Sensor Accuracy and Calibration Theory and Practical Application

Karl Stum, P.E.

Summit Building Engineering

Synopsis

Some construction specifications dictate sensor accuracy and calibration tolerances and some projects have no direction other than "sensors should be calibrated." Some controls contractors follow the requirements whether reasonable or not. Others argue that the sensors are "factory calibrated" and therefore don't need field calibration. The real accuracy of test instruments is also not well understood. Some instrument companies advertise the accuracy of their instruments, but fail to highlight that the accuracy only includes the transducer and not the inaccuracy of the instrument sensor and wire. Even if the user understands the real accuracy of their calibrating instrument, how much more accurate than the sensor being calibrated, does the calibrating instrument need to be? How does the calibration tolerance value used in the field come into play? Do design engineers and commissioning providers fully understand that specifying sensor accuracy is not the same as specifying end-to-end accuracy?

This paper will answer the above questions and provide useful information on the issues surrounding sensor accuracy and calibrating instrument accuracy. Look-up tables will be provided for typical sensor and tolerance types.

About the Author

Karl Stum is registered professional engineer and has been actively commissioning for over 13 years. He specializes in larger, complex facilities and in controls. He is a past recipient of the Benner Award and is a frequent speaker at NCBC and ASHRAE. He is the owner of Summit Building Engineering in Vancouver, Washington.

Introduction

This paper is not about factory calibrating methods, full field calibration instructions or methods for calibration certification services. The information presented is what the commissioning provider should know and be proficient at in the field. The paper applies primarily to HVAC applications and focuses on temperature measurement, but in various locations in the paper taking and calibrating other types of measurements are discussed.

Fundamentals

There are a few fundamentals that warrant discussion including: sensor physical characteristics, accuracy theory and sources of error and field calibration methods.

Sensor Characteristics

The primary temperature sensor types are thermocouple, thermistor and resistance temperature detector (RTD). A brief description of the characteristics of these types of sensors is given in Table 1.

Table 1. Temperature Sensor Characteristics

Sensor Type	How It Works	Application	Advantages	Disadvantages
Thermocouple	Two connected wires of dissimilar metals cause a voltage which is related to temperature.	Hand-held instruments and rugged industrial and high temperature process applications.	Durable, very high temperature, inexpensive; fast response	Low accuracy (see below)
Thermistor	Resistance of a small semi-conductor is related to temperature.	Hand-held instruments, HVAC systems	High sensitivity; accurate	Moderate cost; moderate response time. Narrow temperature range (but plenty wide for HVAC).
RTD (resistance temperature detector)	Resistance of a fine wrapped wire is related to temperature.	HVAC systems and equipment, hand-held instruments	Very stable, wide temperature range; accurate.	Moderate cost; moderate response time. Requires a transmitter or lead wire compensation which adds another source of error.

Source: PECI 3.1; Omega

Sensor Accuracy

The accuracy (to be fully defined later) of the above sensors varies with the type, purpose and manufacturer. Table 2 provides some representative accuracies. It should be noted (and will be explained later) that the values below are for the *sensor only* and do not include the error of the transducer instrument or transmitters.

Table 2. Typical Temperature Sensor Accuracy (sensor only)

Sensor Type	Standard	Special	Typical Range	Notes
Thermocouple Type K	+/- 4.0F	+/- 2.0F	-328F to 2282F	Most common type used with popular hand-held digital thermometers
Thermocouple Type J	+/- 4.0F	+/- 2.0F	32F to 1382F	
Thermocouple Type E	+/- 3.0F	+/- 1.8F	-328F to 1652F	
Thermocouple Type T	+/- 1.8F	+/- 0.9F	-328F to 662F	

Thermistor	Typical [1]: +/- 0.17 to 0.36	N/A	-20F to 300F	Specific temperature range can be narrower. Check specifications.
RTD	Typical [1]: +/- 0.17 to 0.36	N/A	-300F to 1000F	Specific temperature range can be narrower. Check specs. Nickel is typically more accurate than platinum.

Source: Omega; Products

[1] Thermistors and RTD's are also made in precision grades that are considerably more accurate than the values in this table.

It is unclear to the author why all common HVAC digital thermometers come stock with Type K thermocouple bead probes which have such poor accuracy when sensors (Type T) are readily available and are twice as accurate.

Accuracy Theory and Sources of Error

Accuracy

Accuracy of a displayed value is characterized as an uncertainty of a measurement display representing the actual value being measured. It is expressed in terms of how far off any given reading could be from the true value, given in terms of a fixed value (e.g., +/-0.5F), a percent of reading (e.g., 0.2% of reading), a fixed value plus a percent of reading or a percent of the instrument's full scale value.

Sources of Error

The uncertainty of a reading is broken down into two types of errors, fixed and random.

Fixed Errors

Fixed errors (sometimes referred to as bias) are a constant deviation from the true value. Examples include, errors in the transmitter (for some types of RTD's), the conversion of the sensor signal sent back to the transmitter or transducer from a resistance to a voltage, the analog voltage conversion to a digital signal, display resolution (change in display of a value is at larger increments than actual display resolution to reduce network traffic or fluttering of the value), calibration tolerance or offset and lead length resistance (at constant temperature). *None of these errors are represented in the sensor accuracies given in Table 2.*

Random Errors

Random errors (sometimes referred to as precision) are errors that vary over time and are not consistent. Examples include thermal drift of electronic components, changing radiation effects of a poorly placed outside air sensor or sensor place near a copying machine or near drafts, electrical noise, changing resistance of sensor wires with large temperature swings, non-linearity and hysteresis. The total net random error approaches zero with large number of readings (see Table 4). Some of the random errors are accounted for in the sensor accuracies in Table 2, but only for the sensor. Sources of random and fixed error are also found in the equipment that processes and displays the sensor readings and must be accounted for in the overall accuracy of a displayed value.

For a given sensor or instrument, a breakdown of error sources is not provided in manufacturer literature or application guides and it is not practical for the commissioning provider to try and accurately quantify them. The Control System Design Guide (PECI), Section 3.3 provides details and examples of many of these errors. There are a few important concepts the commissioning provider should be aware of that will be discussed in later sections of this paper.

Absolute Accuracy

Sensors that are used for very tight control such as in a research laboratory with very stringent temperature requirements warrant very accurate sensors and calibrating instruments. The sensors must display precisely what the actual temperature is. Chilled water supply temperature sensors and air handler discharge air dew point temperatures for controlling humidity in critical environments are other areas where closer attention should be paid to absolute accuracy. Non-humidity controlling air handler supply air temperature and outside air temperature typically are another step down in absolute accuracy requirements. Sensors where absolute accuracy is much less important are monitoring points not used for control and occupied space temperature sensors where the temperature will be adjusted to satisfy the occupants, regardless of its “absolute” or actual value.

Consistency or Relative Accuracy

Sensors used primarily for measuring temperature or pressure differences need not have tight absolute accuracy, but they must be calibrated accurately relative to each other. For example, for chilled water supply and return temperature sensors being used to calculate building cooling load or energy use, had the return calibrated 1.0F high and the supply 1.0F low they may comply with a calibration tolerance of +/- 1.0F, but the system, in such an instance, could be reading a differential of 2.0F, when it is actually 0F. This is significant when the total dT is only 10F. Relative accuracy is also valuable in larger air handler and chilled water plants even when a temperature difference is not being explicitly used. For these systems it is useful to have all sensors in the air or water stream reading accurately relative to each other. This aids operations, maintenance, troubleshooting and fine tuning. This can be accomplished by calibrating all affected sensors to a 0.0 tolerance to the same reference instrument reading.

When CO2 sensors are used for controlling outside air quantities and the control loop compares the inside with the outside CO2 level, only the difference is really important. No real value is gained by expending effort in accurately calibrating the CO2 sensors to be reading the absolute CO2 levels. What is important is that under the same conditions, both inside and outside sensors read the same. A relative calibration to each other during unoccupied conditions can achieve this.

Combining Sources of Error or Accuracy

For a given instrument or equipment reading, how are the various errors to be combined to provide the overall error or accuracy? Some practitioners and manufacturers just add the accuracies together in a simple sum: overall accuracy = +/- (sensor accuracy 1.1F + transmitter, A/D conversion, display resolution and wire temperature effects 0.8F) = +/- 1.9F. This represents the worst case. A more realistic expected range, using statistical methods, is to combine them by squaring each accuracy, adding the squares together and taking the square root of the sum of those squares (ASHRAE-2, p. 16-20).

$$\text{Overall accuracy} = \sqrt{(A1^2 + A2^2 + A3^2....)} \qquad \text{Equation 1.}$$

This method is abbreviated SRSS. The formulation of the above example would be:
Overall accuracy = $\sqrt{(1.1^2 + 0.8^2)}$ = +/- 1.36F

Repeatability

The repeatability of an instrument or sensor is a measure of its random accuracy. In general, the more accurate a sensor or instrument reading is, the more repeatable it will be. Repeatability data in manufacturer literature is very rare. But in general, thermocouples are considered the least repeatable, with thermistors considerably better and RTD's somewhat better than thermistors.

Field Calibration of Equipment or Building Automation System Sensors

This section is intended to provide a brief overview of typical HVAC calibration to put the rest of the paper in perspective. Field calibration is the exercise of comparing the packaged equipment or building automation system display with an accurate hand-held instrument reading taken near the sensor being checked. Differences are then adjusted out of the system so the reading matches the hand-held reading to within the 'calibration tolerance' allowed. The adjustments are made by applying a simple offset in the equipment or when transmitters are part of the sensor system (with some types of RTD's), performing a two point calibration at either end of the expected range utilizing special electrical current readings and potentiometer adjustments. Details of field calibration requirements and methods for a variety of sensor types besides temperature are found in PECI, Section 3.4 and at http://www.summitbe.com/resources.html.

Why Calibrate?

"Consider a discharge air temperature sensor that reads two degrees high. The controller achieves a 55F discharge temperature, but is actually cooling the air to 53F. For a fairly efficient chiller plant (0.8 system kW/ton) and a 40,000 cfm constant volume reheat air handler, this two degrees of extra cooling translates to 5.8 kW of demand. Based on a typical 2,600 hour office building operating schedule, this will save 15,000 kWh per year, which equates to about $1200/yr (for a 24 hour operation, over $4000/yr). To maintain comfortable conditions, the overcooled discharge air is reheated at the zones using hot water coils. For a hot water plant efficiency of 80%, the reheat energy for a 2,600-hour operating year is about 2800 therms, or $1400/yr (for 24 hour operation, over $4700/yr). The moral of this story is clear - selecting temperature sensors with the appropriate accuracy for the application and making sure they are calibrated is essential for energy efficiency." (PECI, Section 3.5.1)

Accuracies of Hand-Held Calibrating Instruments

Overall Instrument Accuracy

The accuracy of the hand-held thermometers used to calibrate packaged and building automation system (BAS) sensors is reported only for the unit itself. To get overall instrument accuracy you must add the accuracy of the instrument transducer to the accuracy of the probe. The probe is a detachable wire with simple bead end, a stiff metal shaft for sticking into P/T ports or a pipe strap-on end for surface measurements.

The accuracies of the instrument transducer, T, and the instrument sensor probe, P, can be combined into the overall instrument accuracy, I, by an application of Equation 1, above.

$$I = \sqrt{(T^2 + P^2)} \qquad \text{Equation 2}$$

This issue is vitally important for the commissioning provider to understand. It is unfortunate that, almost universally, manufacturers of measuring instruments have not made this more apparent. The misleading product literature and specifications can result in very inaccurate instruments being used for calibration.

Advertised Accuracies

Hand-held instrument literature and specifications will list the accuracy of their instrument *with* different types of thermocouple, thermistors and RTD probes, but the listing with the probe types <u>does not</u> include the accuracy of the probe. In every case the author looked at, when there is a detachable probe, specifications for the instrument accuracy did not include the probe. Look for the fine print that says “does not include probe error.” Often this is not found in the advertising literature, but can be located in the specifications in the operations manual.

Most commercial grade hand-held digital thermometers have an accuracy themselves of +/- 0.44F to 0.64F. A few go as high as +/- 1.8F and a few as low as +/- 0.05F. However, special (better than standard) Type K thermocouple probes have an accuracy of +/- 2.0F. Thus, when you are using a Type K thermocouple, which is most prevalent because of its wide temperature range, the accuracy of the instrument is eclipsed by the large inaccuracy of the probe. Bottom line, if you must use a Type K thermocouple, don’t waste money on an expensive instrument as your overall accuracy won’t be improved much because of the limiting K thermocouple. Also, don’t assume that the accuracy of a given manufacturer’s P/T probe will be the same as the same manufacturer’s wire bead probe for your instrument. One of the most popular P/T probes uses a standard (rather than special) Type K thermocouple and offers an accuracy of a poor +/- 4.0F!

It is the author’s experience that the majority of control contractors calibrate temperature sensors using instruments with accuracies of +/- 0.5F with Type K thermocouple probes at +/- 2.0F, giving an overall accuracy of +/- 2.1F. When calibrating a chilled water sensor system with an assumed end to end accuracy of +-0.5F to a calibrating tolerance of +/-0.1F the overall accuracy ends up being +/-2.2F. If that is the only instrument available, it would be better to not have calibrated the sensor at all!

Selecting Hand-Held Calibrating Instruments

There are few important issues when selecting hand-held temperature thermometers to be used for commissioning and HVAC work.

Accuracy. Select the unit that has an overall accuracy that is adequate for your needs. Refer to Table 3 below to help make this determination. There is no reason to purchase a Type K thermocouple. If +/- 1.1F overall accuracy is sufficient, select a moderately priced unit (+/- 0.6F accuracy). Order it with a Type T special thermocouple (+/-0.9F accuracy). If you need more accuracy than +/- 1.1F then you must move to a thermistor instrument (RTD instruments are rare). Thermistor instruments, like units made for thermocouples, will be around +/- 0.5F accuracy. Most thermistor probes will be around +/- 0.18F accuracy, giving an overall accuracy of +/-0.53F. Some thermistor instruments are available with an accuracy of +/-0.3F and using the same thermistor probe offer an overall accuracy of +/-0.36F. Higher precision instruments are available.

Field Offset. This feature refers to the capability of the unit to have an offset (sometimes called "zeroing") applied in the field by HVAC and commissioning personnel without any special tools (like an ohm meter) or training. One can quickly check the calibration of these units in an ice bath and enter in an offset so that it reads 32.0F in the ice bath. This will improve confidence, allow interchanging of probe types and reduce the frequency of costly certified calibrations. Some units are available with instructions to perform a full calibration of the internal electronics, which is not what an offset is. Because of the specialized equipment and training required, the full calibration feature doesn't offer any real advantage to the typical commissioning provider, that the offset function does.

False Security with Ice Baths. One may feel that if they just check their inexpensive Type K thermocouple unit in an ice bath at the beginning of each project and install the required offset that they are now working with an accurate instrument and there is no value in using something more accurate. However, the ice bath only centers the inaccurate instrument's error around the true value. The range of error for the reading still exists (see Figure 1).

Response Time. Response time is a characteristic of the probe. Thermocouples are faster than thermistors and RTD's, but have a serious accuracy penalty. Pressure and temperature port (P/T) probes are slower responding, especially in air. When selecting a P/T probe, choose one that is "grounded" which means the end of the wires are bonded to the metal sheath probe for a faster response. When selecting thermistors, select ones with smaller diameter ends for a faster response, noting they have lower durability.

Durability. Thermocouple probes offer the greatest durability. Thermistors are least durable and more subject to shock, but are adequate for HVAC use.

Cost. Generally, basic thermistor type instruments and probes offering an overall accuracy of +/- 0.6F cost no more than Type T thermocouple instruments offering a +/- 1.1F overall accuracy. However, these basic thermistor units don't come with the field offset capability, which in the author's opinion is essential. Unfortunately, getting thermistor models with the field offset feature will almost double their price.

Hand-Held Instruments without Probes. Hand-held instruments that have an integral sensor and no detachable wire or probe nominally report their accuracies as total overall accuracy. They typically range in overall accuracy from +/- 1.0F to 1.8F. Compared to hand-helds with detachable probes, they offer the least expensive option for overall accuracies around 1.0F, with the obvious limitations of taking readings through cracks, narrow spaces, remote spaces and P/T ports.

BAS and Equipment Sensor Accuracies

BAS or equipment sensor accuracy is reported in manufacturer literature as the sensor itself, and possibly including a given length of wire or lead. Wire or lead length can affect the readings for sensors that generate a small resistance change per change in the process variable (like RTDs without precision lead length compensation). That is, longer wire used to locate the sensor will increase signal resistance and thus affect the sensor reading. Some controls manufacturers give tables for reference showing when an offset (like -1.0F) needs to be applied depending on wire length, size and ohm rating. Others utilize lead length compensation methods and others utilize transmitters near the sensor to compensate for lead length.

Other sources of error mentioned above, include field installed resistors in the sensor loop, the analog-to-digital conversion and the digital transmission function. However, with current technology, the A-to-D conversion and digital transmission issues are not considered significant for commercial HVAC applications. Thermal drift, effects of wide variations in sensor wire temperature and display resolution change of value are additional sources of error.

Change of Value Limitation. Building automation systems can take and store readings at a given resolution (say 0.1F), but not show them on the computer monitor until the value has changed a specified amount, such as 0.2F. This is sometimes done to reduce system network traffic or to prevent fluttering of the number on the screen, particularly for numbers that are larger like heating water temperatures, which are not important to show to the 10^{th} of a degree. It is important for the commissioning provider to understand if there are any of these change of value governors in the system. If there are, have them removed during calibration exercises or for calibrations, take BAS readings directly from a local control panel prior to where the change of value action is instituted.

End-to-End Accuracy. All of the above inaccuracies are accounted for and summed into what is called the end-to-end (ETE) sensor accuracy. This covers the sensor to the BAS workstation or packaged equipment control panel readout, assuming the displayed reading was calibrated with a calibrating instrument with *perfect* accuracy.

Overall Accuracy. Since all calibrating instruments have inaccuracies, the accuracy of the hand-held calibrating instrument represents another source of error in the final readout in the BAS or packaged equipment panel. So, the real value of interest is the *overall accuracy* of the BAS sensor that includes the inaccuracy of the calibrating instrument. The formulation of this value is described in the next section.

When desiring a specific overall accuracy, it is important to know that the ETE accuracy value assumed or known must be more accurate than the *overall accuracy* desired, since the overall accuracy includes the inaccuracy of the calibration instrument (see Equation 3 below). That means if the desired overall sensor accuracy is +/- 0.5F, then the sensor ETE accuracy must be something less than +/- 0.5F to allow some inaccuracy for the calibration instrument and exercise.

Overall BAS or Equipment Sensor Reporting Accuracy

The overall accuracy of the BAS sensor display after calibrating (**O**) is the sum of the ETE accuracy of the BAS sensor (**S**) the overall accuracy of the calibrating instrument (**I**) and the allowed calibrating tolerance (**C**). The calibrating tolerance is how far from the calibrated instrument reading

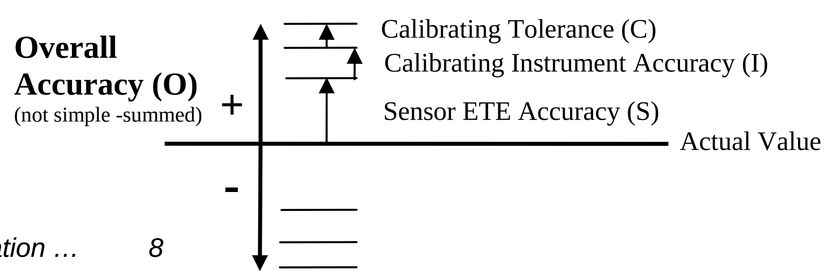

Figure 1. Overall Accuracy

can the BAS sensor be displaying and the sensor be considered calibrated. This is an arbitrary value. Selecting values too large will unnecessarily decrease the overall accuracy of the calibrating exercise and selecting values too small will result in the calibration being more time consuming to execute and not being repeatable due to repeatability limitations of the instrument and BAS sensors.

Figure 1 provides an illustration at the concept of overall accuracy of a BAS readout. The readout can be giving a value anywhere within the bounds of the overall accuracy.

The equation for combining the three sources of error (S, I and C) follows from Equation 1. In the formulation, the accuracy variables (O, S, I; C) are expressed as + or -. Whichever is chosen must be applied to all variables.

The equation is:

$$O = \sqrt{(S^2 + I^2 + C^2)} \qquad \text{Equation 3}$$

Factory Calibration

If the manufacturer can certify that the installation end-to-end (ETE) has a specific accuracy and it is within the desired tolerance, then no further calibration is needed or recommended. However, generally the manufacturer will only certify the calibration of the sensor itself, not the wiring, transmitter, A-D conversion or display. Some packaged equipment controls can offer an ETE certification.

Therefore, it can be assumed that most, if not all, field installed temperature sensors need to be field calibrated. All or a sample of other sensors that don't appear to need field calibration, should at least be checked for reasonableness to ensure no unexpected installation or manufacturer error exists, and if the outcome is close to the instrument check, then assume the sensor is calibrated.

A special case is flow meters that come certified factory calibrated. As long as the conditions in the field are in line with the manufacturer's guidelines, there is not excessive air entrained or debris in the system and if all of the manufacturer's installation and commissioning instructions were followed, the flow meter's factory calibration is considered valid. No further calibration is required. However, it is highly advised to obtain a reality check of the flow meter reading with a balancing valve, pump or coil differential pressure curve.

Needed Accuracy of Calibrating Instrument

The question directly applicable to the commissioning provider and control contractors is how accurate does the calibrating instrument need to be. The author discussed this issue with a few control and measurement experts and commissioning providers and found no consistency and little foundation for the opinions. Some felt that the calibrating instrument should be at least as accurate as the sensor being calibrated (presumably the ETE sensor accuracy). Others indicated that the instrument should be two to four times as accurate as the ETE sensor accuracy. In searching for some rationale for a number, the author considered it appropriate to simply rearrange Equation 3, solving for I, Instrument Accuracy. The equation gives the formula for the required calibrating instrument overall accuracy.

$$I = \sqrt{(O^2 - S^2 - C^2)} \qquad \text{Equation 4}$$

For example, if O = +/-1.0F, S = +/-0.5F and C = +/- 0.1F, then I must be +/- 0.9F or less.

Thus, the first order in a project is to establish what the displayed overall system accuracy, O, is desired to be. Then, select the sensor ETE accuracy, S, and the allowable calibration tolerance, C. Note that C can be 0, if desired. Once those three have been determined, Equation 4 can be used to determine the required overall calibrating instrument accuracy, I.

To relax the accuracy requirements for the calibrating instrument, reduce the calibrating tolerance to 0. For most situations, though, this has no impact in the first decimal place of the required instrument accuracy.

Table of Typical Required Calibrating Instrument Accuracies for Commercial HVAC Applications

Table 3 offers typical scenarios of desired overall BAS or packaged equipment displayed accuracy, a reasonable ETE sensor accuracy for commercial applications and the resulting required calibrating instrument accuracy. The desired overall accuracy, O, is for sensors used for HVAC control or energy use calculations. Points used only for monitoring purposes will typically have desired overall accuracies up to twice those in this table. Points used for critical applications or where monetary reimbursement is at stake warrant increased accuracy. Assumptions and notes are provided at the bottom of the table.

The table and supporting equations show for typical commercial HVAC equipment:

- Temperature calibrating instruments need to have an overall accuracy of +/- 0.9F or better.
- Instruments that utilize thermocouple probes will not comply.
- Thermistor instruments will comply.
- The Overall Calibrating Instrument Accuracy, I, need only be just slightly better than the Desired Overall BAS Reporting Accuracy, O, not two or four times as accurate.
- The larger the Calibration Tolerance, the more accurate the calibrating instrument and/or the ETE accuracy will need to be.

Table 3. Required Calibrating Instrument Overall Accuracy

BAS or Equipment Sensor	Desired Overall BAS Reporting Accuracy O (+/-)	Assumed End-to-End BAS Sensor Accuracy S (+/-)	Maximum Calibration Tolerance, C (+/-)	Required Calibrating Instrument Overall Accuracy I (+/-)	BAS Sensor Alone Accuracy	Units
Cooling coil, chilled & condenser water temps	1.0	0.5	0.1	0.9	0.35	F of rdg
Outside air; duct air temps	1.0	0.5	0.1	0.9	0.35	F of rdg
Normal space air temps	1.0	0.5	0.1	0.9	0.35	F of rdg
Air handler air temperature averaging sensors*	4.0	3.8	0.5	1.1	3.4	F of rdg
Hydronic temp sensors in chilled & heating water plants & secondary loop (for relative calibration)	1.0	0.5	0.0	0.9	0.35	F of rdg
All air stream temp sensors in built-up air handlers (for relative calibration)	1.0	0.5	0.0	0.9	0.35	F of rdg
Critical space air temps	0.5	0.3	0.1	0.4	0.20	F of rdg
Air & water temperature differences <20F	0.5	0.3	0.0	0.4	0.20	F of rdg
Air & water temperature differences >20F	0.7	0.5	0.0	0.5	0.35	F of rdg
Dew point or wet bulb temperature*	4.5	4.0	0.2	2.1	3.6	F of rdg
Hot water coil and boiler water temp	2.0	1.1	0.4	1.6	0.8	F of rdg
Relative humidity	4.0	3	1.0	2.7	2	% RH of rdg
CO2*	20	15	1	13	12	% of rdg
Pressure- space, room, building (differential) [3]	0.03	0.02	0.01	0.02	0.01	inches WC
Pressure- duct air static, water and gas	3.0	0.4	0.5	3	0.3	% full scale
Flow rates, water	10	3	1	10	2	% of rdg
Flow rates, air [3]	13	10	1	8	7	% of rdg
Combustion flue temps	5.0	2.8	1.0	4.0	2	F of rdg
Air velocity	13	10	1	8	7	% of rdg
Steam flow rate	13	10	1	8	7	% of rdg
Natural gas and oil flow rate	13	10	1	8	7	% of rdg
CO*	20	15	1	13	12	% of rdg
Wathour, voltage and amperage	4.0	3	1.0	2.7	2	% full scale

Key:

O = Desired Overall Accuracy is the accuracy of the display after any field calibration and all errors are taken into account. Refer to ASHRAE Guideline 13-2000 Specifying DDC Systems, sample spec & PECI, Control System Design Guide 3.5 for similar values.

S = *Assumed End-to-End BAS Accuracy was estimated by taking the BAS Sensor Alone Accuracy (last col.) and multiplying by 1.4 in most cases, to account for transmitter, lead length compensation, A-D conversion, display change of values and related errors. The 1.4 value is considered reasonable. Some values were input less than 1.4 and are noted with an * in Column 1.

C = Maximum Allowable Tolerance during calibration which is the acceptable deviation from the calibrating instrument reading, beyond which an offset must be applied to correct the BAS reading.

I = Required Overall Instrument Accuracy of calibrating instrument and sensor probe. Overall instrument accuracy is found by taking the square root of the sum of the squares of the instrument only accuracy and the probe alone accuracy. In this table, the needed or Required Overall Instrument Accuracy is the unknown quantity and is solved for using Eq. 4 below. The table gives the required overall instrument accuracy, I, for the given desired overall accuracy, O.

BAS Sensor Only Accuracy is given for reference and is the sensor accuracy not including errors listed under the ETE accuracy. Sensor only accuracy values were taken from performance specifications of typical control systems. More precise sensors exist.

Notes:

[1] **Monitoring Only Points.** Desired overall accuracies in the table are for control points. Monitored points may have accuracies up to twice as large as these values.

[2] **Multiple Readings.** These values are based on taking one calibrating measurement. Taking additional readings over a few minutes time will reduce the random component of error. For example, where the random error is 1.5 times the fixed error, taking two readings will reduce the overall error by about 20%; 10 readings by about 40%.

[3] Air flow rate accuracy for room dP control may not be rated +/- , but ++ or -- to ensure that the worst case scenario will not result in the space pressure requirements being violated.

Equations:

Eq. 3: $O = \sqrt{(S^2 + I^2 + C^2)}$

Eq. 4: $I = \sqrt{(O^2 - S^2 - C^2)}$

Sensor Accuracy for Cx-5.xls

Applying the Information

The above information can be distilled into salient elements that can be useful to the commissioning provider. This application information is divided up by building delivery phase.

Design Phase

- During the development of the owner's requirements, make sure the answers are given to generally how accurate the sensors will need to be and for what purpose they will be used.
- Try to get the designer to provide an opinion on what they feel is the appropriate overall BAS reporting accuracy (O). Getting the designer to think about the value, will aid in establishing appropriate BAS sensor alone accuracy values. This overall BAS accuracy value will be difficult to specify since there are elements that can only be estimated, so it is generally not recommended to try and specify a value to the contractor.
- Make the designer aware they are responsible to provide specifications for the BAS and equipment sensor alone accuracy for each sensor. If chiller performance will be involved in an energy savings performance contract, make sure more accurate factory internal chiller supply and return sensors are specified than the typical +/-1.0F, since even if the BAS will have redundant and more accurate sensors, the chiller is typically controlled internally by its own sensors.
- During construction documents phase review the specifications for BAS sensor alone accuracies for all sensors in the project. Verify that with reasonable ETE accuracies based on the sensor alone values, that the desired overall BAS reporting accuracy can be achieved. Use Table 3 and/or Equations 3 and 4.
- Ensure that in the specifications the contractor is required to calibrate all field installed sensors using a calibrating instrument with overall accuracies for temperature of +/-0.9F or better and that thermocouple instruments will not comply. Require the contractor to perform a documented ice-bath calibration of all temperature instruments.

Construction and Acceptance Phase

- Provide the contractor with a form to submit the performance specifications of their testing instrument accuracies before they use them. Review and approve these submissions.
- Near to startup, bring your temperature, humidity and airflow test instruments on the job, perform a documented ice-bath calibration on temperature instruments and compare readings with the contractor's equipment so all agree with the results.
- Spot check the critical BAS and equipment sensor calibrations.
- Leave the building operators with sensor calibration instructions and a schedule of recalibration frequencies by sensor type.

Calibration Tips

Below are a few calibration tips, but is not intended to be a comprehensive guide. Refer to PECI Section 3.4 and to http://www.summitbe.com/resources.html for additional calibration requirements, techniques and forms.

Relative Sensor Calibration. This procedure makes sure that sensors are accurate relative to each other in a given piece of equipment. Sensors calibrated in this way, do not need separate calibration. For example, for a heating water system all the sensors in the fluid stream would be checked at one time, e.g., boiler entering and leaving temperatures, bypass, building supply and return temperatures. This would include building automation sensors, equipment panel readouts and gages. For an air handler it may include the return air temperature, coil temperatures and supply air temperatures. Calibrating sensors with this method is preferable to calibrating them each separately.

The procedure is as follows. 1) Record all current sensor calibration offsets. 2) Remove all sensor calibration offsets. 3) Put the system in a mode that will offer constant flow of water or air past the sensors, e.g., turn off boilers; turn on pumps, or turn on air handler and close outside air dampers and heating and cooling coil valves, etc. 4) Check with the reference instrument that the temperatures across coils and dampers are equal indicating that there is no leak-by. 5) With the reference instrument record the temperature rise across fans. 6) Use the entering fluid temperature to the system as a reference by inserting a reference measuring instrument there. 7) Compare the sensor readings with the reference reading. Take into account temperature rises across fans and pumps. 8) Install offsets or replace sensors and gages as required so sensor readings, compared to the reference, are within the required tolerances given in Section L above. 9) Record all conditions, readings and offsets and submit. 10) Return systems to normal.

Temperature Averaging Sensors. To calibrate averaging sensors in air handlers, with the air handler running, take hand-held instrument readings at five or more locations to determine if there is significant stratification. If the extreme reading is within 4F of the average, then the following procedure is used. If the extreme exceeds 4F of the average, use the following procedure, informed with the five previous readings to come up with the most appropriate single value.

Close coil valves and fix dampers, wait 30 minutes to let the coil come to equilibrium with the air stream. Then, turn off air handler and wait another 15 to 30 minutes. Compare and calibrate the averaging sensor reading in still air with a hand-held single point reading.

CO_2 Sensors. For CO_2 sensors that monitor space or return air CO_2 that will see essentially the same background CO_2 levels during unoccupied periods: Check the calibration on a random sample of four CO_2 sensors in the building with a calibration test kit. Then, perform a relative sensor calibration by early in the morning, after the building has been unoccupied for at least eight hours. Compare all other CO_2 sensor readings with the four calibrated sensors. The sensors should all read near the same. Sensors that are reading more than 75 ppm from the calibrated sensor values shall be calibrated. When inside CO_2 sensors are being compared to an outside CO_2 sensor for control, then an absolute calibration of any sensor may not be necessary. Only the accuracy of the difference is important. Therefore, only a relative calibration is required.

Value of Repeating Calibration Readings. For instrument readings of a constant environment, the final accuracy of a reading can be improved by taking the average of multiple readings. Statistical theory states that in such cases the random portion of the overall error of a measurement reduces by factor of the square root of the number of readings. (ASHRAE-2, p. 20) Unfortunately, accurately determining the random portion vs. the fixed portion (bias) of the error of a measurement is not trivial and the effort is not likely practical for the commissioning provider, except in the most critical situations (usually involving money with energy savings performance contracts—ASHRAE-14). However, a specific case will be illustrative. When the random error or accuracy is 1.5 times the fixed error or uncertainty, the improvement in overall accuracy of the final averaged value is given in Table 4. This illustrates the importance of taking multiple measurements of critical control parameters such as outside air temperature during calibration. The concept can be applied even during a changing temperature condition by checking the calibration of the BAS sensor against a hand-held instrument multiple times over 10 minutes and repeating one or two times during the day. Then the average of all the calibrating offsets is used in the BAS, rather than the single point measurement.

Table 4. Improvement in Accuracy from Multiple Readings

Number of Readings	Improvement in Overall Accuracy
1	0
2	19%
5	33%
10	39%
25	42%

Summary

The commissioning process entails ensuring that equipment and systems are controlling optimally and monitoring and reporting accurately. This requires that BAS and equipment sensors and hand-held instruments used to check the BAS and equipment sensors are sufficiently accurate. BAS sensor accuracies are only part of the picture and other sources of error should be accounted for when determining the end-to-end accuracy of the sensor system. These errors include wire lead length, analogue to digital conversions, temperature, random installation effects, display change of value impacts. Since the factory calibration of BAS temperature sensors installed in the field does not account for a number of sources of error between the sensor and the equipment or BAS display, all field installed temperature sensors should be field calibrated.

Statistically combining errors to provide a realistic average expected range of error can be done by squaring each error or accuracy, adding all the squared values together and taking the square root of the sum (SRSS). Accuracies of hand-held temperature instruments are given in product literature for the instrument alone, not accounting for the error of the probe. The probe error can be combined with the instrument alone error using SRSS. The very common Type K thermocouple probes are very inaccurate (+/-2.0F) while readily available, but rarely used Type T thermocouples are over twice as accurate (+/- 0.9F). Nonetheless, when the error of the instrument alone is taken into account, the overall instrument accuracy of a Type T thermocouple is still +/- 1.5F, which insufficient for most HVAC calibrating. Temperature calibrating instruments need to have an overall accuracy of +/- 0.9F or better. Thermistor instruments offering overall accuracies of around +/- 0.53F are the preferred calibration tool. The Overall Calibrating Instrument Accuracy need only be just slightly better than the Desired Overall BAS Reporting Accuracy not two or four times as accurate, as is sometimes reported.

References

ASHRAE Guideline 2-2005 Engineering Analysis of Experimental Data. ASHRAE, Atlanta, GA.

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Products Literature and Specifications (Cooper, Dwyer, Extech, Fluke, Johnson Controls, Kele, MicroDatalogger, Omega, Onset (Hobo), Setra, Siemens, Shortridge, Vaisala)