Uncertainty Analysis in Animal Building Aerial Emissions Measurements

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Abstract
Analysis of the propagation of measurement error into a computed quantity such as building aerial emissions provides insight into which measurements should be improved. An analysis of different instrument measurements, sampling period, and different sites all together comprise an objective means of determining optimal sampling strategies. This paper describes the measurement system uncertainty analysis useful for emissions research, and how it can lead to design and project improvements to obtain emissions estimates with statistical confidence. This study is an analysis of the Kentucky broiler house study as part of the US EPA Air Consent Agreement, and was used to develop a category I Quality Assurance Project Plan. Results of the analysis suggest that the standard uncertainty in ammonia emission from broiler houses in the study was typically under 10%, and increased with uncertainty in ventilation rate, but decreased as ventilation rate increased. The uncertainty is quantified for normal conditions and for conditions in which the instrumentation is at the calibration threshold.

Keywords
Emission, Ammonia, Instrumentation, Component error analysis

Disciplines
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Uncertainty Analysis in Animal Building Aerial Emissions

Measurements

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Abstract. Analysis of the propagation of measurement error into a computed quantity such as building aerial emissions provides insight into which measurements should be improved. An analysis of different instrument measurements, sampling period, and different sites all together comprise an objective means of determining optimal sampling strategies. This paper describes the measurement system uncertainty analysis useful for emissions research, and how it can lead to design and project improvements to obtain emissions estimates with statistical confidence. This study is an analysis of the Kentucky broiler house study as part of the US EPA Air Consent Agreement, and was used to develop a category I Quality Assurance Project Plan. Results of the analysis suggest that the standard uncertainty in ammonia emission from broiler houses in the study was typically under 10%, and increased with uncertainty in ventilation rate, but decreased as ventilation rate increased. The uncertainty is quantified for normal conditions and for conditions in which the instrumentation is at the calibration threshold.

Keywords. Emission, Ammonia, Instrumentation, Component error analysis

Introduction

Gaseous and particulate matter emissions from poultry houses vary with season and weather patterns, management and feeding practices, housing styles, and other factors. Two high-quality data studies on ammonia emissions from poultry housing have recently been completed in the U.S. The first study involved seven states and agencies/associations and was funded under the USDA competitive grant program "Initiative for the Future of Agriculture and Food Systems, or IFAFS, to determine ammonia emission rates (ER) from poultry facilities (Gates et al., 2001). Twelve broiler houses in two geographical regions were monitored for more than one year (Liang et al., 2005; Wheeler et al., 2006). The second study involved ammonia emissions from two commercial broiler houses in Kentucky, as part of the US Environmental Protection Agency’s Air Consent Agreement (Burns et al., 2007a,b), in which high frequency (approximately each 120 s) concentration and ventilation rate data were collected over a period of more than one year. This latter project is referred to as the “Kentucky Air Consent Agreement”, or Kentucky ACA, project throughout this paper. A set of Data Quality Objectives (DQOs) were developed to satisfy the requirements that the Kentucky ACA study comply with US EPA category I studies. These DQOs were developed by analyzing how the key input measurements affect uncertainty in ER. The full Quality Assurance Project Plan (QAPP) is being reviewed at the time of this writing for a special publication of the ASABE (Moody et al., 2008).

Estimation of building emissions from agricultural livestock and poultry operations should include a clear statement of uncertainty in published results (National Academy of Sciences, 2003), but often do not. An analysis of uncertainty in ER, as affected by measurements in primary variables such as constituent concentration and ventilation rate, is necessary to identify which instrument measurement errors control the magnitude of ER uncertainty. Some recent efforts to quantify uncertainty in air emissions research include Casey (2005), and Price and Lacey (2003). Casey (2005) established a methodology and provided specific uncertainty estimates for the U.S. IFAFS project. The objective of this article is to provide a similar, expanded uncertainty analysis for the ammonia emissions measurements made in the Kentucky ACA Project.

Component Error Analysis

A component error analysis can provide statistical meaning to a statement on the magnitude of error in building emissions. Propagation of uncertainty from individual instrument measurement error to a quantitative statement of uncertainty in building ER is performed by considering the contribution of each individual measurement’s uncertainty, using a truncated first-order Taylor series approximation to ER (Doebelin, 1990; Taylor and Kuyatt, 1994). The measurement error in each component is propagated through the mathematical relation between measurements and ER (Eq. 1, below). In principle, if all measurement inputs to the ER computation can be specified with a statistical measure of their uncertainties, then the estimate of ER can be provided along with a measure of uncertainty (e.g., via a confidence interval).
Simplified Equations from the USDA IFAFS Study.

The component error analysis for the USDA IFAFS study was developed by Casey (2005), and is documented in this section. The building ER is determined as follows:

\[
ER_{\text{ER}} = Q_T \times [G]_e \times 10^{-6} \times \frac{T_{\text{std}}}{T_e} \times \frac{P_a}{P_{\text{std}}} \times \frac{w_m}{V_m}
\]

(1)

where:

- \(ER_{\text{ER}}\) = Gas emission rate for the house, g hr \(^{-1}\) bldg \(^{-1}\)
- \(Q_T\) = Total exhaust ventilation rate of the building at field temperature and barometric pressure, m\(^3\) hr \(^{-1}\) bldg \(^{-1}\)
- \([G]_e\) = Gas concentration of the building exhaust ventilation air, parts per million by volume (ppmv)
- \(w_m\) = molar weight of the gas, g mole \(^{-1}\) (17.031 for NH\(_3\))
- \(V_m\) = molar volume of gas at standard temperature (0°C) and pressure (101.325 kPa) or STP, 0.022414 m\(^3\) mole\(^{-1}\)
- \(T_{\text{std}}, P_{\text{std}}\) = standard temperature, 273.15 K, and barometric pressure, 101.325 kPa
- \(T_e\) = absolute temperature of exhaust air, K
- \(P_a\) = atmospheric barometric pressure at the monitoring site, kPa

An estimate of variance for an ER, assuming independent input measures, is:

\[
\Delta \frac{ER}{ER} = \sqrt{\left(\frac{\Delta Q_T}{Q_T}\right)^2 + \left(\frac{\Delta [G]_e}{[G]_e}\right)^2 + \left(\frac{\Delta T_e}{T_e}\right)^2 + \left(\frac{\Delta P_a}{P_a}\right)^2}
\]

(2)

where the subscripts “g” on ER is dropped for simplicity, and ammonia concentration \(C\) is used to represent \([G]_e\). The square root of this expression, also termed the “root-mean-square error”, provides an estimate of uncertainty, expressed in physical units of ER. The relative uncertainty, \(\Delta \frac{ER}{ER}\), is the primary metric by which the DQOs were established.

In Eq. (2), there are two classes of terms in each product on the right hand side, namely the partial differentials of ER with respect to a primary measurement and the error in that measurement (denoted by \(\Delta\)). The partial differentials relate the physical relationships between measurements to the computed quantity. Errors in each measurement (\(\Delta\)-values) are the component ‘standard’ uncertainties, equivalent to a best estimate of component standard deviation (Taylor and Kyuatt, 1994). The combined standard uncertainty \(\Delta \frac{ER}{ER}\) is therefore a statistically-derived quantity and statements of confidence regarding an interval about ER are valid. In this work, we adopt the 2-sigma (2\(\sigma\)) approach by using 2\(\Delta \frac{ER}{ER}\) as the 95% confidence interval about a nominal value of ER.

For total building ventilation rate, the partial differential \(\frac{\partial \text{ER}}{\partial Q_T}\) in turn relates individual measurements taken by the Fan Assessment Numeration System (FANS) used to construct an individual fan calibration curve in-situ, thus requiring measurements of building static pressure (\(P_s\)) and a regression slope (\(b\)) and intercept (\(a\)) that is unique to each fan of the building. Other partial differentials are more straightforward, relating ER directly to measurements.

Eq. (2) can be expanded to incorporate the contributions of the individual measurements. This equation (3) forms the basis for the Data Quality Objectives that were established in the Kentucky ACA Project.

\[
\Delta \frac{ER}{ER} = \sqrt{\left(\frac{\Delta Q_T}{Q_T}\right)^2 + \left(\frac{\Delta [C]_e - C_{\text{cal}}}{C_{\text{cal}}}\right)^2 + \left(\frac{\Delta T_e}{T_e}\right)^2 + \left(\frac{\Delta P_a}{P_a}\right)^2}
\]

(3)

Terms in this equation include variables defined previously, plus:

- \(C_{\text{cal}}\) = calibration span gas certified value (within 2 - 3%)
- \(\Delta T_e\) = standard uncertainty in exhaust air temperature, °C
- \(\Delta P_a\) = standard uncertainty in barometric pressure, at location, kPa

Application to the Kentucky ACA Study.

For the Kentucky ACA study, the ammonia concentration in the inlet air was not neglected. Thus, the following relation for ER was used:

\[
ER = Q_T \left(\frac{C}{T_e} \times \frac{T_{\text{std}}}{T_e} \times \frac{P_a}{P_{\text{std}}} \times \frac{w_m}{V_m}\right) \times \frac{T_{\text{std}}}{T_e} \times \frac{P_a}{P_{\text{std}}} \times \frac{w_m}{V_m}
\]

(4)

where:

- \(C_i\) = Gas concentration of incoming building ventilation air, respectively, parts per million by volume, ppm,
\( T_i \) = Temperature of incoming air, °C
\( \nu_i, \nu_e \) = specific volume of incoming and exhaust air, respectively, m³ moist air per kg dry air, calculated from air temperature and RH

The ratio of incoming to exhaust air specific volumes, \( \nu_i/\nu_e \), is:

\[
\frac{\nu_i}{\nu_e} = \frac{T_i(1 + 1.6078P_i/k(1 + W_i))}{T_e(1 + 1.6078P_e/k(1 + W_j))}
\]

Substitution into the equation for ER gives:

\[
ER = \frac{C}{T_e} \left( C - C_j \right) \frac{1}{(1 + 1.6078P_e/k(1 + W_j))} \times 10^{-6} \frac{P_i}{P_{std}} \frac{\nu_i}{\nu_{std}} \frac{w_{in}}{w_{ext}}
\]

Methods

Representative Calculations to Define Measurement Quality Objectives (MQOs).

In designing new studies under EPA category I criteria, measurement performance criteria are to be held to a stated level of uncertainty. Such a statement is called a Measurement Quality Objective, and serves as the outline by which future measurements should be taken to ensure controlled measurement uncertainty. To assess ER uncertainty in the Kentucky ACA study, Eq. (3) was evaluated at representative values (and accuracies) of NH₃ concentration and ventilation rate, with uncertainties in barometric pressure and exhaust air temperature taken as negligible.

A sensitivity analysis was performed for the Kentucky ACA study, using the component error analysis equations provided in the preceding section coupled with estimates of uncertainty for the equipment used in this study. Concentration uncertainty for the ammonia measurements in the Kentucky ACA study was 1% of reading or better, with a 5% limit for required recalibration. Two cases are evaluated to quantify ER uncertainty:

Case 1: Normal Operation: characterized by 1% uncertainty on concentration measurement, 3% uncertainty on calibration standard, and a range of 1% to 10% uncertainty in building ventilation rate. Since building ventilation rate is comprised of multiple fans, we assumed them to be identical and the total building ventilation rate uncertainty is the number of fans multiplied by the ventilation rate uncertainty of a fan.

Case 2: Worst-Case Operation: Similar to case 1, except that concentration measurement uncertainty is increased to the threshold for recalibration, 5% of the reading.

Results

Results of these two cases are presented graphically in Figure 1. Relative uncertainty (%) is plotted against building ventilation rate, and found to follow a power law relation given by:

\[
\frac{\Delta ER}{ER} \% = a \cdot \left( \frac{Q}{Q_{std}} \right)^b
\]

where constants a and b are obtained from nonlinear regression and building ventilation rate is given in units of cubic feet per minute (cfm). These constants are tabulated in Table 2. This allows estimation of uncertainty in ER for other values of input parameters.

Discussion

Standard uncertainty ER estimates can be taken directly from Figure 1. The left-hand pane is representative of a calibrated concentration-measuring instrument (1% uncertainty), with 50% error in calibration gas certification (i.e. 3% uncertainty for a 2% certification). It shows that as building ventilation rate increases the uncertainty drops to around 4%. The ER uncertainty is positively related to ventilation rate uncertainty, with the maximum value of about 12% when the ventilation uncertainty is 10% at very low ventilation rates. Thus, standard ER uncertainty can be maintained to less than 10% since the minimum ventilation rates of the houses monitored were approximately 39,000 m³/h (23,000 cfm) when fans were running.

The uncertainty estimates in the right-hand plot of Figure 1 establish the effect of increasing concentration uncertainty from 1% to 5%, for example, with other factors held constant. For this scenario, standard uncertainty in ER increases very little. Also added is a severe case in which ventilation rate uncertainty is increased to 25%, for example, if fans were not calibrated but instead measured via hot wire anemometer or some less-sophisticated methodology. For studies using such methods, ER uncertainty can approach 30%.
Figure 1. Uncertainty estimates for ER as function of building ventilation rate ($Q_T$) and ventilation uncertainty. Note scale difference on the two plots.

Table 2. Parameters for predicting emission rate (ER) uncertainty as affected by gas (ammonia) concentration and building ventilation uncertainties.

<table>
<thead>
<tr>
<th>Case</th>
<th>Ventilation Uncertainty</th>
<th>Adjusted $r^2$</th>
<th>Parameter “a” (se) of Eq. 12</th>
<th>Parameter “b” (se) of Eq. 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Operation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1% Concentration</td>
<td>1</td>
<td>0.9999</td>
<td>4.180 (0.1604)</td>
<td>-0.024 (0.0036)</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>2.5</td>
<td>0.9994</td>
<td>10.58 (1.055)</td>
<td>-0.103 (0.0094)</td>
</tr>
<tr>
<td>3% Calibration Gas</td>
<td>5</td>
<td>0.9986</td>
<td>62.050 (8.501)</td>
<td>-0.251 (0.0131)</td>
</tr>
<tr>
<td>7.5</td>
<td>7.5</td>
<td>0.9984</td>
<td>205.95 (29.28)</td>
<td>-0.346 (0.138)</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>0.9993</td>
<td>415.28 (38.64)</td>
<td>-0.394 (0.091)</td>
</tr>
<tr>
<td>Worst-Case Operation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% Concentration</td>
<td>1</td>
<td>1.0000</td>
<td>6.200 (0.0988)</td>
<td>-0.004 (0.0015)</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>2.5</td>
<td>0.9999</td>
<td>8.791 (0.4232)</td>
<td>-0.035 (0.0045)</td>
</tr>
<tr>
<td>3% Calibration Gas</td>
<td>5</td>
<td>0.9992</td>
<td>22.43 (2.4846)</td>
<td>-0.116 (0.0104)</td>
</tr>
<tr>
<td>7.5</td>
<td>7.5</td>
<td>0.9987</td>
<td>60.00 (8.2516)</td>
<td>-0.198 (0.0131)</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>0.9985</td>
<td>142.29 (19.70)</td>
<td>-0.269 (0.0133)</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>0.9997</td>
<td>1509.8 (87.17)</td>
<td>-0.436 (0.0057)</td>
</tr>
</tbody>
</table>

From this component error analysis, it is clear that careful control of ventilation rate uncertainty is critical for controlling ER uncertainty, and has probably contributed to the majority of error in such measurements prior to the implementation of the FANS methodology with regular calibration of individual fans. If ventilation rate is estimated by other, less accurate, methods then ER uncertainty is expected to be substantially larger. This defined a critical MQO for the study.
Other Factors that Influence Data Quality.

Three other factors should be evaluated in the analysis of error propagation presented above. These are effect of multiple fans in building ventilation rate, effect of fan performance degradation during each flock grow-out because of accumulation of dirt on fans, and the effect of neglecting background concentration and differences between inside and outside air density and moisture content. Each factor is briefly addressed below.

Effect of Multiple Fans

Variance of an expression that is comprised of a constant multiplied by another varying quantity is the square root of the constant times the variance of the input quantity. Thus, for 14 ventilation fans with identical standard component uncertainty $S_F$, the standard uncertainty in total building ventilation rate is \( \sqrt{14} \cdot S_F \).

Effect of Fan Degradation during Grow-out

As fans accumulate dust and dander (in the case of belt-drive fans, due to loose of fan belt over time), their performance degrades. This degradation has been shown to be significant. Regular cleaning between each flock was performed and confirmed with in-situ recalibration of a random subset of fans in each building; however, quantification of degradation is not realistic and thus introduces a bias towards over-estimating ventilation rate, and hence building ER. Dirt accumulation on fans during the course of a flock grow-out can result in as much as 20% over-estimation of ventilation rate and hence ER. Uncertainty in ER is not symmetrical about zero with this form of bias.

Effect of Background Concentration and Air Density/Moisture Effects on ER

Casey (2005) neglected background ammonia concentration, whereas the Kentucky ACA study (Burns et al., 2007a,b) incorporated background concentration and subtracted the ammonia flux coming into the building from that leaving the building. Other studies have improperly handled the difference in air densities between incoming (fresh) air and the exhaust air leaving through ventilation fans. The ER methodology employed in this study properly accounts for both background concentrations, and differences in air density. In this section we outline how these simplifying assumptions affect the estimate of ER uncertainty. In general, the impact of these omissions on ER is inconsequential. This analysis is provided to document the order of errors involved when quantifying ER errors.

The effect on ER of neglecting background concentration is quantified in Table 3 for a broad range in expected indoor and outdoor temperature and humidity ratios. The following points can be made:

1. Neglecting a positive, non-zero background concentration can over-predict ER
2. The specific volume ratio $\nu_i/\nu_e$ provides a multiplier of 103% to 115% to the background concentration, resulting in potential further over-prediction
3. The greatest over-prediction will occur during the coldest and driest outside conditions coupled with the warmest and most humid interior conditions, and is about 15% for typical Kentucky wintertime brooding conditions.
4. Note that the adjustment in the table below is applied to the background gas concentration, not the ER. Thus, the error in ER from neglecting density effects is less than 15% of the background concentration; the error in ER from neglecting background concentration depends on the magnitude of $[G]_i$ and $[G]_e$.

<table>
<thead>
<tr>
<th>Production Climatic Condition</th>
<th>Range of Humidity Ratio, (g H$_2$O/kg dry air)</th>
<th>Range of Air Temperature (K)</th>
<th>Adjustment* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>winter brooding</td>
<td>0 - 20</td>
<td>263 - 306</td>
<td>115</td>
</tr>
<tr>
<td>winter growout</td>
<td>2 - 12</td>
<td>263 - 293</td>
<td>110.7</td>
</tr>
<tr>
<td>fall/spring brooding</td>
<td>4 - 20</td>
<td>273 - 306</td>
<td>111.0</td>
</tr>
<tr>
<td>fall/spring dry interior</td>
<td>4 - 10</td>
<td>273 - 306</td>
<td>111.7</td>
</tr>
<tr>
<td>fall/spring growout</td>
<td>4 - 10</td>
<td>283 - 293</td>
<td>103.2</td>
</tr>
<tr>
<td>summer brooding</td>
<td>10 - 20</td>
<td>293 - 306</td>
<td>103.8</td>
</tr>
<tr>
<td>summer growout</td>
<td>10 - 12</td>
<td>283 - 293</td>
<td>103.4</td>
</tr>
</tbody>
</table>

* Multiply inlet NH$_3$ concentration (ppmv) by the adjustment ratio to account for air density differences.
Conclusion

According to the analysis presented, if QA-checks are properly performed and all sampling procedures and SOPs followed, the standard uncertainty in ER is 10% or less for building ventilation rates at 34,000 m³/h (20,000 cfm) or greater with a maximum ventilation uncertainty of 10%. A minimum ventilation of approximately 39,000 m³/h (23,000 cfm) was used in both study houses. There is a potential bias towards over-estimation of ventilation rate by as much as 20% as dirt is accumulated on fans which will result in a bias (over-prediction) of ER of about 8-20% depending on ventilation rate. To avoid this bias, all fans should be cleaned between flocks in each production house during a study.

While this analysis was carried out specifically for ammonia, it applies equally to all gaseous contaminants which have stated accuracies of 1% or better. For particulates, the analysis also applies, but since the particulate accuracy is represented in terms of an absolute mass concentration (5 ug/m³), it is directly applicable to concentrations greater than 500 ug/m³.

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