Meteorological Measurement Error Analysis
Based on Proposed ANSI/ANS-3.11 (2005)

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ANSI/ANS-3.11 (2000), "Determining Meteorological Information at Nuclear Facilities," filled significant gaps in guidance when it was issued. However, due to numerous advances (e.g., in-situ and remote sensing instrumentation and data management hardware, software, and techniques), a modernization of the standard was merited. Therefore, as ANSI/ANS-3.11 (2000) approached its automatic sunset date (which required reaffirmation, revision, or withdrawal), it was decided a revision was needed to "modernize" the standard--to be published as ANSI/ANS-3.11 (2005).

One of the key changes in the new standard addressed the issue of meteorological system performance. Specifically, ANSI/ANS-3.11 (2000) was inadequate in defining how to characterize accuracy. The changes to the standard should enable accuracy to be calculated in a consistent manner that permits relevant comparison with specified values.

This paper will discuss the history of meteorological error calculation and describe the methodology in the proposed ANSI/ANS-3.11 (2005).

Accuracy is the primary indicator of meteorological system performance. Observed accuracy must be calculated in a consistent manner to permit comparison with specified values. ANSI/ANS-3.11 (2000) was inadequate in defining how to characterize accuracy. When the standard is revised and published as ANSI/ANS-3.11 (2005), one of the key changes will address this issue.

This paper will discuss the following topics related to meteorological system accuracy calculations.

- Error Calculation History
- ANSI/ANS-3.11 (2005) Method for Calculating Accuracy
- Example Calculation

Error Calculation History

A review of the history of accuracy calculations provides a background about how the method described in ANSI/ANS-3.11 (2005) evolved.

a. Safety Guide 23, "Onsite Meteorological Programs," 1972.

   Section 4, "Instrument Accuracy," provides plus/minus accuracy values for different meteorological variables but does not indicate if the accuracy applies just to the instruments or to the entire data channel.

   No calculation methodology for channel accuracy is defined.

b. Proposed Revision 1 to Regulatory Guide 1.23, "Meteorological Measurement Programs for Nuclear Power Plants," ~1981 (never issued).

   Section 3, "System Accuracy" states:

   > System accuracy refers to the composite accuracy and reflects the errors introduced by the sensor, the cable, signal conditioning and recording, the recorders, and the data reduction process. The errors introduced by each of the separate components of the system should be determined by statistical methods. The system accuracy should be defined by the root sum of the squares (RSS) method, which is calculated by squaring the standard error of each component, summing the squared standard errors and taking the square root of the sum. For time-averaged values, those component errors which are random about the time value may be decreased by dividing the component standard error by the square root of the number of samples used to define the average value.

   The system accuracies are similar to those in Safety Guide 23 (1972).

   NRC better defines what is preferred as a calculation methodology and clearly states that accuracy values apply to the data channels as a whole. The methodology also allows for special handling of time-averaged values. Unfortunately, guidance is still in form of "should" and "may", so other methods are acceptable. Also, by using only a text description of the RSS methodology (with no equations or examples), users may become confused about what is intended.

   The document does not state why the RSS method is to be used and no source reference for the RSS method is provided.

   Finally, this revision was never issued as official policy.

c. ANSI/ANS-2.5 (1984), "Standard for Determining Meteorological Information at Nuclear Power Sites," 1984

Section 6.1, "System Accuracy" states:

> Parameter accuracy for a system refers to the composite accuracy reflecting the errors introduced by sensor, cable, signal conditioner, temperature environment for signal conditioning and recording, recorders, and data reduction process. The errors introduced by each of the separate components of the system shall be determined by statistical methods as discussed in N. Caruthers [4].
>
> 4. C. E. P. BROOKS and M. CARUTHERS, "Handbook of Statistical Methods in Meteorology," M. O. 538, Chapter 5, Her Majesty's Stationery Office, London (1953).
>
> For individual samples, the system accuracy shall be determined by the root sum of the squares (RSS) method considering the error contributions of system components from the sensors through the recording systems. The RSS is calculated by squaring each error, summing the squared errors and taking the square root of the sum. For time averaged values, those parts of the error budget which are random may be decreased from their instantaneous value by dividing by the square root of the number of samples used to define the average value. The RSS calculation can then be made.

The system accuracies are similar to those in Safety Guide 23 (1972) and Proposed Revision 1 to Regulatory Guide 1.23 (1981).

ANSI/ANS-2.5 (1984) fills the gap concerning up-to-date guidance. By using "shall", ANSI/ANS-2.5 (1984) defines RSS as the only acceptable calculation method. However, like Revision 1 to Regulatory guide 1.23, ANSI/ANS-2.5 (1984) uses only a text description of the RSS methodology (with no equations), so users may become confused about what is intended.

The reference to BROOKS and CARUTHERS is unfortunate because the book is out-of-print, is difficult to obtain, and does not clearly describe the applicable statistical methods. Since source equations and examples are not available, user error calculations are often based on second- or third-hand interpretations of what the reference describes.

d. NUMUG Presentation, "A Methodology for Calculating Meteorological Channel Accuracies," by R. Brad Harvey, 1999

THIS IS NOT A GUIDANCE DOCUMENT, BUT PROVIDES INSIGHT INTO HOW THE ANS-2.5 GUIDANCE WAS INTERPRETED AND USED.

Section 3, "Potential Sources of Error" states:

> . . . To determine the overall uncertainty of an instrument loop, a number of potential error sources should be considered to determine their possible effects. Individual errors are . . . combined to determine a total probable loop error. Errors that are random and independent are combined statistically using the square root of the sum of the squares; systematic or bias errors are added algebraically. For determining the error of time averaged values, those random errors that can fluctuate within the averaging period are divided by the square root of the number of samples before taking the square root of the sum of the squares. . .

This document is useful because it illustrates implementation of ANSI/ANS-2.5 (1984) and provides example calculations.

The calculations vary from the ANSI/ANS-2.5 (1984) guidance by distinguishing between random and bias errors, and using different mathematical approaches for including the applicable error contributions in the final loop error value. Bias errors will produce larger loop errors than if they were treated as random error, but the differences should not be large and should result in more correct loop error values.

e. ANSI/ANS-3.11 (2000), "Determining Meteorological Information at Nuclear Facilities," 2000

Section 7.1, "System Accuracy" states:

> Accuracy values shall reflect the performance of the total system. . .
>
> System accuracy should be estimated by calculation of the root-mean-square of the accuracy of the system's individual components. Accuracy tests should be performed by placement of the sensor in a known operating condition and by observation of the result on a display indicative of data recorded during routine operation.

The system accuracies are similar to those in earlier guidance documents.

ANSI/ANS-3.11 (2000) reverts to using "should" so no single calculation methodology applies. Accuracy tests are now identified as an approach to determine system accuracy. Also, the calculation methodology is now described as "root-mean-square" (RMS) rather that "root sum of the squares" (RSS). Further, ANSI/ANS-3.11 (2000) no longer distinguishes between instantaneous and time-averaged values.

Unfortunately, ANSI/ANS-3.11 (2000) does not clearly state that the calculation methodology has changed; and since no description, references, examples, or equations are provided; many users assumed that the calculation methodology has been unchanged. This is not the case as shown below.

root sum of the squares (RSS): $RSS = \sqrt{(r_1)^2 + (r_2)^2 + \cdots + (r_x)^2}$

root-mean-square (RMS): $RMS = \sqrt{\frac{(r_1)^2 + (r_2)^2 + ... + (r_x)^2}{x}}$

where: $r_1, r_2, \cdots, r_x$ are random error components.
x is the number of components.

No information is provided to explain the change from RSS to RMS, so it is not certain that this change was really intended. All prior error calculations and many subsequent calculations were in terms of RSS (when users did not recognize the two methods were different). Further, vendor specifications and system design characteristics were all established assuming an RSS approach. Since the RMS approach results in significantly different results from the RSS approach, this prior information would probably no longer be valid for comparison.

Accuracy calculation guidance limitations in ANSI/ANS-3.11 (2000):

- A standard needs to be the “official” source of guidance (not one choice among many) and needs to be definitive about the methodology for system accuracy calculations—specifically, use "shall" rather than "should" or "may". However, since ASTM is changing guidance concerning uncertainty, the ANSI/ANS-3.11 (2005) Working Group agreed to retain "should" to allow such changes to be implemented within the scope of ANSI/ANS-3.11 (2005).
- ANSI/ANS-3.11 (2000) did not provide any examples, equations, or step-by-step procedures for system accuracy calculations. Therefore, the user was expected to properly interpret what was intended and make the necessary calculations correctly.
- Guidance documents imply that "root sum of the squares (RSS)" and "root-mean-square (RMS)" are commonly-used terminologies. This is not the case. The "Brooks and Caruthers" reference in ANSI/ANS-2.5 (1984) does not explicitly define either term, and other references do not define them or define them inconsistently.

- It is not clear that the Working Group of ANSI/ANS-3.11 (2000) intended to replace RSS with RMS. The significant differences between the two methods would have made comparisons useless between RMS calculations and the extensive experience with RSS calculations. To fully implement, it would have been necessary to recalculate loop errors using RMS and modify applicable documentation accordingly. Such efforts would not have been inexpensive and would have violated a Working Group objective to minimize implementation costs for existing facilities.
- ANSI/ANS-3.11 (2000) did not distinguish between bias errors and random errors. Consequently, both types of errors are treated as random errors. This may have resulted in improper characterization of the overall system error in some cases.

Proposed changes to accuracy calculation guidance in ANSI/ANS-3.11 (2005):

ANSI/ANS-3.11-2005 Text for System Accuracy (section 7.1)
Accuracy values shall reflect the performance of the total system, and shall be based on the more stringent of the individual facility requirements or the minimum system accuracy and resolution requirements given in Table 1 (which provides values for a monitoring system using typical tower-mounted sensors and digital data processing systems). System accuracy should be estimated by performing system calibrations, or by calculating the overall accuracy based on the system's individual components. Accuracy tests involve configuring the system near to normal operation, exposing the system to multiple known operating conditions representative of normal operation, and observing results. Data channels may be separated into sequential components, as long as results from each component are directly used as input for the next component in sequence. Exhibit 1 provides a method that should be used to calculate system accuracy from individual component accuracy values.

Only two approaches are addressed in ANSI/ANS-3.11 (2005):

1) Root sum of the squares calculation

   - For consistency with prior information in ANSI/ANS-2.5 (1984), ANSI/ANS-3.11 (2005) reverts to the RSS approach.
   - ANSI/ANS-3.11 (2005) provides equations and step-by-step procedures for system accuracy calculations to minimize the opportunity for user error due to incorrect interpretation of guidance.
   - ANSI/ANS-3.11 (2005) addresses bias errors as separate values that are added algebraically rather than being included in the RSS calculation.
   - ANSI/ANS-3.11 (2005) clearly distinguishes between instantaneous and time-averaged values, for consistency with prior documents. For procedural simplicity, all random values are divided by the square root of the number of samples (not just the time-averaged values). This approach works because using "1" as the number of samples for an instantaneous value is equivalent to not changing the value.

2) Accuracy tests
   - The system must be in near normal operation configuration.
   - The system must be exposed to multiple known operating conditions representative of normal operation range.
   - The system can be divided into components that are tested individually. The output from one component is used as input for the next component in sequence. Results of accuracy tests must be directly related to input at the sensor.

ANSI/ANS-3.11 (2005) Method for Calculating Accuracy

ANSI/ANS-3.11 (2005) expects the accuracy calculations to address the entire data channel from the sensor that makes the measurement, through all intermediate components, to the final value that is displayed. The following identifies the sequence of steps:

1. Identify the individual components that contribute to system accuracy.

   - Sensor error (e.g., a single value if the sensor is certified by a vendor or a series of values that must be analyzed if calibrations are performed).
   - Installation error (e.g., sensor alignment).
   - Operational error (e.g., solar heating of temperature sensors).
   - Data processing equipment error.
   - Computer error (e.g., conversion equations).
   - Calibration error.
   - Other system errors.

2. Classify the error type for each component.

   - **Bias errors** ($b_1, b_2, \ldots b_n$).
     Bias, or systematic, errors consistently affect the system accuracy in a predictable manner.
     For example: Solar heating only increases apparent air temperatures during daytime.
   - **Random errors** ($r_1, r_2, \ldots r_n$).
     Random errors are independent and can fluctuate within the range between the extreme maximum and minimum values.

3. Estimate the values of the component errors based on engineering analysis, vendor specifications, accuracy tests, or operational experience.

    - If a bias applies to only a portion of the sampling period, multiple calculations of the system accuracy, using different bias values, becomes necessary.
    - The random errors of the individual components should represent ±2σ values or 2 times the standard deviation of errors based on component testing (95.5%). Unless otherwise stated, manufacturer's data for random errors can normally be assumed to be ±2σ values (as discussed in R. Brad Harvey's 1999 NUMUG presentation).

4. Perform time-average adjustments for each random error component.

$$a = r/\sqrt{n}$$

Where: r is the unadjusted random error component.
n is the number of samples.
a is the adjusted random error component.

Note: For instantaneous values (where $n = 1$), $a = r$.

5. Calculate "root sum of the squares" (RSS) for the adjusted random error components.

$$\mathrm{RSS} = \sqrt{(a_1)^2 + (a_2)^2 + \ldots + (a_x)^2}$$

Where: $a_1, a_2, \ldots a_x$ are adjusted random error components.
x represents the number of random error components.

6. Add bias errors to obtain system accuracy (*SA*).

$$SA = \mathrm{RSS} + b_1 + b_2 + \ldots b_x$$

Where: $b_1, b_2, \ldots b_x$ are bias error components.
x represents the number of bias error components.

Note: **Repeat as necessary with different bias values to determine extreme values.**

7. Compare the extreme system accuracy (*SA*) values with applicable requirements to evaluate system performance.

    - In most cases, this will be Table 1 in ANSI/ANS-3.11 (2005).
    - Table 1 values are both system (channel) accuracy and sensor accuracy values.
        - System accuracy encompasses all channel components impacting system accuracy (sensors, data processing equipment, computer, calibrations, etc).
        - Sensor accuracy applies to the manufacturer's instrument specification (this prevents use of a low-grade sensor, since output would appear acceptable with a large number of samples).

Example Calculation – Wind Speed

The example accuracy calculation is based on Tennessee Valley Authority (TVA) wind speed data. TVA uses ultrasonic wind sensors that are certified in a TVA wind tunnel. Because the sensors are certified by TVA, the accuracy values for the sensor certification components are provided as well as the channel components.

1. Identify the individual components that contribute to system accuracy.

    - Sensor
        - Input – Laboratory Standard
        - Input – Transfer Standard
        - Input – Test Position (placement in wind tunnel)
        - Input – Comparison Apparatus
        - Output – Tolerance
    - Sampling (placement in field)
    - Signal Conditioning and Data Logger
        - Final rounding of hourly average value

2. Classify the error type for each component.

    - Sensor
        - [Input] Sensor placement is **bias**
          (The sensor position is not changed relative to wind direction during wind tunnel tests).
        - [Input] Other sensor components are **random**
        - [Output] Tolerance is **random**
    - Sampling (placement) is **random**
      (Since the wind can blow from any direction in the field, the sensor position is changed relative to wind direction).
    - Final rounding is **random**

3. Estimate the values of the component errors based on engineering analysis, vendor specifications, accuracy tests, or operational experience.

   The following values are for the 0-100 mph range.

   [Sensor only]
   - Input – Laboratory Standard [± **0.20 mph**]
   - Input – Transfer Standard [± **0.10 mph**]
   - Input – Test Position [± **0.02 mph**]
   - Input – Comparison Apparatus [± **0.08 mph**]
   - Output – Tolerance [± **0.30 mph**]

   [Field Measurements]
   - Sampling [± **0.04 mph**]
   - Final rounding of hourly average value [± **0.05 mph**]

4. Perform time-average adjustments for each random error component.

   [Sensor only]
   - Only 1 sample is used for calibration
   - Adjusted values equal initial values

   [Field Measurements]
   - Sensor output is random (time-averaged); 0.40/($\sqrt{180}$) = ± **0.03 mph**
   - Sampling is random (time-averaged); 0.04/($\sqrt{180}$) = ± **0.00 mph**
   - Rounding is random (1 sample); 0.05/($\sqrt{1}$) = ± **0.05 mph**

5. Calculate "root sum of the squares" (RSS) for the adjusted random error components.

   [Sensor only]

   $$\mathrm{RSS} = \sqrt{(0.20)^2 + (0.10)^2 + (0.08)^2 + (0.30)^2} = \pm 0.38\ mph$$

   [Field Measurements]

   $$\mathrm{RSS} = \sqrt{(0.03)^2 + (0.00)^2 + (0.05)^2} = \pm 0.06\ mph$$

6. <u>Add bias errors to obtain system accuracy (*SA*)</u>.

   [Sensor only]

   $SA = 0.38 + 0.02 = 0.40$ mph
   $SA = 0.38 - 0.02 = 0.36$ mph

   $SA = \pm$ **0.40 mph**

   [Field Measurements]

   No bias term, so $SA = 0.06 + 0.00 = 0.06$ mph

   $SA = \pm$ **0.06 mph**

7. <u>Compare the extreme system accuracy (*SA*) values with applicable requirements to evaluate system performance</u>.

   - ANS-3.11-2005 Table 1 specifies WS accuracy as:
     0.2 m/s +5% of observation = 0.45 mph at 0 mph
     5.45 mph at 100 mph
   - Applies to both sensor and channel accuracies.
   - Sensor accuracy of ± **0.40 mph** and channel accuracy of ± **0.06 mph** both meet specification.

   Wind measurements satisfy proposed ANSI/ANS-3.11 (2005).

Final Comments

ANSI/ANS-3.11 (2005) provides specific guidance for calculating meteorological measurements accuracy.

The ANSI/ANS-3.11 (2005) methodology is consistent with past practices, prior to ANSI/ANS-3.11 (2000), so calculations should be comparable with historical information.

Hopefully, ANSI/ANS-3.11 (2005) will be adopted by the Nuclear Regulatory Commission and Environmental Protection Agency as an **official** source of guidance regarding meteorological measurements accuracy.

Acknowledgements

The ANSI/ANS-3.11 (2005) standard resulted from the team efforts of approximately 30 members of the ANSI/ANS-3.11 (2005) Working Group. Three of these individuals provided significant input to the accuracy calculation discussion--Paul Fransioli (Bechtel-SAIC), R. Brad Harvey (NRC NRR), and Matt Parker (Savannah River National Laboratory).