Final Presentation: Boat Crew

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2.017 Fall 2009
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Group 2

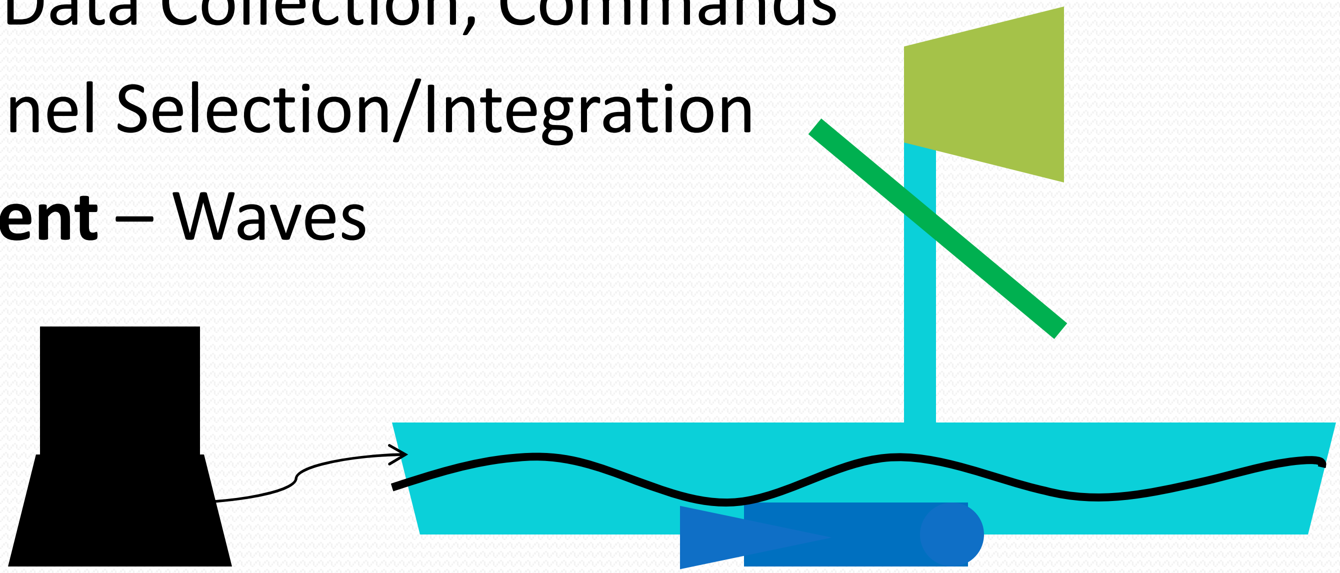
Mission Objective Tree

Goal: Autonomously travel to and survey Harvard Bridge Pylons.

Objectives	Support Tasks
Rugged Vehicle	Analyze Vehicle Capabilities
	Construct Support Structure
Fly Planned Path	Analyze Sensors and Motors
	Navigate Bridge with GPS
Fly Parallel to Wall	Closed-Loop Control
	Navigate Bridge with Sonar
Photo-Survey Bridge	Record Images of Bridge Pylon
Solar Feasibility	Spec/ Select Solar Panels

Project Division

- **Vessel Structure** - Physical Components
- **Sensors** – GPS, Sonar, etc.
- **Propulsion** - Motors
- **Control** – Data Collection, Commands
- **Solar** - Panel Selection/Integration
- **Environment** – Waves



Vessel Design

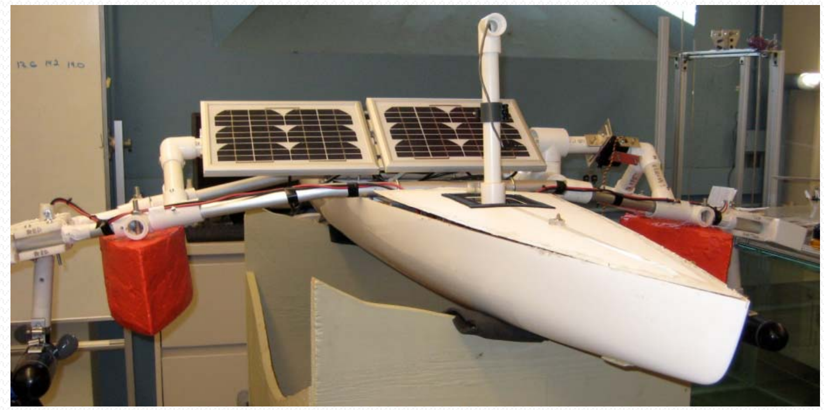
Student D

- Vessel Modifications
- Buoyancy
- Weight and Trim
- Final Design

Vessel Modifications

Motivation: needed survivable & rugged vessel

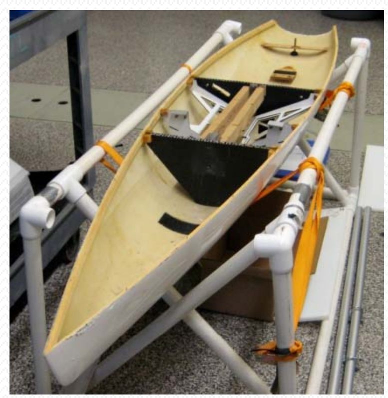
- Functional Requirements:
  - Stable
  - Maneuverable
  - Sensor mounts
  - Rugged design



PT 2017

Photo of the Pro Boat Miss Elam 1/12 Brushless RTR removed due to copyright restrictions.

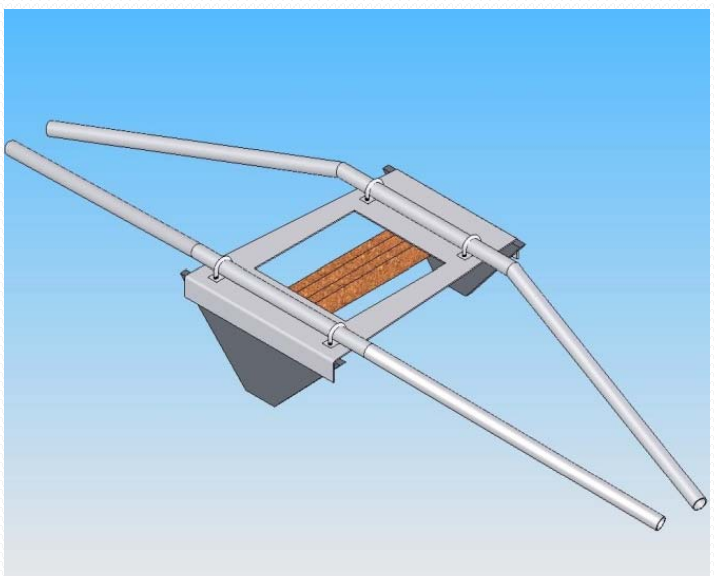
Pro Boat Miss Elam

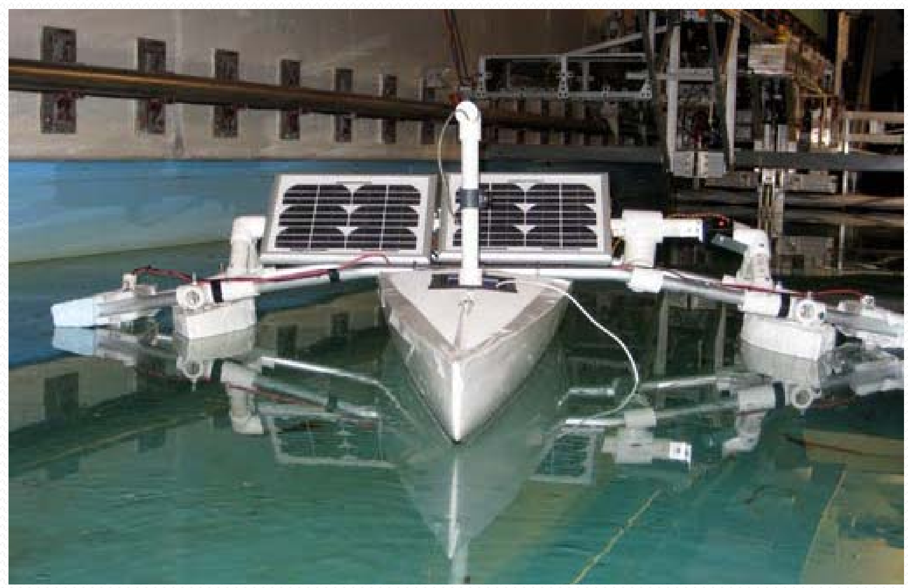


Spirit of the Challenge

Final Design

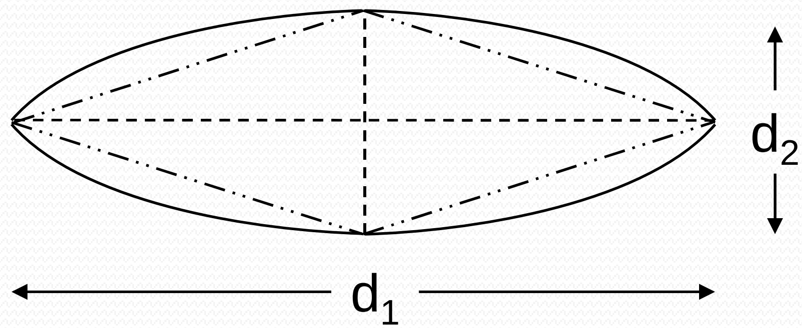
- Trimaran
  - Stability – pontoons
  - Maneuverability = motors mounted outboard
  - Sensor mounts = metal sheet + hull structure





Pontoon Size Calculations

$V = A_{waterline} \cdot h \sim A_{kite} \cdot h$

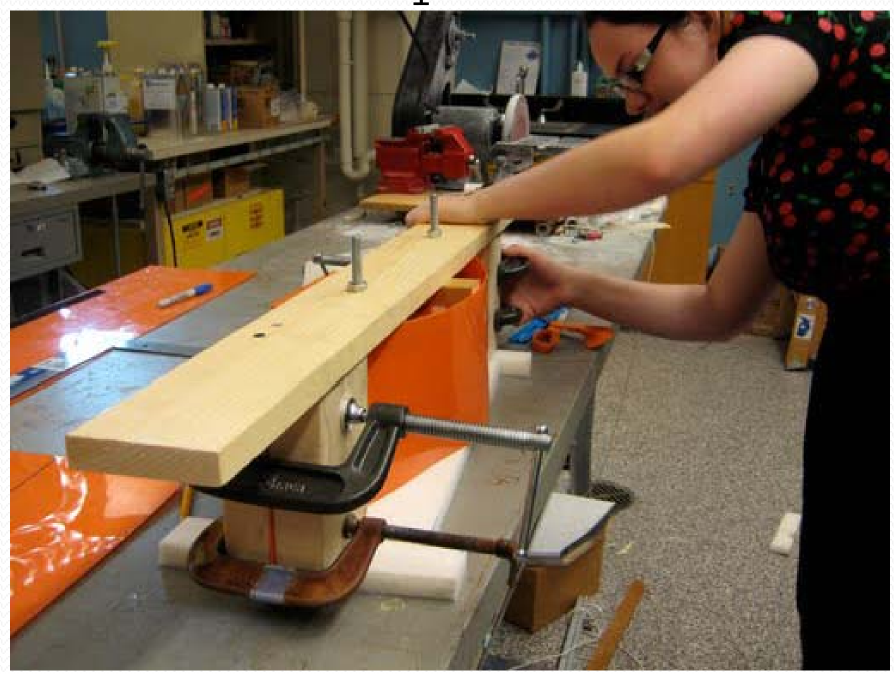


Streamline : $d_1/d_2 \sim 3$

$V = .5(d_1)(d_2)(h)$

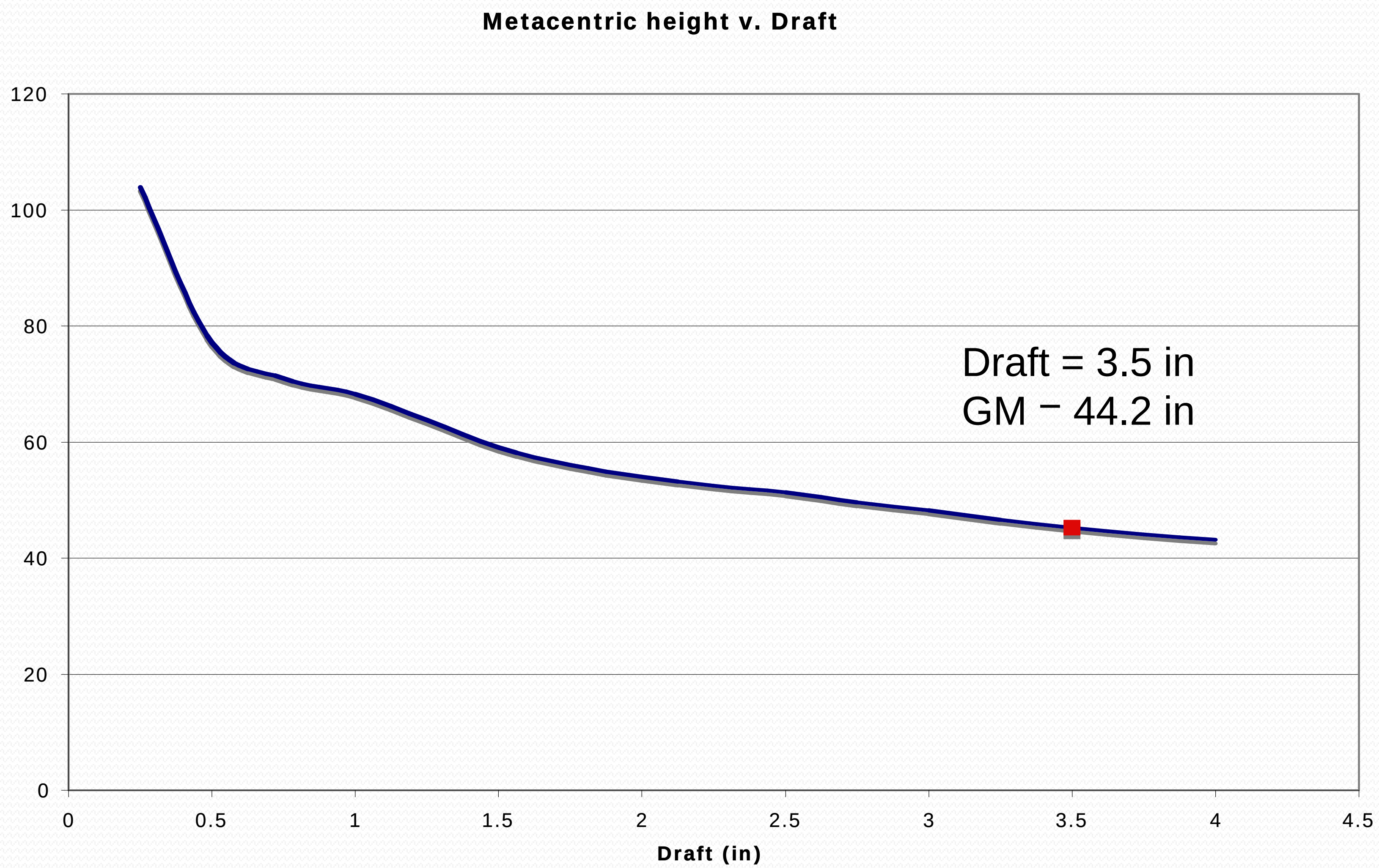
$= .5(6")(18")(5.75")$

$= \mathbf{310.5\ in^3} > 303\ in^3$

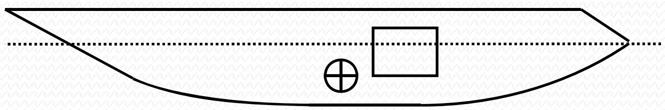


Mold to shape pontoons

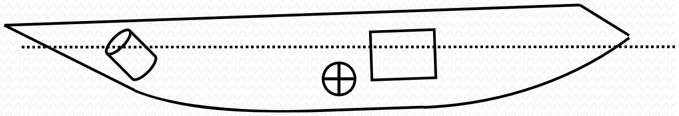
Hull Stability



Hull Trim



• Loaded with battery and pontoon assembly only:
- Freeboard = 0 in !



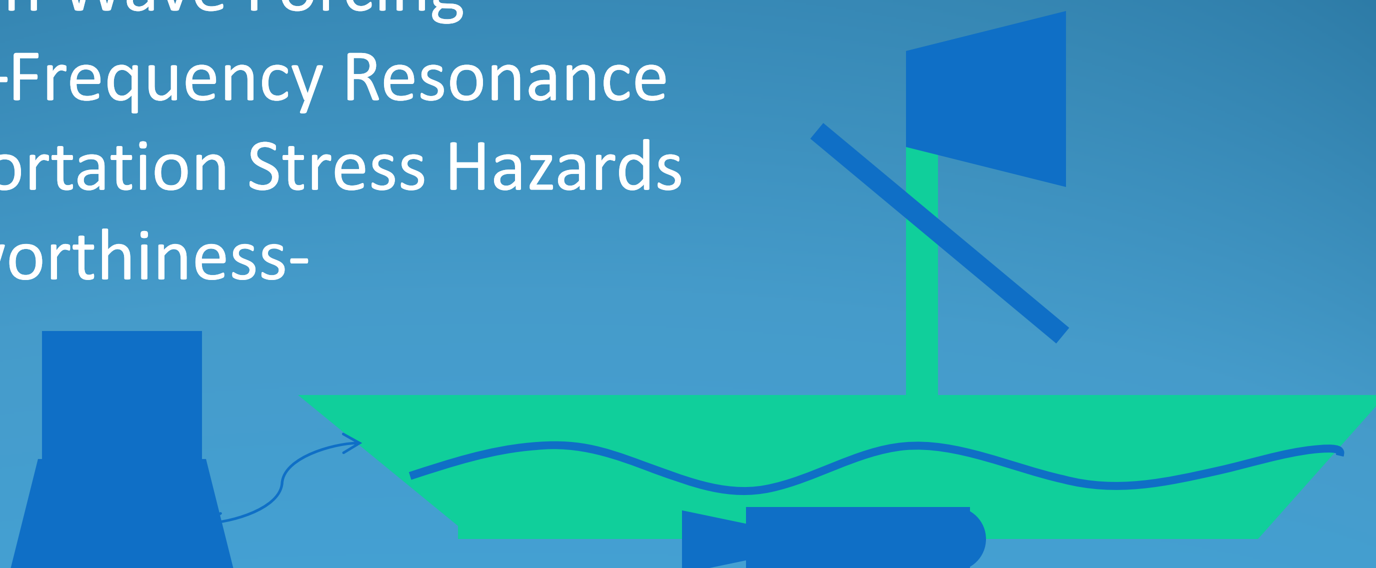
• Loaded with extra 3.5 lbs at bow:
- Freeboard = 0.75 in

• Port-Starboard trim with symmetry

Stress Analysis

Student B

- Pontoon Wave Forcing
- Wave –Frequency Resonance
- Transportation Stress Hazards
- Crashworthiness-



Spring-Mass Resonance Model

- Single cantilever beam w/point loading : Euler Bernoulli Equation

$$EI\frac{d^4u}{dx^4} = w(x) \quad where \quad : \quad w(x) = F\cdot\delta(x-L)$$

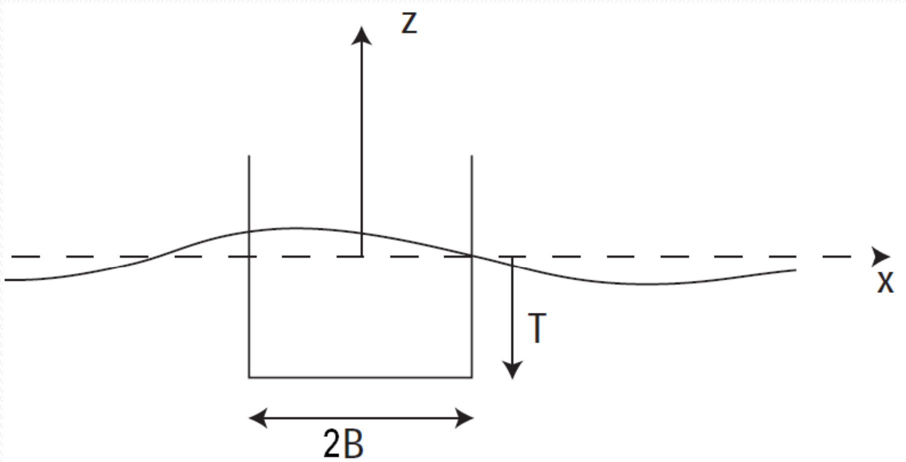
$$u = \frac{F}{3EI}L^3$$

- Mass –Spring System: $F = -k\cdot u \Rightarrow k = \frac{3EI}{L^3}$
- Resonant frequency:

$$\omega = \sqrt{\frac{k}{m}}$$

- Vessel Natural Frequency: ω = 83Hz
- Far higher than frequency of water waves!
- Near frequency of transportation vibrations
  - Switch bolt attachments to delrin wingnuts

Wave Forcing on Pontoon



- B = 0.075m, T = 0.1m
- Worst-case waves :

  ω= 1Hz   A= 0.3m
- Deep water waves:

$$k = \frac{\omega^2}{m} \sim 0.1$$

- Surface pressure integration:

$$\overrightarrow{F}_{FK} = -\iint_{Sw} p\vec{n}ds$$

$$F_Z = \frac{l2\rho age^{-kT}\cos(\omega t)\sin(kb)}{k}$$

$$F_{zMax} = \frac{L2\rho age^{-kT}\sin(kb)}{k} = 166N$$

$$F_x - 2L\rho ag(1-e^{-kt})\sin(\omega t)\sin(kb)$$

$$F_{xMax} = 2L\rho ag(1-e^{-kt})\sin(kb)$$

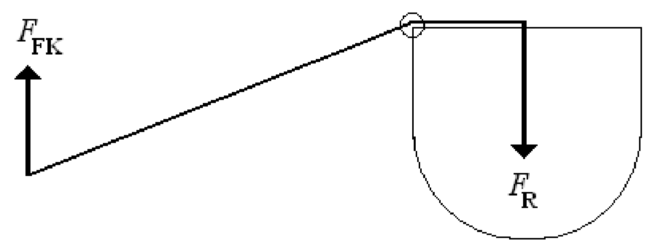
$$F_{x\,Max} = 0.44N$$

Implications of wave forcing

- Forcing moment: 50Nm
  - Horizontal force on pontoon is negligible
  - Vertical force causes moment
- Reaction force on boat structure: 277.8N
- Bend in pipes
  - Stress calculated using $\sigma = \frac{MR}{I}$
  - Max stress: 8.8×10^6 Pa
  - Yield stress of aluminum: 4×10^8 Pa
- Force on bolts
  - Originally, load distributed over 6 bolts
  - Total force on each bolt is 46.3N

Danger zones:

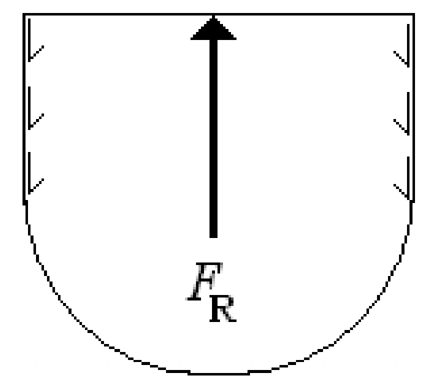
- Strut bend
- Structural bolts



If stress is too high, the internal structure could be ripped completely out of the boat!

Failure of internal boat structure

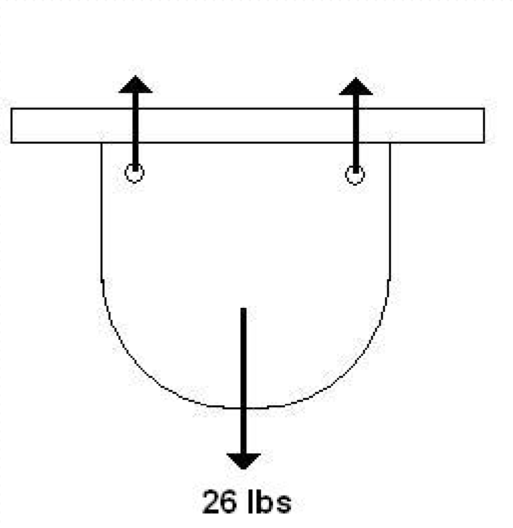
- Internal structure to which pontoons are mounted is held onto hull with epoxy
- Approximate that most stress on epoxy is in the shear direction



- Epoxy much weaker in 'peel' forcing
- Peel forcing unlikely: hull not pulled outwards independent of plate
  - Shear force per unit area of epoxy contact: 1.5×10^4 Pa
  - Shear strength of epoxy: 1.4×10^7 Pa

Transportation and Handling

- Most likely transportation method is to carry by frame
- Potential problems due to weight of boat:



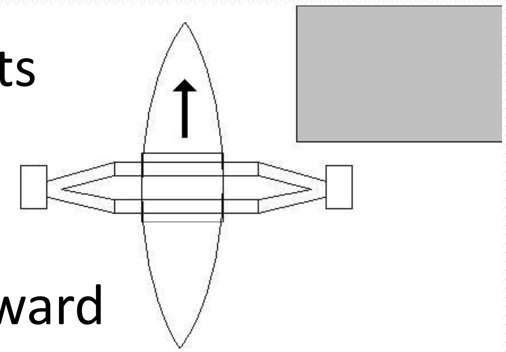
•Total weight of boat hull and components: 26lbs

•Stress on epoxy << than rated shear stress (8,000 PSI)

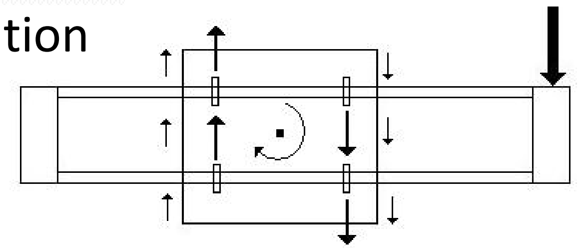
•Original 6-bolt design: 19.3N per attachment point
  - Internal boat structure failure possible

- Design modified to reduce these issues
  - Number of bolts increased to 12

Pontoon Arm Collision



- Impact creates moment around central attachments
  - U-bolts on plate – act as moment constraint
  - Peel forces on epoxy
- Crash 1 pontoon while boat travelling at 1 ms^{-1} forward
  - Relevant for mission and for vessel transportation



- Results:
  - Moment around center – 15.87 Nm
  - Force per U-bolt – 31.24 N (U-bolt max. rating: 1935 N)
  - Average force on epoxy – 89.25 N
  - Total peel strength of epoxy – 91.44 N/mm epoxy peeled

GPS, Compass, and Sonar

Student E

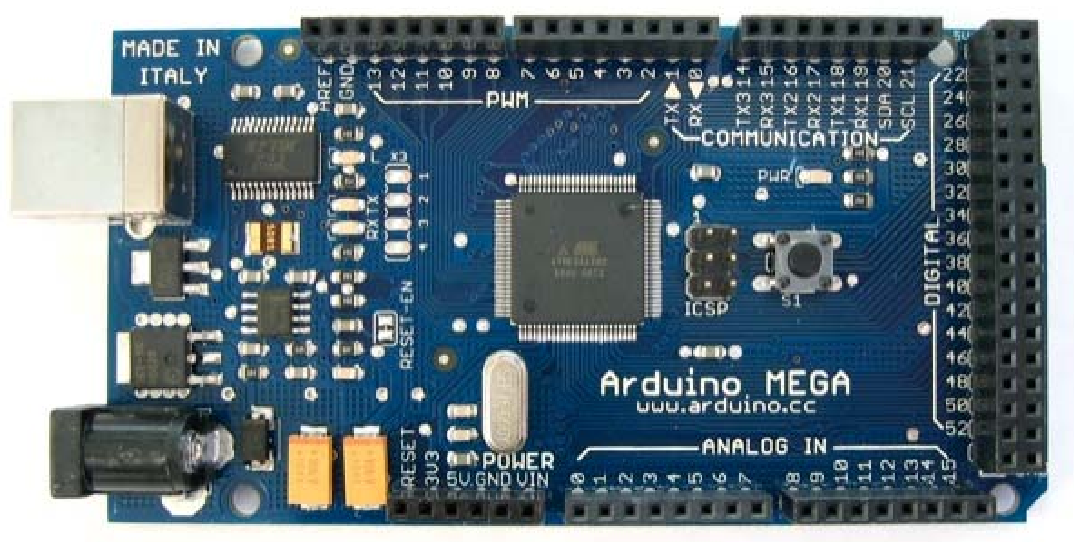
- Reading GPS Data
- GPS Test Results
- Reading Compass Data
- Reading Sonar Data

Global Positioning System

- Standard Format:

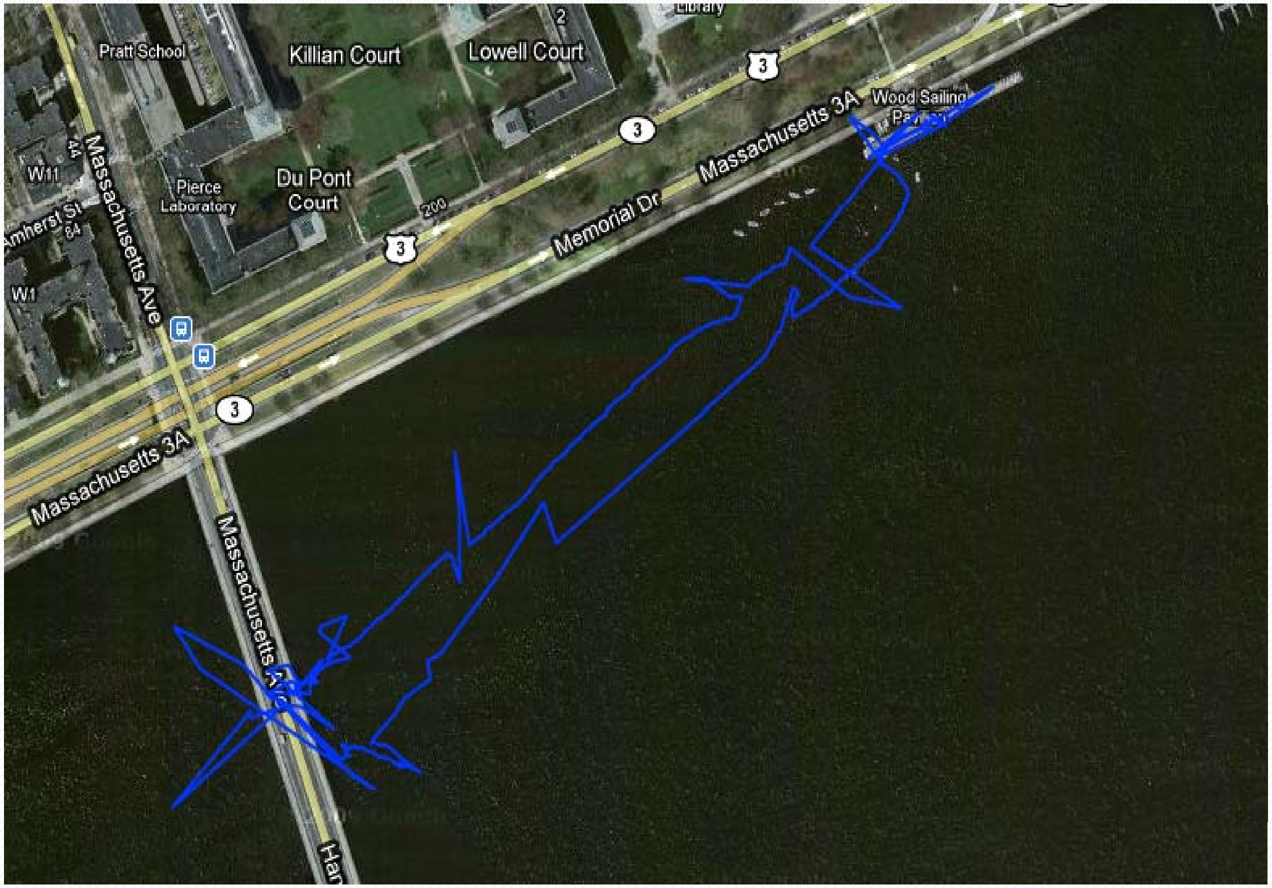
GPRMC,135713.000,A,4221.4955,N,07105.5817,W,4.29,258.17,310809,,*16

- GPS shield is used on Arduino MEGA
  - 1 signal hit/second

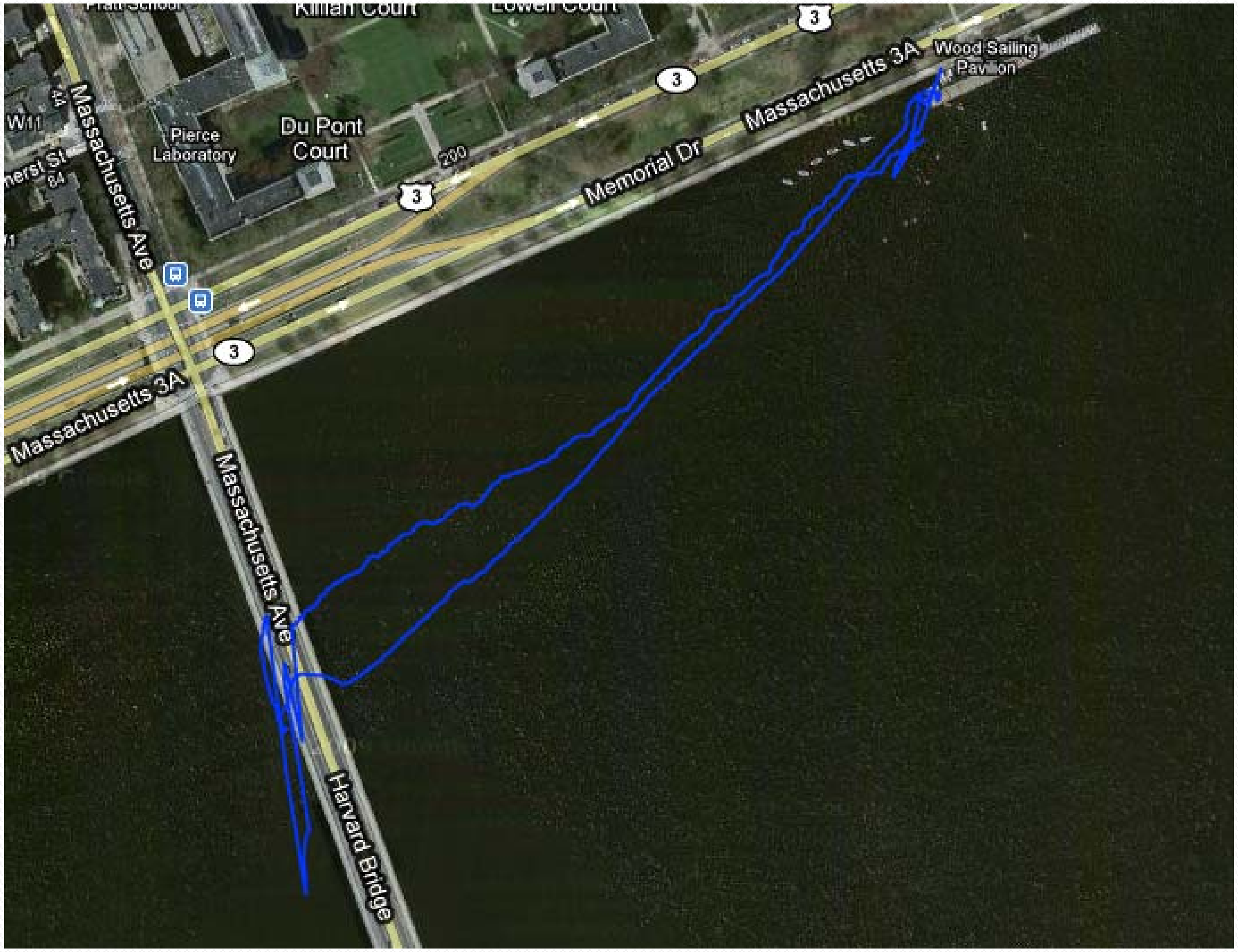


Courtesy of Arduino.cc. Used with permission.

Trial 1

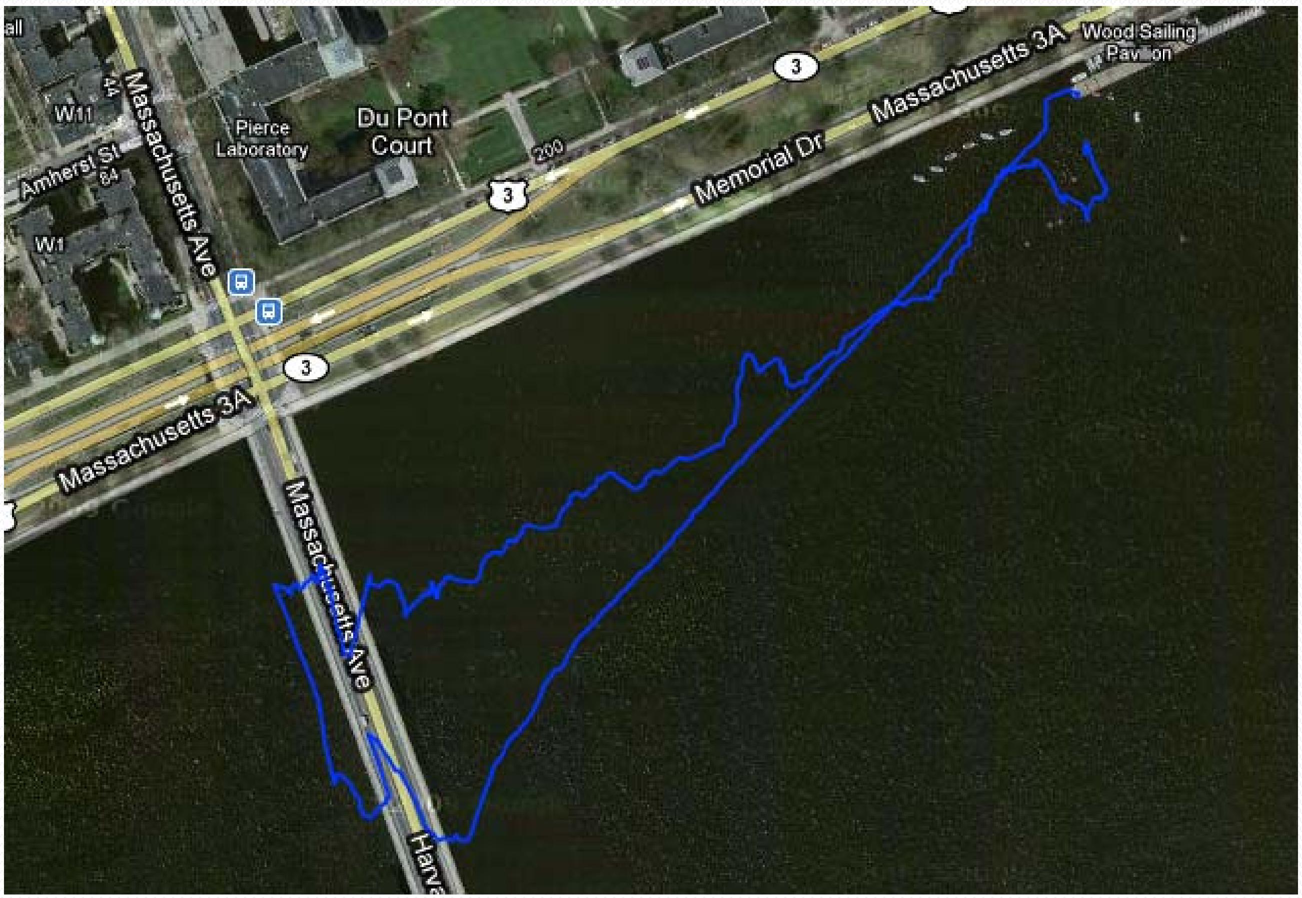

Pratt School
Killian Court
Lowell Court
Pierce Laboratory
Du Pont Court
Massachusetts Ave
Massachusetts 3A
Memorial Dr
Wood Sailing
Amherst St
W11
W1
3
200

Trial-2



Killian Court
Lowell Court
Pierce Laboratory
Du Pont Court
Massachusetts Ave
Massachusetts 3A
Memorial Dr
Wood Sailing Pavilion
Harvard Bridge

Trial-3



W11
Amherst St
W1
Massachusetts Ave
Pierce Laboratory
Du Pont Court
200
3
Memorial Dr
Massachusetts 3A
Wood Sailing Pavilion
Massachusetts 3A
Massachusetts Ave

GPS Output

- Imaginary X-Y coordinate system
  - Sailing pavilion as the origin
- GPS latitude and longitude processing:
  - Decoded into x-y coordinates
  - Sent as an input to control system

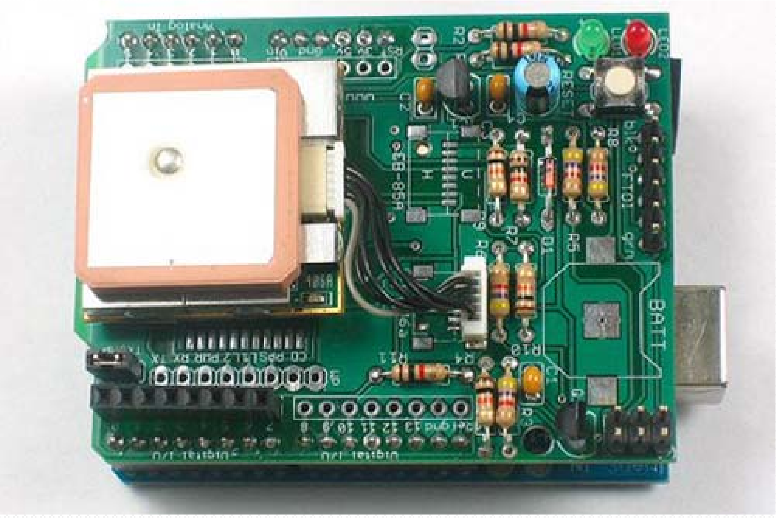


Photo by ladyada on Flickr.

OS5000 3-Axis Compass

- Primary Navigation
  - Low Noise
  - Works under the bridge
  - Faster refresh rate than GPS

- Outputs to Control System
  - Heading: 0 to 360 degrees
  - Pitch: -90 to +90 degrees
  - Roll: -180 to +180 degrees

LV MaxSonar WR-1

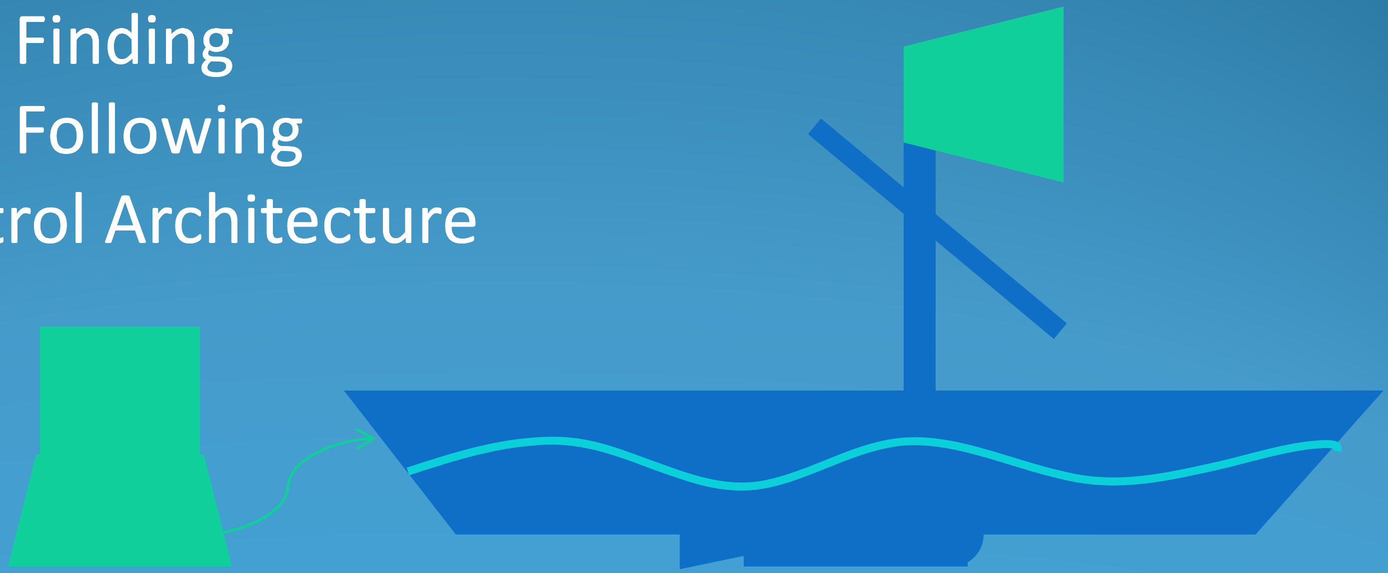
Photo of the MaxSonar WR1 http://www.active-robots.com/products/sensors/maxbotix/WR1-large.jpg removed due to copyright restrictions.

- Range 0-255 inches
- Analog and serial output
  - Analog accurate 1” of serial output
  - Maintain moving average of analog output
- Fully waterproofed
- Mounted to servo
- Run at pre-set heading until wall is detected
- Wall detection @ 3.05 m,
- Accurate reliable readings @ 2.13 m
- Safety buffer of 1.52 m from wall

Mission Planning and Data Logging

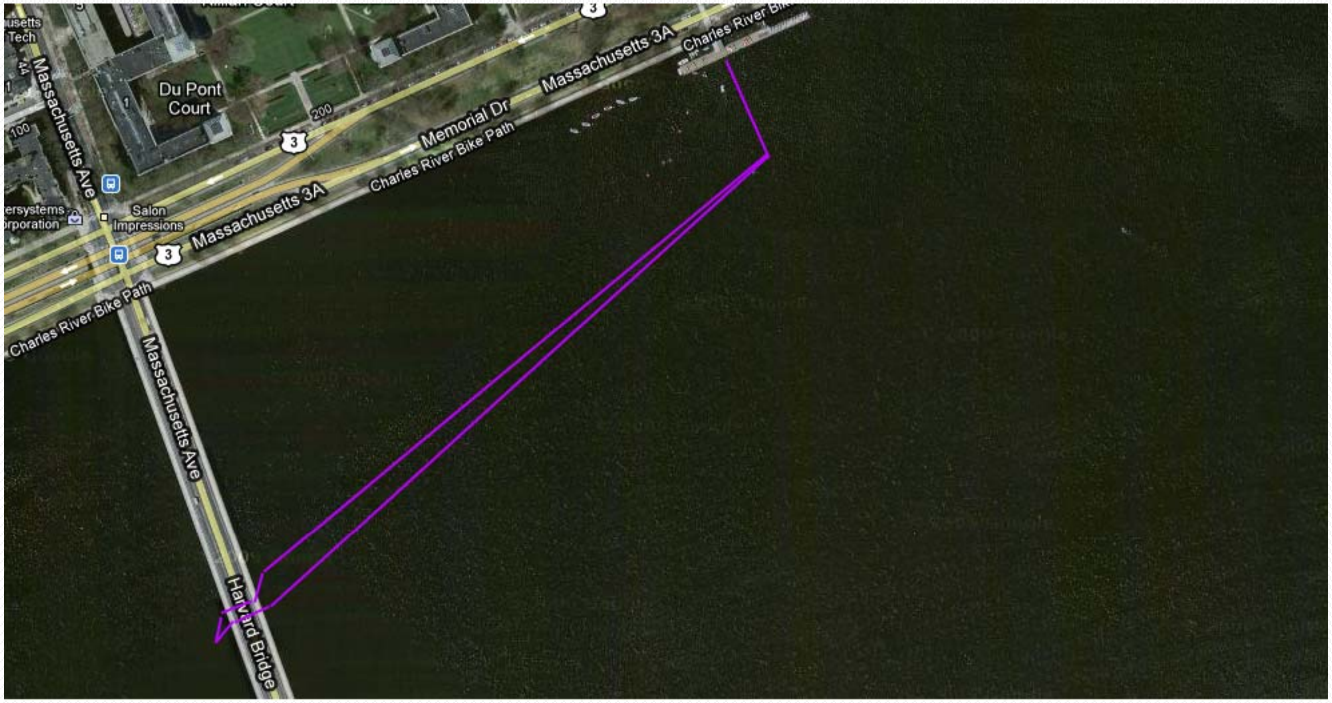
Student A

- Selected Sonar
- Wall Finding
- Wall Following
- Control Architecture



Mission Planning

- Mission stored as an array of way points
  - Sample way point: { x, y, heading, speed, range, mode }
- Modes describe behavior of boat

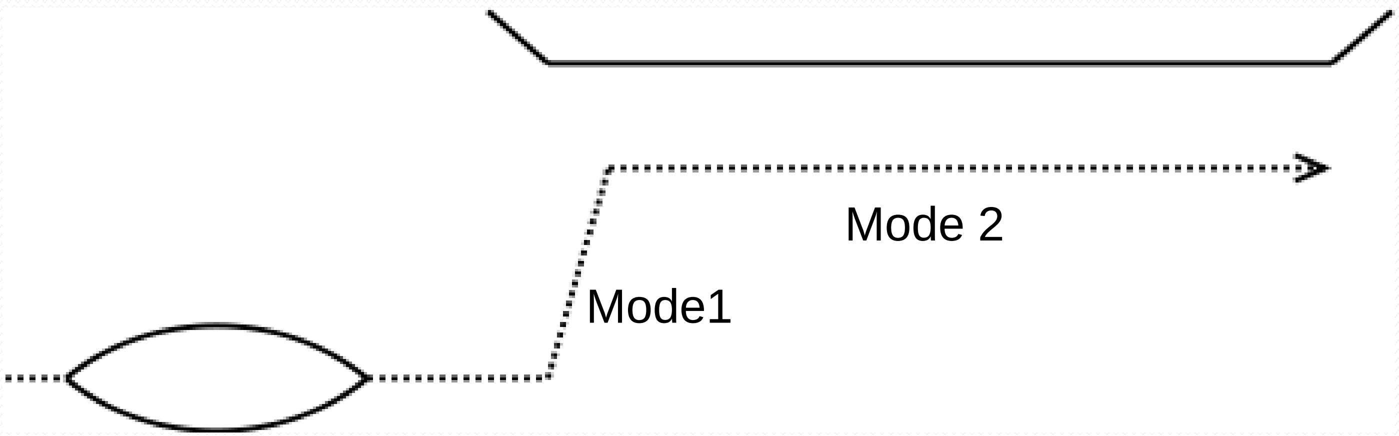


Test Mission

- Unreliable GPS and sonar data
- Reliable compass data
- Internal clock, counting time
- Mission composed of target headings, and times at which to change way points

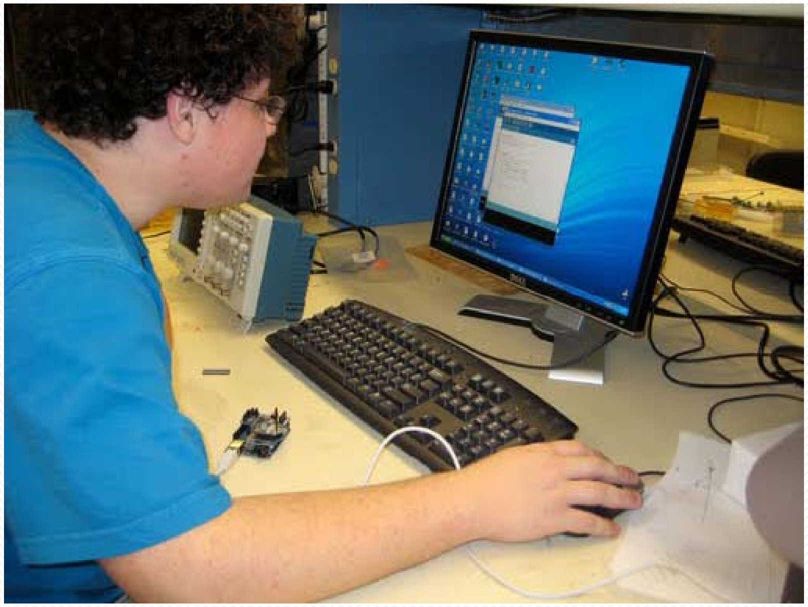
Wall Finding and Following

- Two modes:
  - Mode 1: Travel at set heading until wall is detected
  - Mode 2: Hold constant distance from wall, assumed to face a known heading



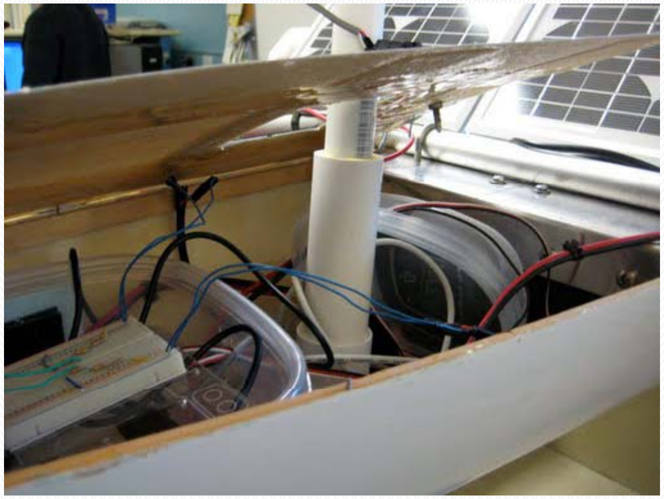
Data Collection

- Serial
  - GPS: Position
  - Compass: Heading, Pitch and Roll
- Analog
  - Sonar: Range
  - Solar: Voltage Output
- Internal
  - Time: Since program start up
  - Way point and error



Data Logging

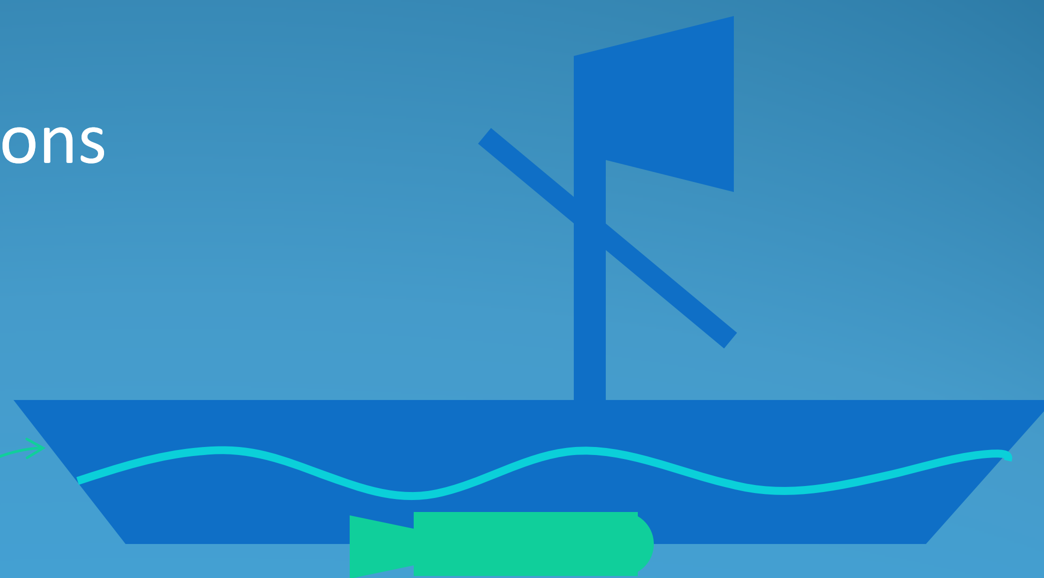
- Logging constrained to <1 Hz
  - Higher speed causes serial buffers to fill
- Logged to an onboard netbook
  - Data stored via Realterm
  - Formatted for MATLAB importing
- External GPS data stored on SD card



Propulsion and Control

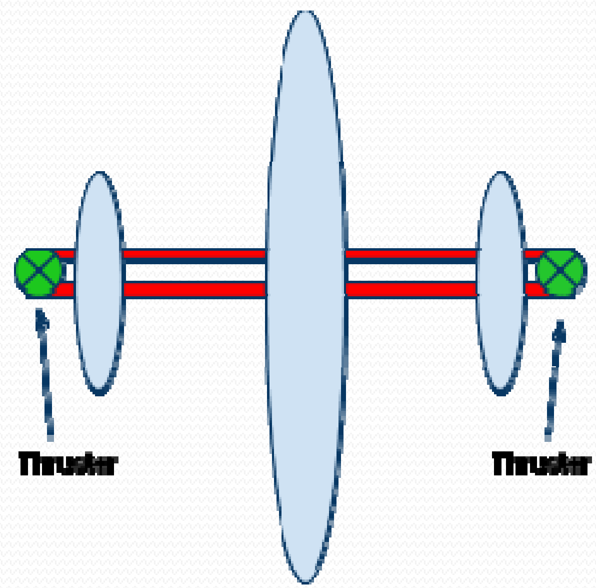
Student C

- Propulsion and Speed Control
- Thrust Tests
- MATLAB Simulations
- Real-World Tests



Propulsion System Design

- 2 Thrusters
  - 1 per outer hull
  - Differential thrust for yaw
- PWM control with Arduino and Speed Controllers
- 12V DC Trolling Motors

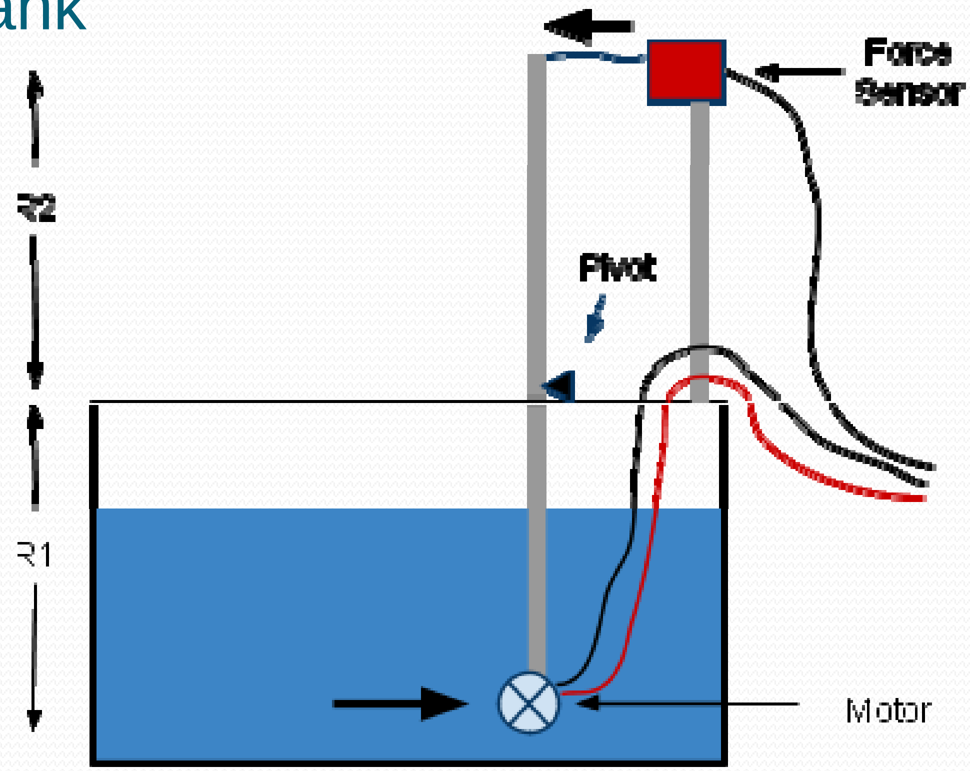


Speed Controller Selection

- Pro Boat 40A Waterproof ESC
  - Limited PWM frequency range
  - Incompatible with Arduino PWM
- Victor 884 ESC
  - Compatible with Arduino
  - Not Waterproof

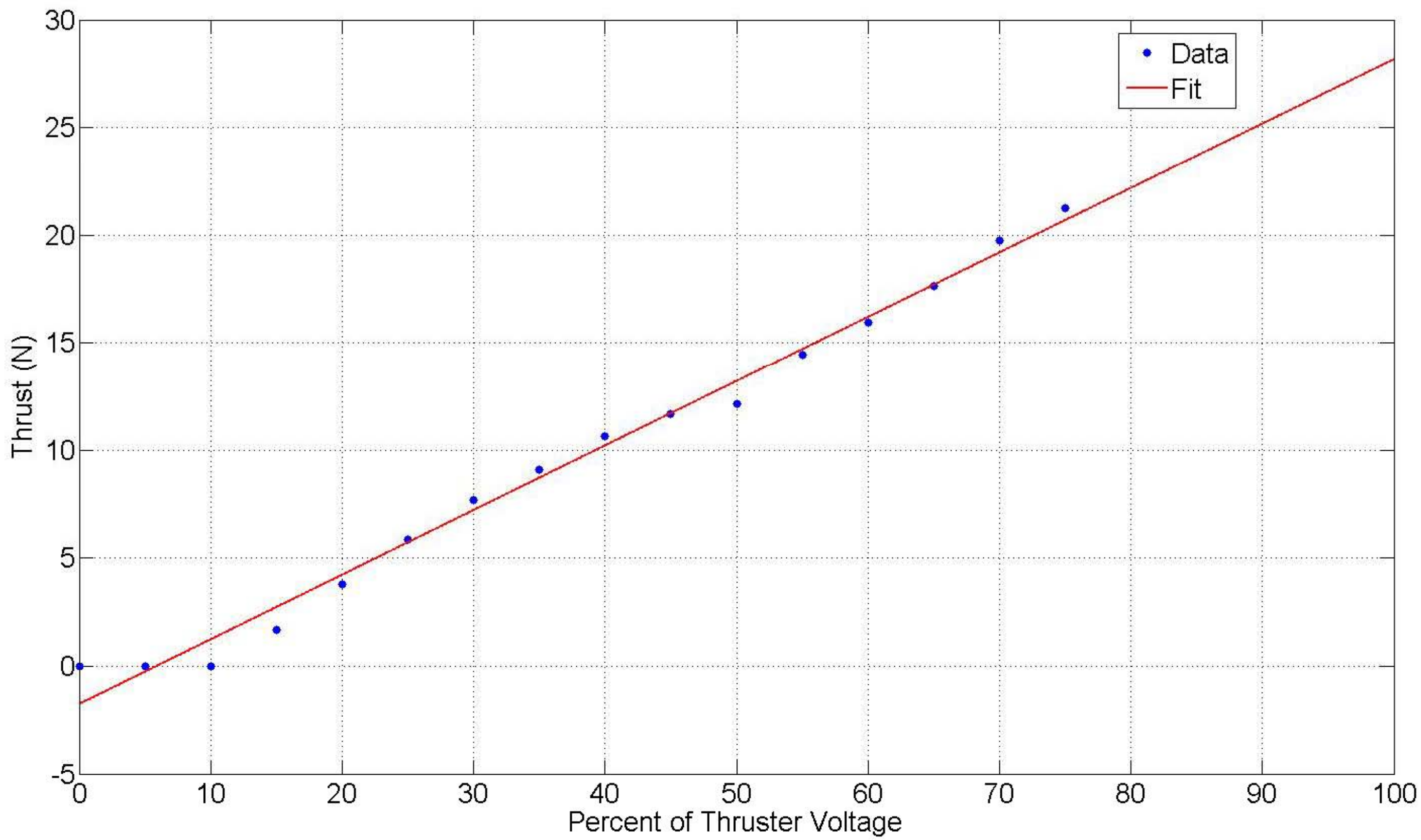
Thrust Test

- Test conducted in water tank
- Thrust was measured at different motor voltages
- Data fit to linear curve
- Maximum vehicle thrust=2X28.17N=56.3N
- Minimum voltage=1.5V



Force=Sensor Force X R2/R1

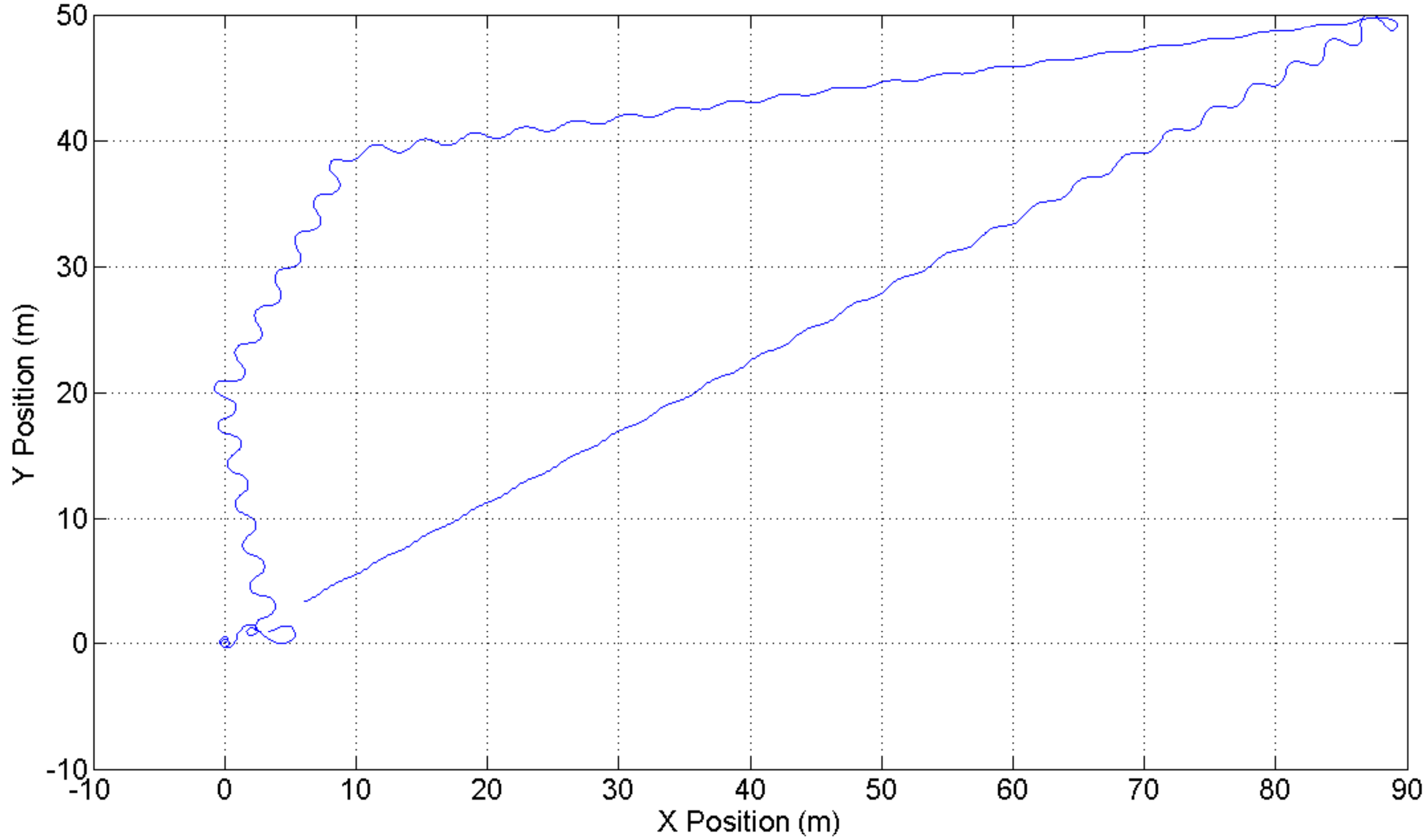
Thrust Test Data



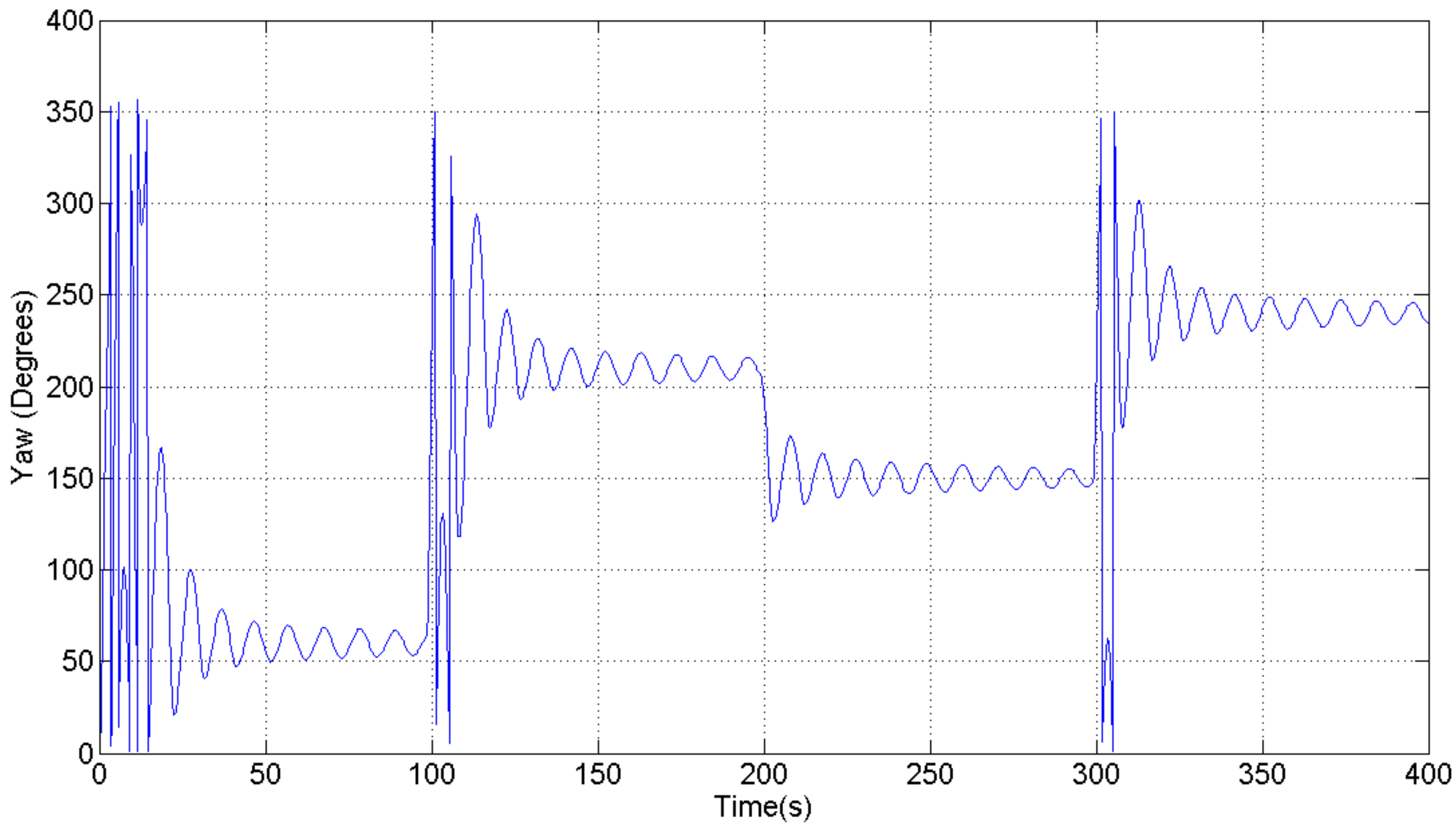
Control System and MATLAB Simulation

- Closed-loop proportional control
  - heading and speed using sonar, GPS, and compass
- Mission set-points determine control behavior
  - Way-point Traveling
  - Static Heading Following
  - Wall Following
- Boat and control system modeled in MATLAB using ODE45
  - M, J, B(lateral), B(rotational)
- Various set-points were used as inputs to adjust the gains

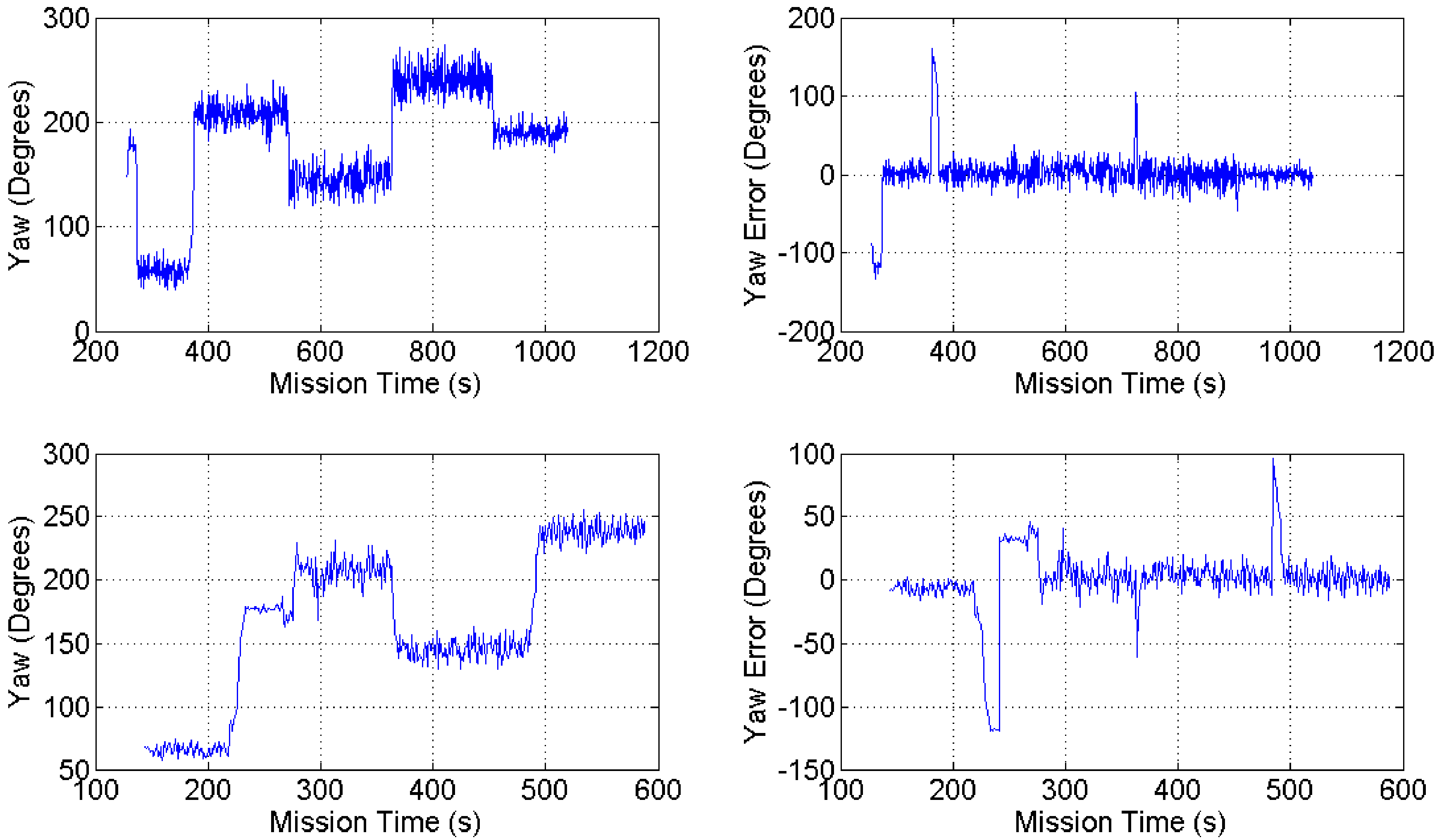
Simulations



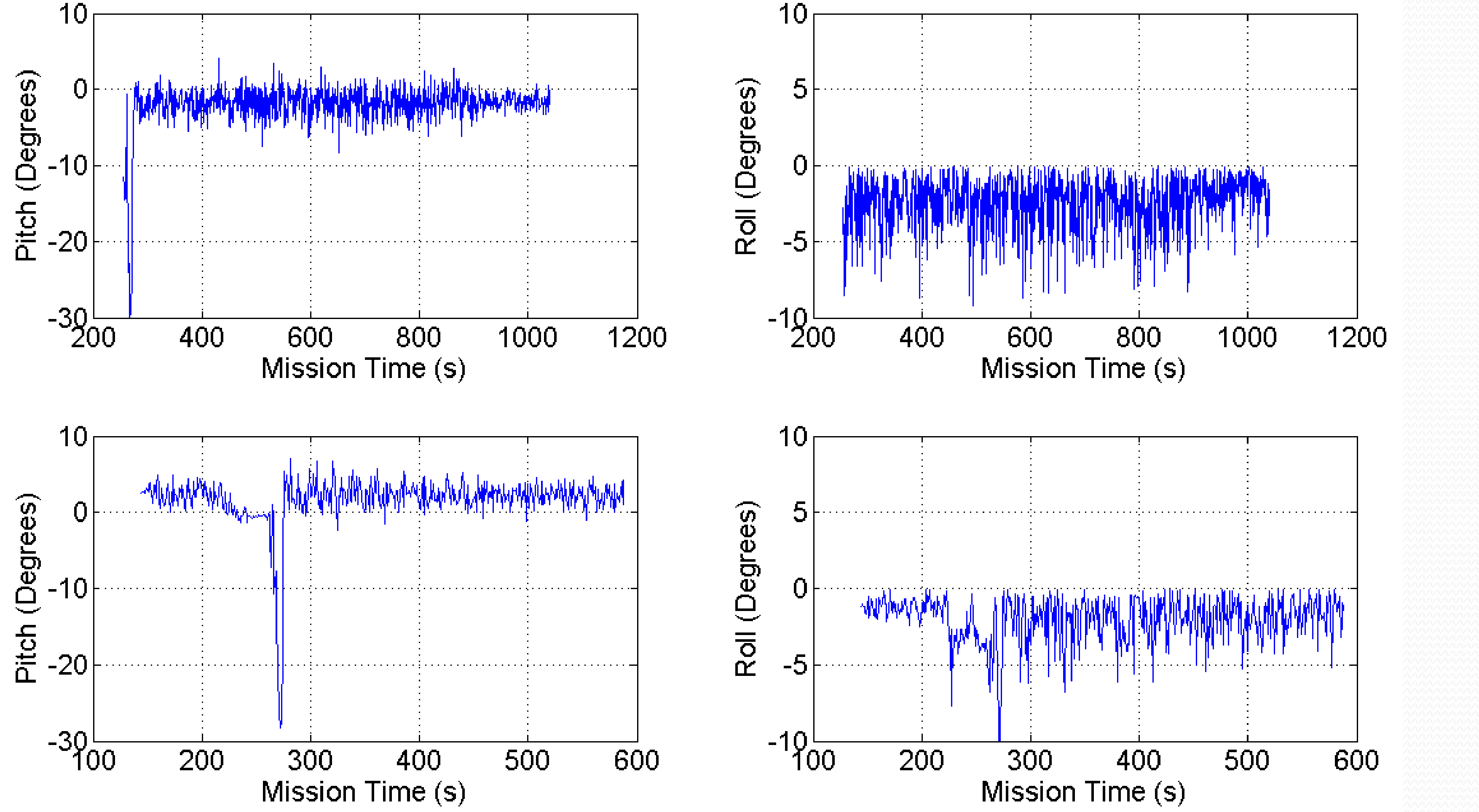
Simulations



Experiments



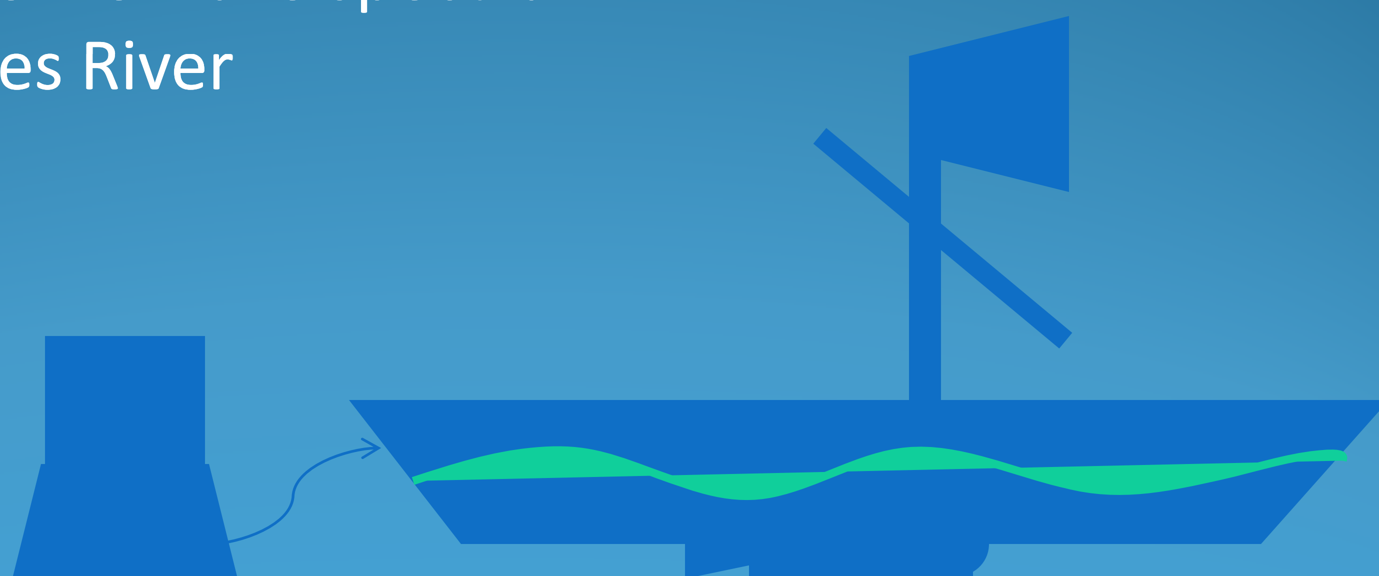
Experiments



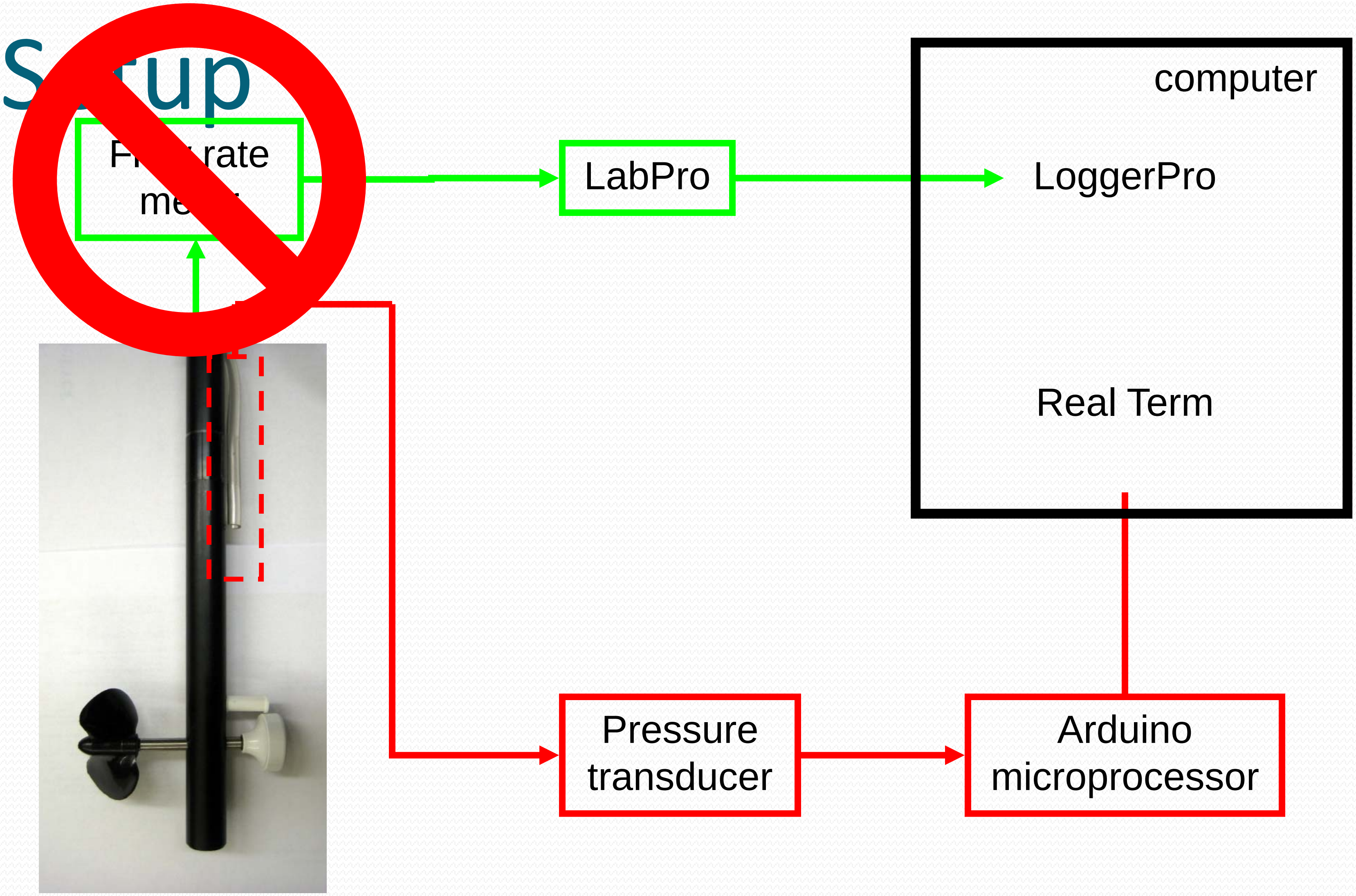
Wave Environment

Student F

Characterize wave spectrum of Charles River



Setup


LabPro
computer
LoggerPro
Real Term
Pressure transducer
Arduino microprocessor

River Wave Data

Case 1 • Fair weather • No Wind • No river activity	Case 2 • Raining • Steady wind • No river activity
• Case 3 • Fair weather • Slight wind • High boat traffic	Case 4 • Raining • High winds • No river activity • **Test Day**

River Wave Data

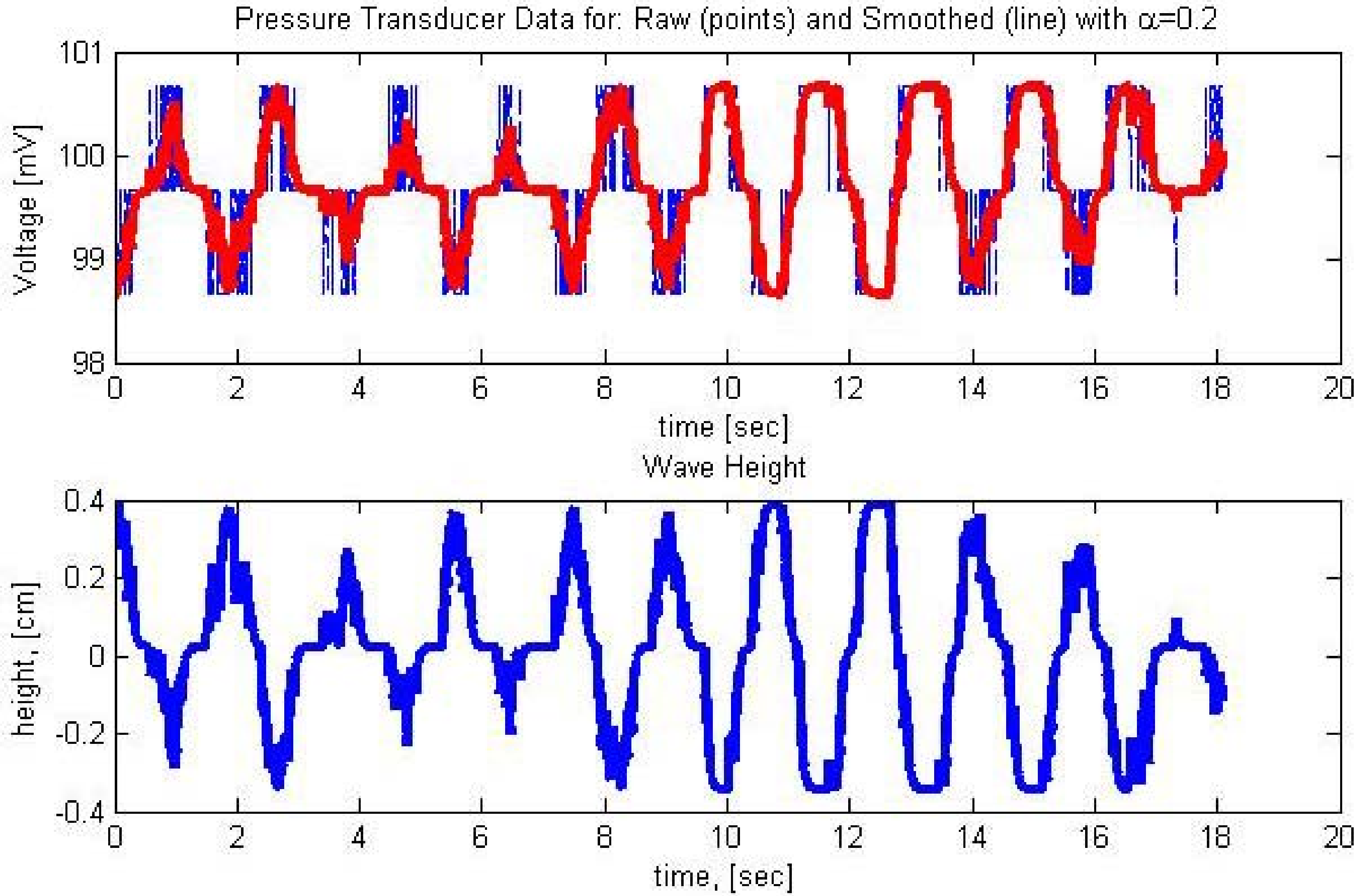
Case 1
- Fair weather
- No Wind
- No river activity

Case 2
- Raining
- Steady wind
- No river activity

Case 3
- Fair weather
- Slight wind
- High boat traffic

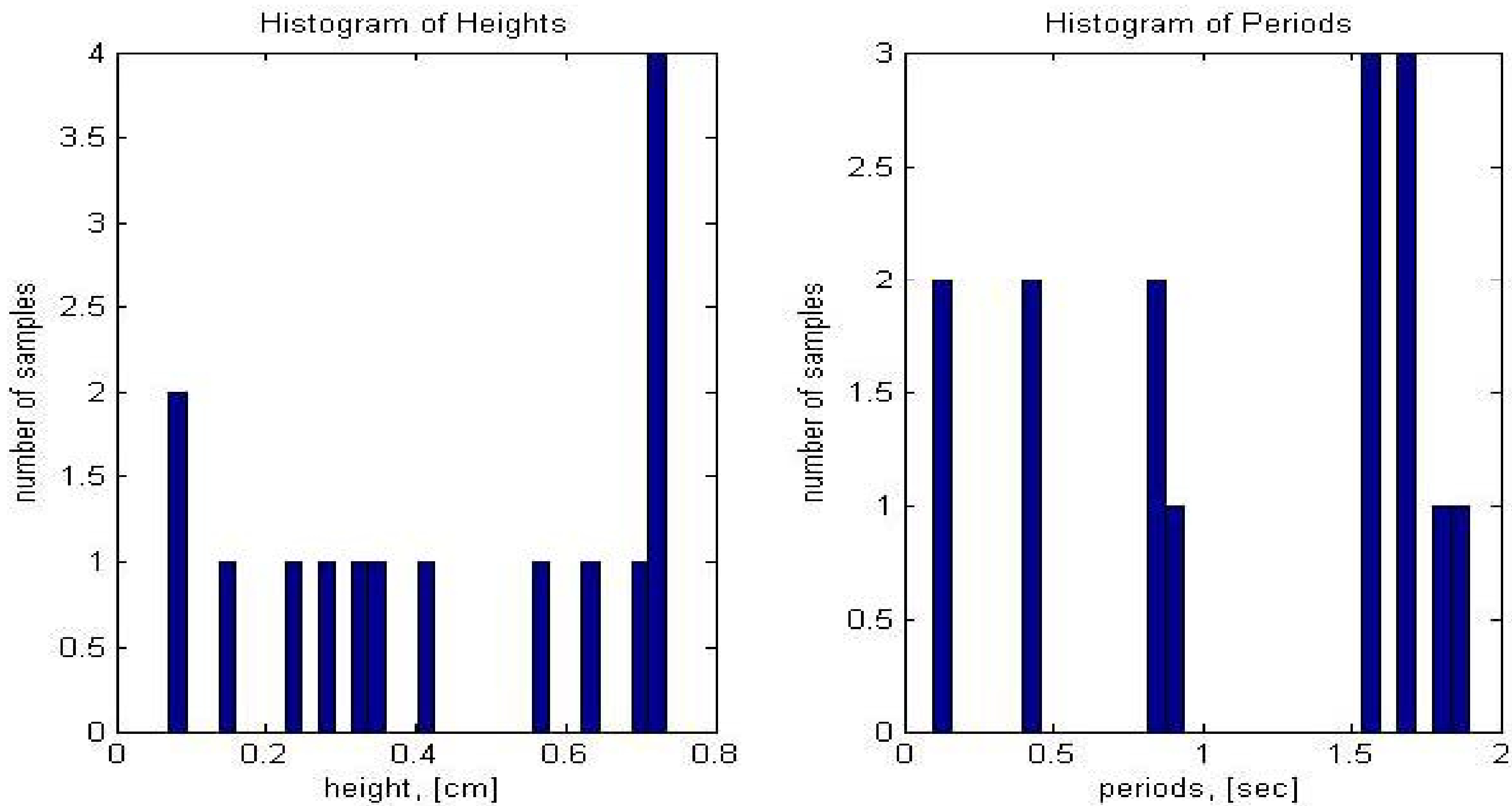
Case 4
- Raining
- High winds
- No river activity
- **Test Day**

Data



Pressure Transducer Data for: Raw (points) and Smoothed (line) with α=0.2
Voltage [mV]
101
100
99
98
0
2
4
6
8
10
12
14
16
18
20
time [sec]
Wave Height
height, [cm]
0.4
0.2
0
-0.2
-0.4
0
2
4
6
8
10
12
14
16
18
20
time, [sec]

Heights and Wave Periods



Average 1/3 wave height = 0.7174 cm

Average period length = 1.1487 s

River Wave Data

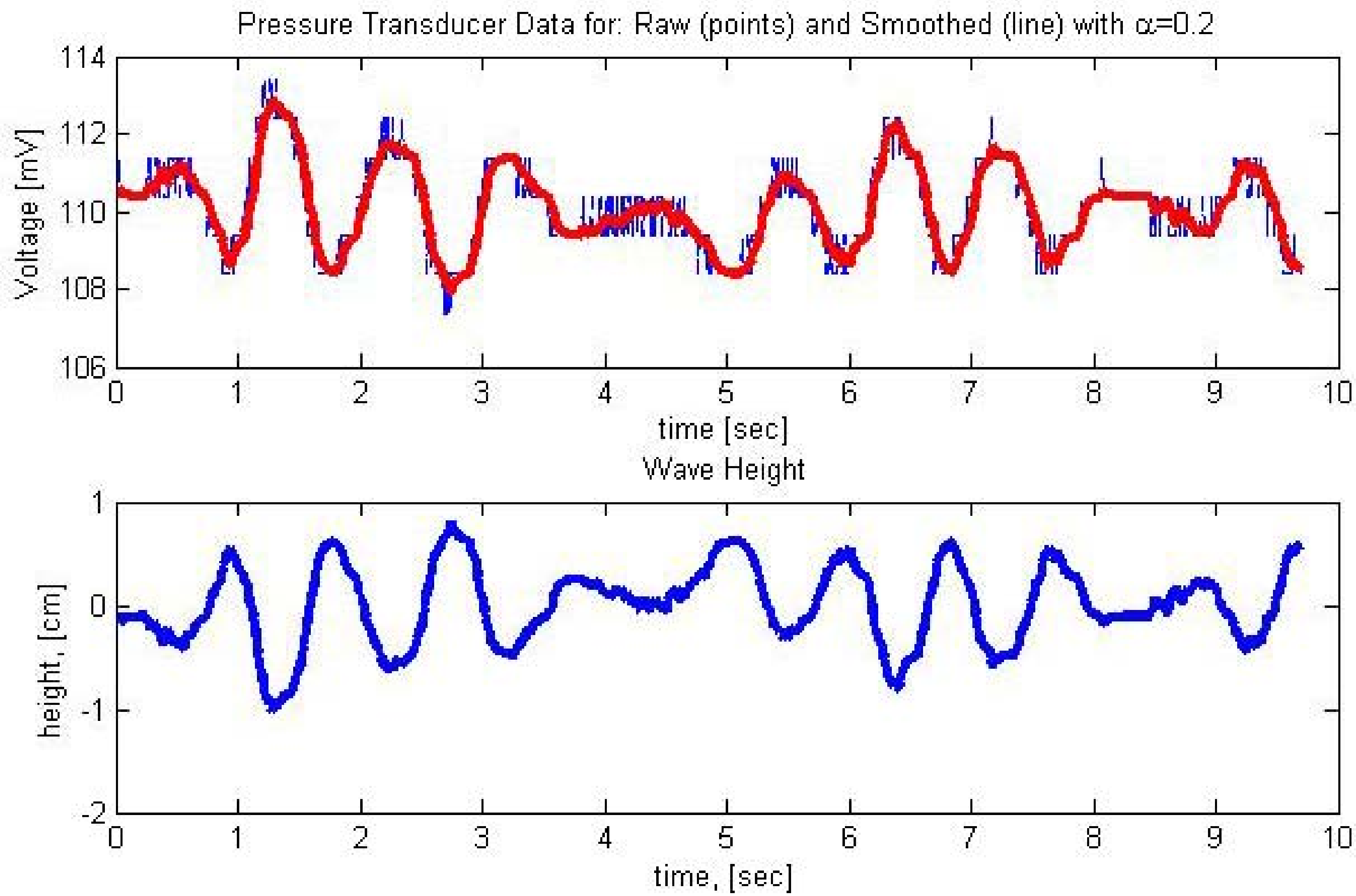
Case 1
- Fair weather
- No Wind
- No river activity

Case 2
- Raining
- Steady wind
- No river activity

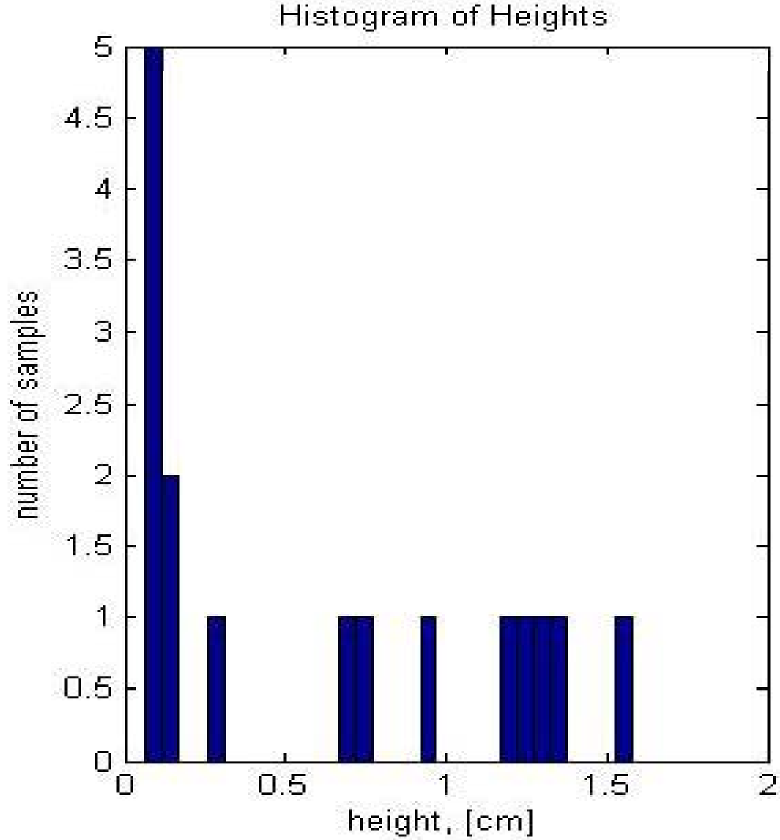
Case 3
- Fair weather
- Slight wind
- High boat traffic

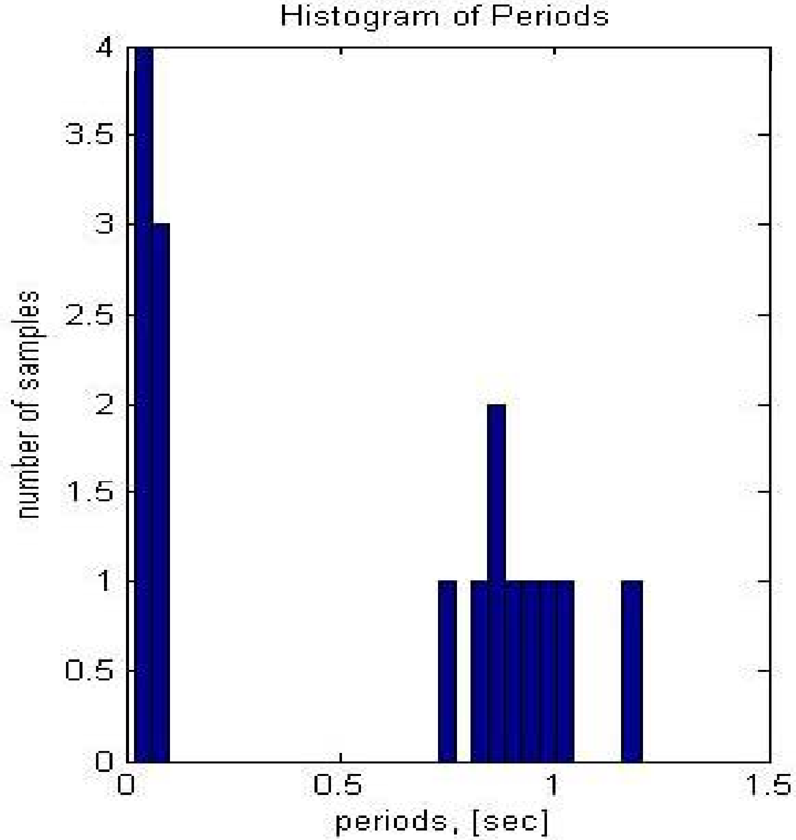
Case 4
- Raining
- High winds
- No river activity
- **Test Day**

Data


Pressure Transducer Data for: Raw (points) and Smoothed (line) with α=0.2
Voltage [mV]
114
112
110
108
106
0
1
2
3
4
5
6
7
8
9
10
time [sec]
Wave Height
height, [cm]
1
0
-1
-2
0
1
2
3
4
5
6
7
8
9
10
time, [sec]

Heights and Periods





Average 1/3 wave height = 1.3295 cm

Average period length = 0.5450 s

River Wave Data

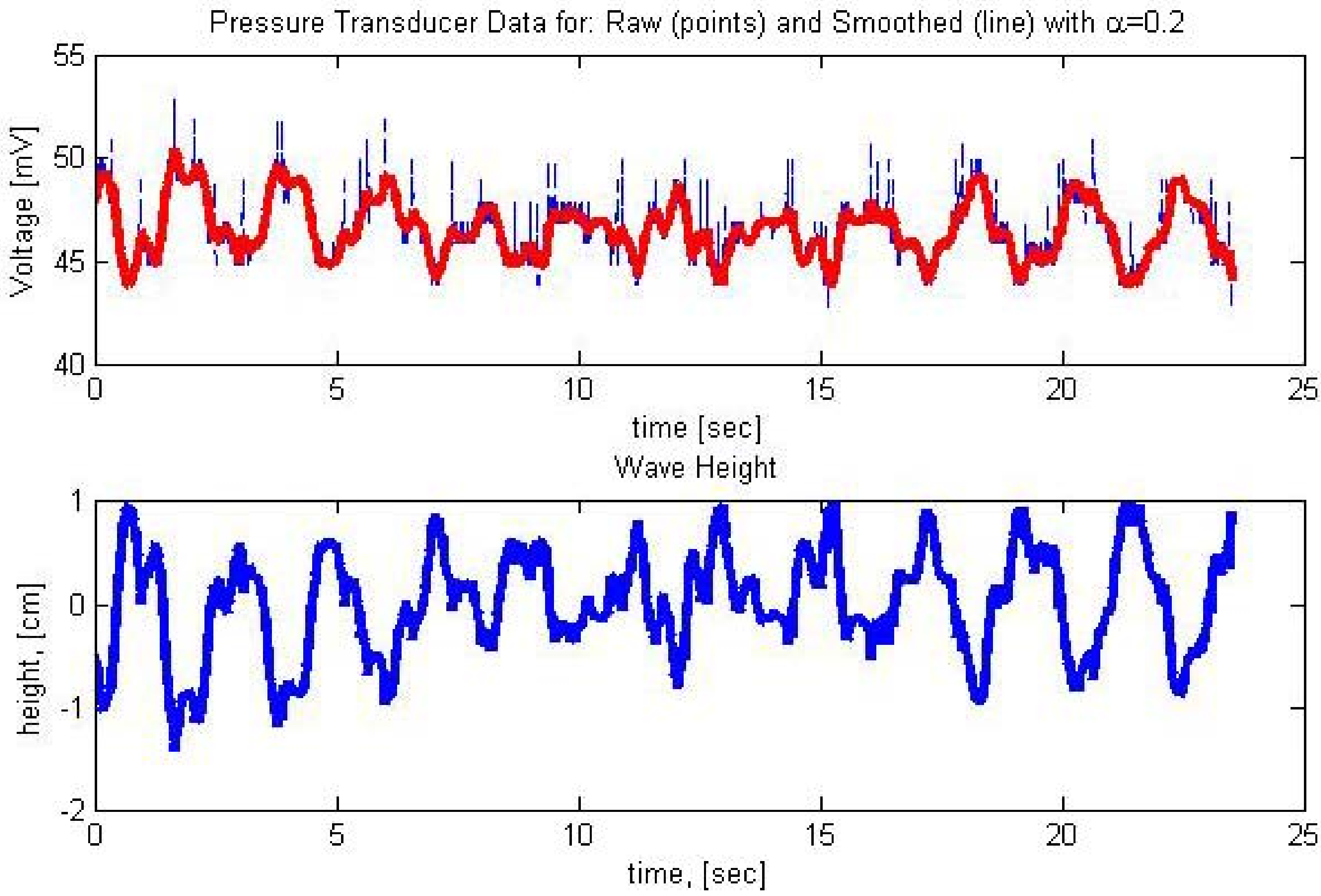
Case 1
- Fair weather
- No Wind
- No river activity

Case 2
- Rain
- Moderate wind
- No river activity

- Case 3
- Fair weather
- Moderate wind
- High boat traffic

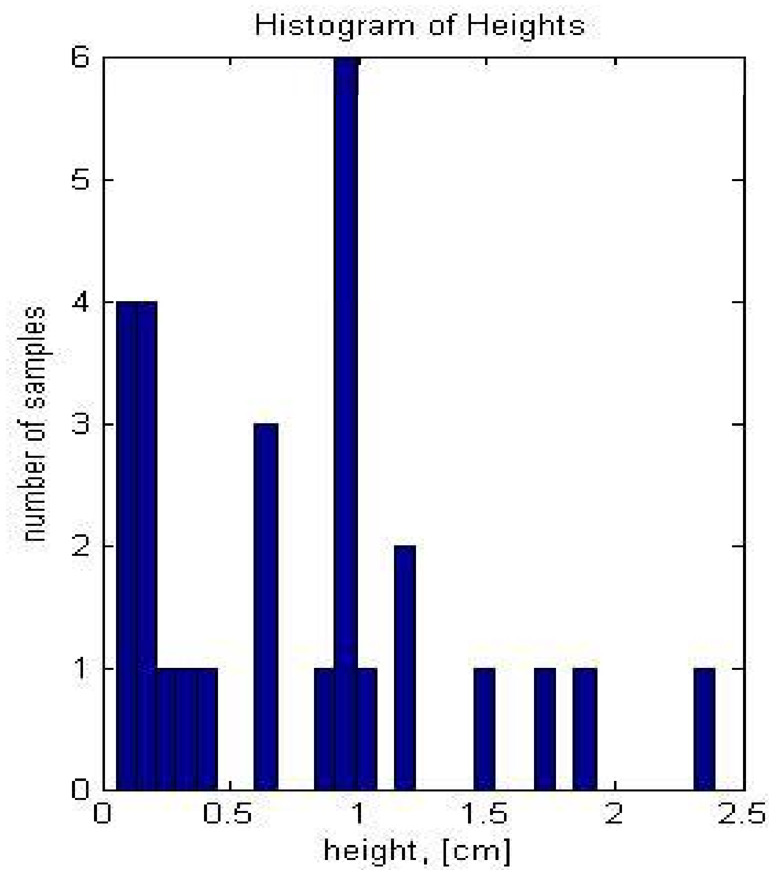
Case 4
- Rain
- High winds
- No river activity
- **Test Day**

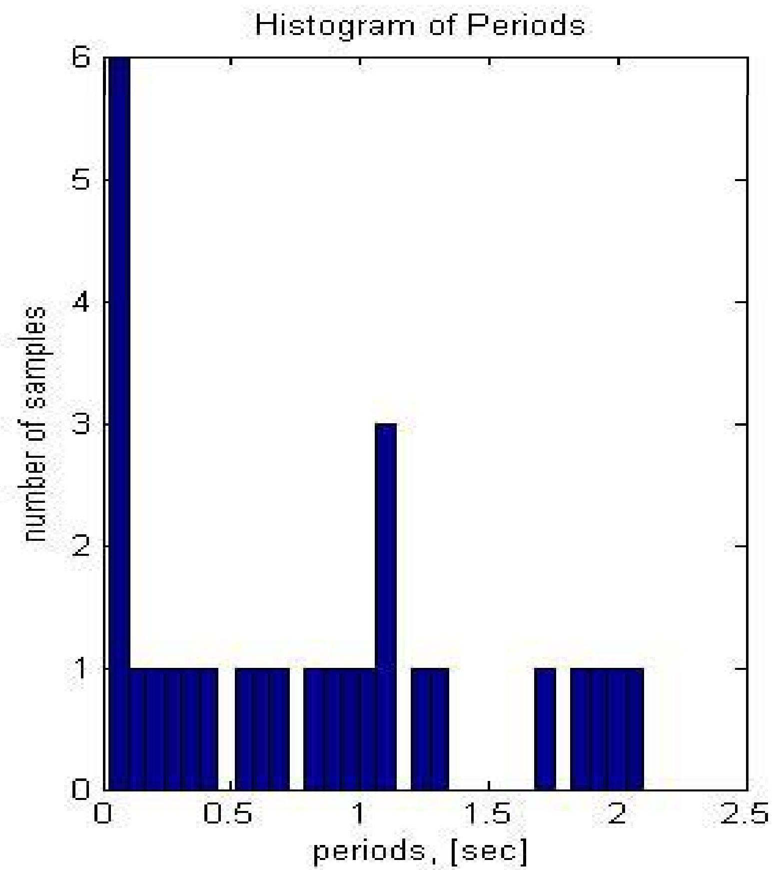
Data



Pressure Transducer Data for: Raw (points) and Smoothed (line) with α=0.2
Voltage [mV]
55
50
45
40
0
5
10
15
20
25
time [sec]
Wave Height
height, [cm]
1
0
-1
-2
0
5
10
15
20
25
time, [sec]

Heights and Periods





Average 1/3 wave height = 1.4242 cm

Average period length = 0.8082 s

River Wave Data

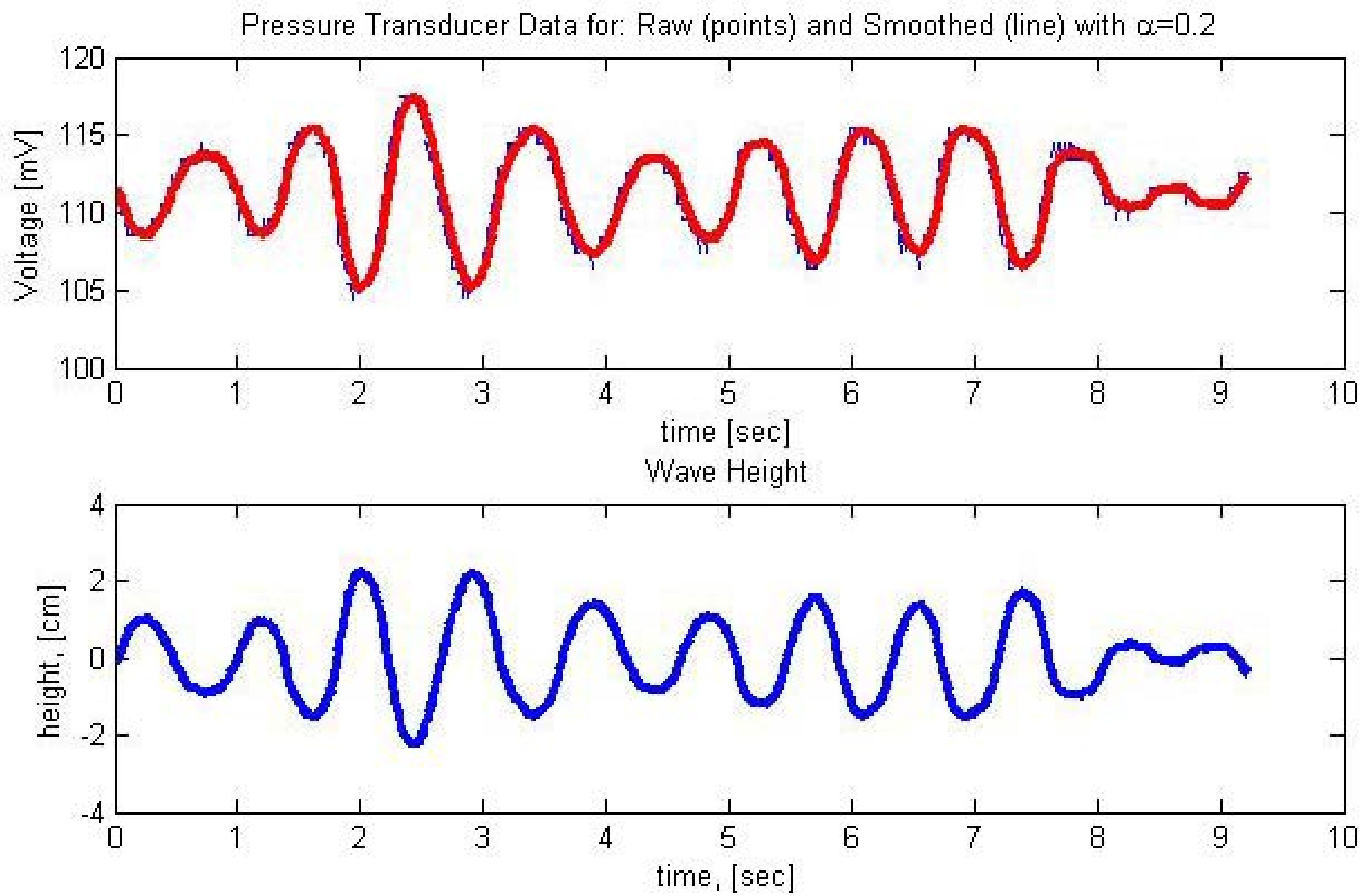
Case 1
- Fair weather
- No Wind
- No river activity

Case 2
- Rain
- Steady wind
- No river activity

Case 3
- Fair weather
- Slight wind
- High boat traffic

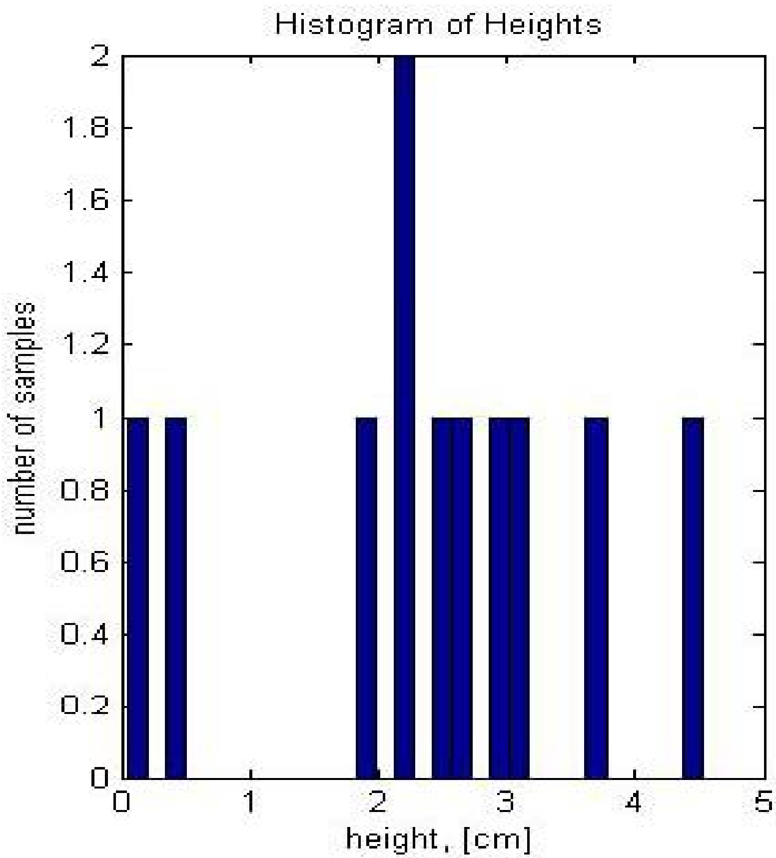
Case 4
- Rain
- High winds
- No river activity
- **Test Day**

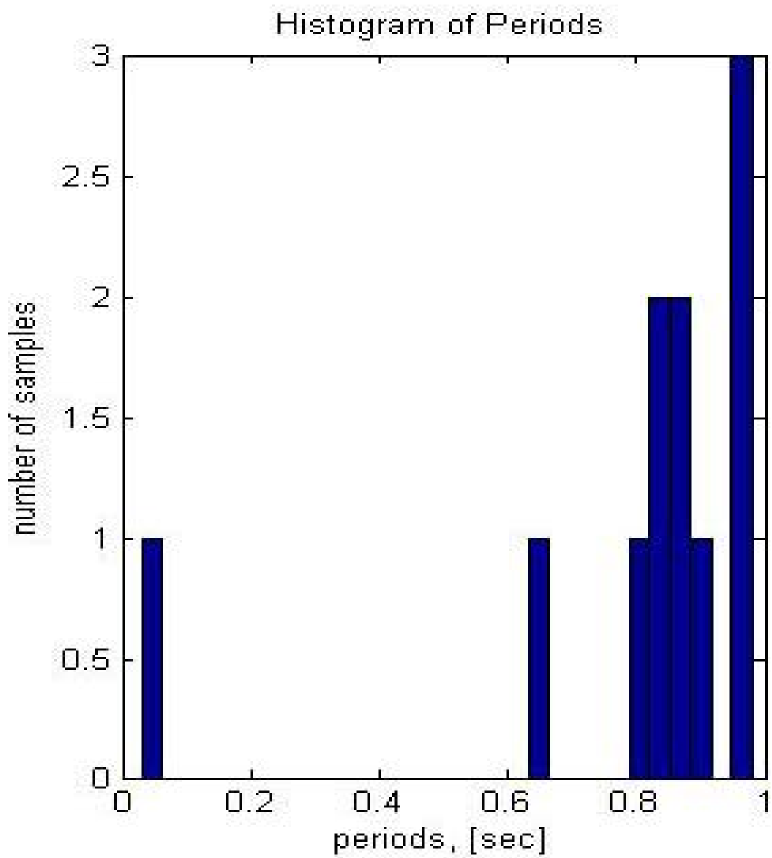
Data



Pressure Transducer Data for: Raw (points) and Smoothed (line) with α=0.2
Voltage [mV]
120
115
110
105
100
0
1
2
3
4
5
6
7
8
9
10
time [sec]
Wave Height
height, [cm]
4
2
0
-2
-4
time, [sec]

Heights and Periods

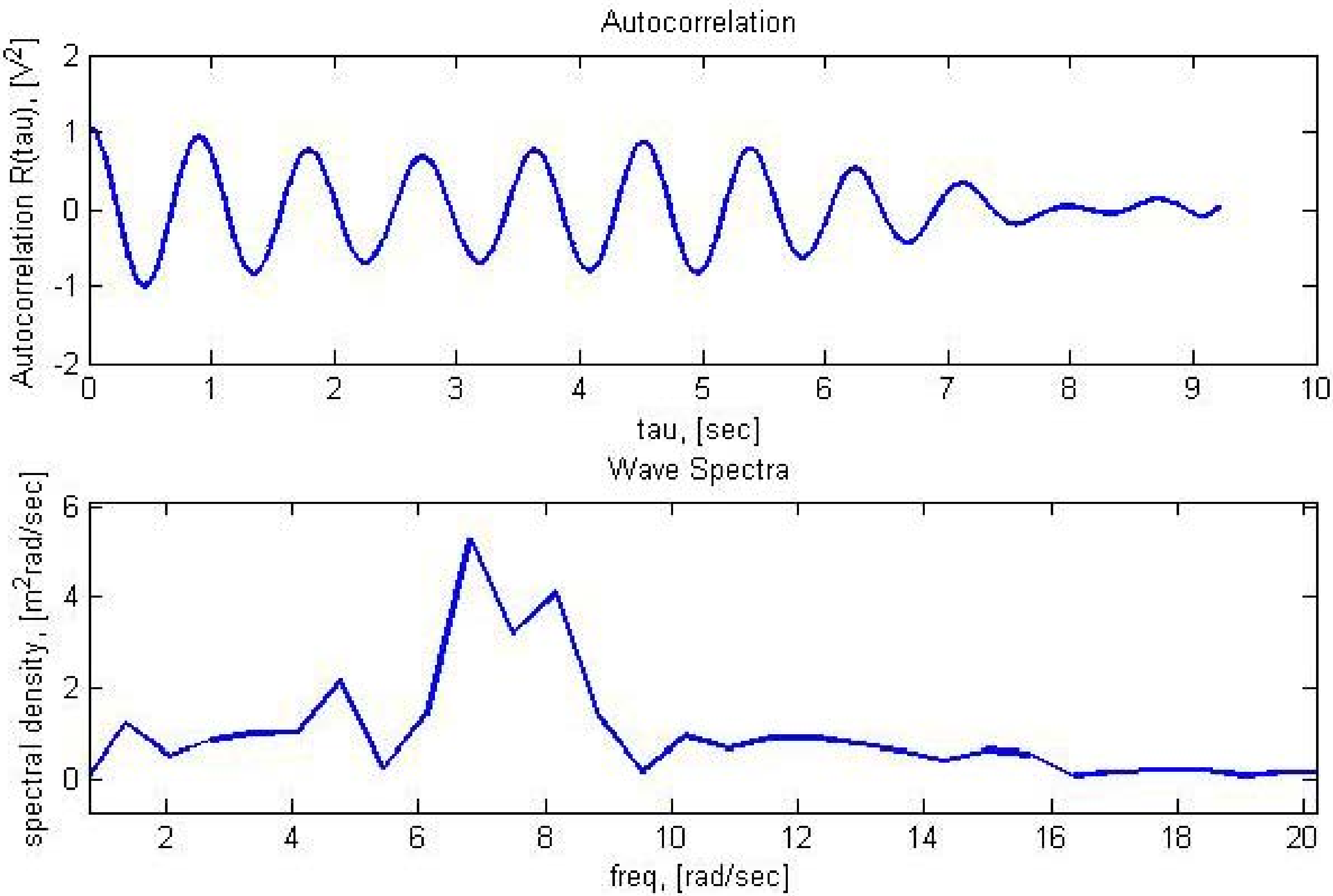




Average 1/3 wave height = 3.5856 cm

Average period length = 0.7936 s

Wave Spectra



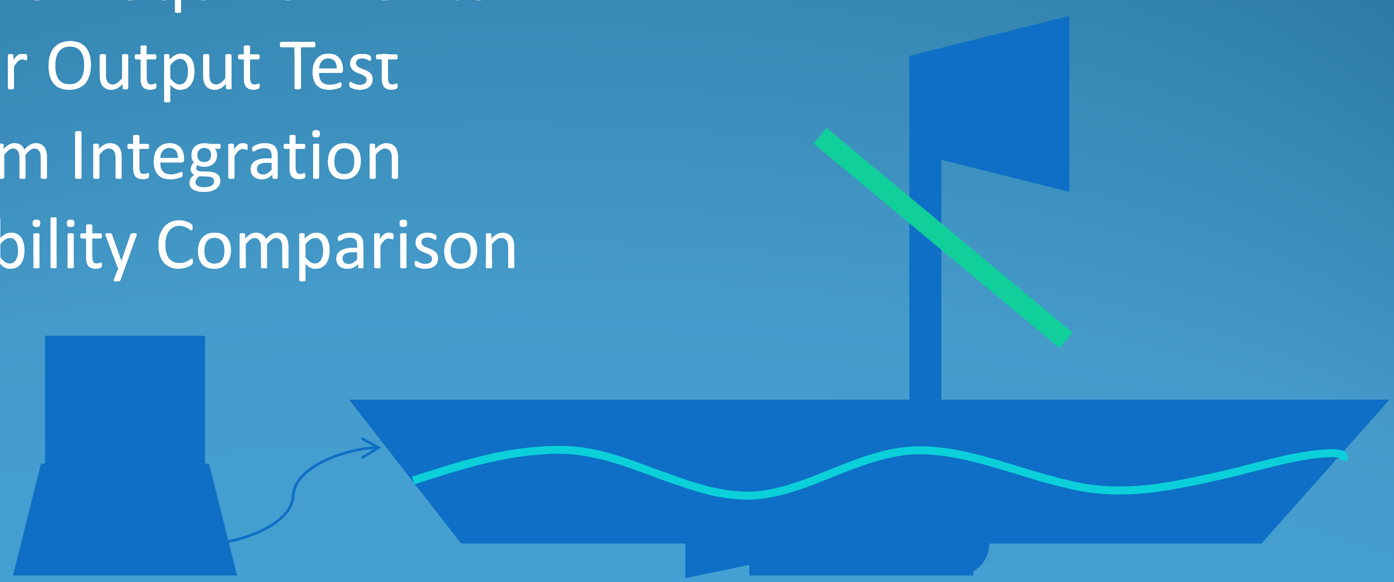
Conclusions

- No real current
- Waves driven by two sources
  - Wind
  - River activity
- Frequency faster in presence of wind source
- Need more data!

Solar Energy

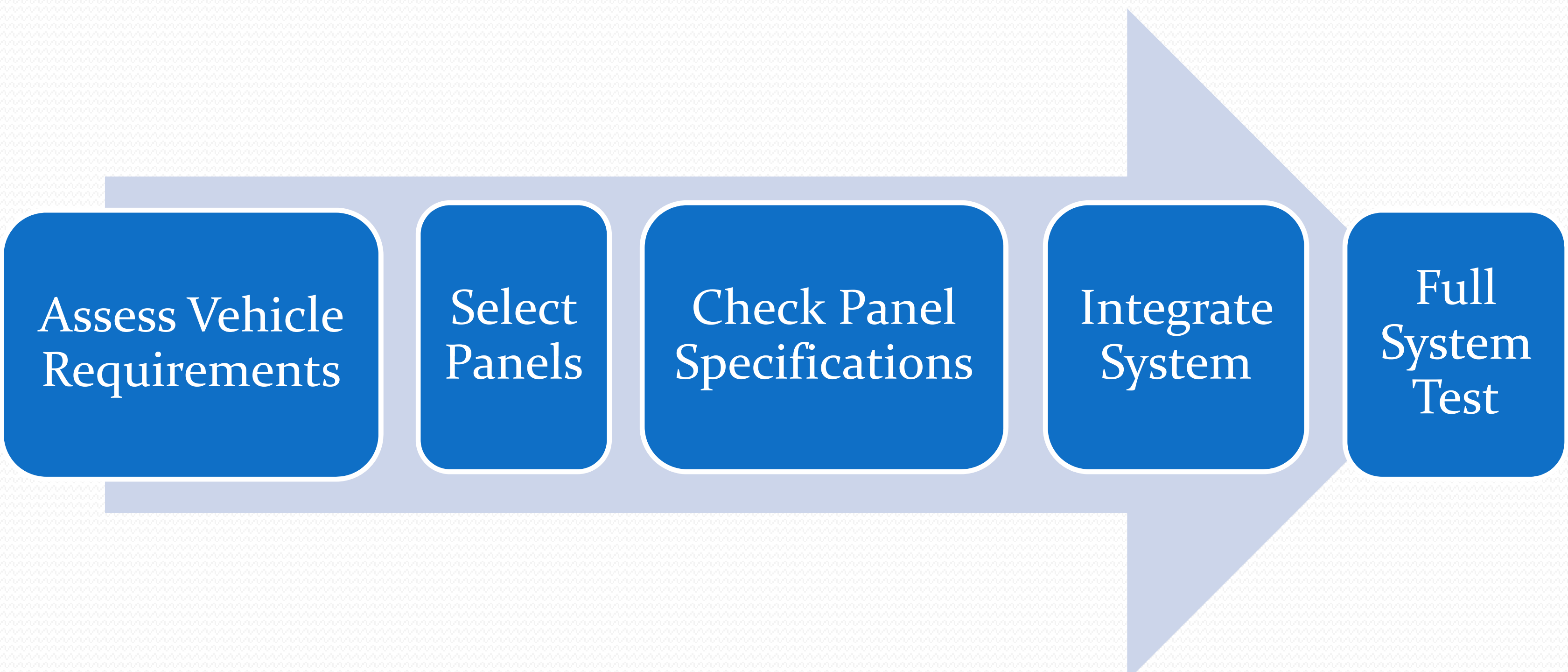
Student G

- Vehicle Requirements
  Power Output Test
- System Integration
- Feasibility Comparison



Project Overview

- Tasked with feasibility assessment for solar power use
- Desired quantitative data



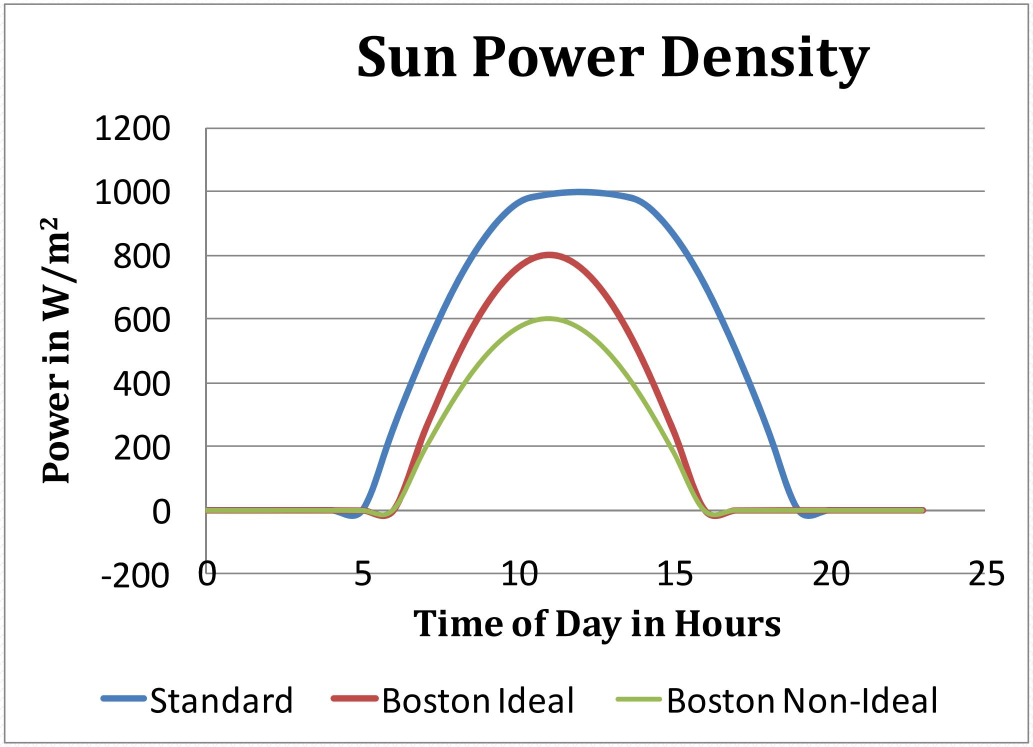
Vehicle Requirements

Component	Voltage	Current	Power
Accelerometer	6 V	50 mA	0.300 W
Sonar	5 V	50 mA	0.250 W
GPS	3.3 V	50 mA	0.165 W
Arduino Mega	5 V	50 mA	0.25 W
		Electronics Total:	**0.965 W**
Motors (Min)	12 V	0.25 A	3 W
Motors (Max)	12 V	2.50 A	30 W
		Vehicle Minimum Total:	**3.965 W**
		Vehicle Maximum Total Total:	**30.965 W**

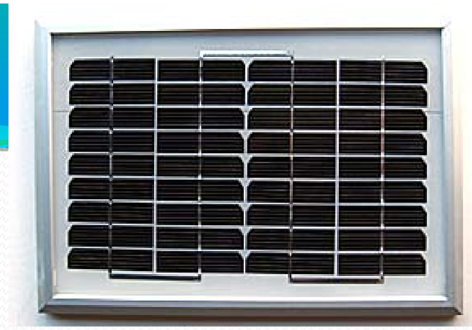
Correcting Specifications

- Panel output: $P_{out} = \eta_{panel} E_{density} A_{panel}$
- Standard Peak $E_{density}$: 1000 W/m^2 (noon @ equator)
- Boston Dec. Peak $E_{density}$: 800 W/m^2
- Ideal: 10am on sunny day
  - 600 W/m^2
- Non-ideal: 10am Cloudy
  - 200 W/m^2
- Power through day:

$$P(t) = P \cdot \sin\left(\frac{t - t_{dawn}}{t_{dusk} - t_{dawn}} \cdot \Pi \right)$$



Suntech STP0055-12

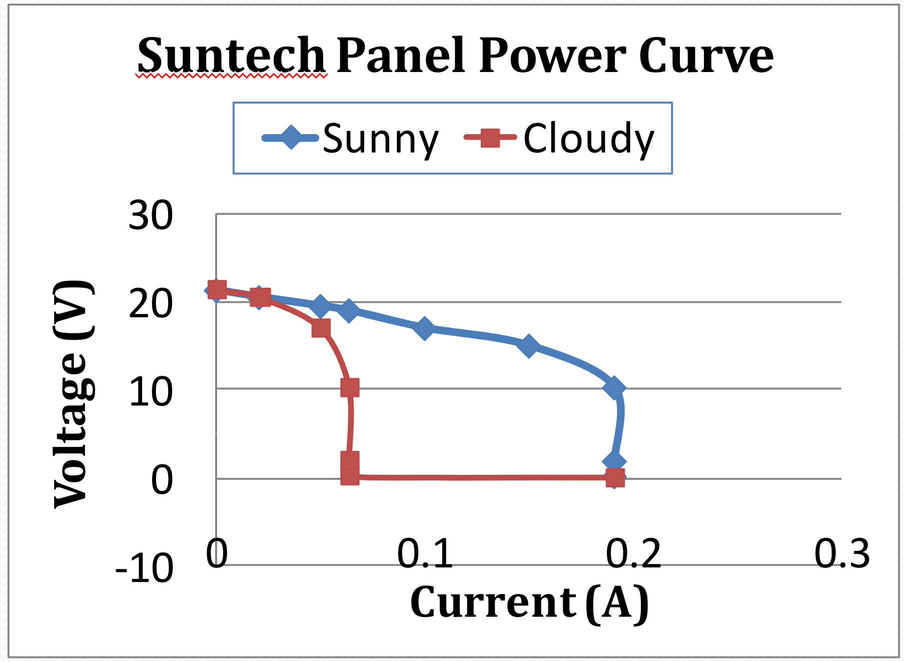


Estimated Capabilities

- Peak Rated Power = 5W
- Peak Power (sunny)= 3W
- Peak Power (rainy) = 1W

Measured Capabilities

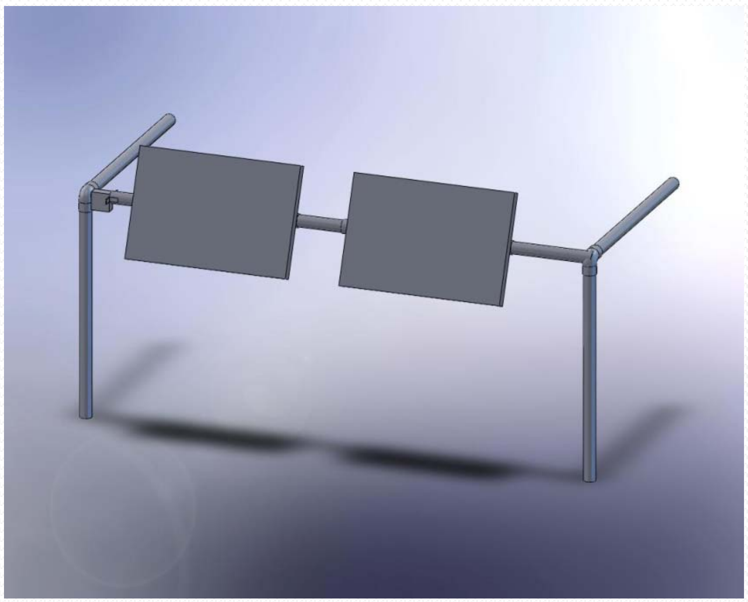
- Sunny:
  - Short Circuit Current : 0.21 A
  - Measured Output: 2.8 W
- Cloudy
  - Short Circuit Current: 0.065 A
  - Measured Output: 0.933 W



$$P = VI + = \frac{V^2}{R}$$

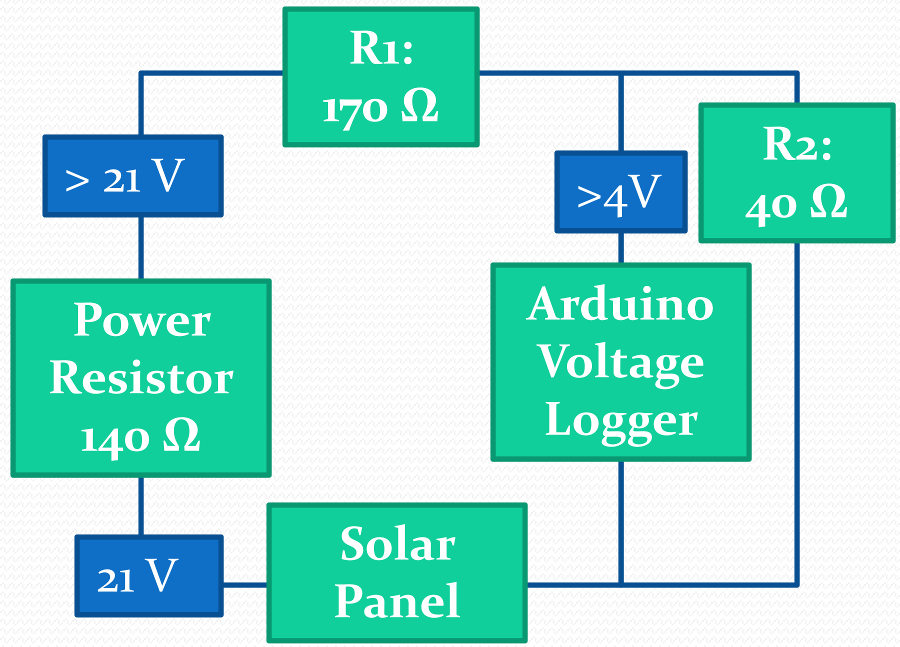
System Integration

Physical System



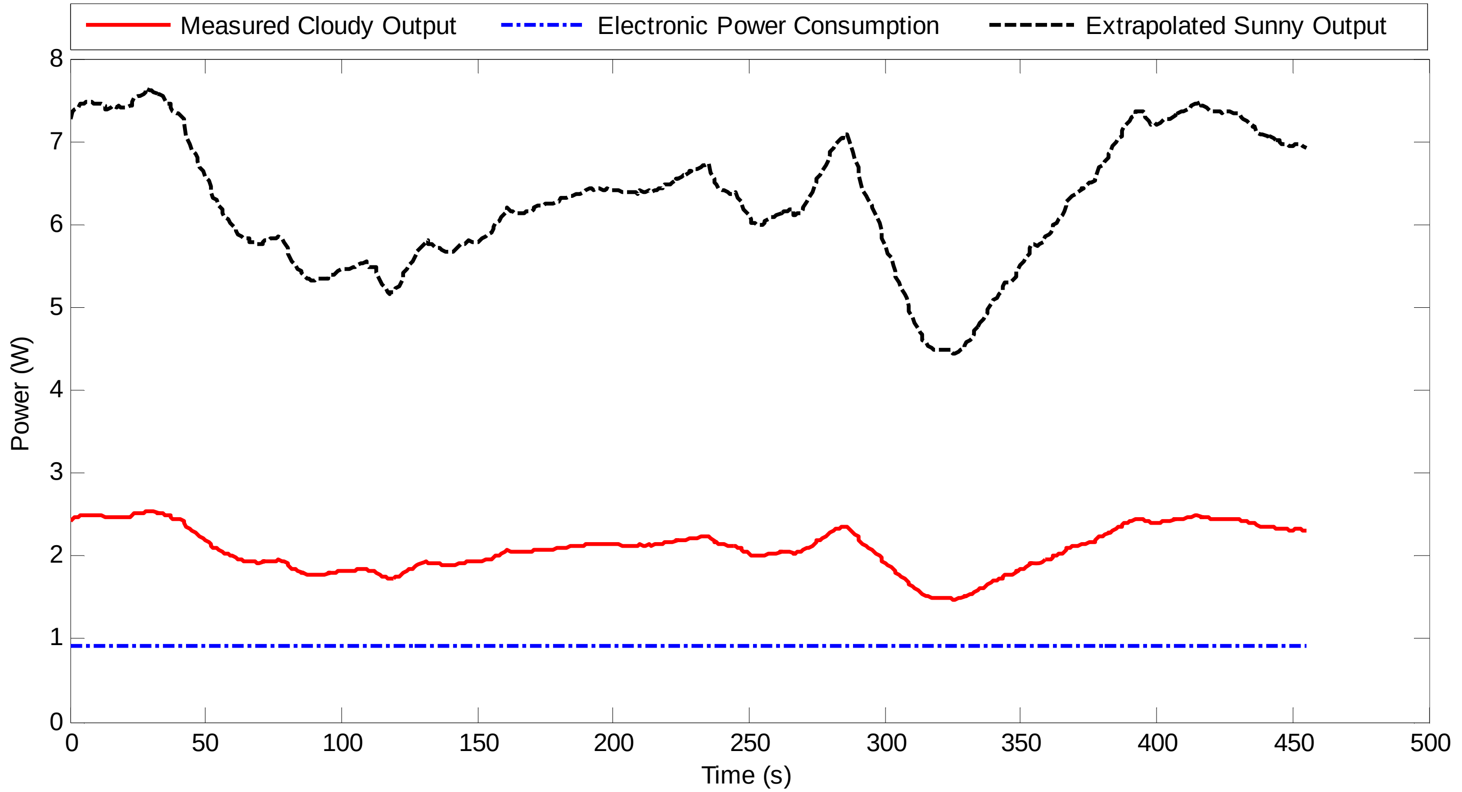
- Panels sit on motor mounting
- Servo available for optimization

Electronic System

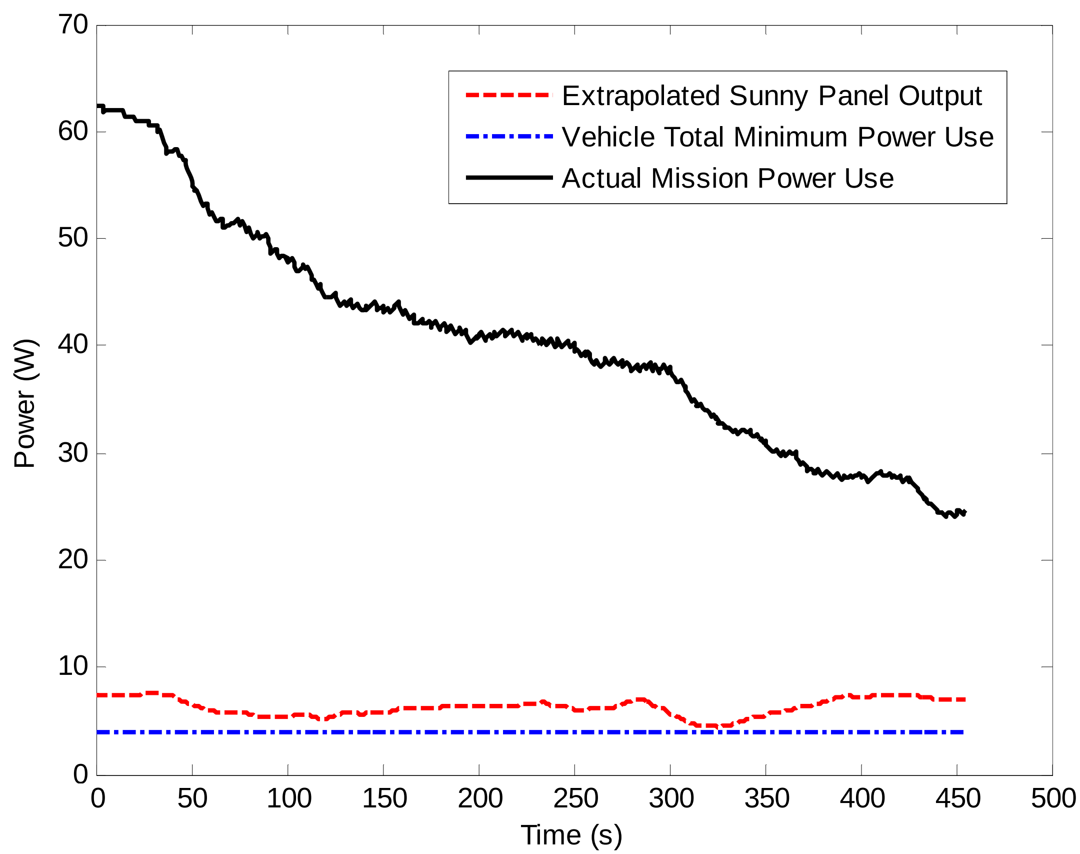


$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$

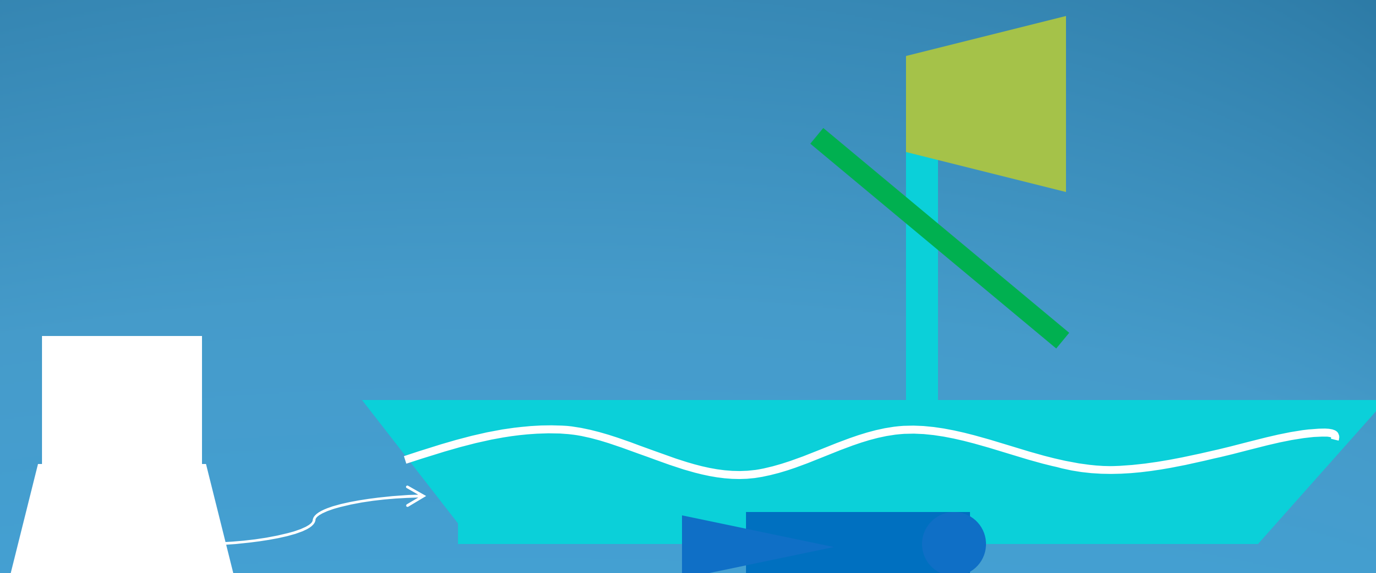
Feasibility- Electronics



Full Vehicle Feasibility



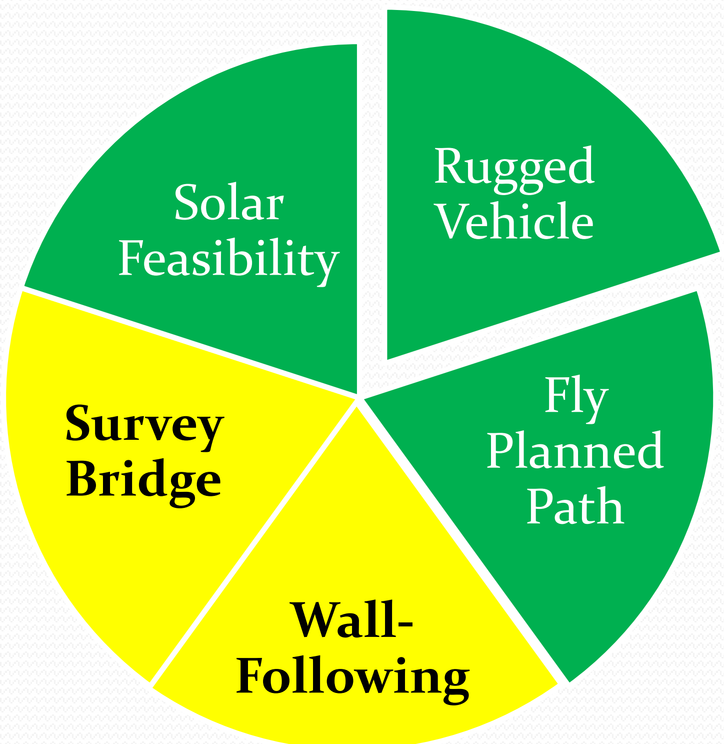
Summary and Next Steps



Mission Video

- View from vessel
- View from shore

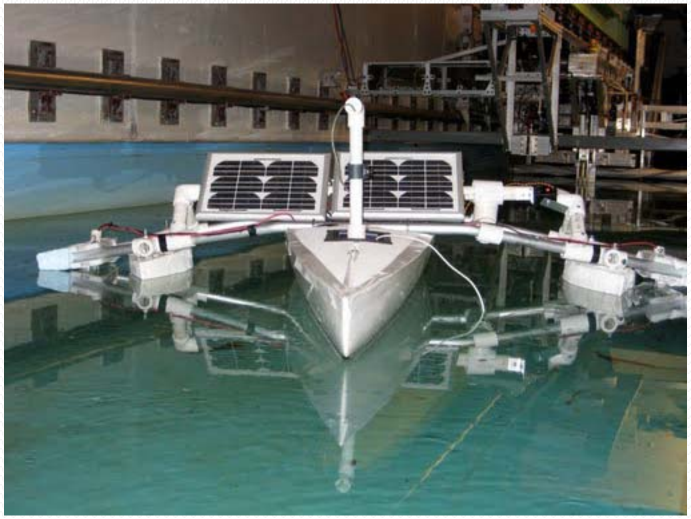
Final Evaluation



- Vehicle survived well
  - Deployment & leaks
- Path followed
- Solar power sufficient
- No time for bridge test
  - Capability Present
- Wall following untested

Future Mission Objectives

- Add full GPS navigation capabilities
- Use Sonar for wall following
- Remote data logging abilities
- Actively control solar panel angle
- Test in warmer drier weather!!



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MIT Towing Tank

Mechanical Engineering Department
Center for Ocean Engineering

Chevron
Schlumberger

Questions?

Naval Architecture Spreadsheet

- Displacement v. draft

		Drafts (in)																
Simpson's Multipier:		0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	
1	Does	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2	Section	0	0	0	0	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	
4	Matter for	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	
2	Draft?	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	
4		0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	
2		0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	
4		0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	
2		0	0	0	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	
4		0	0	0	0	0	0	0	0	0	0	0.25	0.5	0.75	1	1.25	1.5	
1		0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.5	0.75	1	
		Assumed B(T) = sqrt(T/Cx)																
		4.082483	5.773503	7.071068	8.164966	9.128709	10	10.80123	11.54701	12.24745	12.90994	13.54006	14.14214	14.7196	15.27525	15.81139	16.32993	
	Station Number	Integrand : B(T) Draft * Section Coefficient																
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	2	0	0	0	0	0	4.5	9.721111	15.58846	22.04541	29.04738	36.55817	44.54773	52.99057	61.86477	71.15125	80.83316	
	3	0	2.598076	6.363961	11.0227	16.43168	22.5	29.16333	36.37307	44.09082	52.28528	60.93029	70.00357	79.48585	89.36023	99.61175	110.227	
	4	0	2.598076	6.363961	11.0227	16.43168	22.5	29.16333	36.37307	44.09082	52.28528	60.93029	70.00357	79.48585	89.36023	99.61175	110.227	
	5	1.837117	5.196152	9.545942	14.69694	20.5396	27	34.02389	41.56922	49.60217	58.09475	67.02332	76.36753	86.10967	96.23409	106.7269	117.5755	
	6	1.837117	5.196152	9.545942	14.69694	20.5396	27	34.02389	41.56922	49.60217	58.09475	67.02332	76.36753	86.10967	96.23409	106.7269	117.5755	
	7	1.837117	5.196152	9.545942	14.69694	20.5396	27	34.02389	41.56922	49.60217	58.09475	67.02332	76.36753	86.10967	96.23409	106.7269	117.5755	
	8	0	0	0	0	4.107919	9	14.58167	20.78461	27.55676	34.85685	42.6512	50.91169	59.61439	68.73864	78.26637	88.18163	
	9	0	0	0	0	0	0	0	0	0	0	6.093029	12.72792	19.87146	27.49545	35.57562	44.09082	
	10	0	0	0	0	0	0	0	0	0	0	0	0	6.623821	13.74773	21.34537	29.39388	
		Sum Over Sections																
		5.511352	20.78461	41.36575	66.13622	98.59006	139.5	184.7011	233.8269	286.5903	342.759	408.2329	477.2971	556.4009	639.2693	725.7427	815.6801	
	Multiplier:	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	
Submerged Volume:		16.01966	60.41393	120.2364	192.236	286.5684	405.48	536.8646	679.6567	833.0225	996.2862	1186.597	1387.344	1617.272	1858.143	2109.492	2370.91	in^3
Density of Water:		62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	63.4	64.4	65.4	66.4	lb(f)/ft^3
Density of Water:		0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.036111	0.03669	0.037269	0.037847	0.038426	lb/in^3
Displacement:		0.578488	2.181614	4.341871	6.941854	10.3483	14.64233	19.38678	24.54316	30.08137	35.977	42.84934	50.09852	59.33741	69.25023	79.83842	91.10442	lbs (f)

Naval Architecture Spreadsheet

- GM calculation

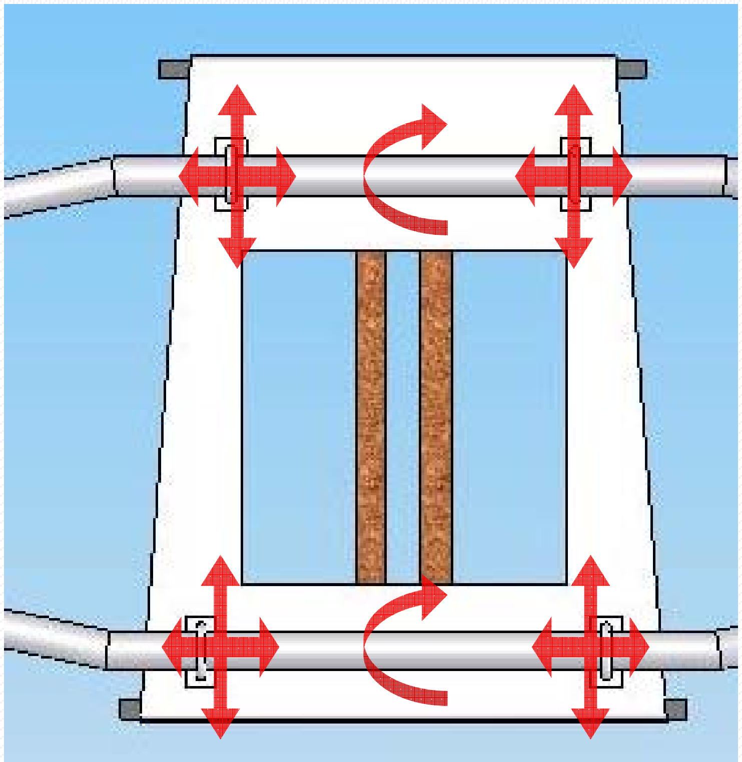
KG Location																
KGT =	3.090909		Element:	Weight:	Approx KG	Multiply:										
			Solar Panels	1.8	10.5	18.9										
			Motors	4	-6.5	-26										
			Main Hull	5.2	3	15.6										
			Mounting Structure	4.2	5.5	23.1										
			Solar Panel Mounts	2.4	9.5	22.8										
			Total Structure:	17.6	3.090909091	54.4										
			Battery	13.4												
			Ballast	3.5												
			Sensors	1												
				35.5												
					Draft											
					0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
					B(T)											
BM Location					4.082482905	5.773503	7.071068	8.164966	9.128709	10	10.80123	11.54701	12.24745	12.90994	13.54006	14.14214
BMT =	It/disp	Station Number	x	Simpson's Multipier:	Integrand:											
		1	0	1	22.68046058	64.15003	117.8511	181.4437	253.5753	333.3333	420.048	513.2002	612.3724	717.2191	827.4484	942.809
		2	8.72	2	45.36092116	128.3001	235.7023	362.8874	507.1505	666.6667	840.096	1026.4	1224.745	1434.438	1654.897	1885.618
		3	17.44	4	90.72184233	256.6001	471.4045	725.7747	1014.301	1333.333	1680.192	2052.801	2449.49	2868.877	3309.793	3771.236
		4	26.16	2	45.36092116	128.3001	235.7023	362.8874	507.1505	666.6667	840.096	1026.4	1224.745	1434.438	1654.897	1885.618
		5	34.88	4	90.72184233	256.6001	471.4045	725.7747	1014.301	1333.333	1680.192	2052.801	2449.49	2868.877	3309.793	3771.236
		6	43.6	2	45.36092116	128.3001	235.7023	362.8874	507.1505	666.6667	840.096	1026.4	1224.745	1434.438	1654.897	1885.618
		7	52.32	4	90.72184233	256.6001	471.4045	725.7747	1014.301	1333.333	1680.192	2052.801	2449.49	2868.877	3309.793	3771.236
		8	61.04	2	45.36092116	128.3001	235.7023	362.8874	507.1505	666.6667	840.096	1026.4	1224.745	1434.438	1654.897	1885.618
		9	69.76	4	90.72184233	256.6001	471.4045	725.7747	1014.301	1333.333	1680.192	2052.801	2449.49	2868.877	3309.793	3771.236
		10	78.5	1	22.68046058	64.15003	117.8511	181.4437	253.5753	333.3333	420.048	513.2002	612.3724	717.2191	827.4484	942.809
				Sum:	589.6919751	1667.901	3064.129	4717.536	6592.957	8666.667	10921.25	13343.21	15921.68	18647.7	21513.66	24513.04
			Multiplying Term:		2.906666667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667	2.906667
				It:	1714.038008	4848.032	8906.403	13712.3	19163.53	25191.11	31744.43	38784.25	46279.03	54202.64	62533.03	71251.22
			Displacement:		16.01966292	60.41393	120.2364	192.236	286.5684	405.48	536.8646	679.6567	833.0225	996.2862	1186.597	1387.344
				BMt	106.9958848	80.24691	74.07407	71.33059	66.87243	62.12664	59.1293	57.06447	55.55556	54.40469	52.69947	51.35802
KB Location																
KBt=	2			KBt	0	0	0	0	0	0	0	0	0	0	0	0
KM Location																
KM = KB + BM				KMt	106.9958848	80.24691	74.07407	71.33059	66.87243	62.12664	59.1293	57.06447	55.55556	54.40469	52.69947	51.35802
GM Location																
GM = KM-KG				GMt	103.9049757	77.156	70.98316	68.23968	63.78152	59.03573	56.0384	53.97356	52.46465	51.31378	49.60856	48.26712

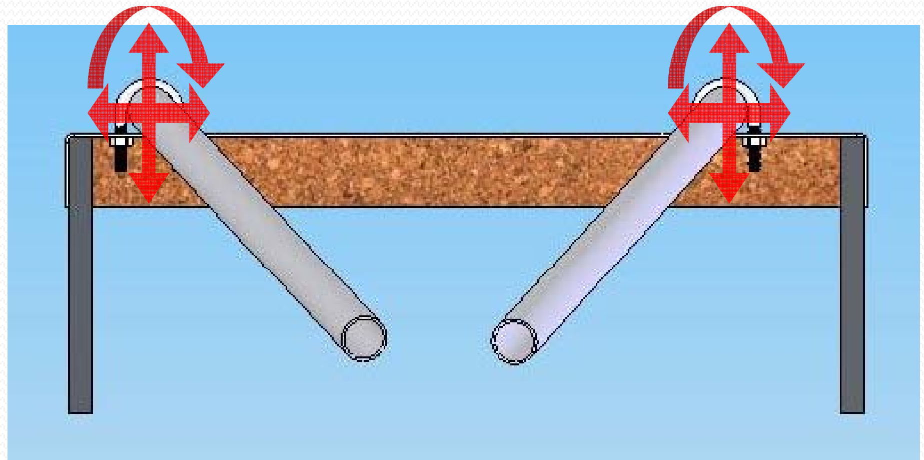
Naval Architecture Spreadsheet

- Trim Calculation

Draft (in)		0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
GM Location (in)													
GM = KM-KG		103.9049757	77.156	70.98316	68.23968	63.78152	59.03573	56.0384	53.97356	52.46465	51.31378	49.60856	48.26712
Change in GM		26.74897119	6.17284	2.743484	4.458162	4.745785	2.997338	2.064833	1.508916	1.150868	1.705222	1.341441	
Estimated MT1 (lb)		0.028395935	0.006553	0.002912	0.004733	0.005038	0.003182	0.002192	0.001602	0.001222	0.00181	0.001424	
Trim	Trim Angle (rad)	Trim Angle (deg)	Trim Moment										
-3.5	-0.08893674	-0.558806026	-19.6791	-85.276	-191.871	-118.075	-110.918	-175.621	-254.934	-348.857	-457.39	-308.696	-392.41
-3	-0.0762848	-0.47931153	-16.8796	-73.1449	-164.576	-101.277	-95.1395	-150.637	-218.667	-299.229	-392.322	-264.782	-336.587
-2.5	-0.06360834	-0.399662997	-14.0747	-60.9902	-137.228	-84.4479	-79.3299	-125.606	-182.331	-249.505	-327.129	-220.782	-280.655
-2	-0.05091138	-0.319885644	-11.2652	-48.8158	-109.836	-67.5911	-63.4947	-100.533	-145.935	-199.701	-261.83	-176.712	-224.633
-1.5	-0.03819797	-0.240004934	-8.45209	-36.6257	-82.4079	-50.7125	-47.639	-75.4285	-109.493	-149.832	-196.447	-132.584	-168.539
-1	-0.0254722	-0.160046531	-5.63625	-24.4237	-54.9534	-33.8175	-31.7679	-50.2992	-73.015	-99.9153	-131	-88.413	-112.389
-0.5	-0.01273816	-0.080036248	-2.81858	-12.2139	-27.4812	-16.9115	-15.8865	-25.1537	-36.5134	-49.9658	-65.5107	-44.2137	-56.2039
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0.01273816	0.080036248	2.818581	12.21385	27.48117	16.91149	15.88655	25.1537	36.51344	49.96576	65.51066	44.2137	56.20385
1	0.0254722	0.160046531	5.636248	24.42374	54.95342	33.81749	31.76794	50.29924	73.01503	99.9153	131.0001	88.41305	112.3895
1.5	0.03819797	0.240004934	8.452088	36.62571	82.40785	50.71253	47.63904	75.42848	109.493	149.8325	196.447	132.5837	168.5387
2	0.05091138	0.319885644	11.26519	48.81583	109.8356	67.59115	63.49471	100.5333	145.9354	199.7011	261.8304	176.7115	224.6333
2.5	0.06360834	0.399662997	14.07466	60.99017	137.2279	84.44793	79.32987	125.6056	182.3308	249.5052	327.1291	220.7822	280.6553
3	0.0762848	0.47931153	16.87958	73.14486	164.5759	101.2775	95.13946	150.6375	218.6673	299.229	392.3224	264.7817	336.5869
3.5	0.08893674	0.558806026	19.67908	85.27603	191.8711	118.0745	110.9185	175.6209	254.9336	348.8565	457.3896	308.6961	392.4103

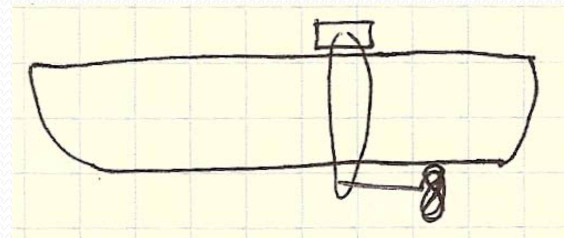
Fully Constrained Pontoon Attachments

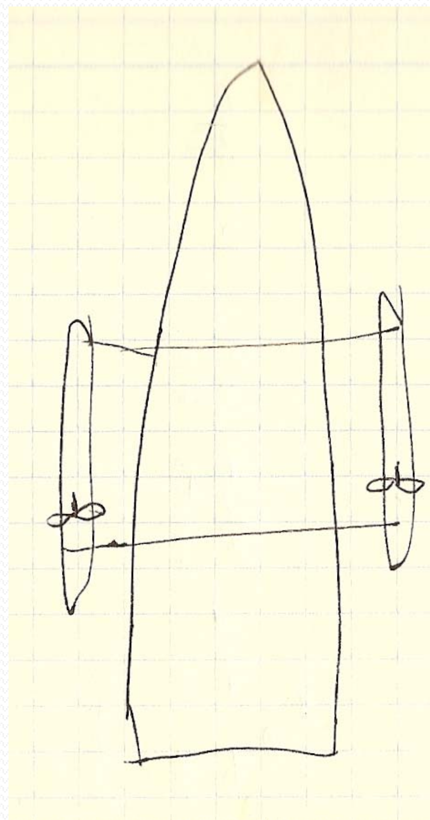


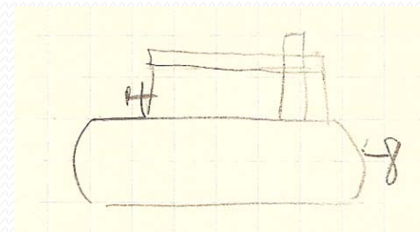


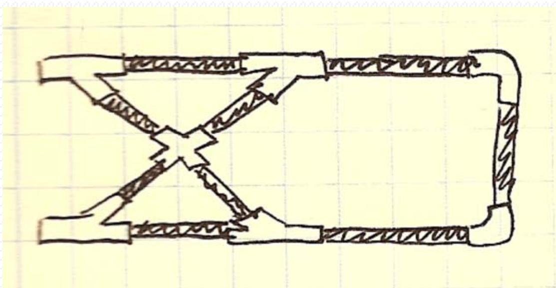
Leads to stress concentrations at joints

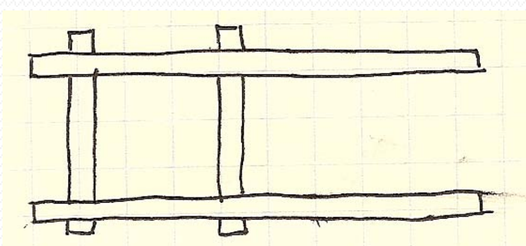
Previous Designs

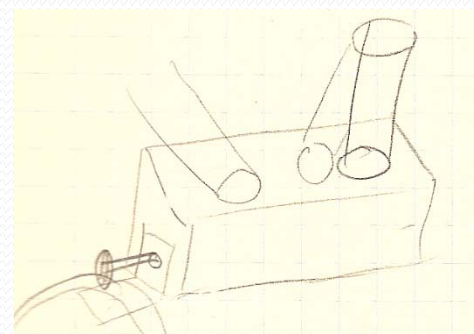












Pressure Transducer: Calibration Curve