Instruments/Measurements

- Measuring
  - Errors, Calibration, Sensitivity, Range, etc
- Temperature
  - Aspiration/Shielding
  - Thermistors, thermocouples, mercury
- Wind
  - Exposure
  - Cups, sonic anemometers
- Radiation
  - Quantum vs Energy
  - Leaf Area Index
- Trace Gases
  - Infrared absorption

Where do our data come from? What instruments do we use? How do they work? How representative and accurate are these measurements?

Old Fashion, Coop Weather station

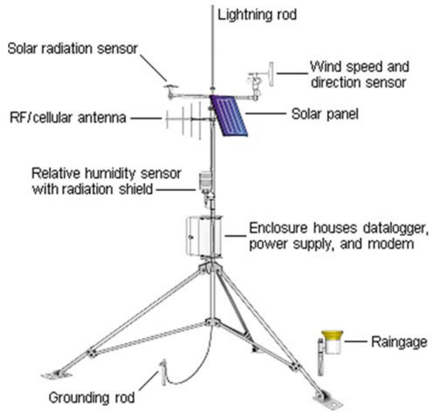
Few Sensors, Max/Min Temperature and Rain Gauge,
Data Written by Hand on Paper

Analog to Digital Conversion of Weather Measurements, Historical Data

Conventional weather station. Stevenson screen to shade and ventilate sensors.

Older and cheaper meteorological sensors tend to be analog

Contemporary Analog to Digital Conversion of Weather Measurements



Typical automated weather station

CIMIS Automated Weather Station

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Automated systems have increased the accessibility and usabilityof meteorological data

Typical Micrometeorological Flux Instrument Station

Our eddy covariance and micrometeorology station at Sherman Island. Flux instrumentation, meteorological sensors, solar radiation sensors, housing for computers and dataloggers. High power requirements, dependent on A/C power

New Wetland Site with Methane Sensor

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Flux system with a methane and CO_2/H_2O sensor. Off the grid, low power, run by solar panels

Attributes of Measurements

- Precision
- Accuracy
  - Random and Systematic Errors
- Sensitivity
- Stability
- Time Response
- Exposure
- Representativeness
  - Aspiration
  - Sheltering, e.g. Sun, Wind and Rain
- Calibration

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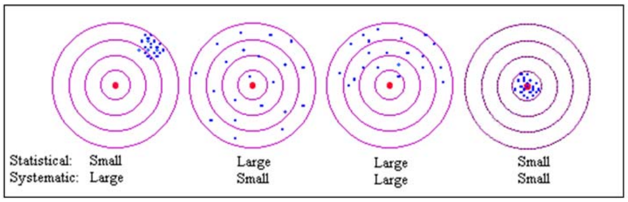
These are the factors we must consider when designing and instrument and when interpreting its data.

Accuracy and Precision



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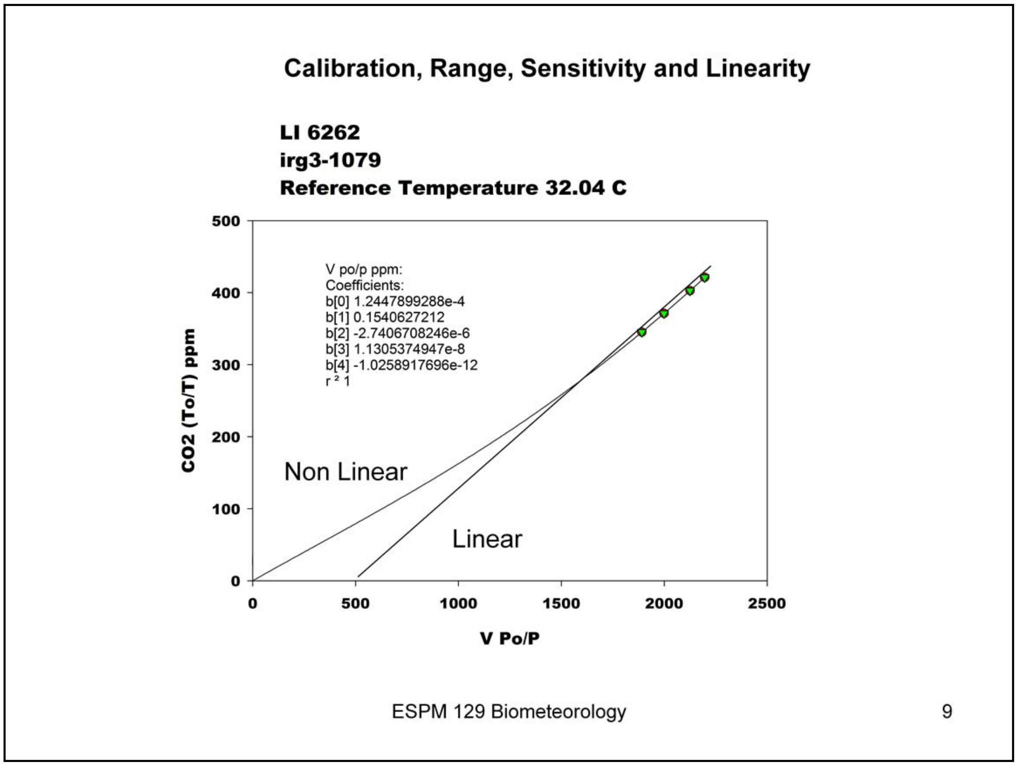
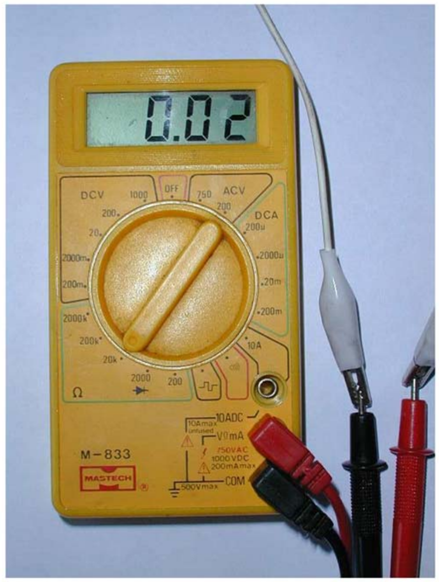
You can be accurate and imprecise, and vice versa (inaccurate and precise).



Many instruments give readings in terms of volts, counts, amps or resistance. We need to calibrate the output of the sensor with its corresponding value. We need to know the range of voltages the sensors responds to and how it relates to output. This may be either a linear or non linear response. We need to know the intercepts and slopes.

Digital Voltmeter



Example of a digital volt meter. Takes analog measurements of voltages and digitizes them on appropriate scale, works for ac and dc currents. Can also measure resistance

Programmable DataLogger

- Single-Ended or Differential Voltage Reading
  - Numerous channels
- Adjustable Ranges
  - 0 – 500 mv
  - 0-5 volt
- Control ports
  - Trigger Relays
- Power output
  - 5 or 12 v
- Pulse counter

Data loggers are the workhorse of meteorological measurements. We need to know how many single or double ended sensors they can record, what type of signal and range. It is important to pick the right range to get the finest bit resolution

New Generation of Programmable Data Logger

Model CR1000 © 2005 Campbell Scientific, Inc.

Newer data logger

Digital vs Analog Sensors

Digital

- Many Modern sensors output Digital Data.
- Distinct values for 0s and 1s
- Signal less susceptible to Noise
- Merging Time Stamps from multiple Digital Signals is not Trivial
- Information can be transferred over long distances

Analog

- Many First Principle Sensors are Analog
- Requires Analog to Digital Conversion
- Susceptible to Noise
- Multiplexor can interface many different channels from slow sensors with common time stamp

Analog to Digital Conversion

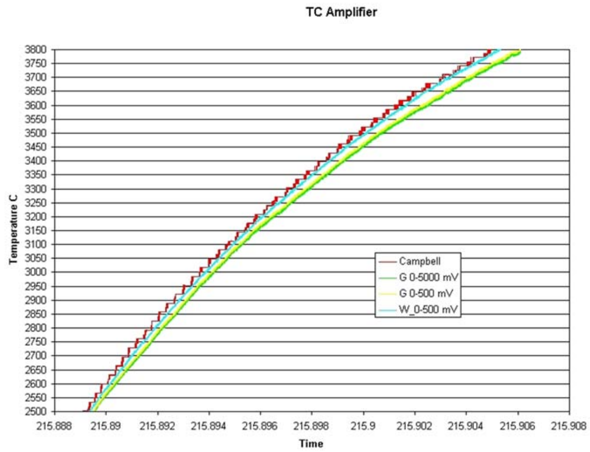
Bit Resolution and Range

Bits resolution	Range: 10 v
256 (2^8)	39.06 mv/bit
4096 (2^{12})	2.44 mv/bit
65536 (2^{16})	0.152 mv/bit

Bits resolution	Range: 1 v
256 (2^8)	3.906 mv/bit
4096 (2^{12})	0.244 mv/bit
65536 (2^{16})	15.2 μv/bit

Number of A/D bits and the range define bit resolution

Stair Step with TC from course resolution A/D



8 Bit A/D on 10 volt range resolves 1 C per bit

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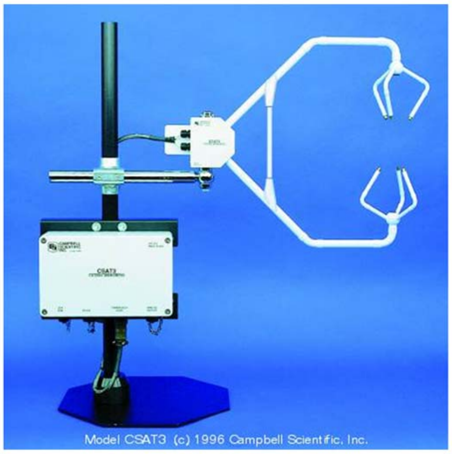
If the bit resolution is too coarse we get a stair step response and can’t resolve intermediate values.

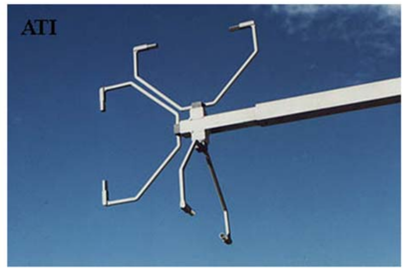
Sonic Anemometer



Sonic anemometers can measure wind velocity along three orthogonal axes and turbulence.

Off-axis, horizontal, sonic anemometer. U,v, and w are not measure directly, but are resolved by an array of 3 sets of non-orthogonal transducers. What are the pros and cons of this arrangement?

Other Configurations



Omni-Directional

Orthogonal Transduces

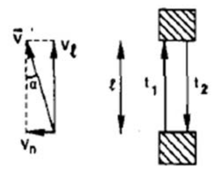
It is important to think about distortion of turbulence due to the separation of transducers, their arrangement and size relative to the path and the position of the sensor on a tower or boom. Other options help minimize flow distortion. Omni-directional, but non orthogonal. This can be mounted on top of a tower and measure winds from all directions. Yet vectors depend on resolving information from 3 axes, so if one is in error it transmit errors to the others. Horizontal, but orthogonal, measures w, u and v directly without biases or errors from the other axes.

Wind Velocity is a function of the time it takes to transmit Sound a known distance, d.

More effective to take the reciprocal of the difference between the sent and transmitted sound pulses

$$V_d = \frac{d}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right)$$

$$c \approx \frac{d}{2}\left(\frac{1}{t_1} + \frac{1}{t_2}\right)$$



Wind velocity is deduced by knowing the distance between two transducers and the time it takes for sound to traverse that distance. By taking the difference of transit times to and fro, between two transducers separated by a known distance, the speed of sound drops out. So all we need is to measure the transit times between sound pulses and when they are received at distance d

Sonic Temperature

$$c^2 = 403\,T_{sonic}\,(1 + 0.32\,\frac{e_a}{P})$$

$$c \approx \frac{d}{2}(\frac{1}{t_1} + \frac{1}{t_2})$$

$$T_{sonic} = \frac{d^2}{1612}(\frac{1}{t_1} + \frac{1}{t_2})^2 + \frac{1}{403}(V_x^2 + V_y^2)$$

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Knowing the speed of sound we can also measure the sonic temperature. This is powerful for measuring sensible heat flux without a fine wire thermocouple that breaks or has thermal inertia.

Attributes of Sonic Anemometer

- Measures wind velocity along 3 orthogonal axes
- Small Transducer to path ratio
- Measurement resolution, 1 to 10 mm s^{-1}
- Accuracy, 1% RMS or 1 to 4 cm s^{-1}
- Frequency Response, ~ 10 to 20 Hz (oversampled, block averaged)
- Range, 0 to 60 m s^{-1}
- Robust, works in rain and snow
- Measures Temperature Fluctuations without a sensor that can break or has thermal inertia

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Sonic anemometers have many positive attributes

2d Sonic Anemometer

Cup Anemometer

Pulse Counts Number of Revolutions

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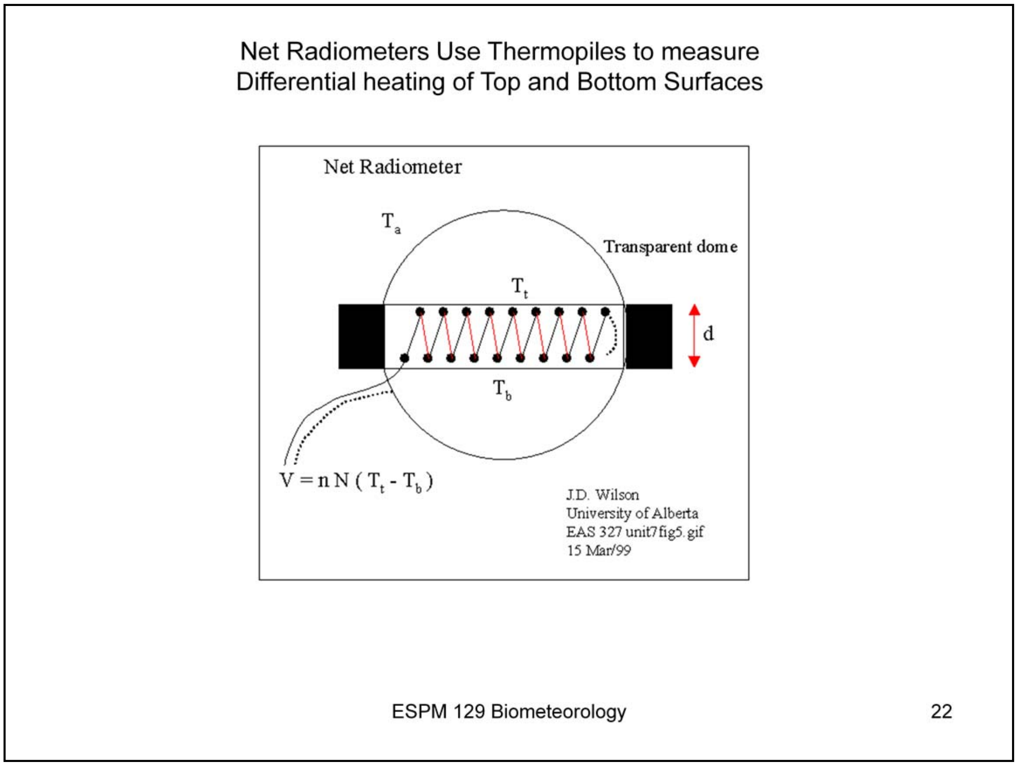
Simpler and cheaper anemometers for routine meteorological measurements. A 2d sonic and cup anemometer



Principles of net radiometers. They use an array of thermocouples, called thermopiles

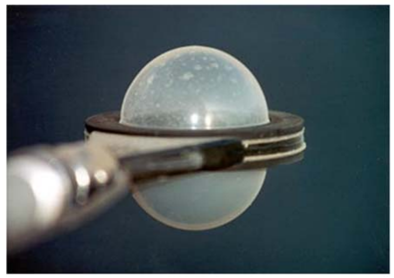
Net Radiometers

Voltage is proportional to the Energy Absorbed and Measured with a Thermopile detecting the Temperature Difference between the Top and Bottom

Model CNR1 (c) 2001 Campbell Scientific (Canada) Corp.

The net radiation balance drives so many energy fluxes of an ecosystem. There are simple sensors or more complex 4 component sensors. Much development and evolution has occurred in the development of net radiometers

Older Net Radiometers



REBS Net Radiometer with
Hard Domes

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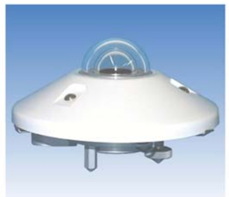
These caused biases. Some with thinner domes, needed air streams to inflate.

Pyranometer, Measures Solar Radiation



Voltage is proportional to the Energy Absorbed and Measured with a Thermopile detecting the Temperature Difference between Dark and Bright Elements

Pyranometer

- Spectral response waveband:
  - 310 to 2800 nm
- Time Response
  - 4 s
- Maximum irradiance: 2000 W/m²
- Linearity
  - < 0.6% at 1000 W m-2
- Sensitivity:
  - 5 to 15 μV/W/m²

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These instruments have small voltage ranges and low sensitivities, so special dataloggers are needed to record them, In this case we have a range of 15 millivolts

Quantum Sensor, Measures Photon Flux Density
Photons displace electrons in silicon and create current.

Model PAR LITE © 2001 Kipp & Zonen

Specifications

Spectral range	400 -1100 nm
Sensitivity (nominal)	100 μV/W/m2
Response time	less than 1 s
Max. irradiance	2000 W/m2
Temperature dependence (typical)	+0.15 %/ºC
Operating temperature	-30ºCto+70 ºC
Directional error	±5 % at 80 degrees

Quantum sensors measure photon flux density. Photons kick out electrons from a silicon wafer and create a current. Placing a 604 ohm resistor across the leads, enable us to convert amps to millivolts

Diffuse Radiation

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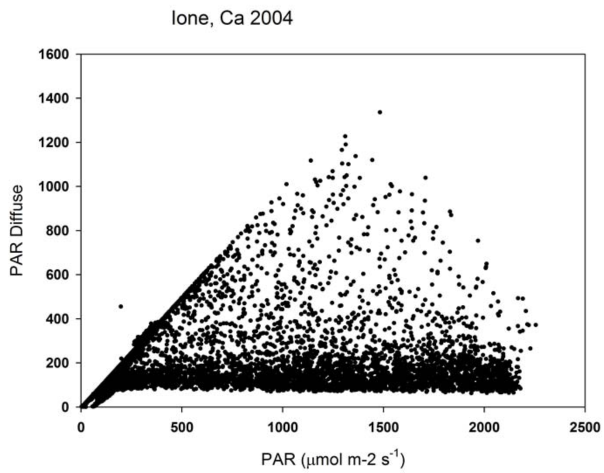
Placing elements between the sensor and the sum enables us to measure diffuse radiation. We also use a rotating shadowband



Ione, Ca 2004
PAR Diffuse
PAR (μmol m-2 s-1)
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500

Some data

Temperature/Humidity Sensor

Model 41003-2 © 2003 Campbell Scientific (Canada) Corp.

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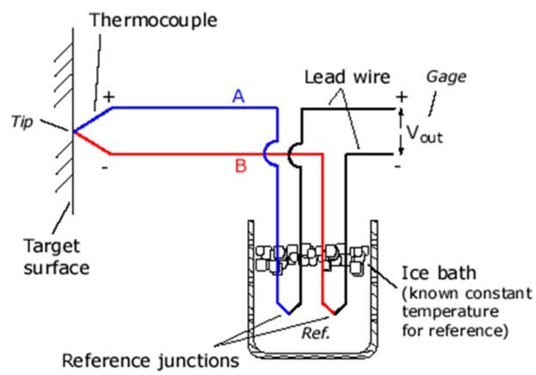
We have to be careful and expose the temperature sensor so it measures the air not itself. This requires us to have it shielded and aspirated. Improper aspiration can cause biases

Thermocouple



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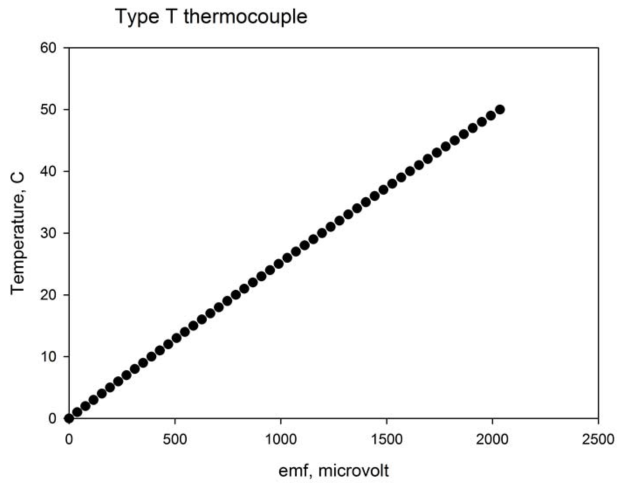
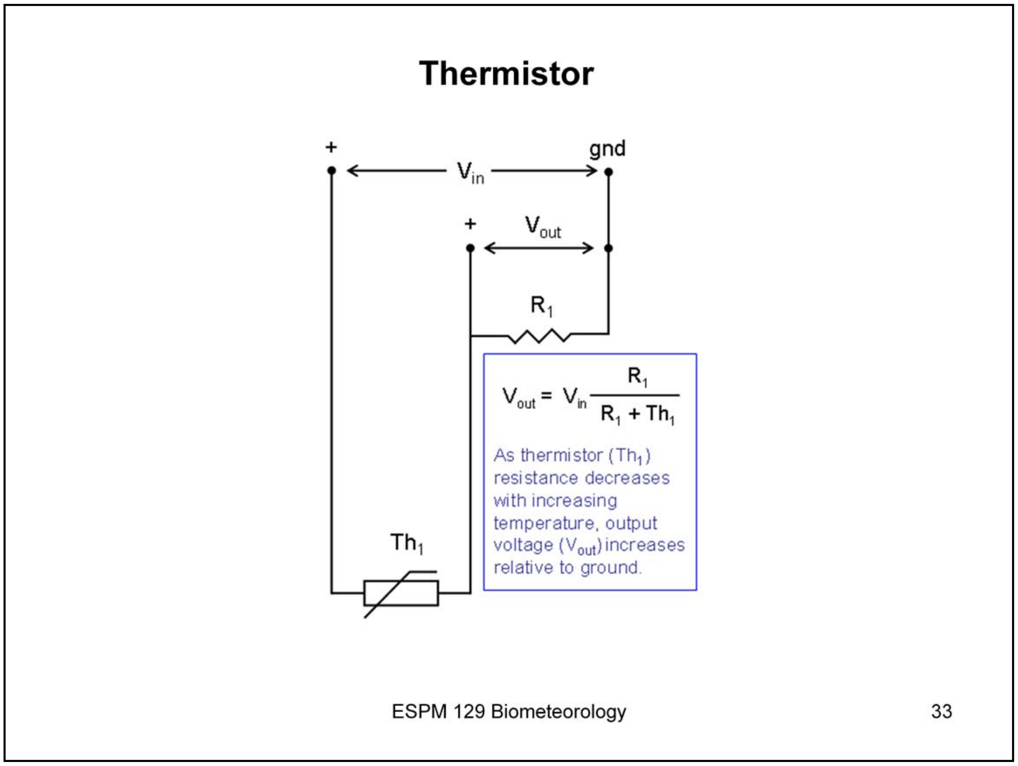
Thermocouples are one way to measure temperature. An emf force is produced if dissimilar metals are exposed to a temperature different from a reference.

Thermocouples, type T, copper-constantan: ~ 40 μV/C



At 40 microvolts per C what is the range in millivolts over a 40 C range? 1.6 millivolts. So the range is tiny using a TC to measure air temperature. Hard to do with a simple and cheap digital volt meter.

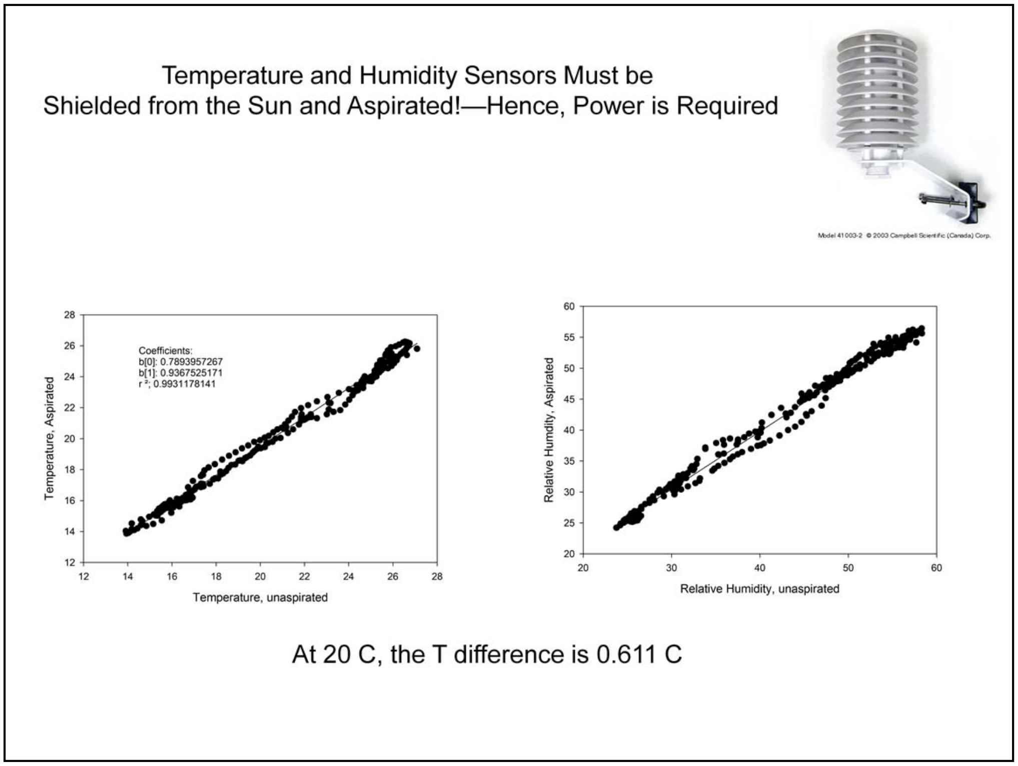


Thermistor, a resistor sensitive to temperature, is another way to measure temperature. This is put into a bridge circuit that is excited and voltage due to the imbalance in the bridge is proportional to temperature

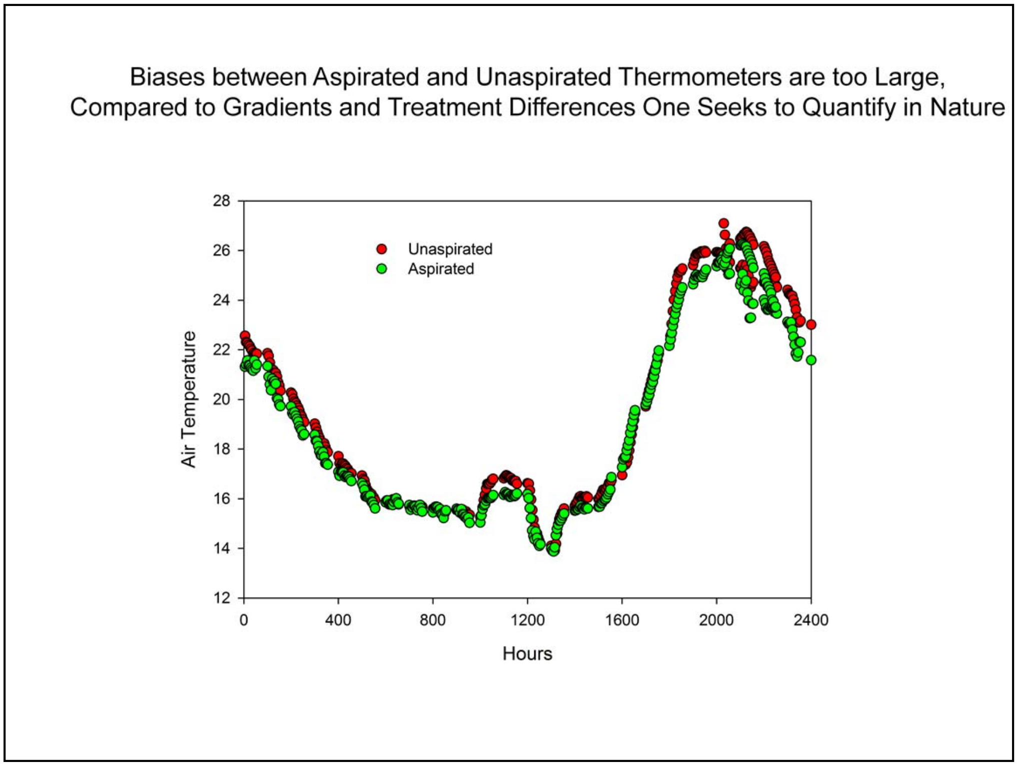
Temperature Sensors

	PRT	Thermistor	Thermocouple
sensitivity	0.4 ohm C-1	0.1 to 1.5 kohm C-1	0.04 to 0.06 mv C-1
accuracy	+/- 0.1 C	+/- 0.1 C	+/- 0.35 C
Linearity	Slightly non-linear	Very non linear	Slightly non linear
Response time	10 s	5 s	< 5s
Excitation	yes	yes	No
T reference	no	no	yes

Platinum resistance thermometers (PRT) are the most accurate



Experiment in the lab comparing an aspirated and unaspirated sensor



Biases seem to be greatest at night as the sensor losses heat to the cold sky through the windows of the lab.

Rain Gauge

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Rain gauges need proper resolution, exposure and volume to capture large to small rain events. This is the type I have at home. I can see events as small at 0.01 inch.

Rain Gauge with Wind Screen

NOAA’s Climate Research Network

Proper exposure to minimize wind losses. https://www.rap.ucar.edu/asr2001/B-snowfall_freezing_precip_files/image002.jpg

Rain Gauge

Model TE525M (c) 2000 Campbell Scientific (Canada) Corp.

Tipping Bucket

Tipping bucket rain gauge. Tipping bucket fills and gives a pulse that is counted.

Soil Heat Flux Plate

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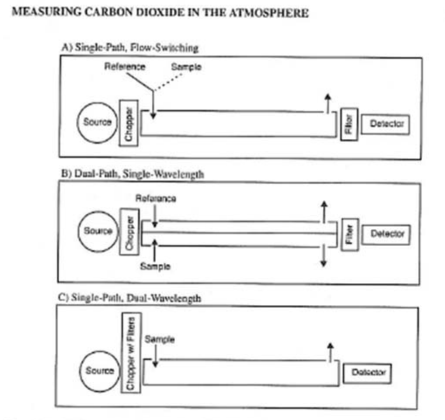
We also want to measure heat conduction through the soil. Exposure, placement and depth are important

Non-Dispersive Infrared Spectrometer



Welles and McDermitt 2005 Micromet in Ag

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Trace gases like CO2 and water vapor are measured with non dispersive infrared spectrometers. These instruments measure the absorption of IR light across a broad absorption band, e.g. near 4.26 microns for CO2, relative to a non absorbing band. We have to be careful and make sure the reference band and absorption bands are not sensitive to water vapor. We want to avoid cross sensitivity.

Vaisala soil CO2 concentration Probe

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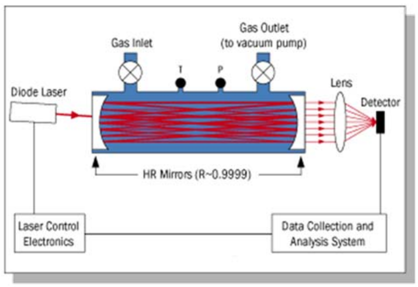
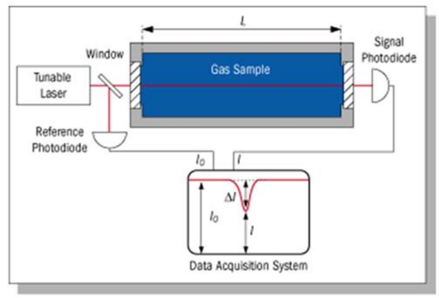
Smaller probes can be put into the soil or water column to measure CO2. These are new systems with an NDIR on a chip.

Tunable Diode Laser Spectrometer





- Methane
- N_2O
- $^{13}CO_2$
- ^{18}O

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Laser spectrometers can focus on the absorption of a narrow line using lasers instead of lamps as light sources. Better, more precise and accurate and better detection limits. More expensive, but costs are dropping for many applications. Can also be used to measure concentrations of stable isotopes real time and continuous, an upgrade from batch sampling of mass spectrometers.

Soil Moisture

- Time Domain Reflectometry
- Frequency Domain Reflectometery
  - Sensitive to Salt
- Capacitance
  - Sensitive to Salt

Soil Moisture is a function of the dielectric constant

There are a number of direct and indirect ways to measure soil moisture. But new sensors give us the ability to have continuous measurements

$$\frac{V - V_f}{V_0 - V_f} = \exp(-\frac{t}{RC})$$

Capacitance (C) is a function of the dielectric permittivity

Soil Moisture:
Time Domain Reflectometry

•Time domain reflectometry (TDR) determines the dielectric permittivity of a medium by measuring the time it takes for an electromagnetic wave to propagate along a transmission line that is surrounded by the medium.

•The presence of water in the medium affects the speed of the electromagnetic wave

•The transit time (*t*) for an electromagnetic pulse to travel the length of a transmission line (L) and return is related to the dielectric permittivity of the medium, κ

$$t = \frac{2L\sqrt{\kappa}}{c}$$

Cable testers are the idea behind time domain reflectometers

Trenton Franz and COSMOS

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Cosmos, cosmic ray soil moisture system, measures fast and slow neutrons associated with the collisions with cosmic rays. Soil moisture is associated with the relation between hydrogen and intensity of low energy neutrons

Pressure ‘bomb’ for leaf water potential

Another way to measure soil moisture is to let the plant and root system do the work and sampling. Pre dawn water potential assumes the water potential in the leaf and soil are in near equilibrium as transpiration is thought to be nil (though night transpiration can occur through leaky stomata).

LI 6400 Photosynthesis System

Controls:
- Light
- CO2
- Temperature
- Humidity
- Flow

Infrared gas systems can be coupled with cuvettes to measure photosynthesis. This system controls light, temperature, humidity and CO2

Soil Respiration Chamber attachment

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Extra head lets us measure soil CO2 efflux, or respiration