SENSORS AND TRANSDUCERS

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E80 - Spring 2012

(Notes adapted from Prof. Qimin Yang's lecture, Spring 2011)

YOU GET TO CHOOSE SENSORS FOR YOUR ROCKET!

- http://www.eng.hmc.edu/NewE80/FlightVideos.html
- http://www.eng.hmc.edu/NewE80/MuddI11_10_06-800Kbps.mov
- Lego Man in Space (just for fun): http://www.youtube.com/watch?v=MQwLmGR6bPA

AGENDA

- Rocket sensors

- Common sensors/transducers
  - Gas sensor
  - Humidity sensor
  - Pressure sensor
  - Vibration sensor

- Rocket hardware (next week)

BRAINSTORM

- What sort of data might you want to collect from your rocket?

BRAINSTORM

- Environment (inside and outside of rocket)
  - Temperature
  - Humidity
  - Pressure

- Motion of the rocket
  - Altitude / time to apogee
  - Velocity
  - Acceleration

- Vibration (of the rocket, of the stand)

COMMON SENSORS

- Temperature Sensor (Done)
- Rate Gyros / Accelerometers (Done)
- **Gas / Chemical Sensor**
- **Humidity Sensor**
- **Pressure Sensor**
- **Vibration Sensor**

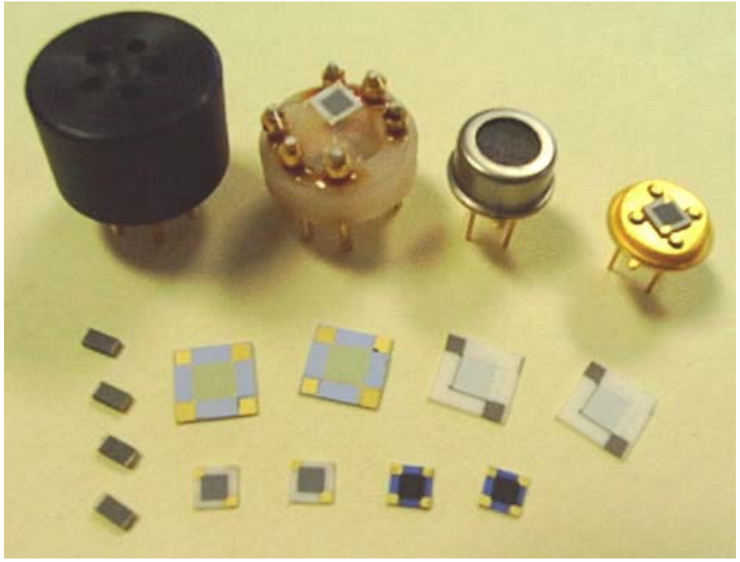
GAS/CHEMICAL SENSORS

- Solid electrolyte sensors [NO_2, CO_2, O_2]
- Metal oxide sensors [combustible & toxic gases]
- Catalytic bead sensors [combustible gases]
- Electrochemical sensors [toxic gases & oxygen]

GAS/CHEMICAL SENSORS

What sort of characteristics are important to consider when choosing gas or chemical sensors?

- Sensitivity (ppm, ppb)
- Operation temperature range
- Power consumption
- Size



http://www.futurlec.com/Gas_Sensors.shtml (output voltage)

http://www.synkera.com/chemical-sensing-analysis/solid-state-gas-sensors.html (output resistance)

http://www.boulder.nist.gov/div853/Publication%20files/NIST_BCC_Nano_Hooker_2002.pdf

EXAMPLE: CO_2 GAS SENSORS

Cathodic reaction:	$2Li^+ + CO_2 + ½O_2 + 2e^- = Li_2CO_3$
Anodic reaction:	$2Na^+ + ½O_2 + 2e^- = Na_2O$
Overall chemical reaction:	$Li_2CO_3 + 2Na^+ = Na_2O + 2Li^+ + CO_2$

Nernst Equation:

$$EMF = E_c - \frac{RT}{2F \ln(P_{CO2})}$$

P_{CO2} = partial pressure of CO_2 gas
E_c = constant cell potential under standard conditions [V]
R = ideal gas constant = 8.31 J/(mol-K)
T = absolute temperature [K]
F = Faraday constant = 9.65×10^4 C/mol

http://chemistry.about.com/od/electrochemistry/a/nernstequation.htm

PARTIAL PRESSURE

- Ideal gas law:

$$PV = nRT$$

n: number of moles

- Dalton's Law of Partial Pressure:

Partial pressure ratio = mole ratio

  - **Partial pressure = total absolute pressure x volume fraction of gas component**
  - 1 ppm = 1 part per 1,000,000 parts

Alternate form of ideal gas law: $PV = nRT = \left(\frac{m}{M}\right)RT$

- Mass per volume: $\frac{m}{V} = \frac{PM}{RT}$

m: mass
M: molar mass

PARTIAL PRESSURE

Example: What is the partial pressure of 1% CO_2 at atmospheric pressure (101.325 kPa) and room temperature (25 °C or 298.15 K)?

Hint: Molar mass of CO_2 = 44 g/mol

- ppm = ?
- Partial pressure of CO_2 = ?
- Mass per volume $\frac{PM}{RT}$ = ?

PARTIAL PRESSURE

Example: What is the partial pressure of 1% CO_2 at atmospheric pressure (101.325 kPa) and room temperature (25 °C or 298.15 K)?

Hint: Molar mass of CO_2 = 44 g/mol

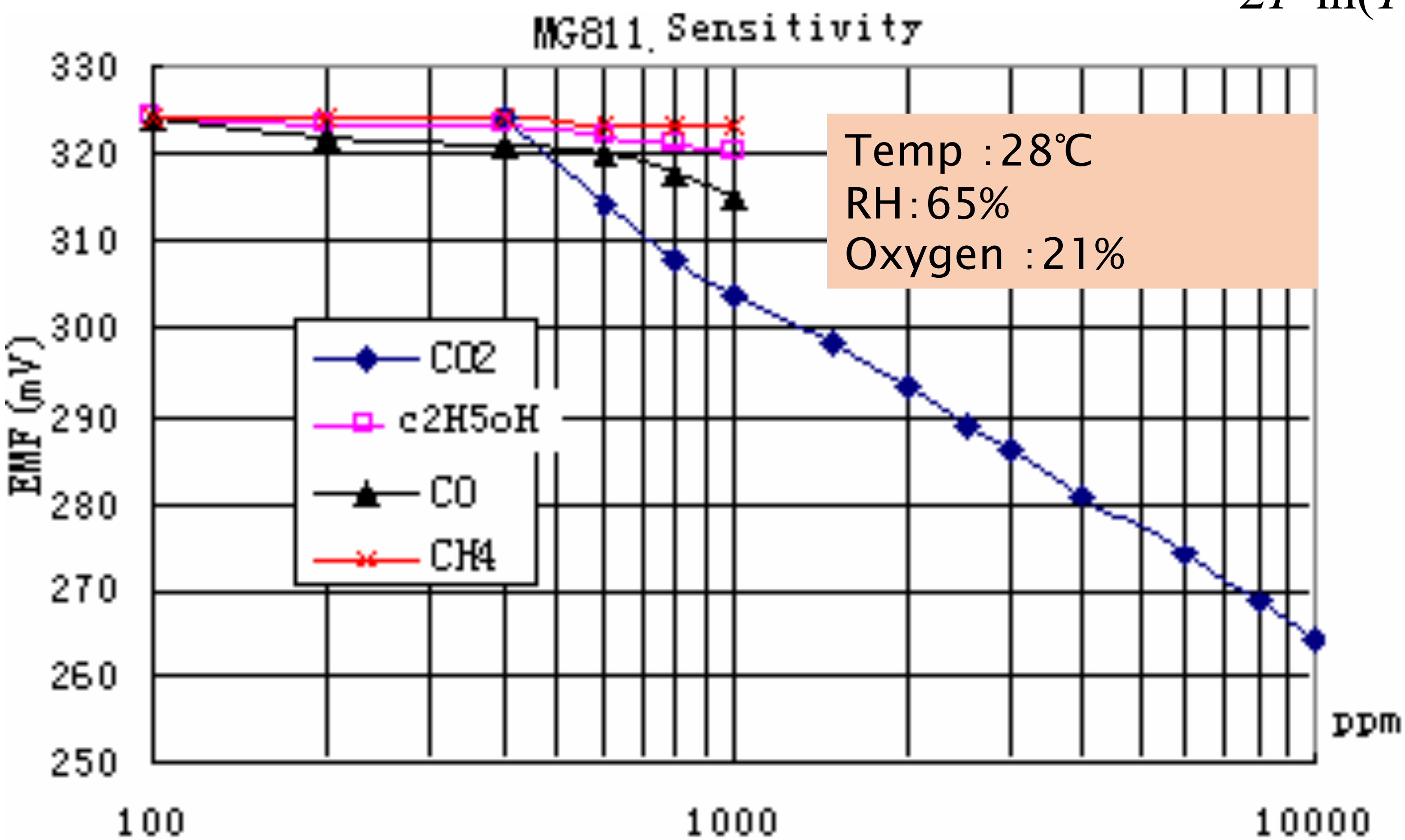
- $\text{ppm} = (0.01) * 10^6 = 10^4$

- Partial pressure of CO_2 = 0.01*101.325 kPa = 1013.25 Pa

- $$\text{Mass per volume} = \frac{PM}{RT} = \frac{(1013.25\ \text{Pa})(44\ \text{g/mol})}{\left(8.31447\ \frac{\text{m}^3 \cdot \text{Pa}}{\text{K} \cdot \text{mol}}\right)(298.15\ \text{K})} = 18\ \text{g/m}^3$$

Example Sensor MG811

$$EMF = E_c - \frac{RT}{2F\ln(P_{CO2})}$$



http://www.futurlec.com/CO2_Sensor.shtml

HUMIDITY SENSOR

What is humidity (relative humidity)?

$$\varphi = \frac{e_w}{e_w^*} \times 100\%$$

e_w : partial pressure of water vapor

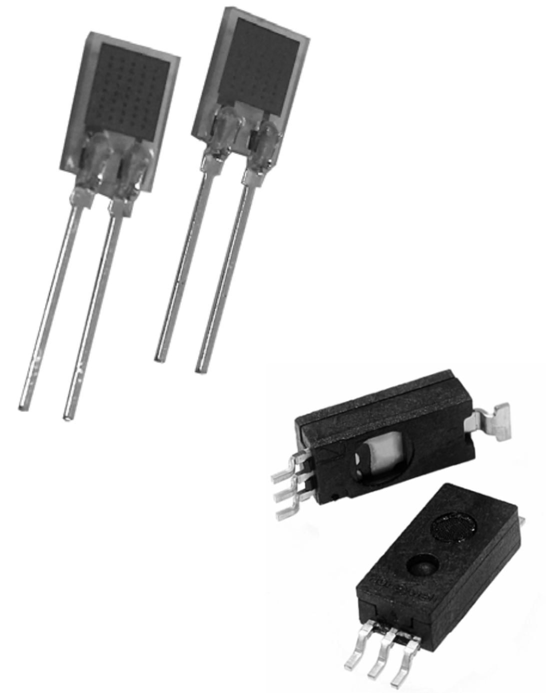
e_w^* : saturated vapor pressure of water at a prescribed T

maximum water vapor that the air can hold without condensing

$e_w^* = f(T, P)$ empirically correlated

http://en.wikipedia.org/wiki/Relative_humidity
http://en.wikipedia.org/wiki/Hygrometer

HUMIDITY SENSOR



Relative humidity measurement (%RH)

- Capacitive
- Resistive

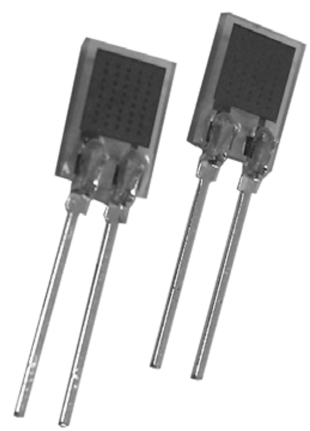
Examples:

- http://media.digikey.com/pdf/Data%20Sheets/Honeywell%20Sensing%20&%20Control%20PDFs/HCH-1000%20Series.pdf
- http://www.sparkfun.com/datasheets/Sensors/Weather/SEN-09569-HIH-4030-datasheet.pdf

HUMIDITY SENSOR

Capacitive RH sensor:

- Dielectric constant of a polymer or inorganic material changes as it absorbs water vapor
- Dielectric constants: 80 (water) vs. 3.4 (polyimide)
- More water → more capacitance?
- How to measure capacitance?



HUMIDITY SENSOR

Resistive RH sensor:

- Electrical resistance of a material changes as it absorbs water vapor
- Typical materials: salts, conductive polymers
- Less sensitive than capacitive RH sensors
- Material properties also tend to depend both on humidity and temperature (in practice, must be combined with temperature sensor)

PRESSURE SENSOR

- What is pressure?

  e.g. atmospheric pressure at sea level is 101.325 kPa

  e.g. tire pressure gauge reads 0 PSI

  e.g. pressure drop for flow measurement

- What kind of pressure do you want to measure?
  - Absolute pressure sensor
  - Gauge pressure sensor
  - Differential pressure sensor

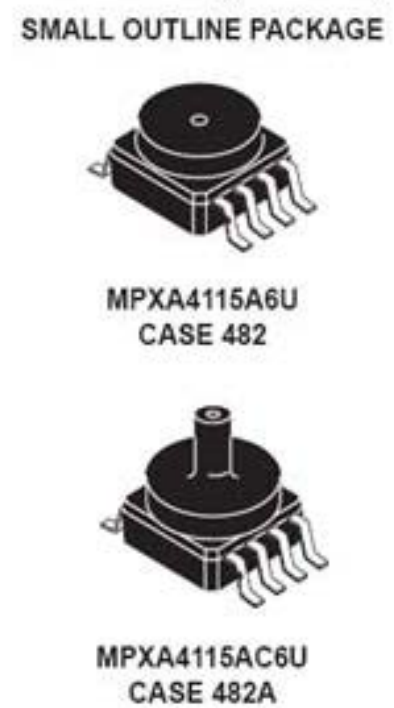
TYPES OF PRESSURE SENSORS

- Force-based
  - Piezoresistive strain gauge
  - Potentiometric
  - Piezoelectric
  - Capacitive

- Other kinds
  - Resonance (MEMS)
  - Thermal (Pirani gauge)

http://en.wikipedia.org/wiki/Piezoresistive
http://www.maxim-ic.com/app-notes/index.mvp/id/871

SENSOR EXAMPLE: MPXA6115A



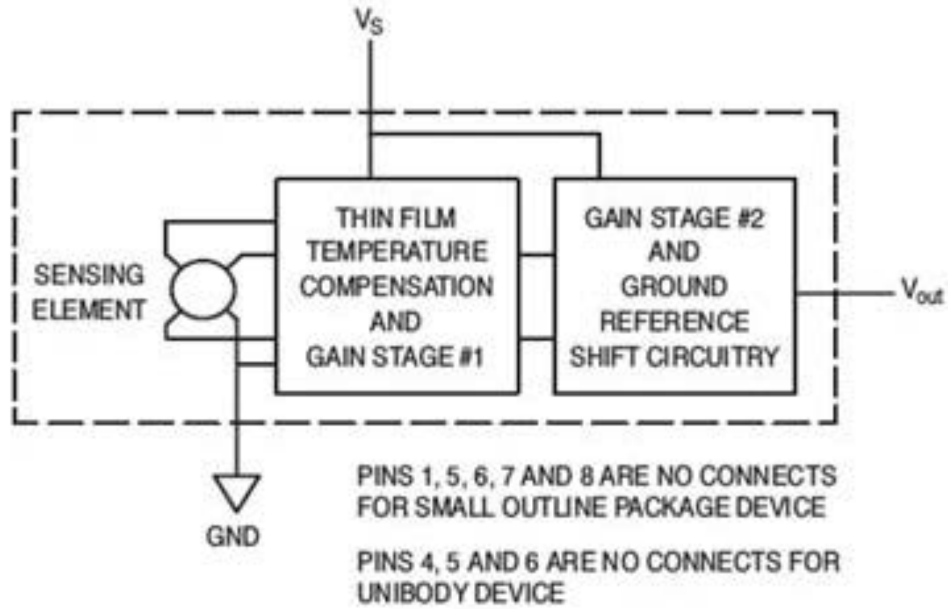


Figure 1. Fully Integrated Pressure Sensor Schematic

Features

- 1.5% Maximum Error over 0° to 85°C
- Ideally suited for Microprocessor or Microcontroller–Based Systems
- Temperature Compensated from –40° to +125°C
- Durable Epoxy Unibody Element or Thermoplastic (PPS) Surface Mount Package

http://shops.eccn.com/freescale/PDFDoc/MPXH6115A6U.pdf

CHARACTERISTICS OF PRESSURE SENSOR:

- **Pressure range:** 15-115 kPa
- **Sensitivity:** 45.9mV/kPa
- **Supply voltage:** 5V
- **Output analog voltage:**
  - Offset voltage (V_{off}): output voltage at minimum rated pressure (Typical@ 0.204V)
  - Full scale output (Vfso): output voltage at maximum rated pressure (Typical@ 4.794 V)
- **Pressure units**
  - Pascal (Pa)=N/m^2: standard atmosphere P_0=101325=101.325kPa
  - Psi= (Force) pound per square inch: 1 Psi=6.89465 KPa

PRESSURE SENSORS FOR ALTITUDE SENSING

$$P \cdot V = nRT \qquad \text{"ideal gas law"}$$

$$\rho = \frac{\text{mass} = nM}{\text{volume} = \frac{nRT}{P}} = \frac{M \cdot P}{R \cdot T}$$

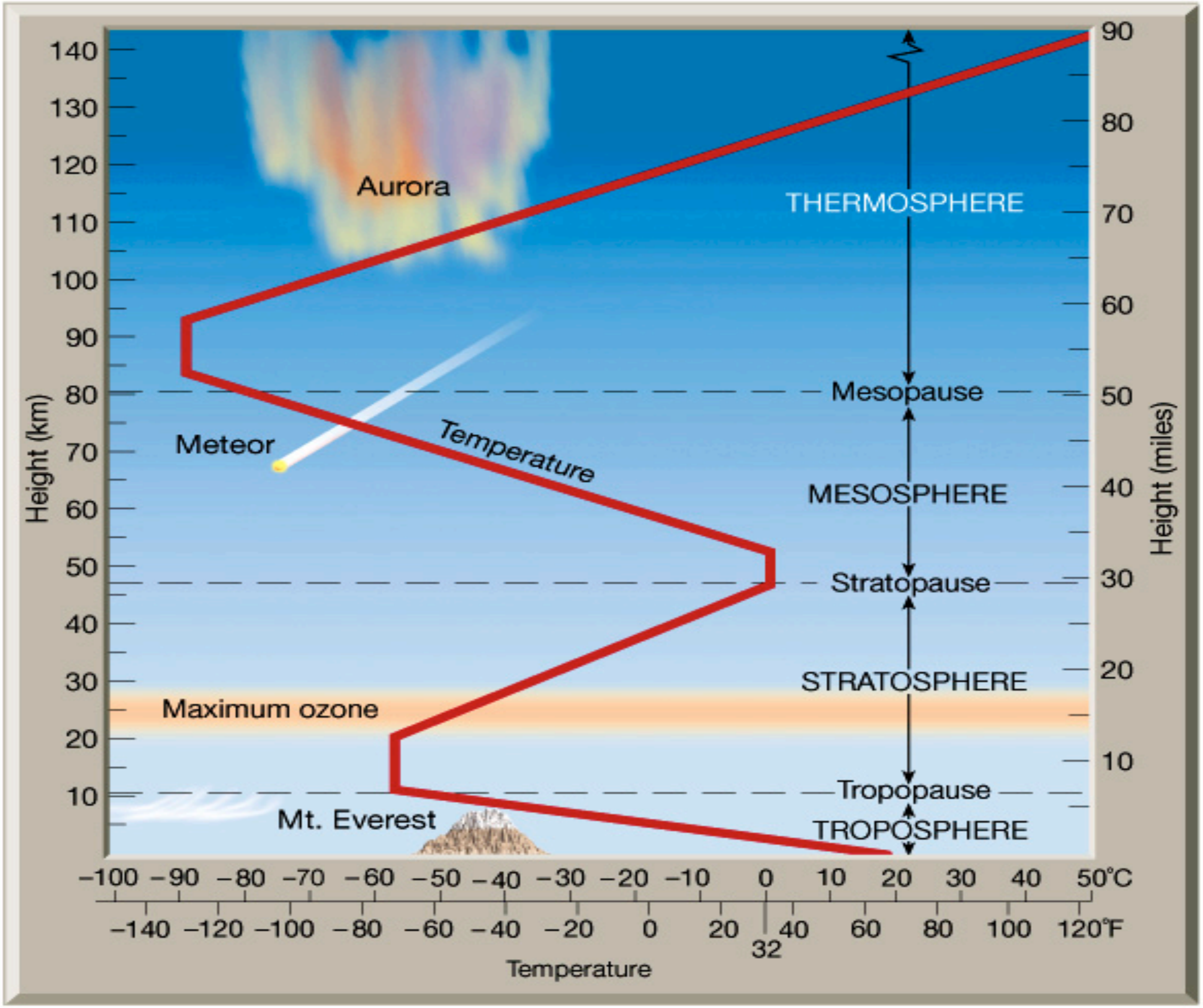
Method #1: $$\Delta P = -\rho g \cdot \Delta h = -\frac{MP}{RT} g \cdot \Delta h$$

Method #2: $$P(h) = P_0 \exp\left(-\frac{Mg}{RT} h\right)$$

M: Molar Mass
n: Number of moles
T: Temperature
P: Pressure
h: Altitude

http://en.wikipedia.org/wiki/Gas_constant

PRESSURE SENSORS FOR ALTITUDE SENSING



PRESSURE SENSORS FOR ALTITUDE SENSING

Method #3:

$$h = \frac{T_0}{-\left(\frac{dT}{dh}\right)} \cdot \left[1 - \left(\frac{P_0}{P}\right)^{\frac{\left(\frac{dT}{dh}\right)R}{gM}}\right]$$

where

- h = altitude (above sea level) **(in meters)**
- P_0 = standard atmosphere pressure= 101.325kPa
- T_0 = 288.15K (+15°C)
- dT/dh= - 0.0065 K/m: thermal gradient or standard temperature lapse rate
- R = gas constant (8.31432 N*m/mol*K)
- g = (9.80665 m/s²)
- M = molar mass of earth's air (0.0289644 kg/mol)

PRESSURE SENSORS FOR ALTITUDE SENSING

Plug in all the constants

Method #3:

$$h = 4.43 \times 10^4 \times \left(1 - \left(\frac{101.325\text{kPa}}{P} \right)^{-0.1902} \right)$$

- h is measured **in meters.**
- Equation calibrated up to 36,090 feet (11,000m).
- Reference: http://en.wikipedia.org/wiki/Atmospheric_pressure
- Different values of dT/dh for different layers of the atmosphere

EXAMPLES

Suppose, **P = 85 kPa** (from Pressure sensor)

Method 1:

$$\Delta h = -\frac{\Delta P}{\rho g} = -\frac{(85-101)kPa}{(1.2\frac{kg}{m^3} * 9.8\frac{m}{s^2})} = 1.36\ km$$

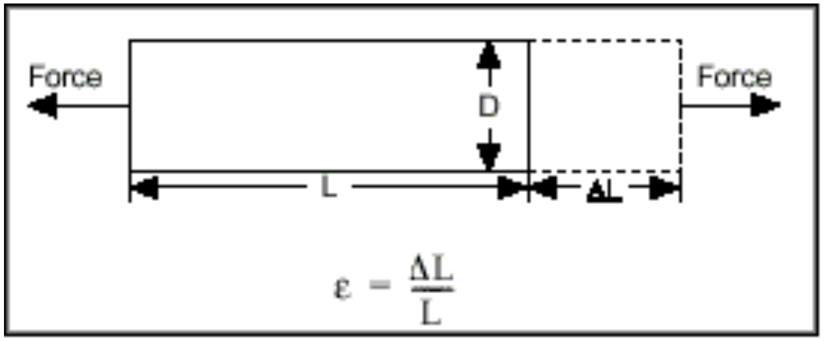
Method 2:

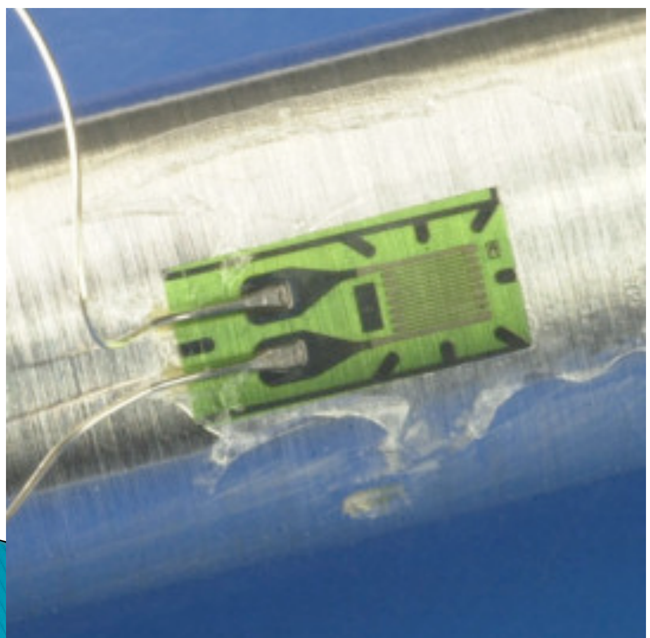
$$h = -\frac{RT}{Mg}\ln(\frac{P}{P_0}) = -8440\ln(\frac{85kPa}{101kPa}) = 1.46km$$

Method 3:

$$h = 4.43\times 10^4 \times \left(1-\left(\frac{101.325kPa}{85kPa}\right)^{-0.1902}\right) = 1.43\,km$$

VIBRATION/IMPACT SENSOR





Mechanical force/ deformation
→ resistance/ voltage output

Examples:

- Strain gauges
- Piezoelectric films

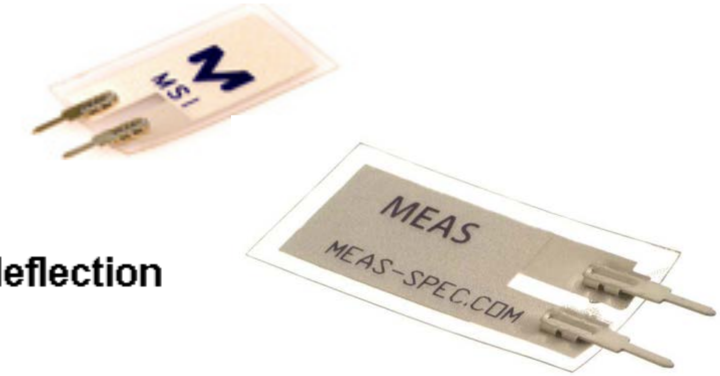
http://www.digikey.com/Scripts/US/DKSUS.dll?Detail&name=MSP1006-ND

http://en.wikipedia.org/wiki/Strain_%28physics%29

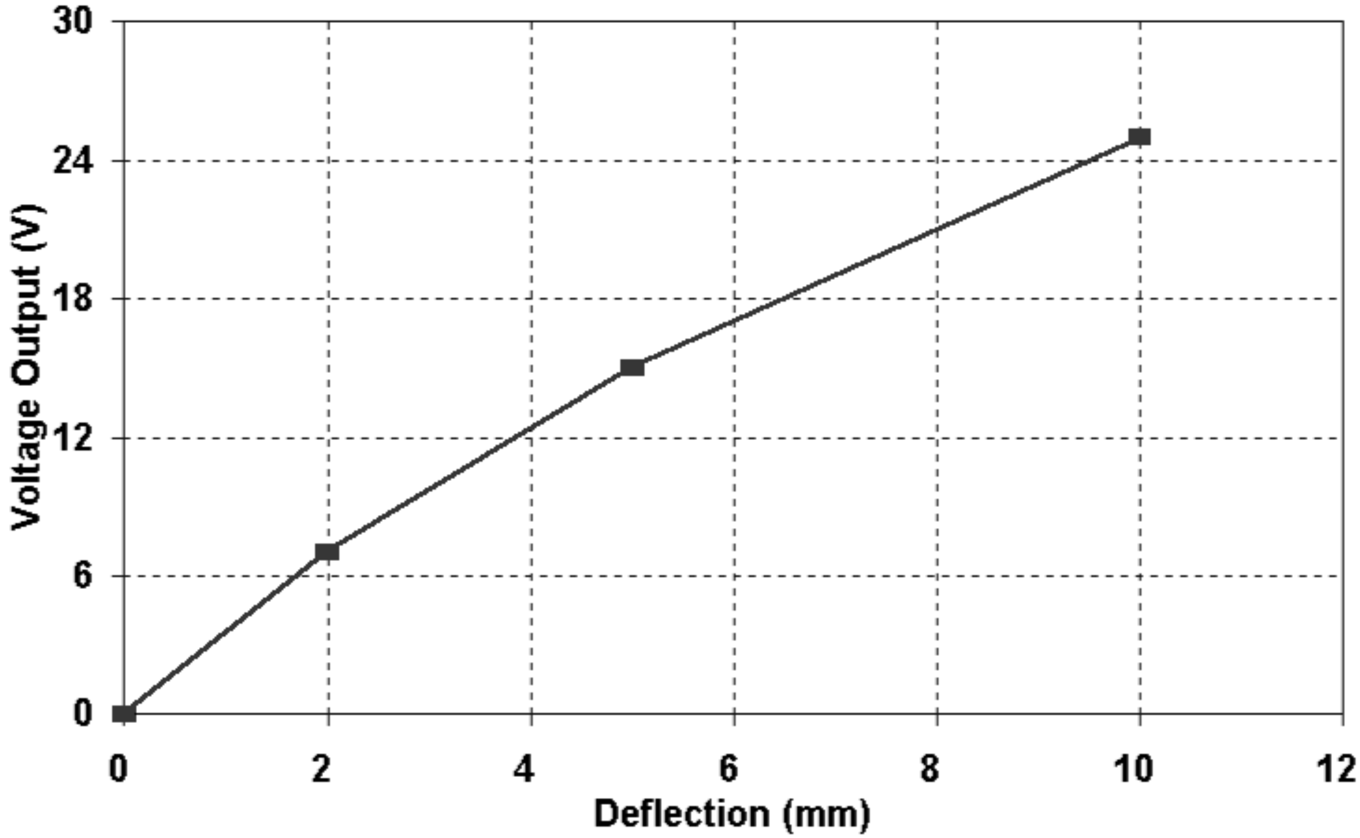
http://www.vishaypg.com/micro-measurements/transducer-class-strain-gages/

http://www.sparkfun.com/datasheets/Sensors/Flex/MSI-techman.pdf

VIBRATION SENSOR



LDT0: Voltage Output vs Tip deflection
(Figure 2)



http://www.meas-spec.com/downloads/LDT_Series.pdf

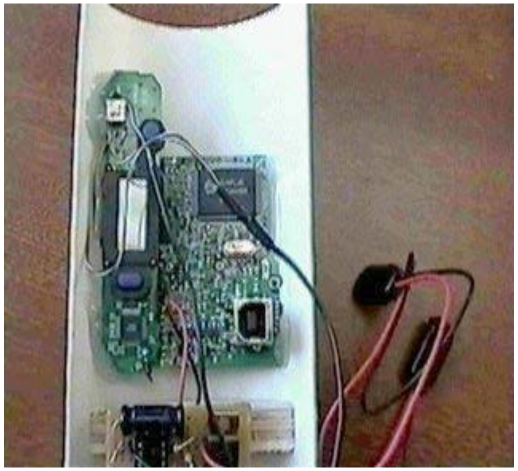
ACCELEROMETERS AS VIBRATION SENSORS

- http://www.sparkfun.com/tutorials/167
- http://www.sparkfun.com/datasheets/Components/General/MMA7361L.pdf

- Full-scale range
- Number of axes
- Interface (analog, digital, pulse output)
- Bandwidth (50-100 Hz)
- Power consumption (supply voltage)

NOW WHAT?

(1) Electronics should fit within rocket
(2) Easy to transmit/store/retrieve data
(3) Telemetry
(4) Video system



http://www.sparkfun.com/products/9228
http://www.sparkfun.com/products/10216

http://www.youtube.com/watch?v=f0Qr1g70aOg&feature=related
http://www.youtube.com/watch?v=2Ax64jfeVCc