Sensor Accuracy & Calibration

Theory and Practical Application

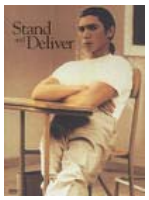
Karl Stum, P.E.

Summit Building Engineering
kstum@summitbe.com

NCBC April 19-21, 2006

What We'll Cover

- **Why this is an issue**
- **Fundamentals & theory**
- **Hand-held instruments**
- **BAS sensors**
- **Overall accuracy**
- **Needed accuracy of hand-helds**
- **Practical application**



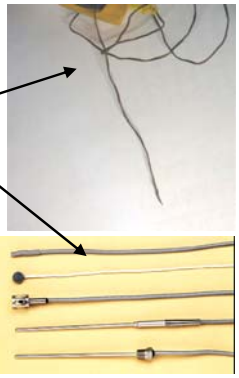
Jaime Escalante, Garfield High School, East Los Angeles, 1982 (18 passed AP, 1987 73 passed)

Who cares?

- **Commissioning requires equipment to be calibrated**
- **Accuracy requirements vary widely**
- **Calibrating instrument accuracy is not well understood**
- **BAS sensor accuracy and calibration requirements rarely include calibration instrument accuracy requirements**
- **Results: Misapplications, wasted effort and less than expected results**

Sensors

- **Sensor types**
  - **Thermocouple**
  - **Thermistor**
  - **RTD** (resistance temperature detector)



Sensor Characteristics

Sensor Type	How It Works	Application	Advantages	Disadvantages
Thermo-couple	Two wires of dissimilar metals cause a voltage	Hand-helds, process	Durable, very high temps, inexpensive; fast	Low accuracy
Thermistor	Resistance of a small semi-conductor	Hand-helds, HVAC systems	High sensitivity; accurate	Moderate cost & response time.
RTD	Resistance of a fine wrapped wire	Hand-helds, HVAC systems	Very stable, wide temp range; accurate.	Moderate cost & response time. Needs a transmitter or lead wire compensation

Source: PECI 3.1; Omega

Sensor Accuracy

Sensor Type	Standard	Special
Thermocouple Type K	+/- 4.0F	+/- 2.0F
Thermocouple Type J	+/- 4.0F	+/- 2.0F
Thermocouple Type E	+/- 3.0F	+/- 1.8F
Thermocouple Type T	+/- 1.8F	+/- 0.9F
Thermistor	Typical [1]: +/- 0.17 to 0.36	N/A
RTD	Typical [1]: +/- 0.17 to 0.36	N/A

Accuracy and Repeatability

- Accuracy is the uncertainty
- Repeatability
  - Measure of random accuracy
  - Data on, is rare
  - Thermocouples worst, thermistors and RTD's much better

Sources of Error

- Fixed errors (bias)
  - Transmitters, A to D, lead length, display resolution, calibration tolerance
  - None of these errors are included in the factory error given in the previous table
- Random errors (precision)
  - Vary over time
  - Thermal drift, radiation, poorly placed sensors, elec noise, non-linearity
- Quantifying for any specific job is difficult

Accuracy Types

- Absolute Accuracy
  - Needing to know what the "real" temperature is
- Consistency or "relative" accuracy
  - Difference is most important (CHW dT, CO2 outside and inside)

Combining Sources of Error

- Simple sum--worst case
  - BAS random and precision: +/- 0.8 F
  - Sensor: +/- 1.1 F
  - Total +/- 1.9 F
- Statistical combination
  - Overall accuracy
    = square root of sum of the squares of the errors

$$\sqrt{(A1^2 + A2^2 + A3^2....)}$$

$$\sqrt{(1.1^2 + 0.8^2)} \quad = \quad \text{+/- 1.36F}$$

What is Field Calibration?

- Comparing BAS or packaged equipment reading with handheld value
- Adjust BAS, if necessary, to within a 'calibration tolerance'
  - Simple offset
  - Two point calibration

Why Calibrate?

- *Air handler DAT sensor reading 2F high
- Coil over-cools air
- Chiller is less efficient having to put out colder water
- For a 40,000 cfm fan that is $1200 / yr
- Plus, overcooled air must be reheated more resulting in another $1400 / yr of boiler energy

*PECI FT Guide online 3.5.1

Why Calibrate?

- **AHU RA RH sensor**
  SOO: If RA RH > 60%, DAT = 52F.
  RH reading high so DAT reset never worked.
  Chiller energy. Reheat energy.
- **Five chiller central plant—CHWST sensors**
  Each chiller's internal sensor reading different. BAS sent needed CHWST SPt. Chillers made what they thought was the SPt. One building didn't get design CHW temps. Insufficient dehum in building. Mold. Litigation.
- **Flow meters:**
  - **Installed for different sized pipe**
  - **Plastic chip clogged one turbine**

Overall Handheld Accuracy With Random Probes

- **Instrument transducer error (T)**
- **Probe error (P)**
- **Overall Instrument accuracy (I)**

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

+

Advertised Accuracies

- **For all major manufacturers (that I looked up), but one, the advertised accuracy of the tool is just the instrument and does not include sensor probe error.**
- **For thermocouples, the probe error is about 4 times larger than the advertised instrument accuracy**
- **When you think you are getting +/- 0.5F, you are more likely getting a +/- 2.2F**
  (with thermocouples)

Advertised Accuracies

Measurement Accuracy, T1, T2 or T1-T2 *(Model 54)*	J-, K-, T-, E-, and N-type: ±[0.05 % of reading + 0.3 °C (0.5 °F)] [below −100 °C (−148 °F): add 0.15 % of reading for J-, K-, E-, and N-type; and 0.45 % of reading for T-type] R- and S-type: ±[0.05 % of reading + 0.4 °C (0.7 °F)]

Accuracy is specified for ambient temperatures between 18 °C (64 °F) and 28 °C (82 °F) for a period of 1 year. The above specifications do not include thermocouple error.

80 PK-1 Thermocouple (supplied with thermometer)

Type	Type K, Chromel Alumel, bead style
Temperature Range	−40 °C to +260 °C (−40 °F to +500 °F)
Accuracy	± 1.1 °C (± 2.0 °F)

Advertised Accuracies

THERMOCOUPLE INPUTS: 2 (T1, T2) miniature TC connectors. Accepts male miniature and subminiature TC connectors.

THERMOCOUPLE TYPES: K, J, T

READOUT: T1, T2, T1-T2, and SCAN (T1, T2, T1-T2)

ACCURACY: (18°C to 28°C ambient, 2 years, excludes thermocouple error):

TC Type	Range	Resolution	Accuracy (T1, T2)	Accuracy (T1-T2)	Extended Temp. Range Acc'y (T1, T2), Typ.
K	−200°C to 1372°C −328°F to 2502°F	0.1/1°C 0.1/1°F	±(0.1% rdg + 0.6°C) ±(0.1% rdg + 1.0°F)	Acc'y (T1) + Acc'y (T2) Acc'y (T1) + Acc'y (T2)	−200°C to −250°C, ±(3°C) −328°F to −418°F, ±(5°F)
J	−210°C to 760°C −346°F to 1400°F	0.1/1°C 0.1/1°F	±(0.1% rdg + 0.6°C) ±(0.1% rdg + 1.0°F)	Acc'y (T1) + Acc'y (T2) Acc'y (T1) + Acc'y (T2)	— —
T	−200°C to 400°C −328°F to 752°F	0.1/1°C 0.1/1°F	±(0.1% rdg + 0.6°C) ±(0.1% rdg + 1.0°F)	Acc'y (T1) + Acc'y (T2) Acc'y (T1) + Acc'y (T2)	−200°C to −250°C, ±(3°C) −328°F to −418°F, ±(5°F)

REPEATABILITY: ±0.2°C typical for 1 week at constant ambient temperature.

Handheld Accuracy Example

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

Thermocouple

- **Instrument: +/- 0.6 F accuracy**
- **Type K thermocouple: +/- 2.0 F accuracy**
- **$\sqrt{0.6^2 + 2.0^2}$ = +/- 2.08 F overall accuracy**

- **Type T thermocouple: +/- 0.9 F will yield +/- 1.08 F.**

Thermistor

- **Thermistor instrument: +/- 0.4 F**
- **Probe: +/- 0.18 F**
- **$\sqrt{0.4^2 + 0.18^2}$ = +/- 0.44 F overall accuracy**

Thermocouple Improvements

1. Use Type T thermocouple probes
2. Have the instrument professionally calibrated WITH the probe, with accuracies given at 3 or more points and,
   - ONLY use that probe with the instrument.
   - This can improve the accuracy of Type K systems from +/- 2 F to as much as +/- 1 F.
   - Accuracies reported in the calibration report may be better than this, but may not be consistent.
3. Use instruments without detachable probes.

Thermocouple Improvements

- Use instruments without probes
- Advertised accuracies include the sensor
- Typical accuracies are +/- 1.0F

Overall Handheld Accuracy

Special note:

- Some metal P/T probes use Standard Type K thermocouples rather than Special grade and give an accuracy of +/- 4.0F !!

Very popular brand (think yellow)

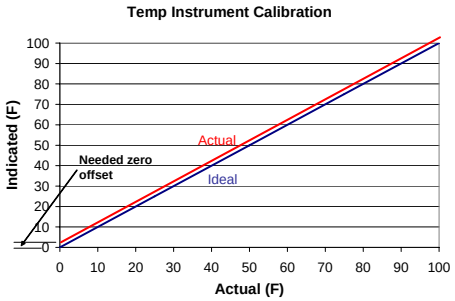
Selecting Handhelds

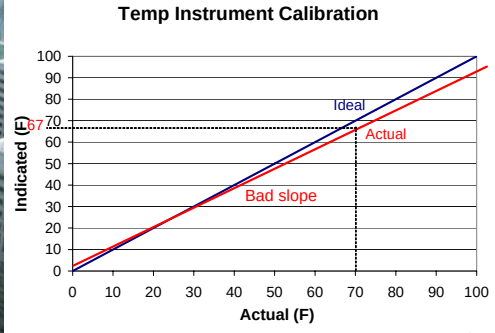
- Determine your needs
  - Accuracy
  - Speed of response
    - Bare bead thermocouples are best. Select P/T probes with small diameter shafts
  - Ability to stick thru small holes
  - Probe length (wire and rod)
  - Durability
    - Thermocouples are toughest
    - Thermistor probes are subject to damage if dropped hard

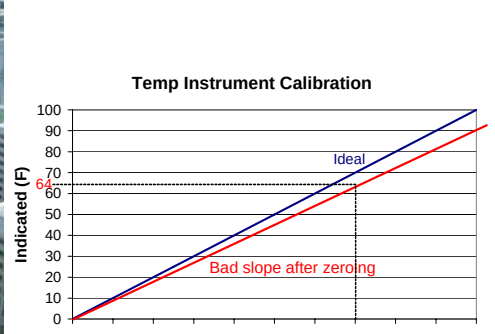
Selecting Handhelds

- If you need more accuracy than +/-1.0F then a thermocouple instrument will not do. Use a thermistor instrument
- If you select a thermocouple unit:
  - Order a Type T probe (buy from another source if your mf'r doesn't offer them)
  - Purchase one with a field zeroing or offset calibration feature
- You won't find thermistor units with a field zeroing feature

Ice Bath and Zeroing Issues







BAS and Equip Sensors
Issues Affecting Sensor Accuracy

- Wire or lead length
  - Some mfr's give compensation tables
  - Some utilize lead length compensation
- Field installed resistors
- Analog to digital conversion and transmission
- Thermal drift
- Change of value limitation

Accuracy

- End-to-end accuracy
  - Sensor to the BAS screen readout (assuming a perfect calibrating instrument)
  - Takes all of above errors into account
  - An approximation
- Overall accuracy
  - Sensor to the BAS screen after field calibration, if used
- Calibrating tolerance

BAS Sensor Overall Accuracy

- Overall accuracy, O =

Sensor accuracy—end-to-end (S)

+

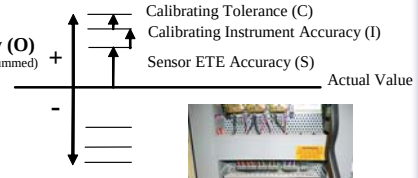
Overall accuracy of calibrating instrument (I)

+

Allowed calibrating tolerance (C)

BAS Sensor Overall Accuracy

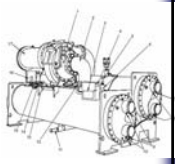
Overall Accuracy (O)
(not simple -summed)



$$O = \sqrt{(S^2 + I^2 + C^2)}$$

Factory Calibration

- If mf'r can certify end-to-end accuracy, then no field calibration is needed
  - Sensor (alone) accuracy specs are not the same as end-to-end calibration certification
- Some packaged controls can offer this
- New chillers need sensors checked
- Most, if not all, field installed temperature sensors need to be field calibrated.
- Special case: Hydronic flow meters



Needed Accuracy of Field Calibrating Instrument

- Four times? Two times? as accurate as the sensor being calibrated?
- Rearranging the previous equation yields: Overall Instrument accuracy, I

$$I = \sqrt{(O^2 - S^2 - C^2)}$$

- Overall accuracy desired of BAS readout (O) = 1.0F, end to end accuracy of BAS sensor (S) is estimated to be 0.5F, calibrating tolerance (C) = 0.1F, then I, the overall instrument accuracy needs to be 0.9F or better.

Table of Required Instrument Accuracies

BAS or Equipment Sensor	Desired Overall BAS Reporting Accuracy O (+/-)	Assumed End-to-End Sensor Accuracy S (+/-)	Maximum Calibration Tolerance, C (+/-)	Required Calibrating Instrument Overall Accuracy I (+/-)	BAS Sensor Alone Accuracy
Cooling coil, chilled & condenser water temps	1.0	0.5	0.1	0.9	0.35
Outside air; duct air temps	1.0	0.5	0.1	0.9	0.35
Normal space air temps	1.0	0.5	0.1	0.9	0.35
Air handler air temperature averaging sensors*	4.0	3.8	0.5	1.1	3.4
Hydronic temp sensors in chilled & heating water plants & secondary loop (for relative calibration)	1.0	0.5	0.0	0.9	0.35
All air stream temp sensors in built-up air handlers (for relative calibration)	1.0	0.5	0.0	0.9	0.35
Critical space air temps	0.5	0.3	0.1	0.4	0.20
Air & water temperature differences <20F	0.5	0.3	0.0	0.4	0.20
Air & water temperature differences >20F	0.7	0.5	0.0	0.5	0.35
Dew point or wet bulb temperature*	4.5	4.0	0.2	2.1	3.6
Hot water coil and boiler water temp	2.0	1.1	0.4	1.6	0.8
Relative humidity	4.0	3	1.0	2.7	2

Implications

- For typical HVAC applications, temp calibrating instruments must be +/- 0.9F or better
- Thermocouple instruments will not comply
- Thermistor instruments will comply
- Overall calibrating instrument accuracy, I, need only be slightly better than the desired overall accuracy, O.
- The larger the calibrating tolerance, the more accurate the instrument will need to be

Design Phase

- Identify general accuracy requirements in early OPR
- Have the designer identify target for overall BAS reporting accuracy for each sensor (O). Don't specify this in const. docs.
- Make designer aware they must specify the accuracy of individual sensors and that it must be tighter than the end-to-end (S) or overall accuracy (O).
- Verify that the above is in the design docs
- Include field calibration requirements in specs, as well as for calibrating instrument accuracy

Construction Phase

- Provide a form for contractor to submit their instrument accuracies
- Near to startup, bring all your instruments to job and compare readings to contractors. ID each.
- Approve contractor's calibration forms
- Check calibration yourself on all critical BAS and equipment sensors
- Leave operators with sensor calibration instructions & frequencies

Calibration Tips

- Relative sensor calibration
- CO2 sensors
- Flow meters
- Mixed air temp sensors
- Space temps
- VAV TU SA temps
- Repeat readings (2 = +19%, 5 = +33%, 10 = +39%)
- Hydronic tool

Hydronic Tool

Hydronic Tool

Hydronic Tool

Summary

- Temp calibrating instruments must be +/- 0.9F or better
- Thermocouple instruments will not comply
- Thermistor instruments will comply
- Overall calibrating instrument accuracy, I, need only be slightly better than the desired overall accuracy, O.
- The larger the calibrating tolerance, the more accurate the instrument will need to be
- Specify sensor and calibrating instrument accuracy and calibrating tolerance