whereas the 10-bit proved to be too crude and led to a 64% error.

Similar to the AD converter grade analysis, the above results can also be directly related to the resolved microelec-
Table 1. Results of flux sensitivity to AD converter type and % of 16-bit full scale resolution for a high production flux (Schwentine River; 30.44 mmol m$^{-2}$ d$^{-1}$) and low consumption flux (Berg et al. 2009; –2.05 mmol m$^{-2}$ d$^{-1}$) system.

<table>
<thead>
<tr>
<th>AD converter bits ($2^n$)</th>
<th>Steps in resolution</th>
<th>% of 16-bit range</th>
<th>$O_2$ resolution $^*$ (µmol L$^{-1}$)</th>
<th>Flux error$^\dagger$ Schwentine</th>
<th>Flux error$^\dagger$ Berg et al. (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>65536</td>
<td>100</td>
<td>0.0038</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>32768</td>
<td>50</td>
<td>0.0076</td>
<td>0.02</td>
<td>–0.32</td>
</tr>
<tr>
<td>14</td>
<td>16384</td>
<td>25</td>
<td>0.015</td>
<td>0.00</td>
<td>–0.81</td>
</tr>
<tr>
<td>13</td>
<td>8192</td>
<td>13</td>
<td>0.031</td>
<td>–0.18</td>
<td>–1.80</td>
</tr>
<tr>
<td>12</td>
<td>4096</td>
<td>6</td>
<td>0.061</td>
<td>0.34</td>
<td>4.22</td>
</tr>
<tr>
<td>11</td>
<td>2048</td>
<td>3</td>
<td>0.12</td>
<td>–0.49</td>
<td>–3.73</td>
</tr>
<tr>
<td>10</td>
<td>1024</td>
<td>2</td>
<td>0.24</td>
<td>–0.84</td>
<td>–63.8</td>
</tr>
<tr>
<td>9</td>
<td>512</td>
<td>0.8</td>
<td>0.49</td>
<td>0.61</td>
<td>89.4</td>
</tr>
<tr>
<td>8</td>
<td>256</td>
<td>0.4</td>
<td>0.98</td>
<td>12.0</td>
<td>–350</td>
</tr>
</tbody>
</table>

$^*$Assumes $O_2$ range of 0 – 250 µmol L$^{-1}$ over the entire converter resolution.

$^\dagger$Relative to the 16-bit AD converter fluxes.

While these two data sets appear to be relatively insensitive to sensor range and AD converter bits, they also demonstrate the added value of the adjustable gain feature of this amplifier. Furthermore, they also illustrate that auto-zeroing of the sensor signal is not essential for good performance.

Field testing: $O_2$

A field test was conducted in the Schwentine River during June 09 with two sensors connected to a single Vector (Fig. 1B). Results are shown in Fig. 7A. Generally, the two sensor fluxes compare well and reflect the same overall trend. Differences could be attributed to particles contacting the sensor tip. Both sensors verify the highly intermittent and variable nature of the fluxes in this eutrophic, shallow system, particularly the dramatic increase from consumption of –20 mmol m$^{-2}$ d$^{-1}$ at 10 min up to 120 mmol m$^{-2}$ d$^{-1}$ $O_2$ production at 22 min (Fig. 7A). However, the cumulative average of the fluxes quickly converge to a very close agreement and level off to about 30 mmol m$^{-2}$ d$^{-1}$. These fluctuations are likely due to wind gusts driving turbulence and variable cloudiness (changing light for photosynthesis) during the testing in this shallow system. The effect of light is apparent in Fig. 7B during the Nov 2009 test at the same location.

In general, the $O_2$ flux follows the PAR signal. The deployment began at 13:30 and ran until 18:17. The day was overcast and sunset was about 3.5 h after the testing began. Fluxes remain fairly constant for the first hour at –40 mmol m$^{-2}$ d$^{-1}$ and then begin to decrease just around sunset. Fluxes leveled off at around –90 mmol m$^{-2}$ d$^{-1}$ in the final hour.

$H_2S$ testing

$H_2S$ EC measurements were performed in the anoxic waters of the Gotland Basin in the Baltic Sea. The fluxes were resolved with 2.5 min windows and averaged over 15 min (Fig. 8). The data show a continually decreasing $H_2S$ concentration ranging from about 47–39 µmol L$^{-1}$ (Fig. 8A), however sensor drift cannot be excluded as no water samples were obtained for calibration. Current direction stayed nearly constant and velocity magnitude varied from ~3–8 cm s$^{-1}$ (Fig. 8B).
The $\Sigma H_2 S$ fluxes (total sulfide) are also very intermittent during the measurement period, ranging from 0 up to 5 mmol m$^{-2}$ d$^{-1}$ using the 15-min bin-average, with much more variability using the 2-min flux extraction. The solid line on Fig. 8C is the cumulative average of the EC $\Sigma H_2 S$ flux. The mean flux over the time series is 1.9 ± 1.2 mmol m$^{-2}$ d$^{-1}$. Two benthic $\Sigma H_2 S$ chamber deployments close by provided very similar flux values of 1.9 and 3.5 mmol m$^{-2}$ d$^{-1}$, respectively (S. Sommer pers. comm.). The results of our field assessments validate the use of our amplifier for both in situ $O_2$ and $H_2 S$ flux measurements in benthic environments.

**Discussion**

The self-contained amplifier is designed to directly plug into any ADV that can record an analog input (and other ADVs) and does not use control units or signal pre-processing. The presented amplifier, unlike the commercially available highly engineered systems, is simple in design and concept. This minimizes cable lengths (potential source of noise) and eliminates any synchronization issues between the velocity and concentration data. These variables must be aligned perfectly in time to avoid distortion of the subsequent flux calculation. The signal is directly read into the ADV files and stored on the internal memory. It is recommended to use a separate power source for the amplifier independent of the ADV to minimize any potential noise (or drift) problems using a single power source for both instruments.

The same amplifier can readily accept both $O_2$ and $H_2 S$ microelectrodes, and could in fact be used with other amperometric microelectrodes with respect to eddy correlation; the limitation is the size and response time of the sensors. It is worth noting that the amplifier could also be used for microprofiling within the sediment. The sensitivity analyses of the amplifier performance, response time testing, and extensive data sets show that this amplifier is extremely adept at accurately capturing high-resolution $O_2$ and $H_2 S$ readings and their high-frequency fluctuations. Reassuring are also the data shown in Fig. 7A where the concentration was recorded with simultaneously deployed $O_2$ sensors with excellent agreement.

The amplifier’s default configuration (see Web Appendix) includes a 1-pole (first order) filter and has low sensitivity to 50/60 Hz interference from indoor electrical sources. However, the amplifier board layout has been designed to readily receive an additional embed 2-pole filter (second order), providing up to an overall third-order filter to further reduce noise for laboratory and flume applications. However, with shielded cables, steel amplifier housing, and proper grounding (such as the grounding wires of laboratory power systems) the amplifier receives nearly negligible interference levels and allows very reliable indoor measurements even without the additional filters.

The results of Figs. 7 and 8 show a lot of variation in the fluxes. As the method resolves the flux due to turbulent eddies, it is expected that a large variability is present in the system on a short time scale. These are not variations due to “noise” in the classical sense, but are a direct result of the intermittent nature of turbulence and inherent characteristics of the approach and should help to provide new insight into benthic-boundary layer dynamics and sediment exchange phenomena.
**Comments and recommendations**

There are still relatively few EC studies present in the literature. With much to be gained with potential future applications, the availability and cost of the equipment should not be the limitation. With the work presented here, an easy, inexpensive, flexible, and robust solution for sensor amplification becomes available. The presented amplifier is relatively simple to build and use and will help fill a much needed demand for this exciting, and promising measuring approach. However, it is essential that the amplifier should be constructed with the highest quality components and as clean as possible to maintain the high performance of the design. To maximize both the confidence in the data sets and the likelihood that data are obtained, it is advantageous to simultaneously deploy two sensors in the same measurement volume.

As O$_2$ (and H$_2$S) EC in aquatic environments is still a relatively new technique, there are still many unknowns and uncertainties with respect to data treatment and handling, and a deeper understanding of what is actually measured. Now with the equipment in place and available, these issues can be further addressed by a broader community. The amplifier was developed as an “open-source” project and the detailed schematics are given in the Web Appendix.

**References**


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