Enabling the Next Generation of Underwater Sensor Networks



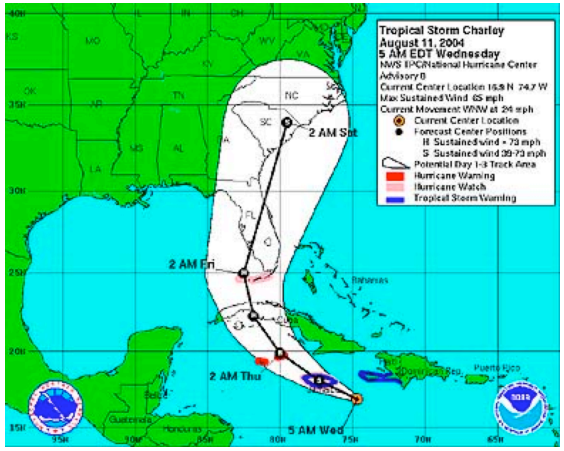
Professor Ryan Kastner
Dept. of Computer Science and Engineering
University of California, San Diego

November 3, 2009

Ocean Observing Systems

Can be used to

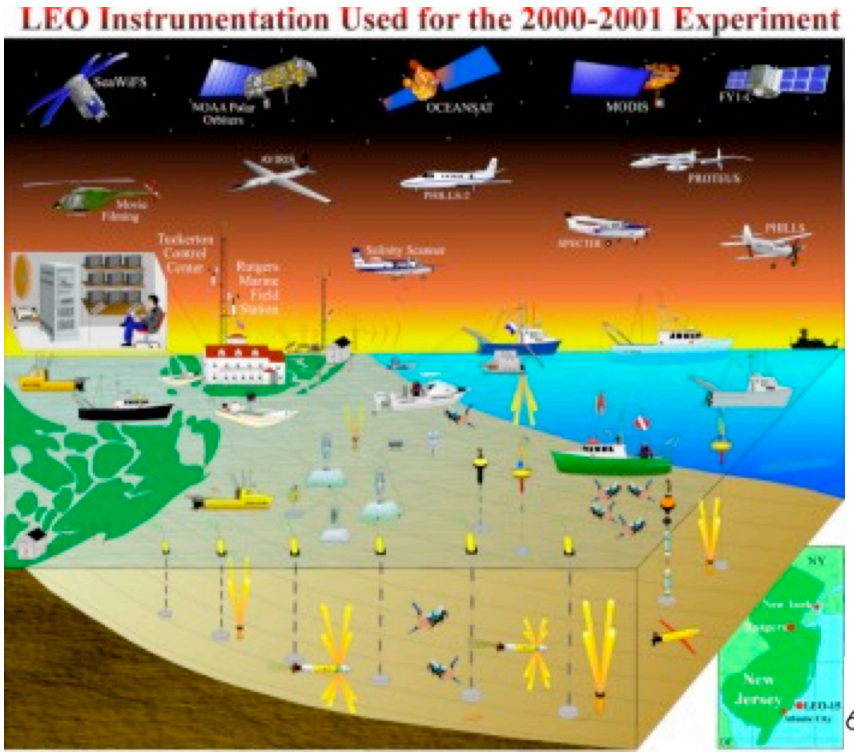
- Monitor earthquakes
- Study and model water column physics for hurricane track predictions
- Measure hydrographic conditions for climate change studies





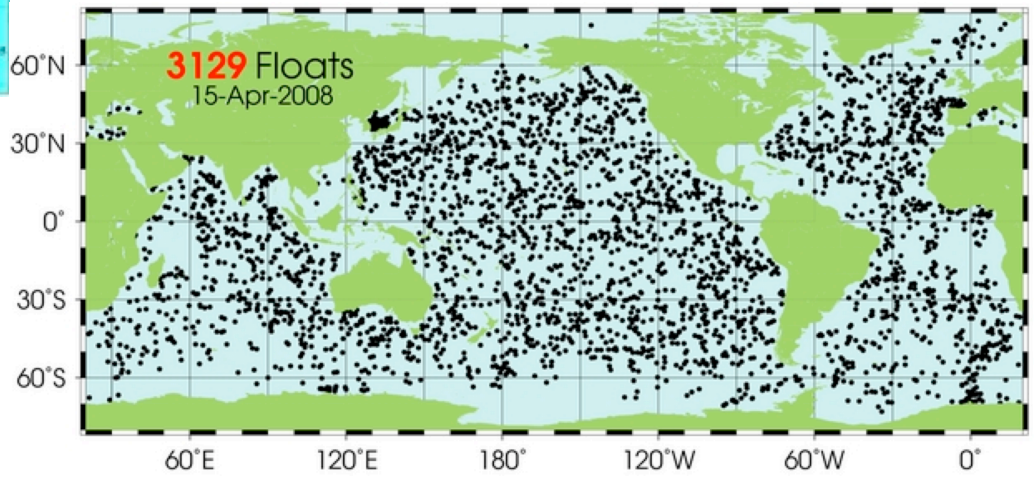
- Collect biological parameters for harmful algal bloom prediction
- Measure chemical parameters for beach pollutant warnings

Ocean Observing Systems



Real-time data allow scientists to

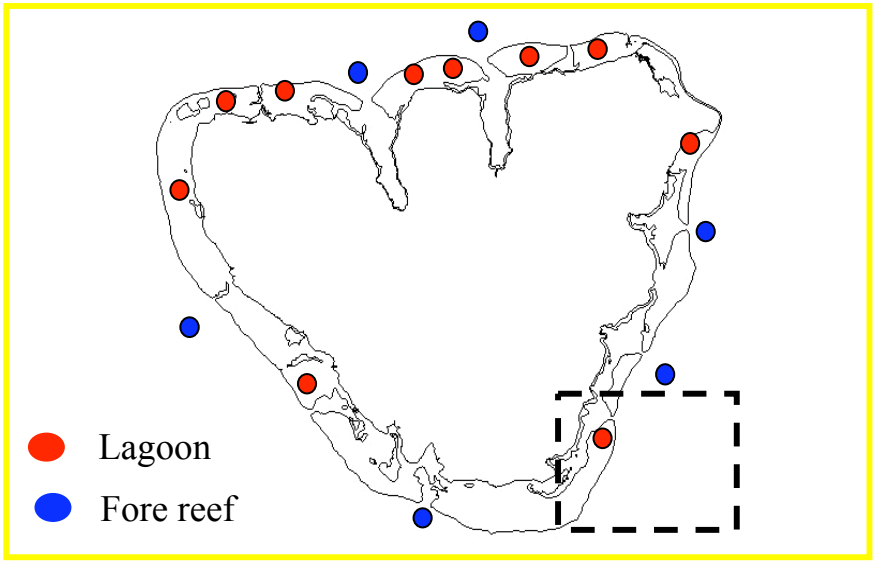
- Create climate prediction models
- Issue tsunami warnings
- Issue hurricane warnings
- Contact authorities to issue beach closure or shellfish consumption warnings
- Begin adaptive sampling (interrogating instruments to increase their sampling rate)

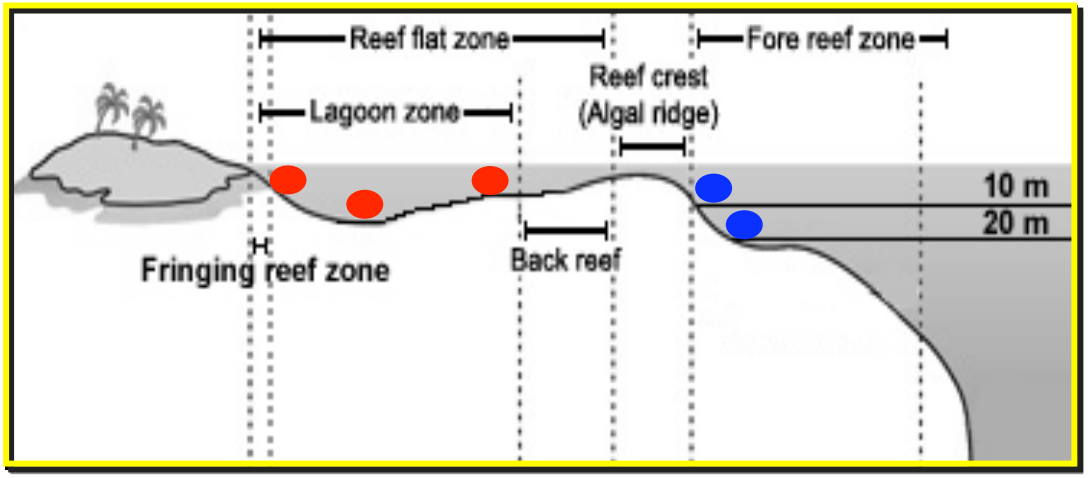


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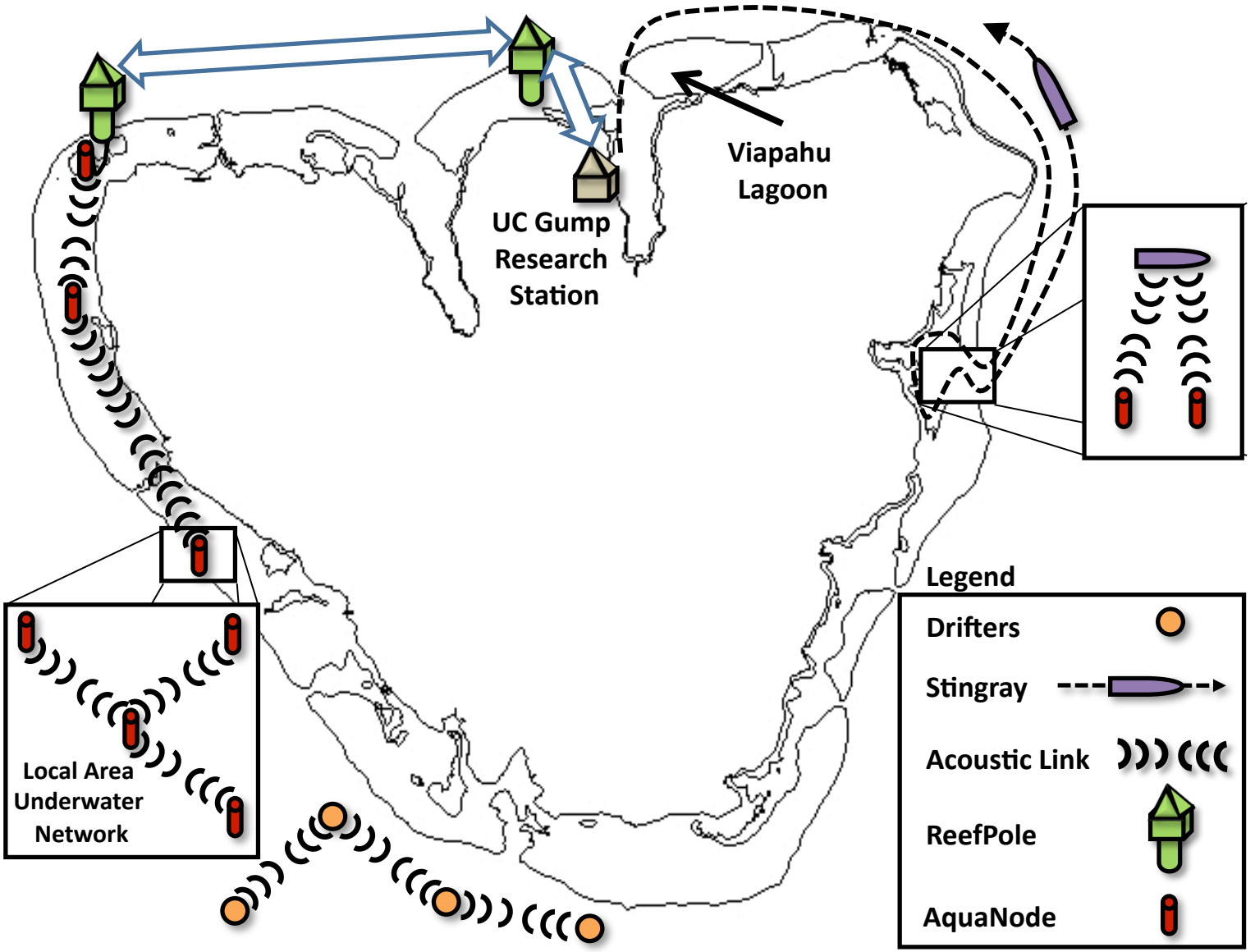
Monitoring in Moorea

- Establish monitoring sites in lagoons and on fore reefs surrounding Moorea
- Response variables measured:
  - Weather
  - Tides, Currents and Flows
  - Ocean Temperature & Color
  - Salinity, Turbidity & pH
  - Nutrients
  - Recruitment & Settlement
  - Size & Age Structure
  - Species Abundance
  - Community Diversity



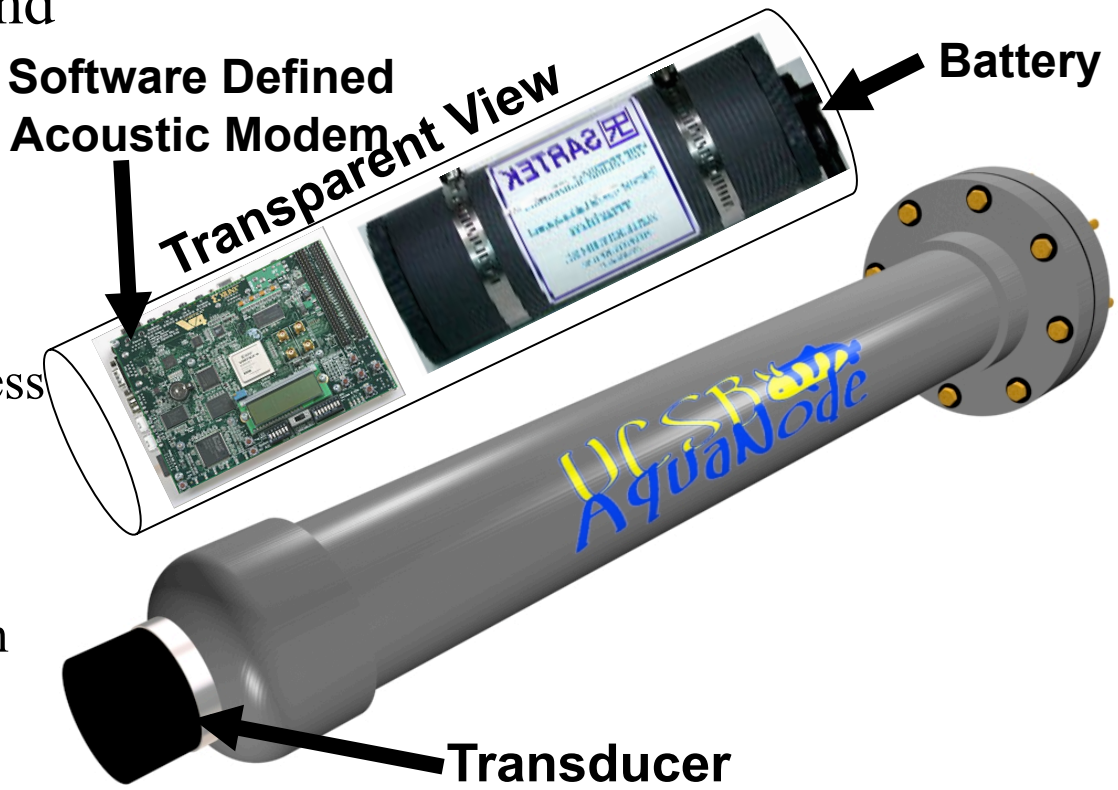


Vision for Underwater Networking in Moorea



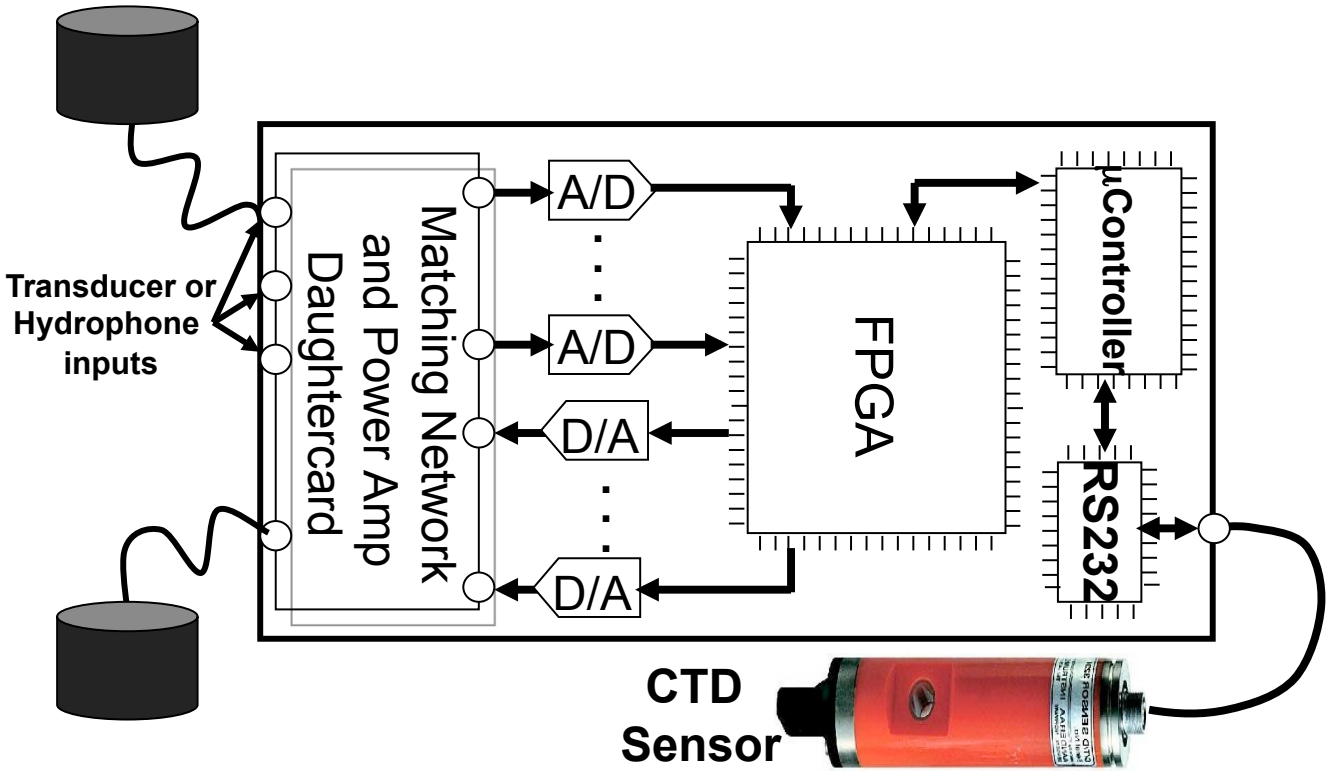
AquaNode

- Deploy ad hoc wireless underwater networks around island
- Transmit data to/from underwater sensors
- Aquanode requirements:
  - Low cost, low power wireless modems
  - Associated networking functionality
  - Plug and play interface with variety of sensors
  - Near real-time data and adaptive sampling



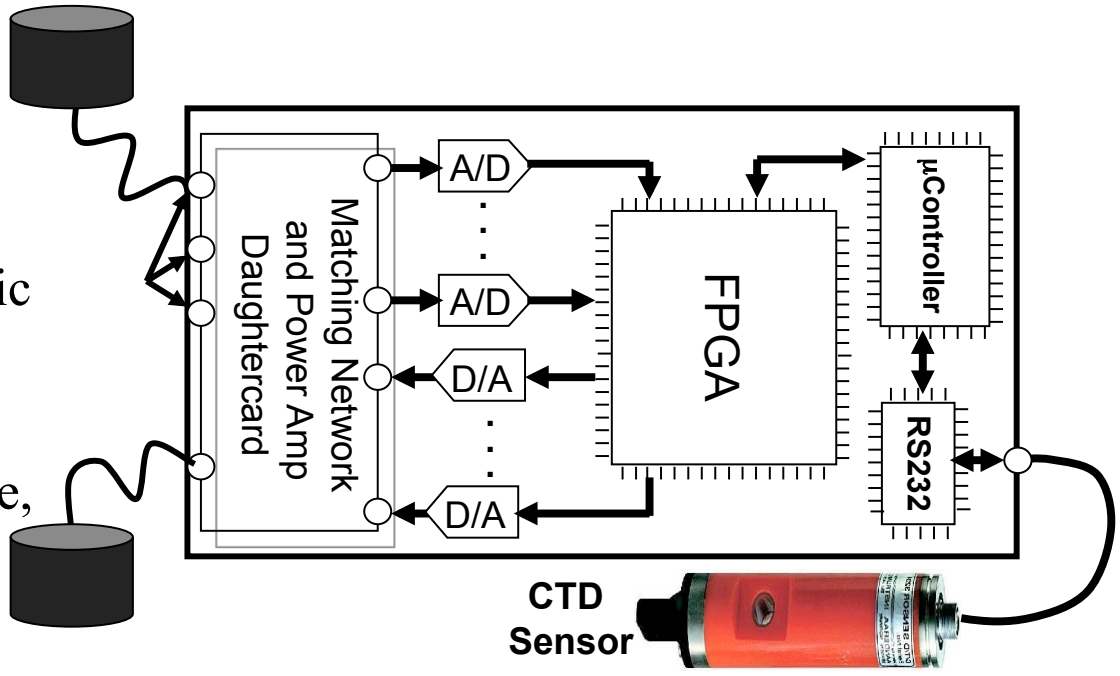
AquaNode Hardware Platform

- Ideal: One piece of hardware for any sensor and scenario
- Hardware is wirelessly updatable: no need to retrieve equipment to update hardware for changing communication protocols, sampling, sensing strategies



Hardware Platform Interfaces

- Sensor Interface:
  - Must develop common interface with different sensors (CTD, chemical, optical, etc.) and communication elements (transducer)
  - Wide (constantly changing) variety of sensors, sampling strategies
- Communication Interface:
  - Amplifiers, Transducers
  - Signal modulation
  - Hardware:
    - Software Defined Acoustic Modem (SDAM)
    - Reconfigurable hardware known to provide, flexible, high performance implementations for DSP applications



What About Existing Modems?

	Data rate	Transmission distance	Transmit & Receive power	Cost	Firmware and software design
Teledyne Benthos	2400 bps	2-6 km	12 W 0.4 W	$18,000	Proprietary
LinkQuest	9600 bps	1500 m	4 W 0.8 W	$15,000	Proprietary
WHOI Micromodem	80 bps (FH-FSK)	1-10 km	10-100 W 100 mW	$5,000	All design information is available online.
	300-5400 bps (PSK)		10-100W 1 W		

- Expensive: Need a low cost solution (similar to terrestrial sensor radios) to enable dense deployments
- Proprietary design: Open source reduces costs, increases innovation
- Targeted towards longer distances

But can we do better? Less power? Wider bandwidth?

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Design Considerations for Moorea Modem

- Acoustic Propagation
  - Multipath Spread – Range of 1 to 10 milliseconds for shallow water at up to 1 km range
  - Doppler Spreads up to 1 Hz
- Transducers
  - Size/weight/cost proportional to wavelength
  - Acceptable propagation losses at 100 meter ranges
  - Sonatech 24 kHz provided enough bandwidth (6 kHz) and avoided higher frequency absorption
- Physical layer communication
  - Frequency Shift Keying (FSK)
    - Narrowband thus sensitive to frequency-selective fading.
    - Use more tones – increasing sensitivity to Doppler spread.
  - Direct-sequence spread spectrum (DSSS)
    - Provides frequency diversity due to wide bandwidth
    - Can be detected noncoherently

Moorea Modem Specifications

Signal and Data Parameters

Data rate: 133 bps

Chip duration T_c = .2 msec.

Symbol duration T_{sym} = 11.2 msec.

Time guard interval T_c = 11.2 msec.

M-sequence length L_{pn} = 7 chips.

Walsh sequence length N_w = 8

Bandwidth = 5 kHz

Carrier Frequency f_c = 25 kHz

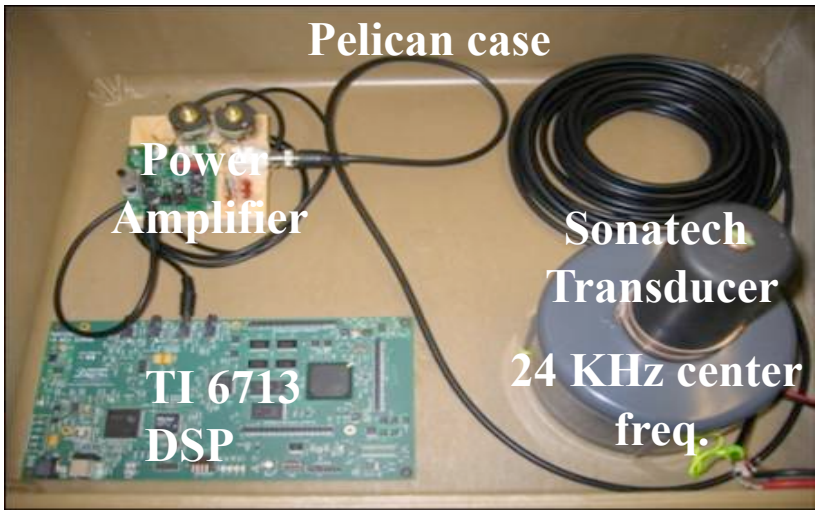
Nominal range 100 – 300 m.

Power Consumption Overview

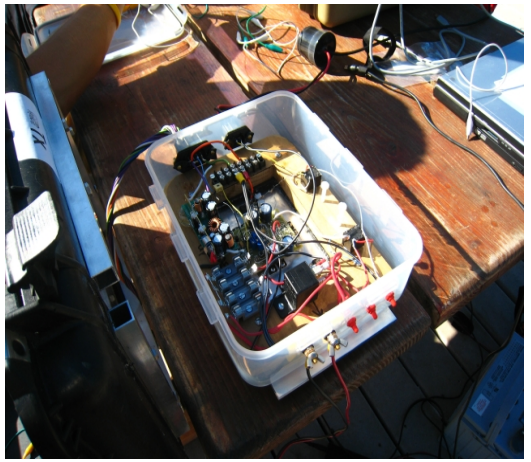
Load	Tx State	Rx State	Sleep State
CPU	440 mW	440 mW	.30 mW
CPU I/O	420 mW	420 mW	.15 mW
Flash Memory	165 mW	165 mW	.10 mW
Power Amp.	7.2 W	.05 mW	.05 mW
Battery Total	9.3 W	2.1 W	10 mW

Battery Life (Based on 20 amp-hours)

Tx Duty Cycle	Rx Duty Cycle	Days
.1%	.2 %	624
.5%	1 %	189
1%	2%	101







R. Iltis et. al. "An Underwater Acoustic Telemetry Modem for Eco-Sensing", MTS/ IEEE OCEANS 2005

Walsh/m-Sequence Waveforms

Chip rate – 5 kcps, approx. 5 kHz bandwidth. Uses 25 kHz carrier.

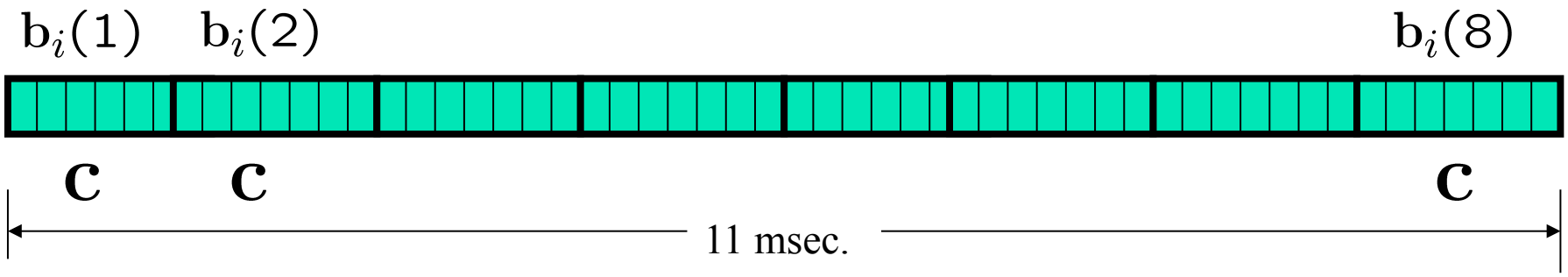
Use 7 chip m-sequence **c** per Walsh symbol, 8 bits per Walsh symbol $\mathbf{b}_i$. Composite symbol duration is thus T = 11.2 msec. (Longer than maximum multipath spread.)

Symbol rate is 266 bps, or 133 bps using 11.2 msec. time guard band for channel clearing.

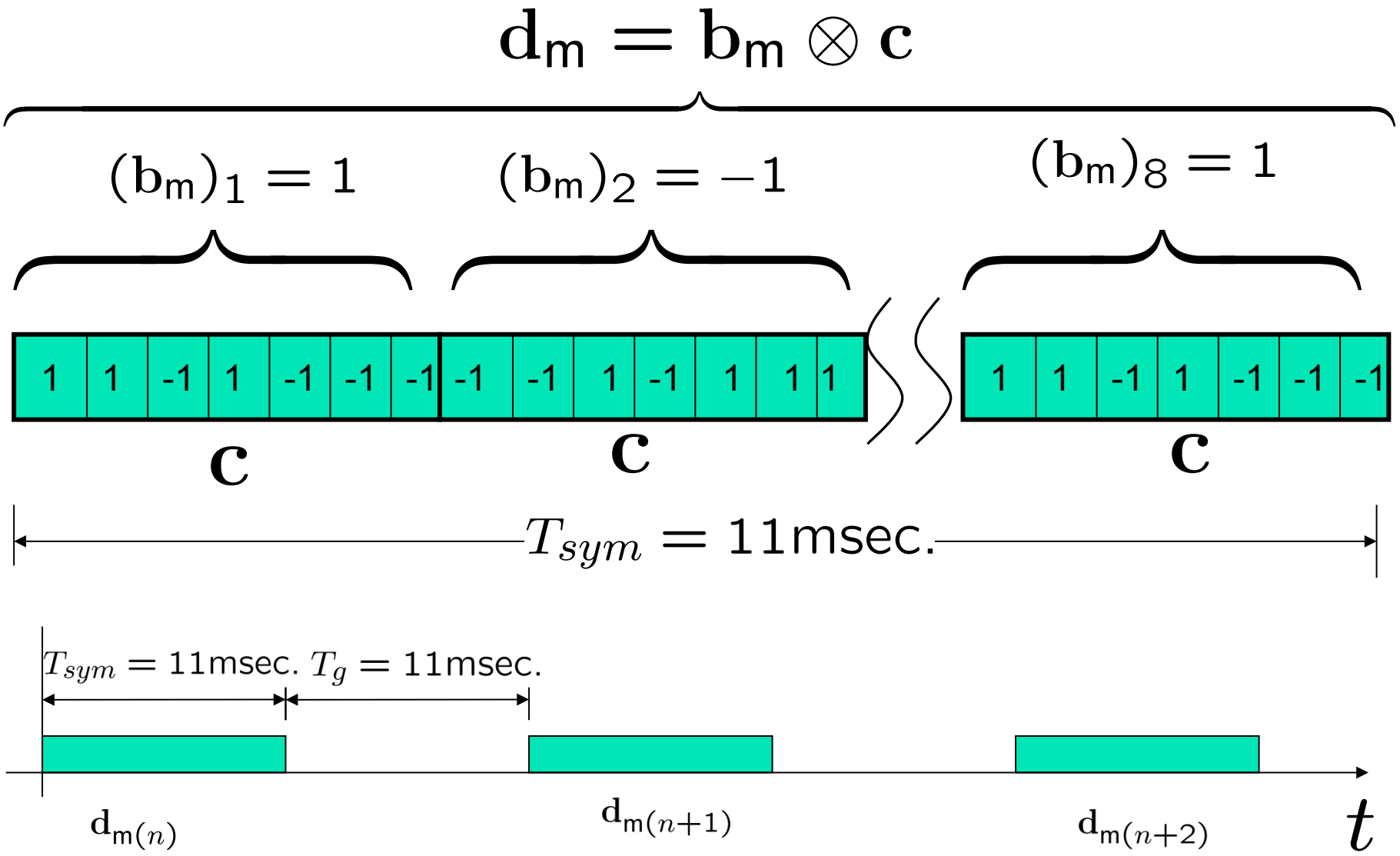
$$\mathbf{c} = [111 - 1 - 11 - 1]$$

$$\mathbf{b}_i \in \{\pm 1\}^8, i = 1, 2, ..., 8$$

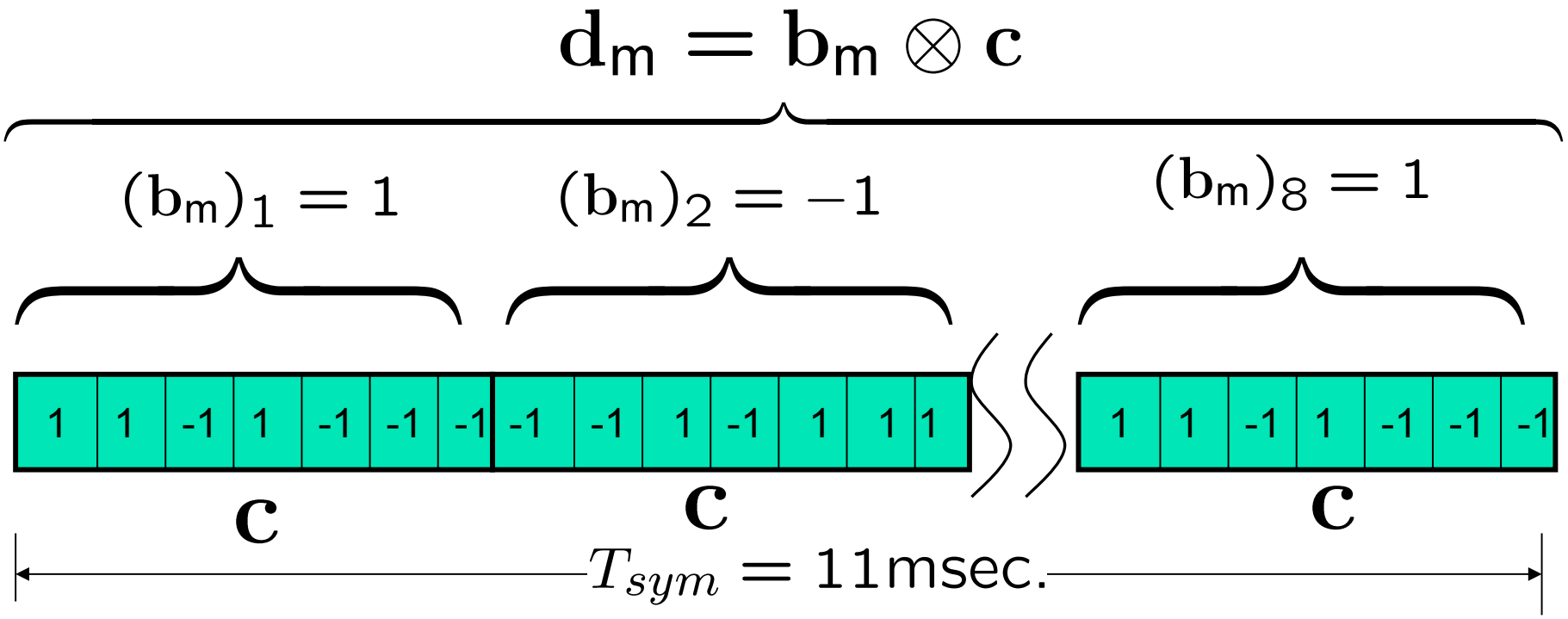
$$\mathbf{b}_i^T \mathbf{b}_j = 0, \ i \neq j$$



Transmitted Signal

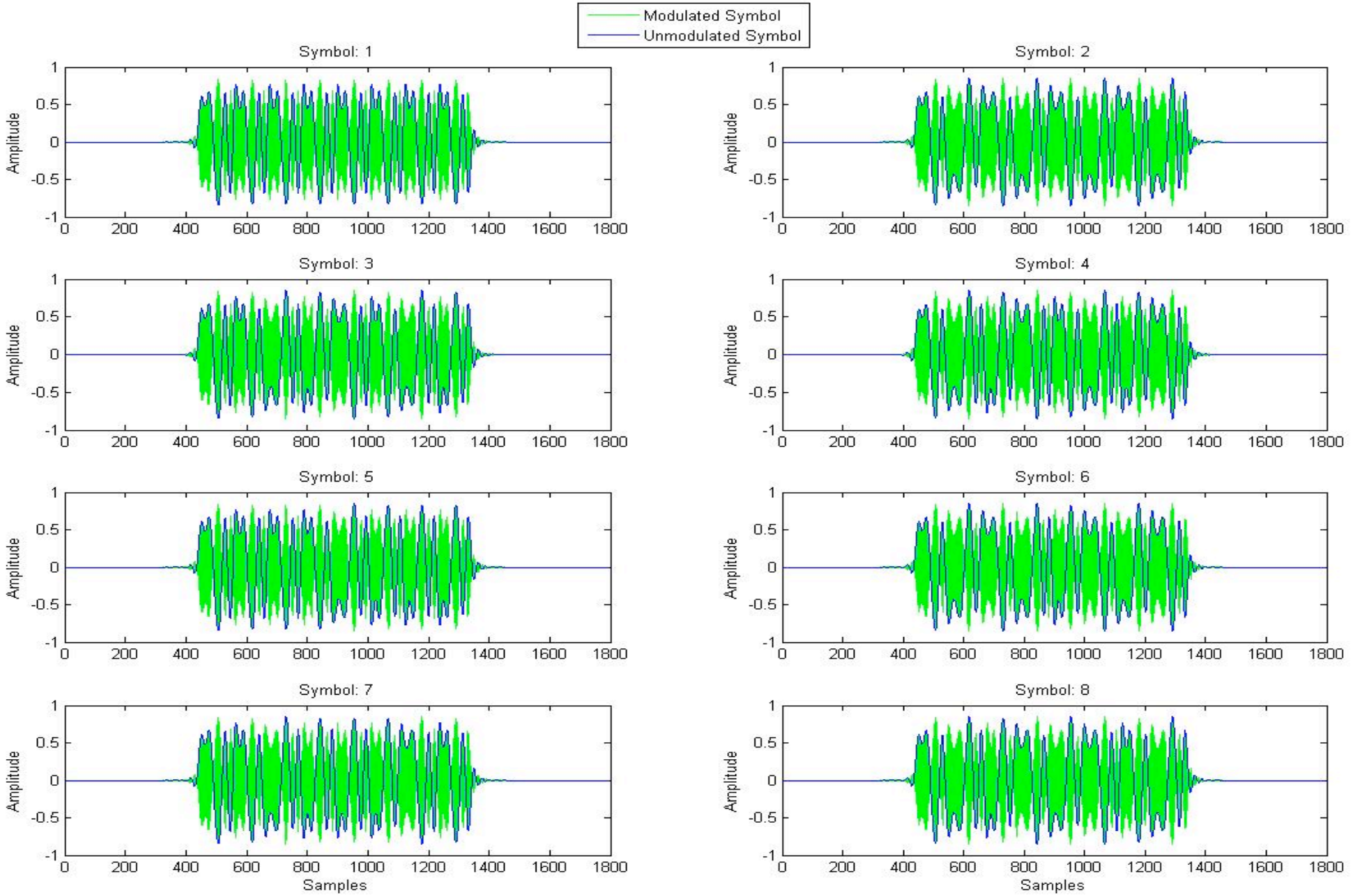


Walsh/m-sequence Signal Parameters



Chip duration $T_c = .2$ msec.	Samples/symbol $N_s = T_{sym}/T_s = 112$.
Sampling interval $T_s = T_c/2 = .1$ msec.	Time guard interval $T_g = T_{sym}$ sec. per symbol.
m-sequence length $L_{pn} = 7$ chips.	Bit rate $R_b = 3(bits/symbol)/(T_{sym} + T_g) = 133$ bps.
Walsh sequence length $N_w = 8$	Center frequency 25 kHz.
Symbol duration $T_{sym} = L_{pn}N_wT_c = 11.2$ msec.	Nominal Range 100 meters.

8 Walsh Symbols

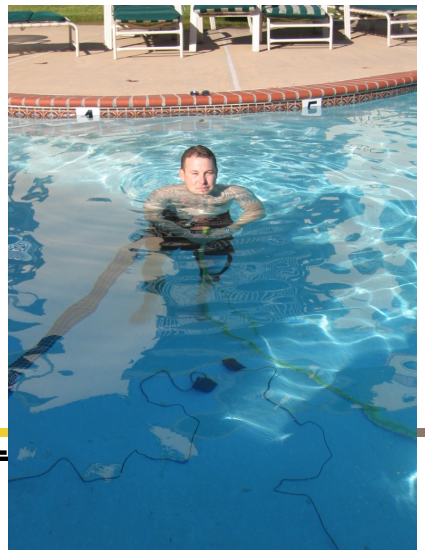


Evolution of AquaNode

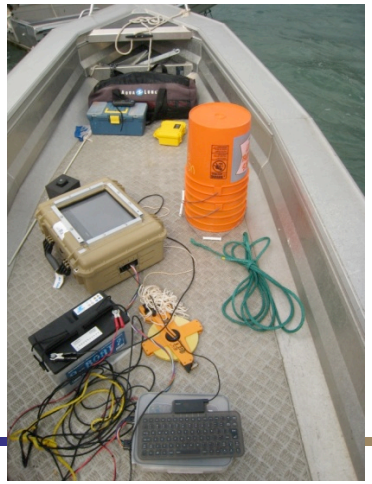
- Air, …

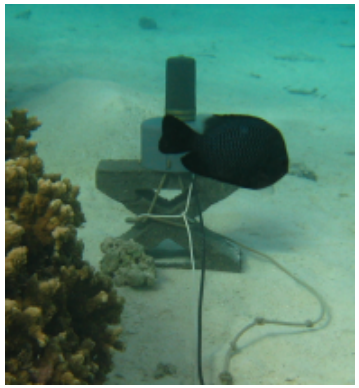


- to pool, … to lake, … to Moorea









Unanchored Transducers: Cook's Bay Test

- Transducers hanging from side of boat.
- Water ~ 30 m deep (boats not anchored).
- High estimated Doppler spread mostly due to transducer movement, and boat movement.



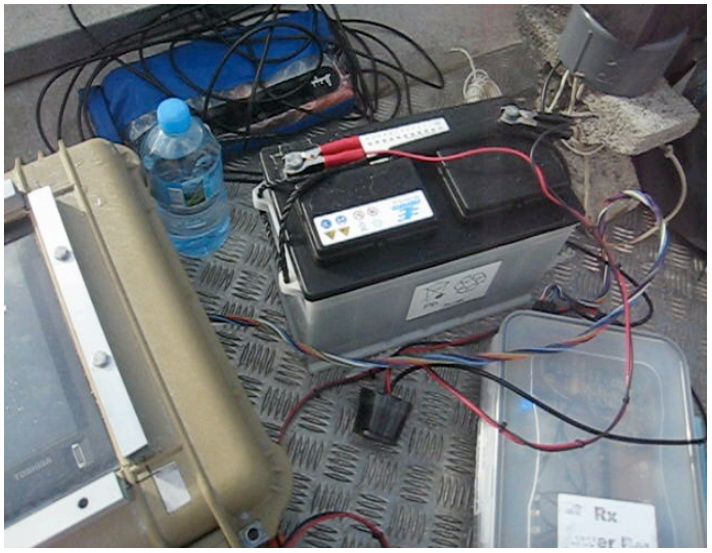
Anchored Transducers: Viapahu Lagoon Test



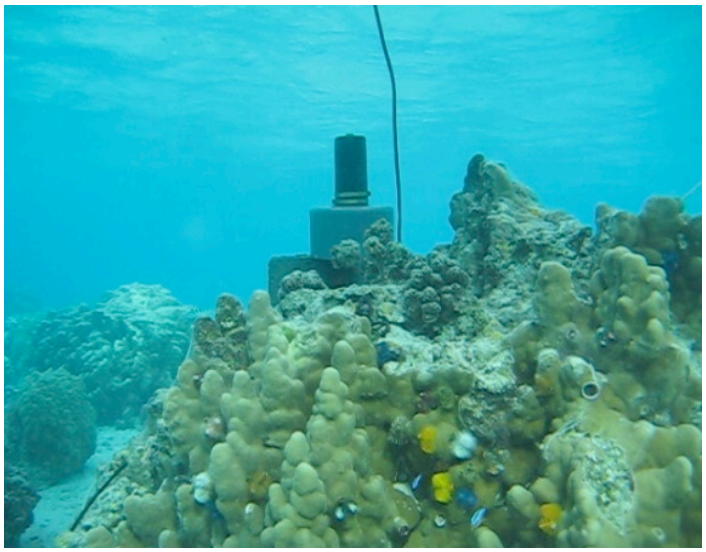
- After Cook's Bay testing, moved to shallower Viapahu Lagoon
- Hardware setup essentially the same, except boats now anchored.
- Two successful tests in this new environment

Viapahu Lagoon Test (50 m, Bommies)

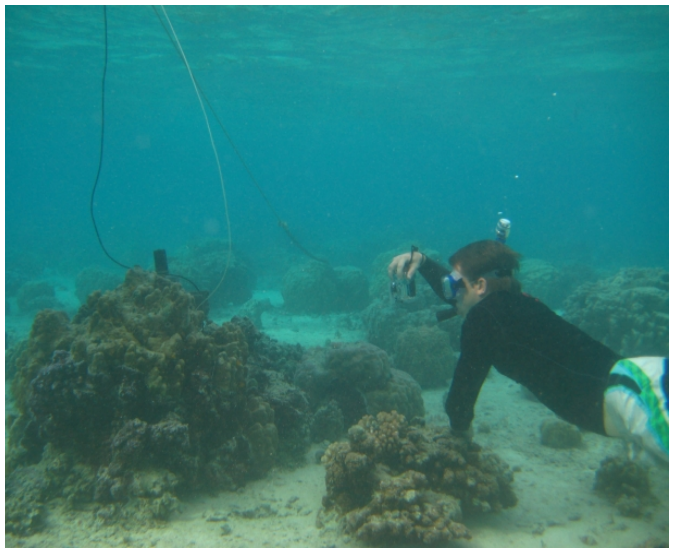






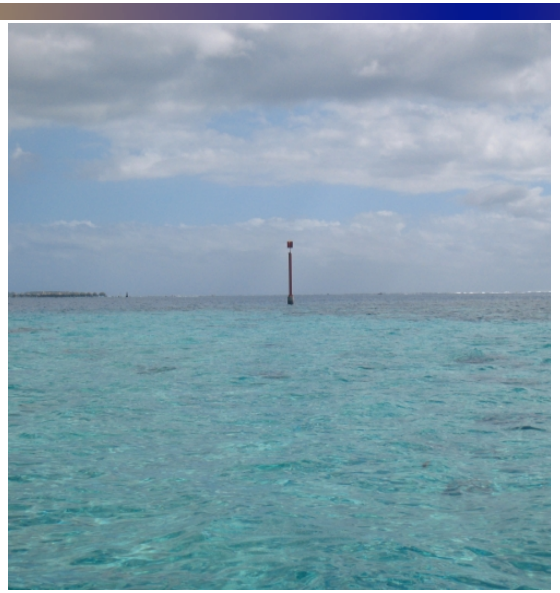
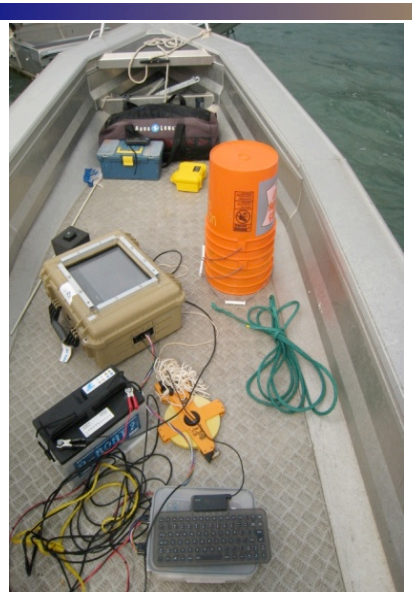
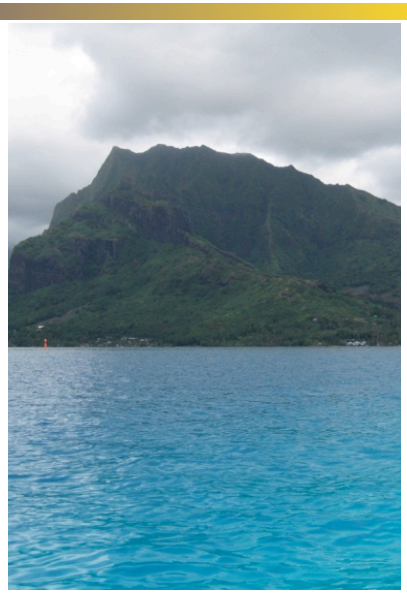


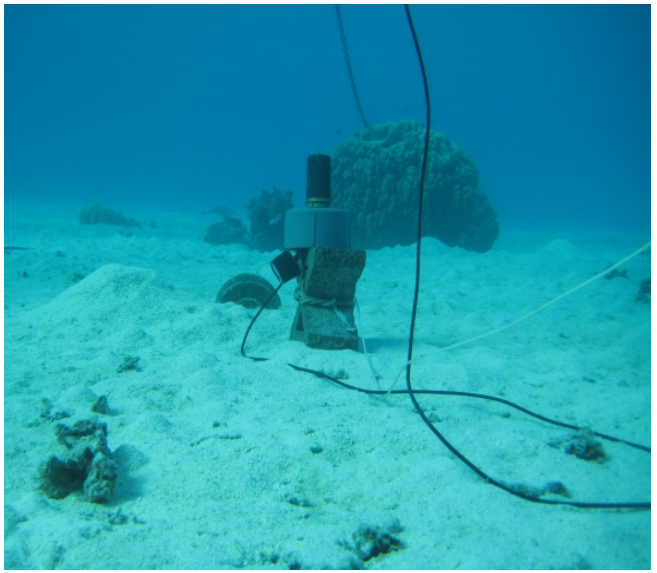




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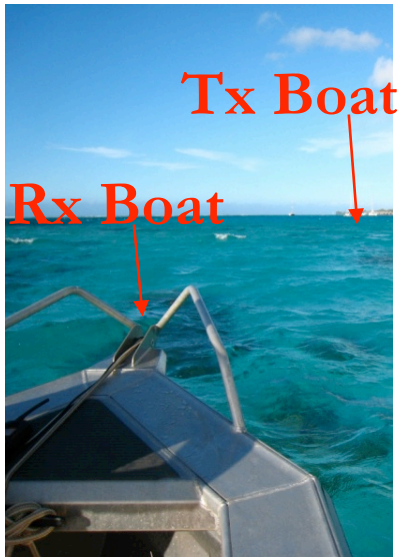
Anchored Testing – Viapahu Lagoon Test (125m)

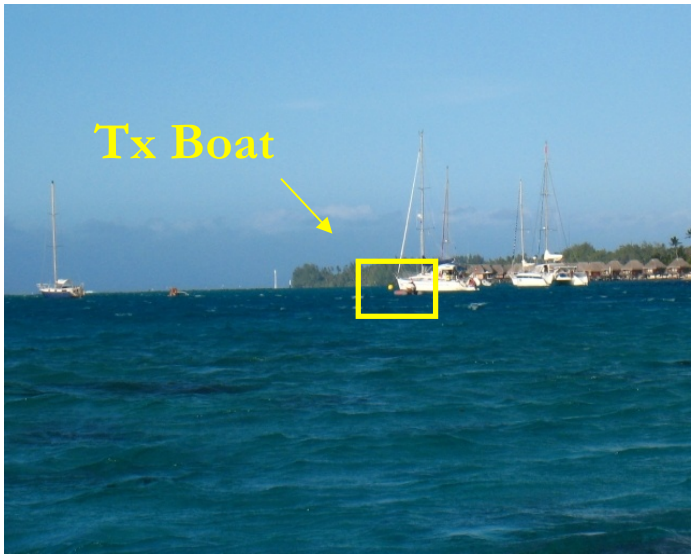





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Viapahu Lagoon Test (280 m)







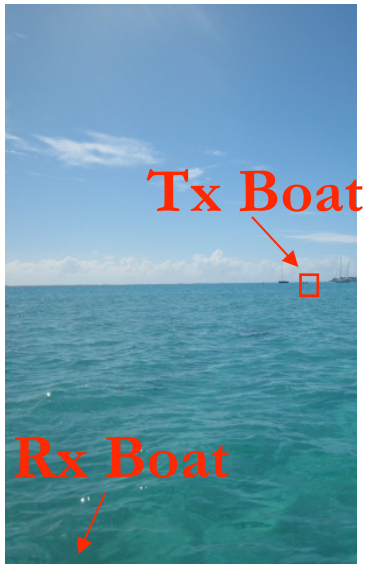




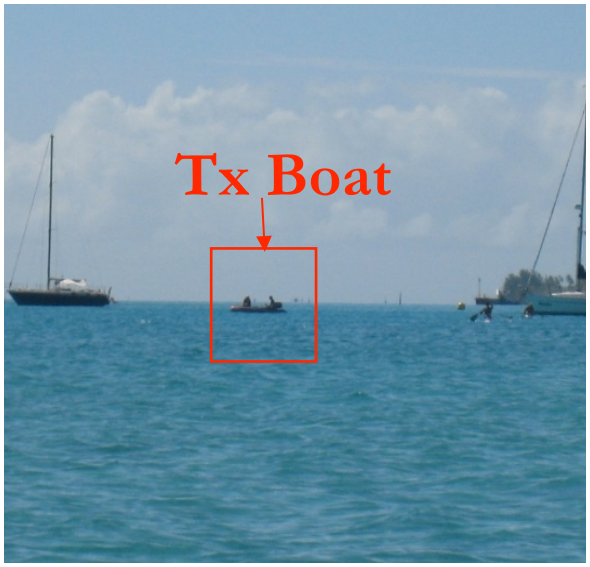




Viapahu Lagoon Test (330 m, 440 m)

















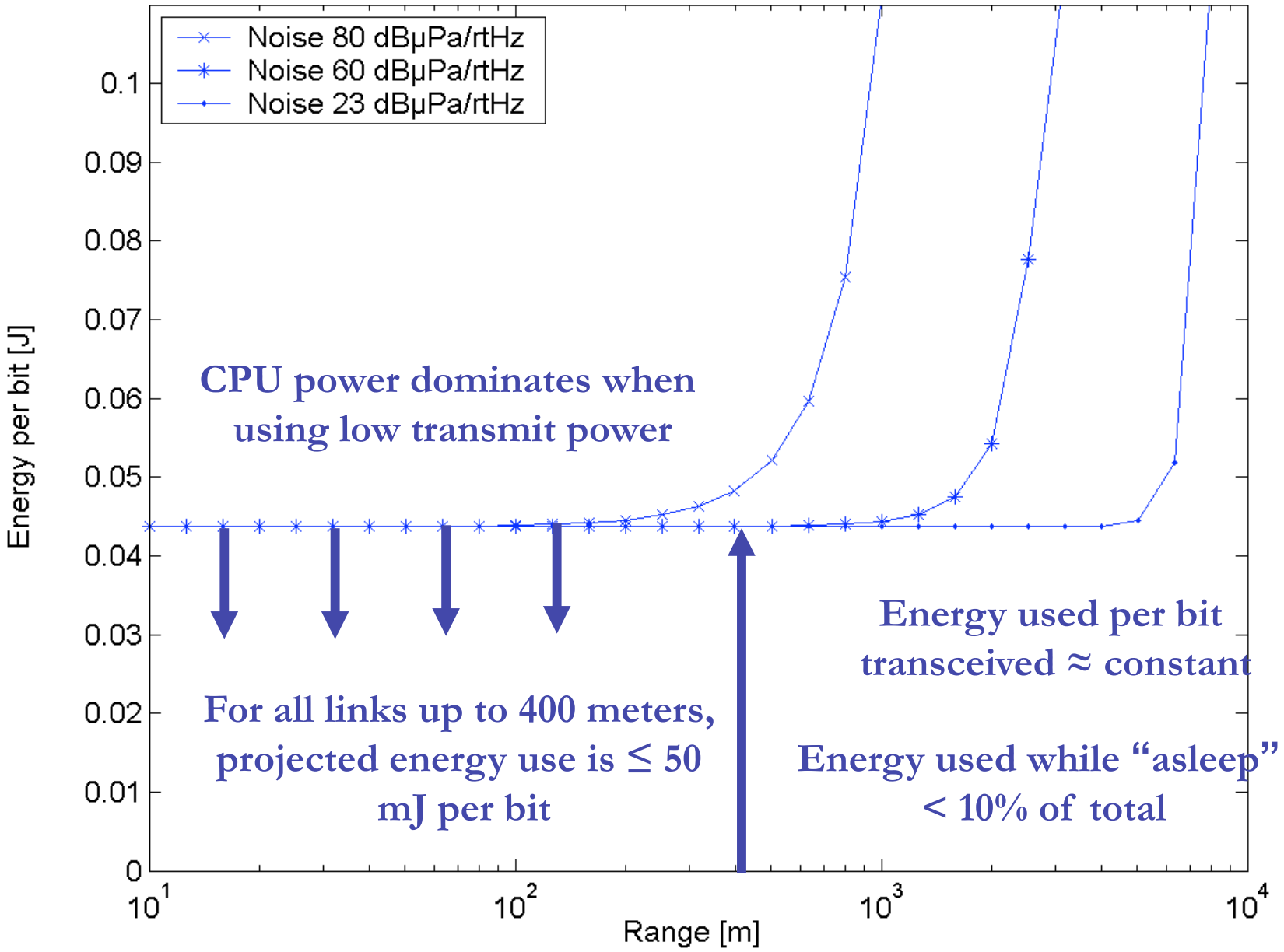
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Results summary

- Doppler spread (averaged, median-filtered):
  - High (averaging > 1 Hz) when boats and transducers are unanchored.
  - Generally averaging on the order of 0.01 Hz with anchored transducers in Viapahu Lagoon.
- Modem Performance:
  - DSSS modem: average SER < 1%
  - Distances up to 500 km



Energy Consumption

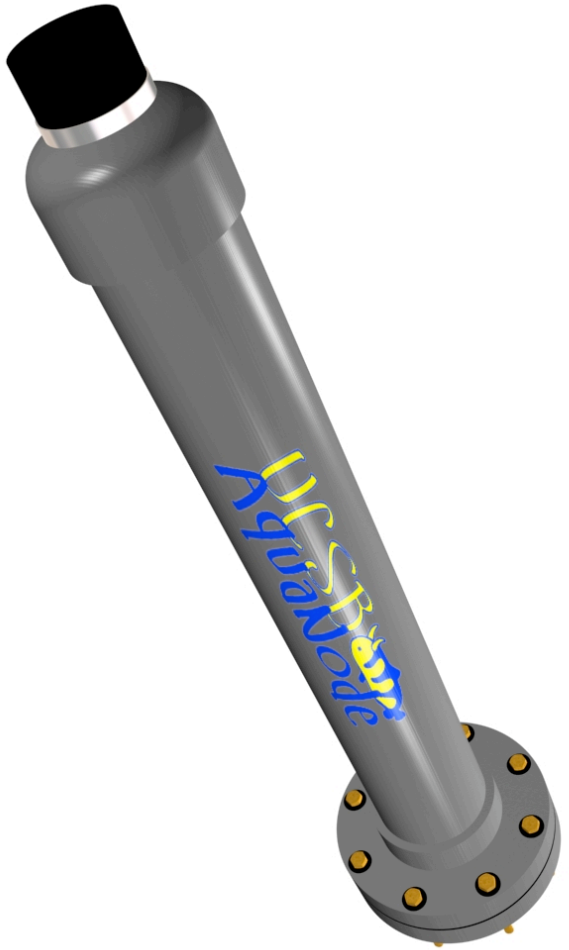


Next Generation Modem

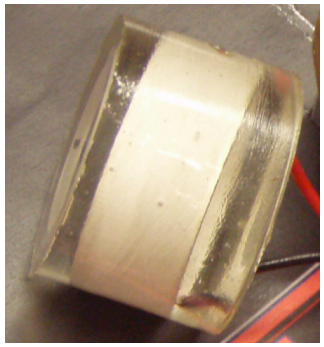
- Moving from this...



to this...

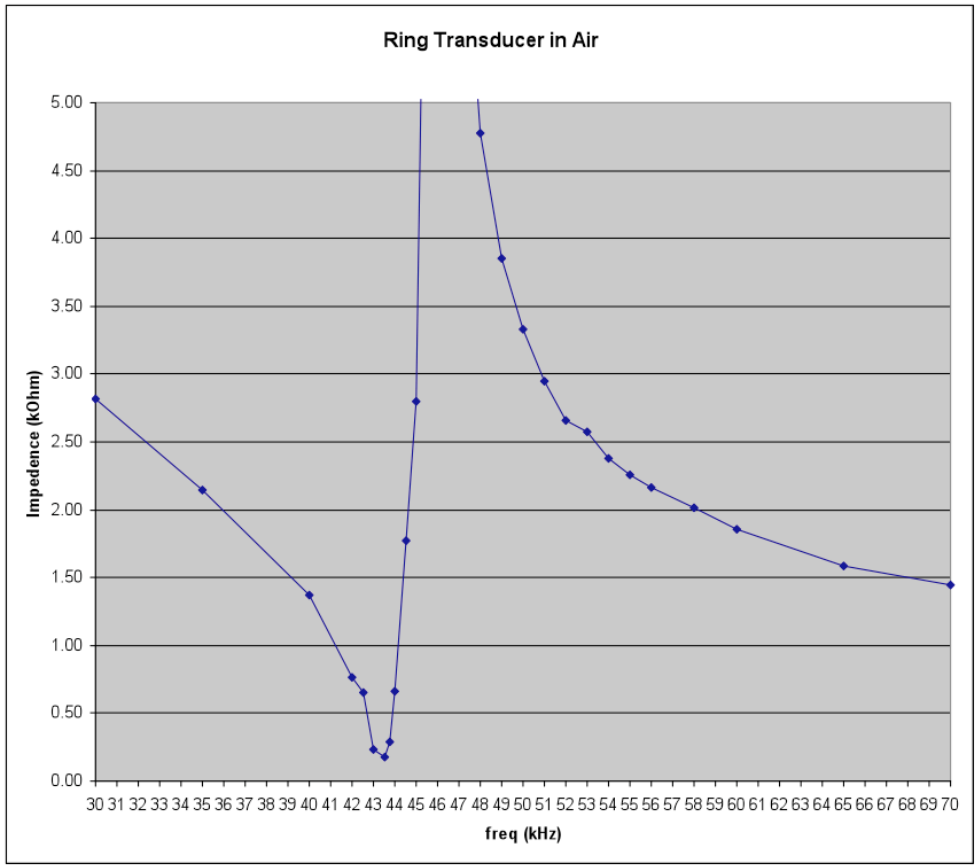


Current Modem Design – Transducer



vs.

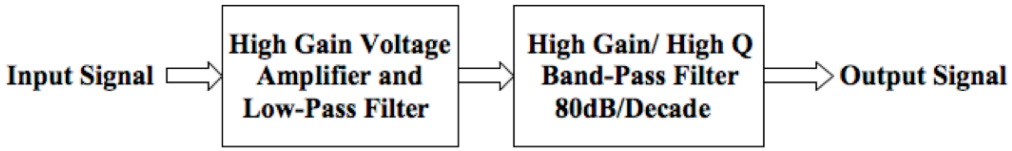


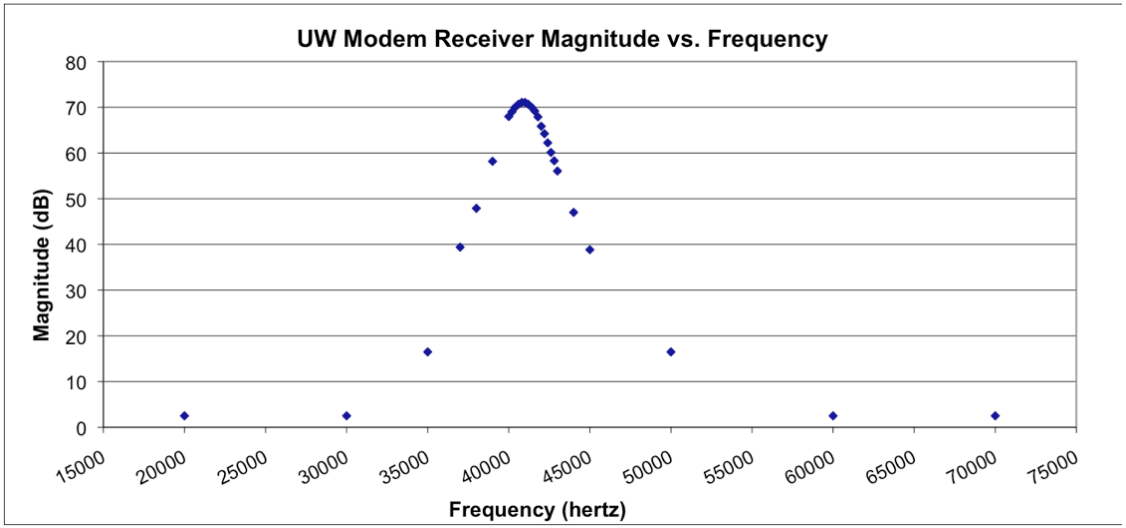


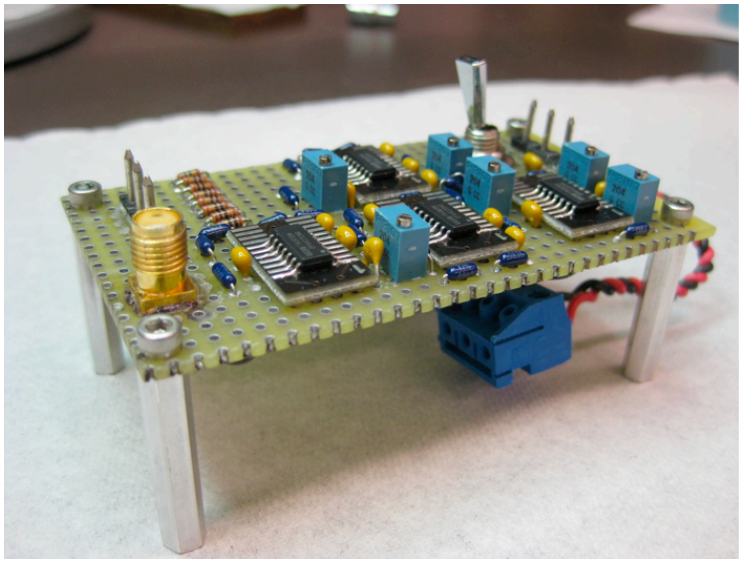
- $5 transducer vs $3000 transducer
- 40 kHz vs 25 kHz
- 1 kHz vs 6 kHz bandwidth

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Current Modem Design – Analog Receiver

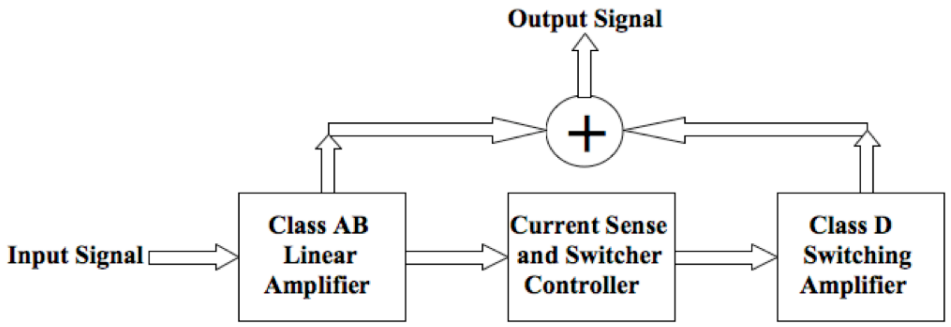


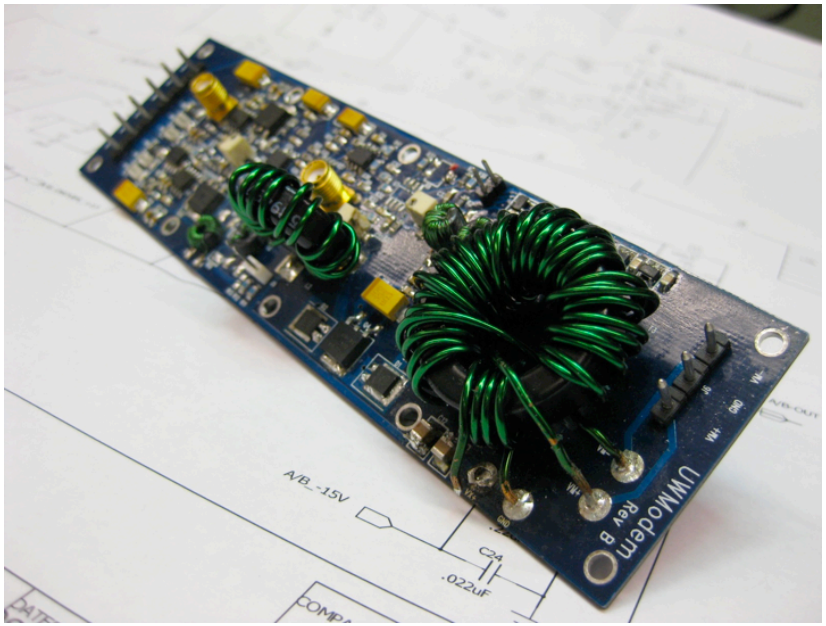




- High gain, high Q biquad band-pass filters centered around transducer resonance (~40 kHz)
- Cost: ~$40 (components and labor)

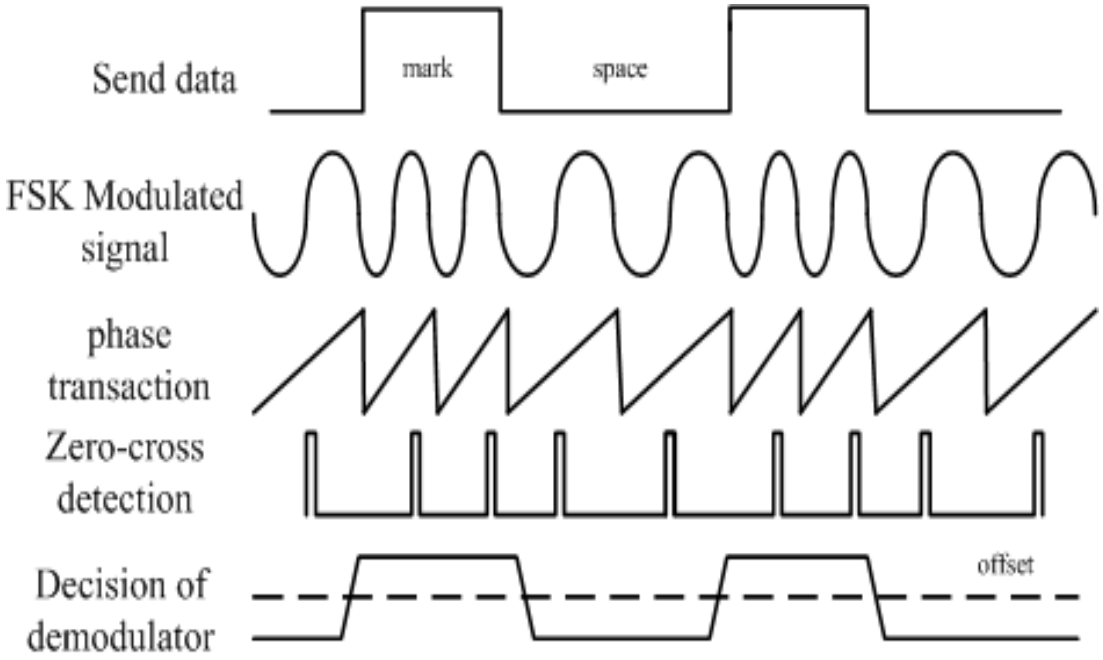
Current Modem Design – Analog Transmitter





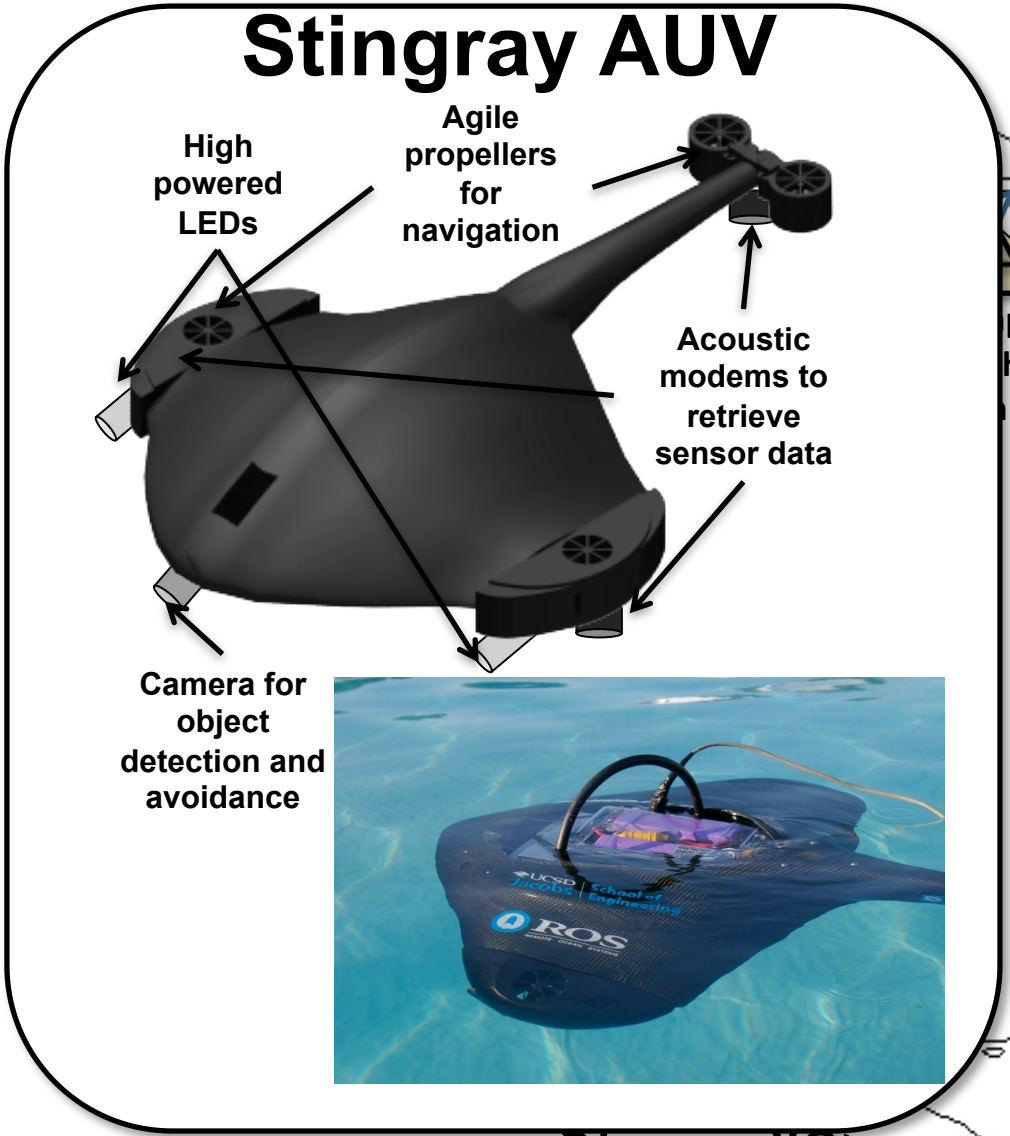
- Traditional Class AB amplifier provides a 20X voltage gain
- Triggers a Class D switching amplifier for efficient power boost
- Targeting overall efficiency of 85%

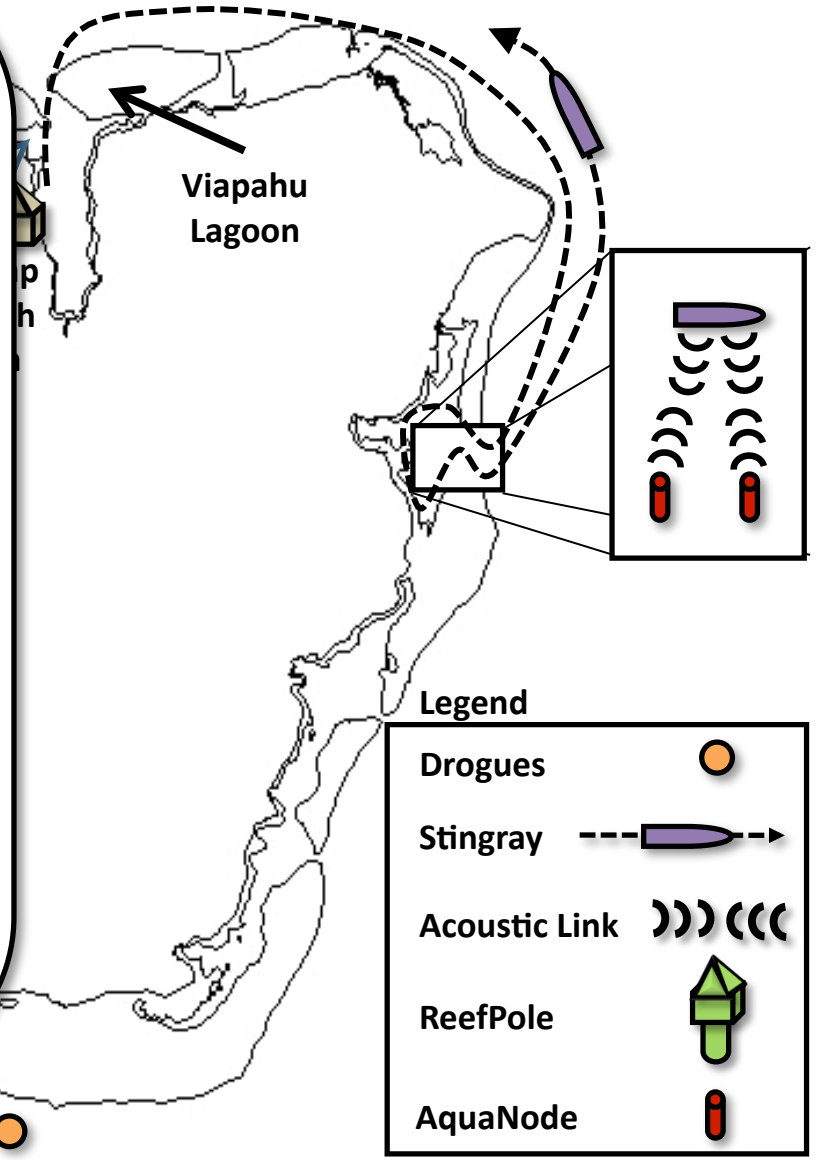
Current Modem Design – Digital Transceiver



- Frequency Shift Keying - simple yet effective
- Coherent vs Non-coherent
- More details: Li et al - ERSA09

Vision for Underwater Monitoring in Moorea





The Stingray

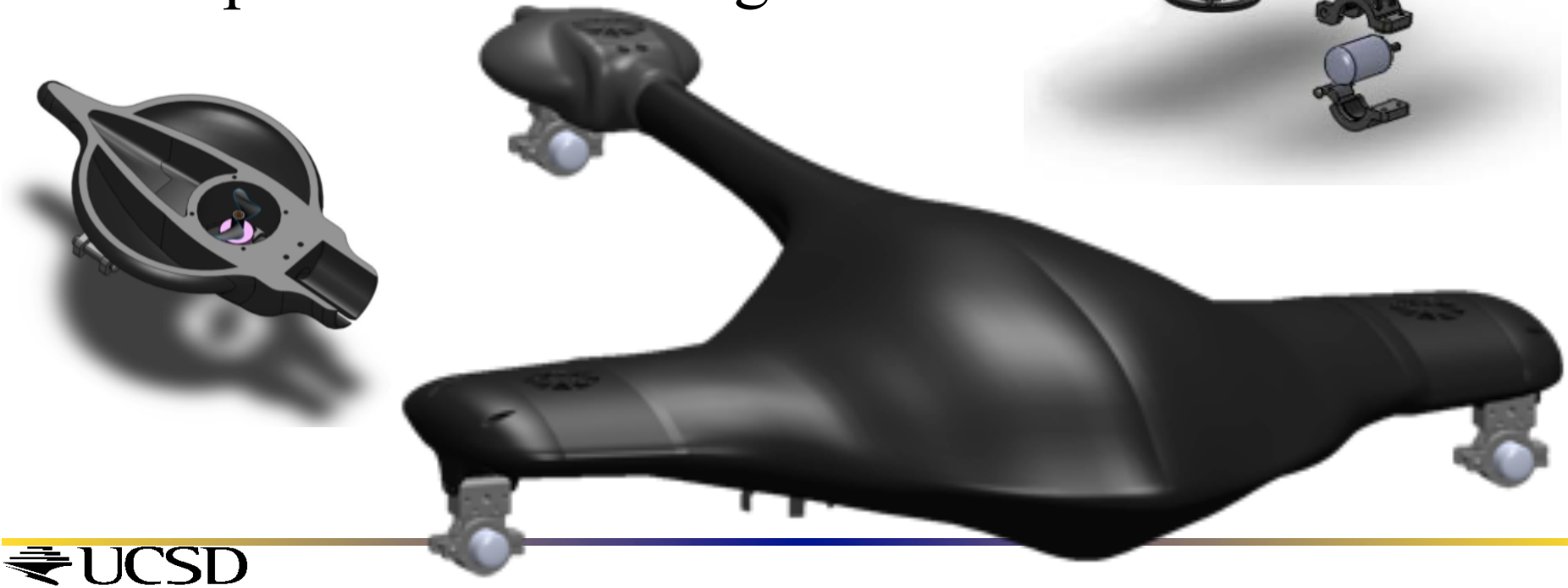


- Small, lightweight, agile autonomous underwater vehicle (AUV)
- Developed for annual AUVSI competition

Hull

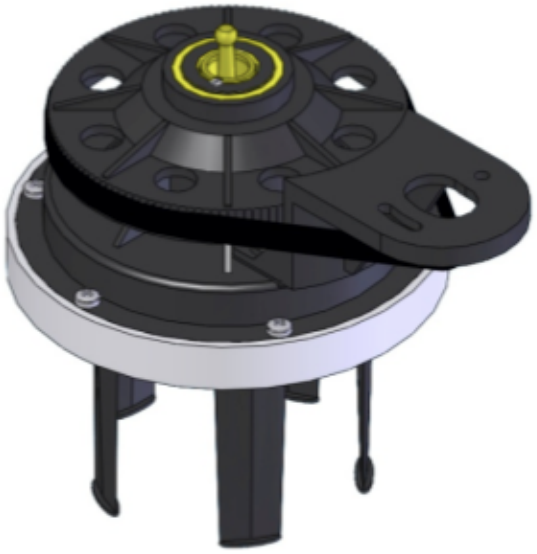
- Custom, carbon fiber hull
  - Biomimetic
  - Light weight
  - Flooded
- 3D printed tail & wings



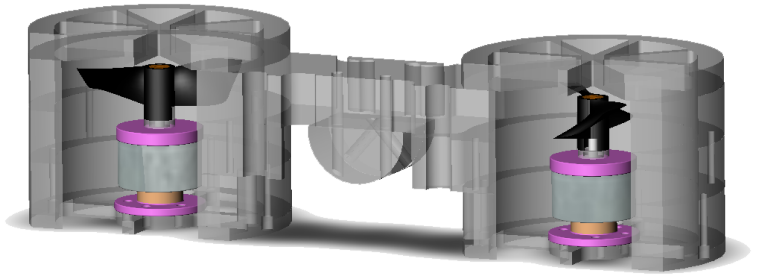


Propulsion

- Voith-Schneider Propellers
  - Two positioned underneath hull
  - Two controls 3 degrees of freedom in the lateral plane
  - http://www.voithturbo.de/vt_en_pua_marine_vspropeller.htm



- Scorpion Motors
  - One on each wing, two on tail
  - Controls depth, pitch and roll

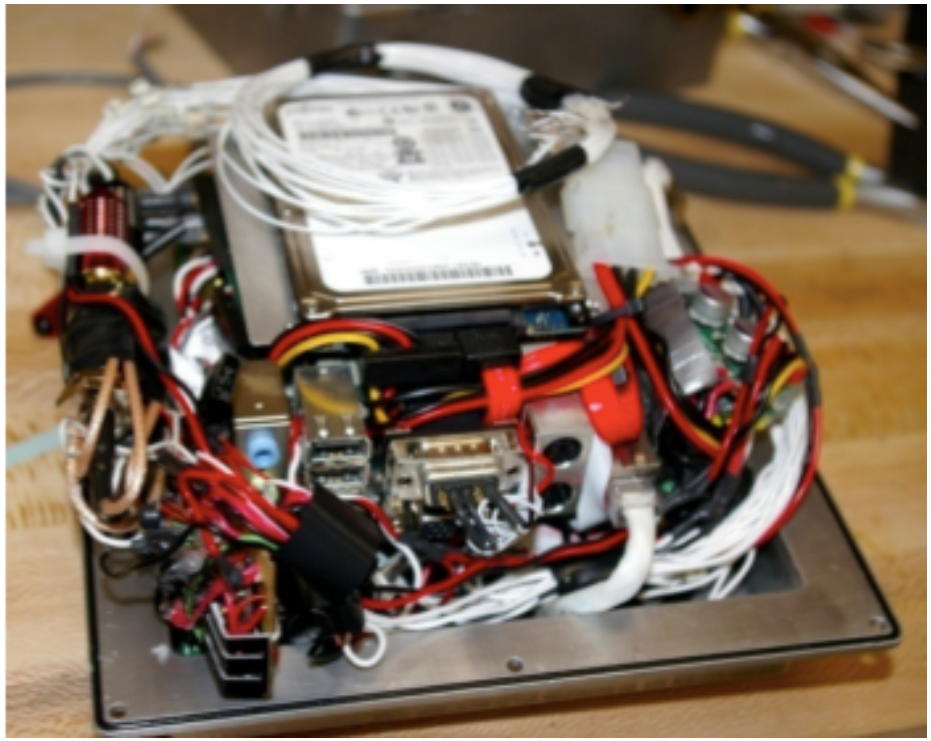


Autonomous Controls



Electronics

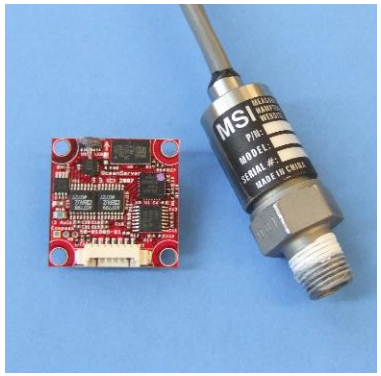
- Electronics housed within a water-tight aluminum enclosure
- Machined aluminum enclosure for superior heat dissipation
- PC/104
  - Dual-core 1.5 GHz processor, 2 GB RAM
  - Dual-channel frame-grabber PCI card
- DAQ attached to PC/104
  - Measures voltages from the battery, pressure sensor, and internal moisture sensor
  - Controls LED intensity



Sensors and Actuators

- MicroStrain 3DM-GX1 IMU
  - Provides orientation measurements
  - Connects to the main computer via a standard RS-232 serial connection.
- Analogue pressure transducer
- Pololu Serial Servo Controller (USB)
- LabJack U3-HV (USB) for digital and analog I/O







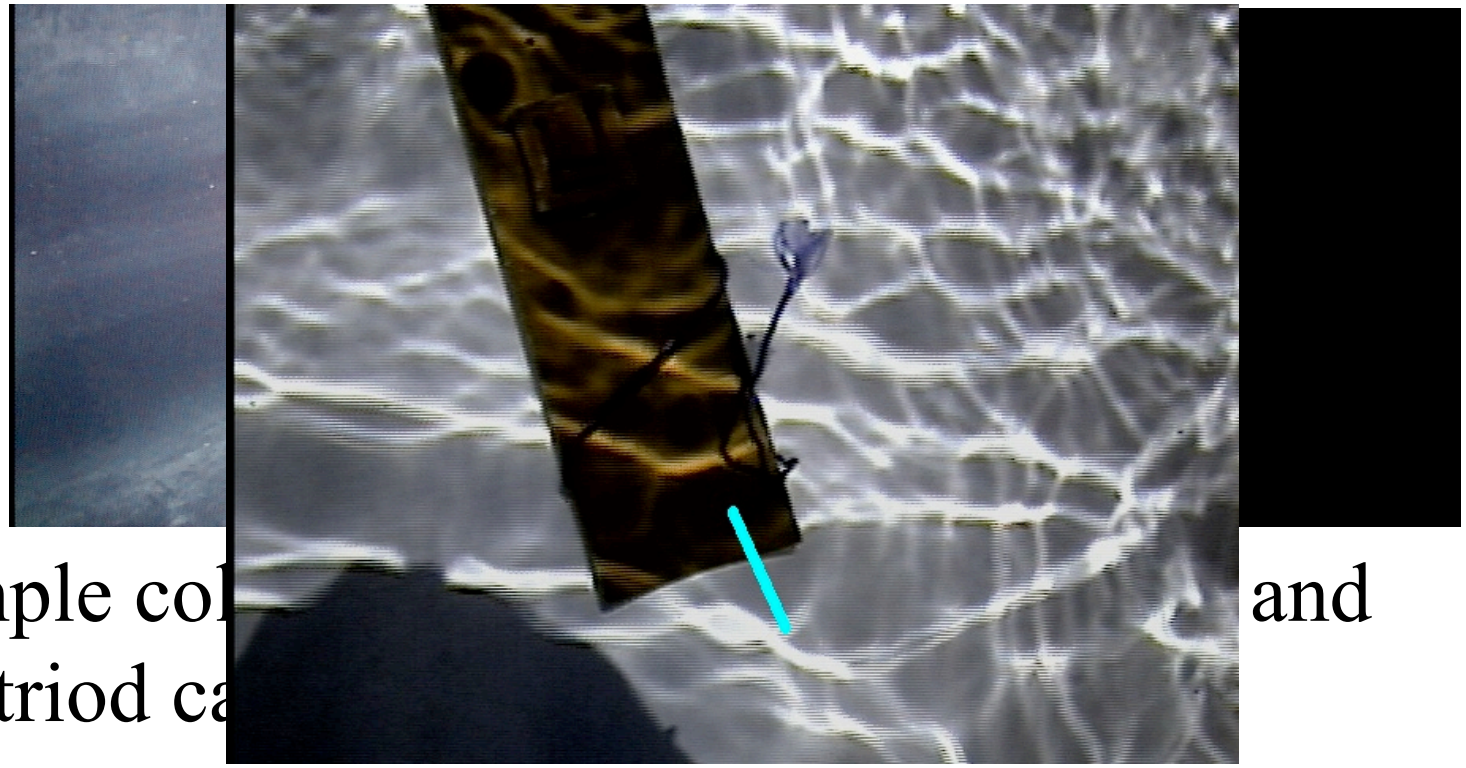
Cameras

- Inuktun FireflEYE – downward looking camera
- Remote Ocean Systems BP-L3C-HR-D6-N – forward looking camera
- Cameras connect directly to the video-capture card



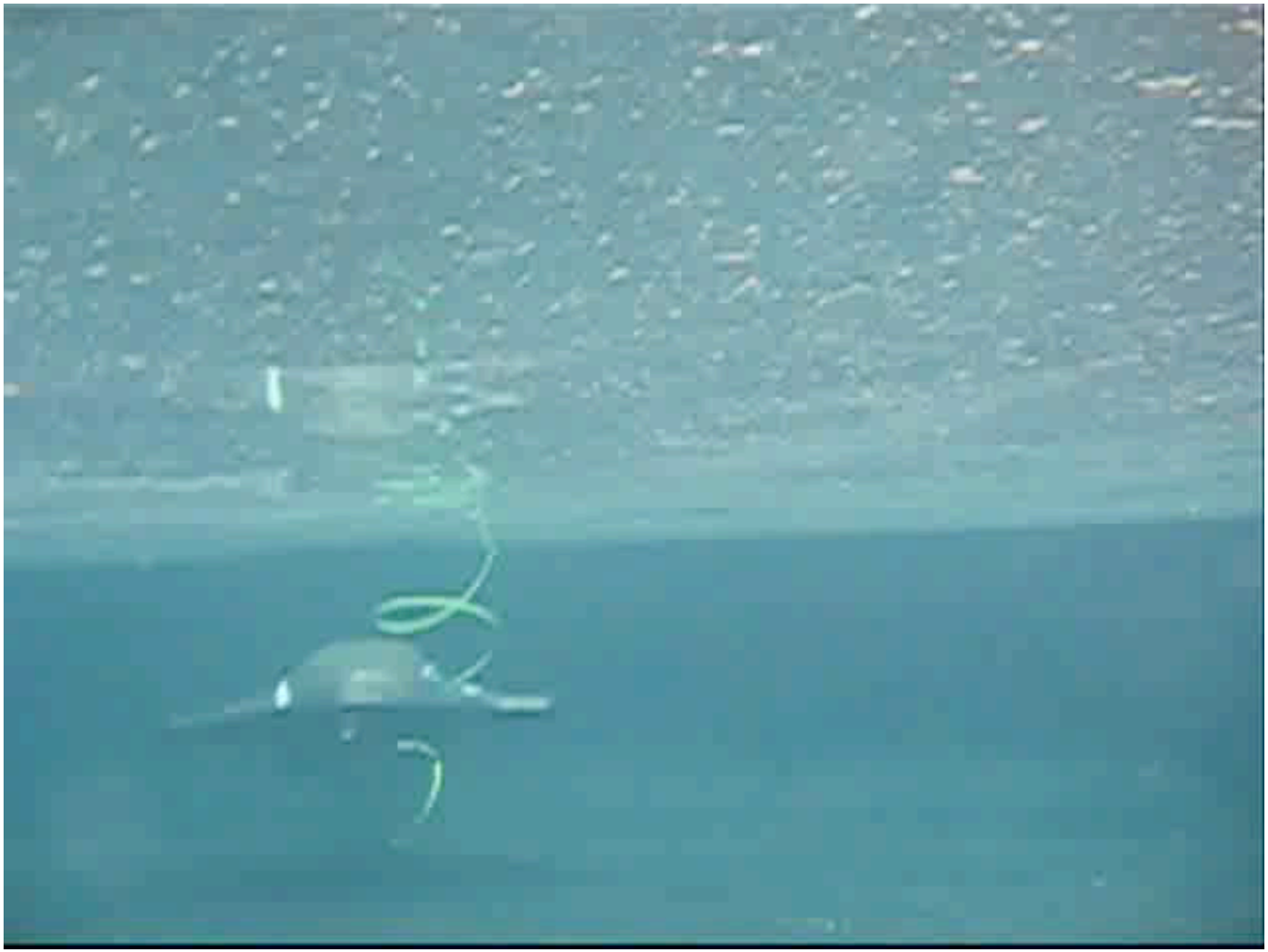
Underwater Object Detection

- Buoys and Pipes (part of AUVSI contest)



- Simple col and centriod ca
- Simple color detection, erosion, dilation and least squares edge estimation

Buoy Tracking



Conclusions

- Underwater sensor networks are in their infancy
- Much work to be done in a large variety of area
  - Wireless communications, Networking
  - Autonomous vehicles
  - Sensors particularly image
  - Streaming “real-time” data

More Information

- Classes that will help me learn more about:
  - Embedded Systems (CSE 30, CSE 145, ECE 156)
  - Image Processing (CSE 8AB, CSE 152, CSE 166)
  - Hardware Design (CSE 140, CSE 141, CSE 148)
  - Communications (ECE 45, ECE 154ABC, ECE 161ABC)
- Stingray (http://www.sdibotics.org/)
- Undergraduate Research
  - Look at professors research webpages
  - Talk to professors and graduate students
  - Talk to me (kastner@ucsd.edu)


That's all Folks!