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A low-cost modular data-acquisition system for monitoring biometeorological variables

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ABSTRACT

We describe the design and implementation of a low-cost electronic modular data-acquisition (DAQ) system in the context of the eddy-covariance technique. The system was fully tested under laboratory conditions and later installed on two eddy-covariance towers (ECTs) sited in natural terrestrial and marine environments, respectively. The system was divided in four parts: signal conditioning, data-acquisition, data-transfer and data-processing. A data-acquisition module (DAM) based on the ADuC848 microcontroller was designed in order to acquire these data. This DAM could transfer data directly to a computer or embedded system. By configuring a RS-485 network, a DAQ system could be expanded up to 8 DAMs working simultaneously. Due to its modular design, different parts of the equipment could be easily replaced without affecting the operation of the ECT. The system registered high-frequency (20 Hz) measurements of CO_2, water vapor and wind velocity in the free atmosphere as well as additional ancillary biometeorological variables (1/60 Hz) such as air temperature, solar radiation, soil heat flux, precipitation, and others. Both towers were installed in remote sites using solar cells providing a continuous and autonomous source of energy. This DAQ system proved to be reliable and useful for long-term deployments (> 1 year). Due to its modularity and flexibility the system can be used for any other application involving data recording.

1. Introduction

Long-term measurements made during the last decades show that the chemical composition of the atmosphere is changing. This change is largely attributed to human activities. The gases with the highest rate of change are carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), sulfur dioxide (SO_2), ozone (O_3), nitrogen oxides (NO, NO_2, N_2O) and chlorofluorocarbons (CFCs). Although the greenhouse effect is a natural atmospheric phenomenon in which the atmospheric gases retain part of the energy that comes from the sun, the increase of the concentration of green house gases (GHGs) has caused the intensification of the greenhouse phenomenon. Because these gases remain active for a long time, it is a problem that will last through generations, being in this way a situation of public interest.

CO_2 is the current main GHG contributor. The atmospheric CO_2 concentration measurements record was started by C. David Keeling of the Scripps Institution of Oceanography at a NOAA facility on Mauna Loa in 1958 (Keeling et al., 1976). This record shows an actual 29.2% increase from 315.9 ppm in 1959 to 408.3 ppm in 2017. The second GHG contributor is CH_4. Tropospheric CH_4

Abbreviations: ADC, analog-to-digital converter; CF, compact flash; CPU, central unit of process; DAC, digital-to-analog converter; DAQ, data-acquisition; DAM, data-acquisition module; ECT, eddy-covariance tower; EMg, Rancho El Mogor; IRGA, infrared gas analyzer; PCB, printed circuits boards; SCM, signal conditioning module; SMD, surface-mount technology devices; TSI, Isla Todos Santos; VWC, volumetric water content.

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concentrations have doubled since the industrial revolution mainly due to human activities such as domestic ruminant rearing, agriculture, mining, burning of fossil fuels and other human-influenced processes. CH_4 traps more heat per unit mass than CO_2 and contributes 20% to the total GHG effect and it has a limited atmospheric lifetime of only 10–15 years.

A variety of GHGs measurement methods have been developed involving micro-meteorological and non-micro-meteorological techniques (see Harper et al. (2011) for details), each one with its own advantages and disadvantages. Among the non-micro-meteorological techniques we describe: (a) flux chambers (or wind tunnels), which allow the precise measurement of gas flows in animals and fields, but interferes with the normal emission process, and (b) tracer-ratio techniques, in which a tracer gas is released with the gas of interest. Micro-meteorological techniques are oriented to the measurement of gas flows in the free atmosphere and relate the measured variables of these flows to the emissions of animals and the field. There is a wide variety of micro-meteorological techniques: (a) mass balance technique, (b) vertical flux techniques (e.g. eddy-covariance, flux-gradient, relaxed eddy accumulation), and (c) inverse dispersion techniques. Among the mentioned techniques the most important are dynamic flux chambers and micro-meteorological techniques (Scotto di Perta et al., 2016).

Micro-meteorological approaches such as the eddy-covariance technique directly quantifies the horizontal and vertical exchange of mass and energy between the surface and atmosphere by measuring the turbulent transport of H_2O vapor, CO_2 and heat, as well as other tracer gases. This state-of-the-art technique is widely used to quantify the net ecosystem exchange of CO_2 and water vapor at time scales from minutes to multiple years, mainly focused on the understanding the carbon cycle from local to global levels, and water use efficiency in plant growth (Verma, 1990; Baldocchi, 2003; Aubinet et al., 2012). The eddy-covariance technique is based on real-time direct measurements and can provide direct measurements over large areas (footprint of 200 m–1 km; (Harper et al., 2011)). However, homogeneity of the studied topography is an implicit assumption and costly infrastructure can limit deployment possibilities (Collier et al., 2014).

Eddy-covariance flux measurements are made using very sophisticated instrumentation mounted on a tower (an ECT), which is much more complex than a common meteorological tower, because vertical fluctuations and changes in gas concentration, density and temperature happen very quickly, and need to be precisely measured at a high-frequency rate (Burba and Anderson, 2010). The tower structure and instrument installation must not be voluminous in order to avoid obstructing the gas flow or shadowing the deployed solar radiation, wind and other sensors. Gas analyzer instruments must be located at least 2 m above the top of the local vegetation. Nevertheless, Hollinger and Richardson (2005) argued that these method provide a limited spatial footprint for fluxes (1 km^2) and rather high uncertainties; however, they seem to possess a large representativeness through up-scaling of site measured ecosystem responses (see Ciais et al. (2014)).

Throughout the globe, functional ECT sites are organized into regional and global networks (e.g. Ameriflux, JapanFlux, MexFlux, EuroFlux, CarboAfrica, AsiaFlux and Fluxnet), now reaching more than 400 sites (Baldocchi, 2014). These networks have provided products such as databases, conceptual models and software tools that are useful for scientists and policy makers (Ciais et al., 2014). However, the great majority of ECT sites are placed in developed countries, in agricultural, forest and rangeland locations. The low density of ECT sites in developing countries is related to various factors, but mainly to (1) the lack of trained human resources, because the installation and maintenance of instruments and data-processing require specialized training, and (2) the lack of funding (Vargas et al., 2013). The initial investment in infrastructure (e.g., tri-dimensional anemometers, non-dispersive infrared gas analyzers, biometeorological instrumentation, power supply and data loggers) is high (although somewhat lower in recent decades (Hutley et al., 2005)). Other long-term costs such as for personnel and maintenance also need to be considered.

The implementation of the Eddy-covariance technique requires the use of very specialized, fast and reliable electronic data-acquisition (DAQ) systems capable of digitizing the information from a large number of biometeorological sensors, with a high and constant sampling-rate, in real-time, for months under all kind of field conditions. These DAQs also must provide data storage capability and enough backup power to operate during long-term periods. They must be programmable for performing complex arithmetical operations and statistical functions, as well as being capable of reading both analog and digital sensors with various types of output.

The experience gained through the design of the climate monitoring stations at the San Pedro Mártir National Astronomical Observatory (OAN-SPM) laboratories in Ensenada, Mexico, was used as a basis for the design of the low-cost DAQ systems that were installed on the ECTs described in this paper. In particular, Martínez-Osuna (2005) developed a modular DAQ system based on the ADuC832 (Analog Devices, Norwood, MA, USA) microcontroller for meteorological purposes at the OAN-SPM. This system was based in turn on an implementation with the AT89C52 microcontroller (ATMEL) (Chapela, 2004), which had replaced a commercial datalogger and associated desktop computer (Michel et al., 2003)) at the OAN-SPM facilities. These stations were based on the construction of modules with multiple analog and digital inputs, which generated robust, efficient, low-cost systems with low levels of wiring.

The eddy-covariance technique by itself is not the topic of this paper, but rather the design of a DAQ system, processing and storage for a fully operational ECT. We successfully designed and tested a low-cost modular DAQ system. The system was integrated in a minimal operative way of a data acquisition module (DAM), a signal conditioning module (SCM), a microcomputer and the associated power-supply and communication features. A single DAM allowed connecting up to 8 pseudo-differential sensors and 3 pulse counters. Through the use of a RS-485 network the number of DAMs able to be connected to our DAQ system could be increased up to 8, greatly increasing the total instrumental capabilities of the DAQ system. This system could be expanded or reduced according to the needs of the users. We installed and operated fully equipped ECTs in two undeveloped sites near the city of Ensenada, Baja California, México (EMg and TSI; see details in Section 5). TSI station was later dismantled due to site access difficulties, but EMg site continues in operation after nine years.

EMg and TSI ECTs were built with a fast-response tri-dimensional anemometer, capable of performing up to 20 measurements per second (required to measure the mean variations of the vertical and horizontal components of wind speed). In order to quantify the local atmospheric concentrations of CO_2 and H_2O vapor, each system also had an open-path IRGA operating in synchrony with an open-path anemometer. By applying a simple filtering process it was possible to obtain the predominant wind vector as well as the concentrations of CO_2 and H_2O vapor in both upward and downward vertical paths. In the context of the eddy-covariance technique it was necessary to register meteorological and soil parameters such as net radiation, photosynthetic photon flux density, diffuse radiation, soil and air temperature, barometric pressure, air relative humidity, soil volumetric water content, rainfall and soil temperature gradients, among others (Burba, 2013). After digitizing all the sensor signals at a user-defined sampling