Title:

An affordable, open-source, microscale conductivity and temperature probe for density measurements in stratified flows

Journal Issue:

International Symposium on Stratified Flows, 1(1)

Author:

Luzzatto-Fegiz, Paolo, UC Santa Barbara
Carminati, Marco, Politecnico di Milano
Stefanelli, Valerio, Politecnico di Milano

Publication Date:

2016

Permalink:

http://escholarship.org/uc/item/6ft077b5

Copyright Information:

An affordable, open-source, microscale conductivity and temperature probe for density measurements in stratified flows

Marco Carminati[1], Valerio Stefanelli[1] and Paolo Luzzatto-Fegiz[2]

[1]Dipartimento di Elettronica, Informazione e Bioingegneria,
Politecnico di Milano, Milano, Italy

[2]Department of Mechanical Engineering,
University of California at Santa Barbara, Santa Barbara, USA

marco1.carminati@polimi.it fegiz@engr.ucsb.edu

Abstract

In stratified flows, conductivity (combined with temperature) is often used to measure density. The conductivity probes typically used can resolve very fine spatial scales, but can be fragile, expensive to replace, and sensitive to environmental noise. A complementary instrument, comprising a low-cost and robust probe, would prove valuable in a wide range of applications where resolving extremely small spatial scales is not needed. We propose using micro-USB connectors as the actual conductivity sensors; these have five gold-plated microelectrodes that can be readily exposed for two-wire or four-wire measurements. To take advantage of our choice of sensor, we design a custom electronic board for simultaneous acquisition from four sensors, with conductivity resolution of 0.1%, comparable to typical existing probes. We demonstrate our system through stratified flow experiments. The multi-channel capability can be used to approximately reconstruct density fields, whereas the customizable design enables measuring density near complex boundaries.

1 Introduction

Conductivity measurement is routinely used (with temperature) to deduce water density in experimental measurements. If high spatial resolution is needed (for example, for measurements of available potential energy, or turbulent mixing), very small (sub-millimiter) electrodes are required; this constitutes a significant challenge for probe manufacturing, and for the attendant electronics, which must maintain a high signal-to-noise ratio while measuring a very small current. By comparison, temperature can be measured with relative ease (e.g. Head, 1983).

A widely adopted design (due to Head, 1983) employs a glass-and-platinum construction to align four electrodes across a distance of only 500 μm. This design has been extremely successful, and has been used in a large number of studies (e.g. Troy and Koseff, 2005; Shravat et al., 2012; Luzzatto-Fegiz and Helfrich, 2014; Carr et al., 2015); however, it is also relatively fragile, such that probe replacements can lead to a significant overall cost and lost measurement time. This issue is particularly pressing if one is attempting to measure conductivity near a solid boundary, where small errors in moving a traverse-mounted probe can result in contact with the wall, yielding sensor damage. Users of relatively delicate sensors can also require substantial training, such that these probes may not be economically viable for use in short projects or undergraduate courses.

An alternative probe design consists of two concentric electrodes, separated by dielectric material (see Hughes, 1996). Fluid is aspirated through the inner electrode, which has an inside diameter of 0.6 mm; since field lines concentrate near the opening, the effective measurement volume is very small. This probe design is very robust, and has been used successfully to yield density profiles in a wide range of studies (e.g. Linden et al., 1990; Davies Wykes and Dalziel, 2014). It remains desirable, however, to have access to sensors that do not require aspiration, as well as to probes that are easier to construct and to customize for different purposes. For example, one may wish to arrange the sensors in a 'rack' for taking a cross section of a gravity current or internal wave, or to embed probes at the interface of a complex boundary.

Interestingly, while the sensors available can access extremely small measurement volumes (which is of great importance, for example, in microstructure measurements of turbulent flows), there exists a large user community that employs these sensors for measurements at somewhat larger scales (for example, in profiling a quiescent stratification before an internal-wave experiment; e.g. Troy and Koseff, 2005; Luzzatto-Fegiz and Helfrich, 2014).

These issues suggest that alternative sensor designs could prove valuable in laboratory settings, as well as in some oceanographic applications. These could consist, for example, of comparably priced, but more robust, probes. Alternatively, one could seek a sensor design that, while still delicate, could be relatively inexpensive and quick to replace.

In this conference contribution, we outline our design for a system for conductivity measurement, which employs readily available components to devise an open-source, affordable, and easily customized design. Section 2 presents our approach to construct suitable electrodes. Section 3 outlines the design of a board that can take advantage of our choice of electrodes. The operation of the board is demonstrated through profiling measurements in a quiescent ambient in sec. 4, whereas an example involving multi-channel measurements of a long internal wave are shown in sec. 5.

2 Connectors as electrodes

For our electrodes, we wish to use standard off-the-shelf components, in order to minimize cost and take a step towards an easily realizable open-source design. We therefore propose using, as electrodes, the pins of standard micro-USB connectors (which are widely used, for example, for battery charging and data transfer on smartphones). These metal pins are gold-plated (thus requiring no treatment to resist corrosion), have an individual width of $250\,\mu$m and separation of $600\,\mu$m, and a cell constant of $130\,\mathrm{m}^{-1}$. By our calculations, this implies an intrinsic thermal noise of at most $30\,\mathrm{pA\,Hz}^{-1/2}$, as well as sub-millisecond time response, making these electrodes highly suitable for stratified flow measurements. Furthermore, micro-USB connectors can be purchased inexpensively, are pre-assembled in four-wire water-proof and shielded cables, and are available in several lengths, ranging from 50 cm to several meters.

We have tested the performance of several other types of connectors for conductivity measurement, but the micro-USB emerged as the best overall solution. For example, while the 'Lightning' connector (used by Apple iOS devices) also can be made to work well, it has two major limitations. First, the electrode area is smaller than for a micro-USB connector (a length of 1.4 mm against 4-5 mm) producing a higher interfacial impedance. Second, there is no direct electrical access to the pins from the other end of the cable; instead, the user must disassemble the cable in order to bypass a small built-in circuit board. By contrast, probe preparation with the micro-USB connector is straightforward:

Figure 1: Assembled micro probe with two micro-USB pins. The shaft outer diameter is 1/4 inch, which can immediately accommodate a standard shielded USB cable.

the metal shield around the plug is easily removed, together with part of the plastic holder, exposing the pins to the liquid. As an additional step, the cable can be inserted in a rigid stainless-steel shaft and sealed with epoxy. An example, using a 1/4 in shaft (which can accommodate a shielded USB cable without additional modification) is shown in fig. 1. Shafts with smaller diameter can of course be used, if the user wishes to assemble a custom-made cable.

3 Designing an open-source system for micro-scale conductivity measurement

To enable using our choice of sensor, we design a custom analog electronic board, for data acquistion. This is coupled with the popular 'Arduino UNO' microcontroller, which is used as gateway to the PC; for convenience, we refer to the resulting system as 'Conduino'. Our board simultaneously samples four probes, in a conductivity range of 0.1 to 15 S/m (corresponding to a density range of approximately 0.9987 to 1.104 g/cm^3), with a sampling time of 10 ms and a resolution of 0.1% (with a noise floor of 2.2 mS/m; if required, better noise performance can be achieved with a lock-in design; see e.g. Rottigni et al., 2011).

The circuit has been designed by balancing the need for low-noise, versatility and simplicity. As illustrated in fig. 2, the core of the system is an off-the-shelf integrated circuit (namely, an 'AD5933' chip), which measures impedance. The chip is complemented with an external buffer for precise adjustment of the output impedance and a transimpedance amplifier at the input. The sensor impedance is probed at 100 kHz; this frequency optimizes performance for our electrodes' area and impedance. An auxiliary network (consisting of a peak detector) allows automatic gain setting and detection of overvoltage, thereby removing the need for user adjustment. For optimal performance and speed, four identical front-ends are connected to the four probes and then multiplexed with a low-parasitics, digitally-controlled analog switch.

The approach described so far enables two-electrode measurements. If long sensor cables are needed (as may be the case, for example, in large laboratory tanks, or field measurements) the resistivity of the cables may affect measurement. This effect can be especially significant in high conductivity solutions (as discussed by Head, 1983). For such measurements, four-electrode measurements are needed to compensate for the resistive

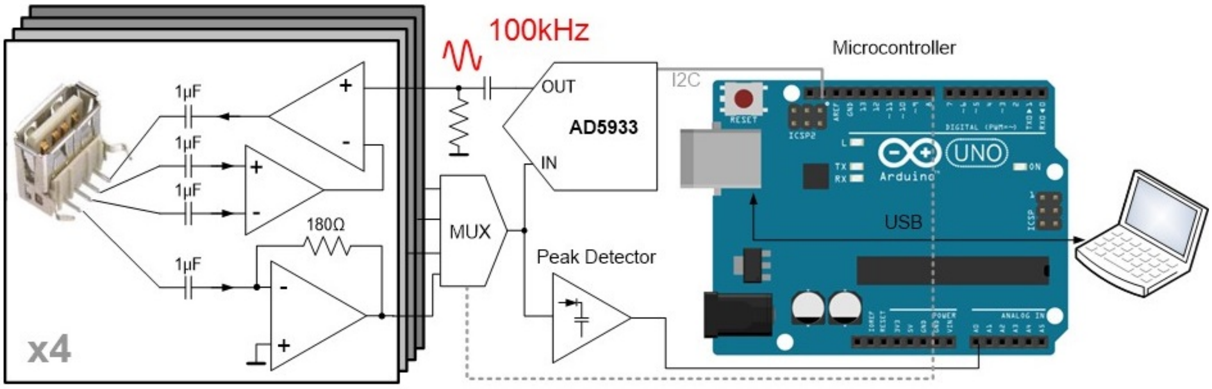

Figure 2: Functional scheme of the 4-channel Conduino board.

loss of the cables. To address this issue, we have included an additional potentiostatic feedback loop, selectable for each channel, which allows four-electrode measurements for high conductivity conditions.

The unit streams data on the USB channel in several programmable modes: single channel mode or multichannel scan, fixed number of samples or free running. Data can be received by any program accessing a virtual serial communication from the USB port (we have succesfully used Matlab, as well as the basic serial monitor Termite). The microcontroller programs can be readily modified using the popular Arduino API.

The Conduino, shown in fig. 3, has a very compact footprint and is powered by the USB port (+5V). Thus, laptop battery supply enables operation in the field as well as completely decoupled from AC power lines, which can carry significant electrical noise. The Conduino is also designed to adapt to other electrode geometries, enabling one to assemble electrodes into custom arrangements (which can include temperature sensors), and to embed them into boundaries or complex geometries. Thanks to the high data rate of the USB connection, several units can be operated in parallel, significantly extending the number of tracked channels.

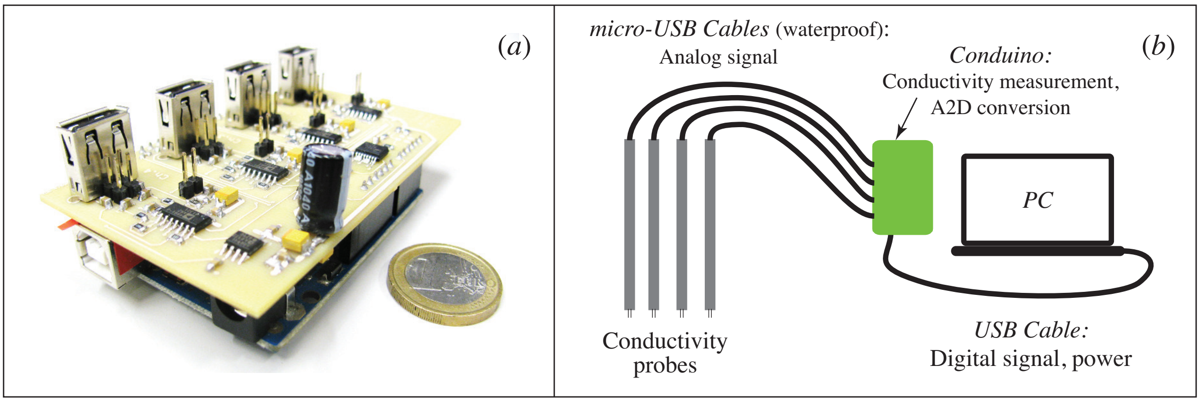

Figure 3: (*a*) "Conduino" prototype, comprising our custom board, mounted on an Arduino UNO microcontroller. The four USB ports on top connect to the four probes, whereas the type-B port (on the left-hand side of the image, towards the left) directly links to the PC. (*b*) Operational schematic: power for performing the measurement is supplied by the PC via USB; there is no need for a separate power supply, or for a distinct analog-to-digital converter.

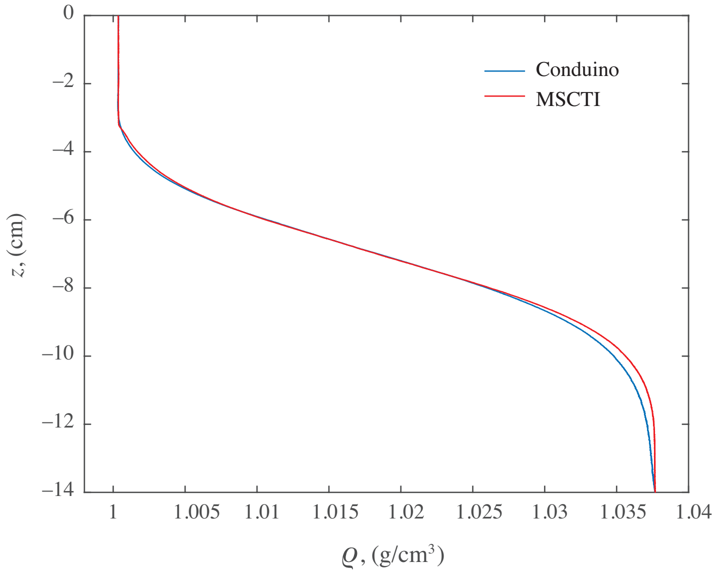

Figure 4: A vertical profile through a two-layer stratification, acquired using a Conduino and an MSCTI probe. Both probes are calibrated using a standard three-point approach, where the top, bottom, and intermediate density are used. The agreement between the two profiles is consistent with this calibration method.

4 Single-channel measurements

We calibrate a probe using a standard three-point procedure, which directly relates probe output and density values using a quadratic fit (this is often deemed sufficiently accurate in stratified flow experiments, see e.g. Shravat et al., 2012); for comparison, we perform a similar calibration on an MSCTI probe by PME. In order to test the stability of the calibration, we first performed 96 hours of continuous measurement in a highly conductive solution ($1.5\,\mathrm{S/m}$), without observing any degradation of the electrodes' coating.

We use a two-bucket arrangement (as described, e.g., by Economidou and Hunt, 2008) to set up a two-layer salt stratification, with $\rho_{top} \simeq 1.0004\,\mathrm{g/cm^3}$ and $\rho_{bot} \simeq 1.0381\,\mathrm{g/cm^3}$. Prior to starting the stratification, we are careful to ensure that all fluid reservoirs have reached thermal equilibrium (the temperature of the laboratory is maintained at 23°C). The Conduino and MSCTI probes are mounted on a motorized, vertical traverse. The resulting density profiles are shown in fig. 4. Note that since the calibrations consist of nonlinear relations between sensor output and density, we do not expect precise agreement throughout the profile, although we do expect very close results in the top and bottom layer, as well as near the midpoint. This is indeed the case in fig. 4, suggesting that the Conduino is performing as expected.

5 An example involving multichannel measurement: long internal waves

We have tested the Conduino in several other laboratory experiments; here we show an example of a multichannel measurement. We calibrate four probes (again, using a three-point procedure) and consider a $1\,\mathrm{m}$-long tank of overall depth $H = 0.2\,\mathrm{m}$, which is stratified to support long internal waves of depression, as sketched in fig. 5a. One probe is used to traverse vertically the background density, before the experiment, as shown on the left of fig. 5b. We use a simple piston arrangement to introduce a disturbance at one

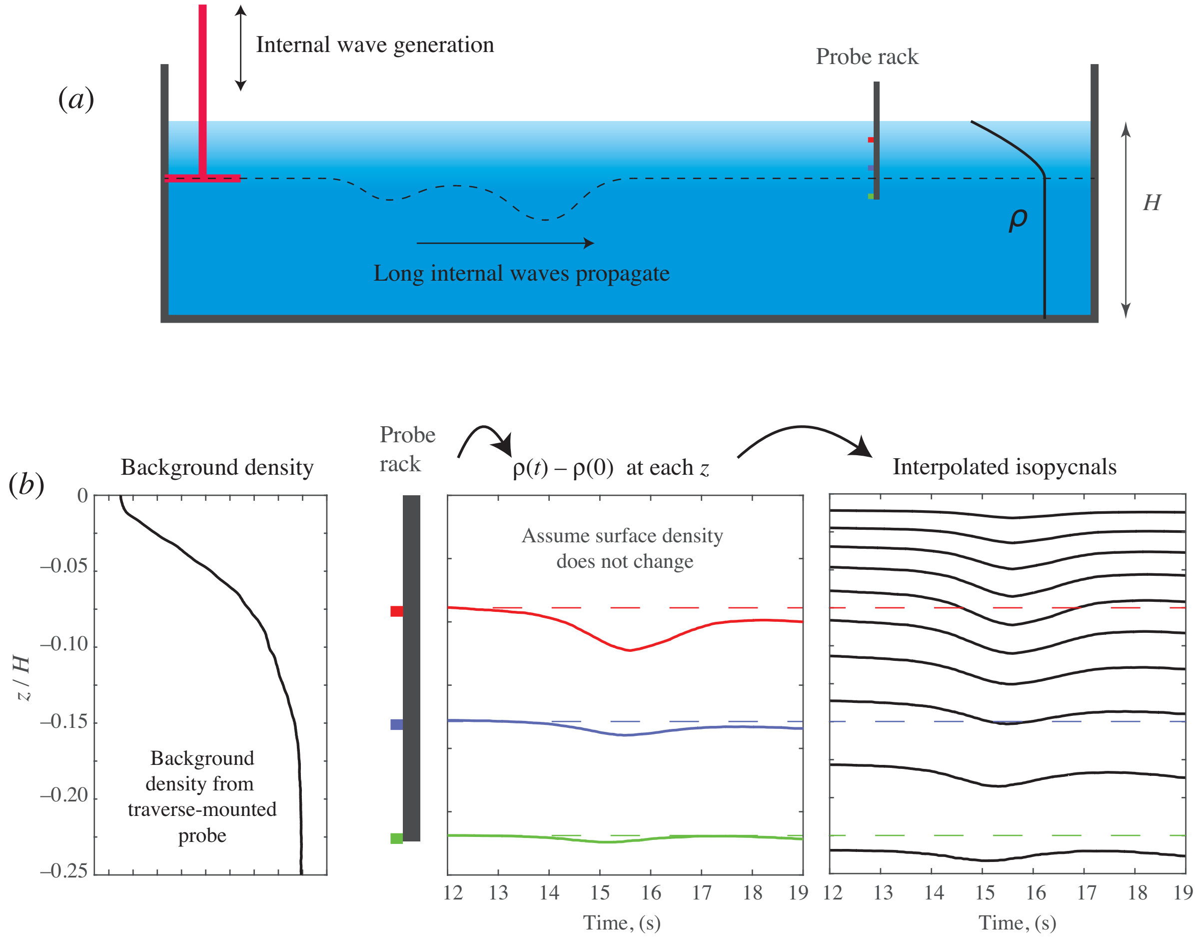

Figure 5: An example of the use of Conduino for measuring long internal waves in a laboratory experiment. One electrode is used to acquire the background profile (shown on the left). The other three electrodes are mounted on a rack away from the wave source. The colored lines show time-traces of density, which enable interpolation of the isopycnal field (right panel).

end of the tank, yielding a train of long internal waves, which propagate away from the source. These waves are measured by the other three probes, which are assembled in a rack arrangement, spaced evenly in depth, and located near the other end of the tank. Time traces of density, at each depth, are shown by colored lines in the mid-panel of fig. 5*b*. Combining these with knowledge of the density at the top and bottom (which is assumed unchanged here), we interpolate the field of density versus time, as shown on the right-hand-panel of fig. 5*b*.

These results illustrate the ease with which electrode arrangements can be customized, as well as the range of measurements made possible by the multichannel capability. Other possible applications may include sensors embedded inside complex boundaries (which may be useful, for example, in modeling building ventilation), conductivity meters for low-cost autonomous underwater vehicles, as well as laboratory demonstrations for courses in engineering and oceanography.

Acknowledgements

We gratefully acknowledge partial support from the DRINK-ABLE Project, Fondazione Cariplo, and the group of Profs. Marco Sampietro and Giorgio Ferrari.

References

Carr, M., Davies, P. A., and Hoebers, R. P. (2015). Experiments on the structure and stability of mode-2 internal solitary-like waves propagating on an offset pycnocline. *Phys. Fluids*, 27(4):046602.

Davies Wykes, M. S. and Dalziel, S. B. (2014). Efficient mixing in stratified flows: experimental study of a Rayleigh–Taylor unstable interface within an otherwise stable stratification. *J. Fluid Mech.*, 756:1027–1057.

Economidou, M. and Hunt, G. R. (2008). Density stratified environments: the double-tank method. *Exp. Fluids*, 46(3):453–466.

Head, M. J. (1983). *The use of miniature four-electrode conductivity probes for high resolution measurement of turbulent density or temperature variations in salt-stratified water flows.* PhD thesis, UC San Diego.

Hughes, G. O. (1996). *Aspects of mixing in stratified flows.* PhD thesis, University of Cambridge.

Linden, P. F., Lane-Serff, G. F., and Smeed, D. A. (1990). Emptying filling boxes - the fluid-mechanics of natural ventilation. *J. Fluid Mech.*, 212:309–335.

Luzzatto-Fegiz, P. and Helfrich, K. R. (2014). Laboratory experiments and simulations for solitary internal waves with trapped cores. *J. Fluid Mech.*, 757:354–380.

Rottigni, A., Carminati, M., Ferrari, G., and Sampietro, M. (2011). Handheld bioimpedance measurement system based on an instrument-on-chip. In *7th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME)*, pages 49–52. IEEE.

Shravat, A., Cenedese, C., and Caulfield, C. P. (2012). Entrainment and mixing dynamics of surface-stress-driven stratified flow in a cylinder. *J. Fluid Mech.*, 691:498–517.

Troy, C. D. and Koseff, J. R. (2005). The instability and breaking of long internal waves. *J. Fluid Mech.*, 543:107–136.