Barometry

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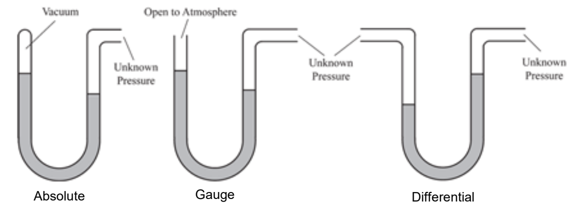
Photo: http://www.rivercityclocks.com/

Pressure Definitions



Absolute pressure
- Total static pressure exerted by gas/fluid
- Barometric pressure

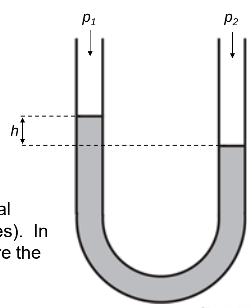
Gauge pressure
- Pressure relative to atmospheric pressure
- e.g., pressure in a tire

Differential pressure
- Pressure relative to another pressure
- Gauge pressure is a special case of differential pressure

Let's make an instrument: Manometer

$$h = \frac{p_2 - p_1}{\rho_{\text{fluid}}\, g}$$

p_1 – ambient pressure (not necessarily atmospheric pressure)
p_2 – gauge pressure

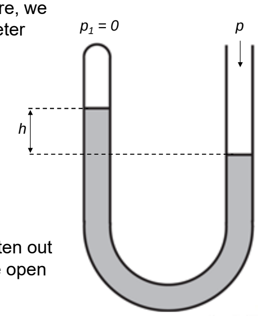


Here, we're measuring differential pressure (two unknown pressures). In meteorology, we want to measure the absolute pressure…

Let's make an instrument: Manometer

To measure atmospheric pressure, we close off one end of the manometer tube.

$$h = \frac{p}{\rho_{\text{fluid}}\, g}$$



In normal operation, we straighten out the tube, invert it, and place the open end in a reservoir of mercury

Mercury Barometers

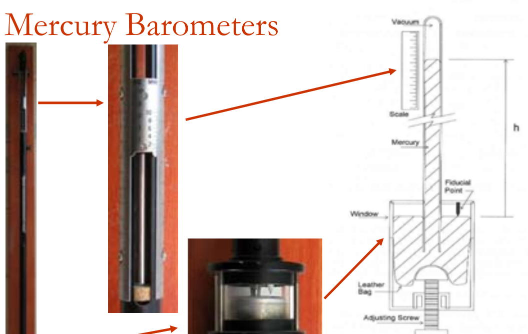


Fig. 2-2 A simple mercury barometer.

Mercury (Fortin) Barometers

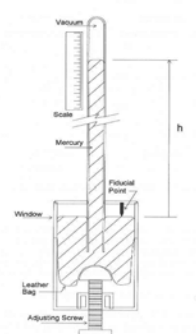
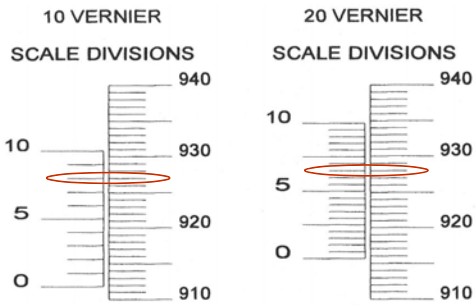


Fig. 2-2 A simple mercury barometer.

- The Fortin design:
  - Level of cistern maintained at zero of scale
    - High accuracy
    - Easy calibration
  - Mercury enclosed in a glass tube that is sealed at the top
    - Almost a vacuum
    - Pressure = vapor pressure of Hg + residual gas
  - Mercury reservoir at the bottom
  - Level of mercury in reservoir is adjusted to a reference (fiducial) point

Vernier Scale



What is the reading for each of these vernier scales?
No peaking…

Mercury Barometer Errors:
Non-uniformity of temperature

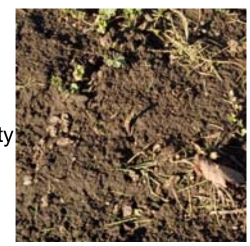
- Mercury is used in thermometers because it expands and contracts with changes in temperature
- Temperature gradients along the mercury column can vary that expansion or contraction in an unknown manner
- Most Fortin barometers are housed in a closed environment to prevent temperature (but not pressure) fluctuations

← This barometer is enclosed in a case

http://www.physics.indiana.edu/~meyer1/historinstr/other.html

Mercury Barometer Errors:
Dirt

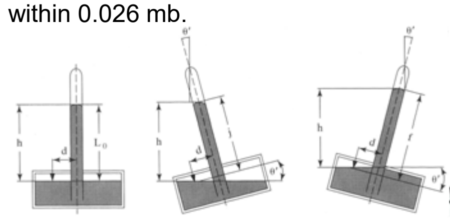
- Dirty mercury
  - Difficult to see when the fiducial point touches the mercury
  - Hard to read the meniscus
  - Impurities can affect density
- Dirty scale
  - Hard to read the scale
  - Corrosion could affect the expansion coefficient



http://www.psych.ndsu.nodak.edu/brady/

Mercury Barometer Errors:
Barometer not mounted vertically

- Typically small errors
- At 1000 mb, barometer must be kept within 1.5 mm of vertical in order to keep error to within 0.026 mb.

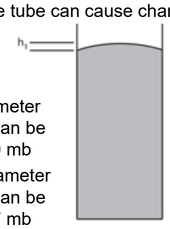


Mercury Barometer Errors:
Gas in the vacuum space

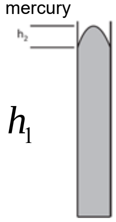
- The pressure of any gas in the vacuum space will tend to counteract the pressure being exerted by the atmosphere
- If we tilt the barometer, a true vacuum won't create a bubble
- What can get in there?
  - Mercury vapor – very small error (low vapor pressure)
  - Air
  - Water vapor – potentially large error
    - 10 μg of water vapor can potentially cause a 2.3-mb error at normal atmospheric pressures

Mercury Barometer Errors:
Capillary depression of the mercury surface

- This error is typically small and known
- Narrowing of the tube can cause changes to the mercury meniscus



$h_2 > h_1$



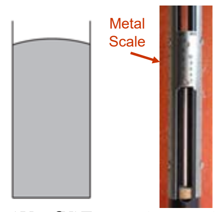
- For a 5 mm diameter tube, the error can be as large as 2.00 mb
- For a 13 mm diameter tube, the error can be as large as 0.27 mb
- Correction for this error is incorporated into the index correction

Mercury Barometer Errors:
Index Correction

- The index correction (C_x) is a table of corrections that account for slight imperfections of the tube diameter and vacuum that are inevitable during manufacture
- Values are supplied to the user by the manufacturer
  - Assume C_x = 0 if not specified
- Values are found by calibrating the instrument with a reference instrument

Mercury Barometer Errors:
Temperature Correction

- Changes in temperature can affect the expansion and contraction of the mercury column and the attached metal scale



$$C_T = -p_1(\beta - \alpha)T$$

The pressure error is a function of the difference between the change in the column height and linear expansion of the scale due to changes in temperature.

Here, T is the temperature in °C and p_1 is the measured pressure.

$\Delta V = \beta V \Delta T$ $\Delta L = \alpha L \Delta T$

Mercury Barometer Errors:
Correctable Error

- Now we have two corrections that we can apply to improve the pressure measurement:

$$p_2 = p_1 + C_X + C_T$$

p_1 = Barometer reading
C_X = Index correction
C_T = Temperature correction

But wait, there's more… Watch this!

http://www.atmospheric-violence.com/

Mercury Barometer Errors:
Gravity Correction

- Gravity is not constant!
  - We must correct for local gravity with respect to gravity at mean sea level

$$C_G = p_2\left(\frac{g_L - g_0}{g_0}\right) \qquad g_0 = 9.80665\ \frac{\text{m}}{\text{s}^2}$$

  - Local gravity, g_L, changes with elevation:

$$g_L = g_\phi - 3.086\times10^{-6}z + 1.118\times10^{-6}(z - z')$$

z = barometer elevation (m)
z'= mean elevation (m) within a 150 km radius

  - Since Earth is not a sphere, gravity at sea level varies with latitude, ϕ:

$$g_\phi = 9.80616\left[1 - 2.6373\times10^{-3}\cos(2\phi) + 5.9\times10^{-6}\cos^2(2\phi)\right]$$

Mercury Barometer Errors:
Correctable Error

- The best estimate of surface pressure is then:

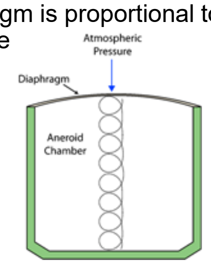
$$p_{sfc} = p_1 + C_X + C_T + C_G$$

p_1 = Barometer reading
C_X = Index correction
C_T = Temperature correction
C_G = Gravity correction

Aneroid Barometer

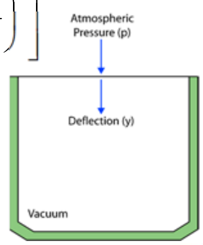
- Aneroid: without fluid
  a- (without) + nero- (water) + -oid (resembling)
- Evacuated chamber with a flexible diaphragm
- Deflection of diaphragm is proportional to atmospheric pressure

The spring keeps the diaphragm from collapsing



Aneroid Barometer
Calibration equation for a flat diaphragm

$$p = \frac{16Et^4}{3R^4(1-v^2)}\left[\frac{y}{t} + 0.488\left(\frac{y}{t}\right)^3\right]$$



p = pressure (Pa)

E = modulus of elasticity (N m^{-2})

y = deflection of the diaphragm center (m)

t = diaphragm thickness (m)

R = diaphragm radius (m)

v = Poisson's ratio (related to ratio of lateral to axial strain) ≈ 1/3 for metals

Aneroid Barometer
Calibration equation for a flat diaphragm

- Define the deflection ratio as the ratio of the diaphragm deflection to the diaphragm thickness:

$$y_r = \frac{y}{t}$$

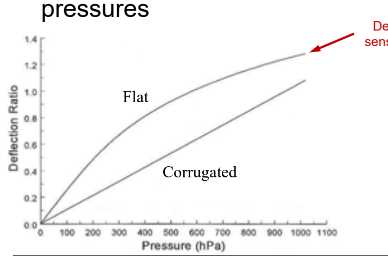
- Substitute into calibration equation for flat diaphragm aneroid cell:

$$p = C_0\left[y_r + C_1 y_r^3\right]$$

  - C_0 and C_1 are the constant values from the calibration equation
- The relationship between y_r and p is non-linear

Aneroid Barometer
Static sensitivity

- Adding corrugations vastly improves linearity and increases static sensitivity at higher pressures



Corrugated Diaphragm

Aneroid Barometer
Transfer equation for a corrugated diaphragm

$$y_r = \frac{y}{t} = \frac{2.25\times10^5 D(1-v^2)}{tE}\left(1000\frac{t}{D}\right)^{-1.52} p$$

p = pressure (Pa)

E = modulus of elasticity (N m^{-2})

y = deflection of the diaphragm center (m)

t = diaphragm thickness (m)

R = diaphragm radius (m)

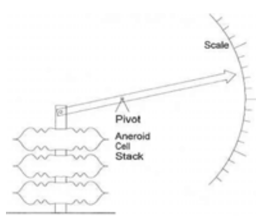
v = Poisson's ratio (related to ratio of lateral to axial strain) ≈ 1/3 for metals

D = 2*R*

$$y_r \sim (\text{constant})\, p$$

Aneroid Barometer
Mechanical Output

Deflection of a single aneroid is typically small; multiple chambers amplify the deflection



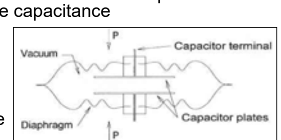
Aneroid Barograph

Aneroid Barometer
Electrical Output

- Piezoresistor
  - Resistance changes in response to an applied force that deforms the resistor
- Capacitive transducer
  - As diaphragm deflects, the distance between capacitor plates changes, changing the capacitance

$$C = \frac{\varepsilon_0 A}{d}$$

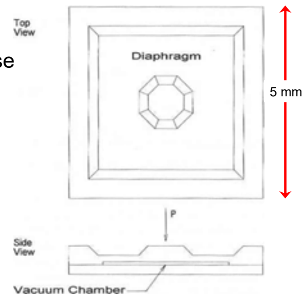
  - *C* = capacitance
  - ε_0 = permittivity of free space
  - *A* = area of plate
  - *d* = distance between plates



Aneroid capsule with a capacitive transducer

Aneroid Barometer
Electrical Output

- Most barometers in use today are aneroid
  - Silicon diaphragm
  - Very small
  - Low leakage (excellent vacuum)
  - Linear deflection
  - Can compensate for temperature-induced errors (mostly)



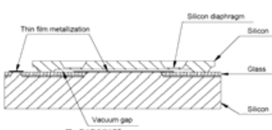
Aneroid Barometer
Vaisala PTB101B Pressure Transmitter

Uses a silicon capacitive pressure transducer

Current Barometric Measurements

ASOS: Setra Model 470

Range: 600–1100 mb
Inaccuracy: ±0.02% full scale
Resolution: 0.01 mb



Inside the Vaisala PTB220

Oklahoma Mesonet: Vaisala PTB220

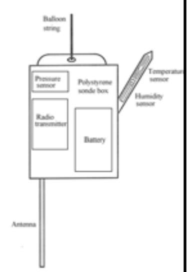
Range: 500–1100 mb
Inaccuracy: ±0.25 mb
Resolution: 0.1 mb

Current Barometric Measurements

Vaisala RS80 Radiosonde

Range: 3–1060 mb
Inaccuracy: ±0.5 mb
Resolution: 0.1 mb

Used in twice daily NWS soundings



Vaisala's latest radiosonde: RS92

Dynamic Wind Effects

- We usually want to measure only the static pressure
- Dynamic pressure affects all barometers and is due to air motion around the barometer
- To avoid the influence of pressure variations inside buildings (due to ventilation systems, open windows, closing doors, etc.), these errors can be reduced using a pressure vent to the outside (a static port)

Dynamic Wind Effects

$$\Delta p = p - p_s = \frac{1}{2} C \rho V^2$$

- ρ is the air density
- V is the fluid speed
- C is the pressure coefficient
  - Usually close to unity
  - Positive or negative
  - Depends on shape of barometer and wind direction
  - Accounts for problems coupling the sensor to the atmosphere
- p is the pressure measured at the sensor
- p_s is the ambient atmospheric pressure

Dynamic Wind Effects

- Dynamic wind effects are responsible for large pressure errors (an exposure error)
- Consider this…

  You are driving a mobile mesonet vehicle at 25 m s^{-1} into a rear flank downdraft that has a surface wind speed of 30 m s^{-1} (directly toward the vehicle). What is the dynamic wind error in the pressure measurement? (Let C=1)

This is a huge error!

Static Pressure Port

We need a device that will remove the dynamic wind effects and will allow a measurement of static pressure without error

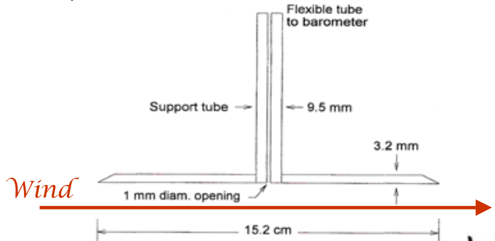
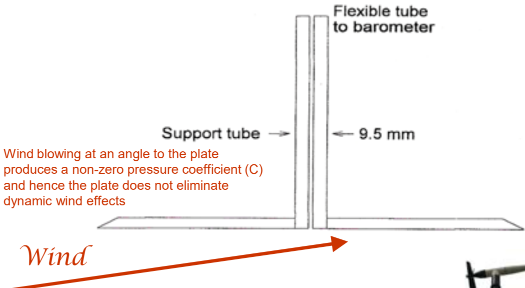


Fig. 2-13 Cross-section of a flat-plate static port.

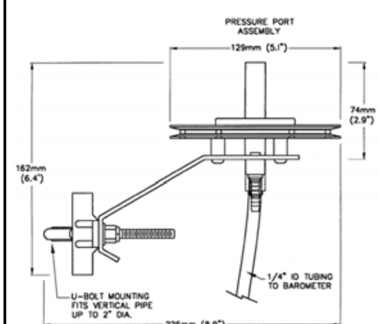
Static Pressure Port

This is nice, but the flat plate has a problem when the wind is incident upon the port at an angle



Wind blowing at an angle to the plate produces a non-zero pressure coefficient (C) and hence the plate does not eliminate dynamic wind effects

Dual-Plate Static Pressure Port



To improve upon this direction problem, engineers devised a dual-plate port

- Used in buoys
- Mounted vertically
- Better error results

Quad-Plate Static Pressure Port

Another design further reduces angle errors

- Used in VORTEX
- Mounted upside down
- Even better error results