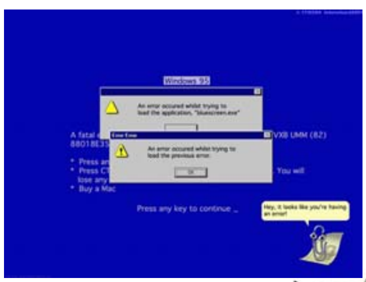
Performance Characteristics

Performance Characteristics

- Used by manufacturers to describe instrument specs
- Static performance characteristics
  - Obtained when sensor input and output are static (i.e., constant with time)
  - Static sensitivity – slope of the transfer curve showing measurand input vs. raw sensor output
- Dynamic performance characteristics
  - Define the sensor response to variable input
  - For example, a time constant describes speed with which a sensor responds to a change in input

Sources of Error

- Four categories of errors:
  - Static
  - Dynamic
  - Drift
  - Exposure



Sources of Error

- Static errors
  - Errors measured when input/output is constant
  - Errors that exist after applying a calibration curve
  - Two types of static errors
    - Deterministic (e.g., hysteresis, sensitivity to unwanted input variables, or residual nonlinearities)
    - Random (e.g., noise)

Sources of Error

- Dynamic errors
  - Errors due to variable input
  - Errors disappear when input is held constant long enough for the output to become constant
  - Example: Time lag
- Drift errors
  - Errors that occur due to physical changes in the sensor over time
  - Generally unpredictable and difficult to account for
  - Avoiding drift requires frequent calibration
  - Drift errors can change abruptly

Sources of Error

- Exposure
  - Due to imperfect coupling between measurand and sensor
    - e.g., radiation and heat conduction influence temperature measurements
  - Instruments report their own state, which is not necessarily the state of the atmosphere!
  - Exposure errors are not present in laboratory settings and are not included in sensor specifications
  - Exposure errors can easily exceed the magnitude of static, dynamic, and drift errors combined!

Standards

- Must consider standards in system design and evaluation:
  - Calibration
  - Performance
  - Exposure
  - Procedural

David Grimsley in the Fred V. Brock Standards Lab (© The Oklahoman)

Standards

- Calibration standards
  - Maintained by standards laboratories
    - National Institute of Standards and Technology (NIST)
    - National Physical Laboratory of India
    - Tanzania Bureau of Standards
  - Organizations operating measurement sites must have calibration facilities
  - Transfer standards used for local calibrations can be sent to a standards laboratory for comparison with primary standards
  - Should be able to trace calibration of a sensor to NIST standards

Standards

- Performance standards
  - Standardize the terminology, definitions of terms, and testing methods for static and dynamic sensor performance
    - Time constant
    - Response time
    - Sensor lag, etc.
  - Established by the American Society for Testing and Materials (ASTM; now *ASTM International*)
  - Without such standards, vendor performance specifications would be difficult to interpret

Standards

- Exposure standards
  - Specified by the World Meteorological Organization (WMO)
  - Define adequate exposure for classes of applications
    - Synoptic-scale wind measurements should represent a large area (i.e., not influenced by buildings or local terrain)
    - For comparability, measurements should be taken at the same heights
      - Anemometers at 10-m above level, open terrain; distance from an obstruction at least 10x height of obstruction
      - Thermometers at 1.25–2 m AGL with radiation screen

Standards

- Procedural standards
  - Define algorithms for commonly computed quantities (e.g., mixing ratio, sensible heat flux, etc.) and selection of data sampling and averaging periods
  - Unfortunately, compliance is lacking
  - Procedural standards become important when combining data from multiple observing networks

Interpretation of Sensor Specifications

- If a vendor specifies a temperature sensor inaccuracy of ±0.2°C, what can we infer about a report of 30°C?

a) There is complete certainty that the actual air temperature is 30°C ± 0.2°C
b) There is a 95% probability that the actual air temperature is 30°C ± 0.2°C (assuming errors are randomly distributed in a Gaussian distribution with a standard deviation of 0.1°C)
c) There is a 95% probability that the actual air temperature is 30°C ± 0.2°C, provided the user can offer reasonable assurances about drift, dynamic error, and exposure errors

Interpretation of Sensor Specifications

- If a vendor specifies a temperature sensor inaccuracy of ±0.2°C, what can we infer about a report of 30°C?
  - a) **There is complete certainty that the actual air temperature is 30°C ± 0.2°C**
  - b) There is a 95% probability that the actual air temperature ... in a Gaussian distribution with a standard deviation of 0.1°C)
  - c) There is a 95% probability that the actual air temperature is 30°C ± 0.2°C, provided the user can offer reasonable assurances about drift, dynamic error, and exposure errors

It's impossible to put absolute limits on error

Interpretation of Sensor Specifications

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Maybe, but only in the context of a laboratory calibration under controlled conditions and no possibility of drift, dynamic error, or exposure error

Interpretation of Sensor Specifications

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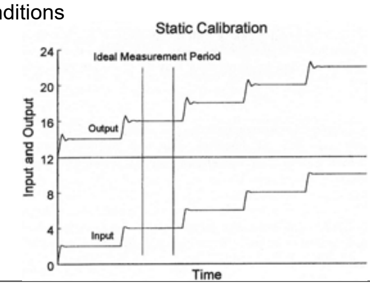
  - a) There is complete certainty that the actual air temperature ...
  - b) ... 0.1°C)
  - c) **There is a 95% probability that the actual air temperature is 30°C ± 0.2°C, provided the user can offer reasonable assurances about drift, dynamic error, and exposure errors**

Correct! In high-quality systems, the largest source of error is exposure error. This is not included in sensor specifications.

Static Calibration

- Vary one input in a stepwise fashion over the range of values
- At each step, output is observed in steady-state conditions



Static Calibration

- Other input variables are held constant
  - e.g., pressure calibration is done with a constant temperature
- Each step is repeated for multiple inputs to obtain a transfer relation describing the raw output response to the measurand over the range of the sensor

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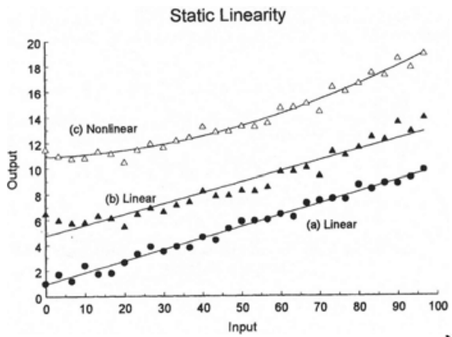
Ultimate objective of static calibration:
Define instrument inaccuracy
(a combination of bias and imprecision)

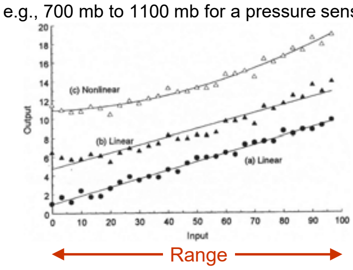
The reference instruments used to measure the input and output must be <u>an order of magnitude</u> more accurate than the test instrument

Static Calibration – The Transfer Plot



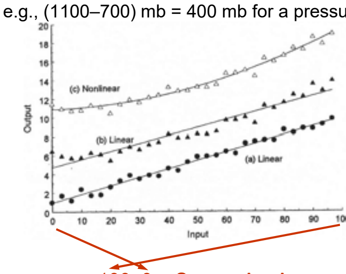
Static Calibration – The Transfer Plot

- Range
  - The measurand interval over which a sensor is designed to respond
    - e.g., 700 mb to 1100 mb for a pressure sensor



Static Calibration – The Transfer Plot

- Span
  - Difference between upper and lower range limits
    - e.g., (1100–700) mb = 400 mb for a pressure sensor



100–0 = Span = $A_H – A_L$

Static Calibration – The Transfer Plot

- Static Sensitivity
  - Slope of the transfer curve:

$$S_S = \frac{d(\text{raw output})}{d(\text{input})} = \frac{dy}{dx} \approx \frac{y_2 - y_1}{x_2 - x_1}$$

  - If the curve is a straight line, the static sensitivity S_S is constant and the sensor is therefore linear
  - If the curve is not a straight line (i.e., the sensitivity varies over the range), the sensor is nonlinear
  - Ideal sensor has LARGE, constant static sensitivity
  - Datalogger microprocessors can correct for small nonlinearities
  - A sensor with zero static sensitivity is useless

Static Calibration – The Transfer Plot

- Static Sensitivity
  - Mercury barometer

Static Calibration – The Transfer Plot

- Static Sensitivity
  - Aneroid barometer with a corrugated diaphragm

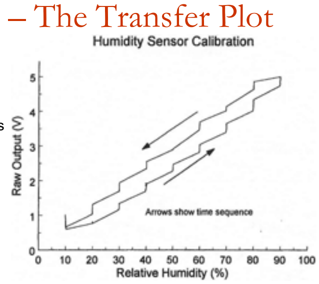
Static Calibration – The Transfer Plot

- Linearity
  - If the data points on the transfer plot are *randomly scattered around a straight line*, then the sensor response is linear
  - Straight line is obtained by a least-squares fit
  - An instrument is linear if the errors due to nonlinearity are acceptably small within the required accuracy specification
  - Large, systematic deviations from a straight-line fit indicate nonlinearity

Static Calibration – The Transfer Plot

- Resolution
  - Smallest change in input that produces a detectable change in output
  - Limited by noise and by friction that inhibits the response
  - Best possible resolution is zero (good luck!)
  - Some vendors claim infinite resolution…

Static Calibration – The Transfer Plot



- Hysteresis
  - Sensor output depends upon whether the input was increasing or decreasing
  - Typical for aneroid barometers and humidity sensors
  - Causes problems for soil moisture measurements
- Threshold
  - Special case of hysteresis when the input is at or near zero
  - Output remains zero until input reaches threshold value
  - Usually caused by static friction
  - Anemometers have threshold values (e.g., 0.5 m s^{-1})

Static Calibration – The Transfer Plot

- Stability
  - If repeated calibrations reproduce the transfer curve, then the instrument is stable and free from drift
- Random error and noise
  - Non-systematic residual error
  - Cannot be corrected and is only predicted statistically
  - Noise is part of the output that did not originate from the input
    - Noise originates from secondary input, interaction of sensor with measurand, or from sensor itself (e.g., current through the wires)