Appendices and References

Appendices Table of Contents

References

Texts

- Allmendinger, E. (editor) "Submersible Vehicle Systems Design", The Society of Naval Architects and Marine Engineers, Jersey City, New Jersey, 1990.
- Baumeister, T. (editor) "Marks' Handbook for Mechanical Engineers – 8th Ed.", McGraw Hill, San Francisco,1978. (newer editions available)
- G. Franklin, J. Powell, and A. Emami-Naeini, "Feedback Control of Dynamic Systems", Addison-Wesley, 1994
- S. Sarns and J. Woehr, "Demystifying PID Control", *Embedded Systems Programming*, Aug. 1990
- C. Dearman, "Getting Control of the Situation", *Embedded Systems Programming*, Nov. 1992
- Loeser, H. (editor) "Sonar Engineering Handbook", Naval Undersea Systems Center, Peninsula Publishing, Los Altos, 1992.
- Dexter, Stephen C. "Handbook of Oceanographic Engineering Materials",Krieger Publishing Company, Malabar, Florida, 1985.

Texts

- Urick, Robert J. "Principles of Underwater Sound" 2nd ed., McGraw-Hill, San Francisco, 1975.
- Linden H.D., "Handbook of Batteries", 2 ed., McGraw-Hill, New York 1995.
- Bazovsky, I. "Reliability Theory and Practice", 1961, Prentice-Hall Englewood Cliffs, New Jersey.
- Military Standard 785A, "Reliability Program for Systems and Equipment Development and Production", March 1969.

References and Papers

- Sibenac M., Podder T., Kirkwood W., and Thomas H., "Autonomous Underwater Vehicles for Ocean Research: Current Needs and State of the Art Technologies," Marine Technology Society Journal, Vol. 38, Number 2, Pgs 63 – 72, Summer 2004.
- Kirkwood, W. (et al), "MBARI / MIT Ducted Propeller Control System Developed for Autonomous Underwater Vehicles," Underwater Intervention 2001 Conference Proceedings, Tampa Bay, Florida, January 2001.
- Caress, D. & Kirkwood, W., "High Resolution Mapping with AUVs: Payload Development issues in Support of Oceanographic Science", Oceanology International - Americas Conference, AUV Sensor Workshop Proceedings, Miami, Florida, April 2001.
- Tervalon, N. & Kirkwood, W., "Ice Profiling Sonar for an AUV: An approach for obtaining SCICEX quality ice draft data", Oceanology International - Americas Conference, AUV Sensor Workshop Proceedings, Miami, Florida, April 2001.
- Kirkwood, W., Bellingham, J., Stannard, J., Stein, P., Overland, J., "Development of Dorado / ALTEX Vehicle and Subsystems," Society for Underwater Technology - AUV Masterclass Symposium Proceedings, Southampton Oceanographic Centre, Southampton, England, September 2001.

References and Papers

- Kirkwood, W. (et al). "Development of a Long Endurance Autonomous Underwater Vehicle for Ocean Science Exploration," IEEE/MTS Oceans 2001 Conference Proceedings, Honolulu, HI, November 5-8 2001. IEEE Press.
- Sibenac, Mark (et.al.) , "Modular AUV for Routine Deep Water Operations", Oceans Proceedings, November 2002, Boluxi, Miss.
- Bellingham, Jim (et.al.), "Field Results for an Arctic AUV Designed for Characterizing Circulation and Ice Thickness", Fall AGU 2002, Poster Session
- Bellingham, J.G., E. Cokelet, W.J. Kirkwood, N. Tervalon, H. Thomas, M. Sibenac, D. Gashler, R. McEwen, R. Henthorn, F. Shane, D.J. Osborne, K. Johnson, J. Overland, P. Stein, A. Bahlavouni, D. Anderson (2001) "Field Results for an Arctic AUV Designed for Characterizing Circulation and Ice Thickness". In: American Geophysical Union. San Francisco, California..

References and Papers

- Kirkwood, W.J., H. Thomas, M. Sibenac, N. Tervalon, R. McEwen, F. Shane, R. Henthorn, D. Gashler, E. Mellenger, D. Au, T. O'Reilly, J.G. Bellingham "An Autonomous Underwater Vehicle System for Arctic Operations". In: Arctic Instrumentation Workshop. October, 2002 Moss Landing, California.
- Bellingham, J. and Willcox, S. "Optimizing AUV Oceanographic Surveys", AUV '96 Proceedings, 1996, pg.391-398.

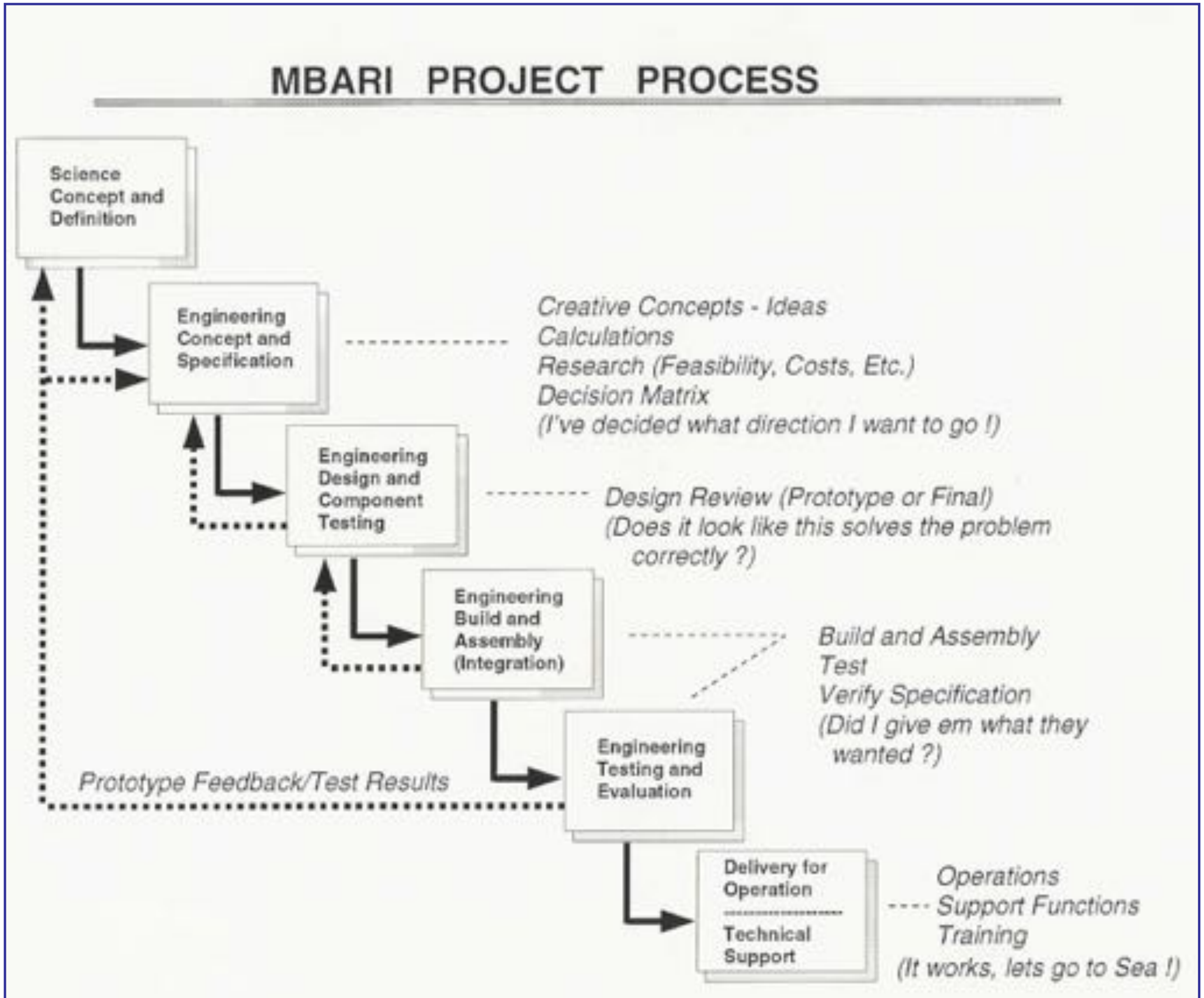
APPENDICES A

Systems Design Concepts

- Functional requirements
- Systems requirements
- Sub-Systems Breakout

AUV Technology and Application Basics

The Process is important



AUV Technology and Application Basics

Systems requirements

Cost (initial, life cycle, destruction)

Type of system (single or multiple cycles)

Duty Cycle (continuous or intermittent)

Load profile (pulse, continuous)

Operating conditions (temperature, humidity, etc)

Service Life

Safety & Reliability & Transportability

System compatibility

Specific Energy (whr/kg)

Energy Density (whr/liter)

Pressure Tolerance

Others...

All factors are equally important and very sensitive to system requirements

AUV Technology and Application Basics

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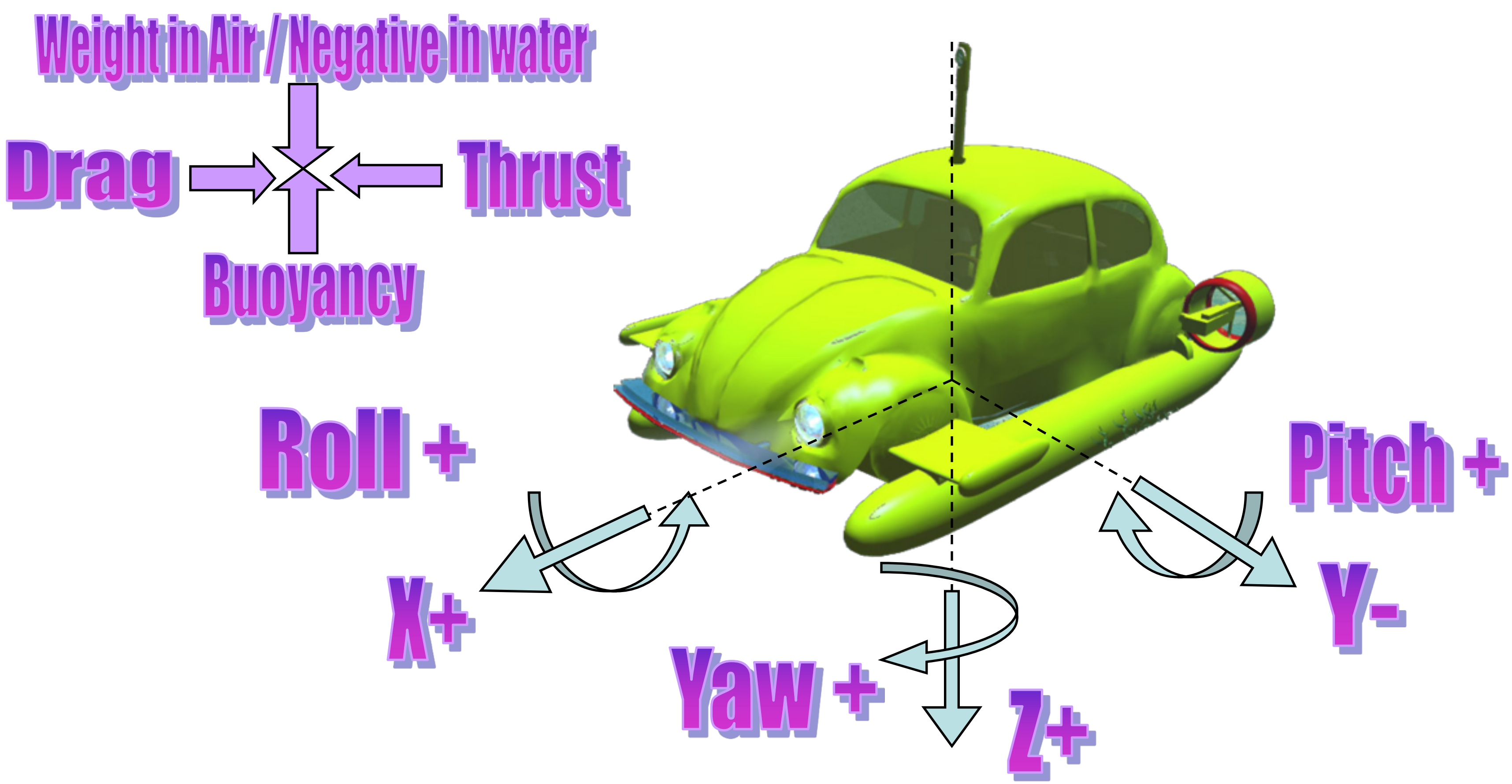
Systems Design

Systems Design

1st : Create a common set of coordinates and terminology!



Functional Requirements

- What it needs to do
- Written as “Shall”
- Specific and measurable
- Softer requirements written as “May”
- Prioritized !!

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- What does it need to do

<u>Interviewing and understanding are key here</u>

Your “customer” doesn’t always know exactly what they want

Your “customer” will often tell you solutions not the problem

Your “customer” will often be looking at a narrow picture

Your “customer” will respond to your questions - be careful how you phrase them!

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- Requirements are written as “Shall”

This system shall operate in sea water to depths of 4000 meters
The system shall be capable of taking water samples
The system shall be able to orient it self in a repeatable fashion for comparative video studies
The system shall collect CTD data at resolution XX
etc. etc.

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- Specific and measurable

The next task is to work with the customer and begin putting measurable and specific numbers to everything you can. Those things that do not get numbers are reworded to be as clear and testable as possible.

Engineer : “Exactly how how many samples and at what spacing or timing do you want to bring back?” “Do they need to be environmentally controlled ?” “Is there anything that I need to do specifically to keep them correlated?” etc. etc.

Customer : I’d like to collect about 30 samples each dive. They don’t have to be temperature controlled because of the chemistry isn’t sensitive. The CTD data needs ot be accumulated at 5 Hz with lag time between sensors less than 100 mSec. etc. etc.

(rewrite your functional requirements to add numbers, temperature … etc. etc.)

- Softer requirements written as “May”

Customer 2 maybe : “I could make use of that on my cruise too. If you could make it red, then I could check the response of mid-water animals to the color red in low light conditions. Also, I’ve got a post doc here for another year and they would like to get acoustic images of Krill patches. etc. etc.

Engineer : The system <u>may</u> collect acoustic imaging data
The system <u>may</u> be built from red material or colored red with a visual package to record animal behavior.
etc. etc.

Note : I prioritized this automatically in this case … since these are secondary drivers for the system they are placed in the order of importance or in this case the easiest to deliver

(again the engineer iterates to get the complete functional requirements)

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- Prioritize !!

Get your customers, engineers, and management to the table and agree on the functional requirements, the detailed numbers and the priority of those things not considered key or critical

Watch for feature creep

Create a structure for revision control

Document all requests and replies

Know who ultimately has the final say!

APPENDICES B

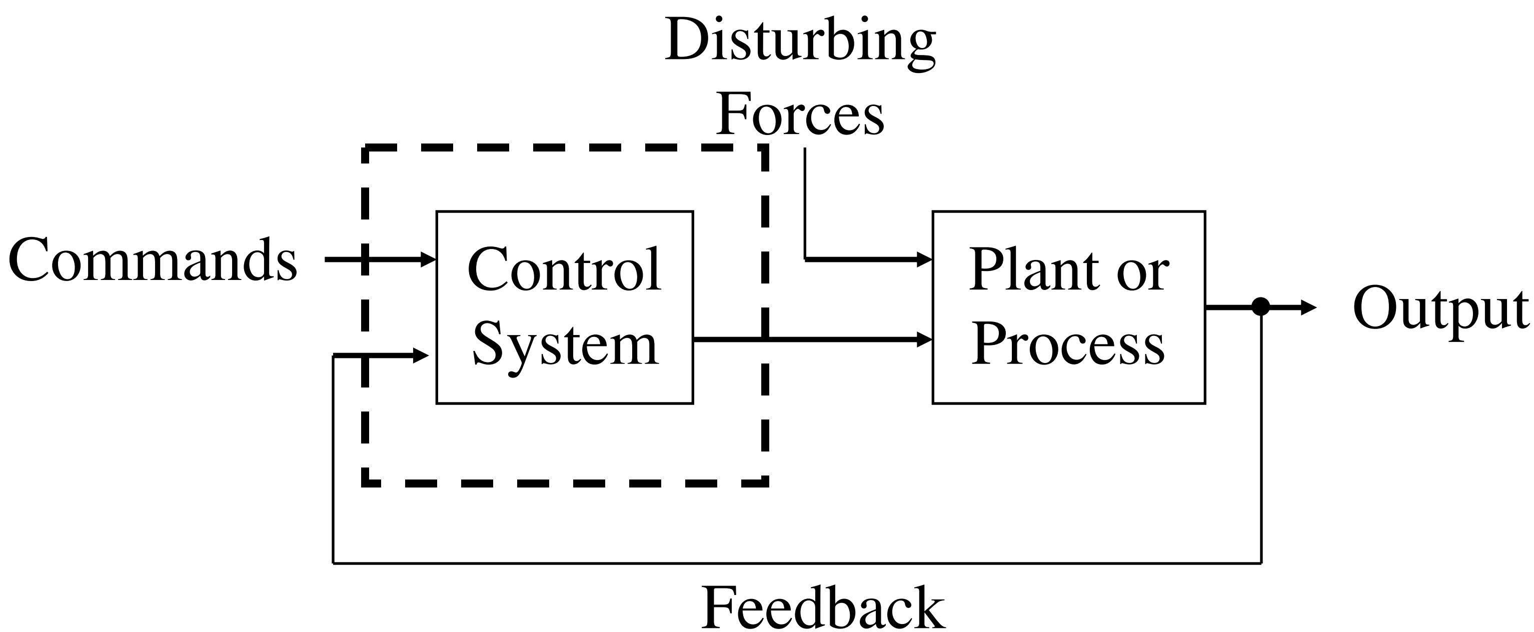
Basic Controls Concepts and Terms

PID Control

Proportional-Integral-Derivative

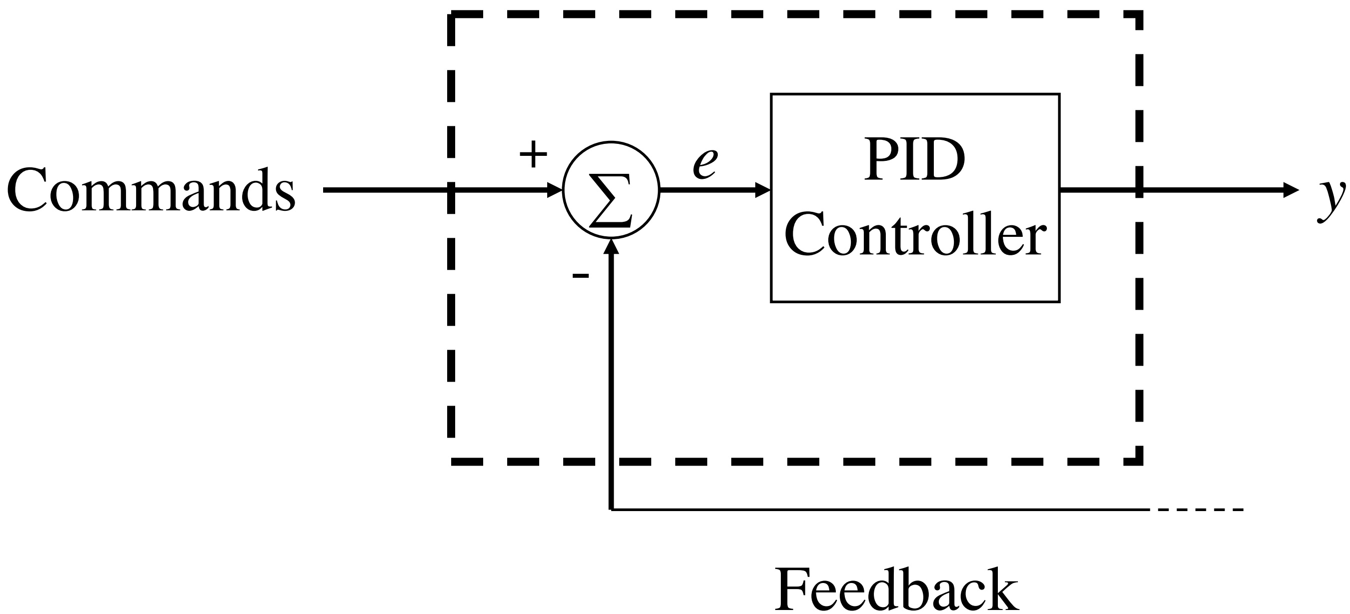
- A very common control law (but not the only one!)
- First described by Callender et al. in 1936

The PID is In Here



images courtesy of P.McGill_MBARI

Inputs and Outputs



images courtesy of P.McGill_MBARI

Proportional Term

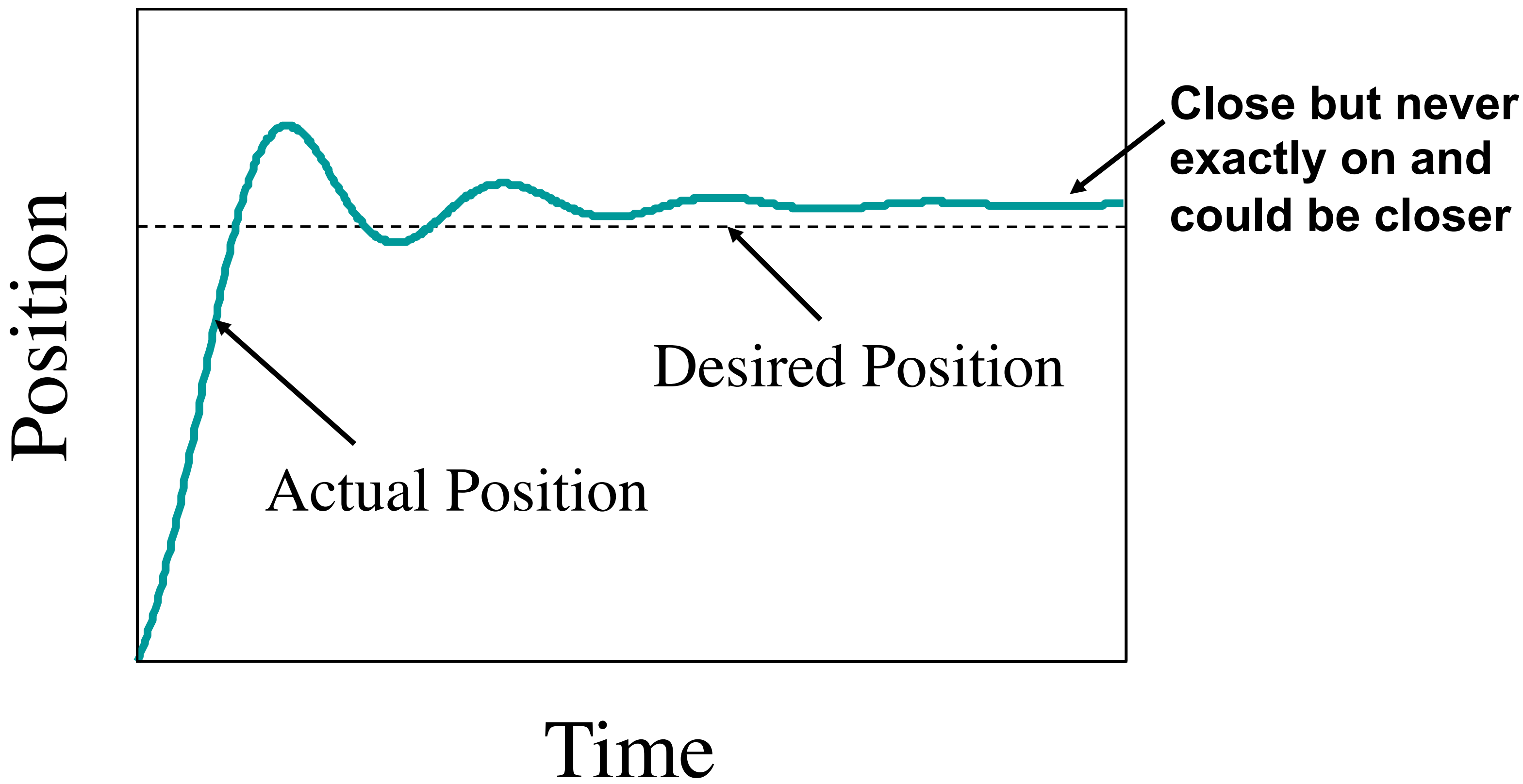
$$y = K_p \times e$$

y is the *output*

K_p is the *proportional gain*

e is the *error*

Proportional-only Response



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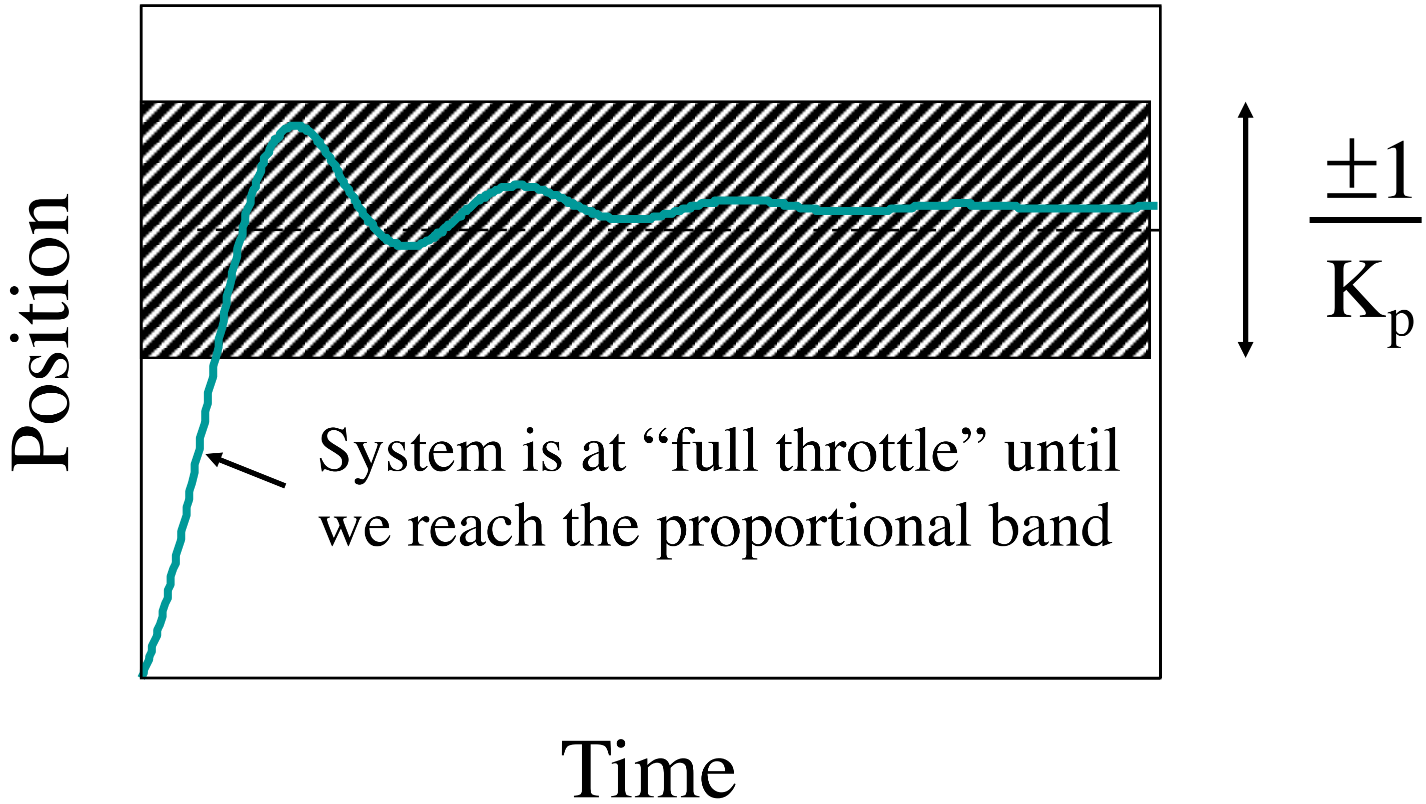
Proportional Band



images courtesy of P.McGill_MBARI

Add an Integral Term

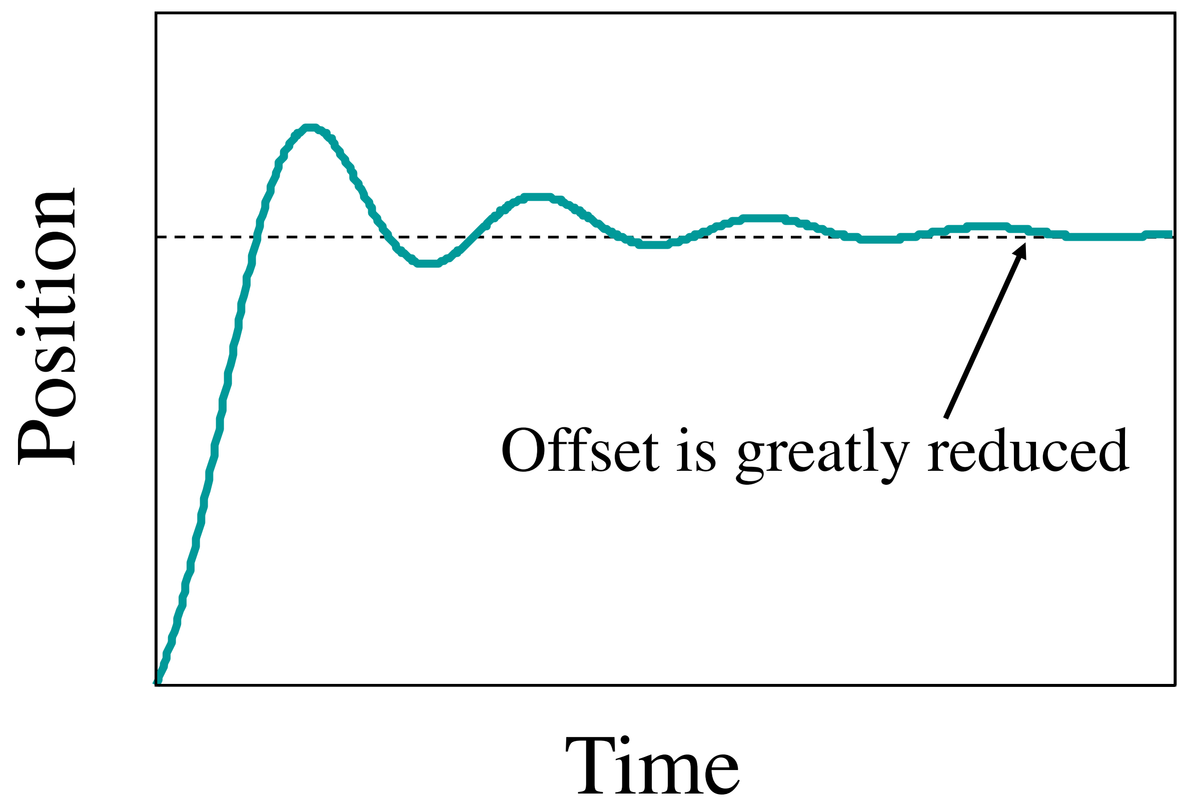
$$y = (K_p \times e) + (K_i \times \Sigma e)$$

K_i is the *integral gain*

Σe is the *summed error*

images courtesy of P.McGill_MBARI

Proportional-Integral Response



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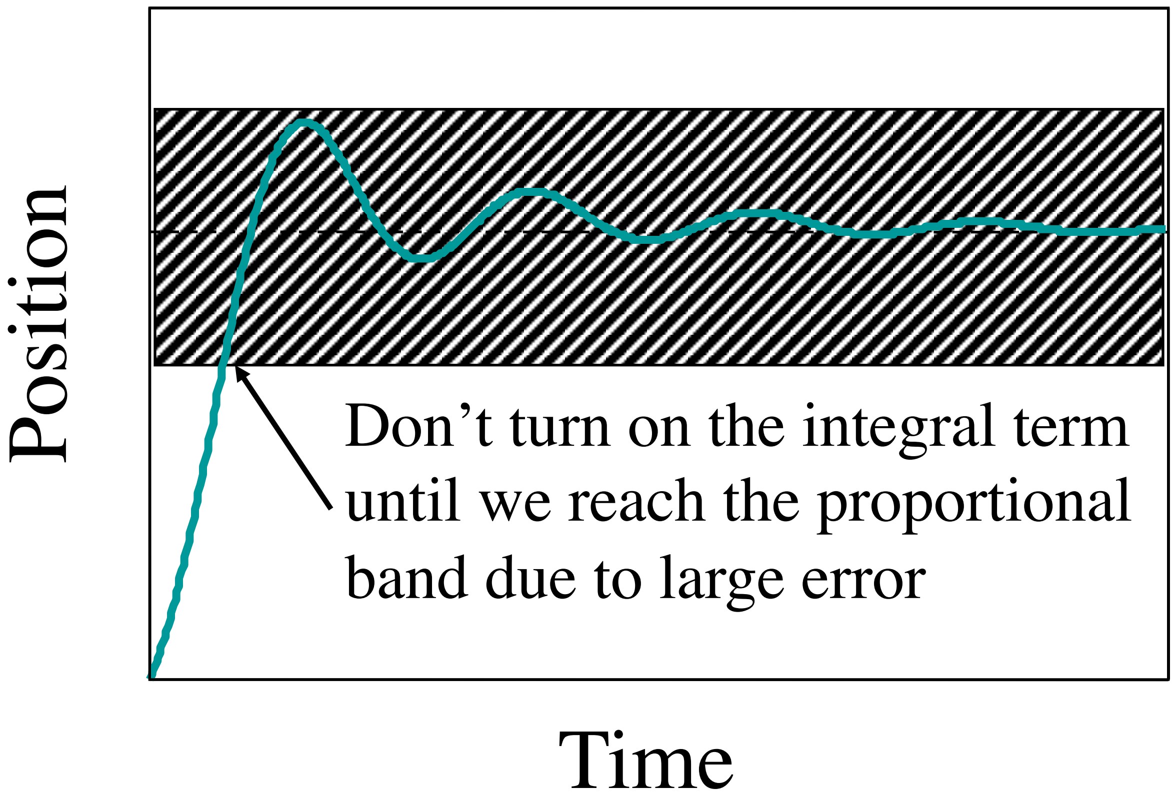
Integrator Anti-windup



images courtesy of P.McGill_MBARI

Add a Derivative Term

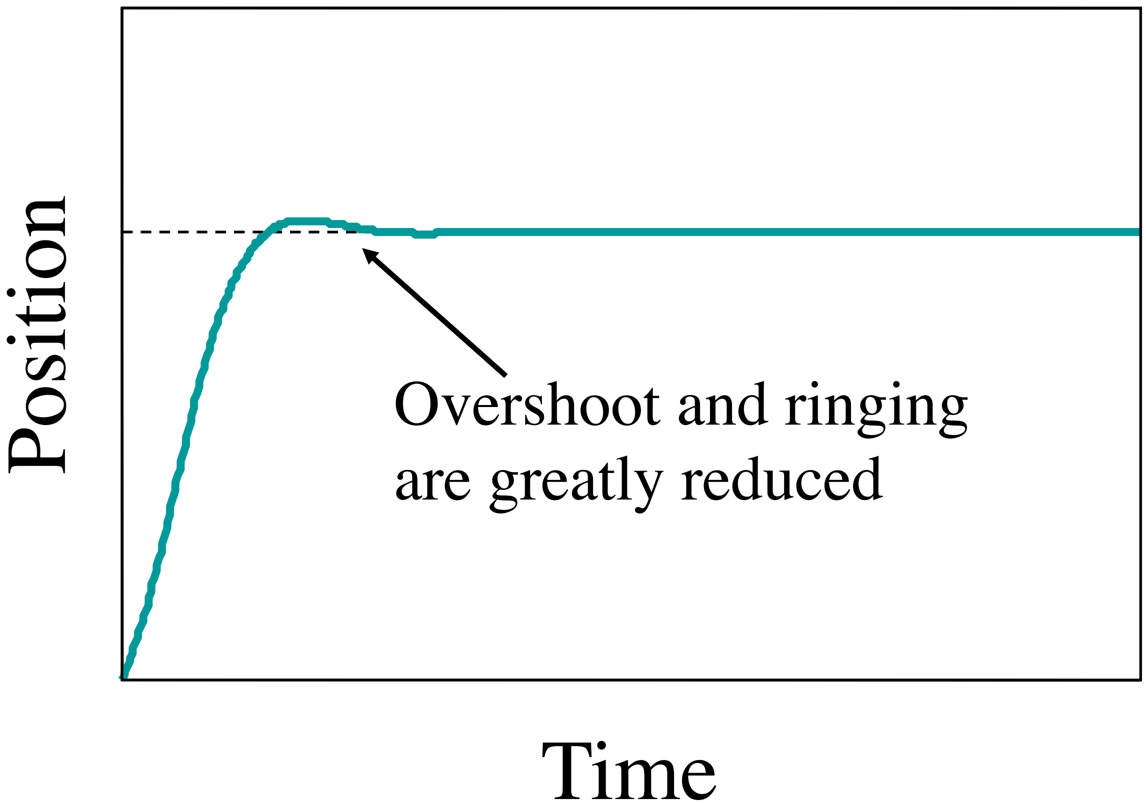
$$y = (K_p \times e) + (K_i \times \Sigma e) + (K_d \times \Delta e)$$

K_d is the *differential gain*

Δe is the *differential error*

images courtesy of P.McGill_MBARI

Proportional-Integral-Derivative Response



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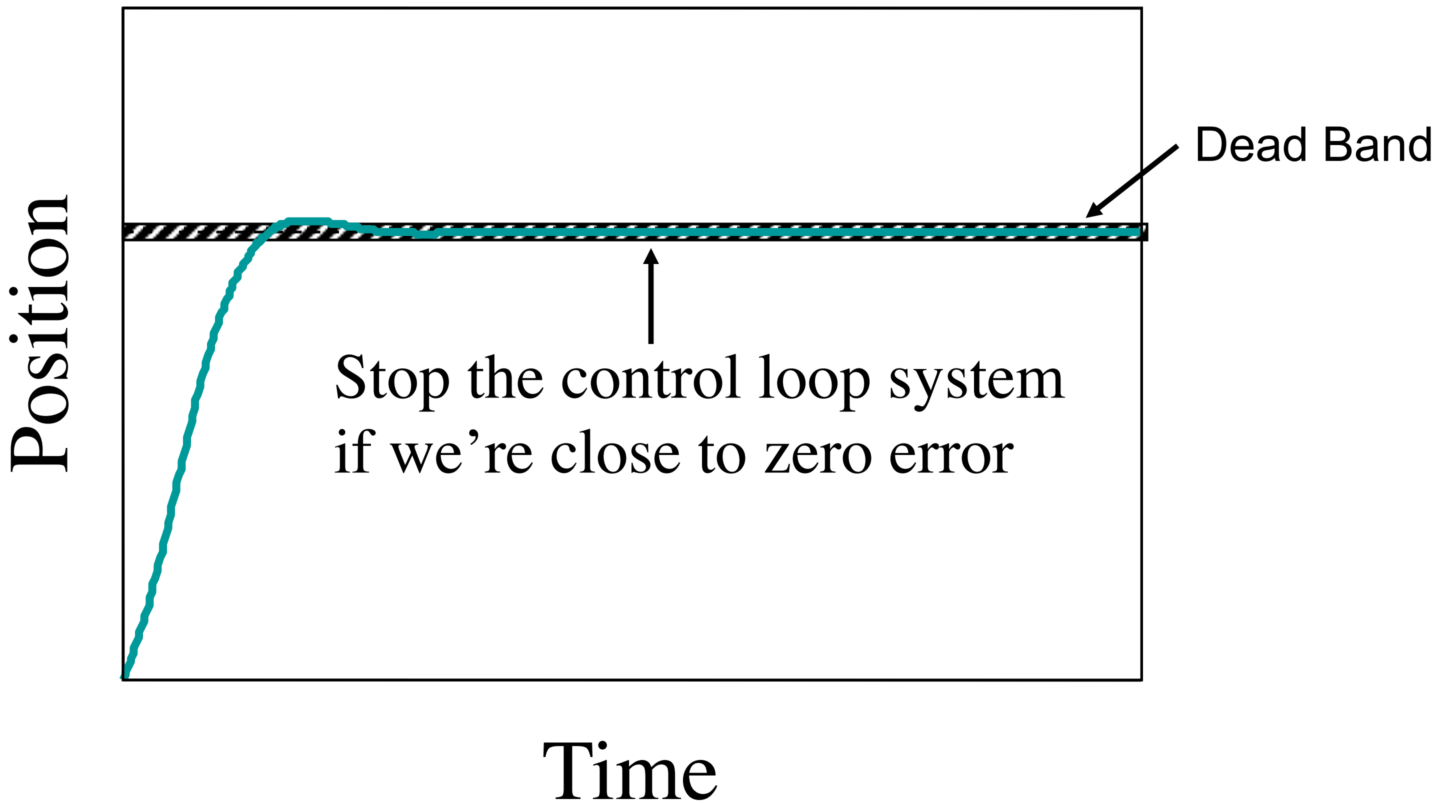
Dead Band

acceptable position close to commanded



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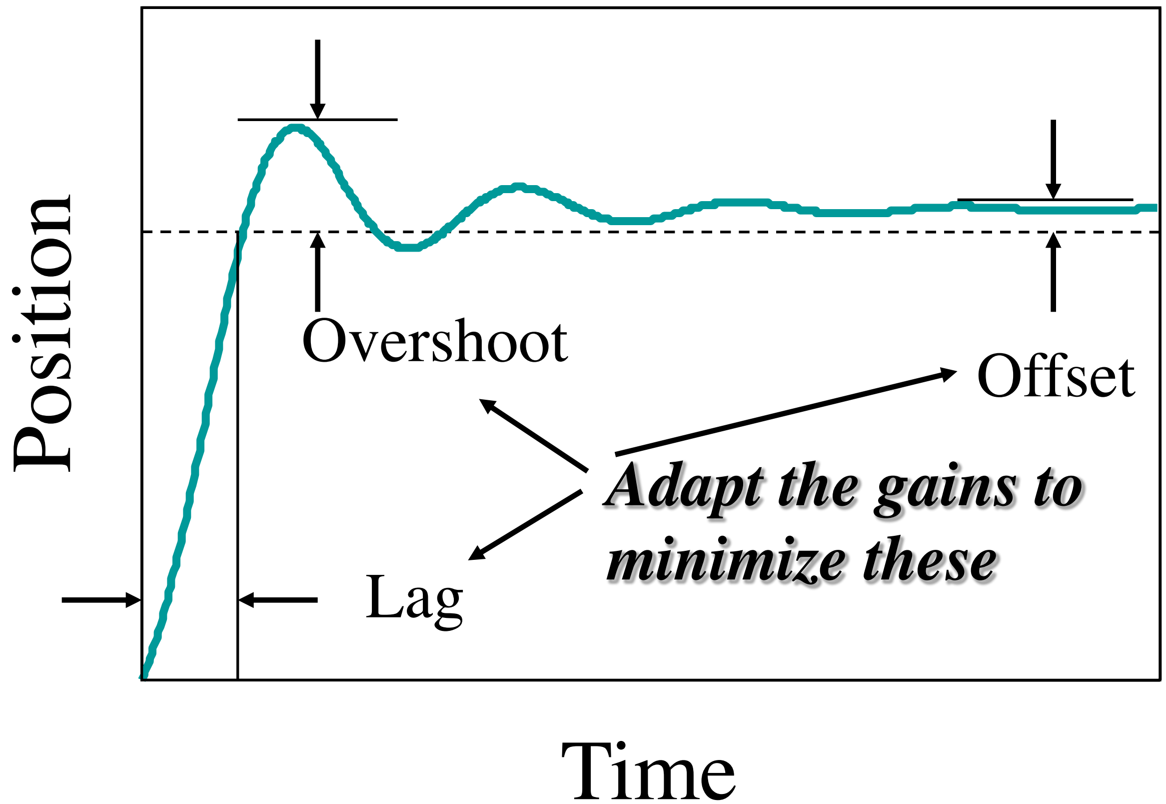
Tuning the PID Control Loop



Setting the Gains

	Not Enough	Just Right	Too Much
K_p	Slow Response	Quick Response	Oscillation
K_i	Constant Offset	Zero Offset	Jittery Response
K_d	Oscillation	Good Damping	Slow Response

images courtesy of P.McGill_MBARI

P, PI, and PD Control

- If the system is naturally damped
  - *you may not need a D term*
- If there are no offsets
  - *you may not need an I term*
- If there are no perturbing forces
  - *you may not need an P term… but then you're not going anywhere either.*

APPENDICES C

Basic Fluid Terms and Drag Tables

Fluid Properties: Dynamic Viscosity

SYMBOL: μ

DEFINITION: Shear stress (τ) in a Newtonian fluid is linearly proportional to the time rate of angular strain (dV/dy). The dynamic viscosity (μ) is the coefficient of proportionality so that

$\tau = \mu$ (dV/dy)

Unlike a solid, a fluid deforms continuously under the action of a shear stress. A non-Newtonian fluid is a fluid where the shear stress is not linearly proportional to the rate-of-strain.

In the case of seawater pressure effects are not substantial because the fluid is relatively incompressible.

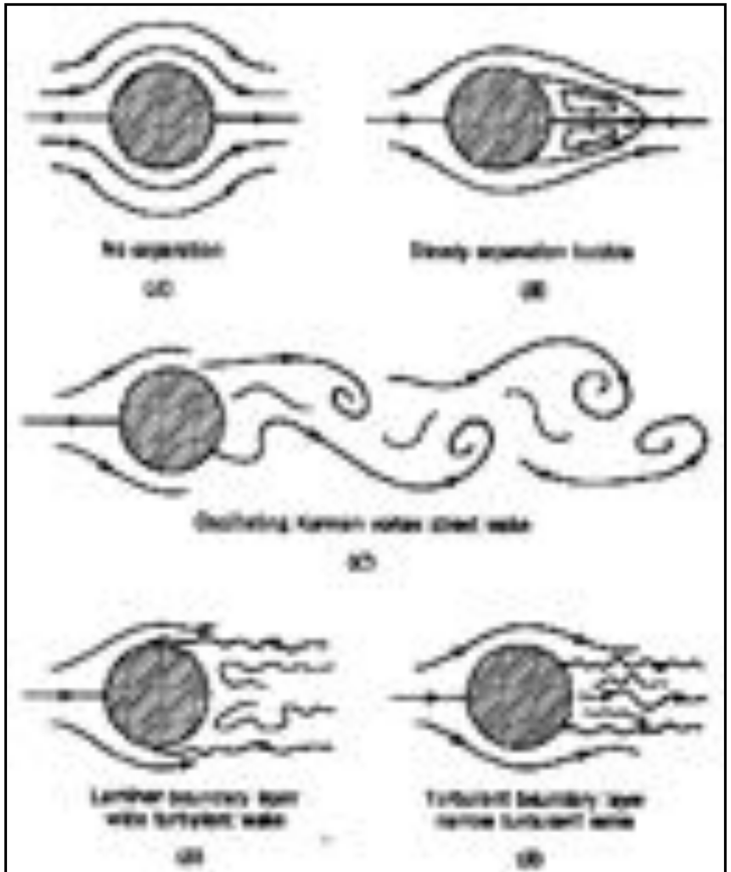
DENSITY AND VISCOSITY OF FRESH WATER AND SEAWATER AT A PRESSURE OF 1 ATM AND A RANGE OF TEMPERATURES

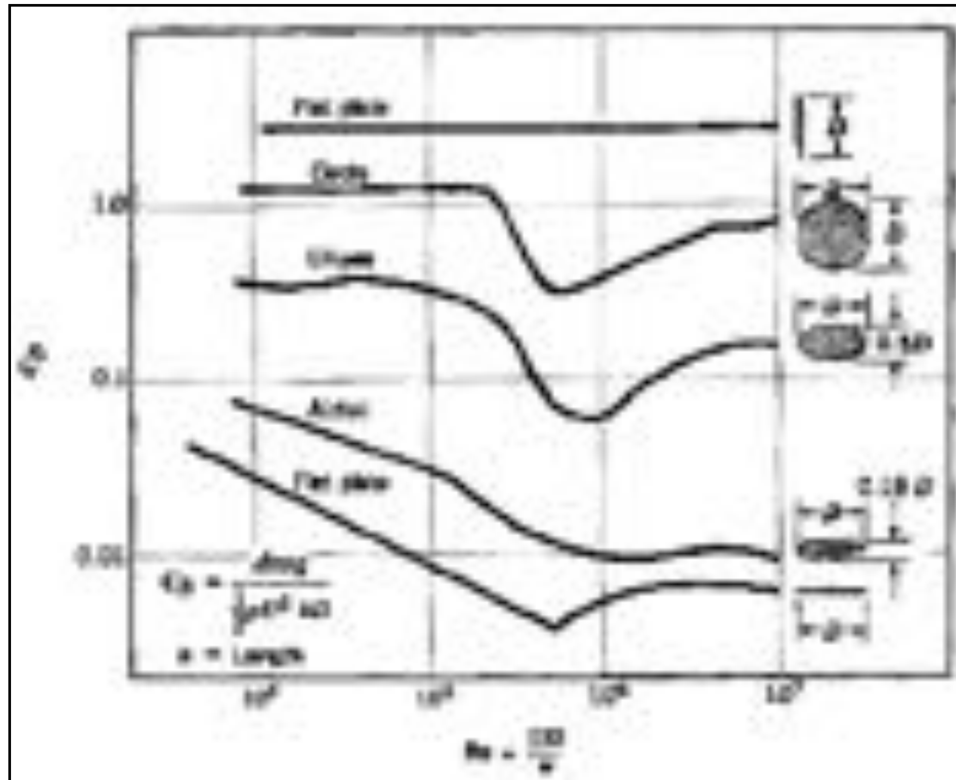
	FRESH WATER			SEAWATER, S=35 ppt		
TEMPERATURE (^oC)	**DENSITY (ρ)g/cm^3**	**DYNAMIC VISCOSITY (μ) gm/(cm sec)**	**KINEMATIC VISCOSITY (ν) cm^2/sec**	**DENSITY (ρ) g/cm^3**	**DYNAMIC VISCOSITY (μ) gm/(cm sec)**	**KINEMATIC VISCOSITY (ν) cm^2/sec**
0	**0.9998**	**1.52×10^{-2}**	**1.52×10^{-2}**	**1.0273**	**1.61×10^{-2}**	**1.57×10^{-2}**
5	**0.9997**	**1.42×10^{-2}**	**1.42×10^{-2}**	**1.0269**	**1.50×10^{-2}**	**1.46×10^{-2}**
10	**0.9997**	**1.31×10^{-2}**	**1.31×10^{-2}**	**1.0262**	**1.39×10^{-2}**	**1.35×10^{-2}**
15	**0.9991**	**1.14×10^{-2}**	**1.14×10^{-2}**	**1.0252**	**1.22×10^{-2}**	**1.19×10^{-2}**
20	**0.9982**	**1.01×10^{-2}**	**1.01×10^{-2}**	**1.0240**	**1.07×10^{-2}**	**1.05×10^{-2}**
30	**0.9957**	**0.80×10^{-2}**	**0.80×10^{-2}**	**1.0210**	**0.87×10^{-2}**	**0.85×10^{-2}**

http://legacy.eos.ncsu.edu/eos/info/mea/mea411_info/VISCOUS.htm

Drag Component of Equation

$$C_D = \frac{\text{Drag}}{0.5 \ell \rho U^2}$$





Drag Component of Equation

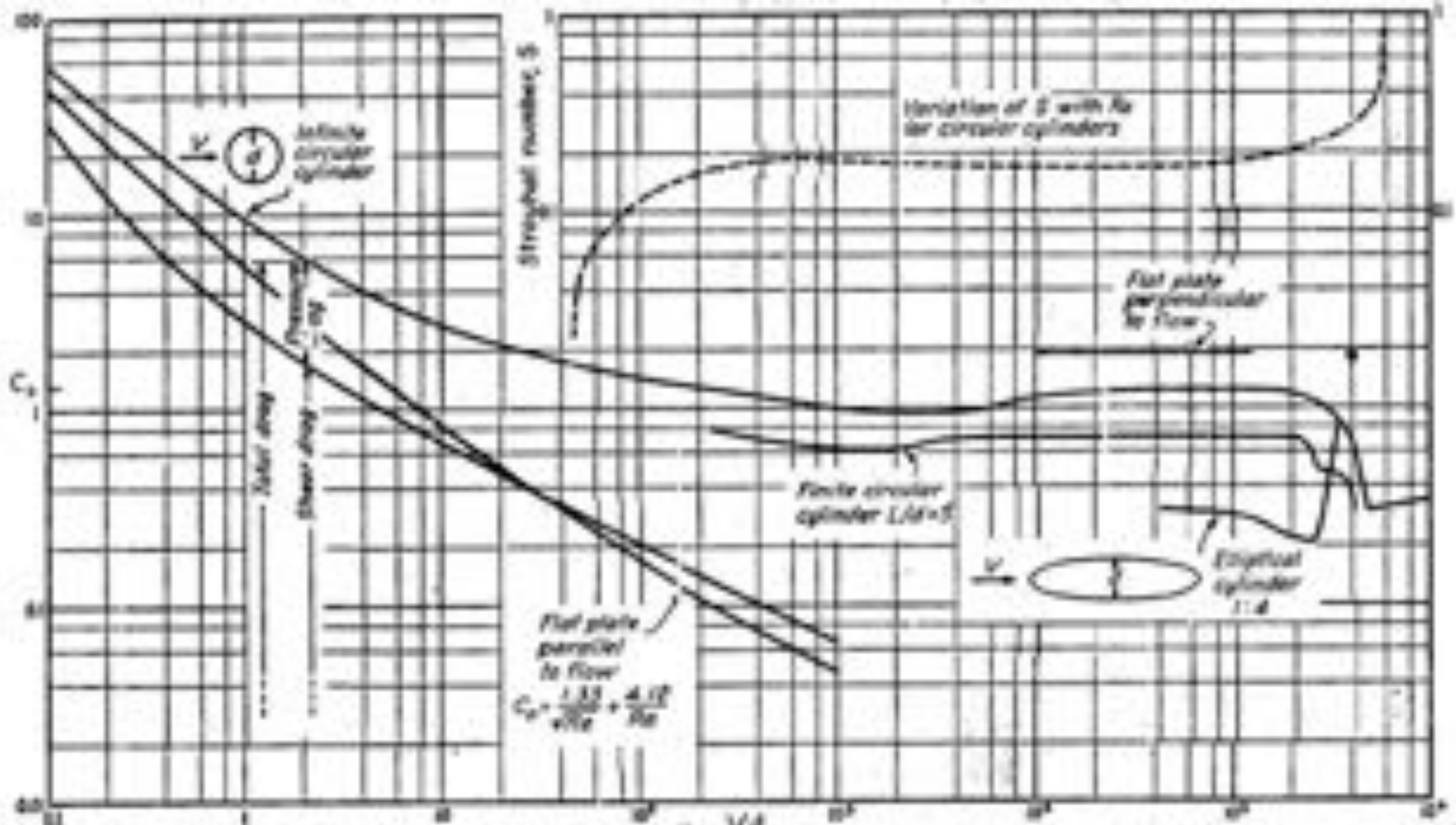


Figure 2 - Drag Coefficient

Image from web page: http://www.dopsys.com/loads.htm

Drag Component of Equation

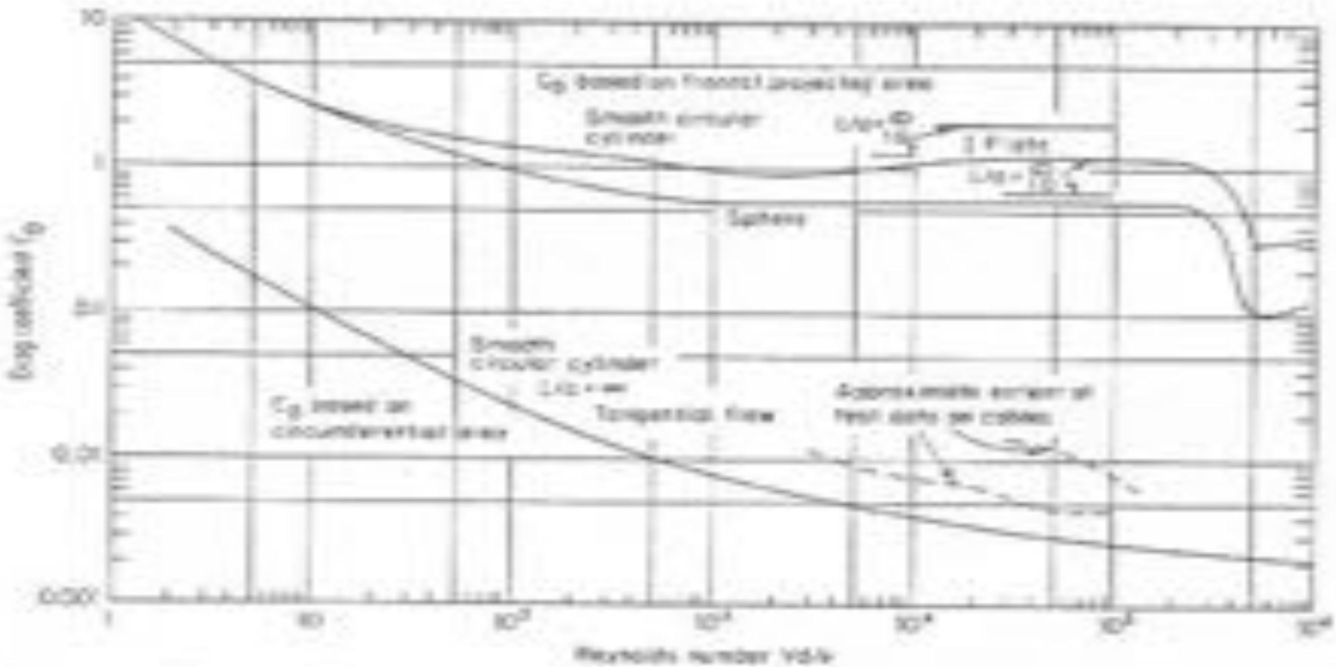


Fig. 2-24 Drag coefficients for cylinders, spheres, and other shapes.

Horner: Fluid Dynamic Drag

Drag Component of Equation

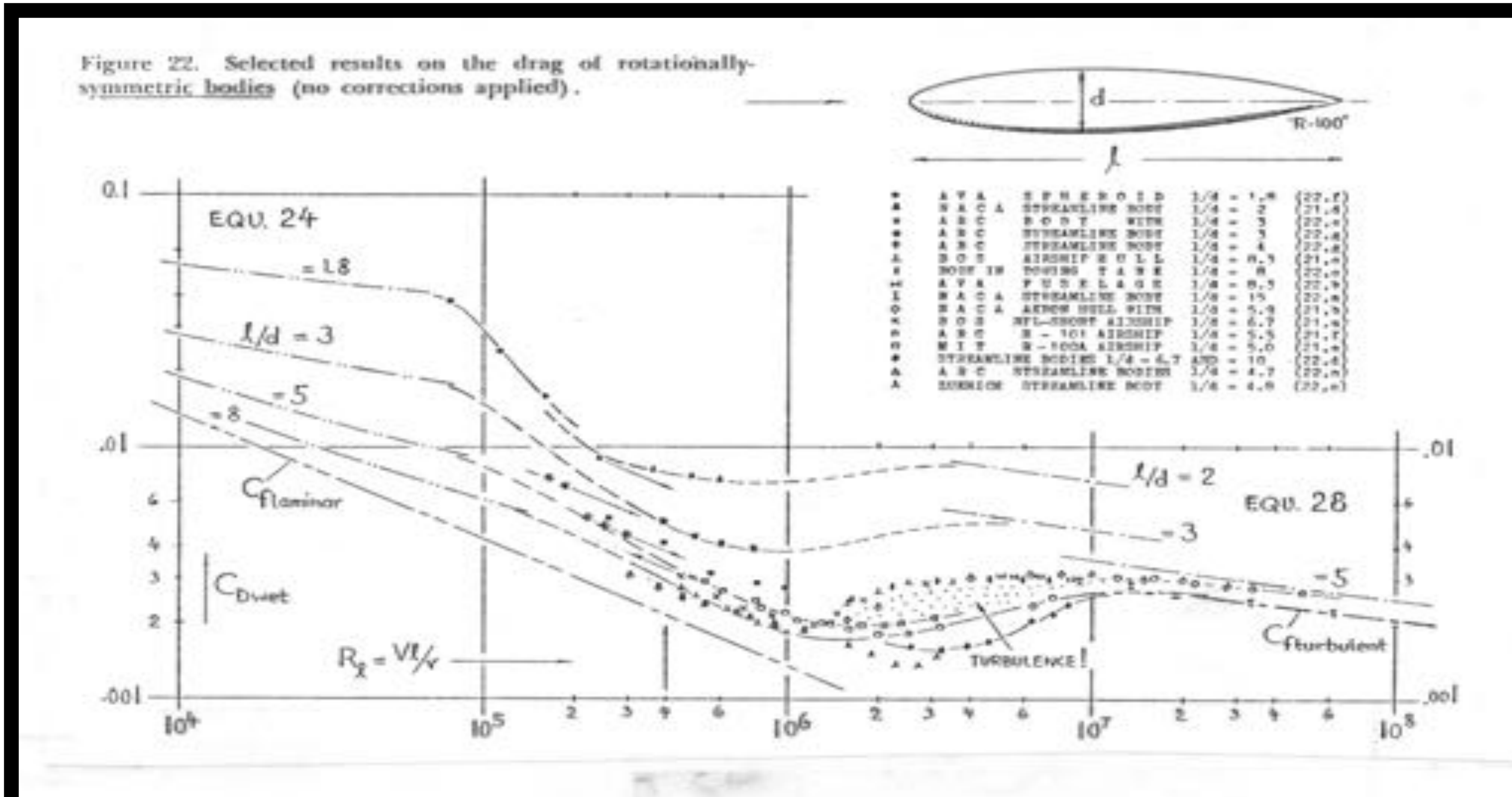


Figure 22. Selected results on the drag of rotationally-symmetric bodies (no corrections applied).

Horner: Fluid Dynamic Drag

Drag Component of Equation

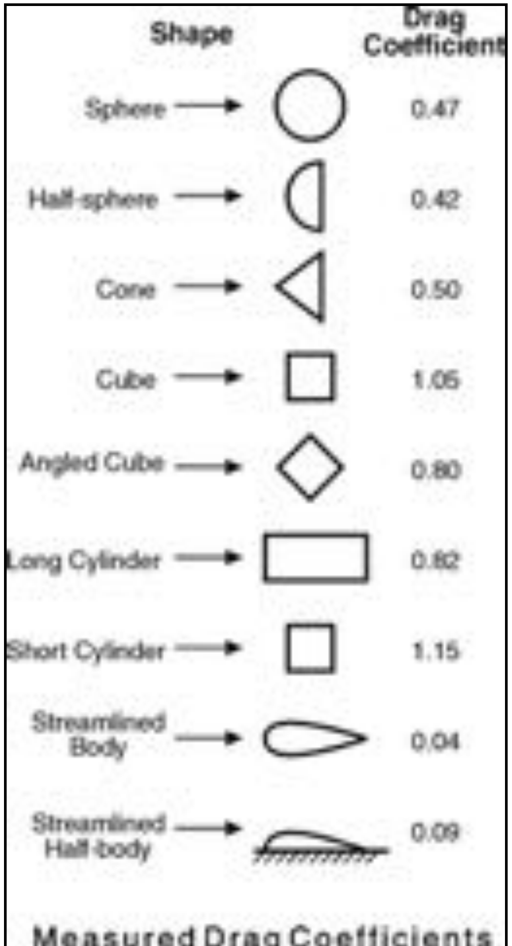


Image from web page: http://www.insideracingtechnology.com/tech102drag.htm

Object (Flow from L to R)	L/d	$Re = Vd/\nu$	C_D
1. Circular Cylinder, Axis Perpendicular to the Flow	1	10^5	0.63
	5		0.74
	20		0.90
	∞		1.20
	5	$>5 \times 10^5$	0.35
	∞		0.33
2. Circular Cylinder, Axis Parallel to the Flow	0	$>10^3$	1.12
	1		0.91
	2		0.85
	4		0.87
	7		0.99
3. Elliptical Cylinder (2:1)		4×10^4	0.6
		10^5	0.46
(4:1)		2.5×10^4 to 10^5	0.32
(8:1)		2.5×10^4	0.29
		2×10^5	0.20
4. Airfoil (1:3)	∞	$>4 \times 10^4$	0.07
5. Rectangular Plate for which L = length, d = width	1	$>10^3$	1.16
	5		1.20
	20		1.50
	∞		1.90
6. Square Cylinder		3.5×10^4	2.0
		$10^4 \times 10^5$	1.6
7. Triangular Cylinder 120°		$>10^4$	2.0
			1.72
60°			2.20
			1.39
30°		$>10^5$	1.80
			1.0
8. Hemispherical Shell		$>10^3$	1.33
		10^3 to 10^5	0.4
9. Circular Disk, normal to the flow		$>10^3$	1.12
10. Tandem Disks, spacing is L	0	$>10^3$	1.12
	1		0.93
	2		1.04
	3		1.54

Image from web page: http://www.dopsys.com/loads.htm

Definition of Reynolds Number

Reynolds number is proportional to { (inertial force) / (viscous force) } and is used in momentum, heat, and mass transfer to account for dynamic similarity. It is normally defined in one of the following forms :

$$\mathrm{Re} = \frac{D.V.\rho}{\mu}$$

$$\mathrm{Re} = \frac{D.G}{\mu}$$

Where:

D	**=**	**Characteristic length**
G	**=**	**Mass velocity**
mu	**=**	**Viscosity**
rho	**=**	**Density**
V	**=**	**Velocity**

Images from web page: http://www.processassociates.com/process/dimen/dn_rey.htm

Drag Coefficient

$$C_d = \frac{g.(\rho - \rho_f)L}{\rho V^2}$$

Where:

g	**=**	**Gravitational acceleration**
L	**=**	**Characteristic dimension of object**
rho	**=**	**Density of object**
rho_f	**=**	**Density of surrounding fluid**
V	**=**	**Velocity**

Images from web page: http://www.processassociates.com/process/dimen/dn_rey.htm

APPENDICES D

Survey Envelopes
(Useful Formulas)

Useful equations for planning your missions

Energy per distance traveled:

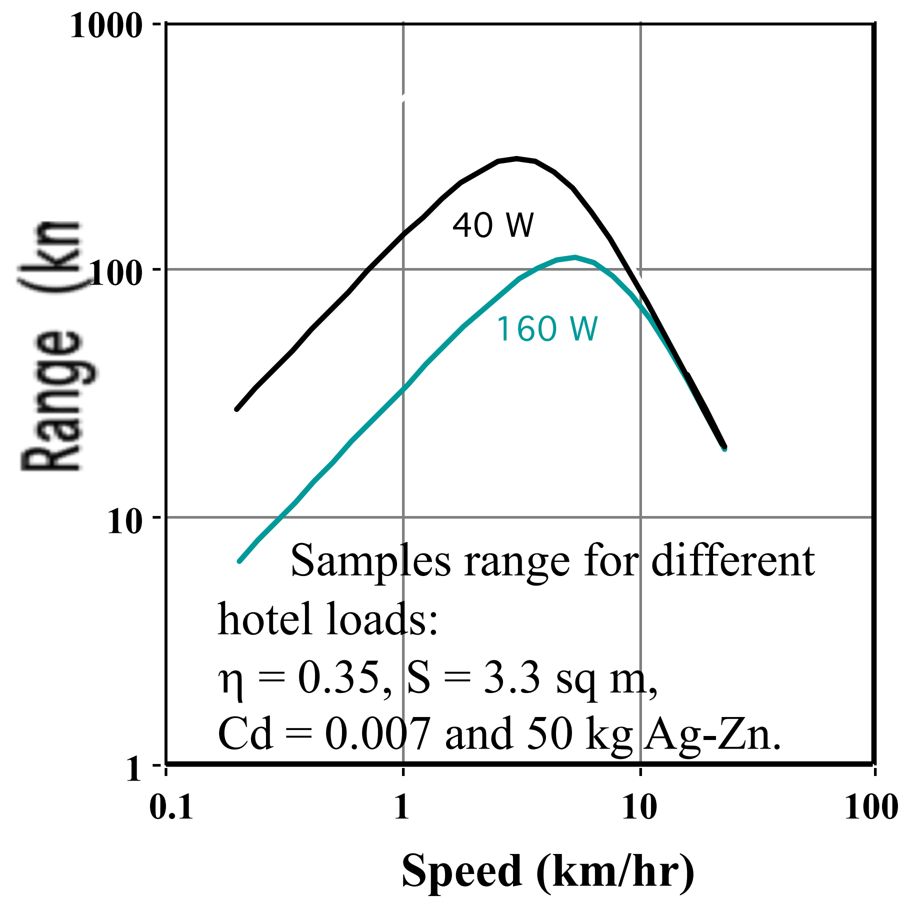
$$e = \frac{1}{2}\frac{\rho\, C_d\, S}{\eta} v^2 + \frac{P_h}{v}$$

Best speed:

$$v_{opt} = \left(\frac{P_h\,\eta}{\rho\, C_d\, S}\right)^{1/3}$$

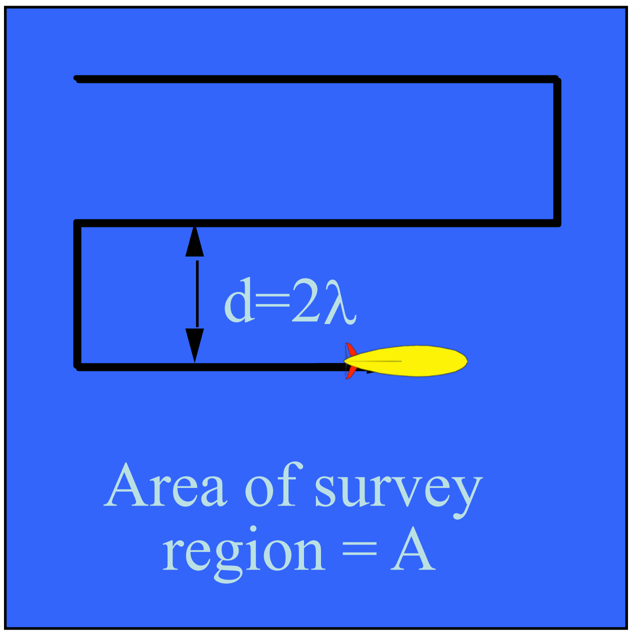
$$\textbf{when}\quad P_p = \frac{P_h}{2}$$

S = effective area of drag



Optimizing Number of Vehicles

Vehicle approaches within λ of any point in region within time τ



Speed to complete survey:

$$v_{eff} = \frac{1}{\tau}\left(\frac{A}{2\lambda} - 2\lambda\right) \approx \frac{A}{2\lambda\tau}$$

Energy per distance traveled:

$$e = \frac{1}{2}\frac{\rho C_d S}{\eta}\left(\frac{v_{eff}}{N}\right)^2 + \frac{N P_h}{v_{eff}}$$

Optimum number of vehicles:

$$N_{opt} = \left(\frac{\rho C_d S}{\eta P_h}\right)^{1/3} \frac{A}{2\lambda\tau}$$

N = number of vehicles

Slide and images courtesy of J.Bellingham

Time Constrained Survey

Cruising speed:

$$v = \begin{cases} \dfrac{d}{f\,\tau} & \text{if } v_{opt} < \dfrac{d}{f\,\tau} \\ v_{opt} & \text{otherwise} \end{cases} \qquad v_{opt} = \left(\frac{P_h\,\eta}{\rho\, C_d\, S} \right)^{1/3}$$

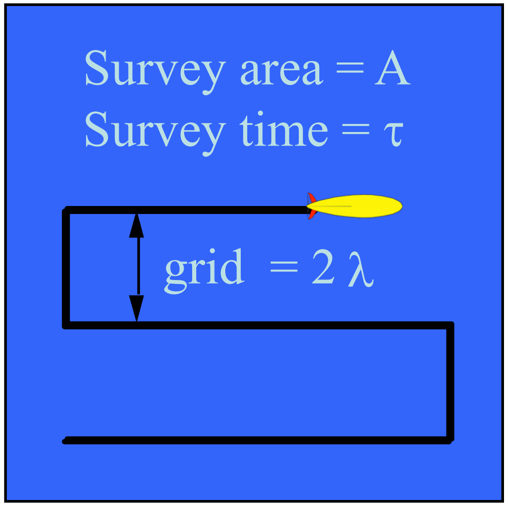
Energy required:

$$E_{as} = \begin{cases} P_h\,\tau + \dfrac{1}{f^3} \left(\dfrac{\rho\, C_d\, S\, d^3}{2\,\eta\,\tau^2} \right) & \text{if } v_{opt} < \dfrac{d}{f\,\tau} \\ \dfrac{1}{f}\,\dfrac{3\,d\,\rho^{1/3}\,C_d^{1/3}\,S^{1/3}\,P_h^{2/3}}{2\,\eta^{1/3}} & \text{otherwise} \end{cases}$$

f = factor of reduced distance based on adaptive sampling, i.e. f = 2 for ½ the distance

Slide and images courtesy of J.Bellingham

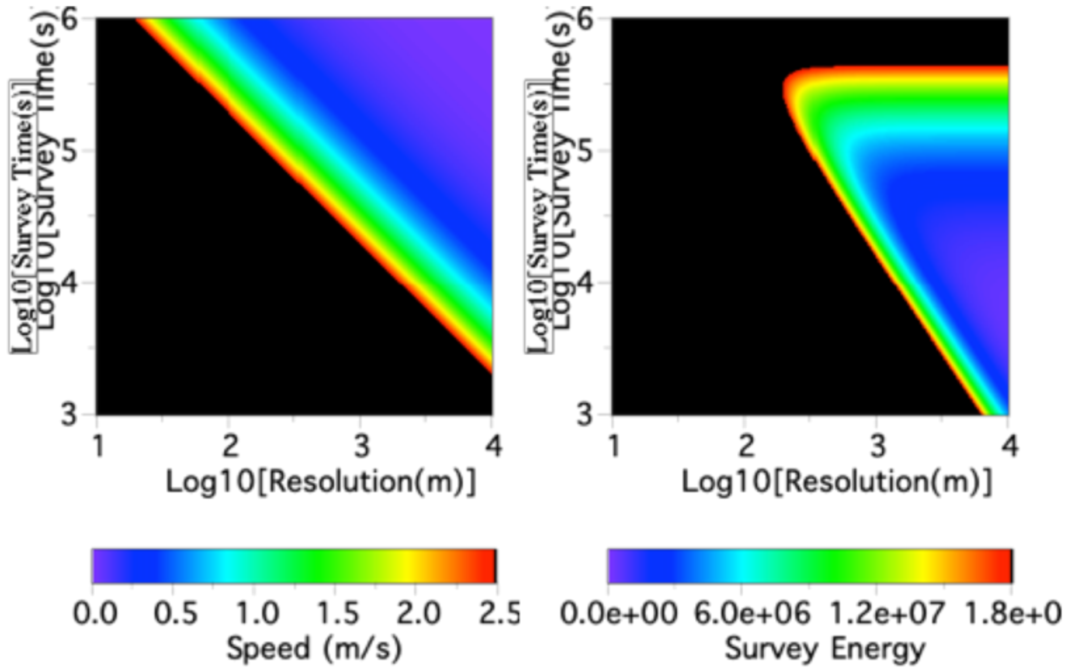
Survey Envelope



Total Survey Distance
d = A/2λ

Required Speed
v = A/2λτ

Example - 100 sq km Area



Slide and images courtesy of J.Bellingham

APPENDICES E

Mission Checklist Sample

(this is a mission sample you will need to modify for your specific mission)

Dorado AUV Mission Checklist

Cruise Information

Date:	Cruise:
Ship:	Vehicle Configuration:

Vehicle Pre-Launch Checklist **Launch Coordinator:**____________________

Item	Reading/Value	Initials
Battery Sphere Sealed (3-5 PSI Vacuum)		
MVC Sphere Sealed (3-5 PSI Vacuum)		
Main Battery Voltage		
USBL Beacon On		
USBL Beacon Voltage		
USBL Transmit/Receive Frequency		
RDF/Strobe On		
RDF Frequency/Channel (C=160.725/D=160.785)		
RDF/Strobe Battery Voltage		
Propeller Set Screws Tight		
Forward & Aft Jbox Compensation Pressure (3-5 PSI)		
Compensation Pressure/Height (verify valve open)		

Dorado AUV Mission Checklist

Payload Pre-Launch Checklist

Payload Coordinator:____________________

Item	Reading/Value	Initials
DCON Compensation Pressure (3-5 PSI OK)		
Optical Backscatter Cap Removed		
Hydroscat Cap Removed		
CTD 1 - Temperature & Salinity		
CTD 2 – Temperature & Salinity		
Hydroscat 2 Operational (External Lights & Software)		
LISST Operational (Pump & Software)		
Biolume Operational (Pump & Software)		
ISUS Operational (Software)		
Confirm $AUV_CONFIG_DIR/devices.cfg correct		

Dorado AUV Mission Checklist

Vehicle Pre-Dive Checklist **Pre-Dive Coordinator:__________________**

Item	Reading/Value	Initials
Elevator & Rudder Actuators Full Range		
Thruster Operational		
DVL Operational		
Parosci (note temperature		
GPS (note fix/no fix)		
MVC Date & Time		
PS8000/LBL		
Metrabyte Battery Voltage & Current		
Crossbow		

AUV Technology and Application Basics

Dorado AUV Mission Checklist

Vehicle Post-Dive Checklist **Post-Dive Coordinator:___________________**

Item	Reading/Value	Initials
USBL Beacon Off		
RDF/Strobe Off		
Vehicle Freshwater Rinse		
LISST Flush		
Bathyphotometer Flush		
HS2 Rinse		
CTD1 & CTD2 Flush		

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APPENDICES F

Materials

- Young’s Modulus and Compressibility
- Density and Specific Gravity
- Yield and Tensile Strength
- Deflection and Displacement
- Corrosion
- Special points on composites and plastics
- Techniques for dealing with corrosion

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- Young's modulus and Compressibility

Young's modulus is the ratio of stress to strain $E = [\text{stress}] \div [\text{strain}]$

Stress is a force per unit area σ (in our case lbs. / sq.in.)

Strain is the dimensionless change in length of a material under stress $e = dl / l$

The bulk modulus is the change in density due to pressure $K = \rho(\delta P \div \delta \rho)$

ρ = density

Compressibility is the inverse of the Bulk Modulus $\beta = 1 \div K$

These material parameters are important since they determine how well a material will hold up strength wise in an application

AUV Technology and Application Basics

- Young's modulus and Compressibility

Material	E	K
Cres-316	28.0×10^6	23.6×10^6
Alum 6061	10×10^6	10×10^6
Ti 6Al-4V	16.5×10^6	
Water		$.32 \times 10^6$

- Density and Specific Gravity

Density = mass / volume (lbs./cu.in.)

Specific Gravity = density / density of water (unit less and we use sea water)

Density of sea water = 64 lbs. / cu.ft.

Density is important to us since it determines the weight in air and is one factor to the weight in water calculation. Specific gravity is key to us since it determines the weight in water

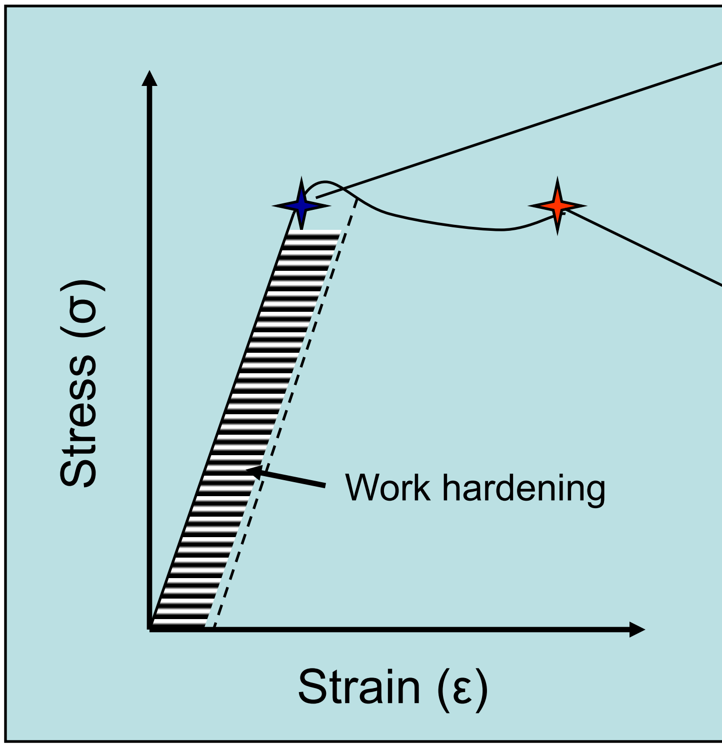
Part A is 25 cu.ft. in volume **Part A is made of Cres316**

Cres316 has a density of .268 lbs./ cu.in.

Part A weighs 11,577.6 lbs. in air and 9,977.6 lbs. in water*

** if I want this thing to float I've got to come up with about 10,000 pounds of buoyancy*

- Yield and Tensile Strength



Yield strength is point where we can exercise the material without deformation

Ultimate tensile strength is the point of failure

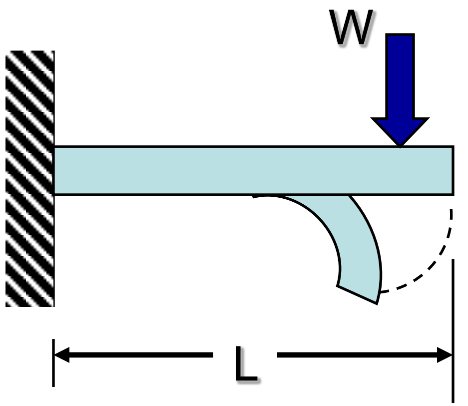
- Yield and Tensile Strength

In 1000 psi

Material	Yield	Tensile
Cres-316	30 - 42	80 - 90
Alum 6061	8 - 40	18 - 45
Ti 6Al-4V	120 - 128	130 -138

- Deflection and Displacement

Deflection : (for our purposes) is the bending of a mechanical component(s) not into the plastic range of the materials curve.

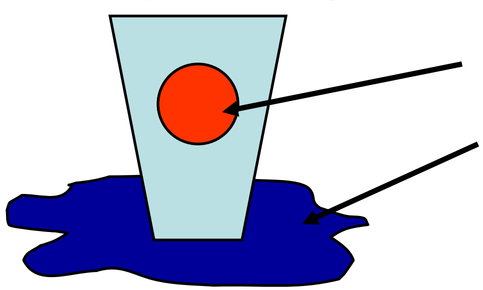


deflection $y = \frac{WL}{3EI}$

y

I is a term called the section modulus. This is a factor that accounts for the shape of the component resisting being deflected about a particular axis

Displacement : for our purposes is the amount of sea water displaced by the component(s) which yields the weight in water.



Component weight A in air

Weight of water displaced B

Component in water C = B - A

- Corrosion

Aluminum 6061-T6

Figure 2.2 Scanning electron micrograph of a corrosion pit on aluminum alloy 6061-T6 after one week in seawater. The diameter of the central pit is about one-thousandth of an inch. Note the extensive branching which amplifies the damage.

Pit corrosion

Image from Handbook of Oceanographic Engineering Materials

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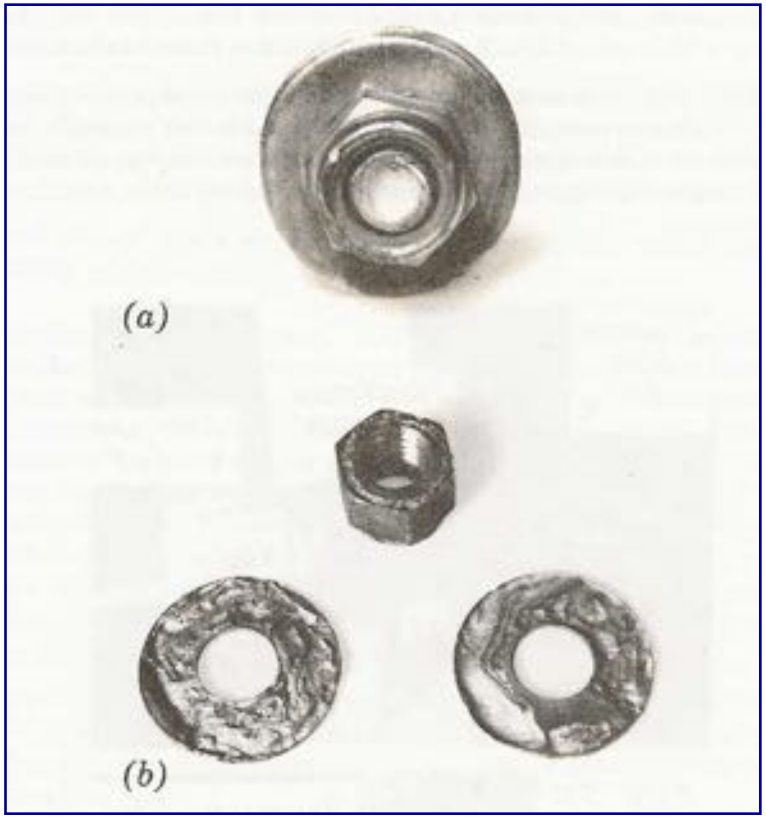
- Corrosion

Stainless Steel – CRES 304



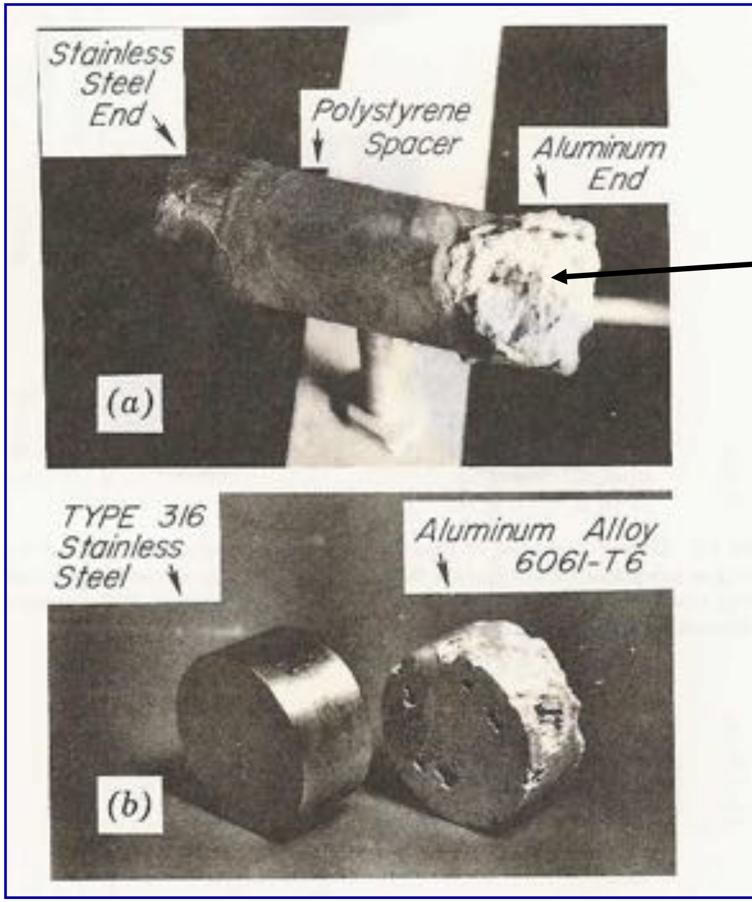
Crevice corrosion

a) as seen assembled in sea water
b) hidden surfaces exposed showing corrosion

Image from Handbook of Oceanographic Engineering Materials

- Corrosion

Stainless Steel to Aluminum



Aluminum acting as sacrificial anode

a) assembled after exposure to sea water
b) hidden surfaces exposed showing corrosion

Image from Handbook of Oceanographic Engineering Materials

- Corrosion

Sample galvanic table in sea water

Material	Calomel Scale (V)
Titanium	+0.06 to -0.05
Lead-tin solder	-0.26 to -0.35
Aluminum	-0.70 to -0.90
Zinc	-0.98 to -1.03
Graphite	+0.3 to +0.2

AUV Technology and Application Basics

- Special points on Composites and Plastics

Great materials in sea water generally

Watch for water absorption

Not necessarily inert

Often have electric potentials

Must also test against other materials being used
(know ester based from ether based in particular)

Watch for cheaper materials with re-grind in them

Filled materials may have water paths

- Techniques for addressing corrosion

Grease – lube the parts that are bolted together well with a water proof grease. Blue Goop (Swagelok) or AquaLube (pool supplies)

Isolation in the design and ground fault sensing

Sacrificial anodes … Zinc or Magnesium depending on the application

Lots of surface area – just leave it bare if it's big enough

Active corrosion control (send a current in the opposite direction)

Annealing of welds

Anodizing, coatings, paint, etc. (these have one problem to watch)

APPENDICES G

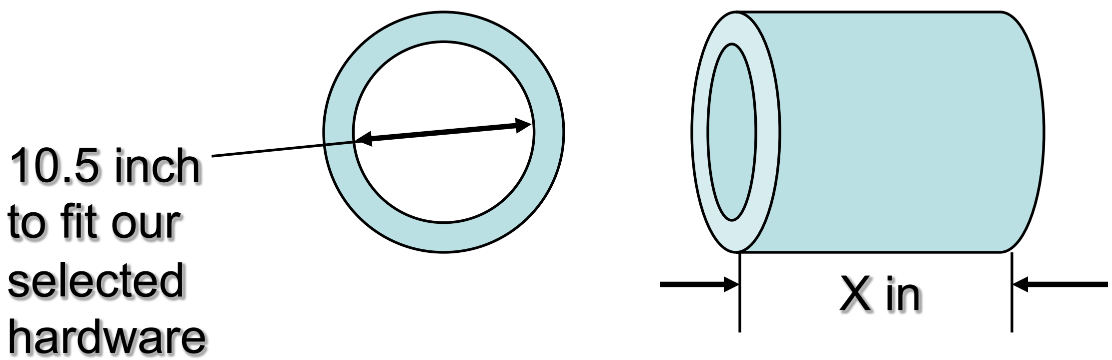
Pressure Vessels

- Design
- Safety
- Testing

Pressure Vessels

Design

We've gotten our functional specs, did our trades, selected an approach, and now we need to design a housing



3000 meter rating including the safety margin

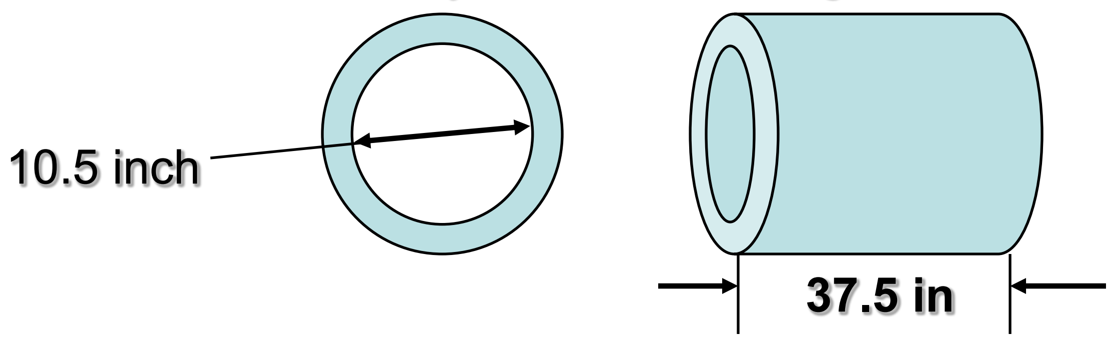
48 inch total internal length with spherical end caps

Material : Aluminum 6061 since it's readily available

Pressure Vessels

Design

To get the can length we'll take the 48 inch max internal dimension and subtract the end caps. The ends caps are spherical halves so the two of them make a complete sphere. We infer that the end caps will have the same internal diameter so 48 – 10.5 yields our can length of 37.5 inches



3000 meter rating including the safety margin

pressure at depth is 3000 m *3.2808 m/ft * 64 lbs. cu.ft. * (1/144) sq.ft./sq.in.

= 4374.3999 **~ 4375 psi**

Pressure Vessels

Design

Elastic bucking pressure of a cylinder (Roarke's reformed in your WHOI Technical Report Handout)

$$p_e = \frac{2E}{1 - \mu^2} (t / D_o)^3$$

p_e = elastic bucking pressure = 4375 psi

E = modulus of elasticity = 10,000,000 psi

μ = Poisson's ratio = .33

t = wall thickness of tube

D_o = outside diameter of tube = 10.5 + 2t

Pressure Vessels

Design

$$p_e = \frac{2E}{1 - \mu^2} (t / D_o)^3$$

substituting:

$$4375 = \frac{2 * 10{,}000{,}000}{1 - (.33)2} (t / D_o)^3$$

$$.000194928 = (t / D_o)^3$$

$$.005798 = (t / D_o)$$

substituting:

$$.005798 = (t / 10.5 + 2t)$$

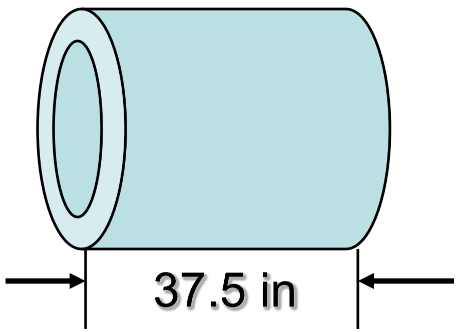
$$.6088 + .11596\ t = t \quad >> \quad .6088 = .884036\ t$$

t = .688659 ~ .690 inch wall thickness rounding ?

the outside diameter is then ID + 2t = **11.88 inches O.D.**

Pressure Vessels

Design



One of the first things we need to know is what does it weigh. Submersible technologies are always sensitive to weight and this may make you go back and change some previous thinking

$$W = \rho\pi\,(r_o^2 - r_i^2)\,l$$

ρ for 6061 aluminum is .098 lbs. cu.in.

$$W_A = .098 * 3.1415 * 37.5\,(5.94^2 - 5.25^2)$$

$$W_A = .098 * 3.1415 * 37.5\,(7.7211)$$

$$\mathbf{W_A = 89.14\ lbs.\ in\ air}$$

$\rho_{sw} = .037$ lbs. / cu.in. $W_{disp} = 153.795$ lbs.

W_{SW} = 153 .795 - 89.14 = **64.655 lbs. buoyant**

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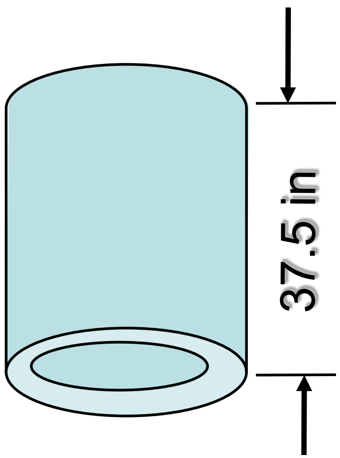
Pressure Vessels

Design



Hypothetical case: (homework has a variant)

I want to know the displacement change of my volume if I alter the length

W_{disp} = .037 * 3.1415 * 37.5 (5.94^2)
is the maximum displacement

If I exchange h for the 37.5 my maximum height I get the amount of new displacement. I then subtract that from the maximum I get the amount of displacement change for the new length.

ΔW_{disp} = .037 * 3.1415 (5.94^2) * 37.5 - h

Pressure Vessels

Sample Pressure Housing Problem and Answers:

One sub-system of our submersible is a variable buoyancy system. This system has to adjust the weight of the submersible by moving 40 lbs of sea water in or out as needed. The material of choice for our buoyancy system is titanium 6Al – 4V since it offers the best all around performance for our needs. The system must operate down to a depth of 4000 meters but we'd like to have a 25% safety factor since this is a pressure housing. For purposes of calculating our housing we'll consider sea water to be incompressible. Internally we've instrumented our housing with a linear height gage to know the height of sea water when adjusting the buoyancy.

Pressure Vessels

1. What is the most economical shape for such a housing to minimize weight in air and maximize performance in sea water?

2. Calculate the housing internal and external dimensions for this variable buoyancy system based on the shape you've selected. (Use the long form of the selected formula for an accurate answer. Rounding appropriately is allowed)

3. What is the weight of our pressure housing in air and what does it weigh in water?

4. Set up the algorithm for our height gage that we need to calculate the weight of water in our variable buoyancy system for any height h of water. Assume our system work perfectly and there is no offset.

5. What is the net buoyancy of our system when the linear height gage reads 2/3 full of water?

Pressure Vessels

1. Sphere

2. Density of sea water is 64 lbs/cu.ft. = .037 lbs/cu.in.
40 lbs divided by .037 = 1081.081 ~ 1081 cu.in.
Volume of sphere is $(4*pi*r^3)/3$ = 1081 >> r = 6.367 >> I.D. ~ 12.75 inch
Using the appendices: Pe = elastic buckling pressure = pressure at depth plus safety

Pe = 4000 meters * 3.2808 m/ft * (64/144) lbs/cu.ft./ sq.ft./sq.in * S.F.
= 13,123.2 (.444) * 1.25 = 7,283.4 psi

Titanium properties : E = 16.5 * 106 psi Young's Modulus
u = .3 Poisson's ratio
p = 0.160 lb/cu.in. density
Sy = 120,000 psi yield strength

2. Continued

Sphere calcs: $P_e = \dfrac{2 * E * t^2}{[\,3\,(1 - u^2)]^{1/2} * R^2}$

where t = wall thickness

R = median radius

$[\,3\,(1 - u^2)]^{1/2} = [\,3\,(1 - .33^2)]^{1/2} = 1.635$ **dimensionless**

$2 * E = 33{,}000{,}000$ **psi**

rearranging the equation becomes $\dfrac{[\,3\,(1 - u^2)]^{1/2}\, Pe}{2 * E} = \dfrac{t^2}{R^2}$

substituting in the numbers it reduces to $.0004 = \dfrac{t^2}{R^2}$

$.0004\, R^2 = t^2$

$R = (Ro + Ri)\,/2$ $\qquad\qquad$ $Ro = Ri + t$

$R^2 = [(Ri + t + Ri\,)/2]^2 = [\,(2Ri + t)/2]^2$

2Ri = I.D. = 12.75 inches >> $[\,(2Ri + t)/2]^2 = (6.367 + t/2)^2$

$(6.367 + t/2)^2 = 40.539 + 6.367\, t + .25\, t^2$

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Pressure Vessels

2. Continued

substituting $.0004\ (40.539 + 6.367\ t + .25\ t^2) = t^2$
reducing the equation $.016 + .003t + .0001\ t^2 = t^2$

further reducing $t^2 - .003t - .016 = 0$

solving the quadratic $t = .003 + (.00001 + .064)^{½}$ $t = .256 /2 = .128$ inches sq

therefore the sphere dimensions are 12.75 inches I.D. and approximately 13.00 inches O.D.

3. The weight of the sphere is the outside diameter volume minus the internal volume times the density in air.

$W = p\ (V_o - V_i)$

$V = (pi * d^3) / 6 = 0.524\ d^3$

substituting $W = .160 * 0.524\ (d_o^3 - d_i^3)$

W = .160 * 0.524 (13.003 – 12.753) = .160 * 0.524 (2197 – 2072.7)

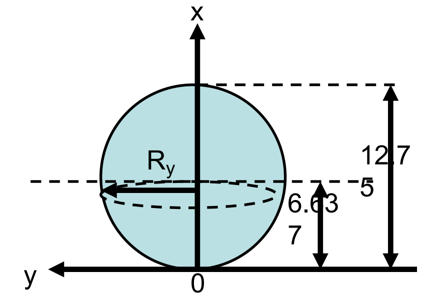
= .160 * 0.524 (124.3) = 10.413 lbs. ~ 10.4 lbs. in air

Maximum buoyancy in sea water is equal to the maximum displacement of a completely empty sphere minus the weight in air. The maximum displacement is:

Max. Disp. = $p_{sw}V = (pi * d_o^3) / 6$ p_{ew} = 64 lbs./cu.ft. = .037 lbs./cu.in.

Max. Disp. = .037 * 0.524 (2197) = 42.595 lbs.

Therefore the spheres weight in sea water is 42.595 – 10.413 = 32.2 lbs. positive



4. R_i = 6.367 inches R_y = water radius @ hgt x
Equation of a circle $X^2 + Y^2 = C^2$ C being the radius
Substituting for our circle $(x - 6.367)^2 + (y - 0)^2 = (6.367)^2$
$x^2 - 12.75x + 40.539 + y^2 = 40.539$
$y^2 = 12.75x - x^2$ >> $y = R_y = (12.75x - x^2)^{½}$

Calculating the volume of water for a given height h :
area at any small delta h is equal to pi * R^2 along the x axis
the volume of water is given by the integral function Vw = pi $\int y^2\,dx$ for x from 0 to h
substituting for y^2 we get $V_w = pi \int (12.75x - x^2)\,dx$
solving we get $V_w = pi\left(\frac{12.75\,h^2}{2} - \frac{h^3}{3} + C\right)$ for x equal to h

C goes to zero since we assume there is no offset in our system
substituting V_w for V in $W = p_{sw}V$ we get $W_w = p_{sw} * pi\left(\frac{12.75\,h^2}{2} - \frac{h^3}{3}\right)$

h is in inches and W is in lbs. p_{sw}

5. When our buoyancy at gage height h reads
2/3 h = .666 * 12.75 = 8.49 ~ 8.5 inches

calculating out the formula the weight of water in the sphere is

$$W_w = .037 * 3.1415 * \left(\frac{12.75 * 72.250}{2} - \frac{614.125}{3}\right)$$

$$W_w = .037 * 3.1415 * (460.594 - 204.708) = 29.743 \text{ lbs.}$$

The net buoyancy is the max displacement minus the weight of the water in the sphere

Therefore the net buoyancy at 2/3 full of sea water is
32.2 – 29.7 = 2.5 lbs. buoyant

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Pressure Vessels

Safety

General notes:

Your designs should have considerations for failure

Put ports behind bolts and other areas that are not part of the pressure housing internal volume

Put a purge port / vent for safety in case of an unknown condition (recall that compressed air is stored energy, water itself is not that compressible to be concerned about)

If the application is external pressure use only enough screws to hold it together in air safely … let the water do the work submerged

Unless you know the condition for certain approach all pressure vessels with a cautious procedure

Only use pressure housings when you need to, oil comps work wonders

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Pressure Vessels

Testing

If you have a chance, pull a vacuum on the housing to test the seals are seating and everything is in place properly

When testing a pressure vessel fill the void with something that will take up as much of the air volume as possible.

Make sure what you use in the test is dry (vacuum pull if you need to to take out the moisture, otherwise you might get a false reading)

At the surfaces you are sealing use a marker to see if there is a weep (diesel fuel water testing supplies work well – KolorKut)

If a vessel implodes be extremely cautious – there could be stored energy
> control the pressure bleed off and see if it fluctuates
> let the housing sit undisturbed if you can't tell it's got open the atmosphere – open a purge port if it is safe to do so

Check the test equipment prior to any further testing

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APPENDICES H

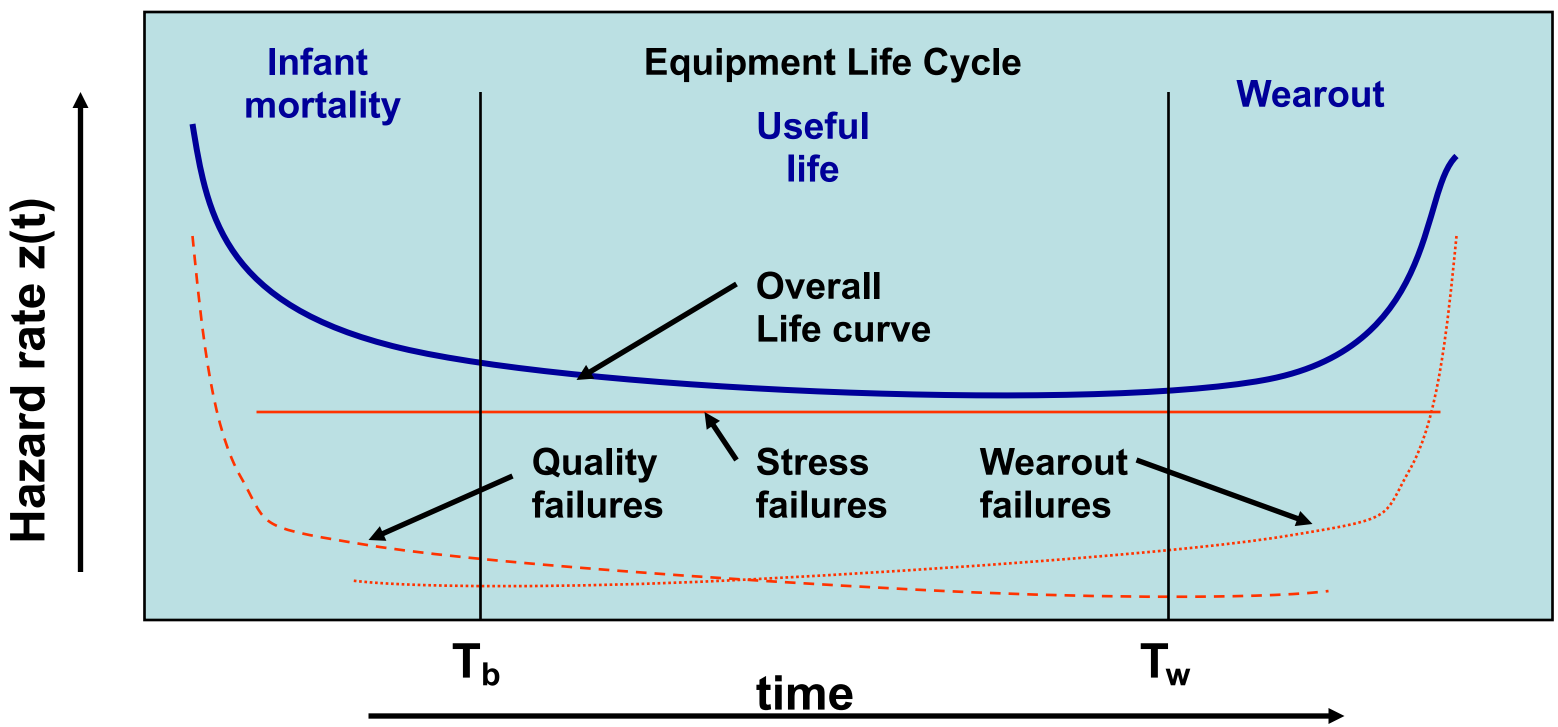
Systems Design Reliability

Systems Design

Reliability and MTBF

Reliability is the measure of the robustness of the design and implementation

MTBF – Mean Time Between Failure



Reliability and MTBF

The previous figure illustrates that during the useful life period the “hazard rate” is constant. With some hand waving (trust me on this) the failure rate is described by the exponential failure distribution (realize the rate is constant but a system of parts is what combines to make the constant). So if a fixed number of N_o of components are repeatedly tested for a time t there will be N_s components that survive and N_f components that failed.

The reliability (or probability) of survival at time t is expressed as:

$$R(t) = \frac{N_s}{N_o} = \frac{N_s}{N_s + N_f}$$

Reliability and MTBF

$$R(t) = \frac{N_s}{N_o} = \frac{N_s}{N_s + N_f}$$

$$N_s = N_o - N_f$$

We can rewrite $R(t) = \frac{N_o - N_f}{N_o} = 1 - \frac{N_f}{N_o} = 1 - F(t)$

Then $\frac{dR}{dt} = \frac{-1}{N_o} \frac{dN_f}{dt} = -f(t)_i$

$-f(t)_i$ is the density function or probability that a failure will occur in the next time increment dt

$$z(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)}$$

z(t) is defined as the ratio of fractional failure rate to the fractional surviving quantity, or the number of components working at time t, or restated the conditional probability of failure

Reliability and MTBF

$$z(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)} = \frac{f(t)}{1 - \int_o^t f(t)dt}$$

For the exponential distribution

$$f(t) = \lambda e^{-\lambda t}$$

$$z(t) = \lambda$$

Based on our assumptions earlier the failure rate is constant for an element over the practical intervals of time being considered

Therefore $z(t)_i = \lambda_i$ is a constant representing the expected number of random failures per unit of operating time for the i^{th} element

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Systems Design

Reliability and MTBF

$$z(t)_i = \lambda_i = \frac{f(t)_i}{R(t)_i} = \frac{\frac{-dR(t)_i}{dt}}{R(t)_i}$$

Solving the equation we get $R(t)_i = e^{-\lambda_i t}$

The mean time to failure is determined by

$$MTBF = \int_o^\infty R(t)dt$$

Therefore $MTBF_i = \int_o^\infty e^{-\lambda_i t}\, dt = \frac{1}{\lambda_i}$

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Systems Design

Reliability and MTBF

Systems modeling concepts

1) Reliability as it impacts personnel safety

2) Reliability as it impacts missions success

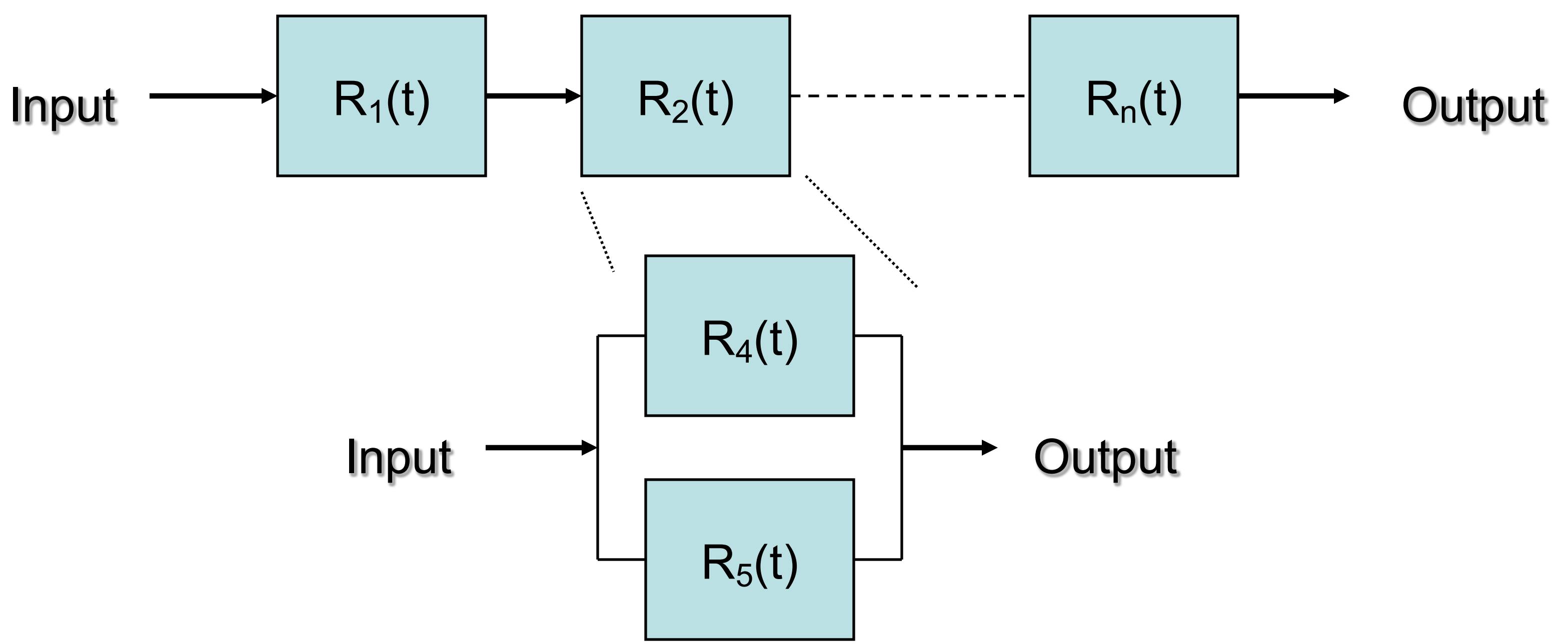
3) Reliability as it impacts unscheduled maintenance of logistics

Systems Design

Reliability and MTBF

Systems modeling concepts

Serial $R_s(t) = R_1(t) \bullet R_2(t) \bullet\bullet\bullet R_i(t) \bullet\bullet\bullet R_n(t)$



Parallel $R_p(t) = 1 – (1 - R_4)(1 - R_5\ )$

Systems Design

Reliability and MTBF

$$R(t) = e^{-(\lambda_1 + \lambda_2 + \dots + \lambda_n)t}$$

$$\text{let } \lambda_j = \sum_{i=1}^{n} \lambda_i$$

$$\text{Therefore MTBF of a system is } = \frac{1}{\lambda_j} = \frac{1}{\sum_{i=1}^{n} \lambda_i}$$

reference: Bazovsky, I. “Reliability Theory and Practice”, 1961, Prentice-Hall Englewood Cliffs, New Jersey.

Military Standard 785A, “Reliability Program for Systems and Equipment Development and Production, March 1969.

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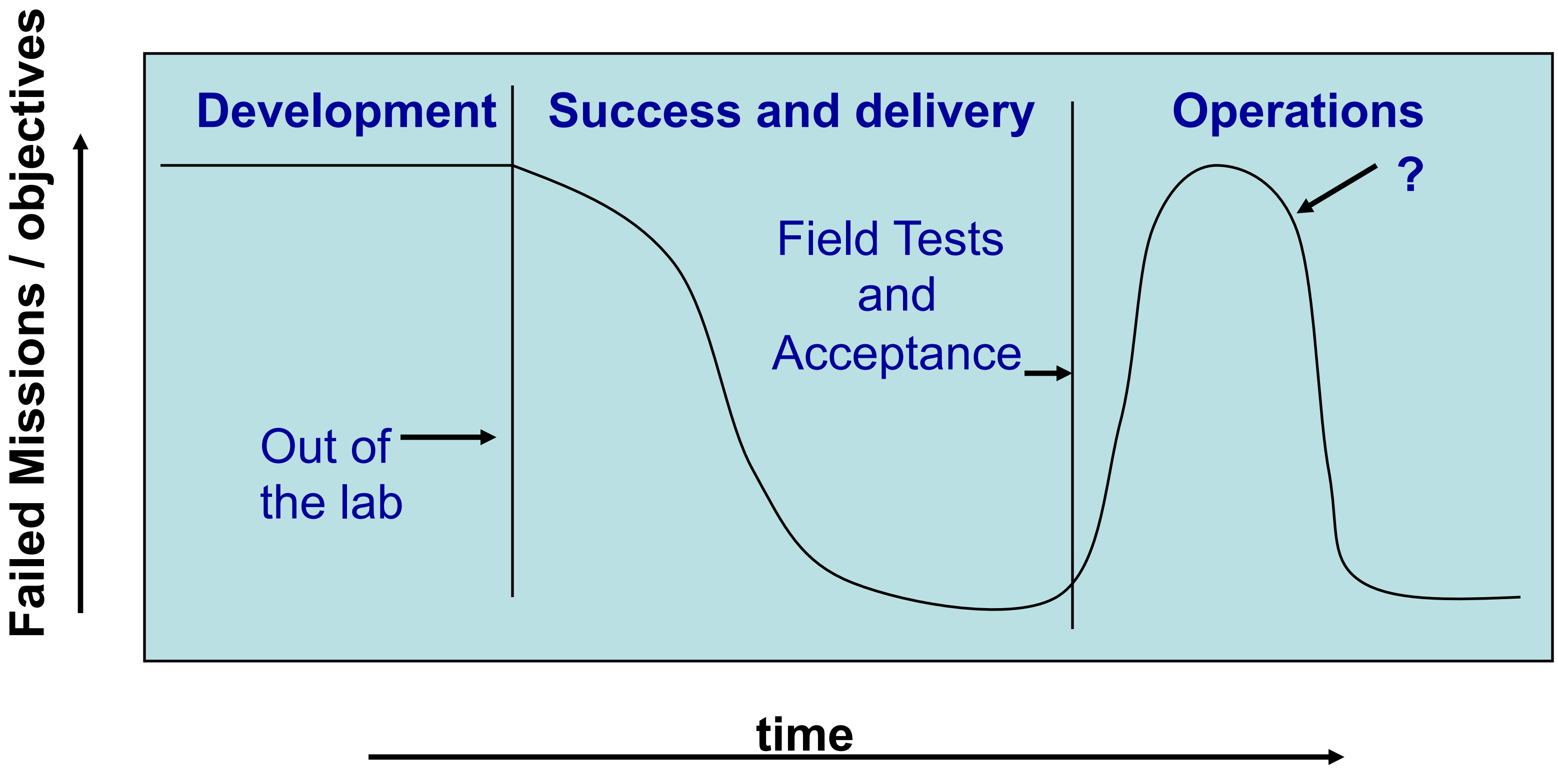
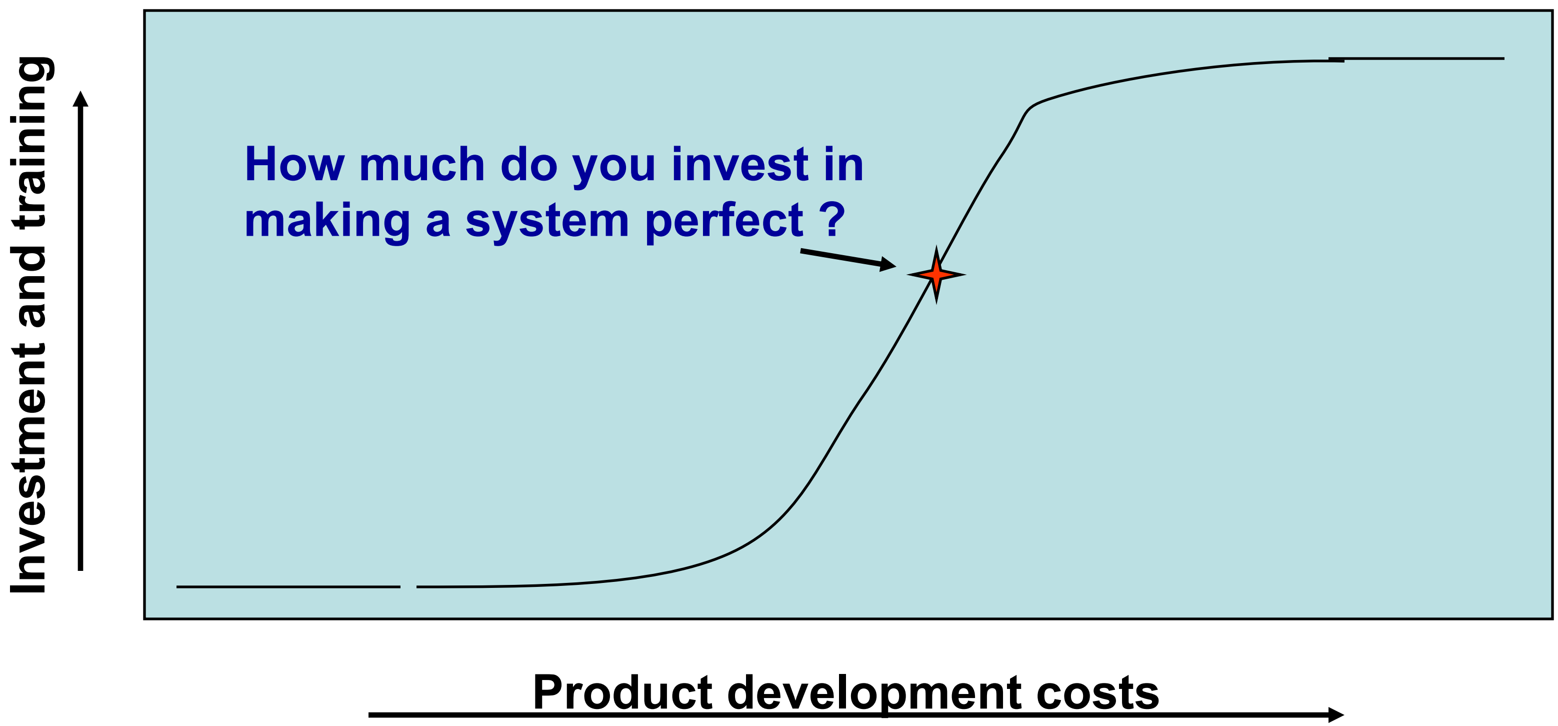
Systems Design

Expert User and Operations



Systems Design

Expert User and Operations



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APPENDICES I

Acoustic Basic Concepts and Equations

Acoustics

Acoustics The science dealing with the transmission of sound waves

Amplitude Shading A method of reducing the side lobe levels in a transducer array. The shading usually causes the main beam to broaden by applying different voltages to the elements of the array.

Attenuation To lessen, weaken, or diminish (i.e. to weaken a signal)

Beacon (Acoustic) An underwater device which continually sends out a repetitive signalat a preset frequency. Pingers are used to mark locations or objects underwater for later recovery or relocation. The amount of time a pinger can be deployed is dependent on its battery life.

Definitions from web page http://www.itc-transducers.com

Acoustics

Beam Pattern Beam patterns show the relative amplitude of the acoustic pressure (generated or received) as a function of direction relative to the transducer. For reciprocal transducers the transmit and receive beam patterns are basically the same. Beam patterns are three-dimensional.

Beam Steering The method of steering the main lobe of a transducer to a certain direction.

Beam Width The width of the main beam lobe, in degrees, of the transducer. It is usually defined as the width between the "half power point" or "-3dB" point.

Definitions from web page http://www.itc-transducers.com

Acoustics

Blanking Distance Minimum sensing range in an ultrasonic proximity sensor. Blanking distance is a function of the ring down time of the transducer as the transducer must ring down before it can receive the sound reflected from the target.

Damping Materials, design, and mounting techniques used to reduce ringing in the transducer.

dB (Decibel) A unit of measure used to express the volume of a sound

Doppler Technique for calculating the relative velocity between two points by measuring the shift in frequency of a sound wave transmitted from one point to the other.

Definitions from web page http://www.itc-transducers.com

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Acoustics

Directivity Index The value in dB of ten times the common logarithm of the directivity factor. The directivity factor is the ratio of the sound intensity produced by a test transducer on a specific axis to that of a point source that is putting out the same acoustic power. Since the specific axis is usually one of maximum radiation, the DI in usually greater than zero.

Echo Location Determining the location of a target relative to the sensor face by means of measuring the time it takes for a sound wave to travel to the target and be reflected back to the sensor.

Definitions from web page http://www.itc-transducers.com

Acoustics

Efficiency In a projector efficiency is defined as the ratio of the acoustic power generated to the total electrical power input. Efficiency varies with frequency and is expressed as a percentage.

Frequency The number of cycles per second of a wave (i.e. sound wave)

Hydrophone A hydrophone converts acoustic energy into electrical energy and is used in underwater passive systems for listening only. Hydrophones are usually used below their resonance frequency over a much wider frequency band where they provide uniform output levels.

Definitions from web page http://www.itc-transducers.com

Acoustics

Hydrophone Directivity The beam width of a hydrophone determines its directivity. A narrow beam will give it greater directivity, i.e. allow determination as to the direction a sound wave is coming from.

kHz (kilohertz) Unit of frequency, equal to one thousand hertz or cycles per second.

Level Sensor Same as a proximity sensor except with the surface of a fluid or bulk solid as the target.

Main Lobe The main acoustic beam in a directional transducer. There are other, smaller lobes called side lobes that are located around the main lobe

Definitions from web page http://www.itc-transducers.com

Acoustics

Maximum Response Axis The MRA or acoustic axis of a transducer is defined as the direction in which the acoustic response has its maximum value.

Omnidirectional Sending or receiving sound waves in or from any direction. 360 degrees receiving capability

Open Circuit Voltage The OCV is the level of the electrical output per one micropascal of acoustic input.

Piezo-electric ceramic A material made of crystalline substance which creates charges of electricity by the application of pressure and vice versa.

Pinger See Beacon (Acoustic)

Definitions from web page http://www.itc-transducers.com

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Acoustics

Projector A projector converts the energy from a power amplifier (generator) into an acoustic pressure output. Projectors are usually driven near their resonance frequencies where they provide the highest acoustic output. Projectors are sound sources.

Proximity Sensor Ultrasonic sensor designed to measure the distance from the sensor face to a target.

Receiver Transducer used to intercept the acoustic wave reflected back from the target. Can be same as transmitter.

Definitions from web page http://www.itc-transducers.com

Acoustics

Resonant Frequency The frequency at which a piezo-electric ceramic will vibrate most efficiently i.e. will produce the highest output with the least amount of voltage applied.

Ringing Analogous to the ringing of a bell, it is the rise and decay time before and after the transducer reaches maximum amplitude. Expressed as the mechanical Q of the transducer which is the number of cycles it takes to get up to 90% of maximum amplitude, or down to 10% above zero amplitude.

Side Lobe Smaller acoustic beams located around the main lobe.

Definitions from web page http://www.itc-transducers.com

Acoustics

Sonar Word is derived from "sound navigation and ranging." It describes a devise that transmits frequency sound waves in water and registers the vibrations reflected back from an object. It is used in detecting objects such as submarines, locating schools of fish, or determining water depth.

Source Level Sound pressure (acoustic power) in dB referenced to 1.0 microPascal measured at 1 meter (one foot in air) from the sound source.

Sub-bottom Profiling Determining the sedimentary structure of the ocean floor by utilizing sound waves.

Definitions from web page http://www.itc-transducers.com

Acoustics

Target Strength A measure of the percentage of the acoustic energy hitting the target that is reflected back to the transducer.

"Time-of-Flight" Technique for calculating the distance to a target by using the timing of the return echo from the target and the speed of sound in the medium between the target and the sensor. Used in echo location and ultrasonic flowmeters.

Transducer In acoustics this term is used to describe an antenna which converts electrical energy into sound wave and vice versa.

Transmitter See "Projector".

Definitions from web page http://www.itc-transducers.com

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Acoustics

Transponder (Acoustic) A devise that automatically transmits sonar signals when actuated by a specific sonar signal from an interrogator. Transponders are used to mark or track objects or sites underwater. They are programmed to be in a continuous passive (listening) mode until they receive a valid signal from a transponder interrogator.

Transmit Current Response (TCR) The level of the acoustic output referenced to one meter (one foot in air) per one amp input

Definitions from web page http://www.itc-transducers.com

Acoustics

Transmit Voltage Response (TCR) The level of the acoustic output referenced to one meter (one foot in air) per one volt input

µPa (microPascal) A unit of pressure used in acoustics

µbar A unit of pressure used in acoustics

Definitions from web page http://www.itc-transducers.com

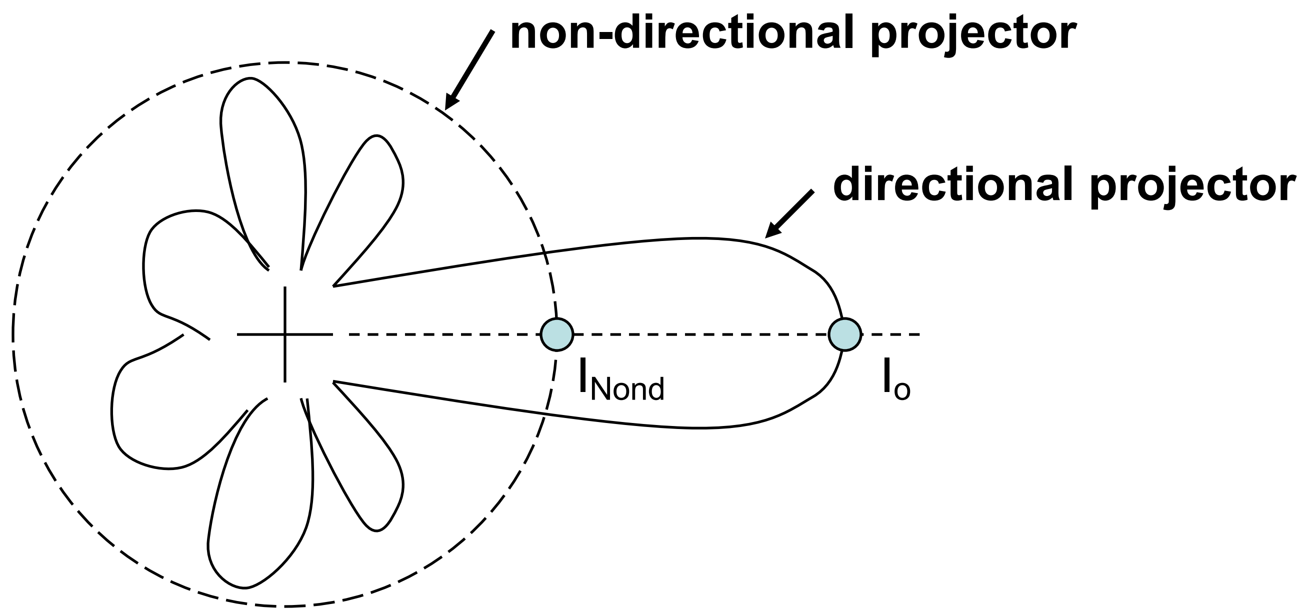
Sonar Topics

Acoustics are the eyes of the ocean and we have only scratched the surface of topics and issues …

The elements and tools in acoustics span all of the areas we would normally consider in vision systems adding in the effects of spring mass systems.

Parabolic reflectors, acoustic lenses, vibrations, self generated noise, electrical noise, along with all the electro-mechanical and other inputs that make noise!

Acoustic Beam Patterns



Bean Patterns of a directional projector and the equivalent nondirectional projector

Acoustic Definitions

Intensity – sound power per unit area proportional to the square of the pressure per:

$$I = p^2 / \rho c$$

ρc is the product of density and the speed of sound

Logarithms of the ratios of intensity in decibels are used for sonar calculations:

$$\text{Decibels} = 10 \text{ Log } (I / I_{ref})$$

I_{ref} is the intensity of the reference wave assumed to be a plan wave of root-mean-sqaure equal to 1 μPa.

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Acoustic Definitions

Example: A sound wave having 100 times the intensity of the reference wave (and therefore a pressure 10 times greater) would have a level of 20dB // 1 μPa.

All sonar calculations are expressed in decibels. This is because it permits the multiplication of quantities by adding decibels equivalents. It's a historic condition from the lack of pocket calculators and pretty handy overall.

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Propagation of Sound in the Sea

Attenuation of sound in the sea is caused by several factors. The main classifications are spreading, scattering, diffraction, and absorption.

These factors combine to weaken the signal be removing energy from the acoustic beam.

Absorption **is the loss of sound to heat.**

Transmission Loss

Transmission loss (TL) is used to express the sum of these attenuation losses.

$$TL = 10 \text{ Log } (I_1 / I_r)$$

where I_1 is the intensity at 1 yard (.9 m) of the source and I_r is the intensity at some distance r yards.

Although TL is a positive from the equation above (I_1 always being greater than I_r) common usage in sonar equations shows the number as negative because it is a loss.

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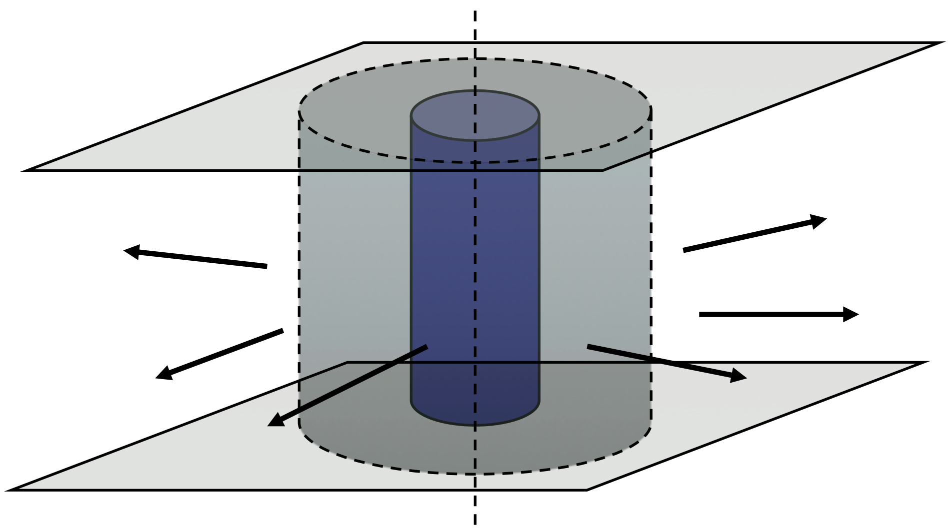
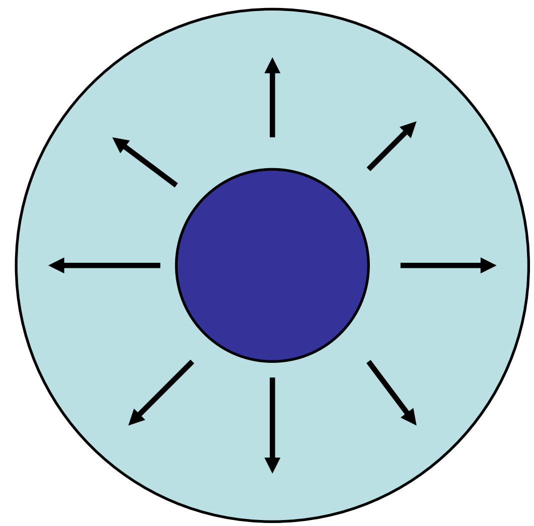
Propagation of Sound in the Sea

Two types of Spreading occur, cylindrical and spherical.



Ducts: Cylindrical Spreading



Free Field: Spherical Spreading

Transmission Loss by Spreading

Transmission loss (TL) is uniform over a sphere or hemisphere. The area of a sphere increases as the square of r, so the intensity (energy/area) varies as 1/ r^2. Therefore:

$$TL = 20 \text{ Log } r + c$$

Cylindrical spreading occurs when the sound spreads uniformly over a cylinder that expands with distance. The area of a cylinder increases linearly with r, so the intensity (energy/area) varies as 1/ r. Therefore:

$$TL = 10 \text{ Log } r + c$$

Transmission Loss with Absorption

One of the major attenuation components contributing to TL is absorption. The amount of intensity lost to heat is proportional to the original intensity at some distance. TL due to absorption increases linearly with range and combines directly:

$$TL = 20 \text{ Log } r + \alpha r \times 10^{-3}$$

where α is the absorption coefficient in dB/kyd and r is in yards. α generally increases as the square of frequency

Very rough estimate: if α is .1 at 2 kHz it is about 1.0 at 20 kHz and 10 at 200 kHz

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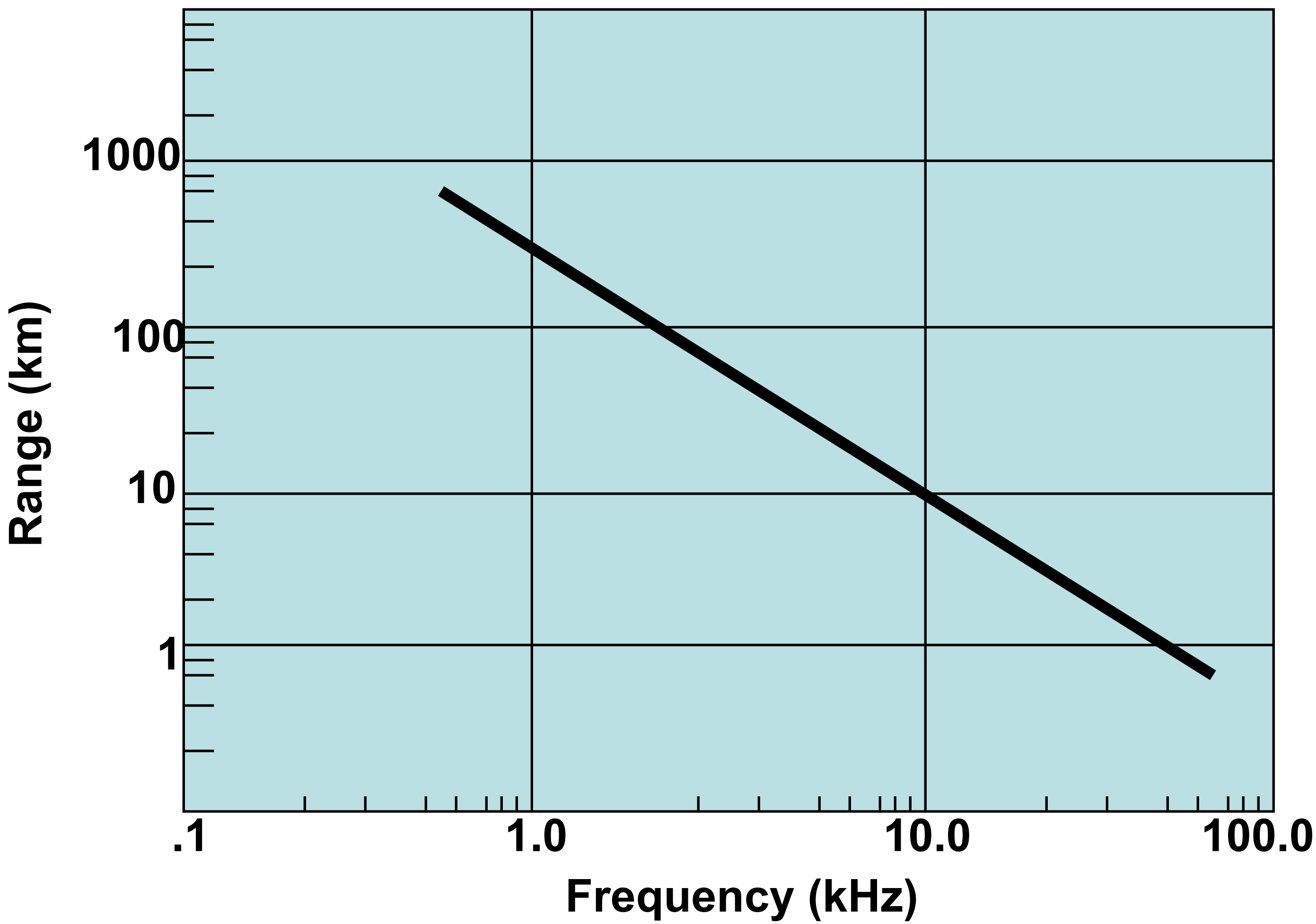
Range at which Absorption approximates 10 dB



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Variation of the Speed of Sound with Depth

This variation is termed the sound speed profile and is very important in modifying the spreading laws and determining the sound field at a distance. The speed of sound is in water is determined by temperature, salinity, and depth. The basic formula is:

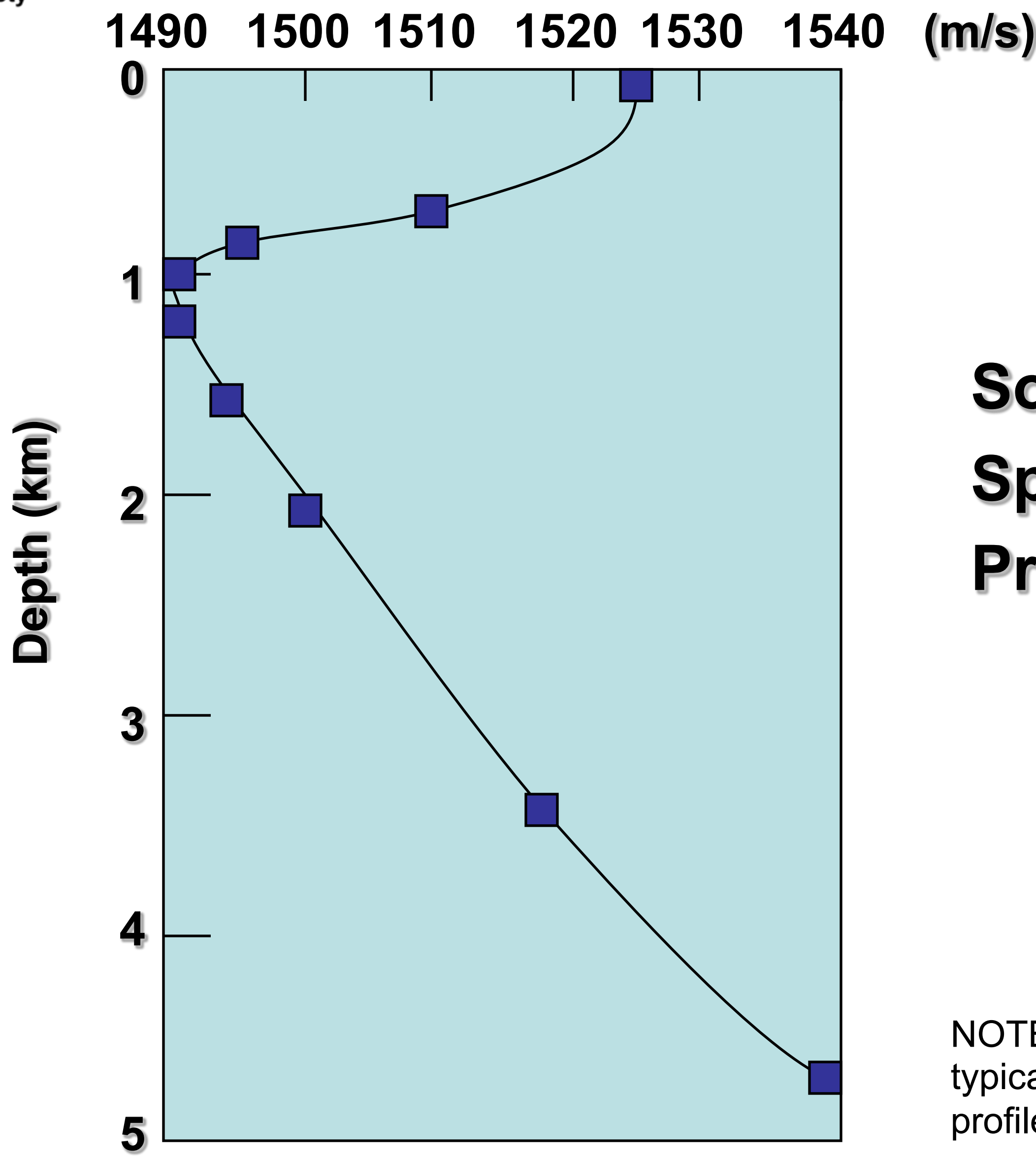
$$c = 1449 + 4.59T - 0.053T^2 + 0.0163D$$

where:

c = speed of sound (m/sec)
T = temperature in degrees centigrade
D = depth in meters

Salinity is not considered here since it is negligible compared with Temperature however some applications do include it

AUV Technology and Application Basics



Sound Speed Profile

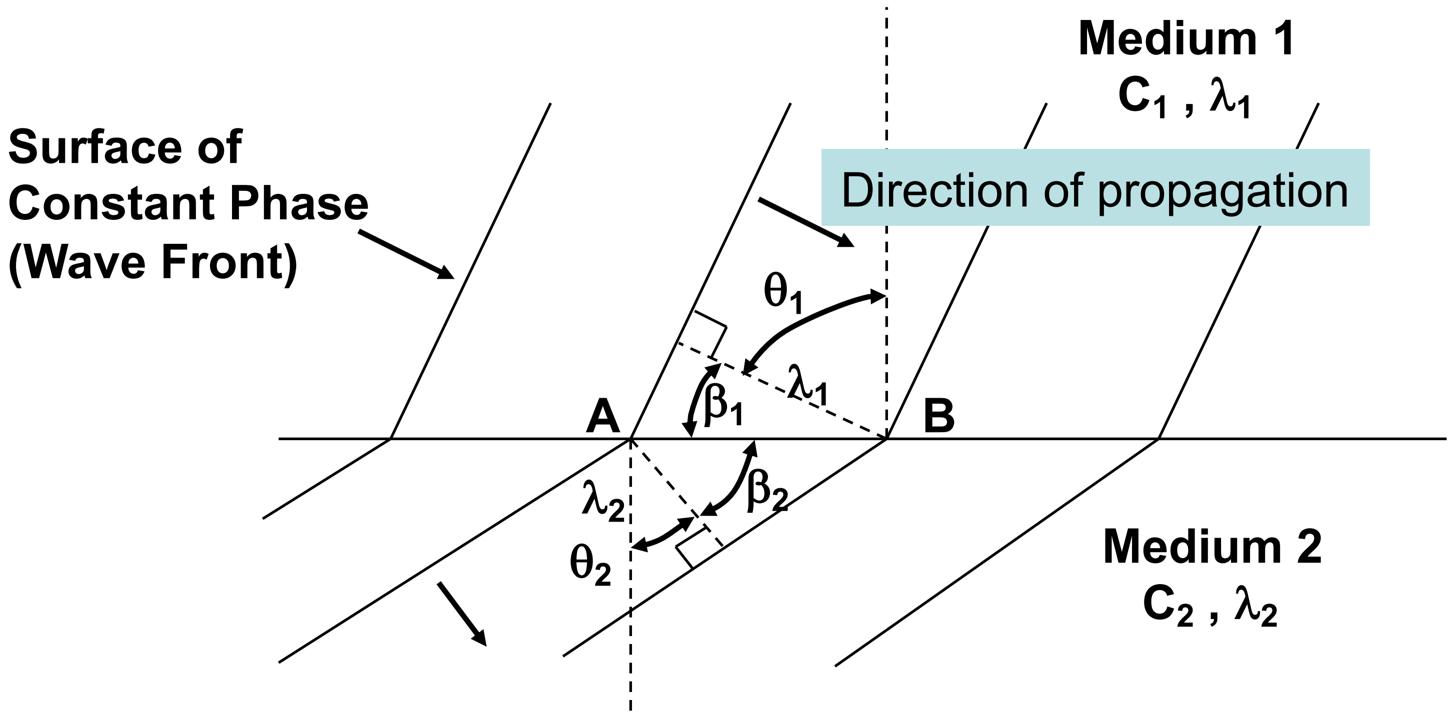
NOTE: This is an example of a typical profile, sound speed profiles are not constant

Snell's Law and Ray Tracing

If the sound speed profile is divided into layers and the speed is assumed to be constant in each one, the sound is refracted according to Snell's Law when traveling between two layers.

This law provides the basis for Ray Trace programming when traveling from layer to layer. Horizontal changes in water depth and speed profile are readily accommodated by these programs.

Snell's Law



$AB = \lambda_1 / \cos \beta_1 = \lambda_2 / \cos \beta_2$

Since $\lambda = c/f$, $c_1 / \cos \beta_1 = c_2 / \cos \beta_2$ or

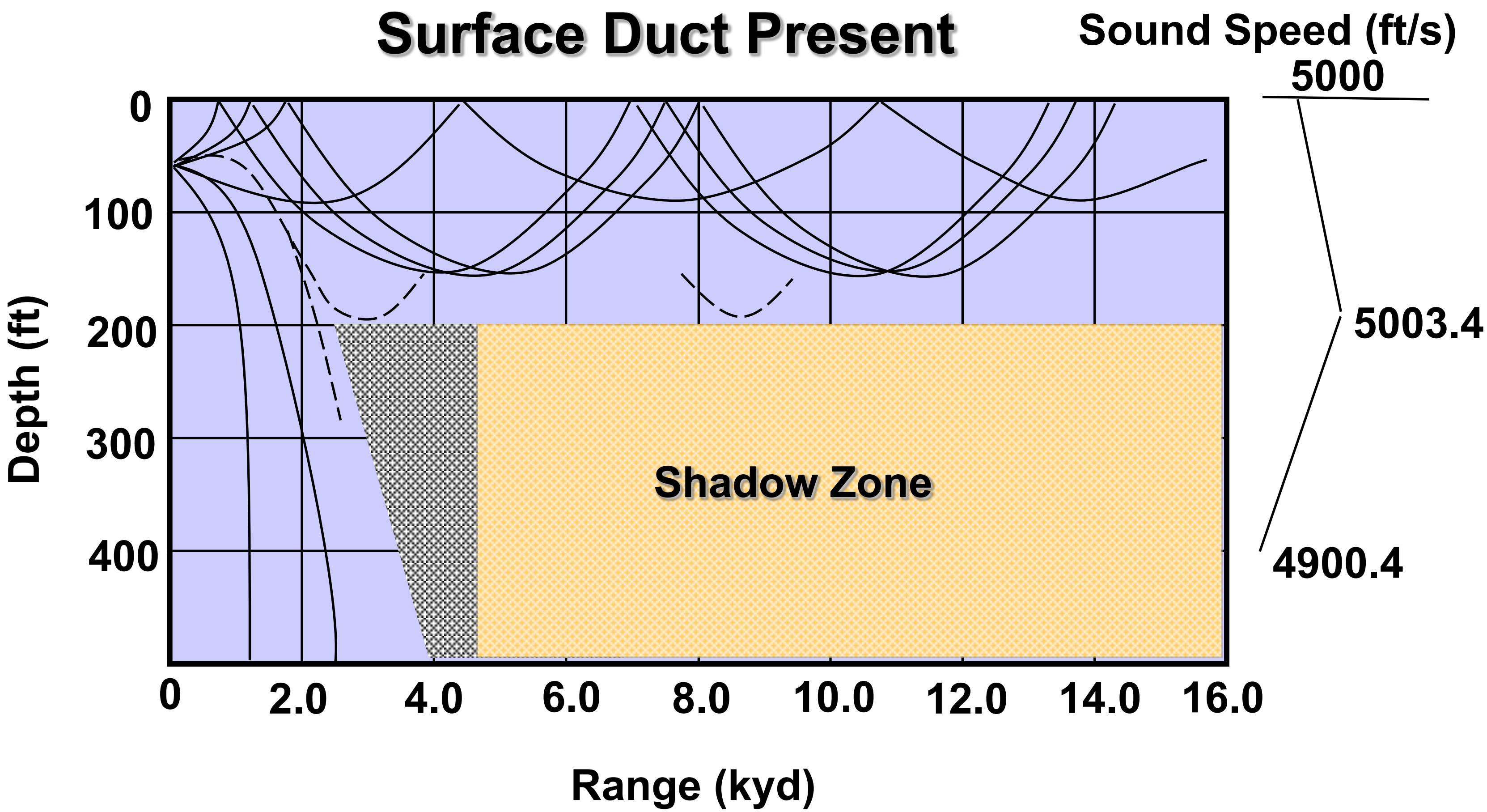
$c_1 / \sin \theta_1 = c_2 / \sin \theta_2$

Ducting

A surface duct occurs when near surface water becomes mixed due to wind turbulence causing an isothermal layer. The layer is characterized by a positive gradient effect on speed of sound. The sound travels outward in a series of upward arcs that meet the air-water interface. There is a "shadow zone" below the layer where only weak diffracted and/or surface scattered sound penetrates. The shadow area is *acoustically black* and any sound in it is weak and incoherent (i.e. this area is devoid of source sound)

When the duct is thick and the surface calm the duct provides an excellent low-loss channel for long range sonars. When the duct is thin, not developed well, and/or the surface is rough the duct can have excessive losses.

Ducting


Surface Duct Present
Sound Speed (ft/s)
5000
5003.4
4900.4
0
100
200
300
400
Depth (ft)
Shadow Zone
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Range (kyd)

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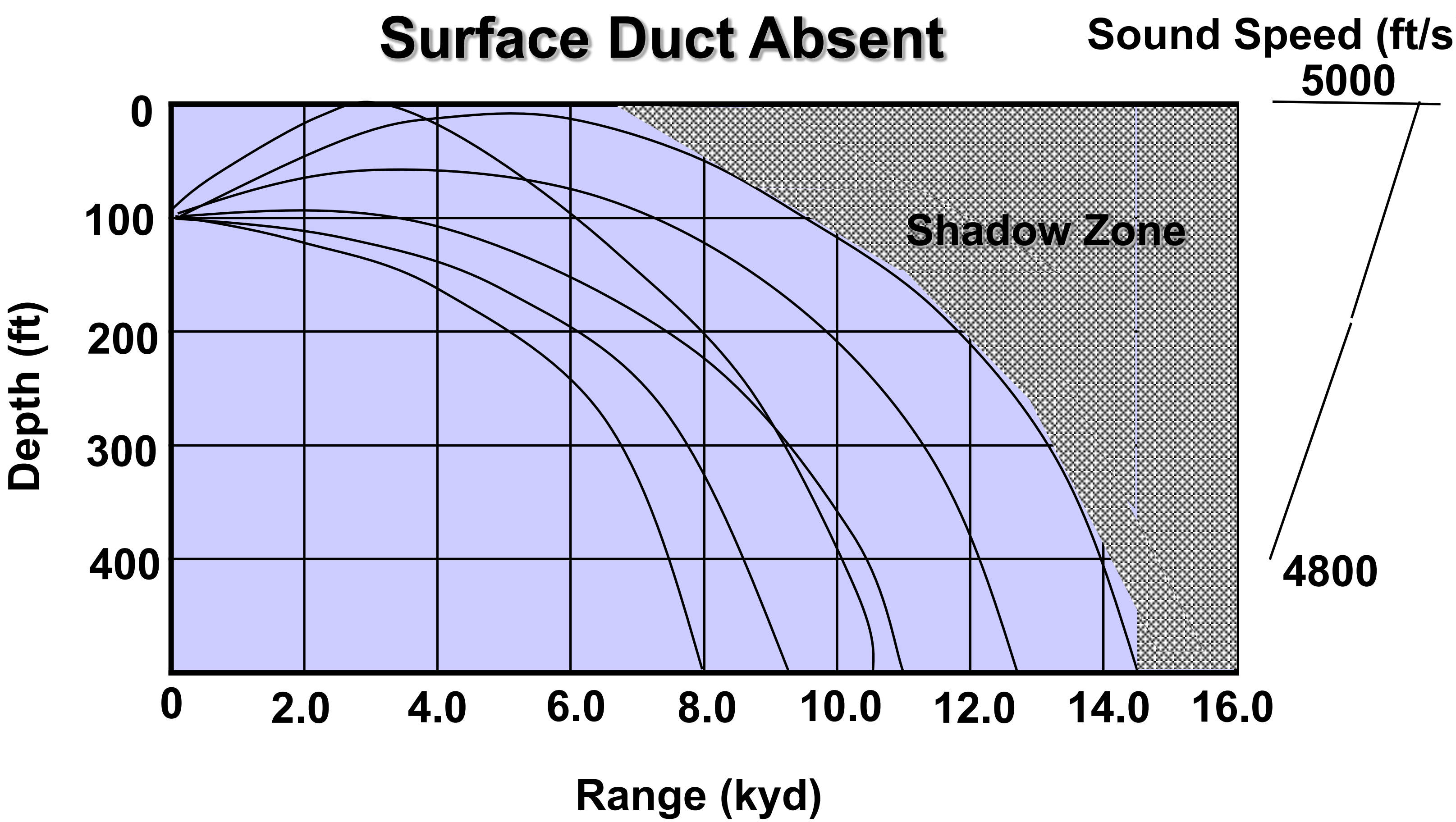
Ducting



Sonar Equations

Definitions (different perspective sometimes from the norm):

SL – Source Level refers to two types, one is the target output for the passive sonar and projector output for the active sonar.

TL – Transmission Loss (the same for all cases)

TS – Target Strength is the ratio (in decibels) of the echo intensity (at 0.9 m or 1 yd from the target) to the incident intensity

NL – Noise Level is measured by a non-directional hydrophone and expressed in a 1 Hz bandwidth (this includes the sum of ship and ambient noise)

AG – Array Gain is the improvement in signal to noise ratio (SNR) by a sonar array

RL – Reverberation Level is the level of a plane wave that produces the same output as the reverberation noise

DT – Detection Threshold is the SNR at the array terminals required for detection

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Sonar Equations

Three basic equation come from the definitions:

for a passive sonar

$$SL - TL = NL - AG + DT$$

for an active sonar (noise background)

$$SL - 2(TL) + TS = NL - AG + DT$$

for an active sonar (reverberation background)

$$SL - 2(TL) + TS = NL + DT$$

Directivity Index and Array Gain

Array directivity is the ratio of the power per unit solid angle radiated (or received) in direction of the maximum amplitude pattern to average radiated power per unit solid angle

$$DI = 10 \log D_R$$

When L (for a uniform line source) >> λ)

$$D_R = 2L / \lambda \quad (\text{i.e., } DI = 10 \text{ Log } 2L / \lambda)$$

The actual DI varies with the L/l but for all practical purposes the approximation if sufficient to describe it

Array Gain

Array Gain is the improvement in signal to noise ratio of the array

AG = signal gain (dB) – noise gain (dB) = G_S - G_N

For a unidirectional signal in isotropic noise;

AG = DI

Array Gain

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Array Gain

The gain of an array for a non-uniformly spaced array of acoustic elements depends on the properties of the beam pattern and noise field.

At low frequencies and isotropic noise:

$$AG = 10 \text{ Log } 2L / \lambda$$

At high frequencies, $L >> \lambda$, the gain is:

$$AG = 10 \text{ Log } N$$

Where N = to the number of elements in the array

Sonar Types

Navigation / Tracking:

- **Long Baseline – 9 kHz to 15 kHz**
- **Short Baseline – 15 kHz to 20 kHz**
- **Ultra-short Baseline – 17 kHz – 30 kHz**

Mapping:

- **Sub-bottom Profiler – 2 kHz to 12 kHz**
- **Side Scan Sonar – 50 kHz to 250 kHz**
- **Multibeam Sonar – 30 kHz to 300 kHz**

Environmental:

- **Acoustic Doppler Current Profiler – 100 kHz to 1 mHz**
- **Doppler Velocimeter Log - 100 kHz to 1 mHz**

Communications:

- **Acoustic Modem - 9 kHz to 17 kHz**

Tomography, Biologic tracking, etc. etc.

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Range at which Absorption approximates 10 dB