Tidal Resource Characterization from Acoustic Doppler Current Profilers

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Masters Thesis Defense

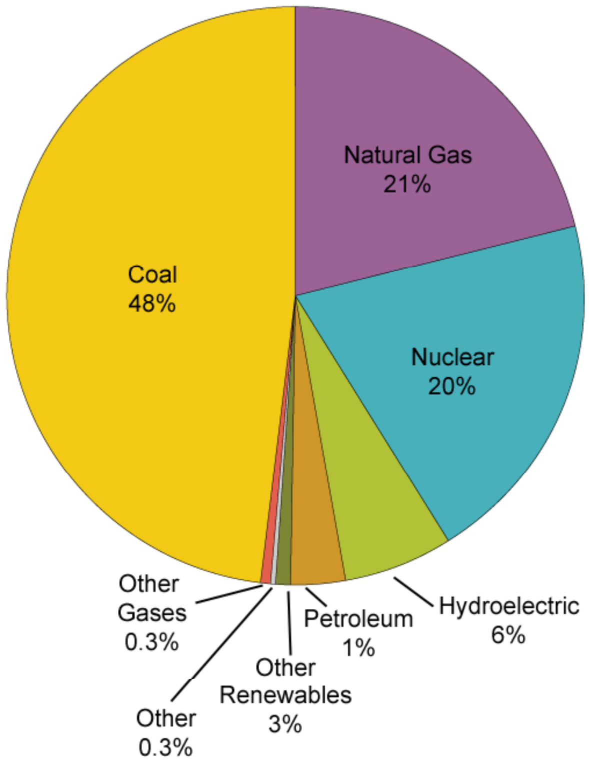
May 28th, 2010

Outline

- Motivation & Background
- Stationary Acoustic Doppler Current Profiler Analysis
- Shipboard Acoustic Doppler Current Profiler Analysis
- Conclusion

Why Tidal Energy?

U.S. Electric Power Industry Net Generation by Fuel, 2008



Source: U.S. Energy Information Administration, *Electric Power Annual* (2010).

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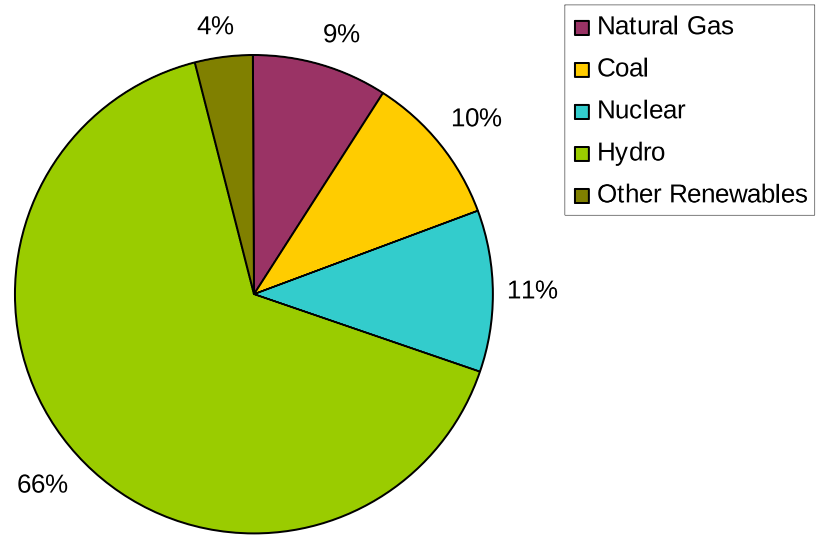
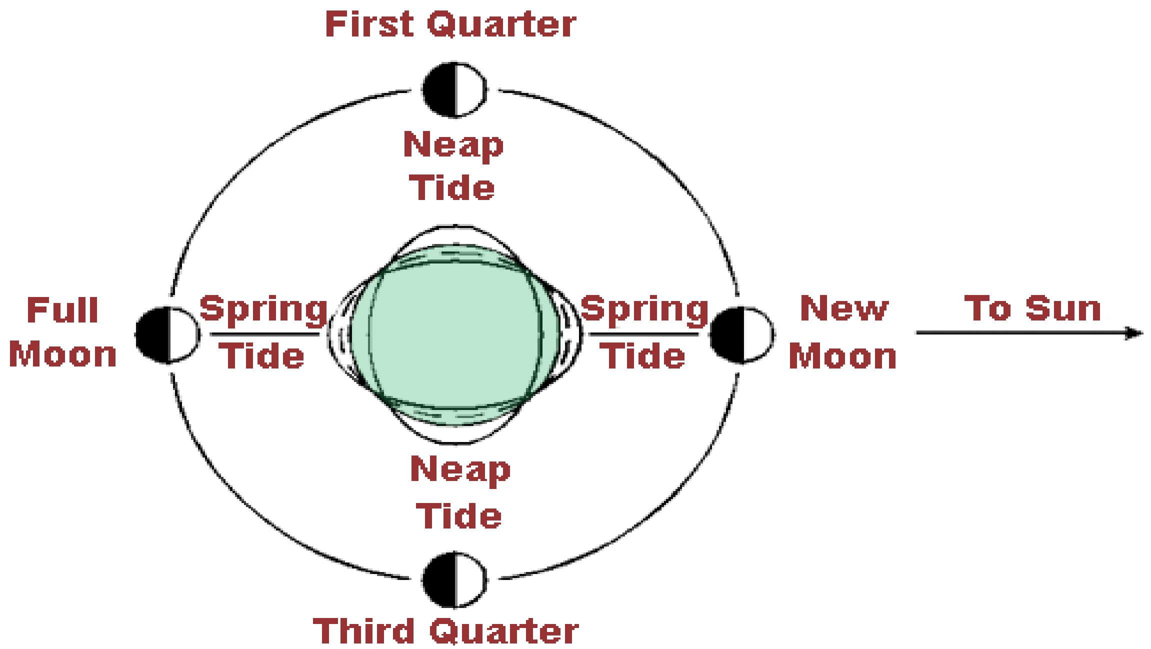
Washington State Net Electricity Generation, Feb 2010



*** WA State Initiative 937**

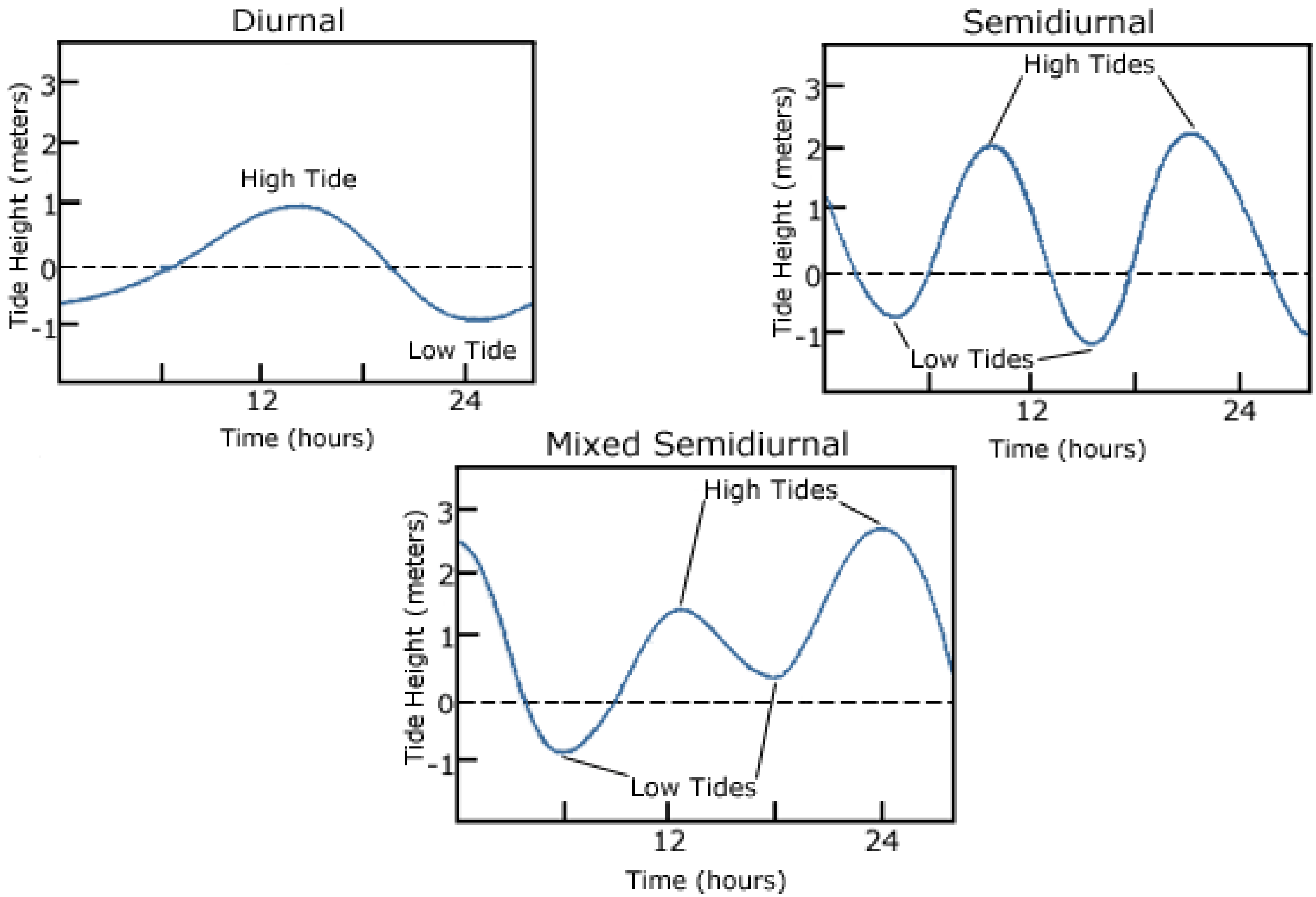
Tides and Currents

- Gravitational interactions of Earth, Moon, & Sun system
- Spring / Neap Tidal Cycle: 14.76 days



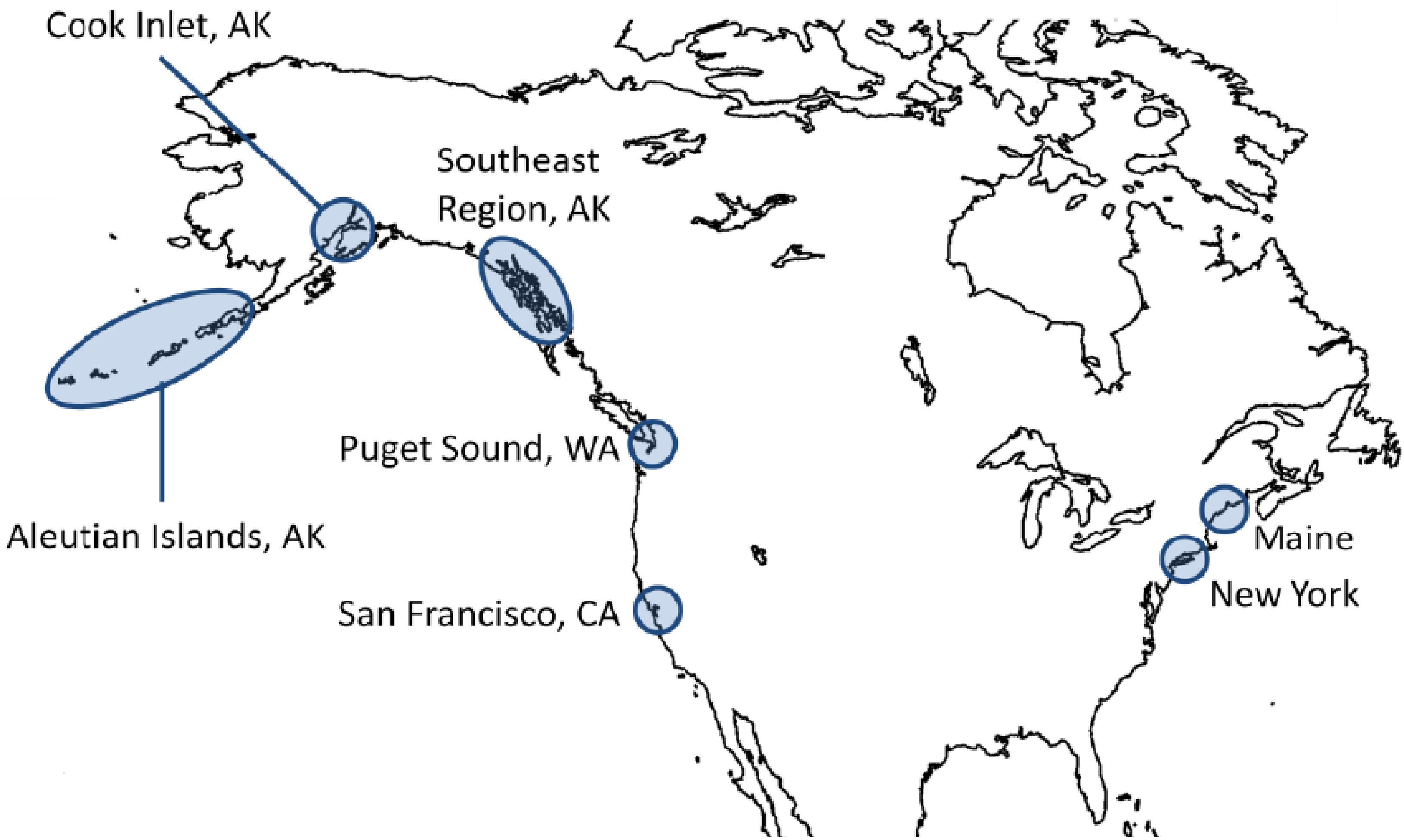
Source: http://www.oc.nps.edu/nom/day1/partc.html, May 1, 2010

Tides and Currents



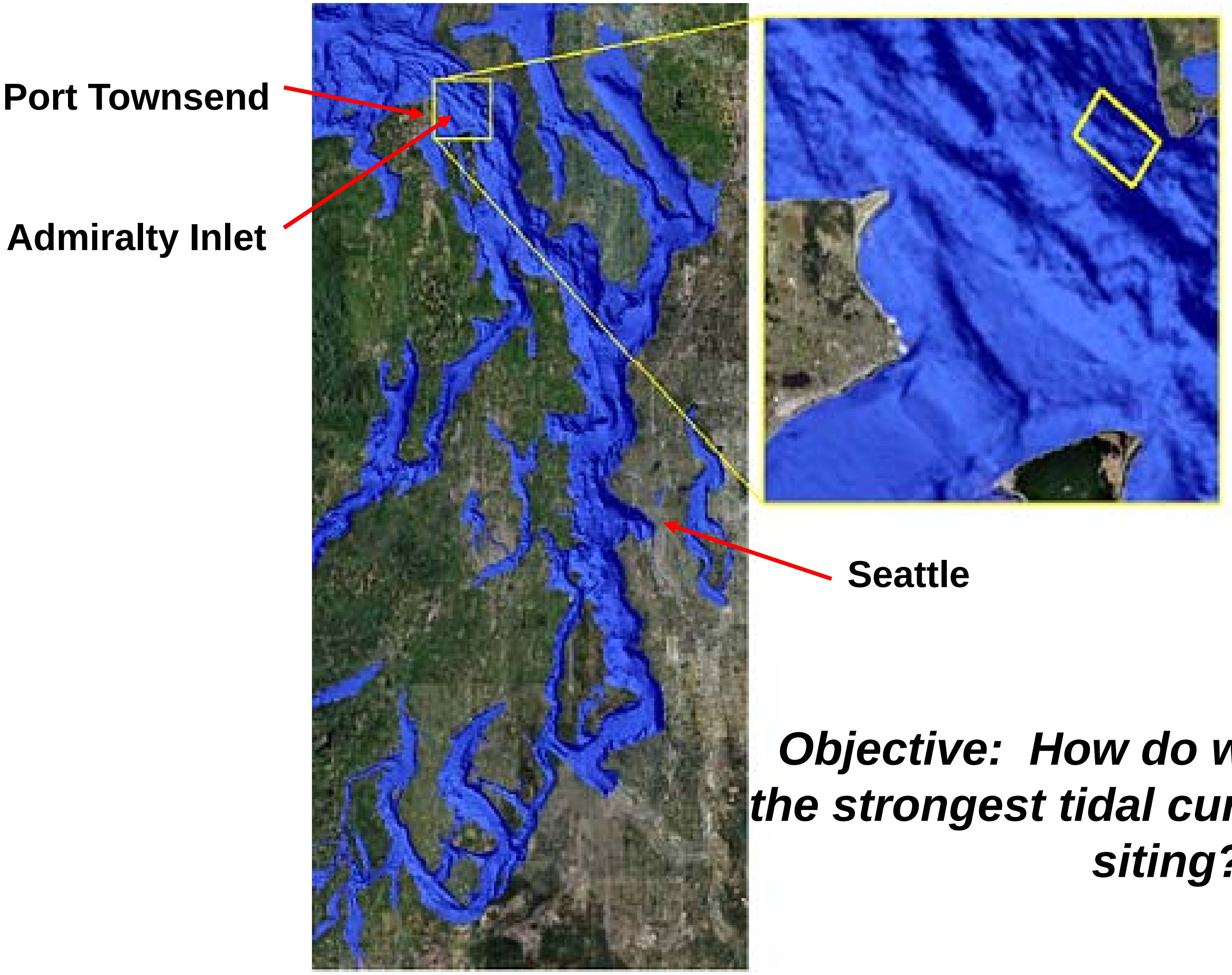
Source: http://oceanservice.noaa.gov/education/kits/tides/media/supp_tide07a.html

U.S. Tidal Current Resources



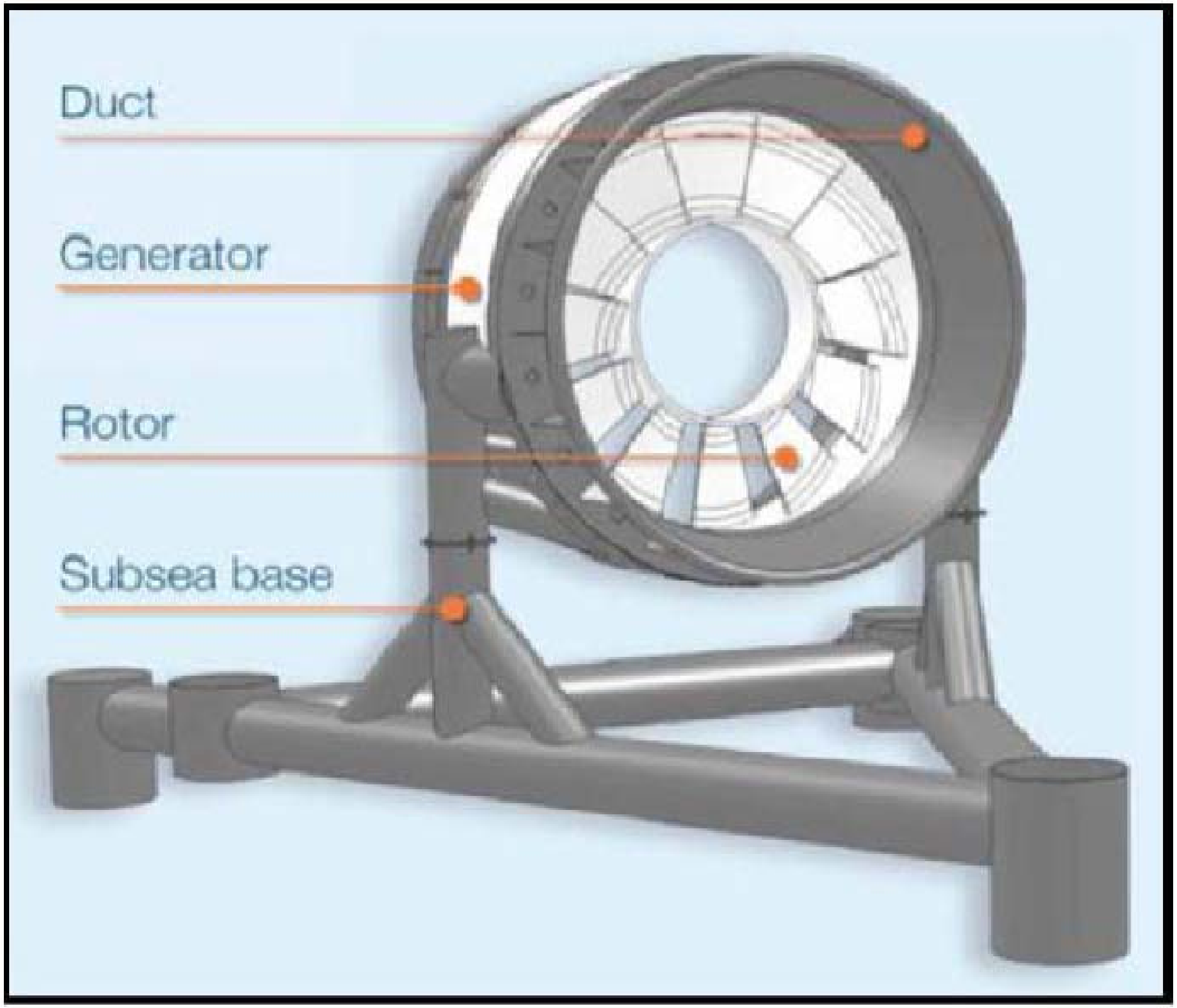
Source: http://depts.washington.edu/nnmrec/workshop/docs/Tidal_energy_briefing_paper.pdf

Puget Sound & Admiralty Inlet



Objective: How do we characterize the strongest tidal currents for device siting?

OpenHydro Tidal Turbine



Source: http://www.snopud.com/Site/Content/Documents/tidal/ai/11-ExhibitF_LargeFormat.pdf

Kinetic Power Density

$$P = \frac{1}{2}\rho \upsilon^3$$

Data Collection

Acoustic Release & Buoy (2)

300 kHz ADCP (velocity)

T-POD (porpoise clicks)

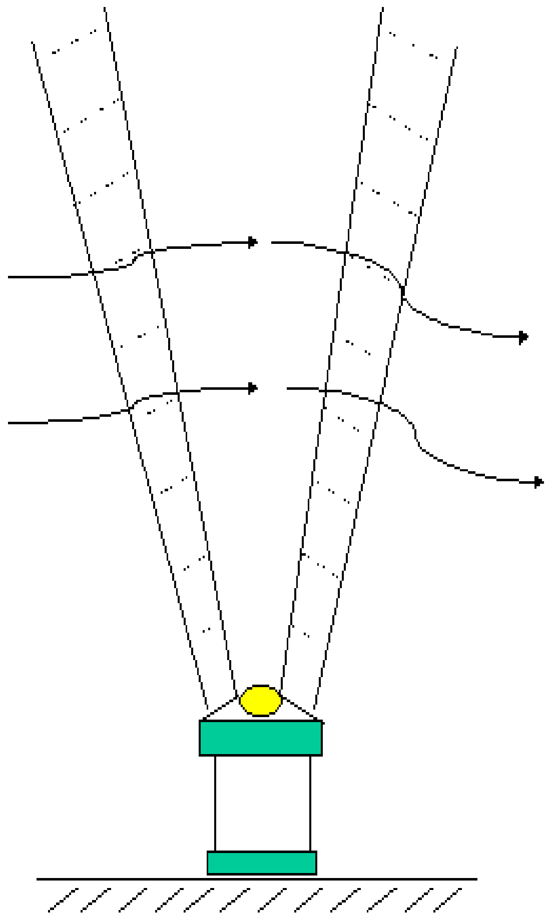
Materials Testing

VEMCO (tagged fish)

Hydrophone (noise)

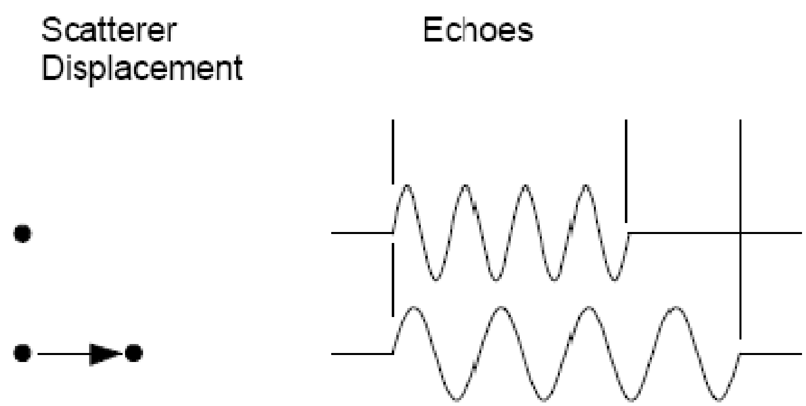
CTDO (conductivity, temperature, depth, oxygen)

ADCP Basics



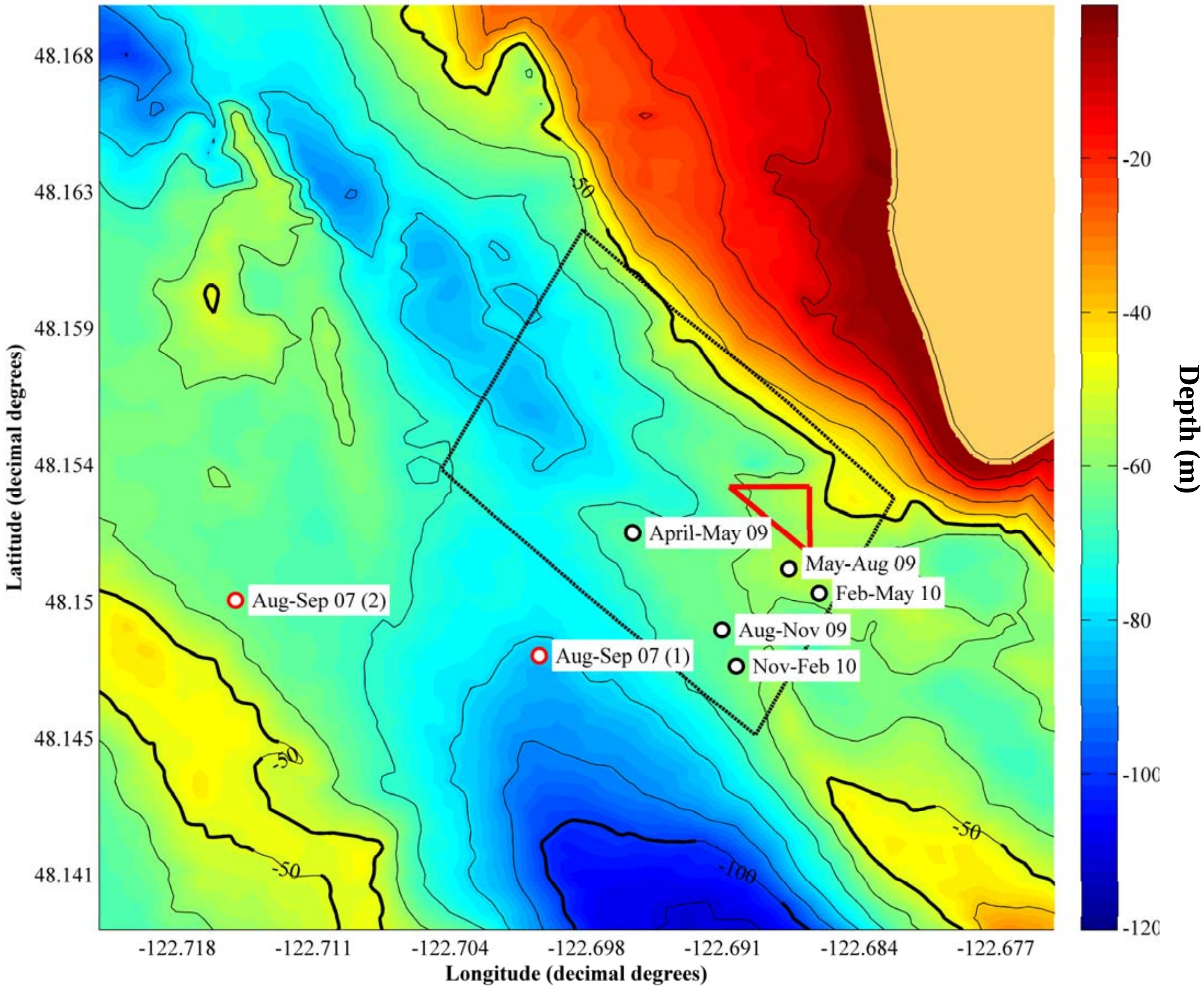
Source: web.vims.edu/physical/research/TCTutorial/currentmeasure_files/image002.gif

Teledyne RDI Workhorse Monitor-300 kHz

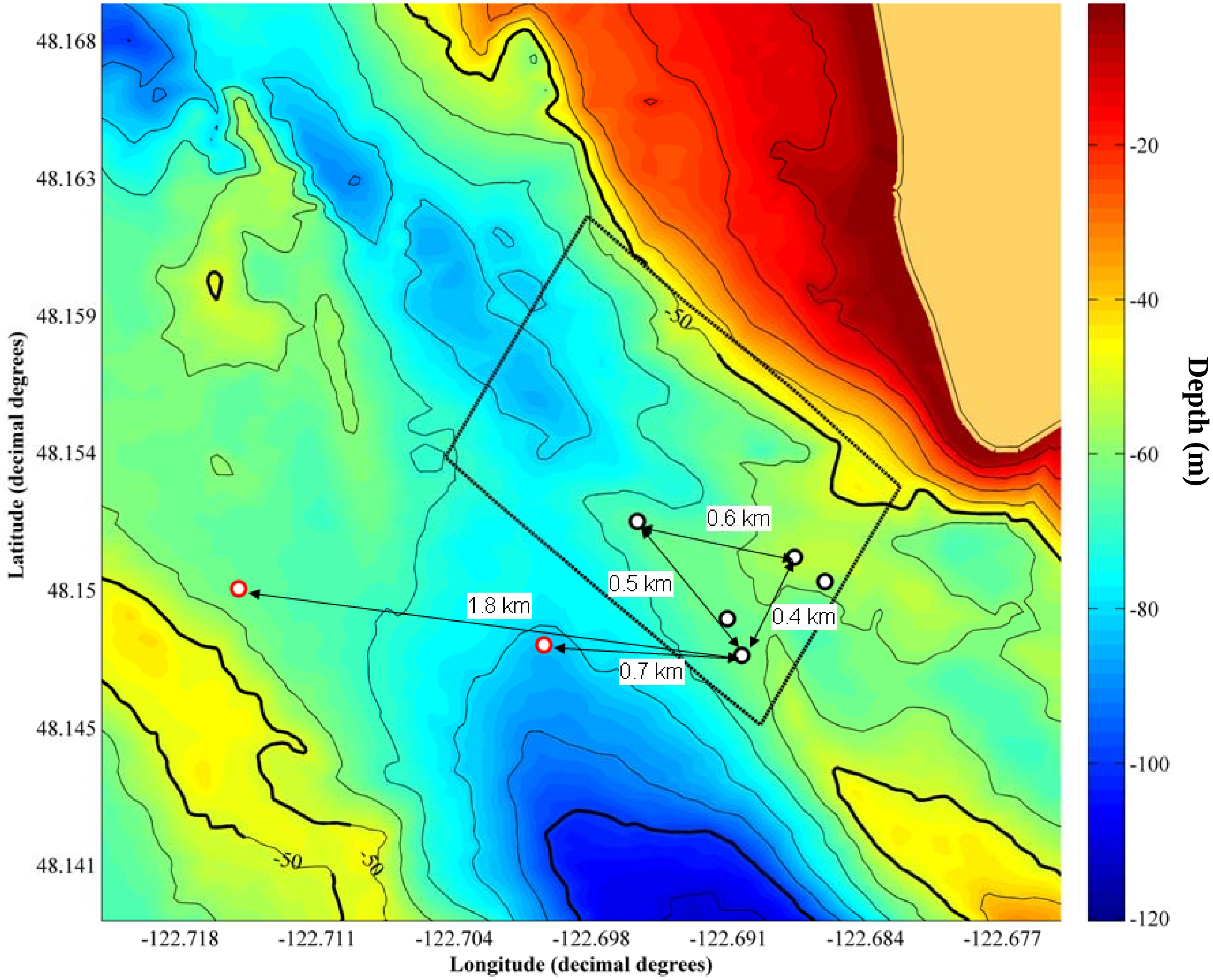


Source: Gordon, *Acoustic Doppler Current Profiler: Principles of Operation A Practical Primer*

ADCP Deployments



ADCP Deployments



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Stationary ADCP Analysis- Overview

- Harmonic Analysis (H.A.) of Acoustic Doppler Current Profiler resolving the data as a superposition of sine waves due to tidal constituents

$$u(t) = \sum A_i \cos(\omega_i * t - \phi_i)$$

- Godin (1972) → Foreman (1977) → Foreman (1978) → Pawlowicz (2002)
- Finds the least-squares fit to the current velocity data
- Generate tidal current predictions

Tidal Constituents

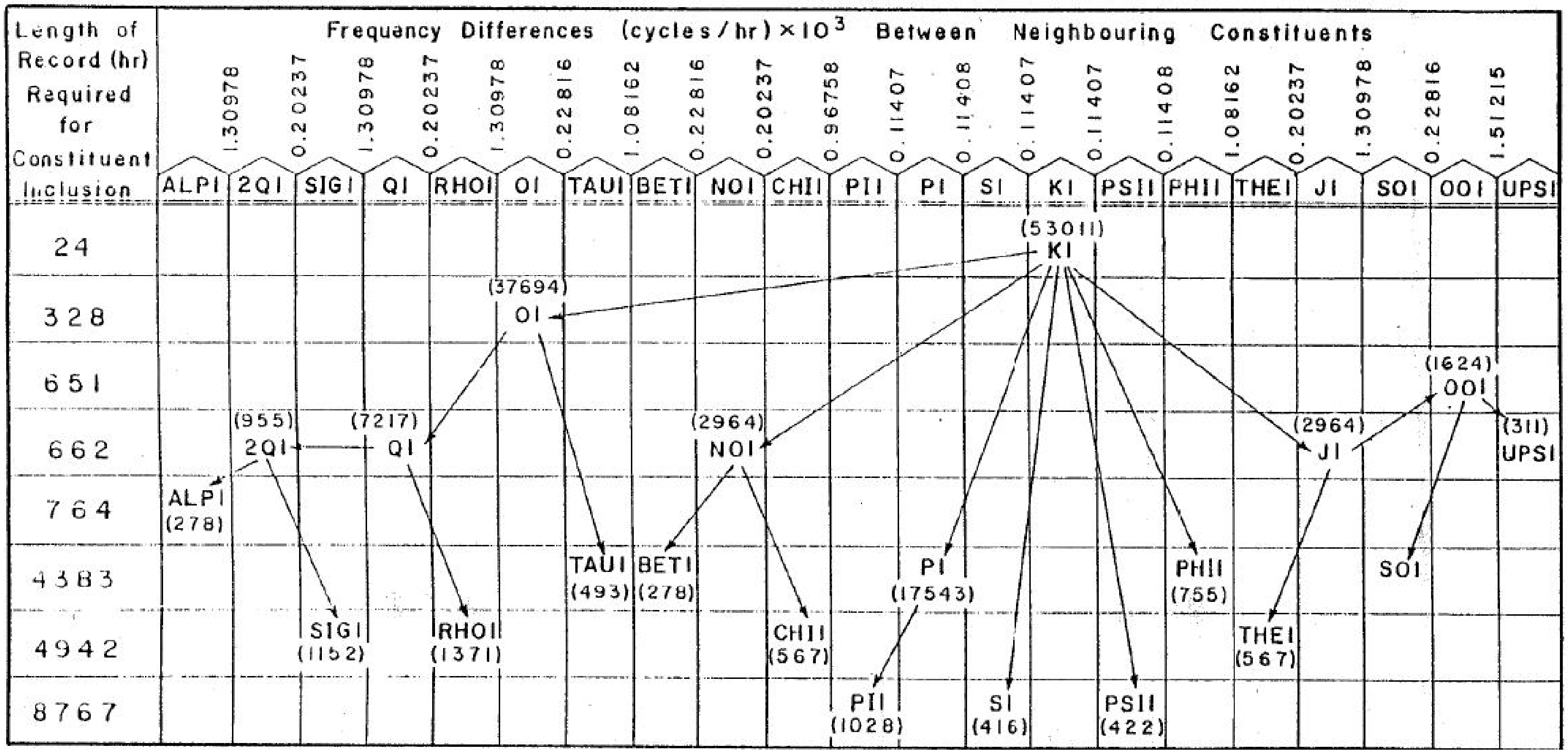
- Representations of the periodic variations of the Earth-Moon-Sun system
  - 45 Astronomical Constituents
  - 343 Shallow Water Constituents

Constituent	Name	Period
M2	Main Lunar Semidiurnal	12.42 hours
S2	Main Solar Semidiurnal	12.00 hours
N2	Larger Lunar Elliptical Semidiurnal	12.66 hours
K1	Lunar-Solar Declinational Diurnal	23.93 hours
O1	Lunar Declinational Diurnal	25.82 hours

Rayleigh Criterion

- A methodology developed by Foreman (1977) to determine which tidal constituents can be resolved with harmonic analysis

$$\left|\omega_2 - \omega_1\right| * T > R$$



Rayleigh Criterion

Ex. Resolving the K1 vs. P1 Tidal Constituents

K1, *Lunar-solar declinational diurnal const.*, ω = 0.041780 cyc / hr

P1, *Solar diurnal constituent*, ω = 0.041552 cyc / hr

$$\left|\omega_{K1} - \omega_{P1}\right| * T > 1 \rightarrow T \approx 182 \quad \text{days}$$

For T < 182 days, K1 contains P1 information

Inference

- Inclusion of constituents which are important to the location but left out by the Rayleigh Criterion

Tidal Height

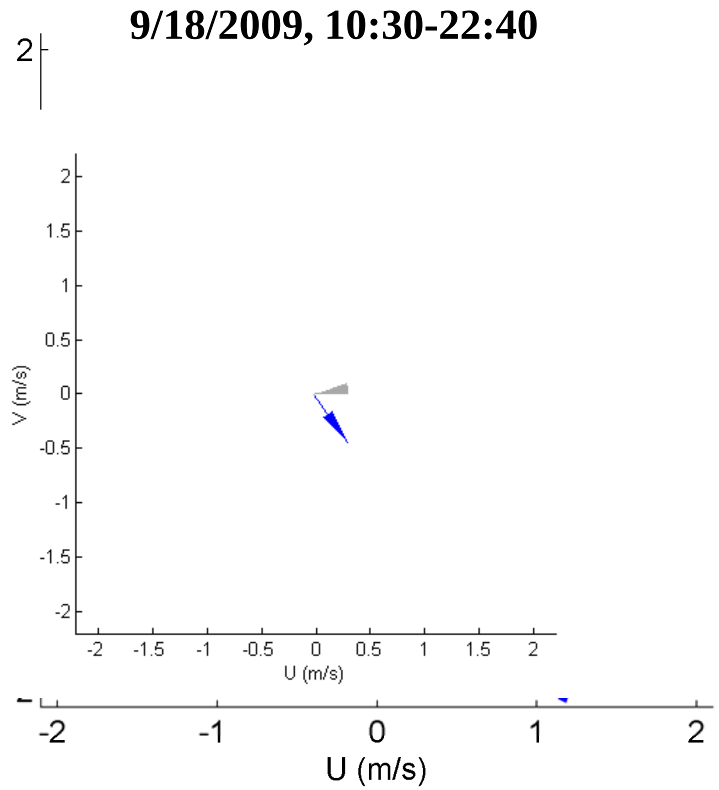
- Long records from the specific location
- Long records from a nearby location
- Tidal Potential Theory

Tidal Current

- Long records from the specific location
- Long records from a nearby location

Current Velocity Representations

- → Progressive Vector- 2 D
- Principal Axis Current- 1 D
- Signed Speed (+ Flood & - Ebb)- 1 D



Current Velocity Representations

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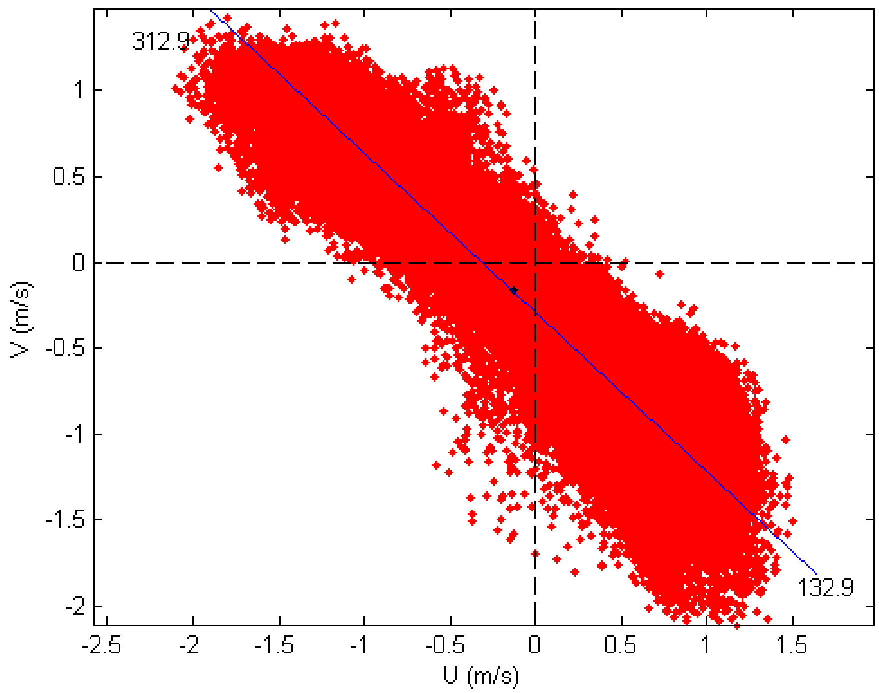
August → November 2009, P.A.V. = 97.4 %



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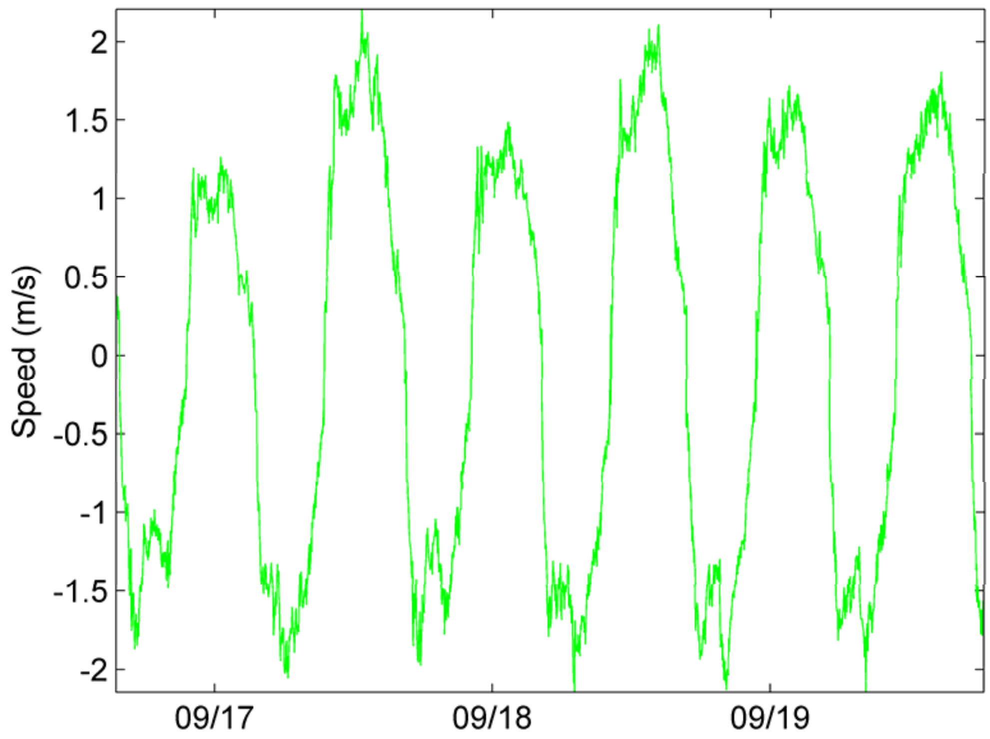
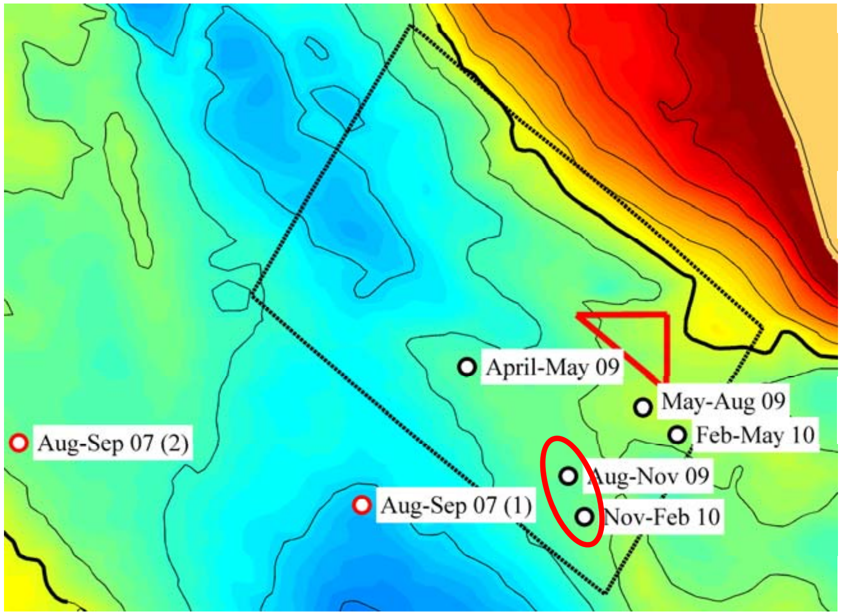


H. A. - Determining Inference

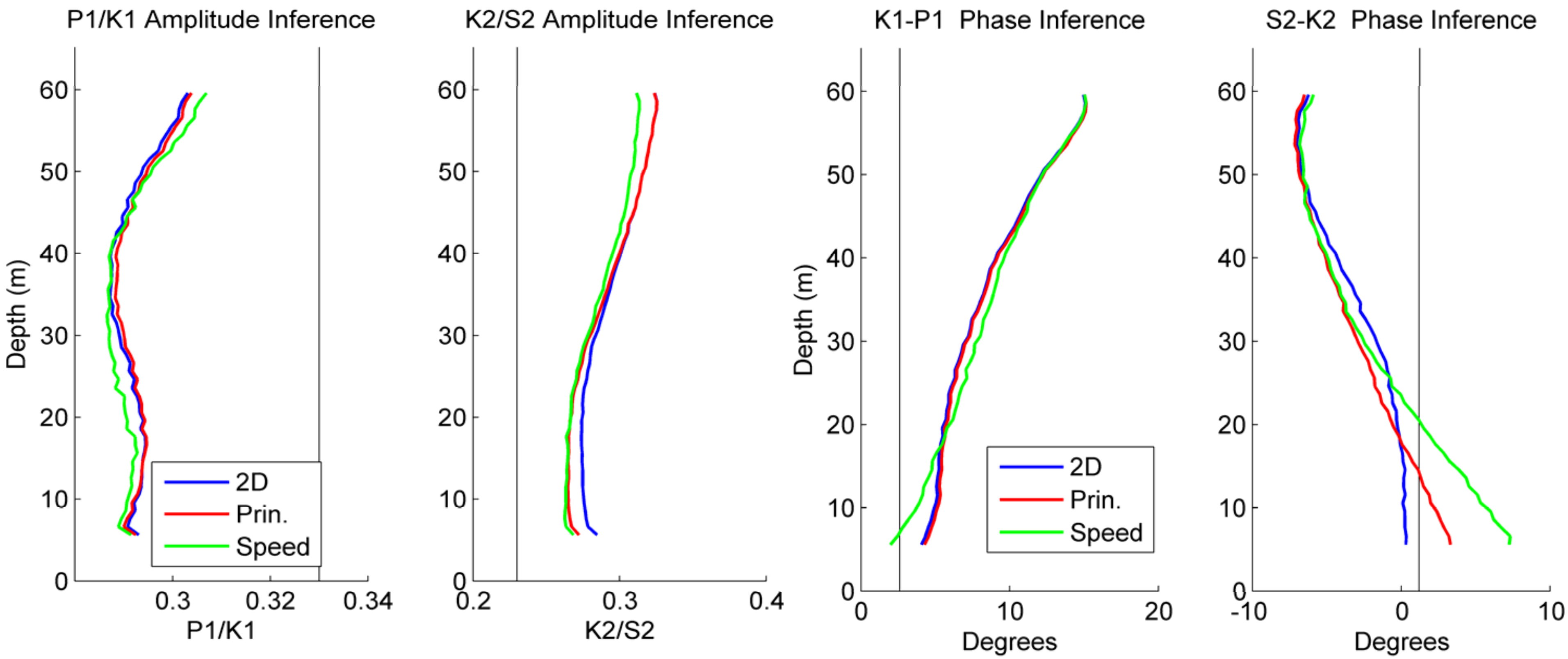
- Record Length ≈ 172 days
- Distance ≈ 140 m
- Water Depth ≈ 63 m
- Parameters
  – Rayleigh Criterion < 1
- Allowed resolving of tidal constituents:
  – P1 from K1
  – K2 from S2



Aug.-Nov. 2009	Nov.-Feb. 2010
63.4 m	62.7 m
98.8 days	72.6 days

Feb. 2010 Sea Spider Deployment

Inference Results



Harmonic Analysis w/ Inference

- Apply inference to from a long term record analysis to improve shorter nearby records

- Apply Inference from Aug. 09 → Feb. 10 combined record to individual records: Aug. → Nov. 09 & Nov. 09 → Feb. 10

- Comparison of velocity representations at water depth ≈ 10 m (OpenHydro hub height)

Harmonic Analysis Goodness of Fit

Coefficient of Multiple Determination

$$R^2 = 1 - \frac{\sum_i (\hat{y}_i - y_i)^2}{\sum_i (y_i - \bar{y})^2}$$

y_i - velocity data point in time series

$\hat{y}_i$ - harmonic fit to each data point in time series

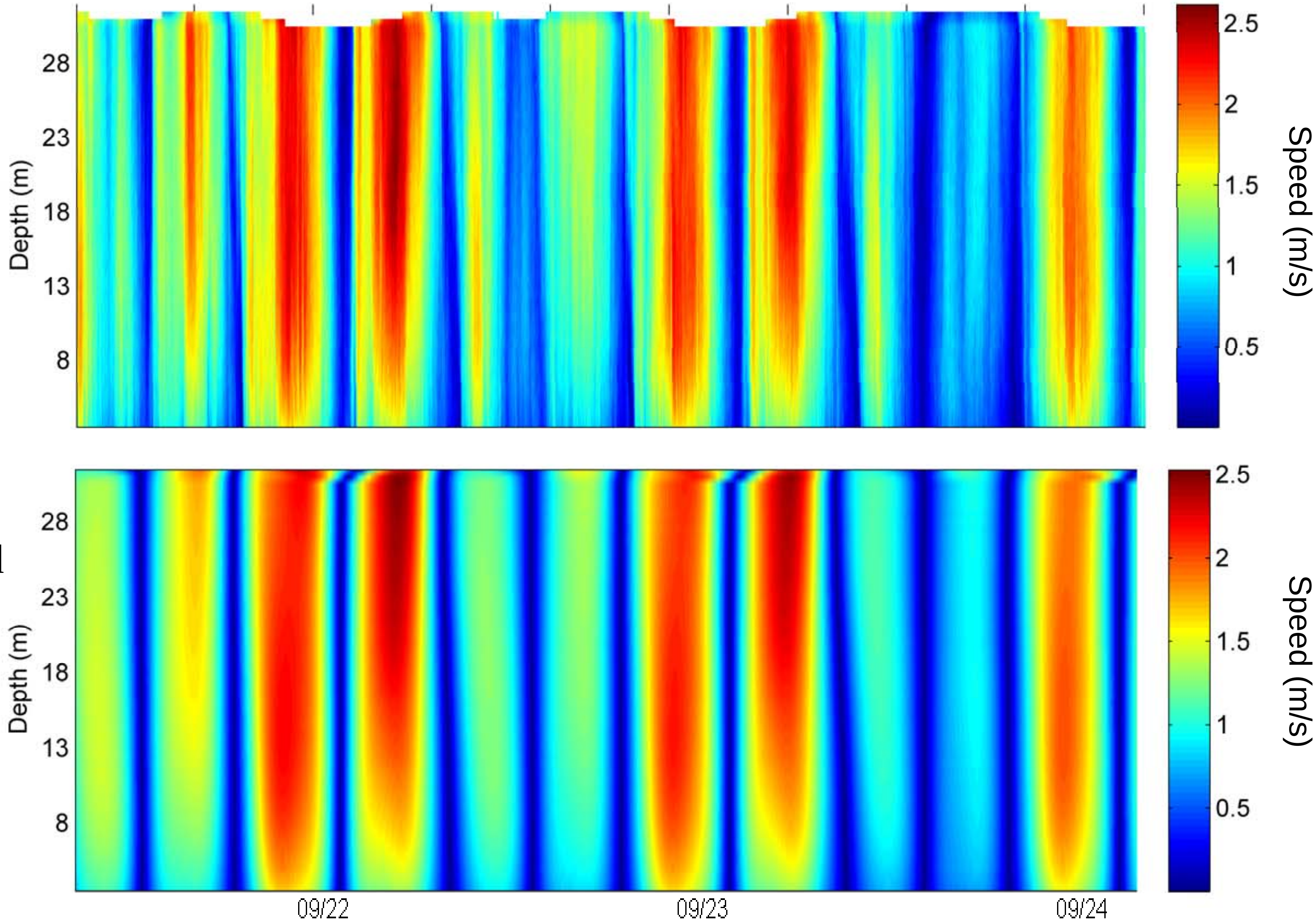
$\bar{y}$ - mean velocity of the time series

ADCP Stationary Deployment	Principal Axis Current	Prog. Vector- 2D	Signed Speed
	R-squared		
August-November 2009	0.94	0.95	0.94
November-February 2010	0.95	0.96	0.95
	R-squared above cut-in speed of 1 m / s		
August-November 2009	0.97	0.97	0.97
November-February 2010	0.97	0.98	0.98

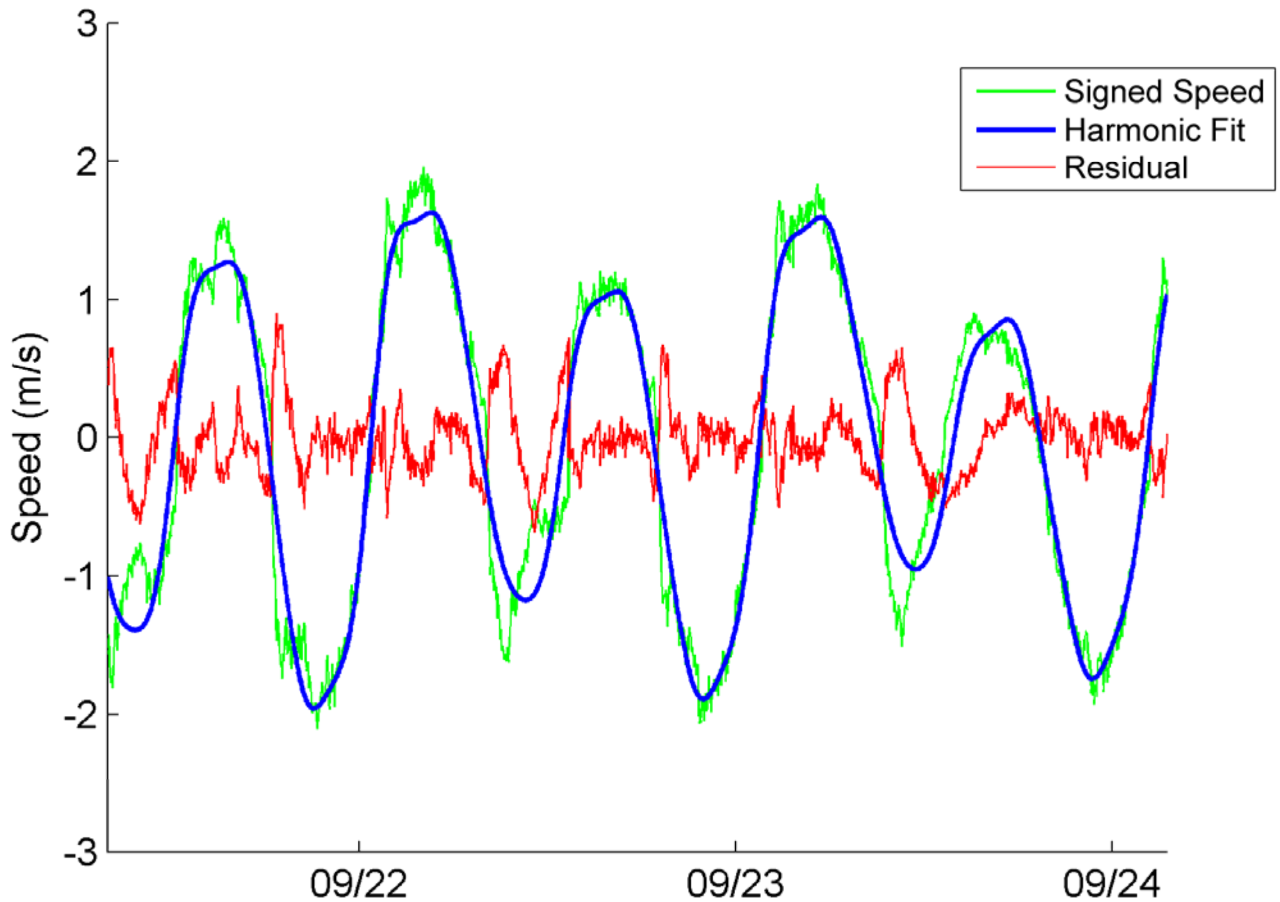
Data vs. Harmonic Analysis

Raw Data- Aug-Nov 09

Harmonic Fit- Signed Speed Analysis

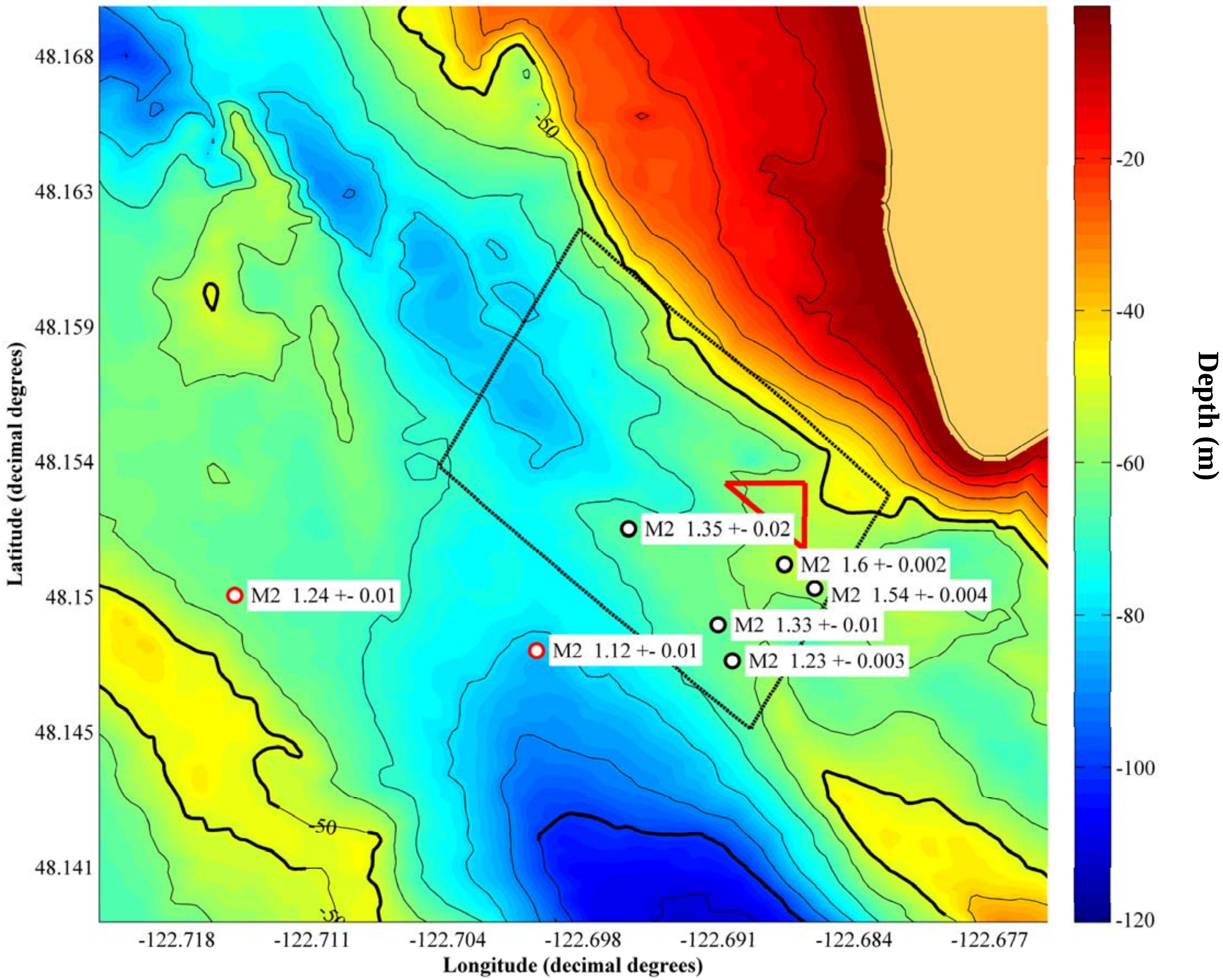


Data vs. Harmonic Analysis

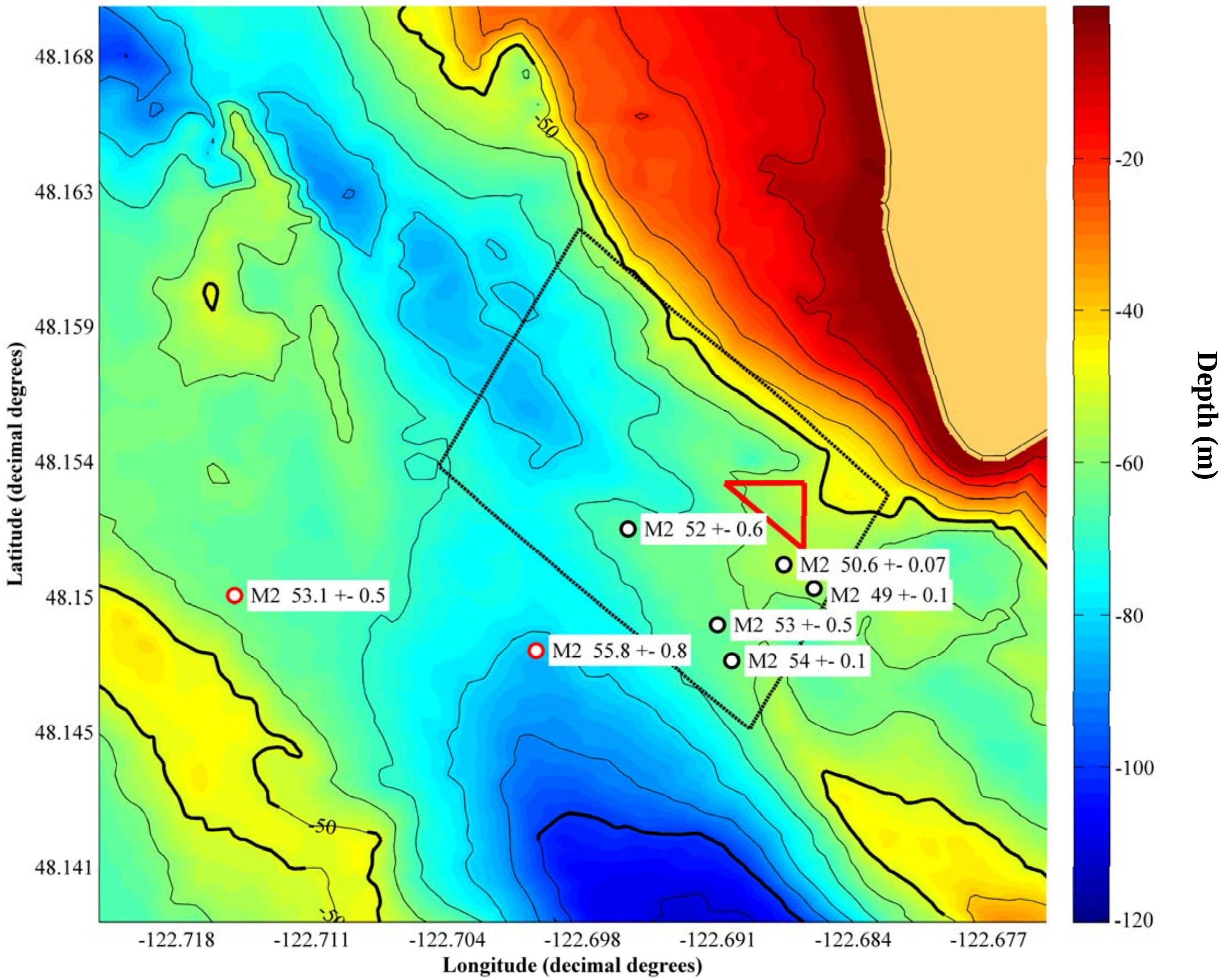


***Inference used for P1 and K2 constituents, water depth (10 m)**

M2- Amplitude Map



M2- Phase Map


48.168
48.163
48.159
48.154
48.15
48.145
48.141
Latitude (decimal degrees)
-122.718
-122.711
-122.704
-122.698
-122.691
-122.684
-122.677
Longitude (decimal degrees)
-20
-40
-60
-80
-100
-120
Depth (m)
-50
M2 52 +- 0.6
M2 50.6 +- 0.07
M2 49 +- 0.1
M2 53.1 +- 0.5
M2 53 +- 0.5
M2 55.8 +- 0.8
M2 54 +- 0.1

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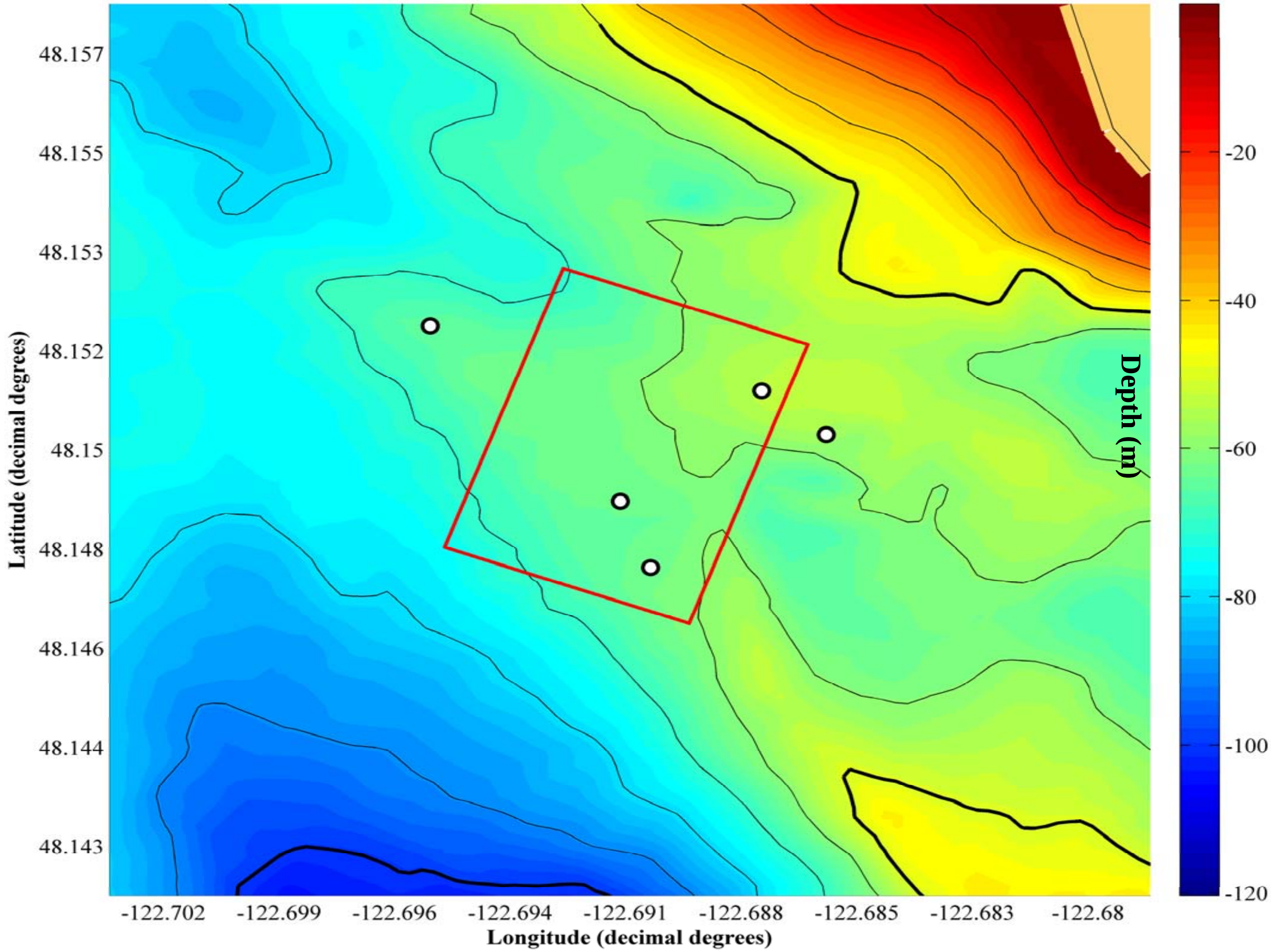
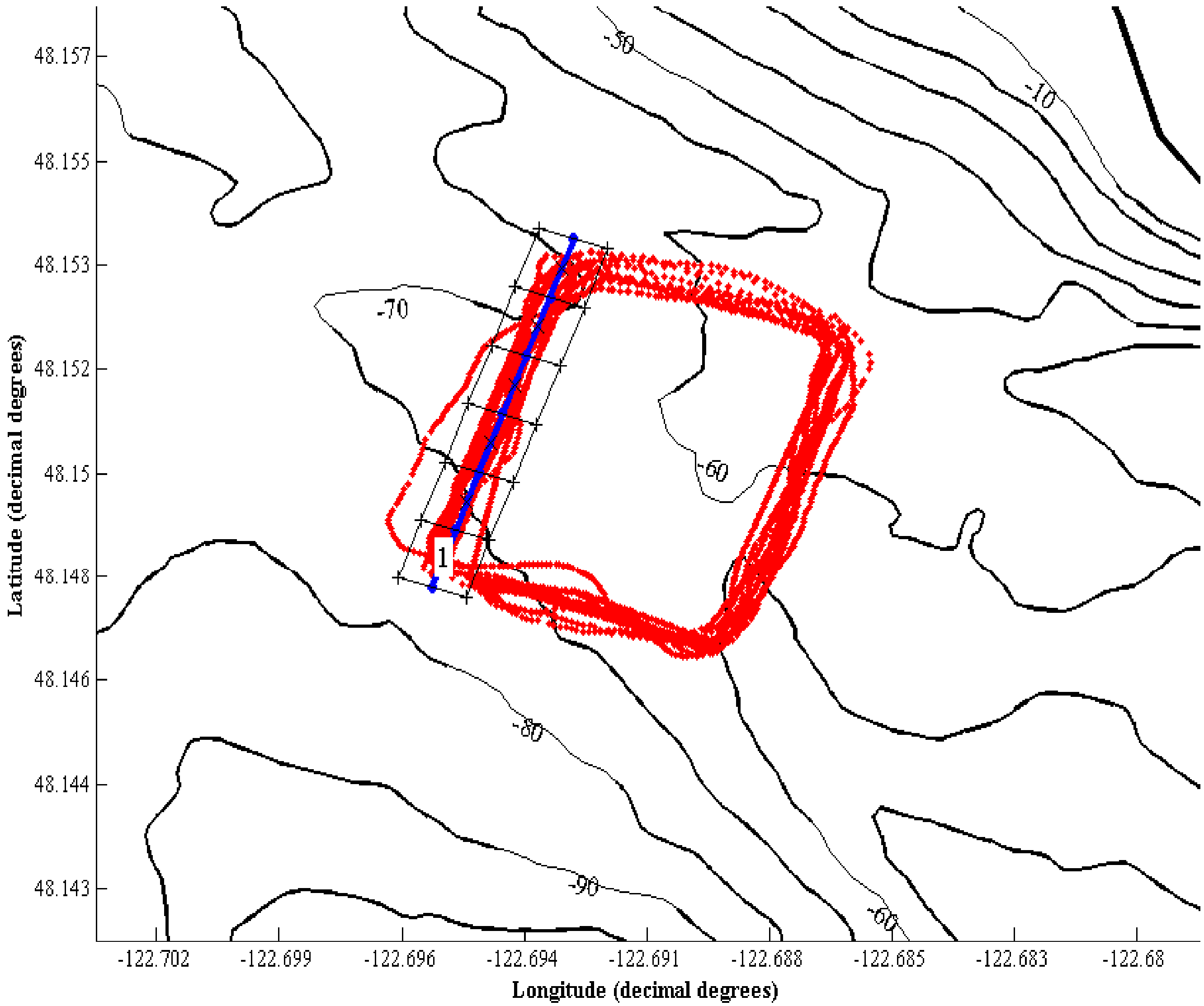
Design of Survey Track

**Ebb Survey-
August 2009**



August 2009 Ebb Survey

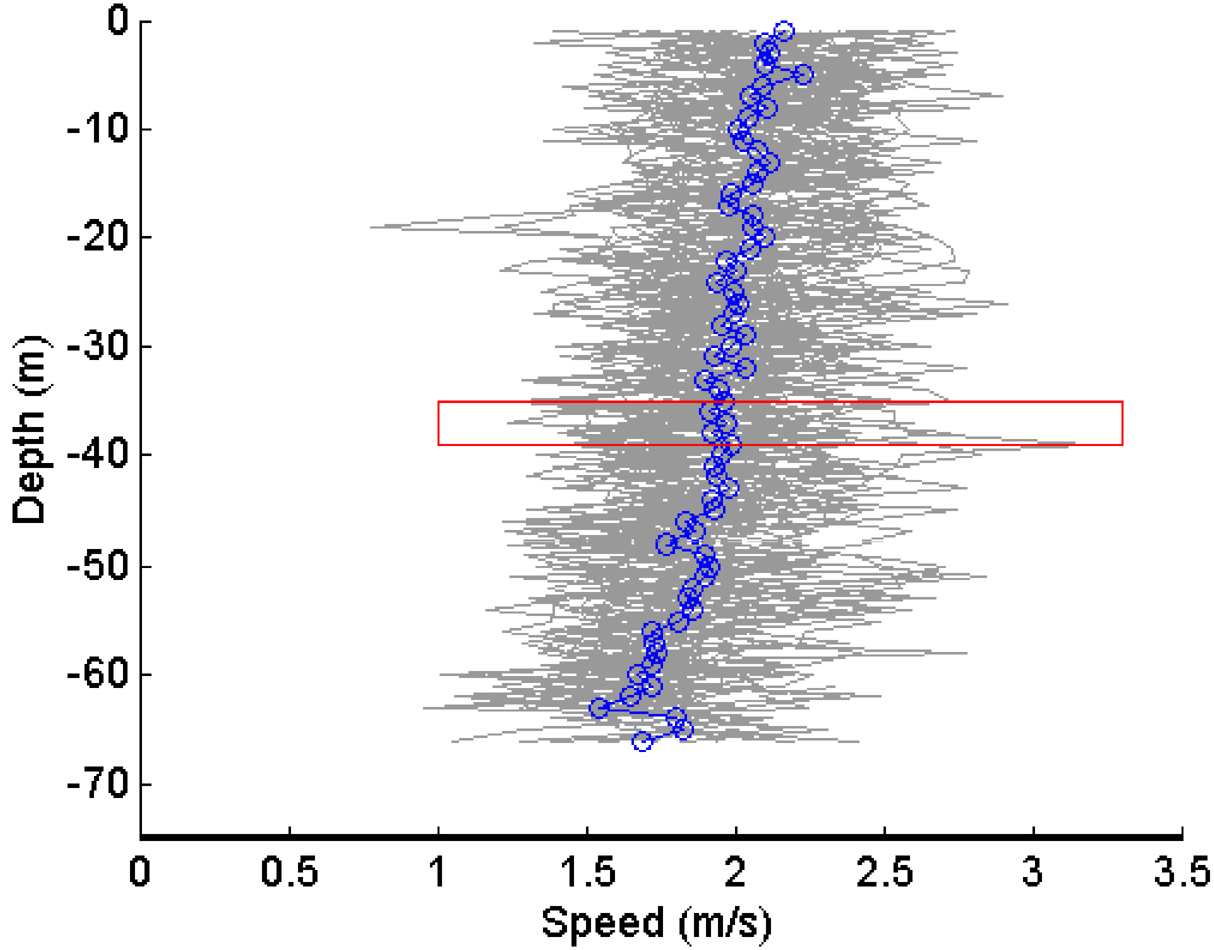


Volumetric Binning:

100m x 100m x 5m

Volumetric Averaging

34 ADCP Velocity Profiles



Velocity PDF

Mean = 1.95 m/s

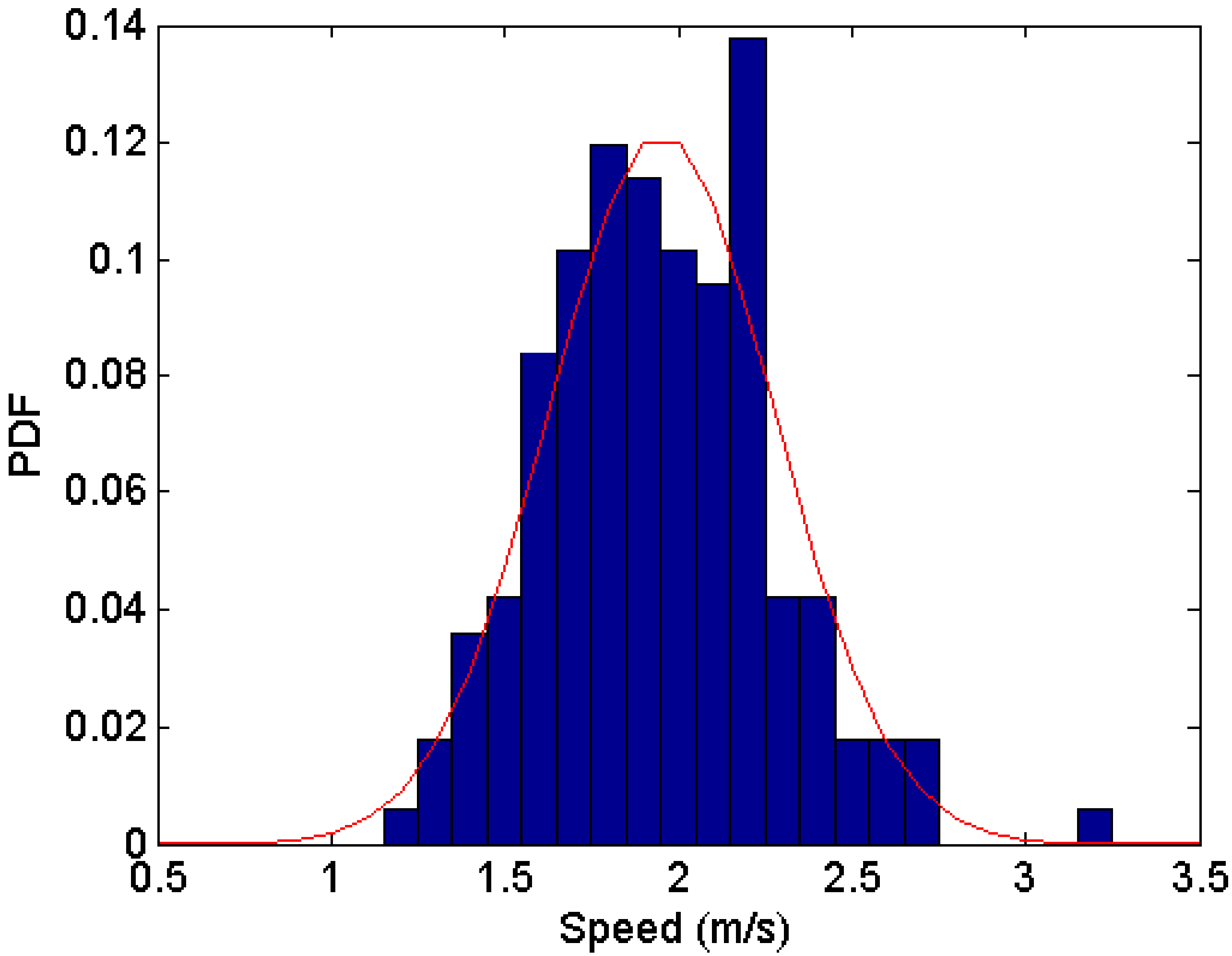
Max = 3.21 m/s

Min = 1.24 m/s

Data Std. Dev. = 0.33 m/s

ADCP Std. Dev. = 0.2 m/s

Ensemble Size = 167



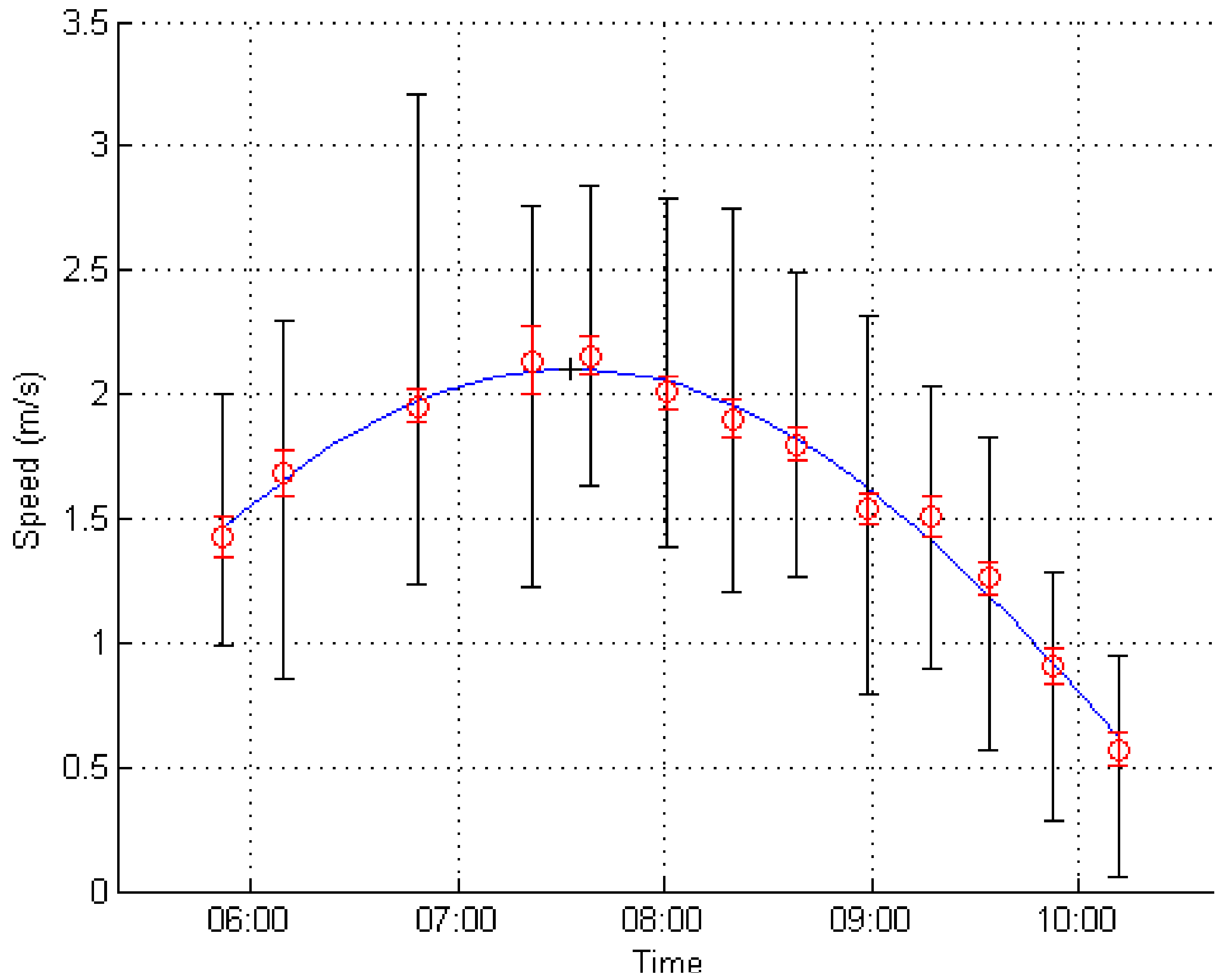
Sinusoidal Fit to Averaged Data

$$u(t) = A\sin\left(\frac{2\pi t}{T} + \phi\right)$$

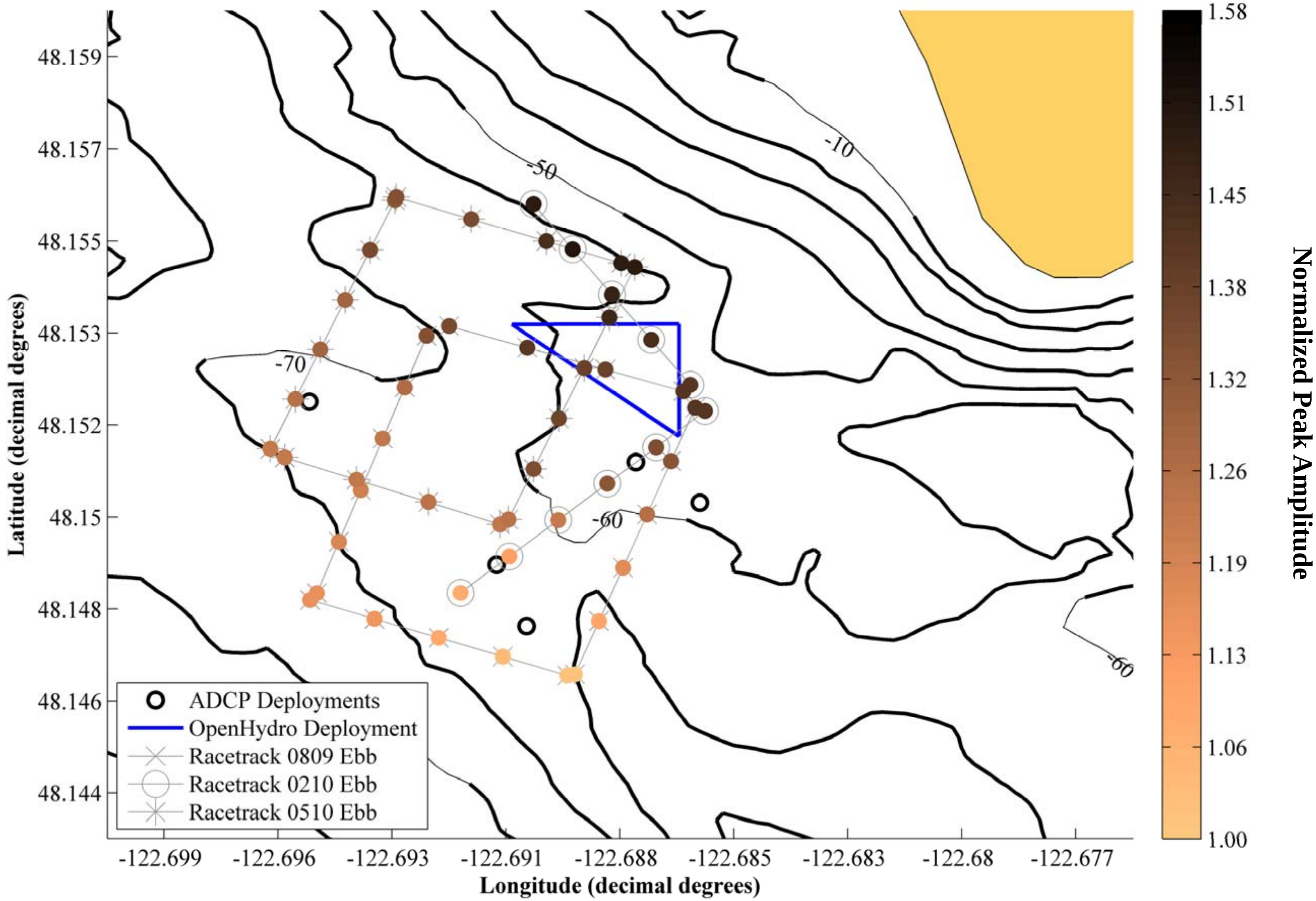
Amplitude = 2.10 m / s

Period / 2 = 6.54 hours

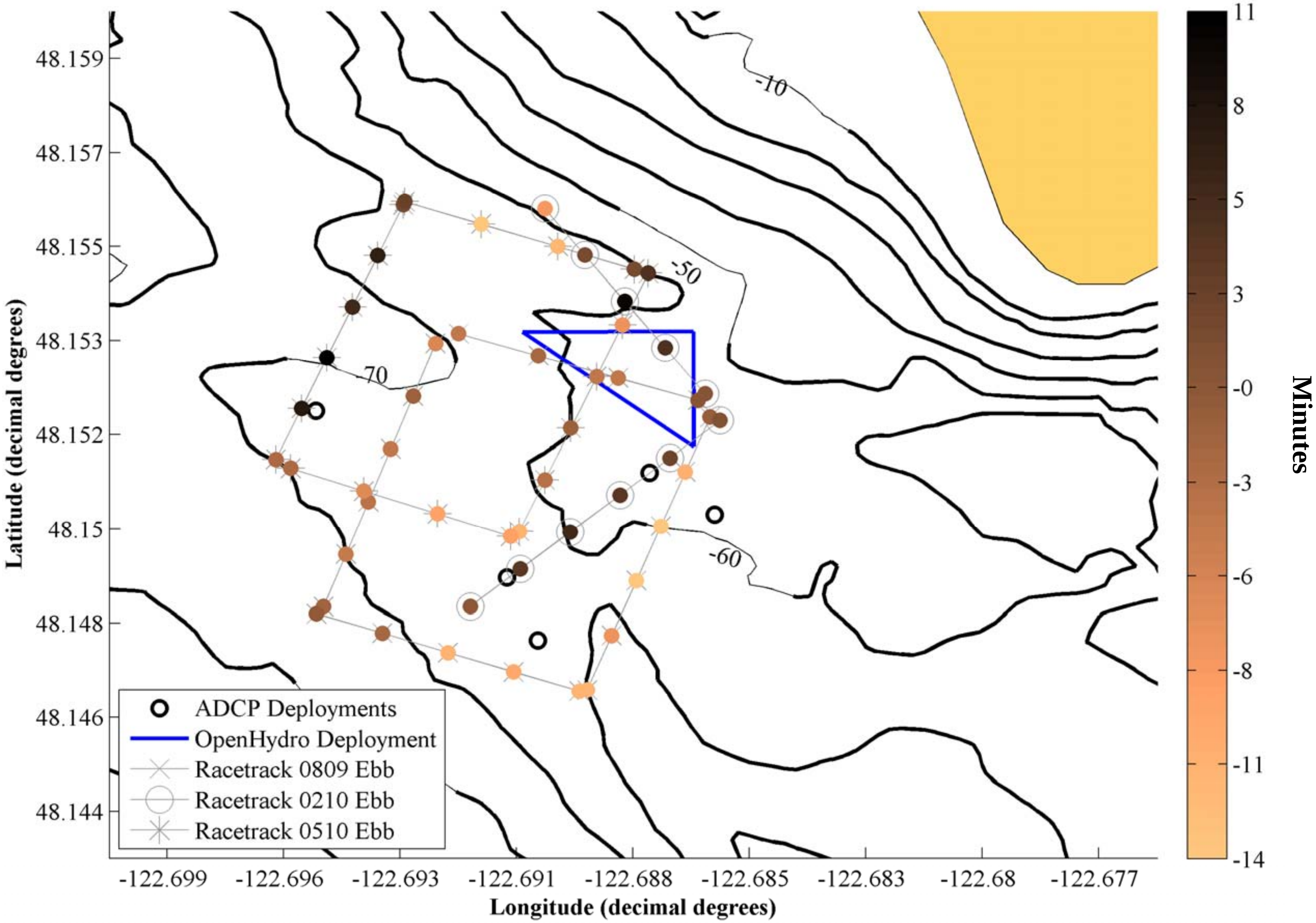
$R^2 = 0.99$



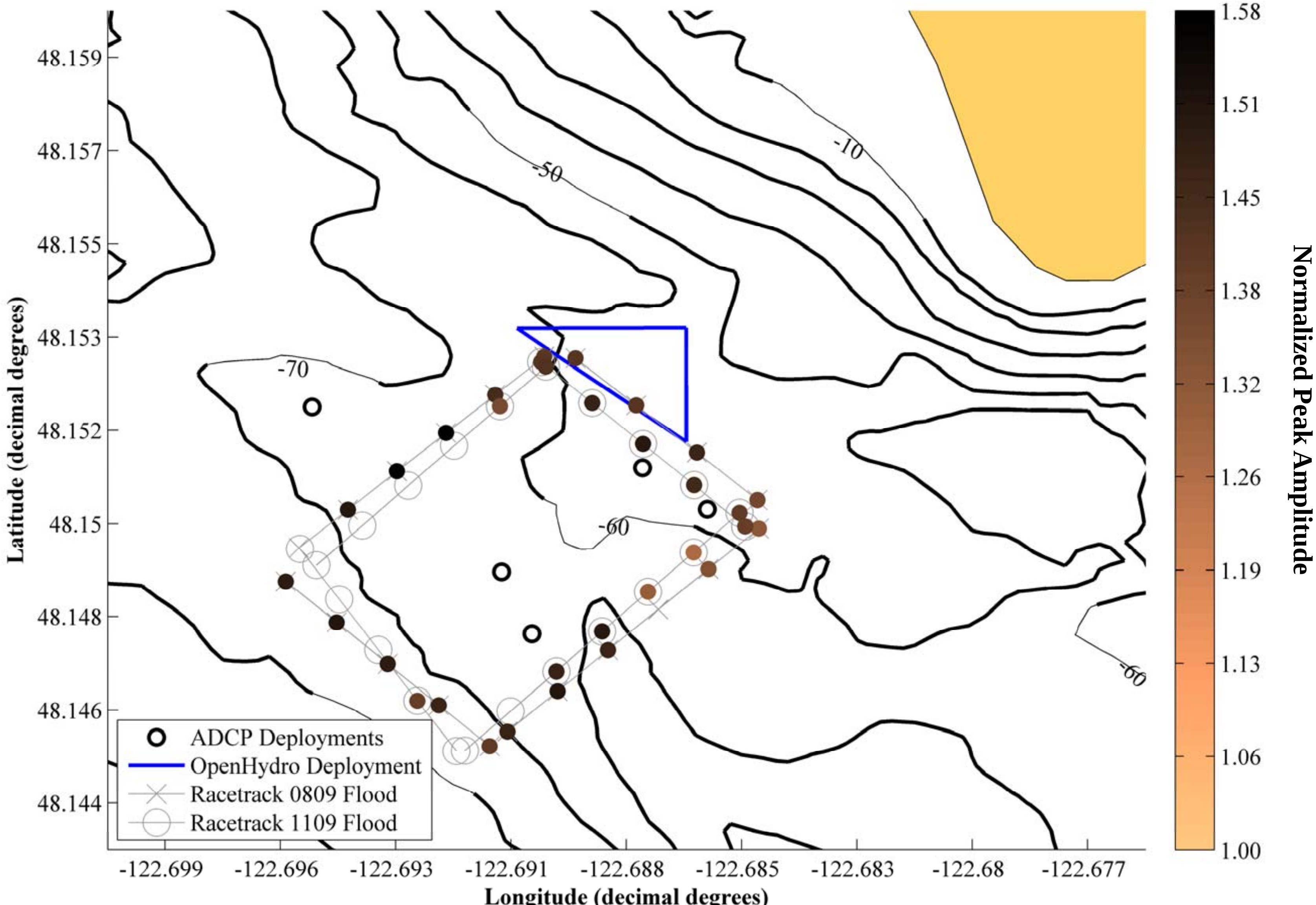
Ebb Survey Amplitude Variation



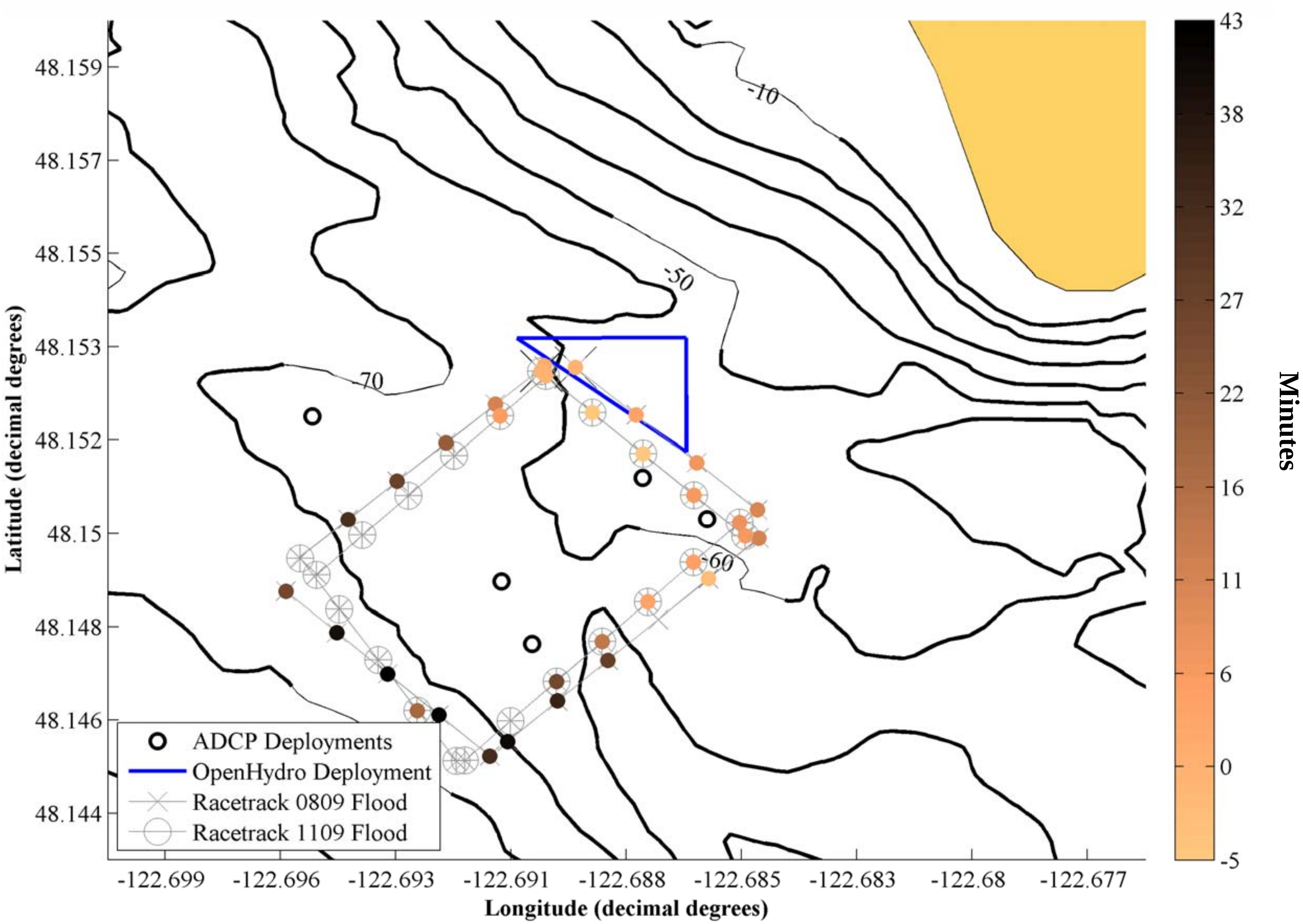
Ebb Survey Phase Variation



Flood Survey Amplitude Variation



Flood Survey Phase Variation



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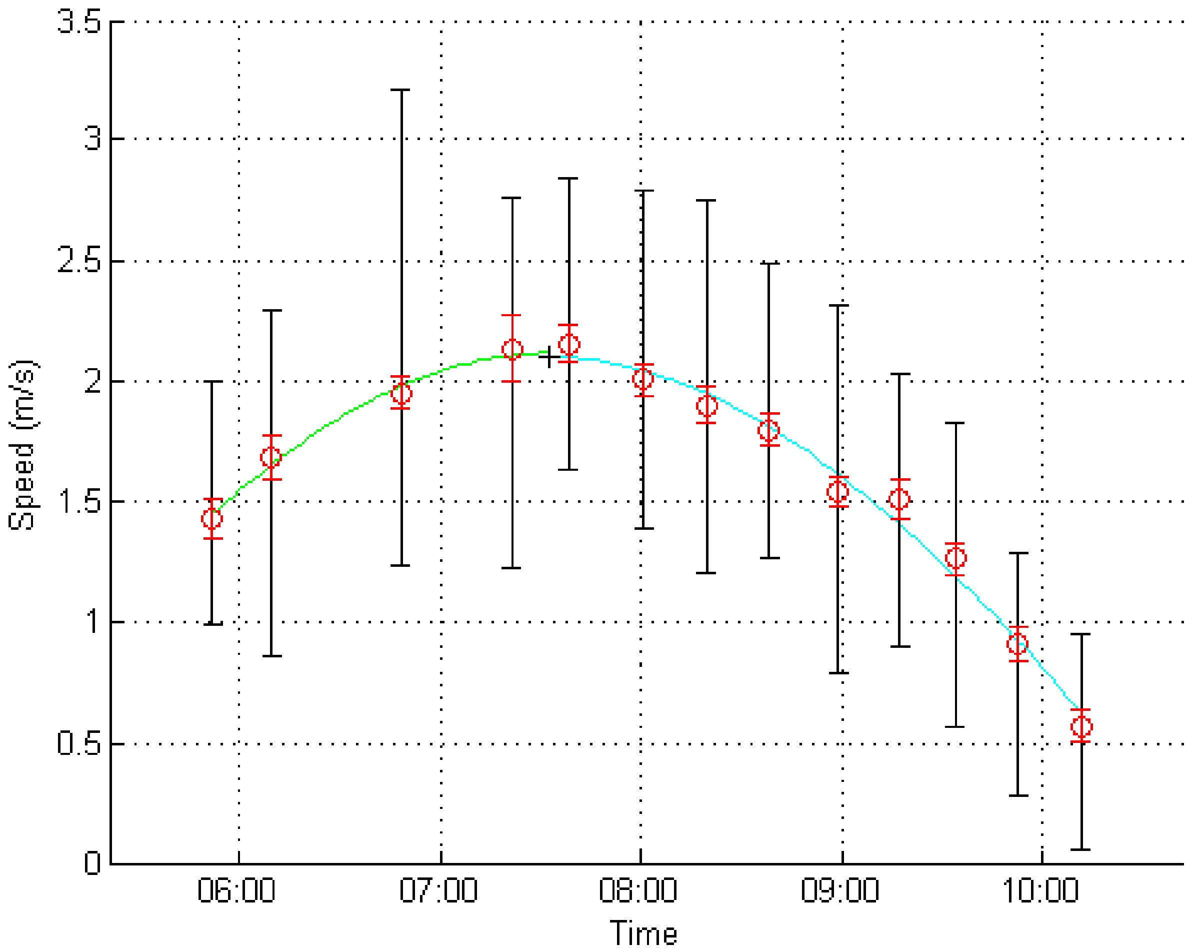
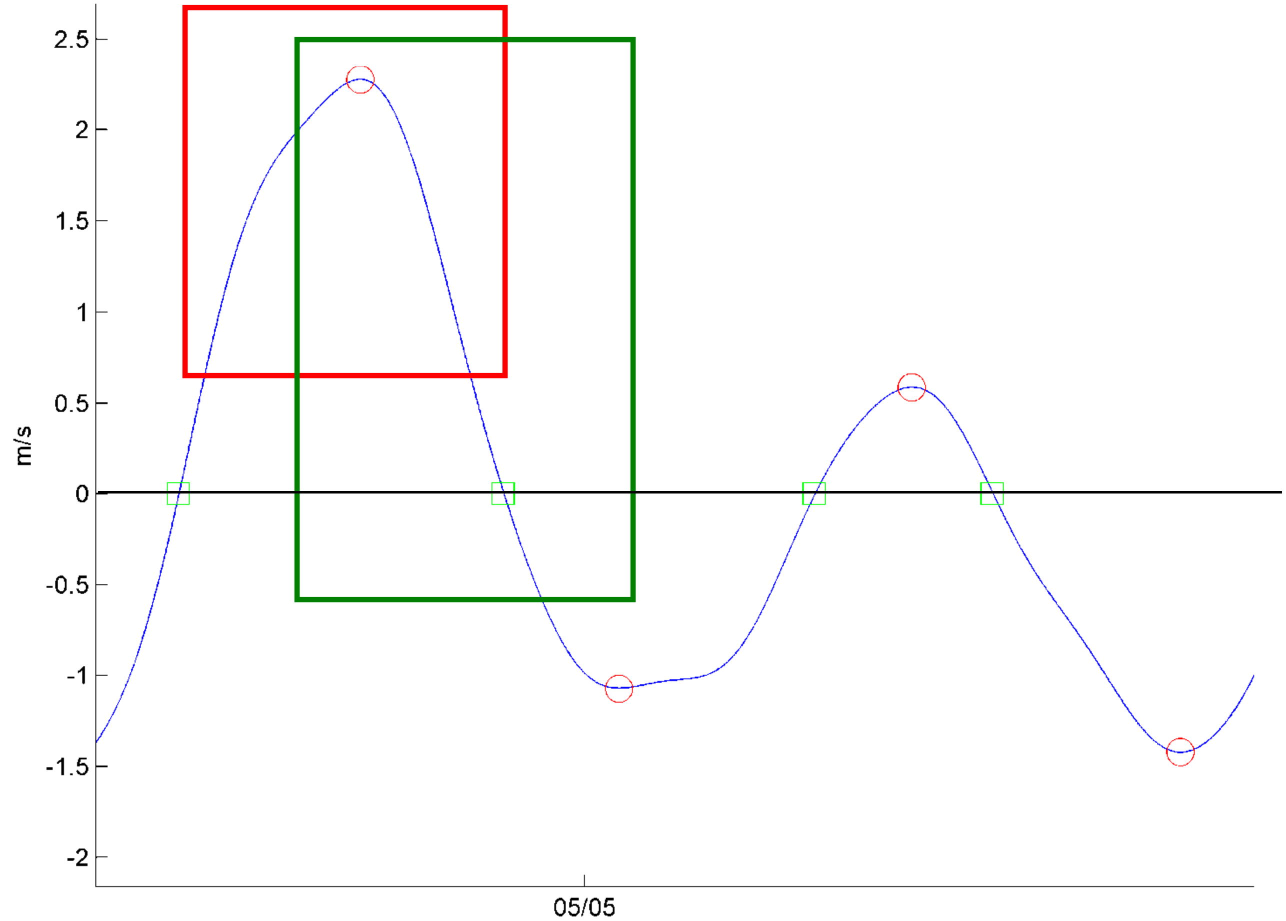
Future Work

- Use ¼ Sine Wave Fits for Shipboard Analysis



Future Work

- Survey Ebb → Flood Transition (Slack Water)



Conclusions

- Stationary ADCP analysis
  - Identification of spatial variation
  - Harmonic analysis → residual

- Shipboard ADCP analysis
  - Efficient spatial characterization
  - Quantitative use of shipboard ADCP surveys
  - Integration of stationary analysis with shipboard surveys

Acknowledgements

- Dr. Brian Polagye
- Dr. Jim Thomson
- Dr. Phil Malte
- Joe Talbert
- Captain Andy Reay-Ellers
- Dr. Roy Martin
- Snohomish County PUD & DOE
- My family & friends


Questions?