AEM 617

Aircraft Systems

Spring 2016

Skills Quiz ~~Friday~~ Wednesday: 20 minutes

- Fundamentals of Engineering
  - Fluids
  - Mechanics (statics, dynamics)
  - Electrical
  - Controls
- Statistics
- Aircraft Identification

Aircraft Systems:

Flight Control

Fuel

Hydraulics

Electrical

Avionics

ECS (Environmental Control System)

Mission Systems

⋮

pilot, crew, ...

ATC

⋮

Development

Testing

procurement

Maintenance

$\boxed{\text{Everything is a system}}$

What makes something good?

When it does what it ought to do

Does a cell phone make a good hammer?

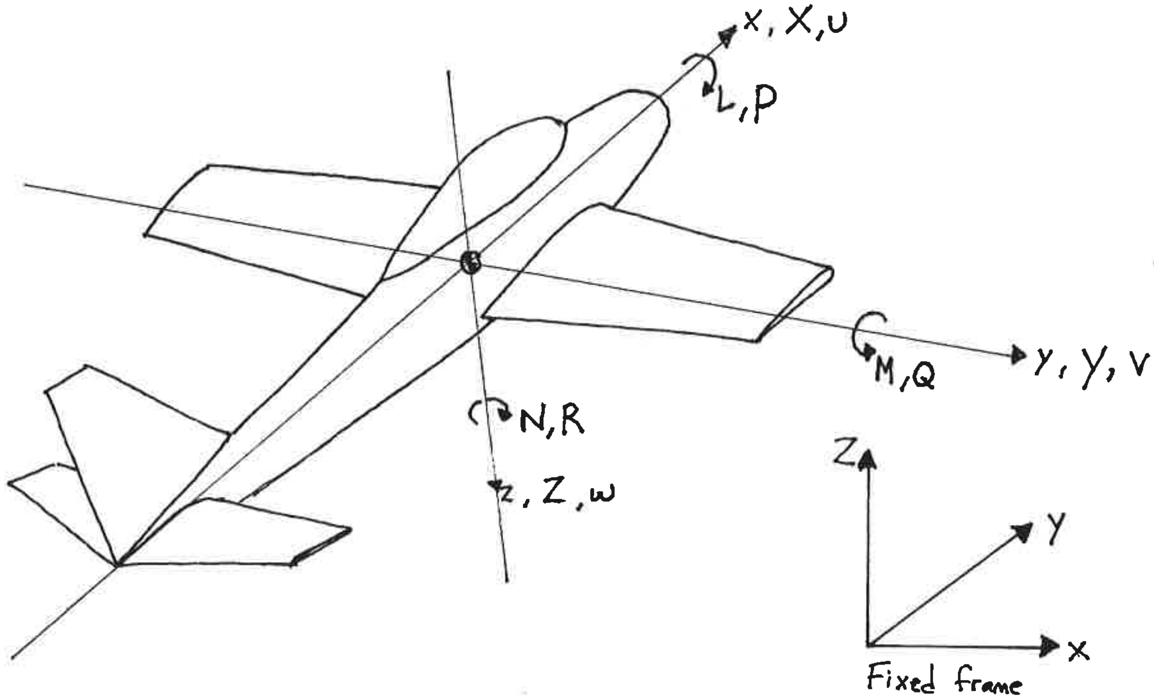
No. The nail is not driven and the phone is destroyed.

What makes a good teacher?

If a man is truly learning, he becomes more and more humble as he studies
He sees new avenues of knowledge down which he might travel for a lifetime.

— F. Sheen

Aircraft Coordinate System



x, y, z	Aircraft "stability" frame location
X, Y, Z	Forces in stability frame
u, v, w	Velocity in stability frame
L, M, N	moment in stability frame
P, Q, R	Angulor velocities (roll, pitch, yaw)
ϕ, θ, ψ	Euler angles (orientation)

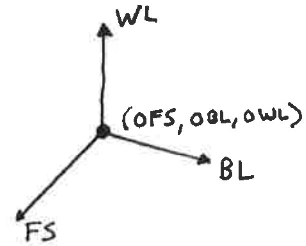
Warning:

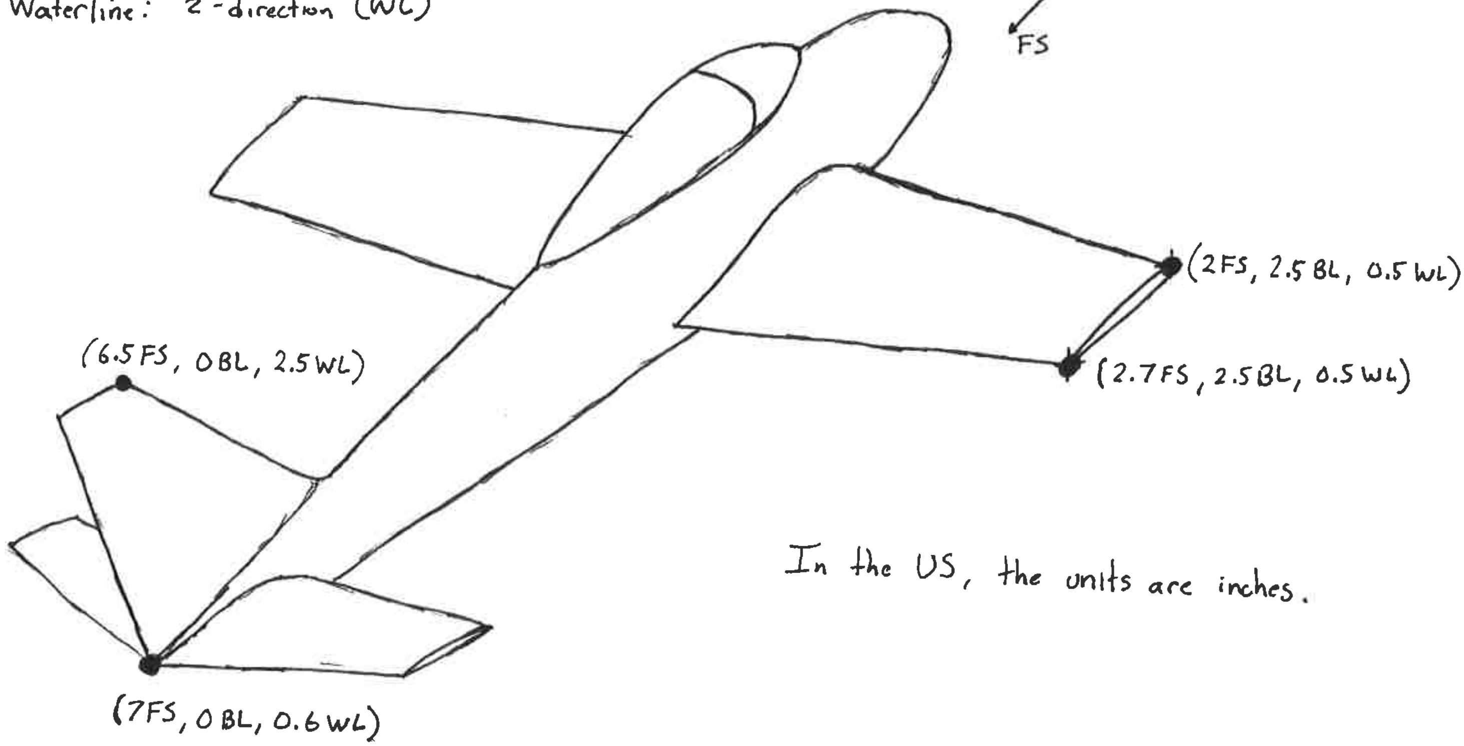
Outside of aerodynamics, the x axis is usually down the length of the a/c.

$$X_{loft} = -X_{aero\ stability}$$
$$Y_{loft} = Y_{aero\ stability}$$
$$Z_{loft} = -Z_{aero\ stability}$$

Locations on an Aircraft (Aircraft Station Coordinates)

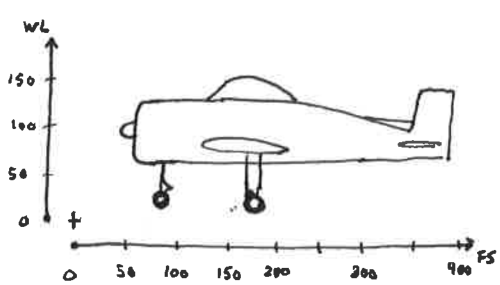
- Fuselage Station: along fuselage (x-direction) (FS)
- Butt line: y-direction (BL)
- Waterline: z-direction (WL)

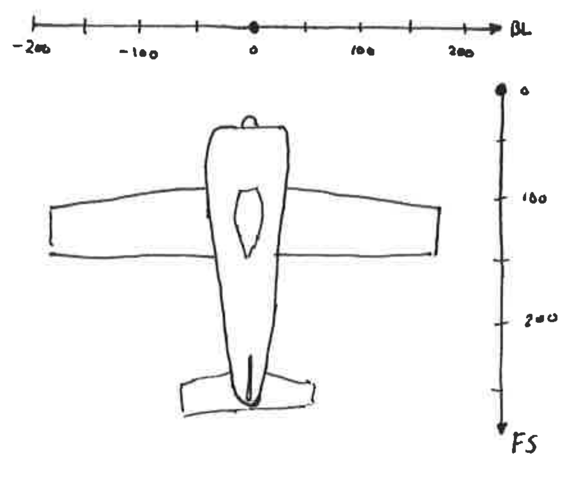




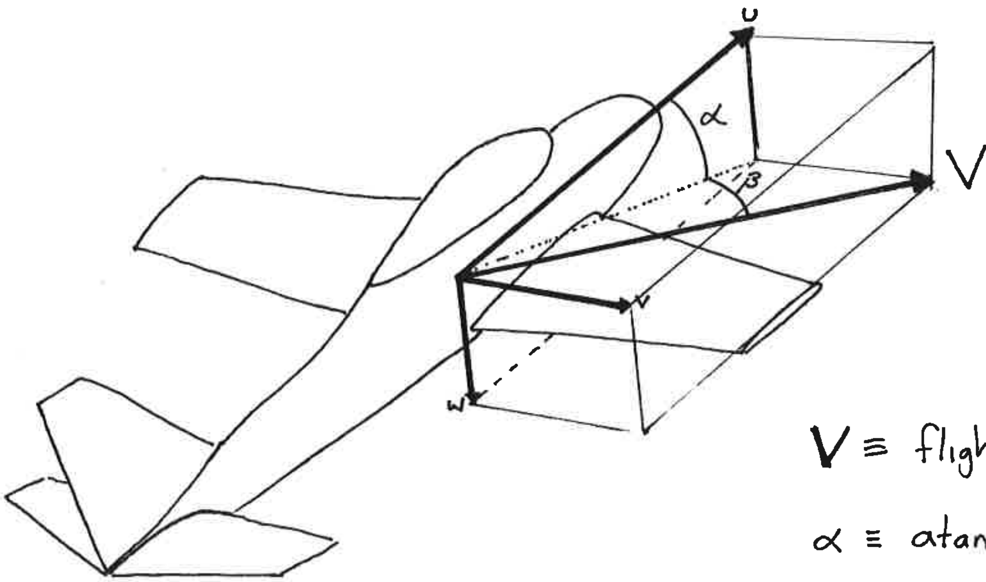
In the US, the units are inches.

- Zero FS is usually not the most forward location of the aircraft. Rather the origin is placed arbitrarily forward such that negative FS does not occur.
- Zero BL is usually along the centerline
- Zero WL is usually placed such that all values are positive





Angle of Attack and Sideslip



$\mathbf{V} \equiv$ flight velocity vector

$\alpha \equiv \operatorname{atan}\left(\frac{w}{u}\right)$ Angle of Attack

$\beta \equiv \operatorname{asin}\left(\frac{v}{\mathbf{V}}\right)$ Sideslip

α is defined wrt the projection of V onto the body fram (i.e. u)

β is defined wrt the v projection and V.

Wing:

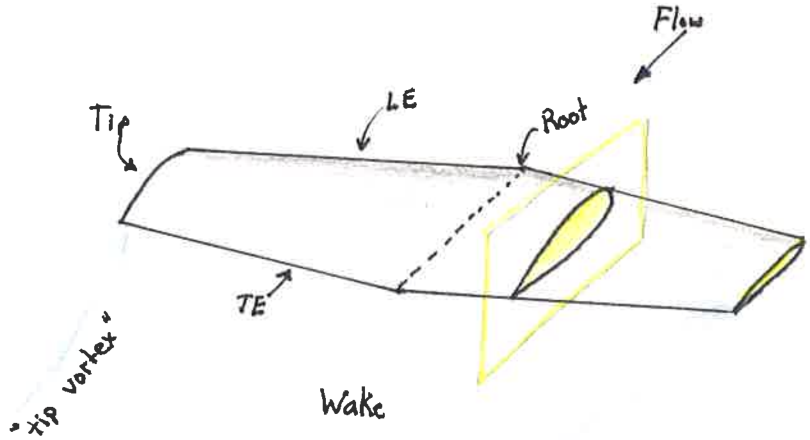
- Three dimensional closed surface
- Generates aerodynamic force
- Cross sections are airfoils

Etymology:

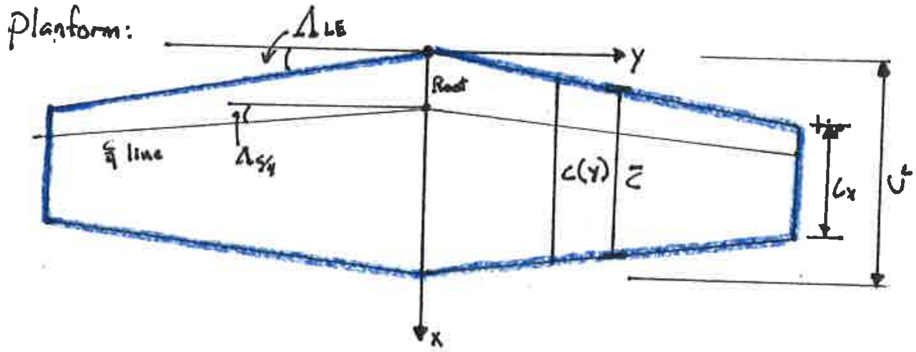
wing — English
↓
wenge — middle English
↓
Vaenger — Norse
↓
we-ingyaz — Old German
↓
we (to blow) — Indo-European

vent (english) → vent (Latin) → we

Interestingly, not from Indo-European word for "fly" which is "peth" from which we get "feather" and "pen".



Planform:



$S \equiv$ Wing Area $[L^2]$

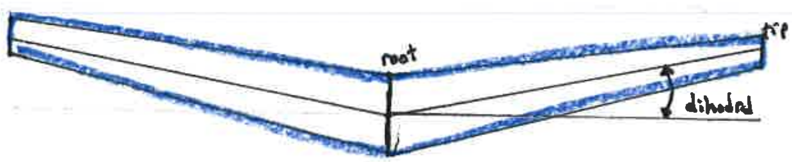
$b \equiv$ Span $[L]$

$c \equiv$ chord

$AR \equiv$ Aspect Ratio $\equiv \dfrac{b^2}{S}$

$\lambda \equiv$ taper ratio $\equiv \dfrac{c_t}{c_r}$, $\left(\dfrac{\text{tip}}{\text{root}}\right)$

Front view

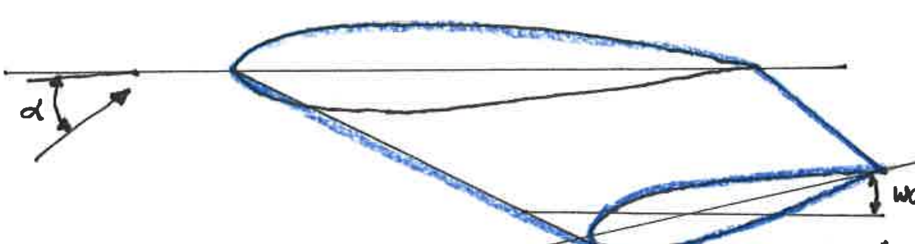


MAC $\equiv$ Mean Aerodynamic Chord $\equiv$

$$\frac{1}{S}\int_{-b/2}^{b/2} c(y)^2\,dy$$

$\bar{c} \equiv$ Average Chord

Side view

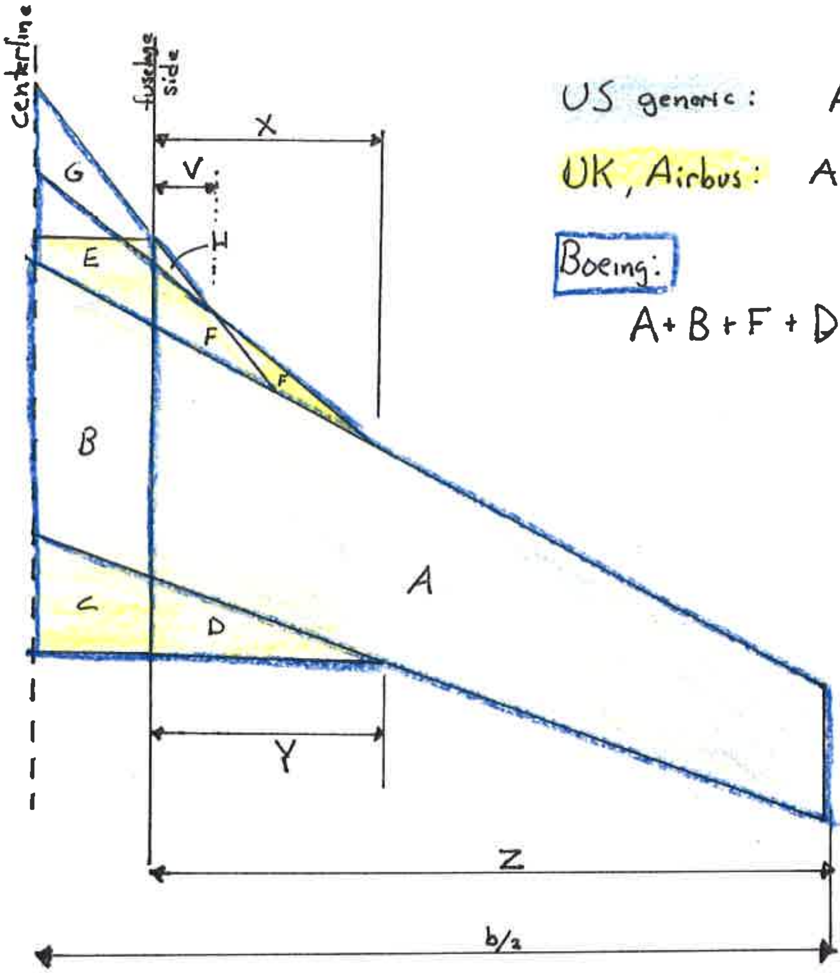


wash out $\equiv$ decrease in incidence angle at tip

"wash in" is a positive increase ... usually a bad idea

Wing Reference Area

ADTA p 269



US generic: $A + B$

UK, Airbus: $A + B + C + D + E + F + H$

Boeing:

$$A + B + F + D + H + \frac{X}{Z}E + \frac{Y}{Z}C + \frac{V}{Z}G$$

Or, S could be a planform projection from a CAD model.

Or, S could be the reference area of a previous version (i.e. historical).

Why is this important?

- Single most important ref #
- Compare performance

The atmosphere on Earth

Dry Air (= Atmospheric air − H_2O − contaminants (dust, pollen, …))

	Mole Fraction	Molecular Weight $\frac{kg}{kmol} = \frac{lbm}{lbmol}$	
Nitrogen	78.08%	28.02	$N \equiv N$ strong triple bond!
Oxygen	20.95%	32.0	$O = O$ double bond
Argon	0.93%	39.94	Greek αργον "inactive" Ar no bond
Carbon Dioxide	0.03%	44.01	$O = C = O$ linear shape double bond
Other	0.01%		
	100%		

Apparent Molecular Weight $= \sum a_i M_i$

$$M \approx 28.02 \cdot 0.7808 + 32.0 \cdot 0.2095 + 39.94 \cdot 0.0093 + 44.01 \cdot 0.0003$$

$$\approx 28.97 \ \frac{lbm}{lbmol} = 28.97 \ \frac{kg}{mol}$$

Gas Constant for air

$$R = \frac{\bar{R}}{M} = \frac{1545.34 \text{ ft lbf}}{R \ \cancel{lbmol}} \cdot \frac{\cancel{lbmol}}{28.97 \ \cancel{lbm}} \cdot \frac{32.124 \ \cancel{lbm}}{slug} = 1716.5 \ \frac{\text{ft lbf}}{R \text{ slug}}$$

$$= 53.35 \ \frac{\text{ft lbf}}{R \text{ lbm}}$$

Air density SSL (14.696 psi, 59°F)

$$\rho = \frac{PM}{\bar{R}T} = \frac{14.696 \text{ psi}}{} \cdot \frac{28.97 \ lbm}{lbmol} \cdot \frac{R \ lbmol}{1545.34 \text{ ft lbf}} \cdot \frac{}{518.67 R} \cdot \frac{slug}{32.174 \ lbm} \cdot \frac{144 \text{ in}^2}{ft^2} \cdot \frac{lbf}{\text{psi in}^2}$$

$$= 0.00237 \ \frac{slug}{ft^3}$$

Wet air

The addition of water vapor changes the properties of "air":

N≡N   O=C=O   N≡N

Ar   N≡N

H_2O O=O

Water vapor behaves as an ideal gas, thus we can model the mixture as an IG.

$$\rho = \frac{P_{dry}}{R_{dry}\,T_{dry}} + \frac{P_{vapor}}{R_{vapor}\,T_{vapor}}$$

where the partial pressures add to total pressure

$$P = P_{dry} + P_{vapor}$$

$$= \frac{P_{dry}\,M_{dry}}{R\,T_{dry}} + \frac{P_{vapor}\,M_{vapor}}{R\,T_{vapor}}$$

Temps are identical

$$= \frac{P_{dry}\,M_{dry} + P_{vapor}\,M_{vapor}}{RT}$$

Partial pressure of vapor

$$P_{vapor} = \phi\, P_{sat}$$

ϕ = relative humidity

$$= \frac{(P - P_{vapor})M_{dry} + P_{vapor}\,M_{vapor}}{RT}$$

$$= \frac{(P - \phi P_{sat})M_{dry} + \phi P_{sat}\,M_{vapor}}{RT}$$

$$= \frac{P\,M_{dry} + \phi P_{sat}\,(M_{vapor} - M_{dry})}{RT}$$

$M_{dry} = 28.97$

$M_{vapor} = 18.0$

Thus, $M_{vapor} - M_{dry}$ is <u>negative</u>

Increasing the water vapor <u>decreases</u> air density

Saturated Water Vapor $\Rightarrow$ Partial Pressure

Arden - Buck Equation (curve fit)

$$P_s^{[hPa]}(T^{[C]}) = 6.1121 \exp\left(\left(18.678 - \frac{T}{234.5}\right)\left(\frac{T}{257.14 + T}\right)\right)$$

$$P_s^{[psi]}(T^{[R]}) = 0.08865 \exp\left(\frac{-0.002369\,(T - 8375.65)(T - 491.67)}{T - 28.818}\right)$$

Ex:

what is the partial pressure of water vapor at $100°F$?

$$P_s(100^F) = 0.08865 \exp\left(\frac{-0.002369\,(559.67 - 8375.65)(559.67 - 491.67)}{559.67 - 28.818}\right)$$

$$= 0.9502 \text{ psi}$$

$P_s(100^F)$ from my thermodynamics steam table is 0.9503 psi

Ex: What is $P_{s_{H_2O}}$ at 212^F? Hint: Boiling Water

You don't need the formula! $P_s = P_{SSL} = 14.7^{psi} = 1$ atm

Ex: At what altitude must you fly to boil water in your hand?

Human body $\approx 98°F$

$P_s(98°F) = 0.89$ psi

Consult a standard atmosphere table

$h \approx 63000^{ft}$

please don't try at home!

Wet air (continued)

$$\rho = \frac{p M_{dry} + \phi \, 0.08865 \exp\left(- \frac{0.002369 (T - 8375.65)(T - 491.67)}{T - 28.818} \right) (M_{vapor} - M_{dry})}{\bar{R} T}$$

function of p, ϕ, T

Ex: $p = 14.696$ psi, $90°F$, 90% rh

$\rho = \cdots\cdots = 0.00220 \ \frac{slug}{ft^3}$

Ex: " " 0% rh

$\rho = 0.002243 \ \frac{slug}{ft^3}$

Impact of Wet Air.

%SSL

- Standard Sea Level (SSL) Std-Day 0^{ft}_{MSL} 59°F 0% rh
  $\rho = 0.00237 \frac{slug}{ft^3}$ 100

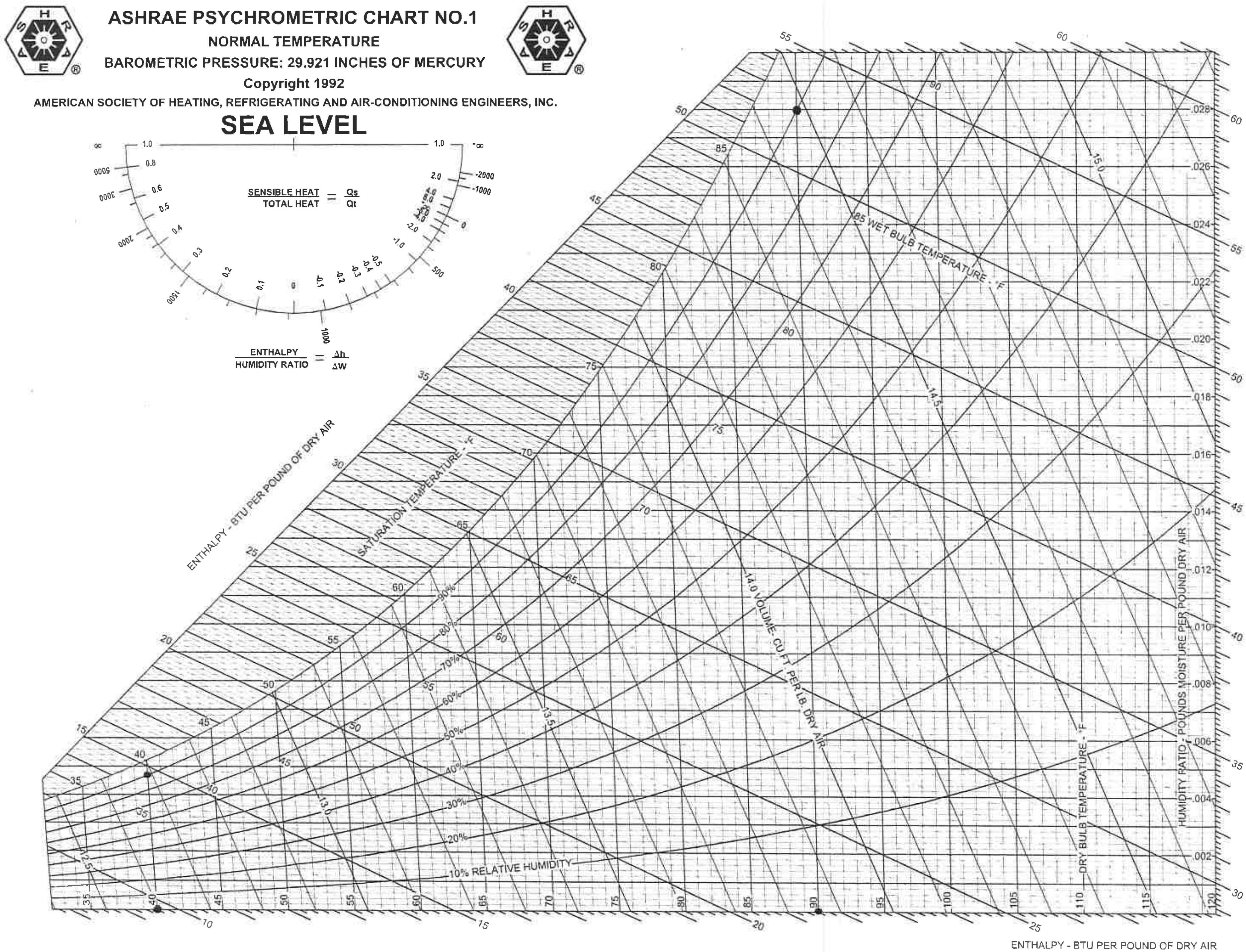
- Alabama Summer (hot + humid) 90°F 90% rh $\approx 0^{ft}_{MSL}$ $\rho = 0.002206 \frac{slug}{ft^3}$ 93%
- " " Dry 90°F 0% rh $\rho = 0.00224 \frac{slug}{ft^3}$ 94%

- Alabama Winter (wet) 40°F 90% rh $\rho = 0.00246 \frac{slug}{ft^3}$ 104%

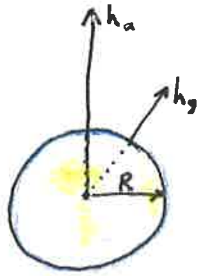
- " " Dry 40°F 0% rh $\rho = 0.00246 \frac{slug}{ft^3}$ 104%

- Antarctica (cold + dry) −126°F 0% rh $\rho = 0.00369 \frac{slug}{ft^3}$ 155%
- Denver, CO (std day) 40°F 0% rh 5000^{ft}_{MSL} $\rho \approx 0.00205 \frac{slug}{ft^3}$ 86%

ASHRAE Chart Comparison


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
BAROMETRIC PRESSURE: 29.921 INCHES OF MERCURY
Copyright 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SEA LEVEL
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY - BTU PER POUND OF DRY AIR
SATURATION TEMPERATURE - °F
WET BULB TEMPERATURE - °F
VOLUME- CU.FT. PER LB. DRY AIR
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE - °F
HUMIDITY RATIO - POUNDS MOISTURE PER POUND DRY AIR
ENTHALPY - BTU PER POUND OF DRY AIR

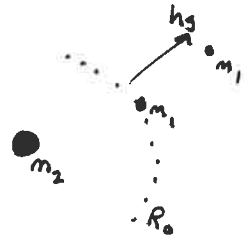
Atmosphere



Distinguish between absolute altitude from center of Earth (h_a) and altitude from the Earth's surface (h_g)

$$h_a = h_g + R$$

Gravity is not constant wrt altitude.



$$F = G\frac{m_1 m_2}{r^2}$$

How does gravity change with altitude?

$$F_{R_0} = \frac{G m_1 m_2}{R_0^2} \quad \text{force at } R_0$$

$$\Rightarrow \frac{G m_2}{R_0^2} = g_0$$

$$F_{R_0+h_g} = \frac{G m_1 m_2}{(R_0+h_g)^2} \quad \text{force at } R_0+h_g$$

$$g = \frac{G m_2}{(R_0+h_g)^2} = g_0 \frac{R_0^2}{(R_0+h_g)^2}$$

$$g = g_0 \frac{R_0^2}{(R_0+h_g)^2}$$

Define a new altitude called "geopotential altitude", h, where gravity is constant (g_0).

$$dh = \frac{g}{g_0} dh_G$$

geopotential (dh), geometric (dh_G)

$$\Rightarrow dh = \frac{R_0^2\, dh_G}{(R_0+h_G)^2} \Rightarrow h = \frac{R_0}{R_0+h_g} h_g$$

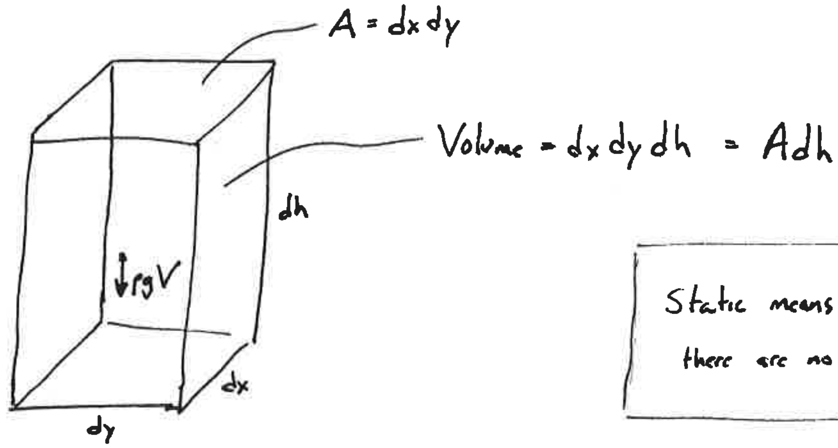
Negligible for most aircraft applications.

$\approx$ 0.1% error at 21 000 ft

1% error at 200 000 ft

Nevertheless, we will use h (geopotential) altitude.

Static Column of Fluid



Static means no velocity, so no $\frac{du_i}{dx_j}$, thus there are no viscous forces.

Summation of forces in h direction

$$P_{bottom} A = P_{top} A + \rho g V$$

Taylor Series expansion for $P_{top} = P_{bottom} + \frac{dP}{dh} dh$

$$PA = \left(P + \frac{dP}{dh} dh\right) A + \rho g A dh$$

Reduce (divide by A, cancel PA terms)

$$\frac{dP}{dh} dh + \rho g dh = 0$$

Divide by dh

$$\frac{dP}{dh} + \rho g = 0$$

Gov Equ

$$\boxed{dp = -\rho g_0 dh}$$

Atmosphere (continued)

$$dp = -\rho g_0 dh$$

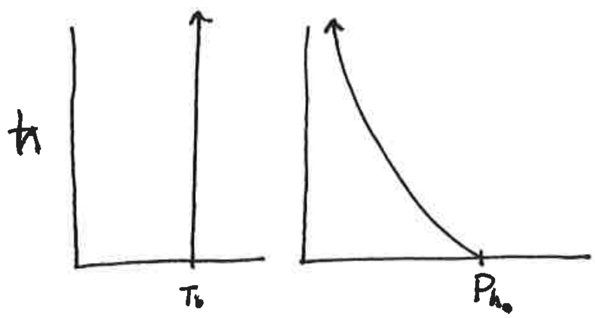
Ideal Gas is $p = \rho RT$, substitute for ρ

$$dp = -\frac{p}{RT} g_0 dh \Rightarrow \frac{dp}{p} = -\frac{g_0 dh}{RT}$$

- Isothermal
  Zero lapse rate $(T \neq f(h))$ $(T = T_0)$

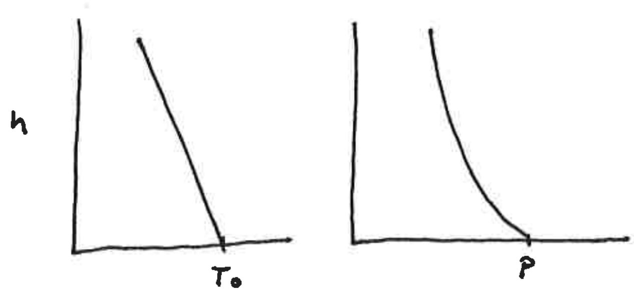
$$\frac{dp}{p} = \frac{-g_0}{RT_0} dh \quad \text{Integrate} \quad \ln p \Big|_{p_{h_0}}^{p_{h_1}} = -\frac{g_0}{RT_0} h \Big|_{h_0}^{h_1}$$

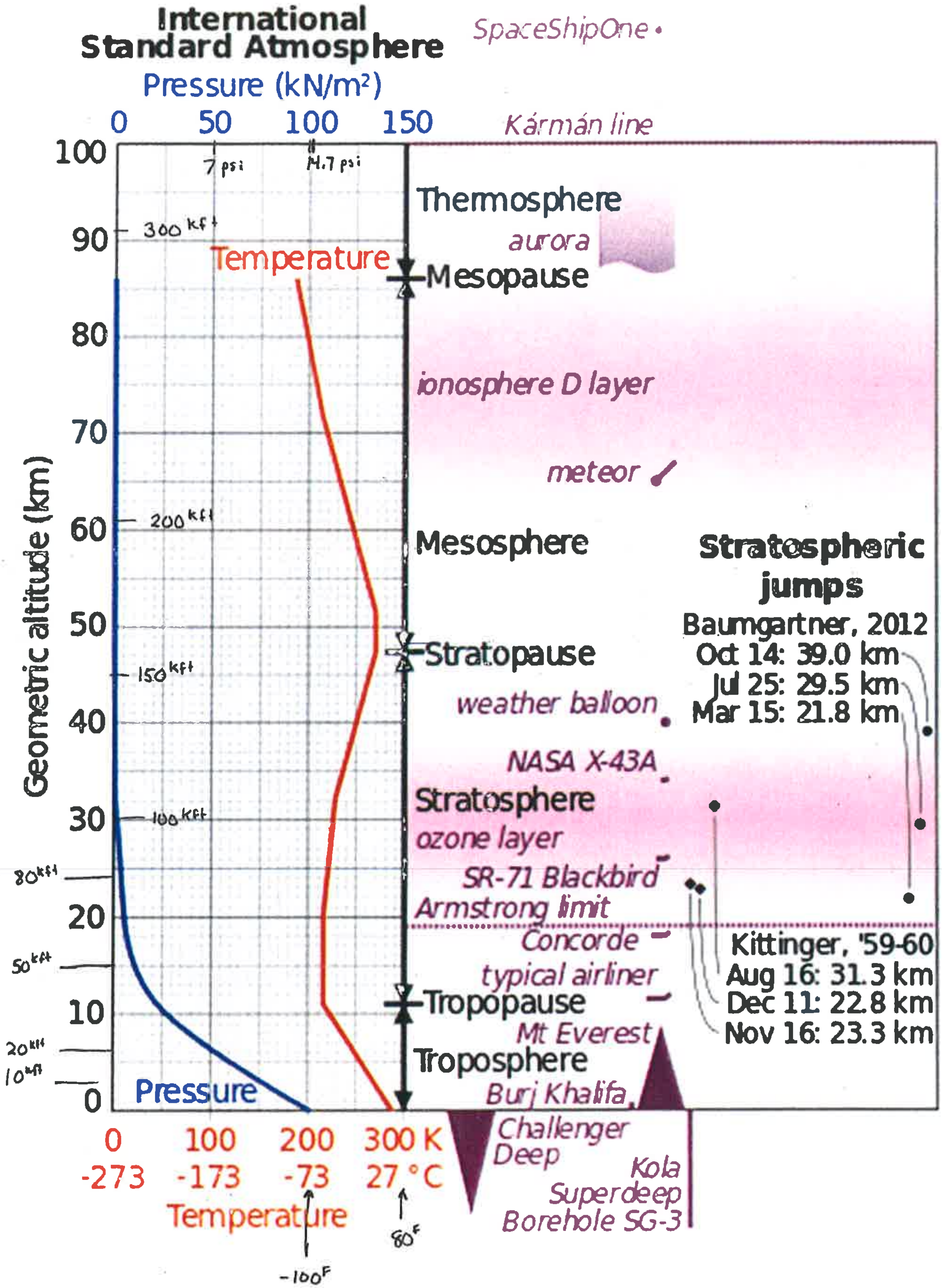
$$\underbrace{\ln p_{h_1} - \ln p_{h_0}}_{\ln \frac{p_{h_1}}{p_{h_0}}} = \frac{-g_0}{RT_0}(h_1 - h_0) \Rightarrow p_{h_1} = p_{h_0} e^{-\frac{g_0(h_1-h_0)}{RT_0}}$$



- Linear lapse rate $(T = T_0 - \lambda(h_1 - h_0))$

$$\frac{dp}{p} = \frac{-g_0}{R(T_0 - \lambda(h_1 - h_0))} dh \quad \text{Integrate (slightly involved)} \quad \frac{p}{p_0} = \left(\frac{T}{T_0}\right)^{-\frac{g_0}{R\lambda}}$$




International Standard Atmosphere
Pressure (kN/m²)
0 50 100 150
Kármán line
SpaceShipOne
7 psi
14.7 psi
300 kft
200 kft
150 kft
100 kft
80 kft
50 kft
20 kft
10 kft
Geometric altitude (km)
100
90
80
70
60
50
40
30
20
10
0
Thermosphere
aurora
Temperature
Mesopause
ionosphere D layer
meteor
Mesosphere
Stratospheric jumps
Baumgartner, 2012
Oct 14: 39.0 km
Jul 25: 29.5 km
Mar 15: 21.8 km
Stratopause
weather balloon
NASA X-43A
Stratosphere
ozone layer
SR-71 Blackbird
Armstrong limit
Concorde
typical airliner
Tropopause
Mt Everest
Troposphere
Burj Khalifa
Kittinger, '59-60
Aug 16: 31.3 km
Dec 11: 22.8 km
Nov 16: 23.3 km
Pressure
0 100 200 300 K
-273 -173 -73 27 °C
Temperature
-100F
80F
Challenger Deep
Kola Superdeep Borehole SG-3