GUIDELINES FOR MAKING EDDY COVARIANCE FLUX MEASUREMENTS

Munger JW, Loescher HW

Rationale

Measurement consistency is essential for realizing the potential of AmeriFlux as a network. In general there is not a single perfect method that can be recommended. Instead the benefits, drawbacks, and costs of various methodologies must be evaluated to define an optimum solution that best meets the precision and accuracy requirements of the site and network science goals. Whatever the level of accuracy, site data need to include results of ***ongoing quality assurance tests*** that verify whether a particular measurement system ***as installed*** is operating within its stated accuracy and precision limits over time. Accuracy goals depend on the questions being addressed and the inherent variability of the quantity being measured. Generally as the flux data record lengthens the importance of small variations in flux responding to the subtle shifts in weather pattern or successional change increases. Ultimately, the science team at each site is responsible for setting and implementing a quality assurance program for their particular site. Measurement uncertainty needs to be small enough for instance that hypotheses can be accepted or rejected with confidence, or meaningful comparisons can be made among sites, between years, or to model predictions. The essential element is for measurements to include a traceable record to demonstrate their consistency and accuracy in order to allow comparisons across the network and to include complete documentation of the QA/QC procedures in a site description. This document updates the core and desired measurement lists as well as providing specific recommendations for their implementation and some quality assurance measures. The guidelines presented here are a distillation of collective experience making long-term flux measurements and have incorporated many of the recommendations adopted by Fluxnet Canada (Margolis *et al.* http://www.fluxnet-canada.ca/home). Tables 1 and 2 list the core and desired measurement, its ID, and technique. Guidelines for site setup and measurement techniques are described in subsequent sections.

1.0 TOWER PLACEMENT

Site requirements

The EC technique was established over uniform vegetative canopies with short roughness lengths on flat terrain and large fetch. But our interest in measuring net ecosystem carbon fluxes forces us to work in ecosystems with aerodynamically rough canopies and challenging terrain. Site requirements vary depending on the research questions, some general guidelines and quality requirements apply in all cases. The tower should be sited to maximize the time with winds blowing from the desired land cover type, and with the longest upwind fetch attainable. If the surroundings are not of a uniform cover type, there needs to be some analysis of prevailing winds to demonstrate that the desired sectors are sampled uniformly through time. Consider the extreme example of a site with two different forest types and a consistent daily wind cycle that blew from one forest type and in the day and the other at night. Daily integrated NEE in this situation would be uninterpretable. This extreme condition is unlikely, but many sites could have more subtle wind direction biases that need to be examined and considered in data interpretation. All systems are subject to horizontal flux divergence, advective motions and drainage of air sheds. The question becomes, how much do these motions affect measured fluxes, and at what timescales. If the terrain is complex and below-canopy drainage or advection is a concern, placement of the tower should be on a relatively flat portion of the fetch to minimize flows to- or away from the site. Regular motions due to orographic effects or circulations associated with large bodies of water should either be well studied and quantified, or avoided. For further discussion see Loescher *et al.* in review). Footprint analyses to determine the source area under different stabilities, wind speeds and direction provide valuable guidance for appropriate tower placement, documentation of site characteristics, and definition of data acceptance criteria (Foken and Leclerc 2004, Schmid 1994, Schuepp *et al.* 1990).

The tower needs to be high enough to place the sensors well above the surrounding canopy, but not so high that the footprint during stable night-time conditions extends beyond the boundary of the ecosystem type of interest. The tower should be constructed with minimum disturbance to the adjacent ecosystem, but without compromise to safety or tower reliability. Extensive clearing or use of large construction equipment should be avoided as much as possible. Regularly scheduled tower inspection and preventative maintenance according to tower manufacturer recommendations are essential for assuring site reliability and safety of personnel.

In many locations lightning is common and measures need to be taken to minimize the potential for instrument damage and loss of data. Proper grounding of the tower, guy wires, anchors, and buildings is an essential component of construction. Local experts in the grounding of radio and cell-phone towers may be the best source of specific designs appropriate for the tower site. Induced voltages can occur in long signal wires from sensors to data acquisition systems. It is inexpensive insurance to place surge voltage protectors (i.e., breakaway fuses) on each signal line (e.g., model SVP48 Campbell Scientific, Logan UT). Serial communications and short haul modems should also be protected, e.g. with optical isolation. Obviously, site personnel should never risk their lives by working on or around a tower when lightning storms are nearby.

2.0 EDDY COVARIANCE FLUXES – CO_2 H_2O, heat and momentum

2.1 Required equipment

Basic required equipment includes a three-dimensional sonic anemometer-thermometer (SAT) and a fast response infrared gas analyzer (IRGA).

AmeriFlux has not made specific recommendations for which SAT to use. Available choices include ATI, Campbell, Metek, R.M. Young, Koshin-Denki, and Gill Instruments (contact info listed on equipment sources webpage http://public.ornl.gov/ameriflux/resource-equip-tips.shtml). Each has their own advantages and disadvantages. Comparison between the Campbell and other sonic thermometers suggest a 5 – 10 % discrepancy in sonic temperature (Hollinger pers comm.), and may be due to Campbell accounting for the temperature dependency of the sonic transducers to measure the speed of sound (Tanner pers comm.). Comparisons of wind statistics between the different SATs have shown reasonable agreement. Available evidence suggests that bias due to choice of SAT is less than 10% in favorable weather conditions (Hollinger *et al.* in review).

Proper installation, maintenance, and data assurance of the SAT are more important than choice of manufacturer. However, sensor configurations that place the transducer array at the end of a horizontal boom are the best choice. Vertically oriented transducer arrays appear to have significant errors when the attach angle of wind is very steep (Gash and Dolman, 2003). The SAT should be installed on a firm and steady support (mast or post) facing into mean wind direction to minimize disturbances and flow distortions caused by the tower structure itself (i.e., winds through and around the tower) that require data to be rejected. SATs should be clean and free of debris (i.e., bird droppings). Manufacturers often require a zero (wind) offset to be periodically calibrated. For example, ATI supplies zero air chambers and suggest that zero offset calibrations be made for specific humidity and temperature operating ranges. SAT fail when wet or when the path is obstructed, as in the case with hoar frost or freezing rain. SATs may have to be heated when frozen over with frost. Age and wear of sonic transducers may require replacement. Rain, dew (water droplets), snow and frost on the end of the sonic transducer changes the path length to estimate speed of sound. Each SAT model reacts differently to light rain events, but all fail in heavy precipitation. Many SATs report data quality flags, which need to be recorded and interpreted. Independent checks on air temperature and wind statistics are essential for demonstrating long-term accuracy of the SAT and for identifying periods for which the SAT data are unreliable. The SAT should be kept level to reduce uncertainties in wind direction and minimize errors associated with large rotation angles. Each time the SATs are moved rotation angles have to be recalculated if planar fit rotation schemes are used. The importance of tower stiffness and guy-tension adjustment becomes apparent when considering long-term maintenance of SAT level.

Two types of gas analyzers can be used to simultaneously measure high frequency CO_2 and H_2O concentrations, (i) closed-path and (ii) open-path. The first has an internal sample cell (optical bench) through which sampled air must be drawn. Temperature and pressure within the sample cell are different from the ambient condition and with appropriate plumbing configuration can be precisely controlled to constant values. The open-path sensor makes a measurement in situ where the gas density is affected by ambient pressure and temperature. In both cases the analyzer consists of a light source and detector. In the closed path analyzer, a second, or reference cell, with gas having zero or a known concentration of the analyte is used to account for variability in the light source and detector. For the open path sensor, an adjacent non-absorbing wavelength is used as reference. Models Li-6262 and Li-7000 (Li-Cor Inc., Lincoln NE) are examples of the first and model Li-7500 (Li-Cor Inc., Lincoln NE) is an example of the second. The krypton hygrometer (model KH20, Campbell Scientific, Logan UT, or model BLR Lyman-α hygrometer, Electromagnetic Research Inc.) are common alternatives to measure high frequency H_2O concentrations. The LI-7000 has a higher frequency response (real 10 Hz or greater) than the LI-6262 (DAC and 0.1s channels operate at ~ 8 and ~ 5 Hz for CO_2 and H_2O, respectively). In order to minimize zero calibration drift (discussed further below), either closed-path instrument should be enclosed in a temperature-controlled environment. Pressure within the sample cell should also be accounted for. Li-7000 has pressure sensor factory installed, and the Li-6262 it is an accessory (model Li-6262-03). The pressure correction can either be applied by the instrument's software, or if raw signals are recorded the pressure is recorded as well and the correction term is applied off-line during data reduction. The inlet tube required to bring ambient sample from the outside into the analysis cell will have an affect on frequency response in the closed-path analyzers. Selection of tubing material, design of the overall plumbing configuration, and maintenance of tube cleanliness can mitigate the attenuation of high frequency components. Examination of signal spectra and co-spectra is necessary to identify and quantify the magnitude of high frequency attenuation and its affect on the computed fluxes for an individual site.

Open-path analyzers (e.g. Li-7500) have the advantage of an excellent high frequency response but do not operate when the windows are wet or icy. Furthermore, the open-path analyzers are not amenable to automated routine calibrations and are not suitable for measuring high-precision high-accuracy CO_2 concentrations.

If high-frequency response were the only consideration, open-path sensors would be the ideal solution. However, the gain in high frequency response is made at the expense of increased down time (from rain and inclement weather), and the need to include heat fluxes in the calculation of CO_2 and H_2O fluxes (Webb *et al.* 1980, Luening *et al*. 2003), which add additional uncertainties. At sites with frequent precipitation, or large heat fluxes this may not be an acceptable tradeoff. If high-frequency flux components are observed to be negligible, the open path sensor has less advantage.

2.2 Closed-path IRGA arrangement

Temperature control. Temperature should be controlled to minimize the zero signal drift in the IRGA. For instruments that are mounted outdoors, a temperature-controlled housing with a set point at few ºC above ambient maximum is ideal. Maintaining temperature above ambient allows heat loss to the environment to be used for temperature control and ensures that non-condensing conditions within the system are maintained at all times. Obviously this approach is not universally applicable, as it would require instruments in hot climates to operate above the acceptable range for the IRGA. Placement of the instrument inside a climate-controlled building reduces the need for an actively temperature-controlled enclosure; however, the IRGA needs to be placed where air conditioning and space heating will not cause rapid temperature variations. Signal drift that is not avoided by temperature control will need to be compensated for through frequent calibrations. For instruments inside air-conditioned buildings in humid climates pressure drop in the sample line along with heating the inlet lines is needed to prevent condensation. Damping the temperature fluctuations in the tubing before entering the IRGA is essential (see Webb *et al.* 1980). Often the tubing is insulated and heated to a constant temperature for a few meters before the IRGA inlet. An alternative to this approach is using a few meters of metal (non-reactive) tubing before the IRGA inlet as a heat sink.

Evaluate frequency response. The Li-7000 has an inherently higher frequency response than the Li-6262, which makes it preferable for low-stature or aerodynamically smooth sites. Spectra (IRGA signals) and cospectra (between IRGA and SAT signals) need to be examined to demonstrate that the selected instrument in its deployed configuration responds to all relevant frequencies. The use of ogive analyses (integrated cospectra) can assess the time periods needed to capture low frequency flux (e.g., the effects of local and mesoscale motions), thus determining the appropriate averaging times (Berger *et al.* 2001).

Tubing choice and Flow rates. Best choices of tubing have been found to be Dekoron, Teflon or stainless steel. These materials have acceptably low H_2O and CO_2 adsorption if kept clean and above dew-point temperature (see below), and they are resistant to UV damage and embrittlement in cold temperatures. Evaluation of tubing by examination of spectra and periodic testing by introducing step changes in H_2O and CO_2 concentrations is required to confirm continued data quality. Turbulent flow is desired in order to insure maximum frequency response of the gas analysis system, typically indicated by a Reynold's number (***Re***) > 2300, eq 1.

$$\mathrm{Re} = \frac{ud}{v} \qquad \text{Eq. 1}$$

where ***u*** is mean free stream velocity (cm s^{-1}), ***v*** is kinematic viscosity of air (cm^2 s^{-1}), and ***d*** is characteristic dimension and in this case, the tubing inner diameter (cm). Selection of tubing diameter and flow rate requires for a given inlet length requires optimization. High flow rate reduces sample delay (sensor separation) and maintains turbulent flow. Analytical sensitivity however, is sacrificed as pressure drop increases. In practice, the frequency response continues to improve with increasing Re, Re = 3000 to 3,500 is recommended. Dead volumes, sharp bends, and restrictions in the tubing, that introduce mixing will attenuate high-frequency variability and should be minimized as much as practical. Flow rate through the Li-6262 should not surpass 10 L min^{-1} because it exceeds the time constant within the sensor. To achieve large flow rates needed to minimize delay and ensure turbulent conditions without exceeding the flow limits of the sample cell set up a bypass pump to draw a large volume of air through a relatively large diameter tubing and take a subsample of air through the analyzer

The entrance to the sampling tube should be positioned as close to the center of the sonic transducer array as possible and slightly behind the transducers so that there is no distortion of wind flow from prevailing winds. The SAT should be oriented facing the direction of prevailing winds. Directing the inlet downward and inserting it through a small funnel or drip-tip will minimize the chance of ingesting liquid during rain. A mosquito mesh over the mouth of funnel is also helpful if insects are prevalent. Fine particles should be kept out of the sample line and instrument using a filter. An open face filter will act as the rain shield and introduces less of a mixing volume than many inline filters do. Filters should be changed often enough so that flow rates are not decreased below desired values and there is no evidence of degradation of high frequency responses for water vapor by sample air interacting with collected dust. Likewise, replacement of the inlet tube can be determined by monitoring the high-frequency response for water vapor.

2.3 Open-path IRGA arrangement

When an open -path IRGA (e.g. LI-7500) is used, an independent method of determining absolute CO_2 concentrations with high accuracy is required. The open path instrument is useful where high frequency fluctuations contribute significantly to flux. It is valuable to compare open- and closed-path systems to assess the high frequency losses associated with closed-path systems.

The open-path IRGA should be mounted following the recommendations for positioning the entrance of the sampling tube in the closed–path IRGA arrangement (see above), e.g., such that the open-path should be co-located with the sonic volume without causing flow distortions in the wind velocity measurements. Orienting the main axis of the instrument 15° - 30° with respect to the horizontal helps drain water from rain or dew off the light-source (lower) window. An inexpensive rubber o-ring (1.875”) placed over the detector head (upper) can also act as a drip-tip, shedding water from light rains from migrating over the window. Because the open-path IRGA does not measure during precipitation it is not recommended as the sole instrument for long-term CO_2 flux measurements. The open-path IRGA is ideal when power supply is low. They can run for long periods of time unattended on 12v DC, eliminating the need for pumps and climate control of a closed-path IRGA.

3.0 DATA ACQUISITION EQUIPMENT AND PROCESSING

3.1 Signal measurement frequency

Sampling frequency should be as high as practical, and high enough to demonstrate that the full range of frequencies carrying the turbulent flux has been sampled. The necessary sampling frequency will depend on site characteristics, with lower sampling frequencies being acceptable over tall rough canopies than over smooth short-stature vegetation.

The choice of data collection hardware does not directly influence the data quality as long as the hardware configuration is sufficiently reliable to avoid data loss and has enough resolution to capture the relevant signal fluctuations. Linking the SAT and IRGA data stream together often utilizes some configuration of A2D processing. The A2D resolution limits the available concentration range that can be measured. For example to achieve resolution of 0.1 ppm with a 12-bit A2D the range between maximum and minimum concentration can be 400 ppm, which is probably adequate for most situations. For greater resolution or a wider concentration range a higher resolution A2D may be required. Obviously, if the data system can directly store the serial data from the IRGA, A2D resolution issues are eliminated. However, serial data introduces the need for a system that can read multiple serial inputs, and software to ensure that the data streams are time synchronized.

3.2 Data processing programs

Periodic comparisons of data processing software have shown that differences in the processing do not significantly affect the final results as long as the same rotation, averaging routines, and correction terms are applied. A standard set of raw closed-path data file developed by the Euroflux network ('gold files' http://cdiac.ornl.gov/ftp/ameriflux/gold/Closed_Path/) has been used to intercompare results of existing processing codes. Whenever new processing routines are developed they should be compared to pre-existing routines by processing the same data. The gold files should be analyzed to intercompare processing between groups. New gold files developed by Ameriflux for open-path sensors can be found at http://cdiac.ornl.gov/ftp/ameriflux/gold/Open_Path/ . Results to each of the 'gold' files can be acquired by emailing James.Kathilankal@oregonstate.edu .

3.3 Flux calculations

Basic equations and conversions for calculating flux densities of sensible heat, latent heat and carbon dioxide from eddy covariances are given below. The standard properties of air are from List (1951). Of course, the units of scalar quantities may be different depending on the type of instrument and its configuration for the data had been collected.

Sensible Heat

$$H = \rho C_p\left(\overline{w't_s'} - \left(0.000321 T_k \overline{w'q'}\right)\right) \qquad \text{Eq. 2}$$

where

H is sensible heat (W m^{-2}), $\boldsymbol{\rho}$ is the density of air (kg m^{-3}), $\boldsymbol{C_p}$ is the specific heat of air (J K^{-1} kg^{-1}), $\overline{w't'}$ (m ºC s^{-1}) is the time-averaged (i.e., 30-min) covariance of vertical wind velocities ***w*** (m s^{-1}) and sonic temperature $\boldsymbol{T_s}$ (Eq 8, º C), $\boldsymbol{T_k}$ is the actual air temperature (º K) estimated from the sonic temperature (Eq 9, Kaimal and Gaynor 1991) or an accurate thermistor or thermocouple, and $\overline{w'q'}$ (m s^{-1} mmol H_2O mol air^{-1}) is the time-averaged covariance of ***w*** (m s^{-1}) and water vapor ***q*** (mmol mol^{-1}). The term ρC_p in equation 2 can be expressed as

$$\rho C_p = C_{pm} \times \rho_v + C_{pd} \times \rho_a \qquad \text{Eq. 3}$$

where, $\boldsymbol{C_{pm}}$ and $\boldsymbol{C_{pd}}$ are the specific heat capacity (J K^{-1} kg^{-1}) of water vapor and dry air with densities $\boldsymbol{\rho_v}$ and $\boldsymbol{\rho_d}$ (kg m^{-3}). These terms can be calculated as follows

$$\rho_v = \frac{e \times 1000}{R_v \times T_k} \qquad \text{Eq. 4}$$

$$\rho_d = \frac{p_d \times 1000}{R_d \times T_k} \qquad \text{Eq.5}$$

$$C_{pm} = 1859 + 0.13 \times RH + (T_k - 273.15) \times (0.193 + 0.00569 \times RH) + (T_k - 273.15)^2 \times (0.001 + 0.000005 \times RH) \qquad \text{Eq.6}$$

$$C_{pd} = 1005 + \left(\frac{(T_k - 250.03)^2}{3364} \right) \qquad \text{Eq.7}$$

Where $\boldsymbol{p_d}$ and $\boldsymbol{e}$ are the partial pressures of dry air and water vapor in kPa and ***RH*** is the relative humidity. The partial pressure of dry air can be estimated by subtracting the water vapor partial pressure from the measured air pressure/atmospheric pressure. $\boldsymbol{R_v}$ (461.495 J kg^{-1} K^{-1}) and $\boldsymbol{R_d}$ (287.05 J kg^{-1} K^{-1} are the specific gas constants for dry air and water vapor.

$$T_s = \frac{c^2}{\left[403 \left(1 + \frac{0.32q}{P} \right) \right]} \qquad \text{Eq. 8}$$

where, ***c*** is the measured speed of sound (m s^{-1}), ***403*** is the product of ***R*** (287.04 J K^{-1} mol^{-1}) and the ratio of the specific heats of moist air at constant pressure and constant volume (C_p^*/C_v^*). This ratio is very close to that for dry air, thus $C_p^*/C_v^* \sim C_p/C_v = 1.4$.

T_k is the actual air temperature, estimated by,

$$T_k = \frac{T_s + 273.15}{(1 + 0.000321q)} \qquad \text{Eq. 9}$$

If a correction for crosswind effects on the temperature measurement (typically derived from the vertical wind velocity component) is required, then the above equation should be modified as follows (Kaimal and Gaynor 1991).

$$H = \rho C_p \left(\overline{w't_s'} - \left(0.000321 T_k \overline{w'q'}\right) + \frac{2\bar{u}\overline{u'w'}}{403} \right) \qquad \text{Eq. 10}$$

where, $\bar{u}$ is the time-averaged horizontal wind velocity (m s^{-1}), $\overline{u'w'}$ is the time-average covariance of u and w (m^2 s^{-2}). Correction for crosswind effects are not required for ATI probes, Campbell CSAT3 or Gill R series SATS).

Latent Heat

$$\lambda E = \frac{\lambda M_w \overline{w'q'}}{V \cdot 1000} \qquad \text{Eq. 11}$$

where, $\boldsymbol{\lambda E}$ is the latent energy flux (W m^{-2}), $\boldsymbol{\lambda}$ is the latent heat of vaporization of water (2500.8 - 2.3668 T_s, J g^{-1}, List 1951), $\boldsymbol{M_w}$ is the molecular weight of water (18.015 g mol^{-1}).

$$V = \frac{RT_k}{P} \qquad \text{Eq. 12}$$

where, $\boldsymbol{V}$ is the molar volume of air (m^3 mol^{-1}), $\boldsymbol{R}$ is the ideal gas constant (0.082 L atm K^{-1} mol^{-1}), and $\boldsymbol{P}$ is atmospheric pressure (1.10325 atm).

CO_2 Flux

$$FCO_2 = \frac{\overline{w'c'}}{V} \qquad \text{Eq. 13}$$

where, $\boldsymbol{FCO_2}$ is the estimated carbon flux (μmol m^{-2} s^{-1}), and $\overline{w'c'}$ is the measured covariance (m s^{-1} μmol C mol^{-1}).

3.4 Quality control

Eddy covariance and profile data are typically screened for validity and removed when either i) SAT or IRGA data flags indicate problem data, ii) SAT or IRGA signals were out-of-range (Hollinger *et al*. 1995, Anthoni *et al*. 1999), iii) rain occurred, or, iv) 30-min data collection periods were incomplete. Other diagnoses often include i) variance filters (i.e., when signals are outside a preset, physically meaningful variance threshold, assuming a Guassian distribution), ii) stability parameter (either monin-obukov stability parameter, eq. 2, or Richardson number eq.3), or iii) some indication of non-stationarity (time series for wind statistics in steady state, Foken *et al.* 2004, Foken and Wichura 1996).

$$l = (z-d)\frac{-\rho C_p T_a u^{*3}}{gkH} \qquad \text{Eq. 14}$$

where $\boldsymbol{z}$ is the measurement height (m), $\boldsymbol{d}$ is zero plane displacement (m), $\boldsymbol{\rho}$ is the density of air (kg m^{-3}), $\boldsymbol{C_p}$ is the specific heat capacity of air (J kg^{-1} K^{-1}), $\boldsymbol{T_a}$ is air temperature in Kelvin (K), **u*** is friction velocity (m s^{-1}), $\boldsymbol{g}$ is acceleration due to gravity (m s^{-2}), **k** is the von Karmen constant (0.41, dimensionless), and $\boldsymbol{H}$ is the sensible heat flux density (J m^{-2} s^{-1}, Rosenberg *et al*. 1983, Montieth and Unsworth 1990, Pahlow *et al*. 2000).

$$Ri = \left(\frac{g}{T_a}\frac{\partial T_a}{\partial z}\right) \Big/ \left(\frac{\partial u}{\partial z}\right)^2 \qquad \text{Eq. 15}$$

where u is horizontal wind velocity (m s^{-1}).

Assumptions in the eddy covariance technique require turbulent conditions, i.e., shear stress and surface heating. Researchers have found that empirical relationships between u* and scalar fluxes can determine 'well-mixed' conditions. Hence, a u* threshold is often employed to remove data during stable conditions when vertical turbulence is not the dominant transport pathway. This is an active area of research though, and use of a u* threshold must be rigorously examined. Further discussion on u* and its role in estimated of turbulent exchange can be found in Loescher *et al.* (2005). There is no set standard for data removal, or recommendations that work universally across sites.

Gaps in the data sets are unavoidable. Filling or averaging routines are required for providing integrated fluxes over longer intervals. Falge *et al*. (2001) discuss three methods for gap filling carbon flux data; mean diurnal variation, non-linear regressions, and look-up tables based on meteorological and seasonal conditions. Unfilled data need to be presented for use in comparing responses to environmental forcing over time or between sites. Integrated, or gap-filled data is not suitable for instance to compare light-response curves among sites because the filling routine may have imposed a light response.

4.0 CALIBRATION PROCEDURES

4.1 IRGA calibration

Ultimately, measurement data are only as good as the calibrations. It is encouraged that all sites make their measurements with the highest level of precision and accuracy that is practical. The level of precision and accuracy--and frequency of calibrations to achieve these desired levels rely on the Principle Investigators experience to capture the abiotic and biotic events needed to answer their research questions (*e.g.*, synoptic-to-local circulations, punctuated rain events, soil CO_2 pulses, etc..), and rely on those in the network that use these data for among-site research questions.

Independent verification by periodic calibration (lab, factory and *in situ*) is required to demonstrate that calibration drift, artifacts, or other interferences do not affect the data. External desiccants and filters need to be inspected frequently (~ 7 d) and exchanged when necessary. Internal filters and desiccants should be replaced every 6 months, regardless of contamination. It is also important to recognize that measurements of concentration and flux face different sources of uncertainty. CO_2 flux measurements are mainly dependent on the accuracy with which the instrument's gain (span) is determined. Variations in the zero over time scales longer than the flux-averaging interval (typically 30-min) are less important because they are removed by the averaging operator (*i.e.*, block average, detrending, etc.). Calibration to within ±0.2% accuracy will generally be sufficient to meet the needs for flux measurements. Both the zero and span affect concentration measurements, and the accuracy requirements become more stringent. A 2% error in concentration of a purchased standard gives an associated uncertainty of 7 ppm or more--which is unacceptable when analyzing spatial gradients between sites across a network, or vertical gradients between surface sites and aircraft which can be $\leq$ 1 ppm. Moreover, when flux and concentration measurements are made available to the greater flux community, they have a great utility in developing ongoing research questions (*i.e.*, data assimilation projects, regional constraints, etc.).

There are measurement uncertainties caused by i) the factory polynomial that determines the instrument response to the scalar, ii) the repeatability of the measurement, and iii) the reproducibility of the instrument (zero and gain function). Each of these uncertainties has more than one contributing factor (*cf*. Ocheltree and Loescher 2007). The first two sources of uncertainty are often determined by the manufacturer. Even though the factory calibrations are not adequate by themselves as a measurement standard, the polynomials and reproducibility can be estimated in the lab with the proper equipment and scalar standards. Hence, IRGA polynomials and reproducibility should be checked, and changed if necessary every 3-12 months depending on the application (regardless of either open- or closed-path design). *In situ* calibrations that adjust the zero and span (gain) of the IRGA addresses the third source of uncertainty, *i.e.*, reproducibility. AmeriFlux recommends that the gain does not change more than 5% across a 10 ppm range between *in situ* calibrations. The frequency between *in situ* calibrations can be different for open- and closed path designs, and should be determined dependent on the specific research questions to be answered. Manual *in situ* calibrations for closed-path IRGAs are typically more frequent than open-path designs, every 3-7 d. A better alternative is to automate zero and span calibrations to every 4-10 h to assess the drift in gain (see below). Open-path IRGAs tend to be less accurate while maintaining similar high levels of precision compared to closed-path designs. But they are also subject to ambient conditions that may affect its operation, *e.g.*, wet and dry deposition. At minimum, inspection of the windows, diagnostic flags should occur ca. every7 d, and *in situ* open-path calibrations should be checked and changed if necessary every 21- 42 d.

Additional information on CMDL gas standards see;
http://www.esrl.noaa.gov/gmd/ccgg/refgases/
And on making high precision CO_2 measurements see, Zhao *et al.*1997 and
http://rflux.psu.edu/

Closed-path instruments should be configured for automatic routine calibrations. The simplest approach is to supply an excess of CO_2-free air (N_2) or working standards that bracket the range of observed concentrations to the sample inlet. An excess flow of 20-30% assures that no ambient air is drawn into the optic bench during the calibration. The calibration needs to run long enough that the entire volume of tubing and analyzer cell is flushed completely and data from the end of calibration interval are collected for a sufficiently long period to return valid statistics. By delivering calibration gas to the inlet and venting it to the atmosphere there is no need for pressure and flow control, but excess gas is consumed. If the pressure and flow in the analyzer are actively controlled it is preferable to calibrate by operating a valve to switch between ambient sample and calibration source. A needle valve, frit, or mass flow controller can be used to provide pressure drop between the high pressure standard tank and the low pressure analyzer cell. If only the instrument gain needs to be determined, a standard addition calibration by adding a small known volume of high concentration CO_2 to the main flow is an option. Two mass flow meters are required to measure the flow of sample and of calibration gas. Any calibration approach that involves introduction of a calibration gas near the inlet has the added benefit of providing a test of wall interactions and mixing in the inlet tube by evaluating the rise and fall of signal when the calibration is turned on and off.

There are differing opinions on whether it is better to configure the CO_2 analyzer in absolute mode, using CO_2-free air or N_2 as a zero reference gas or in differential mode using a near-ambient CO_2 in air as the reference. Differential mode requires that the analyzer is configured to maintain the same pressure in sample and reference cell but the concentration range between ‘zero’ and sample that must be recorded is narrower. Absolute mode reduces the dependence on pressure in the reference cell because there are no gases that absorb IR, however, the data system will need to have adequate resolution to record the entire span between 0 and ambient CO_2 concentrations in order to include a zeroing in the calibration sequence.

4.2 Sonic anemometer-thermometer calibration

Each flux station should attempt to carry out short-term (3 - 10 day) comparisons of their operating field sonic anemometers with their spare unit. The spare unit should be mounted at the same level as the field unit. An important goal of the cross-site EC calibration program is to assess the performance of the sonic anemometer operating at the main site of each flux station. Another important daily check is the comparison of half-hour values of "cup wind speed" and wind direction calculated from horizontal wind vector components (*u* and *v*) measured by the sonic anemometer (2*uv*2+) with wind speed/direction measured independently by a wind-vane and anemometer. The agreement should be within 5%.

Air temperature (T_a) and sonic temperature (T_s), differ due to the contribution of water vapor to air density. T_a should be measured using an aspirated shield (discussed below). T_s may also have to be adjusted to approximate T_a and subject to cross-wind effects. For further discussion see Kaimal and Gaynor (1991) and Schotanus *et al.* (1983).

4.3 Temperature and Humidity

In principle, temperature and humidity these are simple measurements to make, yet, as experience tells us, they have high disagreement between site sensors and those in the AmeriFlux portable EC system site. To avoid errors due to solar heating, temperature and humidity sensors need to be protected by an aspirated radiation shield. If temperature sensors are used in conjunction with flux profile measurements, sample inlets can be collocated with temperature sensors inside a radiation shield to quasi-aspirate the sensor. Platinum resistance probes, thermistors, or thermocouples can all be used to measure with sufficient precision and accuracy. If PT100 probes are used, they should be connected according to manufacturer's recommendation for using the 4-wire output to compensate for resistance changes in the cable and linearizing the signal. Thermistors (e.g., 30k ohm) have high enough resistance that variations due to the cable length are insignificant. Thermocouples are inexpensive and need an independent reference temperature. In all cases, temperature sensors should be calibrated initially at known temperatures. An insulated ice bath and water vapor at boiling point are two suitable standards (AmeriFlux temperature sensor calibration procedures can be found in http://public.ornl.gov/ameriflux/SOP/Temperature_webSOP.doc). Periodic comparisons to a calibrated thermometer can be made *in situ* to verify performance over time.

Capacitance sensor chips (e.g. Vaisala HMP45) are suitable for long-term humidity measurement. Factory calibration should be verified periodically by comparison to *in situ* measurements such as wet-bulb psychrometer, a chilled-mirror instrument, or measurement of humidity over a series of saturated salt solutions.

4.4 Radiation sensors

Net radiation is frequently measured with a net radiation sensor, which utilizes two optically black thermopiles to detect the difference in total incoming and outgoing radiation (e.g., Kipp and Zonen NR lite, REBS Q*7.1). Preferably the individual components of up- and down-welling short- and long-wave radiation are measured separately to derive the net radiation, albedo, and effective surface temperature (e.g., Kipp and Zonen CNR1, Eppley PSP). These data are primarily used for understanding surface energy budgets and are reported in Wm^{-2}. Some of these black thermopiles are sealed and require little maintenance besides cleaning. Others are housed inside glass or plastic domes and can require heating and dried air to prevent condensation. As in the case with the REBS Q*7.1, the domes may be particularly prone to attack by birds. The portion of solar radiation utilized by vegetation (photosynthetically active radiation) is measured as a photosynthetically active photon flux density (PPFD) by quantum sensors. The fraction of light absorbed by the canopy is also a critical parameter for evaluating CO_2 uptake over time, across sites, or between models and observations. Sites should include a PPFD sensor below the canopy, but the optimum strategy for quantifying spatial variability beneath the canopy is highly site dependent.

Because radiation sensors age, cross-site comparisons or long-term trends in surface energy properties or photosynthetic light-use efficiency are critically dependent on maintaining accurate calibrations to ensure that the radiation measurements are comparable through time. To detect a 10% change in photosynthetic efficiency between different growing seasons requires that the PPFD calibration is constant to better than 10%. Sensor placement must be made so that upward facing sensors are not subject to shadowing from the tower. Downward facing sensors should be as high above the canopy and extend as far from the tower structure as possible to provide a maximum field of view and minimize the portion of their viewing area that is tower structure and not canopy. Calibration using a transfer standard instrument is required at least annually. The transfer standard is only exposed for a few days at a time during calibration and should be calibrated at the factory or suitable radiation facility periodically. Intersite comparisons require shared transfer standards or that all the calibrations are referenced to a common scale. The calibration procedures for AmeriFlux PPFD sensors and the reference PPFD sensors lend to each research group can be found at http://public.ornl.gov/ameriflux/SOP/PAR_webSOP.doc .

4.5 Wind speed and direction

Although the Sonic anemometer provides wind speed and direction, it is preferable to have an independent measurement with which to compare the sonic data. Standard meteorological wind vanes and cup anemometers should be installed according to routine meteorological guidelines. Single units that include wind vane and propeller anemometer are convenient, but separate wind vanes and spinning cup anemometers are suitable as well. All mechanical anemometers need a minimal wind speed to overcome inertia; this break through volume should be as low as money permits. Proper placement of the wind monitor is crucial. Wake turbulence (flow distortions) from trees and other tall structures upwind can greatly influence measurements. To get meaningful measurements, situate the wind monitor well above (including the tower on which it is installed) or upwind of major obstacles. A single measurement at an arbitrary height above the canopy has limited value as a network measurement. More useful is to determine a vertical profile of wind speed that can be used to define drag coefficients and zero plane displacement height. For meaningful comparisons across sites it is essential that data below minimum wind speed threshold be treated consistently. Data documentation for each site must include information on the wind sensor performance specifications and define the procedures for treating low wind speeds. Frequent inspection of the raw data to evaluate the wind speed cutoff is required to detect any sensor degradation. Mechanical anemometers will need periodic maintenance (bearing replacement).

4.6 Precipitation

Precipitation is another seemingly trivial measurement that is in fact prone to large uncertainty. Significant differences in precipitation may be observed between a gauge mounted above the canopy on the tower and one at the ground in a nearby clearing. Collection efficiency is dependent on wind speed. Spatial variability may be significant for small rain showers or at sites with orographic precipitation. The best approach for precipitation measurements that can be compared across the network is to adopt standard precipitation protocols for National Weather Service observing stations, or rely on NWS observations made nearby, particularly if there is a spatially dense network of cooperative observation sites in the region. Rain gauges should be cleaned and leveled often. Throughfall, the precipitation that reaches the ground below-canopy, is extremely heterogeneous. Methodologies should embody the spatial variability inherent in the ecosystem in question. For more on throughfall see Roberts *et al.* (2005) and Loescher *et al.* (2002).

5.0 PROFILE AND CO_2 and H_2O CONCENTRATIONS

The change of CO_2 storage between the EC measurement height and the ground would be close to zero over a daily cycle if there are not net losses due to advection. The small change in storage from variations in the mean concentration are likely insignificant. Over short intervals, particularly at the dusk and dawn transitions, storage is important and Net Ecosystem Exchange is unequal to the vertical eddy flux of CO_2. The storage term is derived as the time derivative of the column integral of concentration. An ideal measurement of storage would use a vertically integrating inlet to get a true column average between the ground and eddy sensor height. In practice, the shape of the concentration profile can be of interest for quantification of source and sink structure in the canopy. The profile is determined from individual inlets that are sampled sequentially. The number of inlets and their spacing need to be designed to adequately capture the shape of the concentration profile. Exact spacing and number are site dependent. Typical installations deploy 6 - 8 inlets per 30 m and a separate closed-path IRGA to measure the CO_2 and H_2O concentrations. Calibration and quality assurance protocols need to be consistent with consistent with those for the eddy CO_2 measurements. Changes in pressure will affect the CO_2 signal, so pressure differences should be eliminated by matching the inlet lengths or installing an active pressure control system.

Table 1. Core AmeriFlux Measurements

Parameter/Variable	ID	Note
Biosphere-atmosphere interface CO_2, water vapor, and energy flux		
CO_2 flux	Fc30 or Fc60	Eddy Covariance
Sensible heat flux	H30 or H60	Eddy Covariance
Water vapor flux	E30 or E60	Eddy Covariance
Latent heat flux	LE30 or LE60	Eddy Covariance
Momentum flux measured as Kinematic momentum	TAU30 or TAU60 Uwcvar	Eddy Covariance
Meteorological data and consequences (e.g. wetness)		
Air temperature	Ta30 or Ta60	Aspirated/Shielded temperature sensor
Relative humidity	Rh30 or Rh60	Aspirated/shielded humidity

Direct measure, or computed from absolute humidity		sensor, or absolute water vapor measurement
Vapor pressure deficit (calculated)	VPD30 or VPD60	Calculated
Net radiation	Rn30 or Rn60	Net radiation sensor or sum of components
Global Radiation	Rg30 or Rg60	Global Radiation sensor
Photosynthetic Active Radiation (Photosynthetic active Photon Flux Density, Incident PAR)	PPFD30 or PPFD60	Quantum sensor
Wind speed	WS30 or WS60	Sonic or cup anemometer
Wind direction	WD30 or WD60	Sonic anemometer or
Friction Velocity (calculated from u’w')	USt *	Calculated
Atmospheric stability parameter (calculated)	ZL30 or ZL60	Calculated
Precipitation	P30 or P60	Standard rain gauge
Within canopy data, e.g. profiles		
CO_2 concentration profile	Co30 or Co60	CO_2 analyzer with inlet manifold
Humidity	Ho30 or Ho60	H_2O analyzer with inlet manifold
Dew-point temperature (Calculated or direct measure)	T0dew30 or Tdew60 *	Calculate from humidity and temperature, or direct measure using wet-bulb or chilled mirror
Need a sub-canopy light msmt.		
Derived variables: CO_2, water vapor and energy storage		
CO_2 storage in canopy air layer	Sc30 or Sc60	Calculate from profile,or measure as concentration from integrating inlet
Soil efflux of CO_2, water vapor, and energy in addition to soil moisture and temperature profiles		
Soil CO_2 flux, Soil respiration	FCSOIL30 or FCSOIL60	Soil respiration chamber protocols discussed elsewhere
Soil heat flux	G30 or G60	Heat Flux plates
Soil temperature (profile) (5/10/20 etc cm)	Tscm30 or Tscm060 *	Buried temperature probes

Soil water potential	SWP *	In units of MPa

Table 2. Additional desired measurements

Canopy air temperature profile	Tap30 or Tap60 *	Multiple temperature sensors
Relative humidity profile	Rhp30 or Rhp60	Multiple humidity sensors
Short-wave Radiation	Rgs30 or Rgs60	Solar radiation sensor
Long-wave Radiation	Rgl30 or Rgl60	Solar radiation sensor
Reflected Radiation	Rr30 or R360	Downward facing radiation sensor(s).
Direct Radiation	Rb30 or Rb60 *	Part of global radiation, which is due to the relatively unmodified parallel radiation in the direct beam W m^{-2}. (Pearcy 1991)
Diffuse Radiation	Rd30 or Rd60	Part of global radiation, which includes reflected and scattered radiation from all portions of the sky in units of W m^{-2}. (Pearcy 1991)
UV Radiation	Ru30 or Ru60	Radiation of wave-lengths between 0.1 and 0.4 m m. In units of mW m^{-2} nm^{-1}
Absorbed PPFD	APAR30 or APAR60	Compute from incident, reflected and subcanopy PPFD
Percent (Fraction) Intercepted Radiation	FIPAR30 or FIPAR60	Compute from above
Barometric pressure	Pa30 or Pa60	Pressure transducer
Throughfall	TF30 or TF60	Below canopy precipitation collection
Stem flow	SF30 or SF60	Stem flow collars
Snow depth	SNOWD30 or SNOWD60	Depth of the snow at the ground, averaged over the observed time period in mm
Canopy wetness	CW30 or CP60	Wetness sensor
Light profile/tram data	Rprof30 or Rprof60	In W m^{-2}
Soil Albedo	SAlb	???
Litter Albedo	LAlb *	???
Canopy Albedo	CAlb *	Derive from up/down radiation measurements
Within canopy process parameters (Not addressed in this document		
Pre-dawn water potential	PSI	(Note time of day: dawn, pre-dawn) in units of MPa (Strongly suggested)

Leaf water potential	LWP *	In units of MPa
Stomatal conductance	Gs	(minimum, spring) (vpd response, vpd in kPa at stomatal closure). The gas exchange measurement systems usually provide temperature, humidity, and light. In mmol m^{-2} s^{-1}
Leaf net photosynthesis	Psat	Light response curves (maximum photosynthetic rate at light saturation, A/Ci curves). The gas exchange measurement systems usually provide temperature, humidity, and light. In µmol m^{-2} s^{-1}
Foliar respiration	RLD	In units of µmol m-2 leaf area s-1
Bole respiration	RB	In units of µmol m^{-2} bole area s^{-1}
Xylem sapflow	TR30 or TR60	(transpiration) in units of mm hr-1
CO_2 Drift	FcD30 or FcD60 *	In units of µmol m^{-2} s^{-1}
Heat storage in canopy air layer	Sa30 or Sa60	Compute from integral of density and heat capacity with delta T profile
Heat storage in canopy biomass	Sb30 or Sb60	Scale from deltaT and density and heat capacity in the biomass
Latent heat in canopy air layer	Sw30 or Sw60	Compute from profile of dq/dt

Poorly defined measurements that need some work

Bole temperature	Tbole30 or Tbole60	Inserted temperature probes
Soil water vapor flux	ESOIL30 or ESOIL60	???
Soil moisture (0-30cm/ etc)	SWCcm	Gravimetric or TDR type probes

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