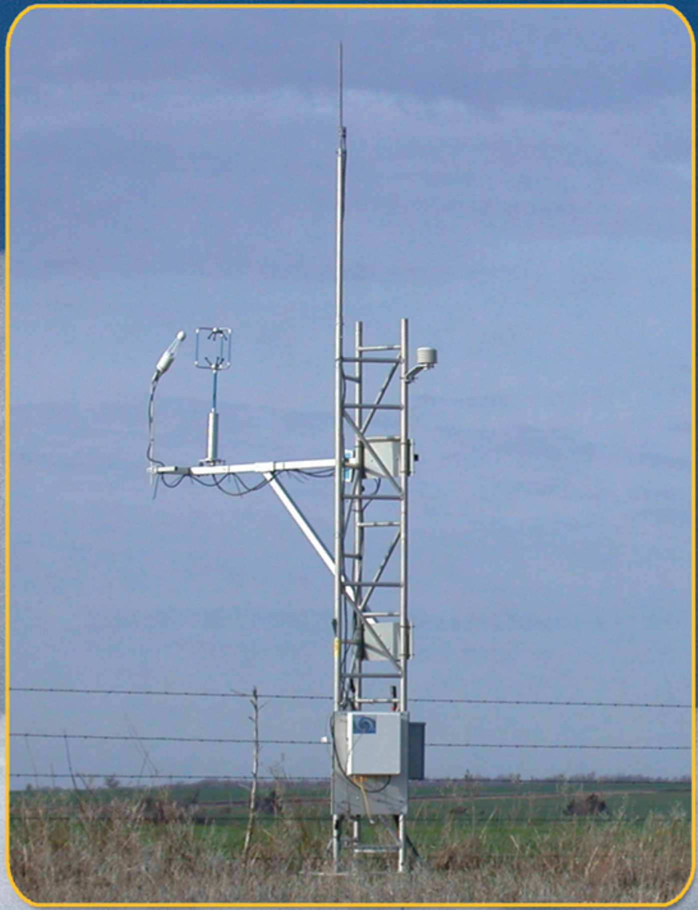
ARM TR-052

# Eddy Correlation Flux Measurement System
## Handbook



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## Tables

## 1. General Overview

The eddy correlation (ECOR) flux measurement system provides in situ, half-hour measurements of the surface turbulent fluxes of momentum, sensible heat, latent heat, and carbon dioxide. The fluxes are obtained with the eddy covariance technique, which involves correlation of the vertical wind component with the horizontal wind component, the air temperature, the water vapor density, and the $CO_2$ concentration. Instruments used are

- A fast-response, three-dimensional (3-D) wind sensor (sonic anemometer) to obtain the orthogonal wind components and the speed of sound (SOS) (used to derive the air temperature) and

- An open-path infrared gas analyzer (IRGA) to obtain the water vapor density and the $CO_2$ concentration.

The ECOR systems are deployed at the locations where other methods for surface flux measurements (e.g., energy balance Bowen ratio systems) are difficult to employ, primarily at the north edge of a field of crops.

## 2. Contacts

### 2.1 Mentor

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### 2.2 Instrument Developer

**Sensor Vendors**

3-D sonic anemometer, model WindMaster Pro: Gill Instruments, Limited, http://www.gill.co.uk (U.S. distributor: PP Systems, 978.834.0505, support@ppsystems.com)

Infrared gas analyzer, model LI-7500: LI-COR, Inc., http://www.licor.com/env (LI-COR Environmental, 402.467.3576, 800.447.3576)

## 3. Deployment Locations and History

**Table 1.**

| Facility | Location | Date installed | Status |
|---|---|---|---|
| SGP/EF1 | Larned, KS | March 9, 2004 | Operational |
| SGP/EF3 | LeRoy, KS | March 7, 2004 | Operational |
| SGP/EF5 | Halstead, KS | Sept. 9, 2003 | Operational |
| SGP/EF6 | Towanda, KS | Sept. 15, 2003 | Operational |
| SGP/EF10 | Tyro, KS | Oct. 3, 2003 | Operational |
| SGP/EF14 | Lamont, OK | June 3, 2003 | Operational |
| SGP/EF16 | Vici, OK | Sept. 25, 2003 | Operational |
| SGP/EF21 | Okmulgee, OK | Feb. 11, 2004 | Operational |
| SGP/EF24 | Cyril, OK | March 18, 2004 | Operational |

## 4. Near-Real-Time Data Plots

Near-real-time data plots can be accessed via the Atmospheric Radiation Measurement (ARM) Program Data Quality Health and Status (DQ HandS) Plot Browser (http://dq.arm.gov/plotbrowser/); choose Southern Great Plains (“SGP”) as “Search Site” and “sgp30ecor” as “Datastream” in the corresponding scroll boxes.

## 5. Data Description and Examples

### 5.1 Data File Contents

Currently, the ECOR systems produce 00- and b1-level data files. Initial processing takes place on the ECOR computer at the end of each half-hour measuring period. The data ingest process adds quality control (QC) flags and generates daily b1-level netCDF files, in keeping with ARM policy. See a complete ECOR netCDF file header description (http://science.arm.gov/tool/dod/showdod.php?Inst=ecor).

Both raw data (00 level) and b1 data streams are routinely shipped to the ARM Archive. Although b1 data are available though the standard Archive interface, the raw data (00 level) are available only by request to the Archive (armarchive@ornl.gov). A detailed description of the raw data files (00 level) is available from the instrument mentor upon request (mspekour@anl.gov).

#### 5.1.1 Primary Variables and Expected Uncertainty

The ECOR system makes direct measurements at a rate of 10 Hz of the following parameters:

- Three wind components: *u*, *v*, and *w* [m $s^{-1}$]
- SOS, *s* [m $s^{-1}$], which is used to derive atmospheric temperature, $t_a$ [°K]
- Water vapor density, *q* [mmol $m^{-3}$]
- $CO_2$ concentration, *c* [mmol $m^{-3}$]

- Atmospheric pressure, $p_a$ [kPa]

**Table 2.**

**Calculated quantities for each 30-min interval**

| Variable | Name in netCDF file | Unit |
|---|---|---|
| Sensible heat flux, $H$ | H | $Wm^{-2}$ |
| Latent heat flux, $L_vE$ | lv_e | $Wm^{-2}$ |
| Momentum flux (dynamic), $M$ | K | kg $m^{-1}s^{-2}$ |
| Friction velocity, $u_*$ | Ustar | m $s^{-1}$ |
| $CO_2$ flux, $F_{CO2}$ | Fc | µmol $m^{-2}$ $s^{-1}$ |
| Mean wind speed (vector averaged), $V$ | wind_spd | m $s^{-1}$ |
| Mean wind direction, $D$ | wind_dir | deg |
| Mean atmospheric temperature, $T_a$ | mean_t | °K |
| Mean water vapor density, $Q$ | mean_q | mmol $m^{-3}$ |
| Mean $CO_2$ concentration, $C$ | mean_c | mmol $m^{-3}$ |
| Mean atmospheric pressure, $P_a$ | atm_pres | kPa |

Expected uncertainties of the fluxes, due to measurement accuracies of primary variables, are within the following limits: $\delta H = 6\%$, $\delta L_vE = 5\%$, $\delta M = 5\%$, $\delta F_{CO2} = 4\%$.

#### 5.1.1.1 Definition of Uncertainty

This section is not applicable to this instrument.

### 5.1.2 Secondary/Underlying Variables

The b1-level data file contains all statistics that were used for estimating fluxes and a number of additional variables to support a variety of advanced QC procedures.

Calculated statistics include mean, variance, covariance, skewness, and kurtosis of each of the primary measured values: u, v, w, Ta, q, and C. A two-axis coordinates rotation procedure is applied to find vertical turbulent fluxes; all relevant rotated statistics (rotation angles, means, variances, and covariances) are included in the data file. The file also contains standard deviations of wind direction and wind elevation angle. Several air parameters needed to obtain fluxes in conventional "density"-based units (moist air density, specific heat capacity, etc.) are also in the data file.

### 5.1.3 Diagnostic Variables

Several types of diagnostics variables are kept in the b1 file:

1. **Data processing:** Number of valid samples for each primary variable, number and means of detected and removed outliers, number of invalid or out-of-range samples.

2. **Sensor status:** Serial number of the sensor, number of samples with invalid sonic status flag, number of samples with invalid IRGA status flag ("hardware problem" and "blocked optical path" given separately), IRGA calibration factors used to convert voltages into physical units, and the time lag value used to synchronize sonic and IRGA data streams.

3. **Environmental:** Average voltage of IRGA cooler, average temperature inside the IRGA electronics enclosure.

### 5.1.4 Data Quality Flags

The b1 data file contains basic data-quality flags for most important variables; the flags indicate the variable status (bit values), as follows:

- 0x0 = value is within the specified range.
- 0x1 = value is equal to "missing_value."
- 0x2 = value is less than "valid_min."
- 0x4 = value is greater than "valid_max."
- 0x8 = value failed the "valid_delta" check.

### 5.1.5 Dimension Variables

The global attributes section of the netCDF data file contains geographic coordinates (location) of the ECOR system and the altitude of the ground where the instrument is deployed; the "sensor location" parameter refers to the height of the instrument above the ground. The time variables denote the beginning of the 30-min measuring period.

The sign convention for primary (measured) variables and estimated quantities is positive for upward vertical wind component and upward atmospheric flux.

The standard ARM site arrangement has the sonic sensor "North" mark pointing along the boom to the tower; the boom is usually pointing due south; the u wind component is north-south with positive toward the north; the v wind component is east-west with positive toward the west. NOTE: No correction is made to convert the u or v component into the meteorological "north" or "east" wind component when the tower boom is not aligned to the south; the u wind component is "along boom," the v wind component is "cross boom."

## 5.2 Annotated Examples

Not available at this time.

## 5.3 User Notes and Known Problems

Currently, we are aware of one problem that affects ECOR performance. Real temperature values derived from SOS measurements of the WindMaster Pro are significantly overestimated at low temperatures and underestimated at high temperatures. Calibration of nine sonic anemometers in a temperature- and humidity-controlled environment showed that each sensor temperature response was biased and had a "slope" that differed significantly from 1:1, ranging from 0.71 to 0.87. Bias has no influence on sensible heat flux estimates, but these "slopes" translate directly into a significant heat flux underestimation. That problem became apparent during final tryouts of the system, when it was too late to change to another sonic model or vendor. A linear correction procedure was implemented to account for the identified sensor deficiency; a more detailed discussion is in Pekour (2004).

### 5.4 Frequently Asked Questions

*Where do I get more information about SGP ECOR systems?*
Contact the instrument mentor (mspekour@anl.gov).

## 6. Data Quality

### 6.1 Data Quality Health and Status

The following links go to current data quality health and status results.

- DQ HandS (http://dq.arm.gov)
- NCVweb for interactive data plotting (http://dq.arm.gov/ncvweb/ncvweb.cgi)

The tables and graphs shown contain the techniques used by ARM's data quality analysts, instrument mentors, and site scientists to monitor and diagnose data quality.

### 6.2 Data Reviews by Instrument Mentor

- **Visual QC frequency:** Daily to weekly
- **QC delay:** Typically 1-3 days
- **QC type:** Instrument mentor routinely views graphic displays that include plots (day courses) of all calculated quantities and comparison plots (time series or scatter plots) of relevant parameters with data from the nearby Surface Meteorological Observing Station.

### 6.3 Data Assessments by Site Scientist/Data Quality Office

Not available at this time.

### 6.4 Value-Added Procedures and Quality Measurement Experiments

None available at present; density effects correction (so-called Wave Propagation Laboratory [WPL] correction) to fluxes and advanced QC procedures are being developed.

# 7. Instrument Details

## 7.1 Detailed Description

### 7.1.1 List of Components

**Ultrasonic anemometer:** WindMaster Pro by Gill Instruments, Ltd. (http://www.gill.co.uk):

- **Full wind vector in the form of orthogonal wind components u, v, and w Accuracy:**
  - For u and v = 1.5% root mean square (RMS) error for winds below 20 $ms^{-1}$, 3% otherwise
  - For w = 3% of magnitude

- **SOS**
  **Range:** 307 to 367 $ms^{-1}$
  **Resolution:** 0.01 $ms^{-1}$
  **Accuracy:** 3% RMS error for winds <20 $ms^{-1}$, 6% RMS error for winds 20 to 60 $ms^{-1}$

- **Analog inputs**
  **Type:** 8 single-ended or 4 differential (software selectable)
  **Range:** –5 to +5 VDC
  **Resolution:** 14 bit
  **Accuracy:** 0.05% of full scale (for temperature from +5 to +35°C)
  0.1% of full scale (for –40 to +5°C, +35 to +60°C)

**Open-path $CO_2/H_2O$ IRGA:** LI-7500 by LI-COR, Inc. (http://www.licor.com/env):

- **water vapor density**
  **Range:** 0 to 2000 mmol $m^{-3}$ (software selectable)
  **Accuracy:** About 1% (limited by calibration)
  **Precision:** About 0.14 mmol $m^{-3}$ (typical RMS noise).

- **$CO_2$ concentration**
  **Range:** 8 to 32 mmol $m^{-3}$ (software selectable)
  **Accuracy:** About 1% (limited by calibration)
  **Precision:** About 4 µmol $m^{-3}$ (typical RMS noise).

- **Analog outputs**
  **Type:** Two-user selectable
  **Range:** 0 to 5 V DC
  **Resolution:** 16 bit
  **Update rate:** 300 Hz

**Data acquisition computer**

- Personal computer (PC) clone computer under Linux operating system; currently 266-MHz environmentally hardened laptop
- Data collection and initial processing performed with ECOR software (written in C by M. Pekour at Argonne National Laboratory).

### 7.1.2 System Configuration and Measurement Methods

In a typical arrangement, the ECOR system is placed on the north side of a wheat field; sonic and IRGA sensor heads are mounted on a small tower at 3 m above ground level, at the end of a horizontal boom pointing south. The computer and communication devices are installed in an enclosure with basic temperature control (ventilation or heating). One exception to the usual arrangement is the Okmulgee site (EF21), where the ECOR system is installed on a tall tower (15 m above ground, about 3 m above the canopy) in a hardwood forest.

The IRGA provides fast-response measurements of water vapor density and $CO_2$ concentration in digital and analog form; the sonic anemometer provides three wind components and the SOS data in digital form (retrieved via serial link) at a rate of 10 Hz and performs synchronous digitization of the IRGA analog outputs. The digital data stream from the IRGA is also recorded by the data acquisition computer; it is used to extract IRGA diagnostics values and as a second copy of the water vapor density and $CO_2$ concentration data.

The raw data stream is recorded into raw data files by 30-min portions and is processed every half hour by the ECOR computer. The raw and processed data files are transferred to the Central Facility for ingest (conversion into the netCDF format and incorporation of QC flags) and shipment to the ARM Archive.

### 7.1.3 Specifications

This section is not applicable to this instrument.

## 7.2 Theory of Operation

The WindMaster Pro sonic anemometer uses three pairs of orthogonally oriented, ultrasonic transmitter/receiver transducers to measure the transit time of sound signals traveling between the transducer pairs in both directions. Pairs of measurements made along each axis, 30 times per second, are averaged appropriately to provide a 10-Hz data stream. The wind speed along each axis is determined from the difference in transit times. The SOS is determined from the average transit time along all three axes. The air temperature can be derived from the SOS with a well-known correction for the humidity effects.

The IRGA measures water vapor density and $CO_2$ density by detecting the absorption of infrared radiation by water vapor or $CO_2$ in the light path. Two infrared wavelength bands are used, centered on strong water vapor or $CO_2$ absorption lines. The sensor provides digital (serial RS232) and analog (two

16-bit DAC) outputs. Details of the IRGA principles, design, and performance can be obtained from LI-COR Environmental (http://env.licor.com/PDF_Files/LI7500.pdf).

The sonic anemometer samples the gas analyzer analog outputs ten times per second, synchronously with wind measurements, and combines all the data into a single serial data stream.

The data acquisition computer continuously records serial data streams from both sensors and stores them into 30-min files. Half-hourly flux data processing is accomplished on the same computer, independently of the data acquisition process. Half-hour-averaged ambient air temperature, water vapor pressure, and barometric pressure derived from the sonic anemometer and the IRGA raw data are used in the calculations of moist air density, specific heat of dry and moist air at constant pressure, and heat of vaporization of water necessary for presentation of the fluxes in “density-based” units.

Data analysis includes a de-spiking procedure, basic QC of every data point (sensor status, minimum/maximum check), time delay for the sonic data to account for the internal delay in the IRGA, conversion of the SOS into air temperature, and computation of statistics (mean, variance, covariance, skewness, kurtosis, etc.). Two-dimensional (2-D) coordinate rotations are applied to the variances and covariances to achieve zero mean vertical and transverse wind speeds.

Momentum flux is determined from the correlation between horizontal and vertical wind components in “rotated” coordinates. Similarly, the vertical fluxes of sensible heat, latent heat, and $CO_2$ are determined directly from the correlation between the “rotated” vertical velocity and temperature, water vapor density, and $CO_2$ concentration, respectively.

In general, the fluxes calculated as described represent vertical fluxes from a variable area (a footprint) of the surface upwind of the instrument. The size of this area usually varies from 10 to 100 times the height of the sensors above the surface. The footprint depends on surface properties (roughness, displacement height, etc), atmospheric state and stability, and turbulent intensity within the atmospheric surface layer. The surface conditions (crop height, density, and state) can be found in the ECOR section of Extended Facility Surface Conditions Observations weekly reports (http://198.124.96.210:591/sfc_cond1/default.htm).

See Sitable References for further discussions.

## 7.3 Calibration

### 7.3.1 Theory

Ideally, the sonic anemometer does not require calibration for either wind or temperature measurements, although the WindMaster Pro SOS channel needs to be calibrated to achieve accurate sensible heat measurement (see Pekour, 2004, for more detailed discussion). The IRGA sensors need to be calibrated periodically. The IRGA is calibrated by passing gas of known concentration through a calibration tube installed in the sensor head, so that the tube surrounds the light path over which infrared absorption is measured. The zero (offset) is typically calibrated by using “zero” gas or dry nitrogen from a gas cylinder. The gains of the $CO_2$ and $H_2O$ channels are calibrated by using a cylinder with a known concentration of $CO_2$ and flow from a water vapor generator (e.g., Licor Inc. LI-610 Dew Point Generator).

#### 7.3.2 Procedures

No detailed description of calibration procedures is available yet. The calibration procedure for the IRGA basically follows the manufacturer's recommendations (LI-7500 User Manual, Section 4).

#### 7.3.3 History

The Calibration Test Reports can be accessed here (http://198.124.96.210/menus/caltopmenu.html).

### 7.4 Operation and Maintenance

#### 7.4.1 User Manual

No single comprehensive user manual for the ECOR system is available for general use; rather, vendor-supplied documentation on sensors and a collection of procedures prepared by mentors are provided for internal use by Site Operations.

#### 7.4.2 Routine and Corrective Maintenance Documentation

The ECOR Preventive Maintenance procedures and reports are online (http://198.124.96.210:591/ef_pm1/default_1.htm), as is a database of Corrective Maintenance reports (http://198.124.96.210/menus/cmreports.html).

#### 7.4.3 Software Documentation

Contact the instrument mentor (mspekour@anl.gov) for software documentation.

#### 7.4.4 Additional Documentation

This section is not applicable to this instrument.

### 7.5 Glossary

Also see the ARM Glossary.

### 7.6 Acronyms

| | |
|---|---|
| 2-D | two-dimensional |
| 3-D | three-dimensional |
| ARM | Atmospheric Radiation Measurement (Program) |
| DQ | Data Quality |
| ECOR | eddy correlation (flux measurement) |
| IRGA | infrared gas analizer |

| | |
|---|---|
| PC | personal computer |
| RMS | root mean square |
| SGP | Southern Great Plains |
| SOS | speed of sound |
| QC: | quality control |
| WPL | Wave Propagation Laboratory |

Also see the ARM Acronyms and Abbreviations.

## 7.7 Citable References

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