A Self-Powered Underwater Robot for Ocean Exploration and Beyond

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2011 von Karmen Lecture Series

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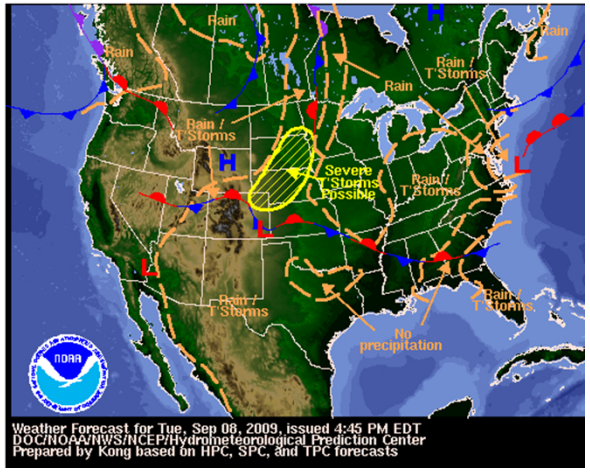
Numerical Weather Prediction (NWP) as a successful example from research to operations/applications

Observing

Model

NOAA National Weather Service: $>1B/year



Users

weather.com

Private service (112+): $200M/yr +5%/yr

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
UNITED STATES DEPARTMENT OF COMMERCE

NOS NOAA

NATIONAL OCEAN SERVICE

$1+B

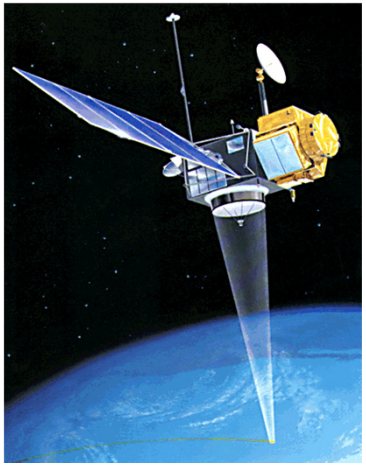
NOAA FISHERIES SERVICE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

$1+B

Where is my App for ocean forecast?

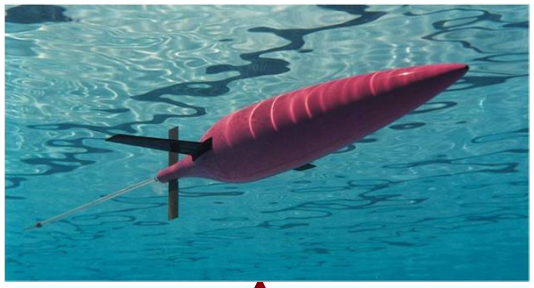
Real-Time Oceanography: Forecasting; from Research to Operations/Applications

Observation → **Model** → **Users**



Data Assimilation

Forecasting



Products

Chinook salmon. (Photo: NOAA)

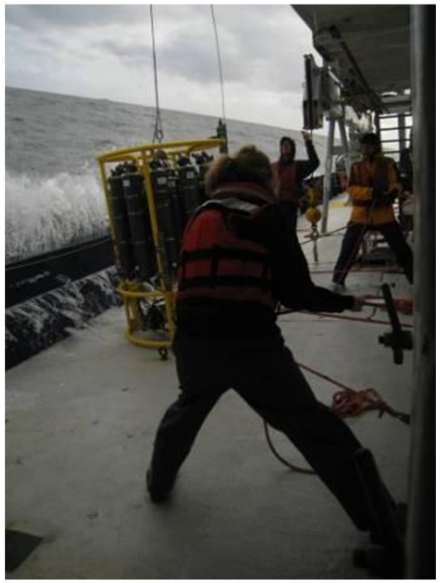
Feedback

Today, tomorrow, and next year's information of wind, wave, current, upwelling, ecosystem, productivity, fishery

Unlike over land, setting up “weather” stations at sea is difficult & expensive

$~30K/day

Traditional ways to observe the ocean: “Bottles” on Ships



(Moving “weather” station at sea)

Ship cost: $~30K/day

~3 stations per day (free: scientist/student)

A single profile data costs ~$10,000

Quest for Unmanned Underwater Vehicle (UUV): Profiling Floats ("Weather balloon")

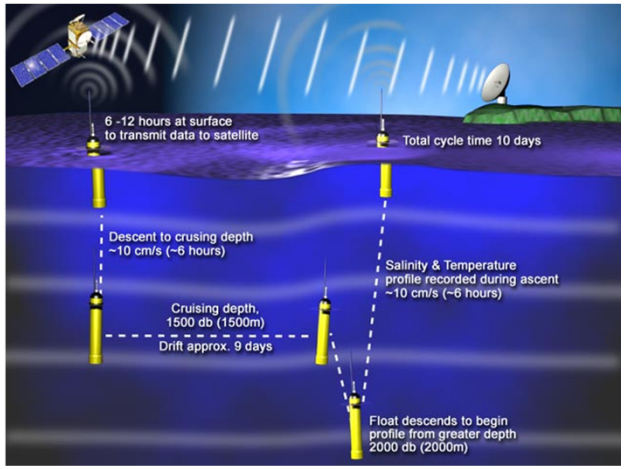
To collect a vertical profile in the ocean now costs ~$100

1950-60

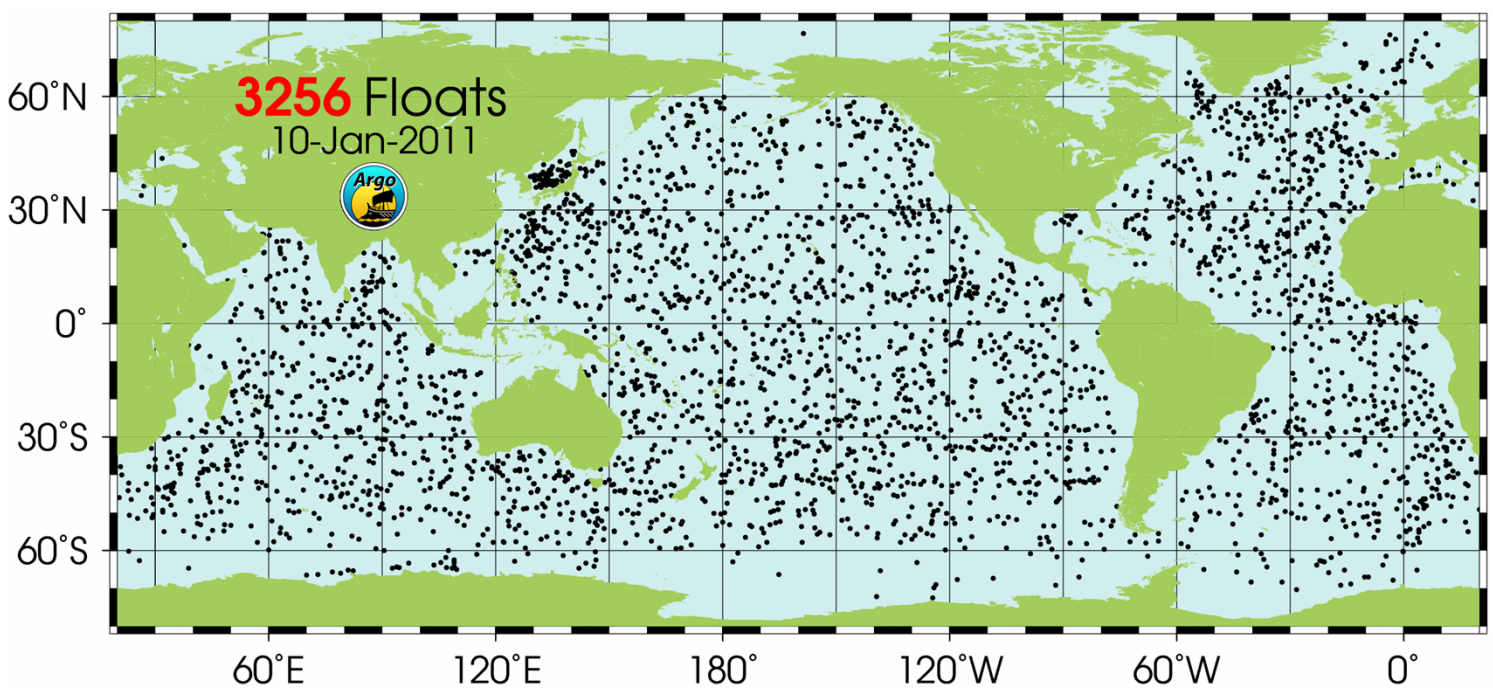
1970-80

1990-2010
Commercially available
$20,000/float
~200 dives/profiles

Ocean Floats to Monitor Ocean/Climate

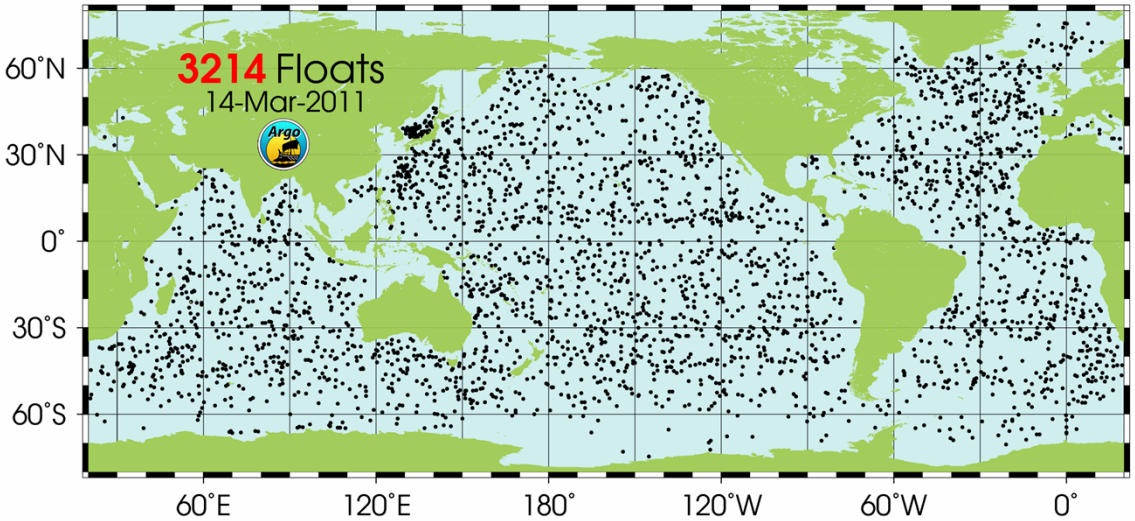


Argo Program: 3000+ floats



Challenge to Sustain and Enhance Argo Array

Argo Steering Team (AST-12), March 15-17, 2011, Buenos Aires



✓**To maintain 3000+ Argo floats with a 3.7-year average life (Kobayashi et al., 2009) and 10-day cycle, about 813 floats need to be deployed yearly at $20,000 each.**

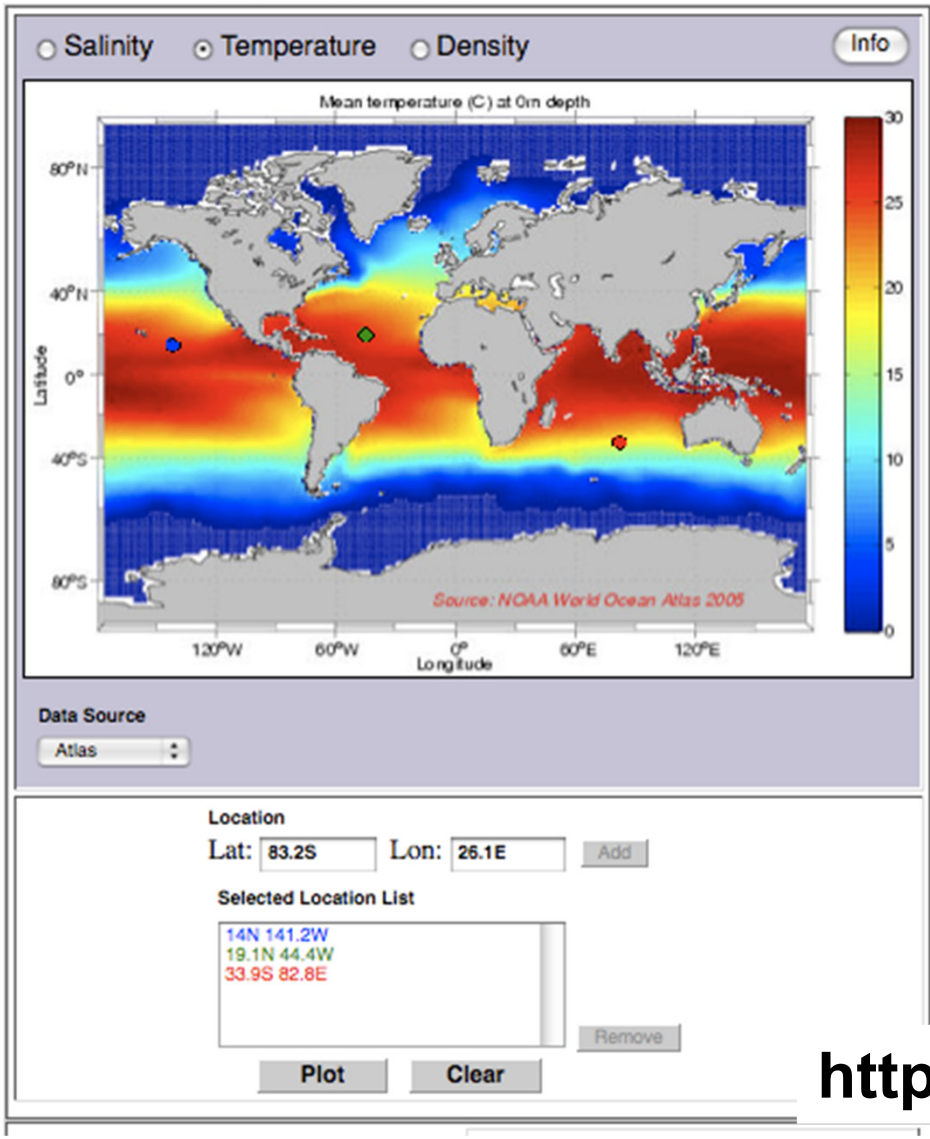
Major Limitation: Power, Power, Power

How many Lithium battery packs can you throw into the ocean?

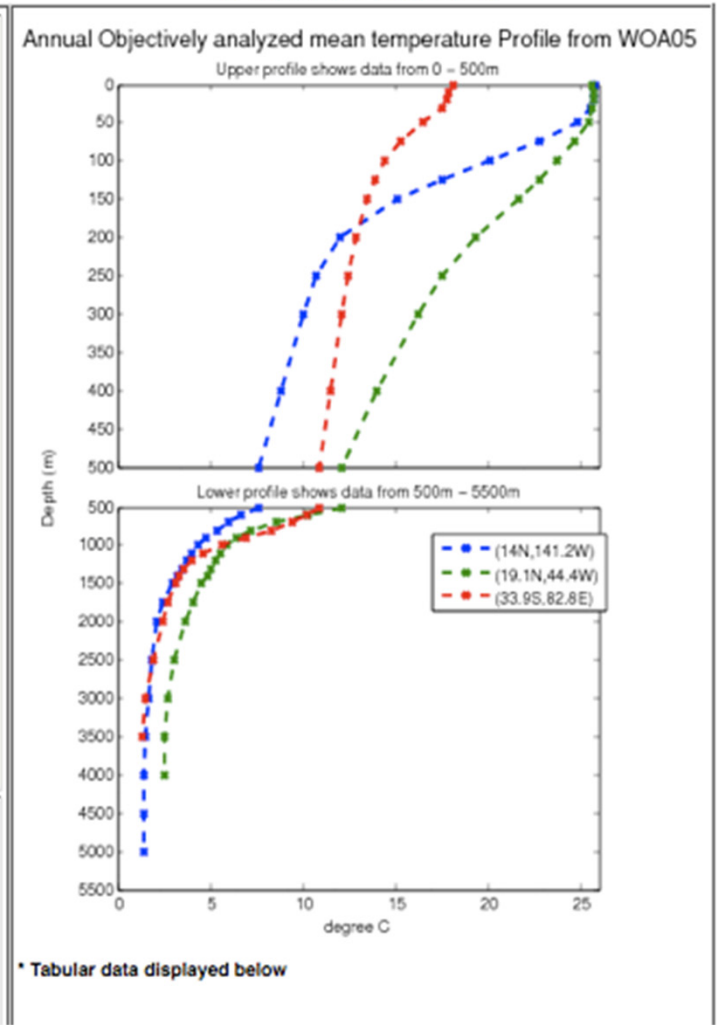
✓**There are needs and demands to enhance the Argo array with chemical-biological (O_2, PH, NO_3, Chl-a), acoustic (wind, rain, PP waves) and optical sensors.**

A Solution: Thermal Energy Powered Float

INTERACTIVE MAP



IN-WATER PROFILES



http://aquarius.jpl.nasa.gov

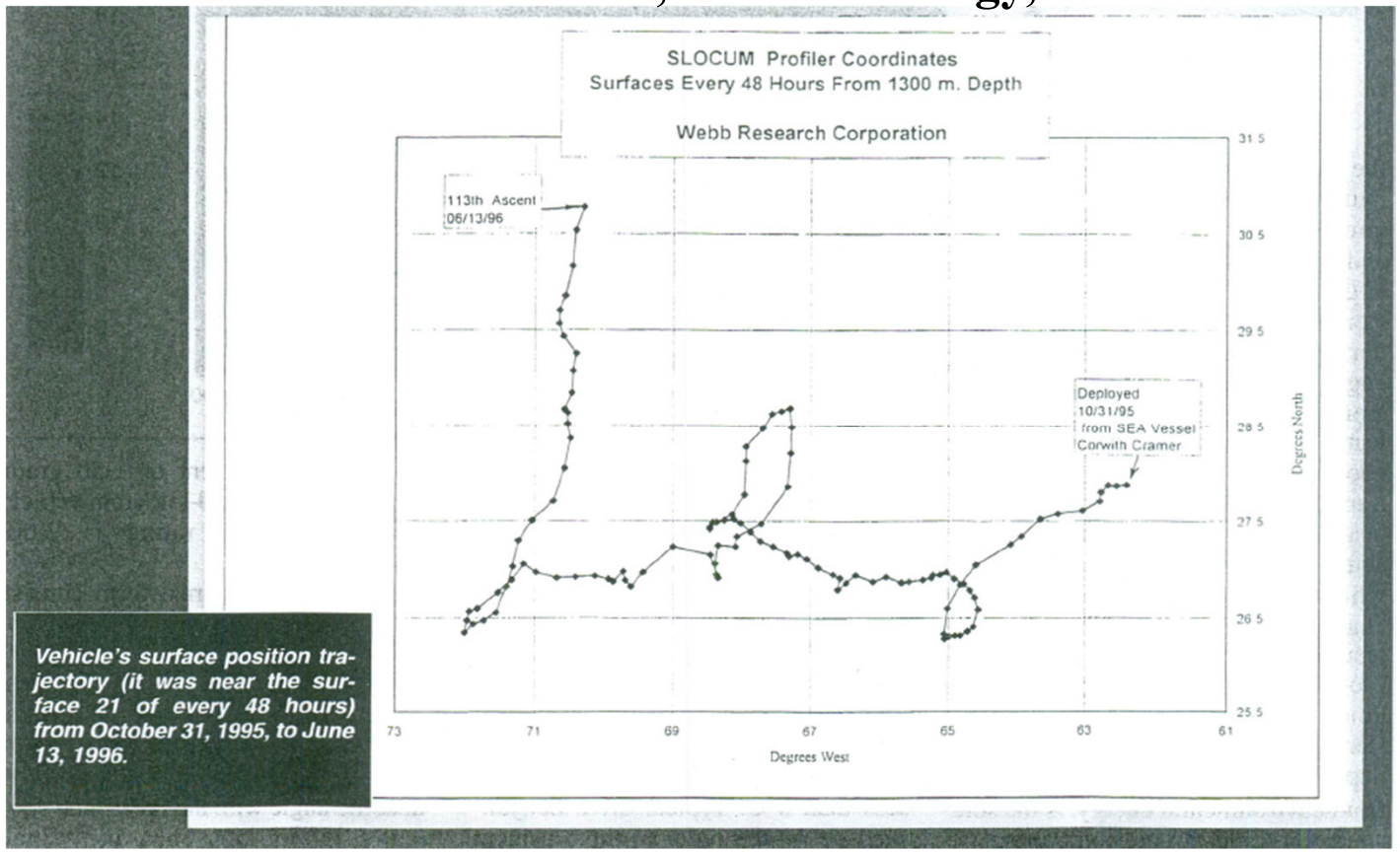
Henry Stommel, "The SLOCUM Mission", *Oceanography, pp. 22-25*, April 1989.

"The Slocum float is named after Joshua Slocum, …, They migrate vertically through the ocean by changing buoyancy, and they can be steered horizontally…surface six times a day to contact Mission Control via satellite. We have a fairly large fleet of Slocums, about 1,000. Half are devoted to a program of routine hydrographic observation, much like the meteorologists' upper air network…make soundings of temperature, salinity, oxygen, nutrients. The other half of the Slocum fleet is devoted to purely scientific purposes: special research programs carried out under the instructions of academic scientists, by contract.

First Slocum Float by Webb

"It was deployed from the Sea Education Association training vessel *Corwith Cramer on October 9, 1995, at* 27.54°N, 62.07°W in the Sargasso Sea. The unit successfully transmitted 120 consecutive temperature profiles over 240 days before failure. The exact cause of failure is unclear."

---------Paul Simonetti, Sea Technology, Feb. 1998.



Vehicle's surface position trajectory (it was near the surface 21 of every 48 hours) from October 31, 1995, to June 13, 1996.

History and Background

- ✓ 1989, Slocum Mission concept proposed by Henry Stommel
- ✓ 1991, Webb patent filed: thermal energy for buoyancy change
- ✓ 1995-1996, Webb thermal float tested and failed
- ✓ 1991-present, Webb started R&D on thermal gliders
- ✓ 2005-2007, JPL Research & Technology Development (R&TD) Fund to design and lab-test thermal-recharging (TREC) floats
- ✓ 2008, Caltech patent filed: thermal energy for power generation
- ✓ 2008-2010, Office of Naval Research (ONR) fund to develop SOLO-TREC by JPL & SIO/UCSD

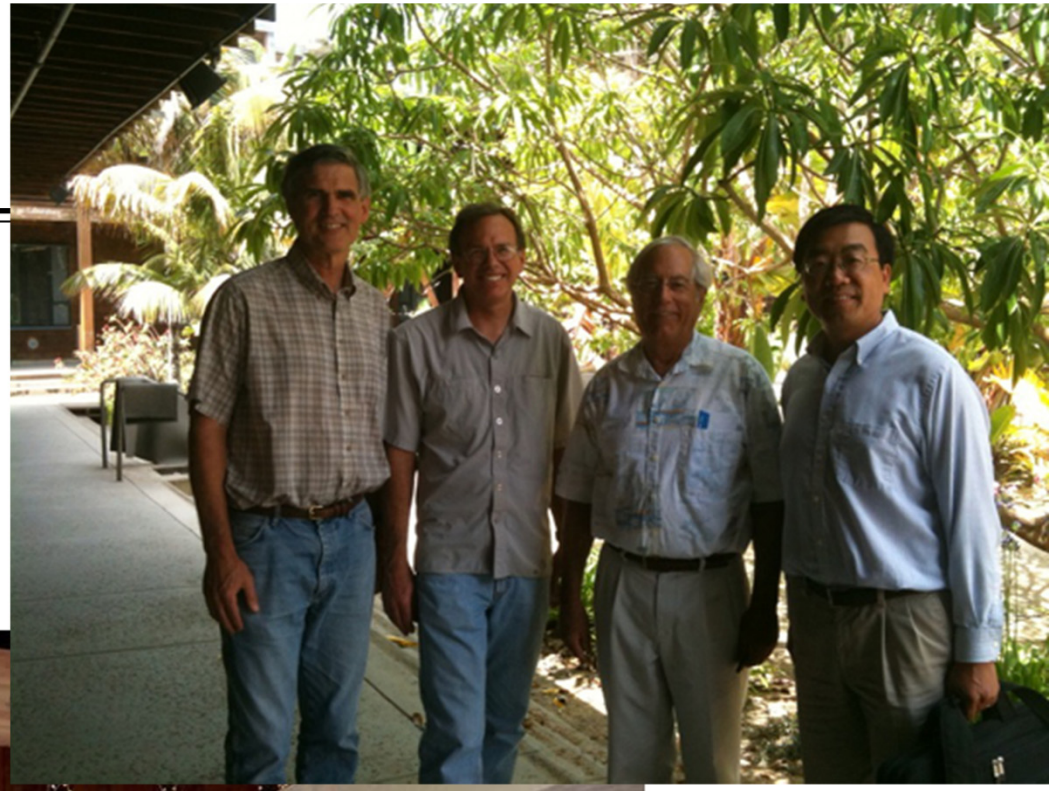
First Self-Powered Profiling Float

SOLO-TREC:

Sounding Oceanographic Lagrangrian Observer (SOLO)
+
Thermal RECharging (TREC)

SIO/UCSD Team

Russ Davis
Kyle Grindley
Jeff Sherman
Mike McClune

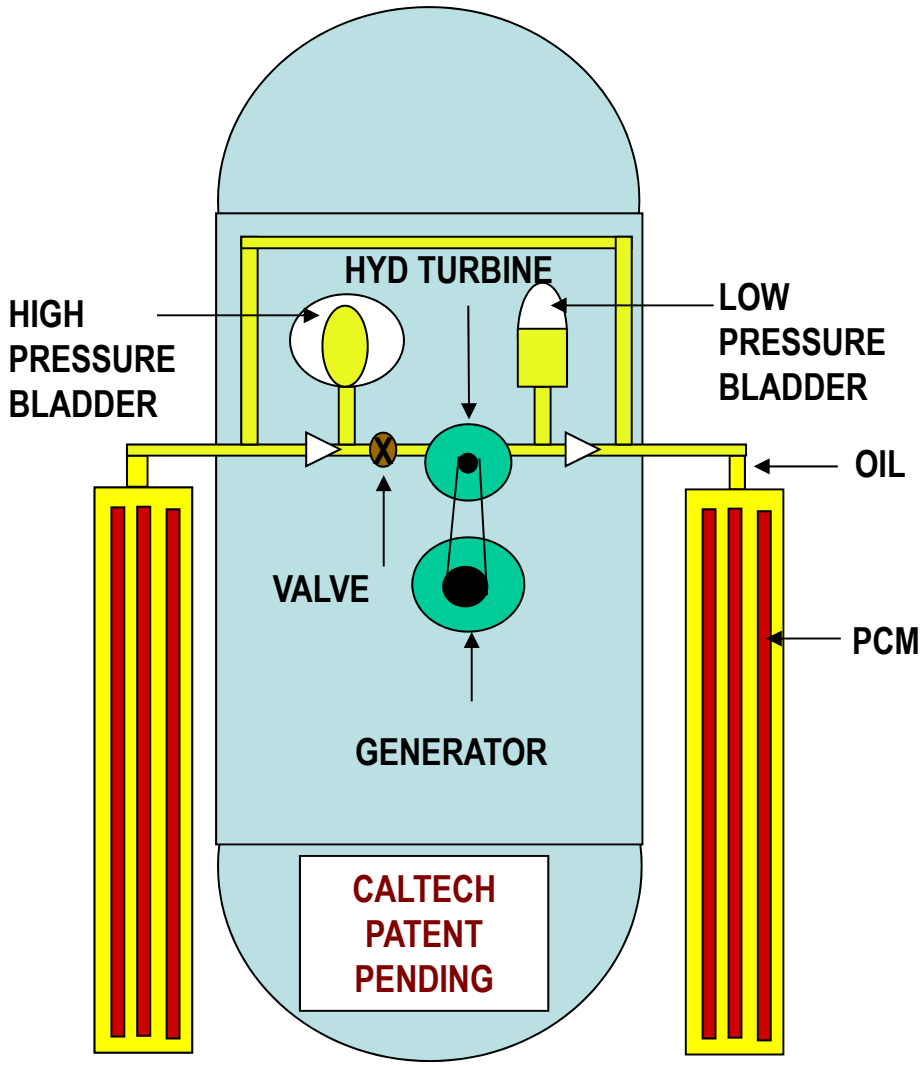


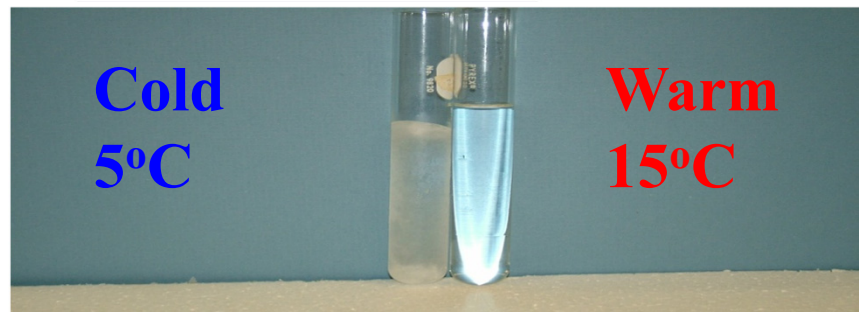
JPL Team:

Yi Chao
Jack Jones
Thomas I.Valdez
Robert Leland
Shannon Jackson
Jay Wu
Harry Aintablia
Christopher Stell

Technology Innovation

Temperature Difference → Volume Change → Pressure Difference → Battery Recharging

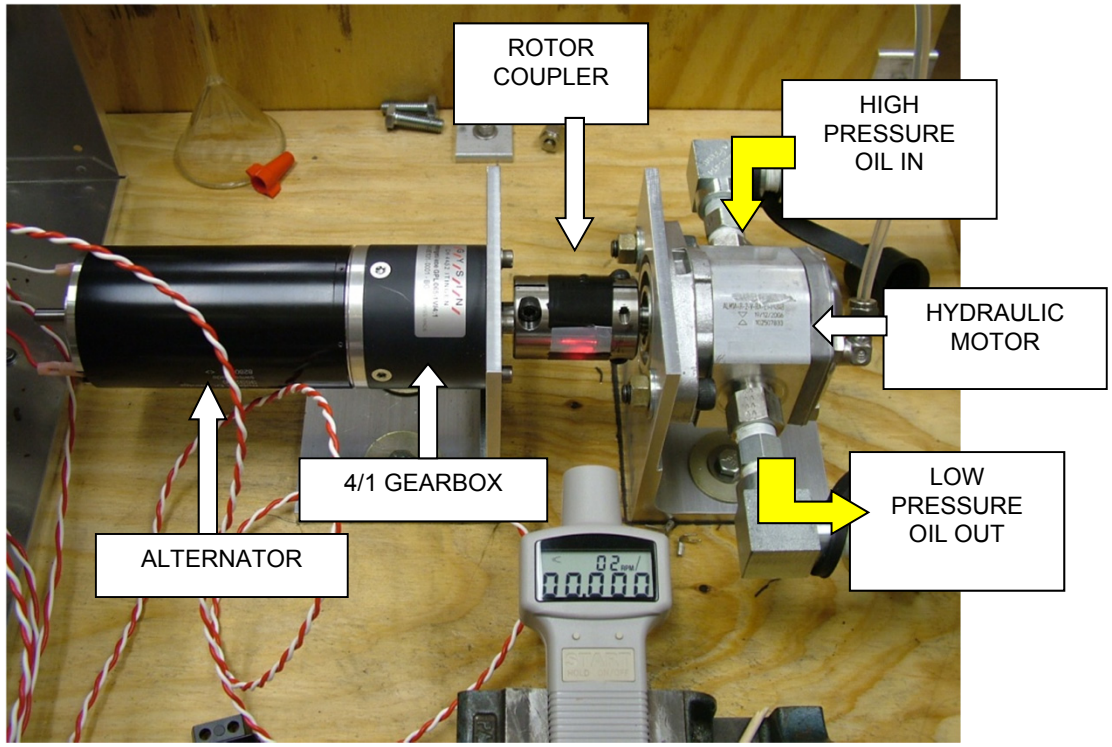




Phase Change Material (PCM)

PCMs expand/contract as they encounter warm/cold waters at surface/depth, and create a pressure differential, which will drive a hydraulic motor to generate electricity and charge battery.

ONR Hydraulic Power Generation Tests



SOLO-TREC uses a direct rotor coupling with a gearbox to an alternator. Total power efficiency is 0.45.

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Energy Storage: Battery Round Trip Efficiency Characterization

Nominal capacity and voltage	2.3 Ah, 3.3 V
Internal impedance (1kHz AC)	8 mΩ typical
Internal resistance (10A, 1s DC)	10 mΩ typical
Recommended standard charge method	3A to 3.6V CCCV, 45 min
Recommended fast charge current	10A to 3.6V CCCV, 15 min
Max continuous discharge	70A
Pulse discharge at 10 sec	120A
Cycle life at 10C discharge, 100%DOD	Over 1,000 cycles
Recommended charge and cut-off V at 25°C	3.6V to 2V
Recommended charge and cut-off V below 0°C	4.2V to 0.5V
Operating temperature range	-30°C to +60°C
Storage temperature range	-50°C to +60°C
Core cell weight	70 grams

A123 Lithium Iron Phosphate 4-Cell Pack

http://www.a123systems.com/html/products/

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A123 2.20 Ah High Power Lithium-Ion Cells

Charge Efficiency Characterization Test at 23°C

Tabulation of Results

Cell SOC Prior to 10A Charging	Charge Capacity (Ah)	Charge Energy (Wh)	Discharge Energy (Wh)	Watt-Hour Efficiency (%)
0	2.304	8.007	7.486	93.50
30	1.645	5.797	5.438	93.80
40	1.423	5.029	4.709	93.62
50	1.201	4.257	3.981	93.51
60	0.980	3.483	3.254	93.42

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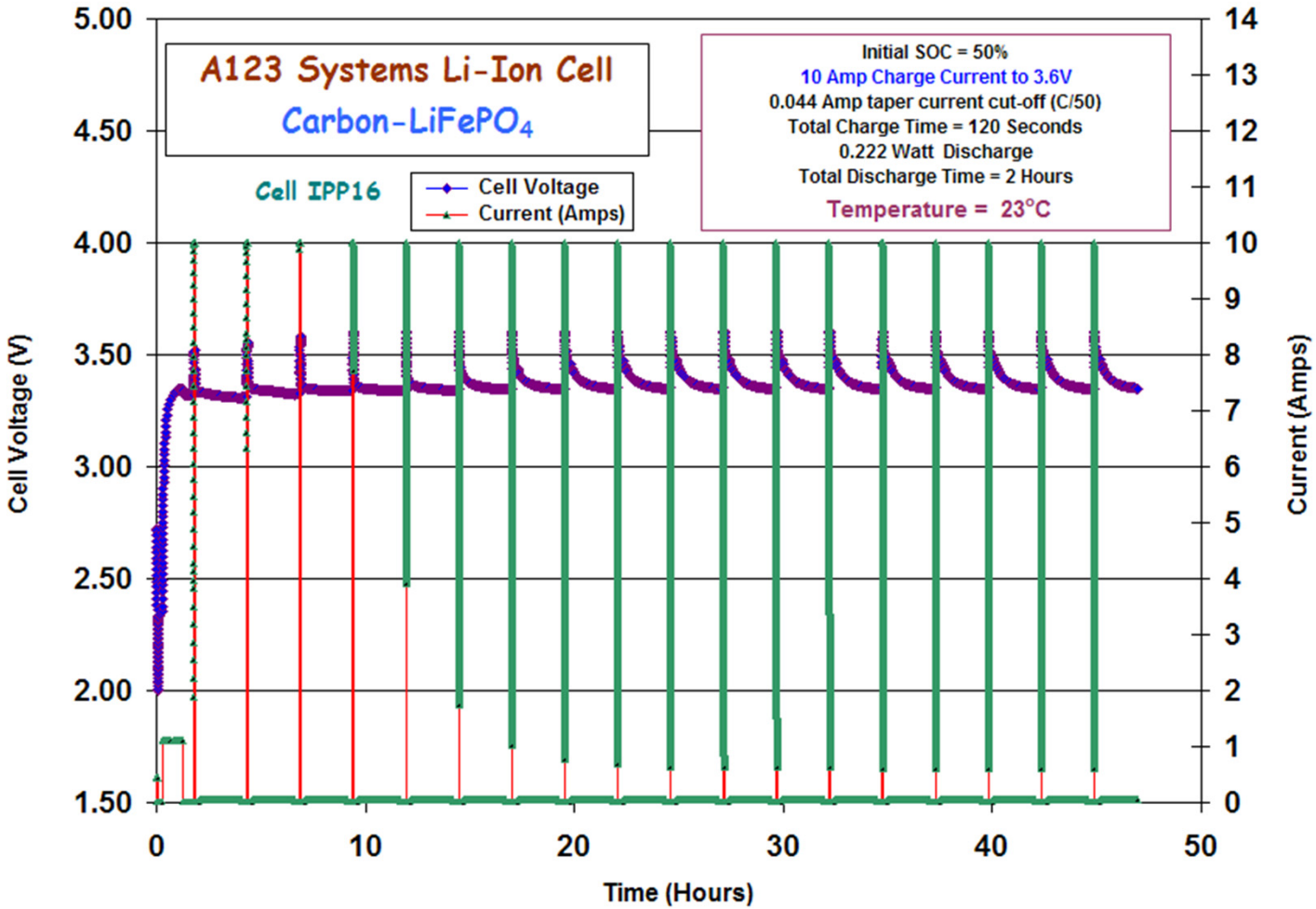
A123 2.20 Ah High Power Lithium-Ion Cells

Mission Simulation Testing at 23°C

Testing Overview



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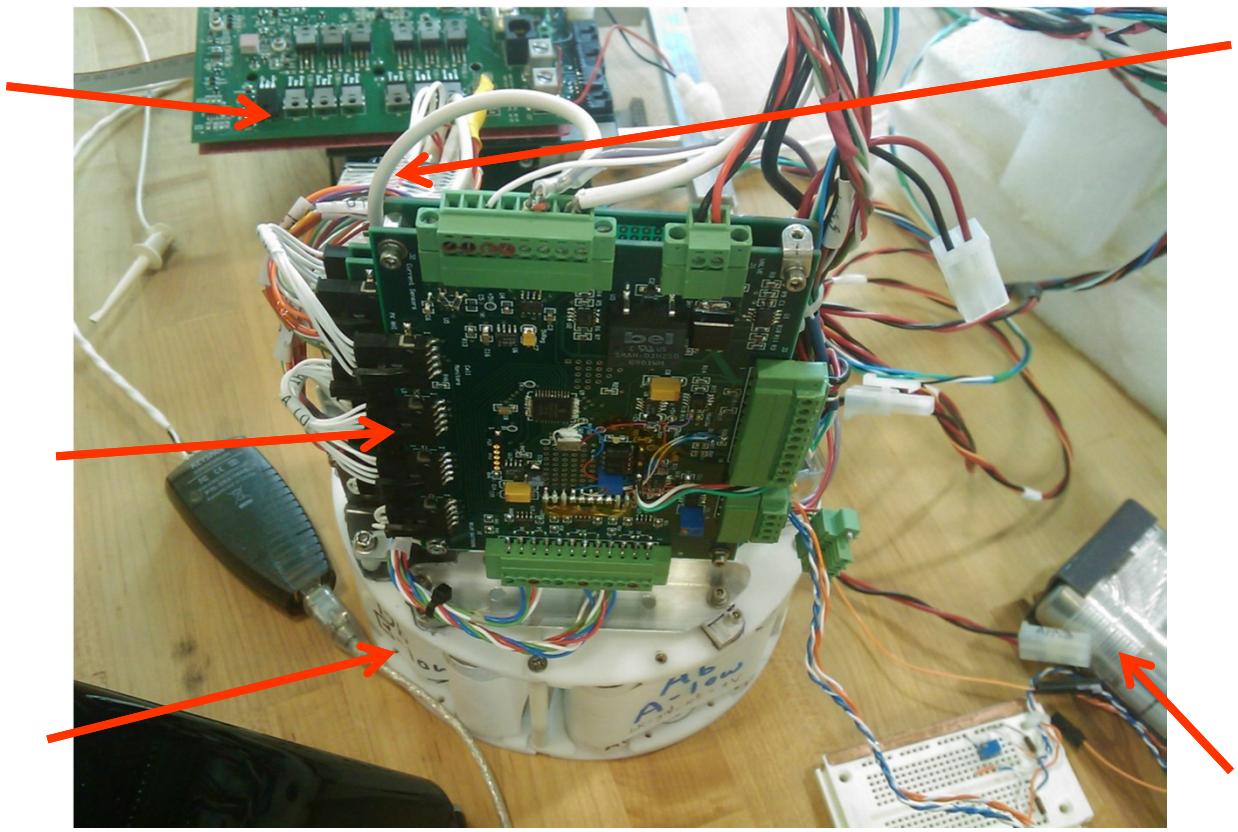
Energy Storage Control



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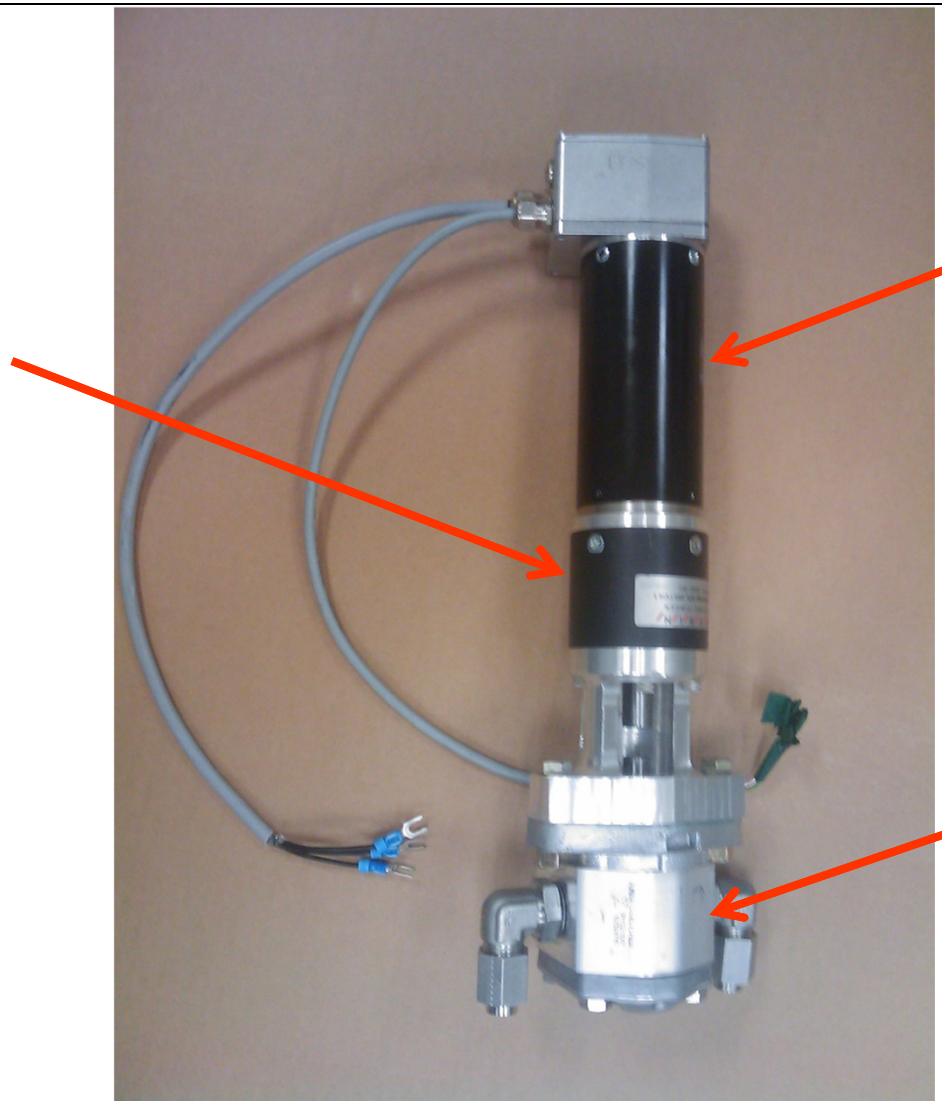
Generator Subsystem



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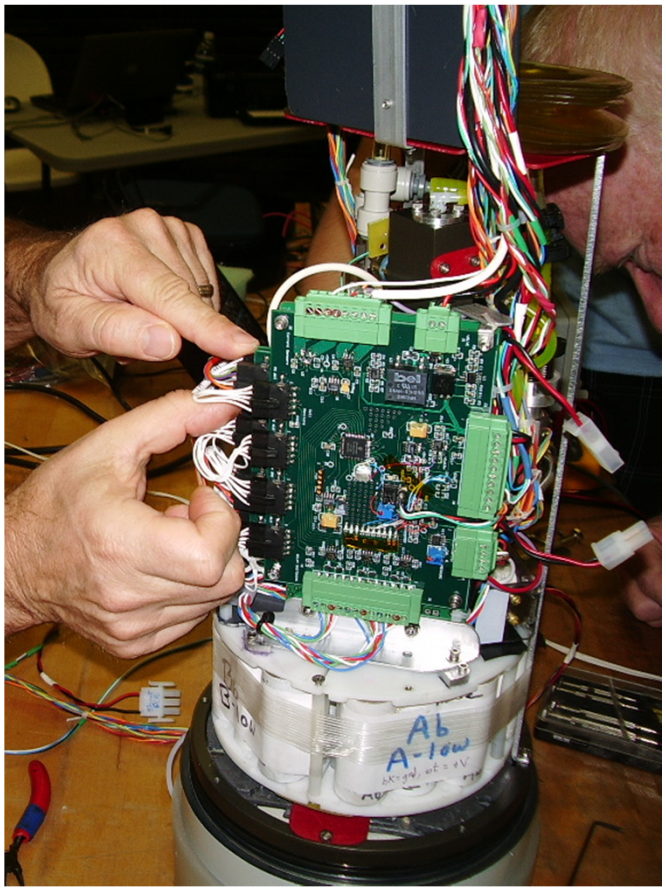
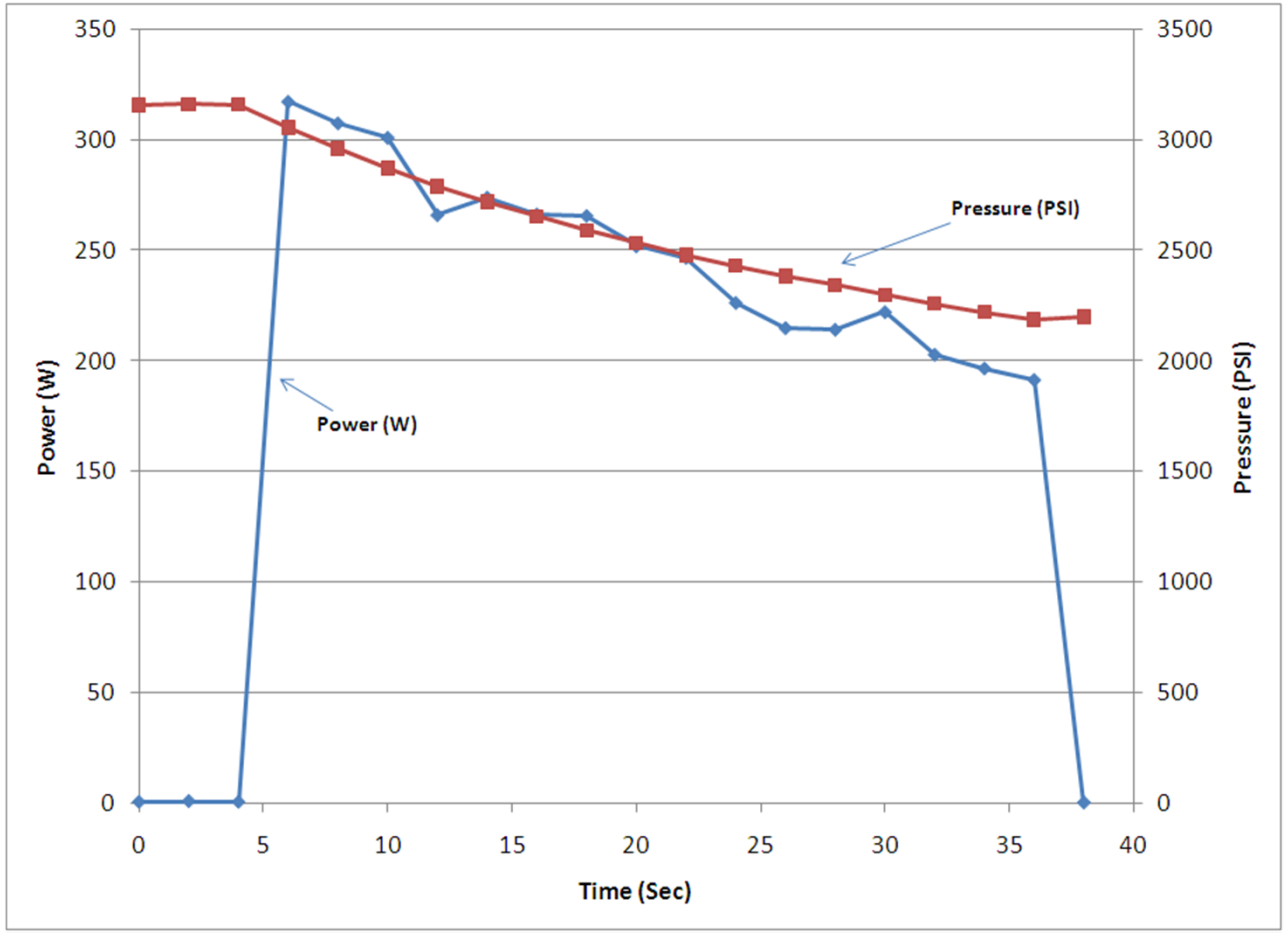
Assembly in Hawaii
Before deployment
November 2009



Generation Cycle Performance



- Max power generated: > 300 Watts
- Up to 2.2 Watt-hours generated per cycle

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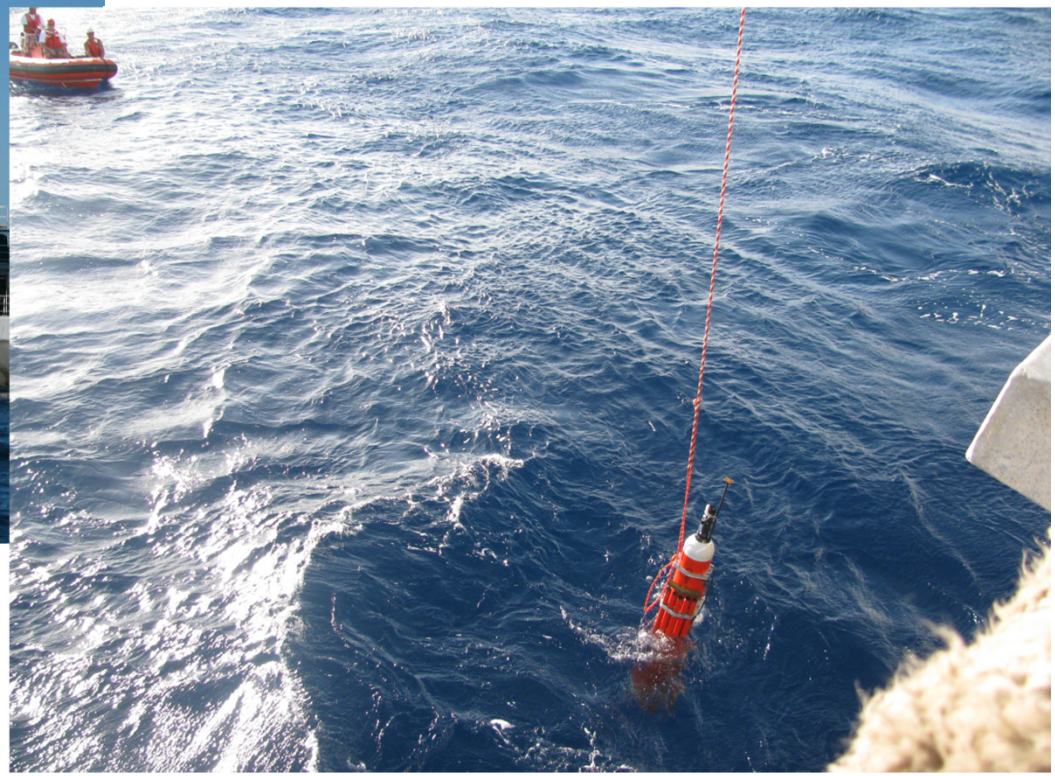
Field Deployment



<u>November 29, 2009</u>: Deployment from Kilo Moana

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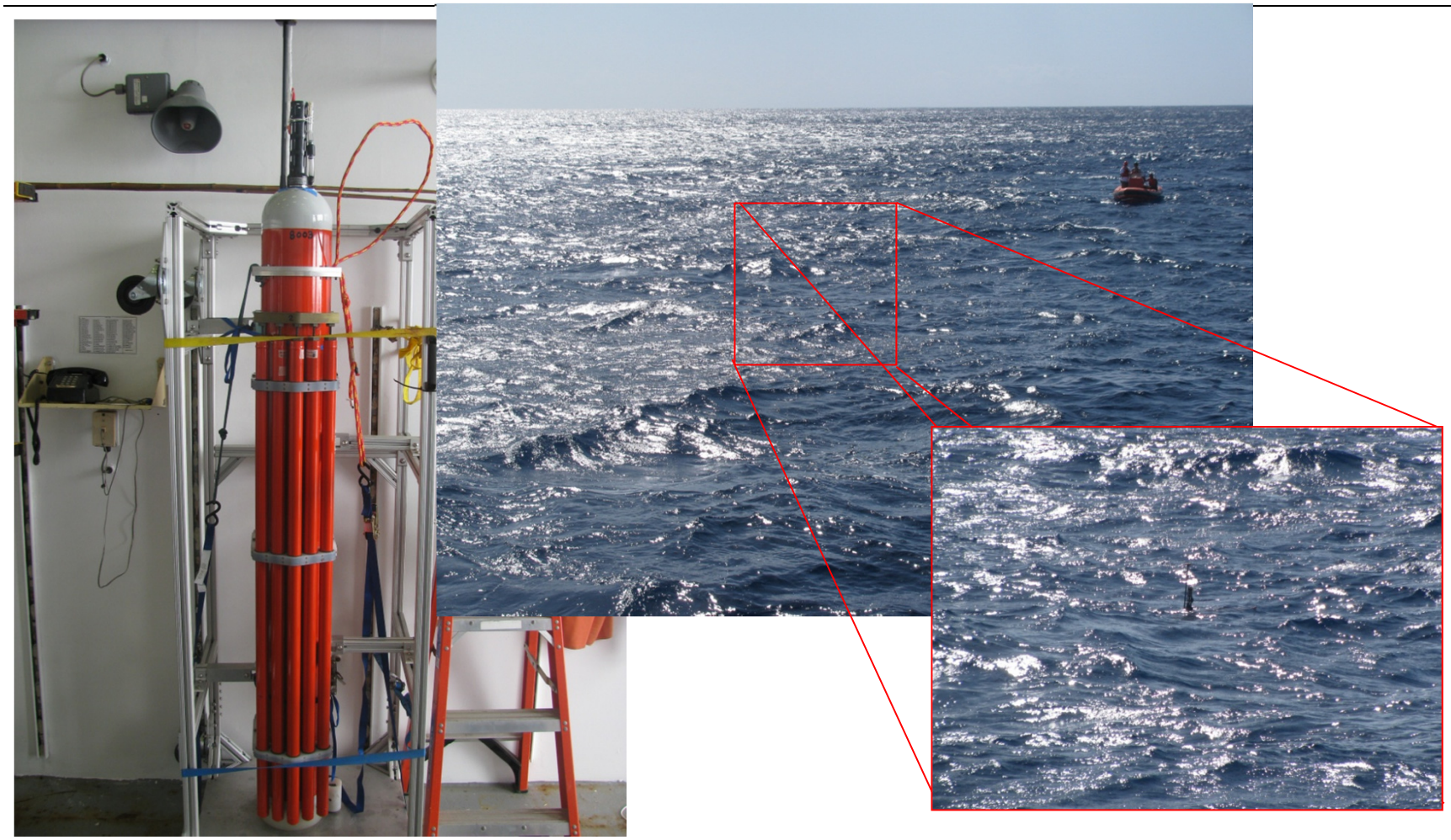
Float Deployment



First Surfacing on November 30, 2009

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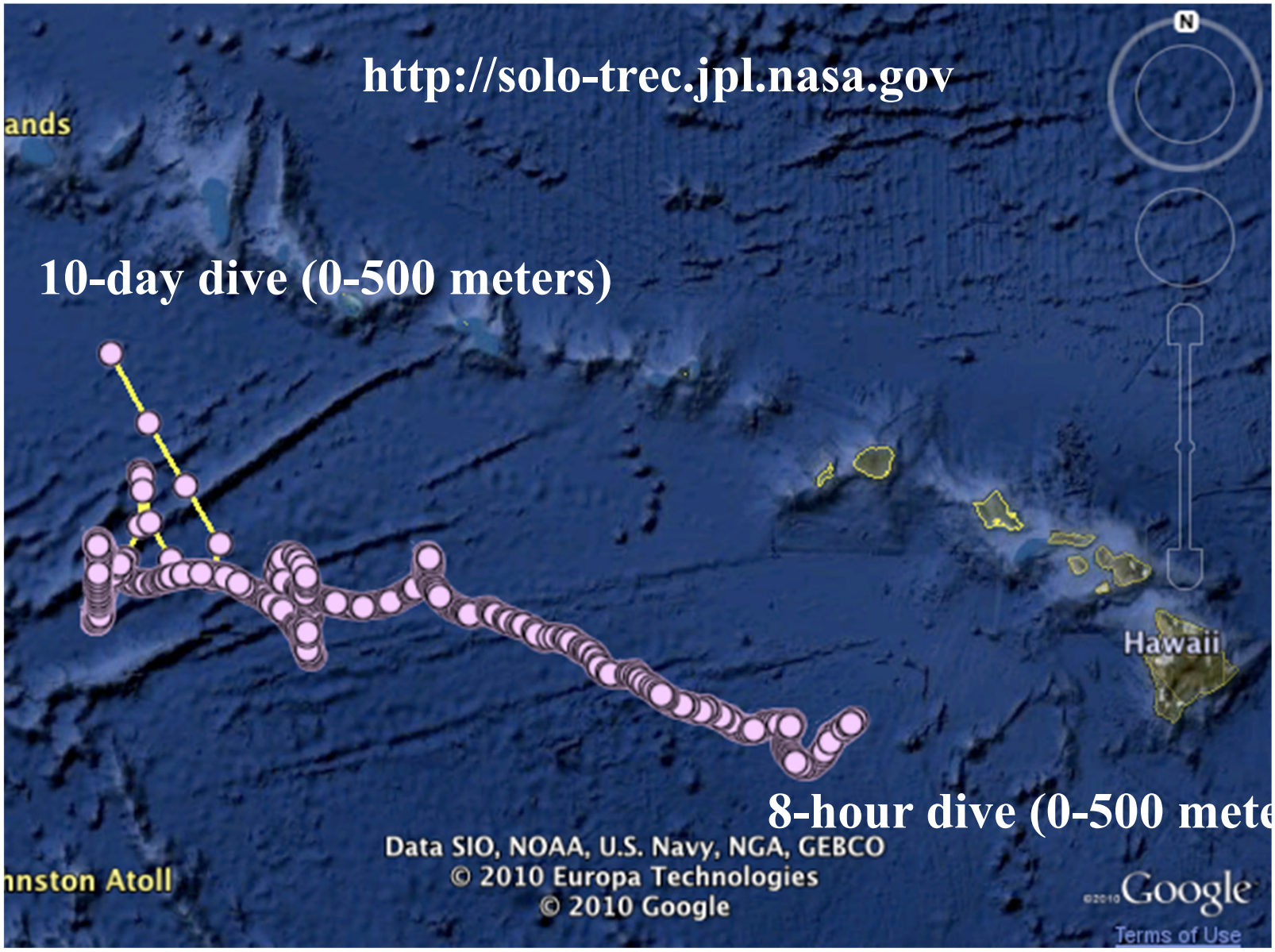
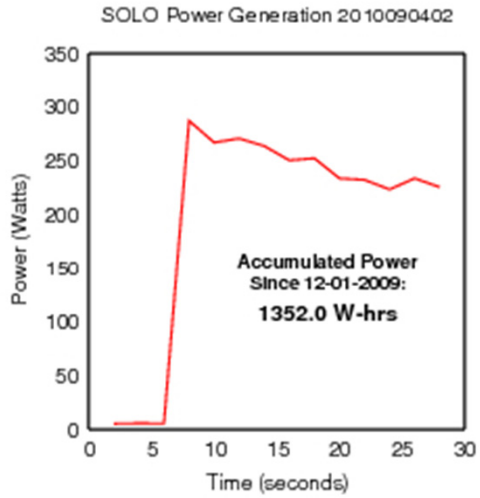
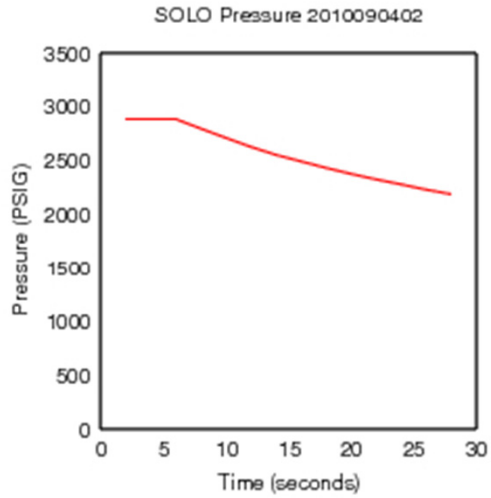
SOLO-TREC 1-Yr Test: 12/01/2009 – present



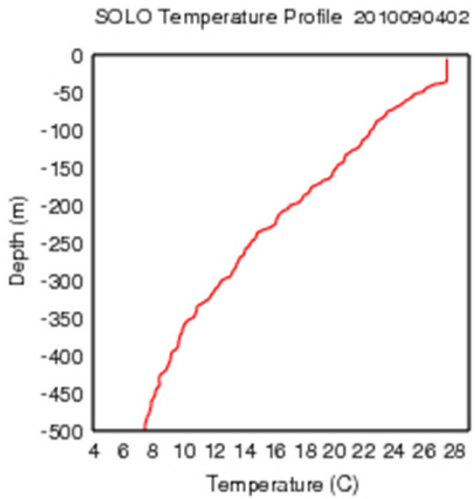
SOLO-TREC Results

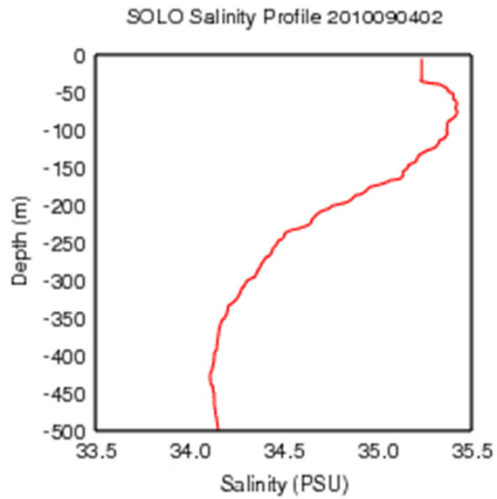
Engineering Data





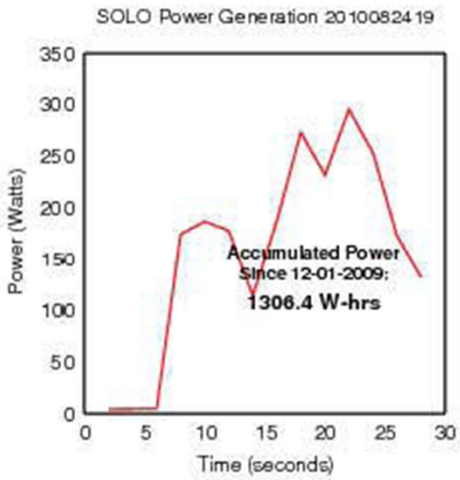
Science Data



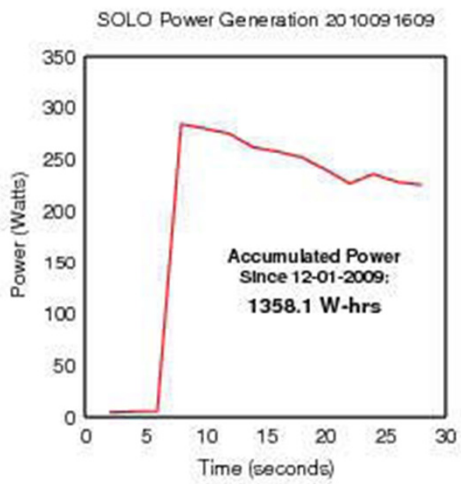


SOLO-TREC Thermal Profiling Float: Charging Issues

- On October 18th, 2010, after 826 dives, the system underwent a charge anomaly
- The voltage of the battery pack being charged was low
  - A low battery pack voltage will place a high torque load on the motor
  - The resulting charge profile is erratic and thus the batteries do not charge efficiently
- Correcting the charge pack voltage allows for system recovery and efficient energy storage
- Battery pack voltages controlled by weak cells in the pack
- Charge balancing to be implemented in future designs to minimize cell divergence and maintain battery pack voltage

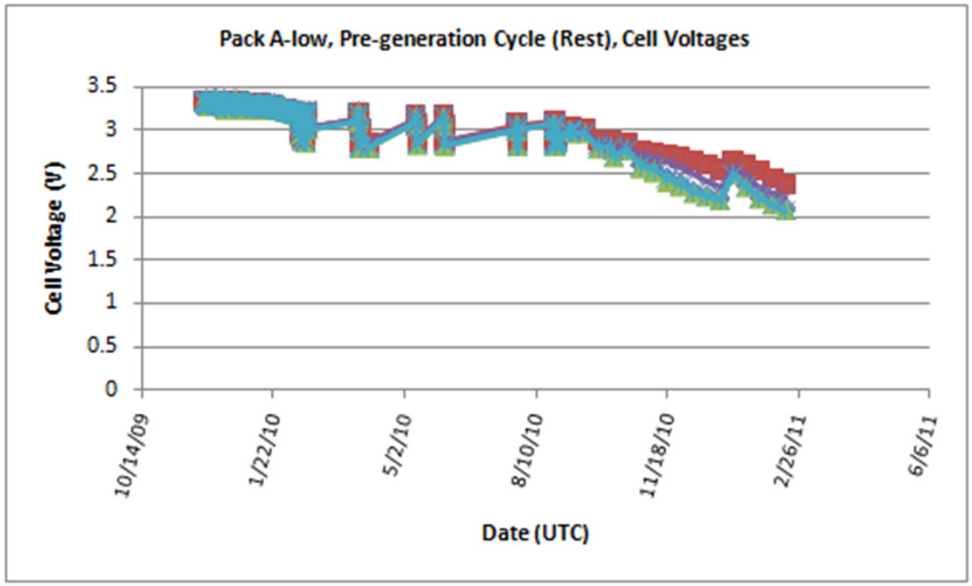


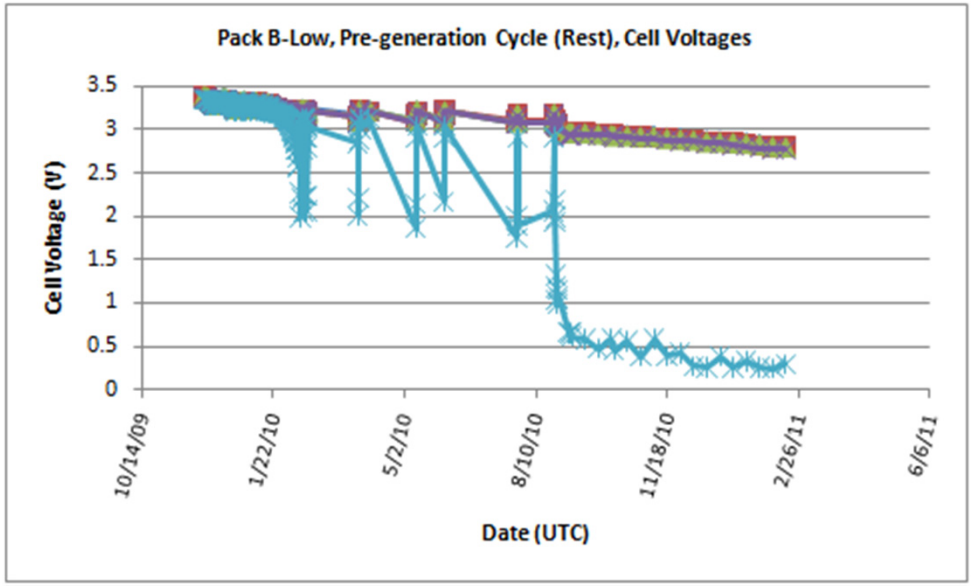
Dive 882, Charge Anomaly



Dive 919, Typical Charge Profile

Battery Pack Performance





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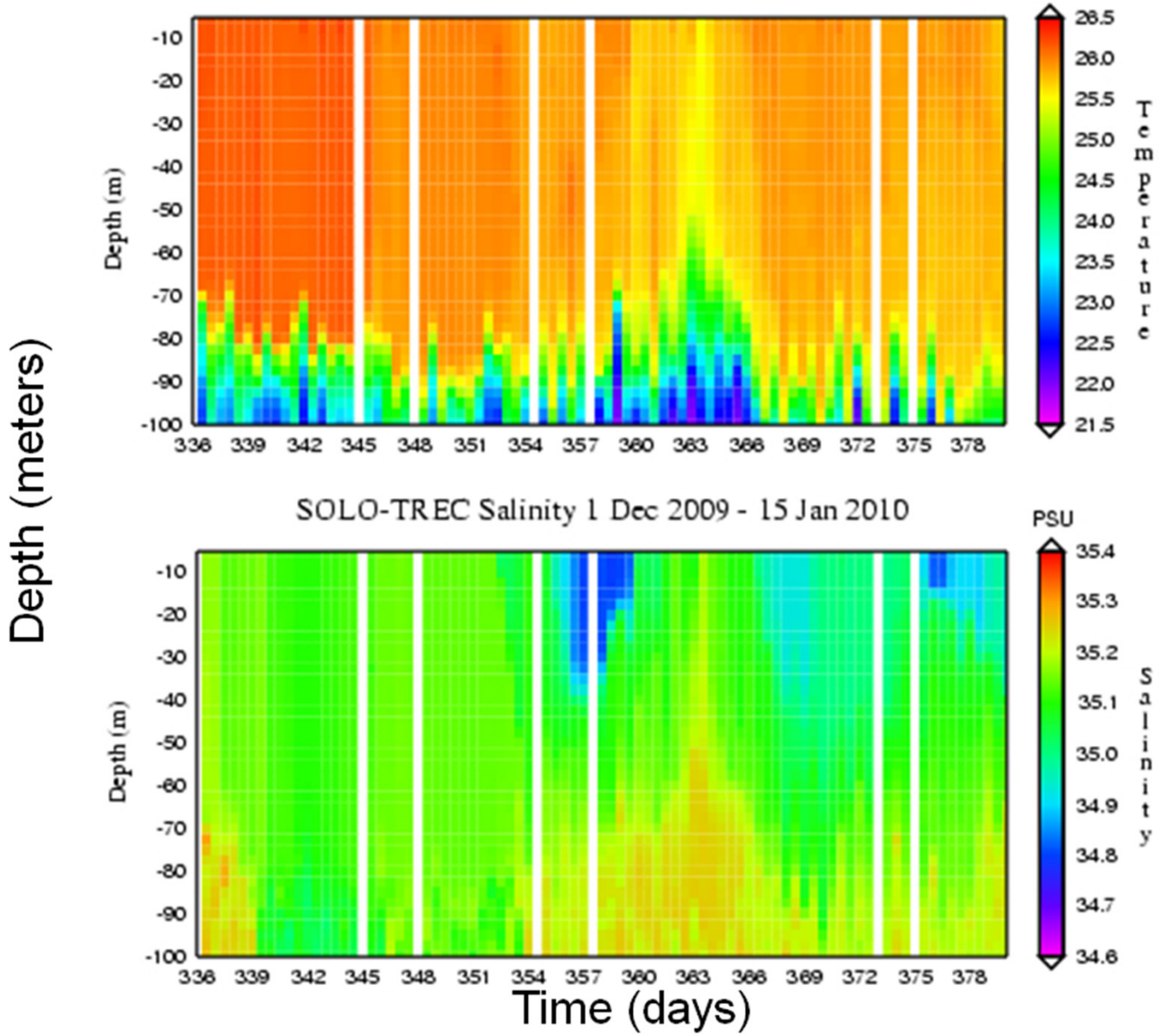
SOLO-TREC Data



SOLO-TREC (not quite Slocum yet) Mission

Accomplishments:

1st self-powered UUV

Exceed 1-year endurance ocean test (vs. original 3-month)

Approaching 1000 dives between surface to 500 meters

Generate 1.6 Watt-hour or 6100 Joules per dive, 110% sufficient to provide buoyancy, power CTD, GPS, and communication sensors

Future I: Sustain and Enhanced Argo Array

- **Enhanced Argo array**
  - ✓Six-hourly surfacing (as envisioned by Stommel to resolve diurnal cycle)
- **Argo+ interdisciplinary science**
  - ✓Additional payloads such as chemical/biological, acoustic, and optical sensors to link physical oceanography with marine geology (e.g., seafloor mapping) and chemical/biological/fishery oceanography

Summary

- SOLO-TREC has executed over 1000 generation cycles as of January 27, 2011.
- Battery charge and discharge response was as expected at about 6100 Joules/dive for the first nine months with an average of about 2920 PSI pressure generated by the PCM.
- One cell in the 20-cell battery pack was not properly matched to the other dells and resulted in a short on September 7, 2010. SOLO-TREC has been diving once every ten days since then with only intermittent charging.
- SOLO-TREC recovered

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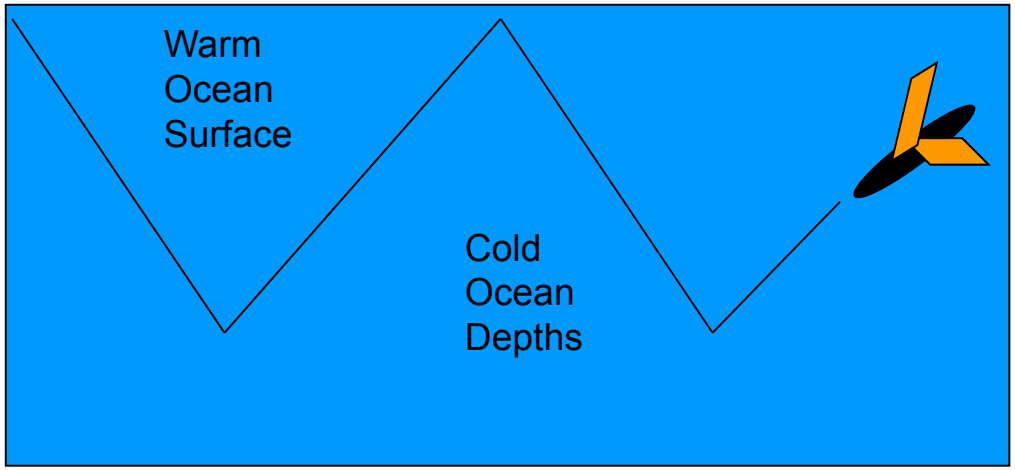
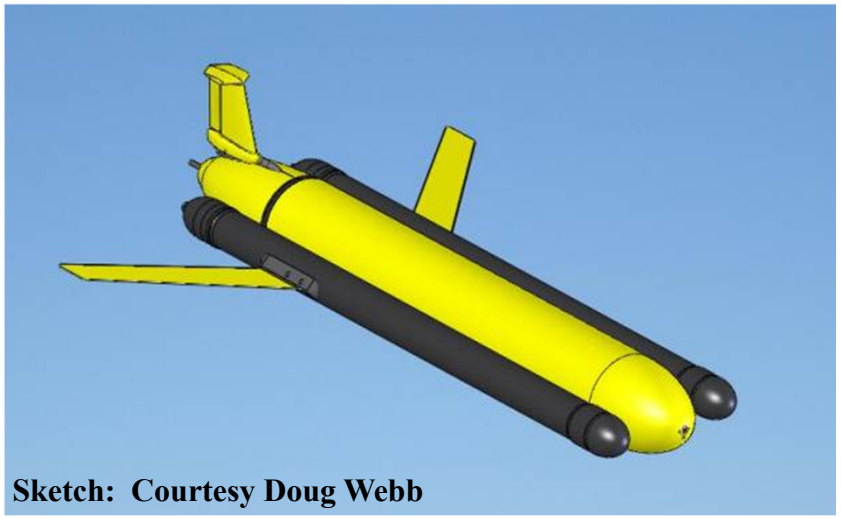
Slocum-TREC Glider
-Future Plans-




Sketch: Courtesy Doug Webb

- JPL will be teaming with Teledyne-Webb-Research to produce the first thermal glider that uses PCM for direct buoyancy control (not electronic pumps) and to produce all other required electricity.
- We expect to increase electrical production total efficiency from 0.45 to at least 0.55.
- Design is expected in 2011, with fabrication in 2012, and deployment by Rutgers University in late 2012.
- The goal of the ocean endurance test will be to perform continuous dives for a period of at least one year

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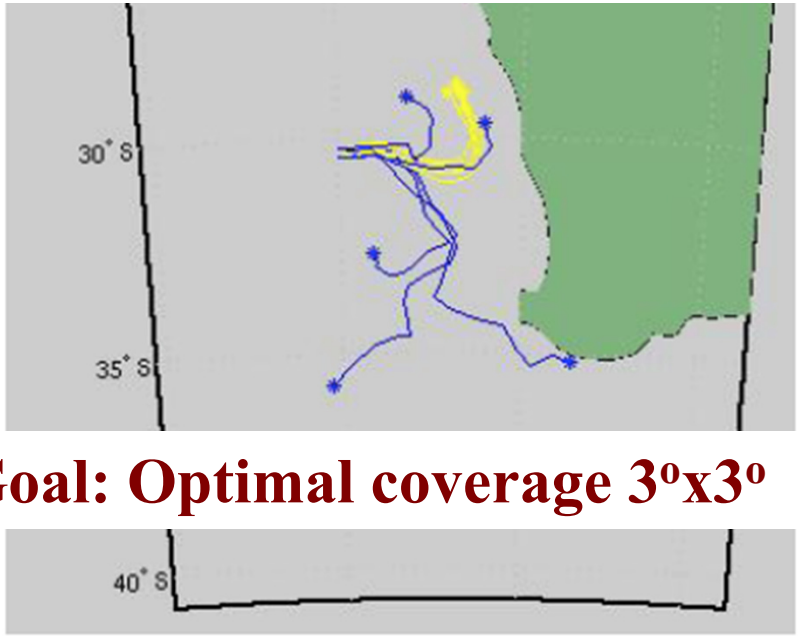
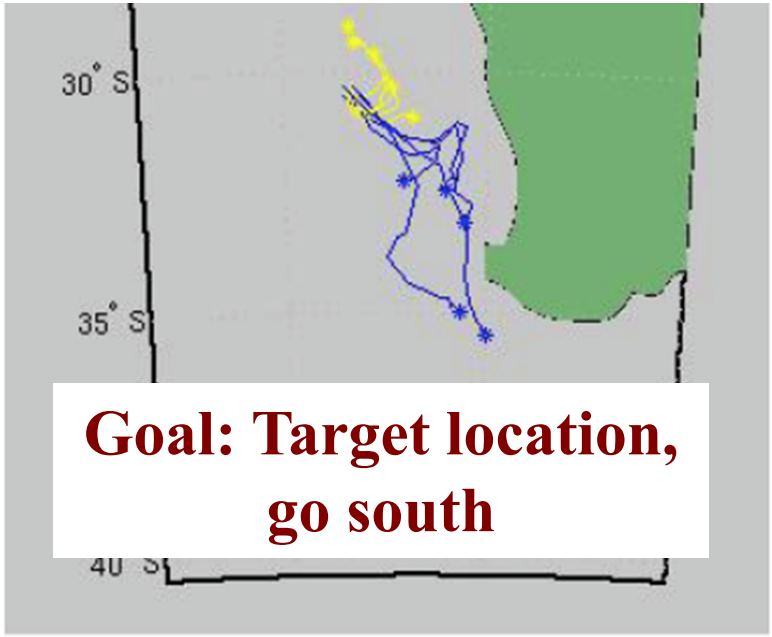
Stommel's Slocum Mission Control Center

"flat screen…can be zoomed to any time or space scale...swimming through the ocean, much like being aboard a fictional space ship. We can observe the data in a vast variety of ways. We can switch from observations to predictions of the great numerical models; we can visualize the interplay and balances between various terms in the dynamical equations as computed from data or models...imagine what the sense of excitement must have been in the attic control center when they started to control the navigation…rather like that in the spacecraft control room when Voyager 2 rendezvoused with the moon of Neptune in August 1989."



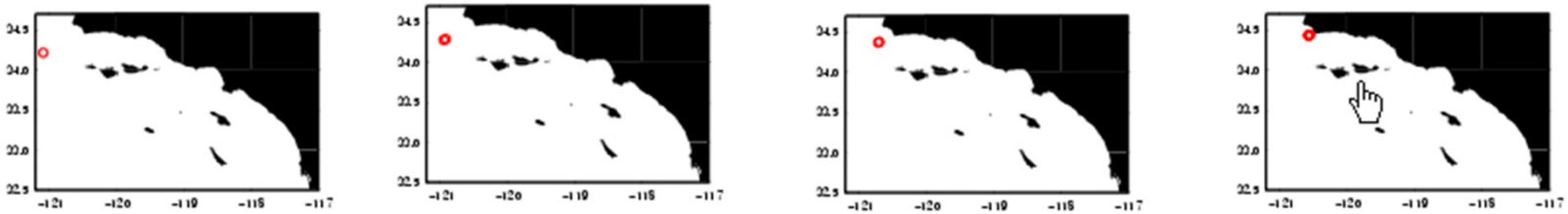
Goal: Optimal coverage 3°x3°

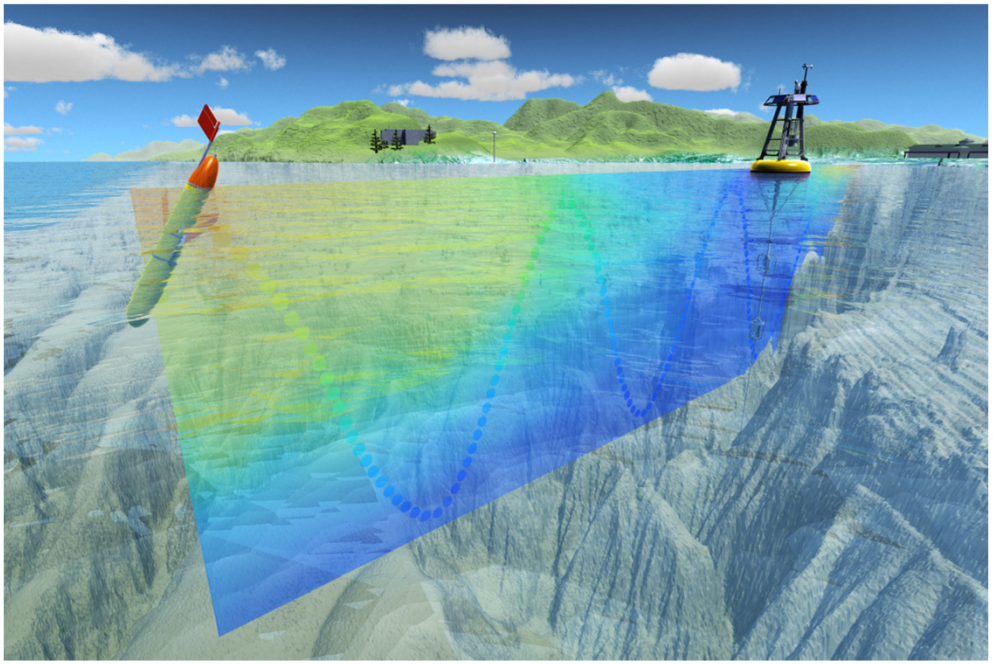


Goal: Target location, go south

Routine Glider Data to enable Real-Time Data Assimilation and Forecasting

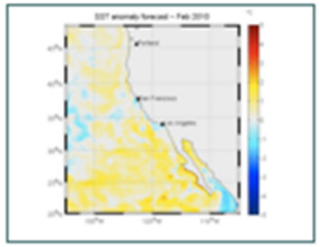
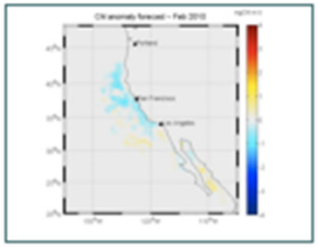
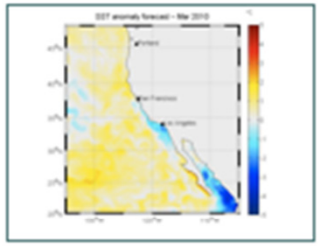
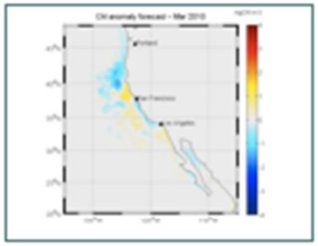
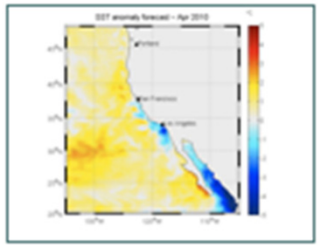
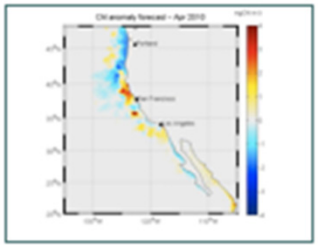
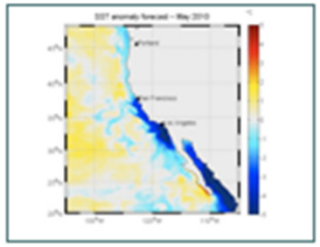
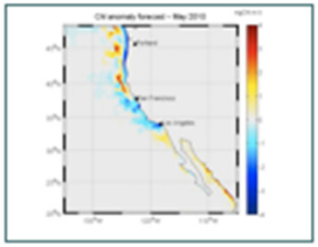
2/15 2/16 2/17 2/18



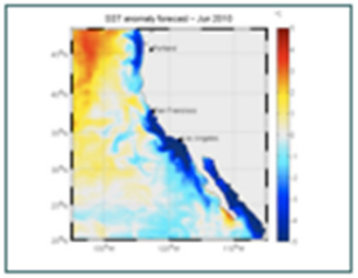


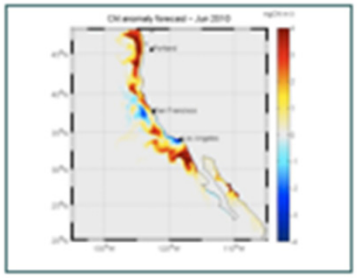
http://ourocean.jpl.nasa.gov/SCB

9-Month Global Forecast System (GFS) to Regional Upwelling/Ecosystem Forecast

Current Forecast	SST (°C)	Chlorophyll (mg m-3)
February 2010 top		
March 2010 top		
April 2010 top		
May 2010 top		

June 2010 top





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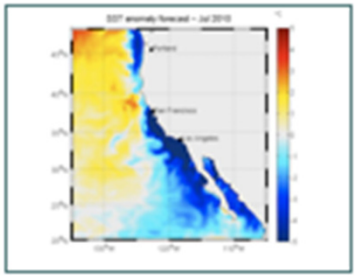

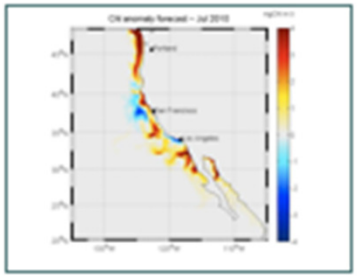

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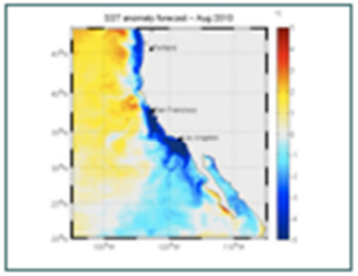

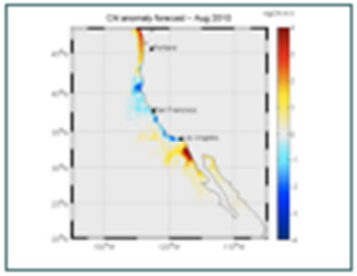

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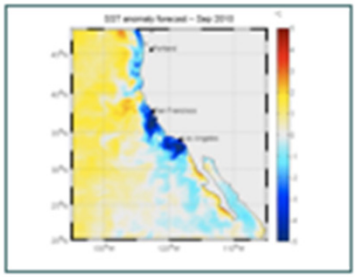

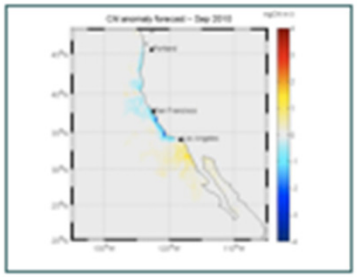

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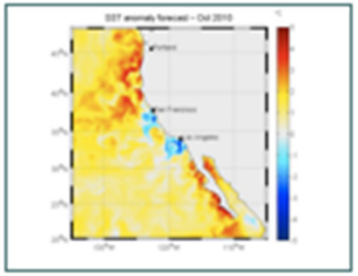
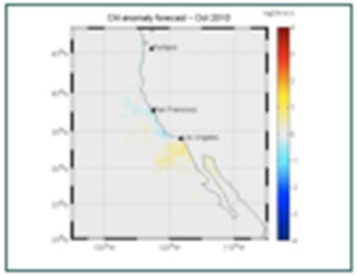
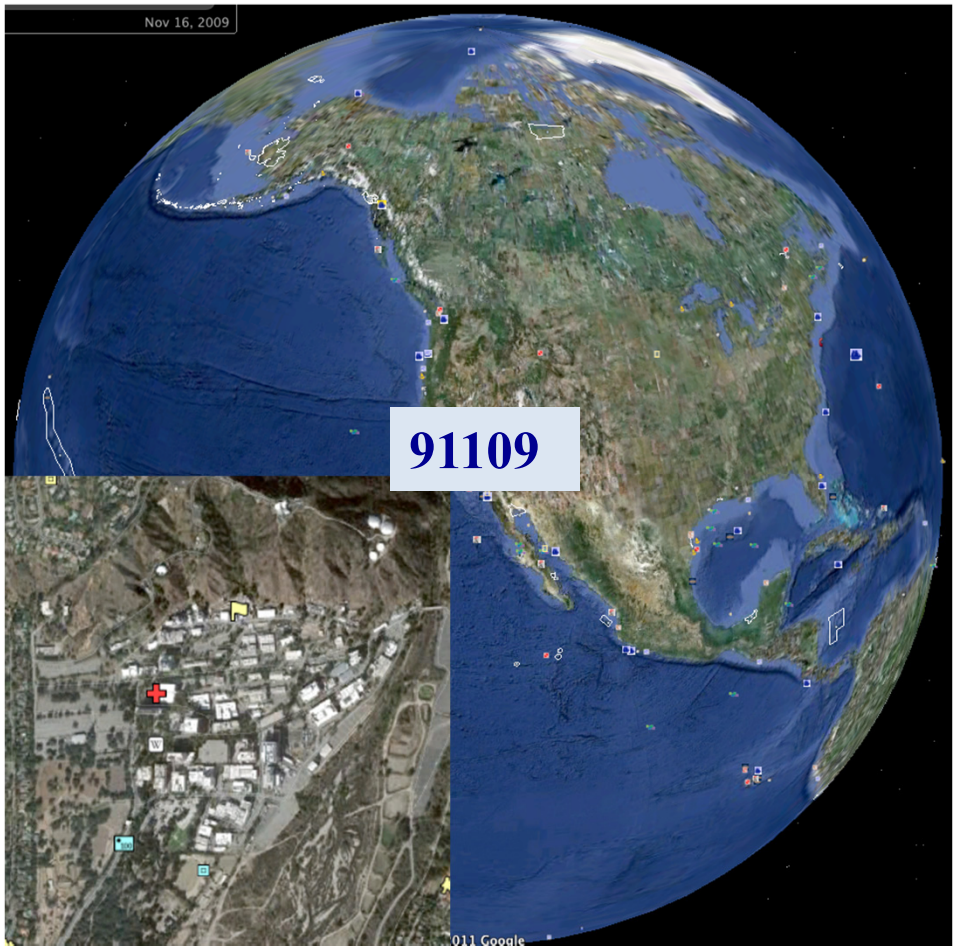
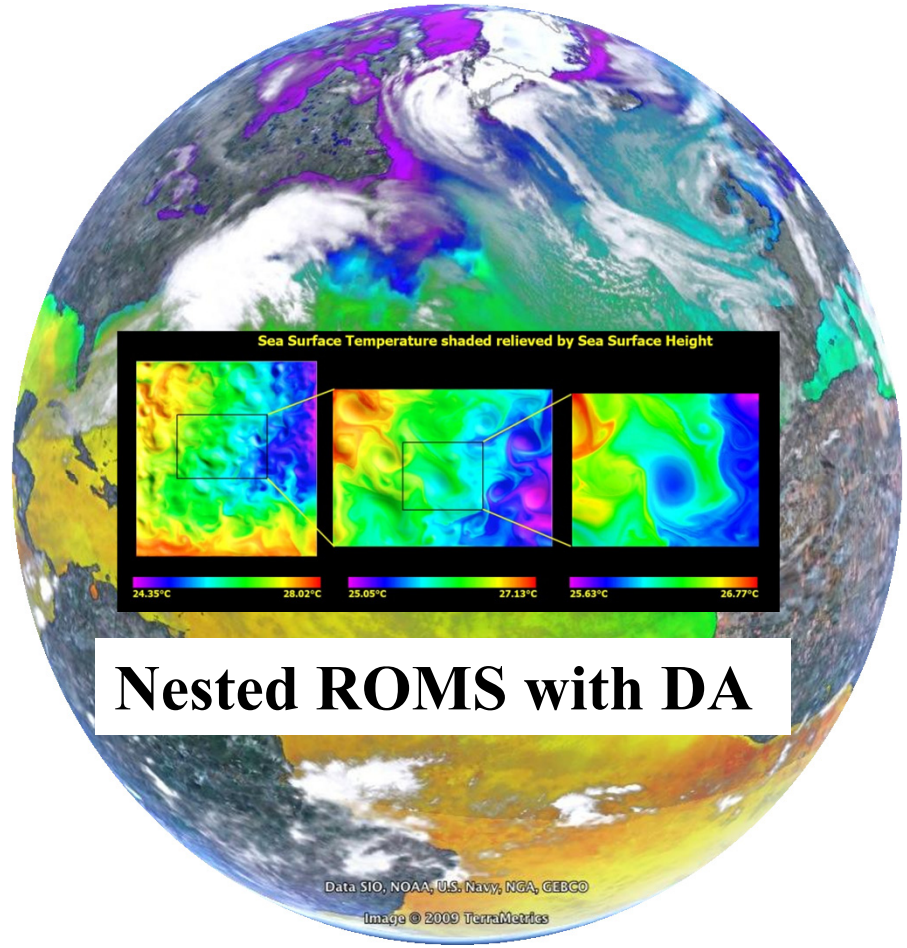




Future III: Interactive 3D Ocean + Time

Anytime & Anywhere in the Changing Ocean





2-order of magnitudes more challenging than OOI and Google Earth!

Acknowledgements

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More Info: http://ourocean.jpl.nasa.gov

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