The Environmental Sample Processor: Running an Underwater Laboratory on a Fixed Energy Budget

Brent Roman

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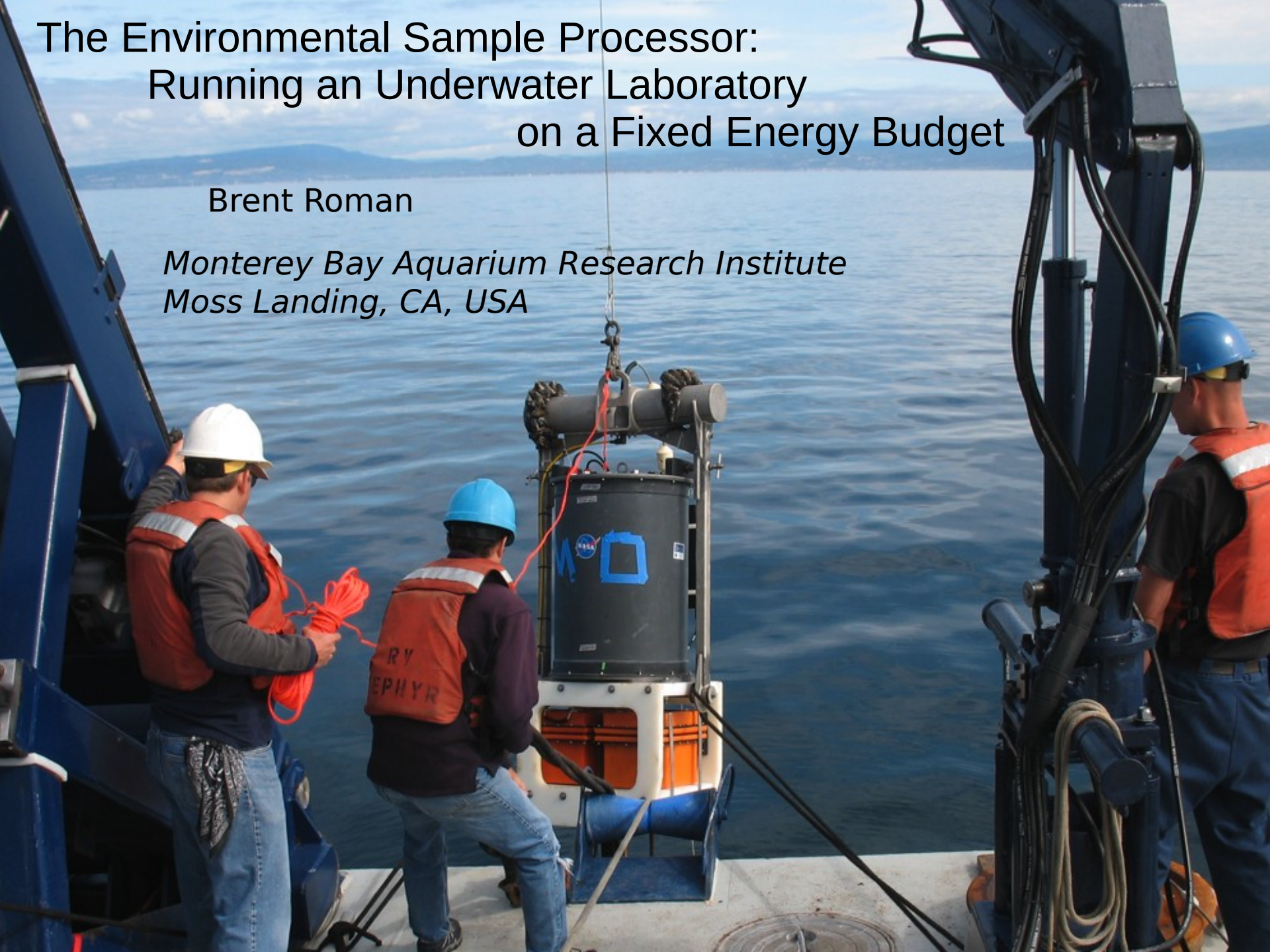
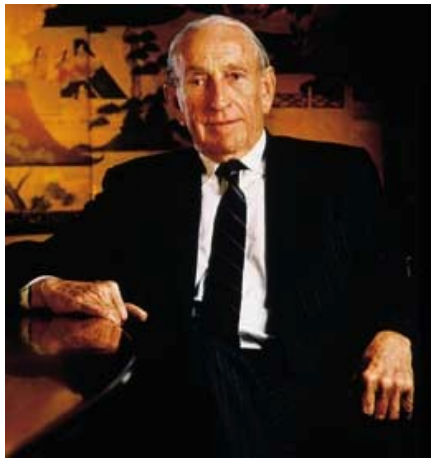
Moss Landing, CA, USA



The Monterey Bay Aquarium and MBARI



David Packard (1912-1996)

Monterey Bay Aquarium

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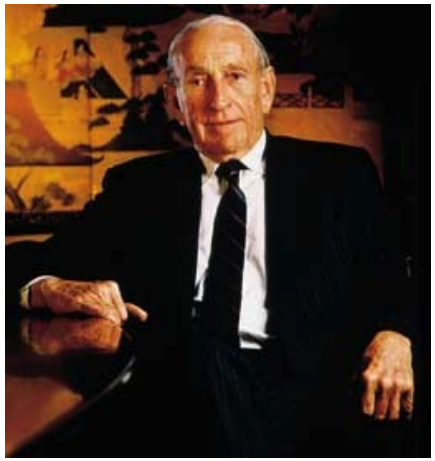

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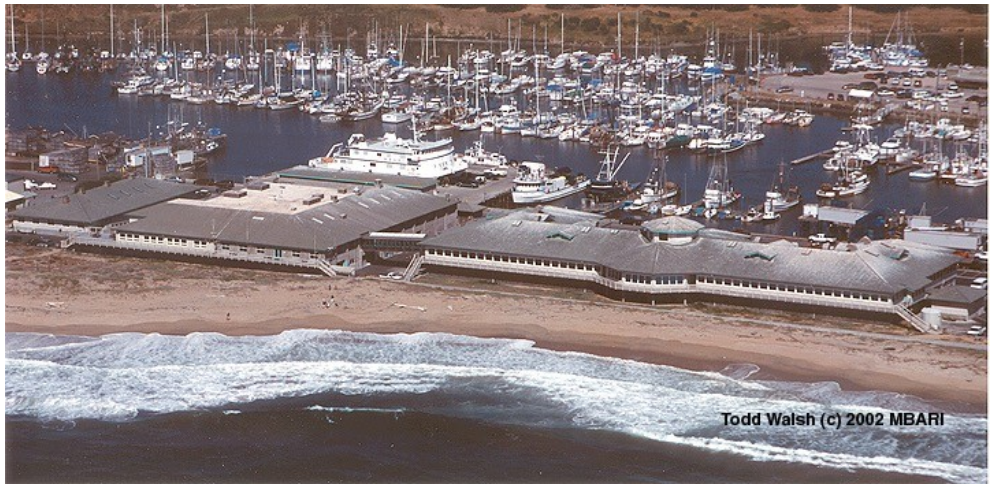
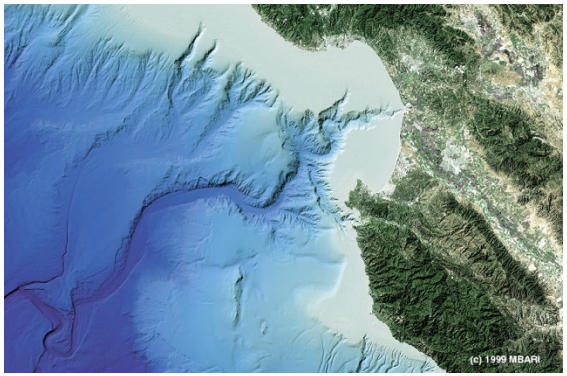


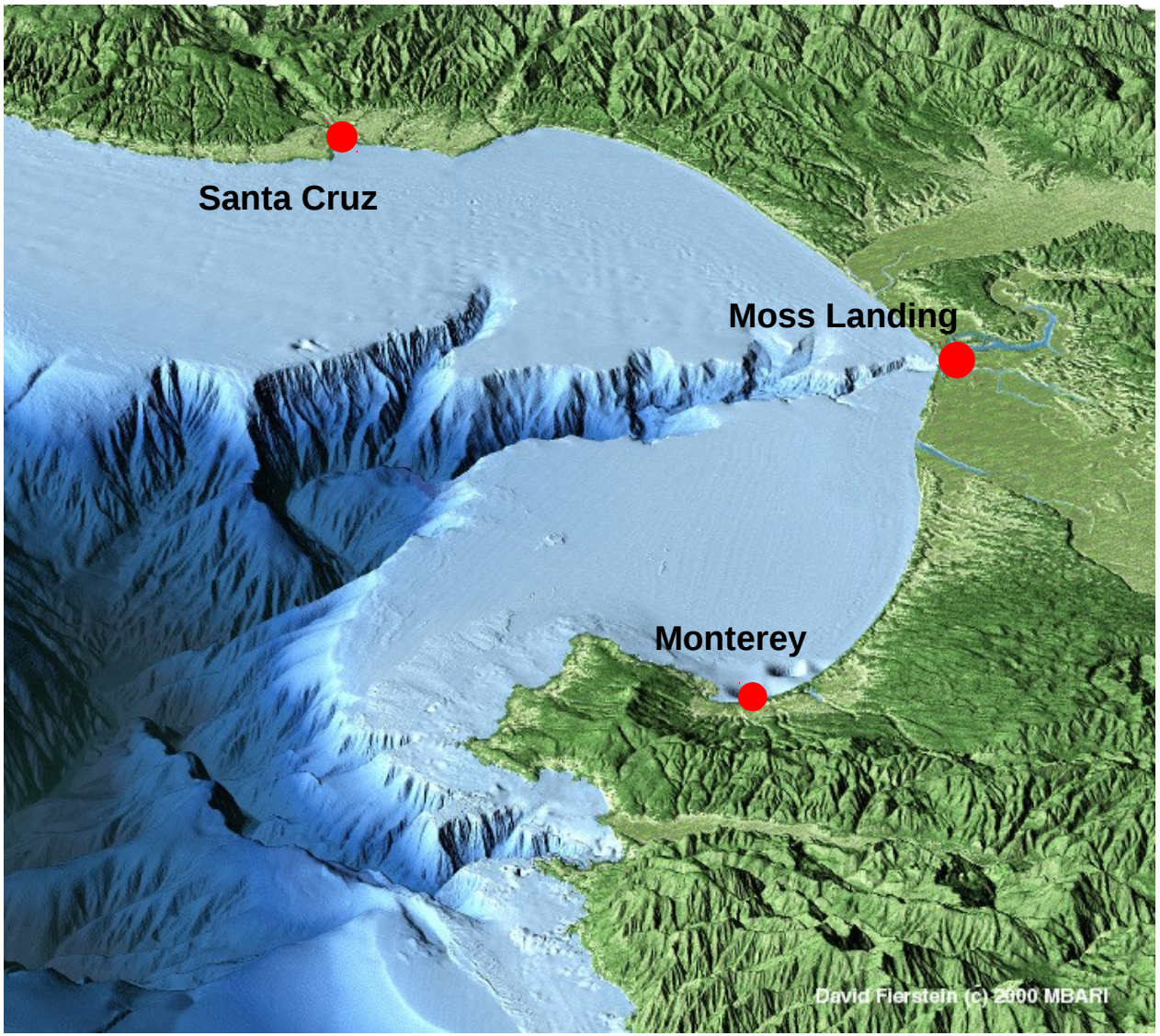
Monterey Bay Aquarium Research Institute (MBARI)

Monterey Bay

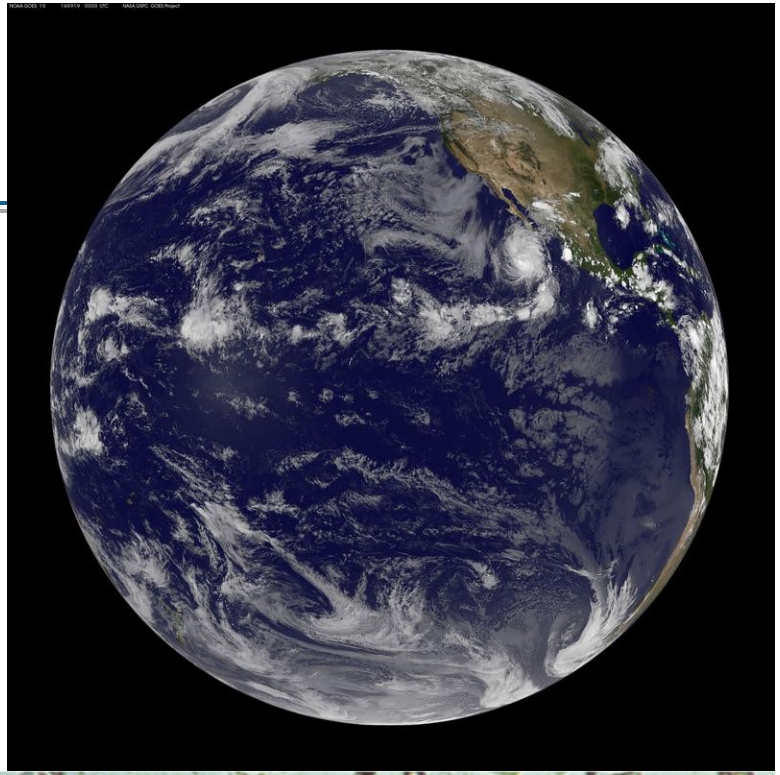
Why Moss Landing?

- Monterey Bay Submarine Canyon within 1-day steam
- Canyon is ~2000 meters deep, comparable to Grand Canyon
- Monterey Canyon Fan is ~3600 meters deep





The Microbial Ocean

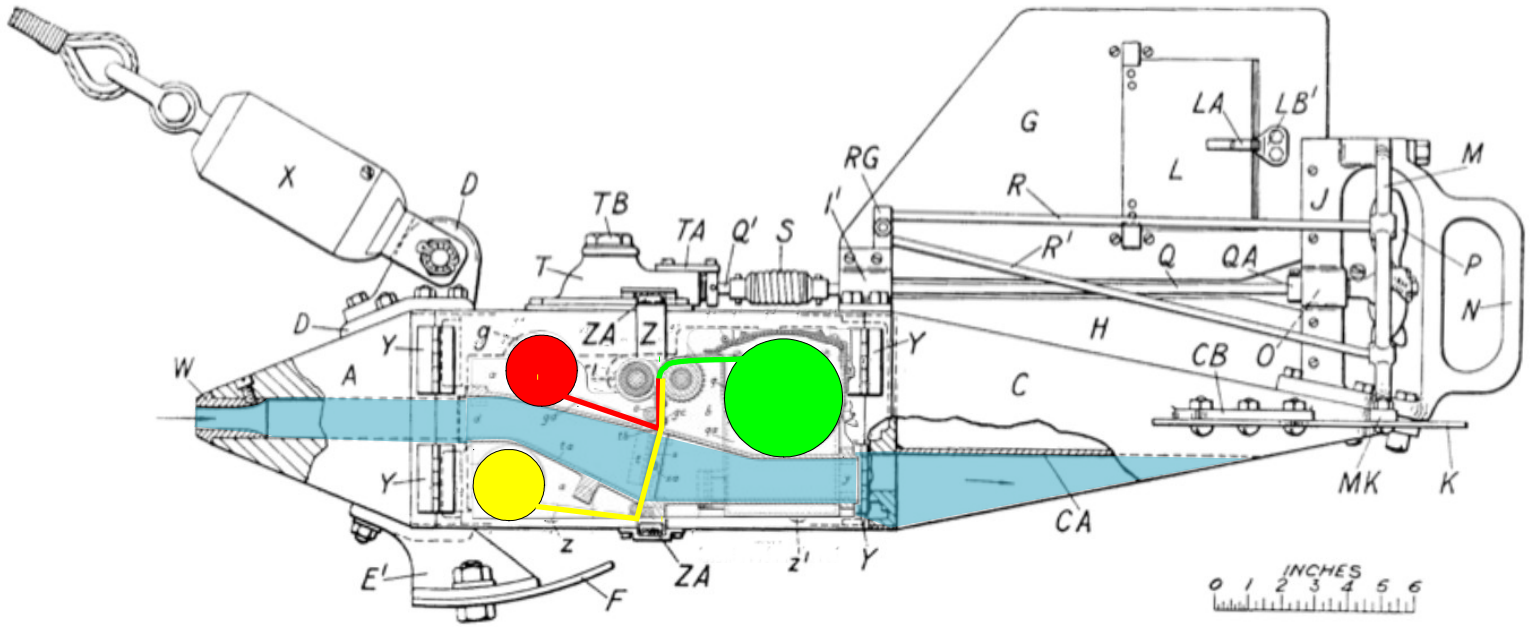


71% of the earth's surface
➔ is covered with water
(96% of which is in oceans)

Where there is water and light:
➔ *there are plankton!*

Plankton:
+ Produce >50% of our oxygen
+ Form base of ocean's food web
+ Regulate CO_2 in our air
- Release greenhouse gases
- Secrete neurotoxins

Automated Filtering is a surprisingly Old Idea

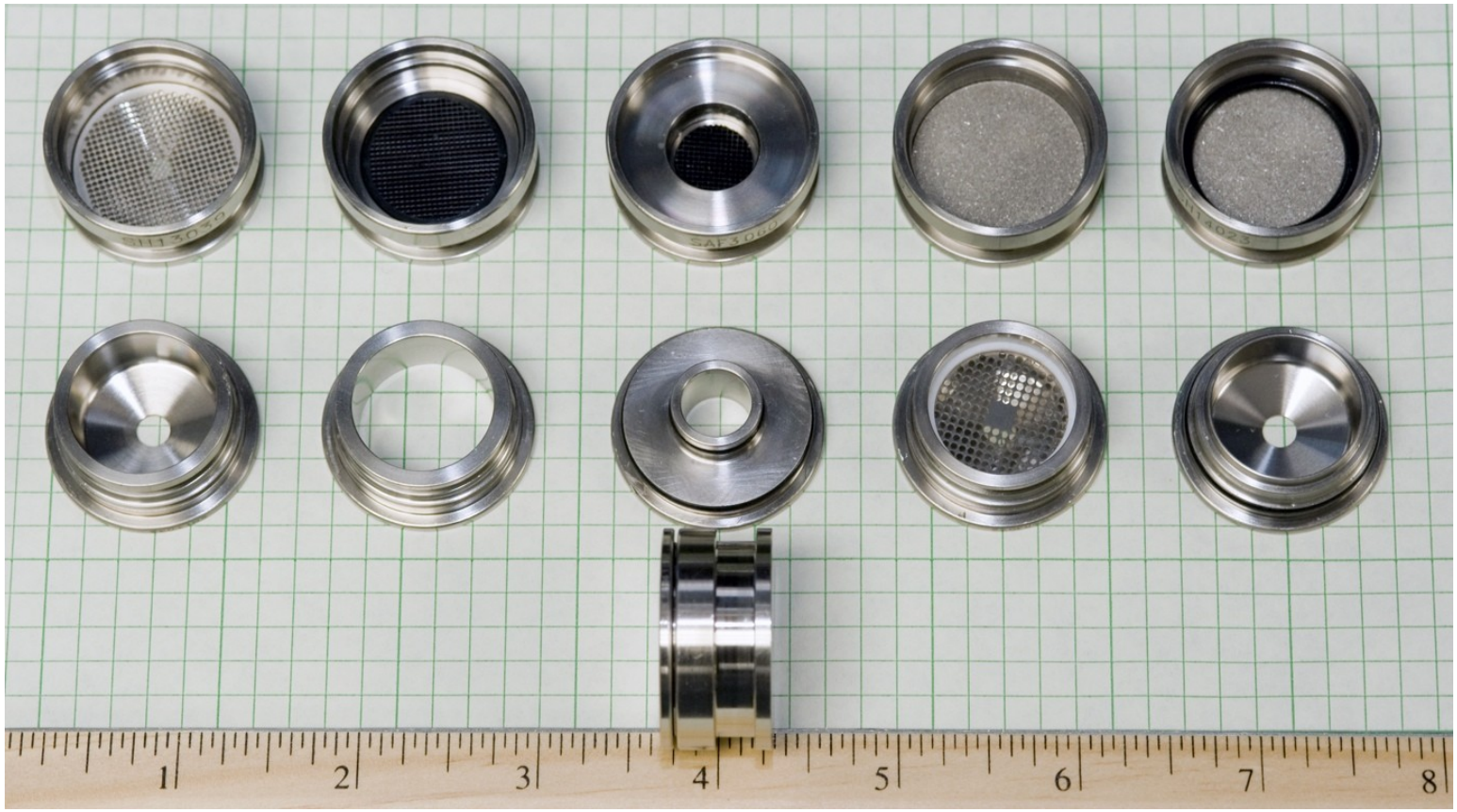


Continuous Plankton Recorder (CPR)

- First deployed on the R.R.S. Discovery in 1925-27.
- Towed behind ship, prop drives scrolling gauze filter
- Designed to document plankton “patchiness”
- Took ~10 yrs to become “operational”, but now >60 years of continuous marine plankton dynamics.

Pucks Replace Scrolling Filter

Function as filter holders and reaction vessels



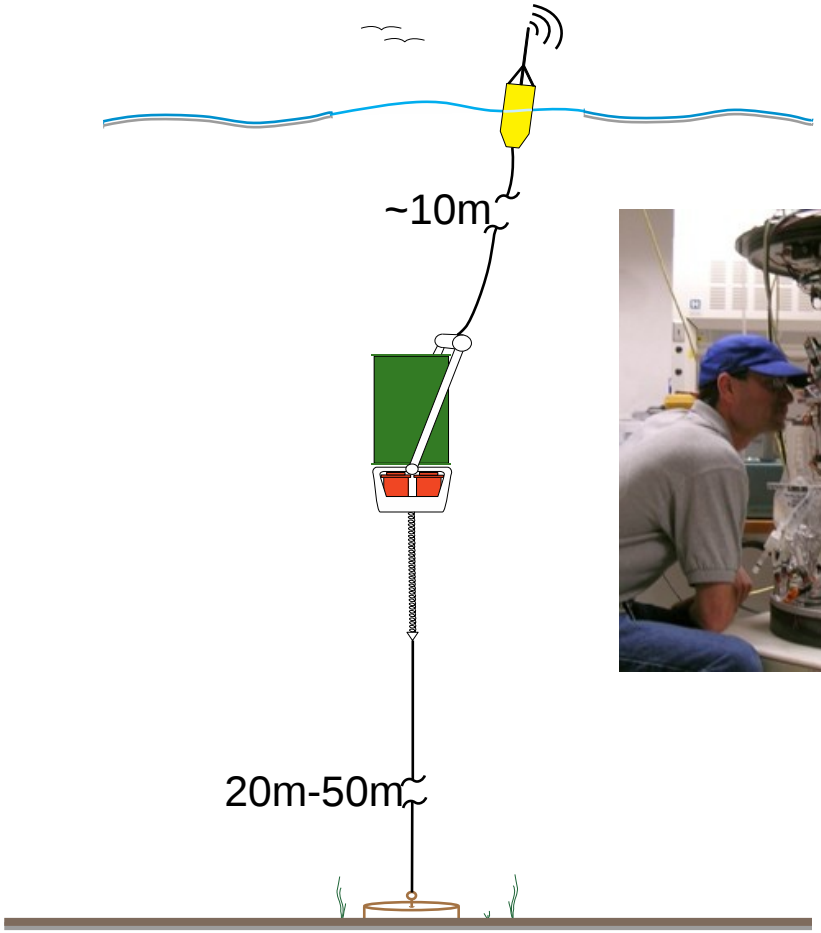
- Raw water collection
- Sample preservation
- Real-Time Array Imaging

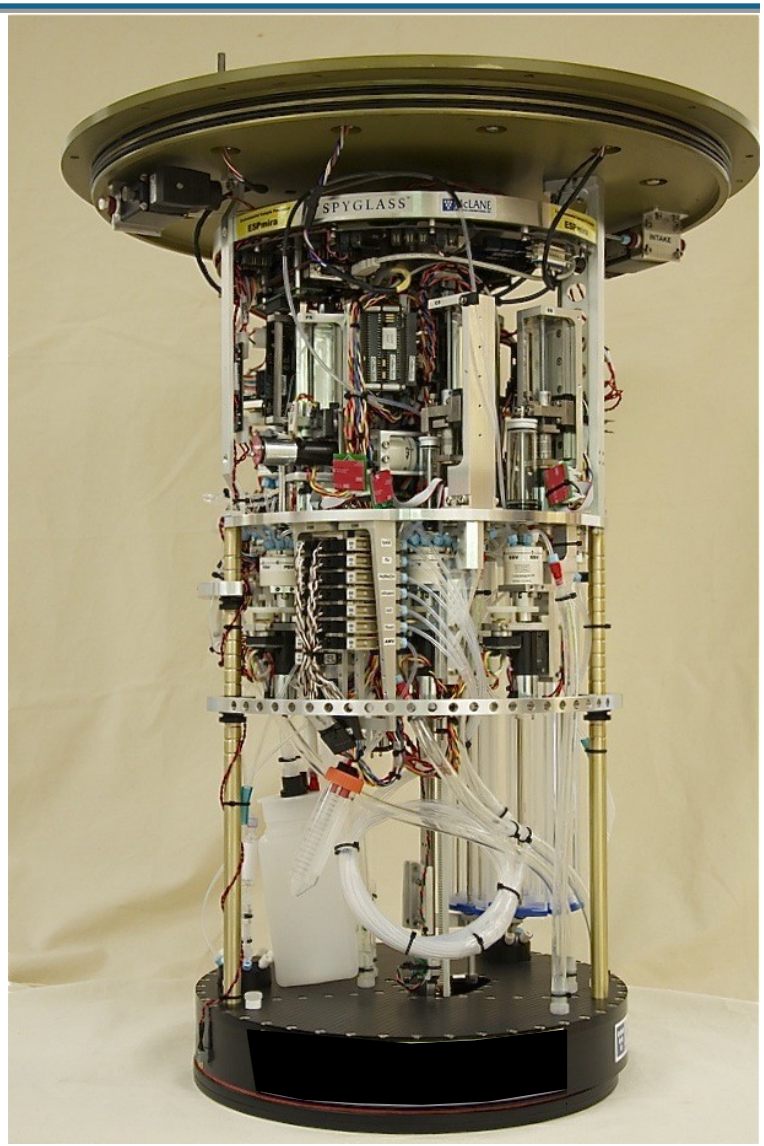
1 inch = 2.54cm

Top & Bottom halves snap together with rubber O-ring seals

Environmental Sample Processor

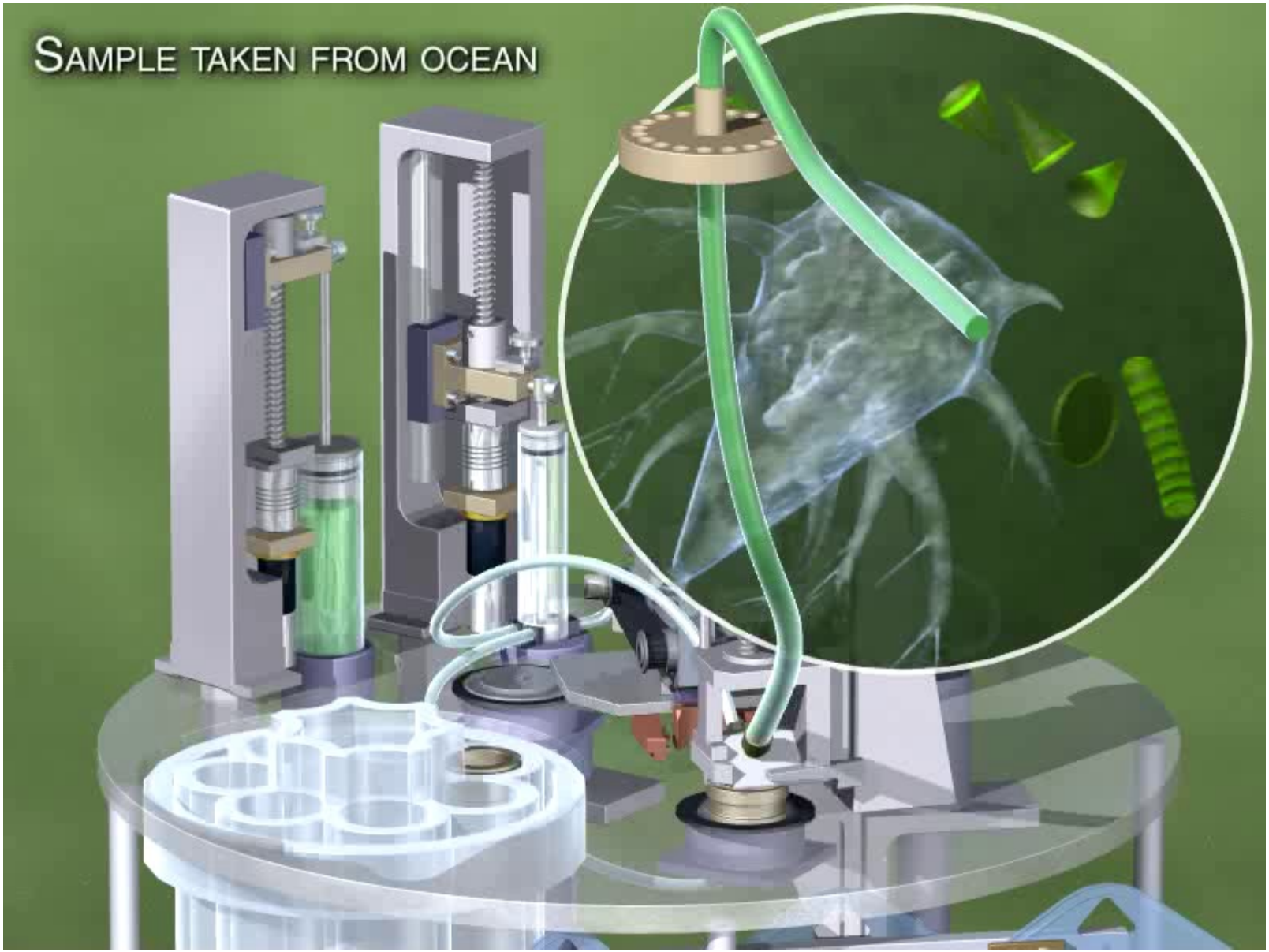
“Lab-in-a-can”



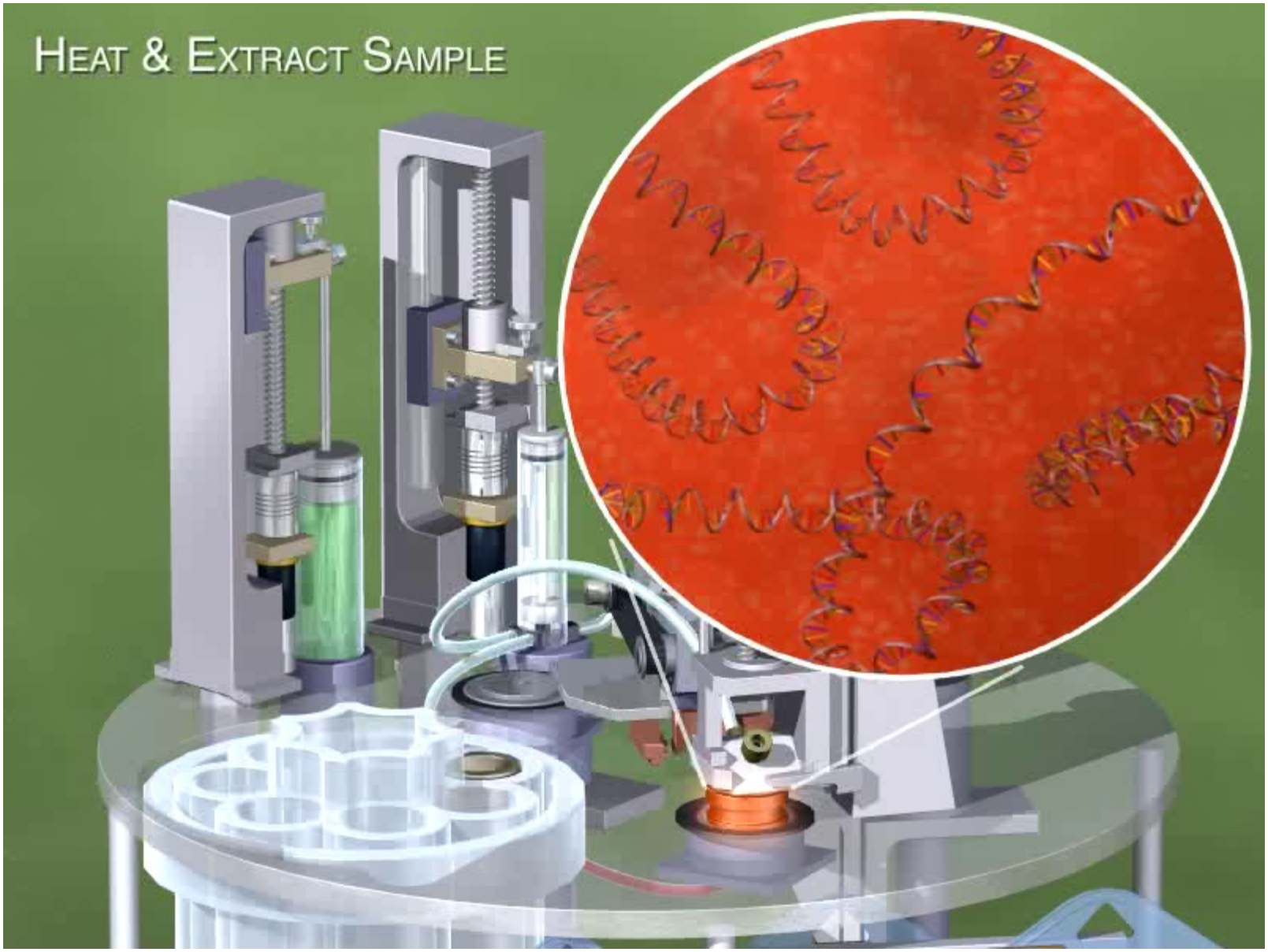


Development begun 1996

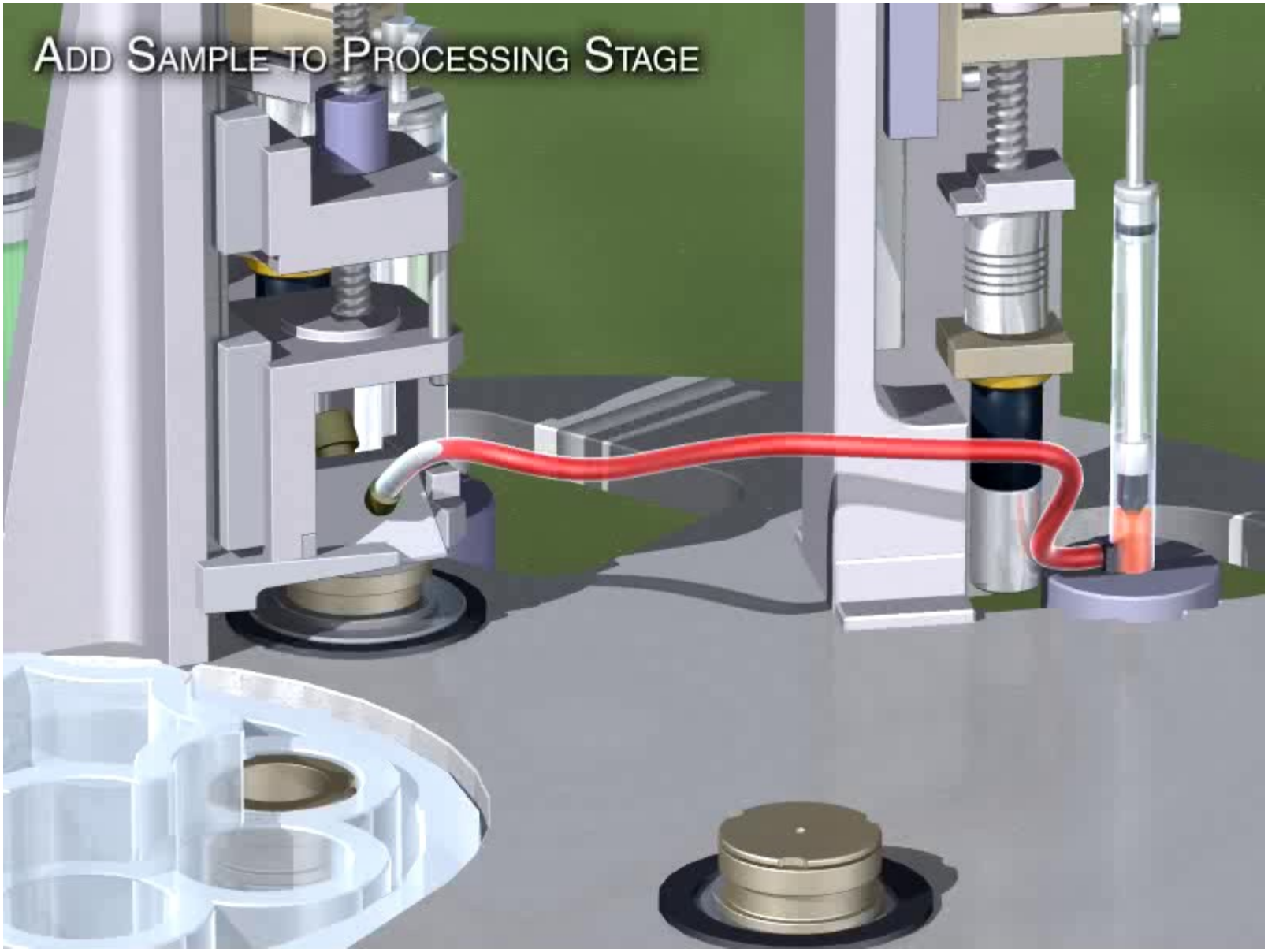
Filter Raw Water and Dry Filter



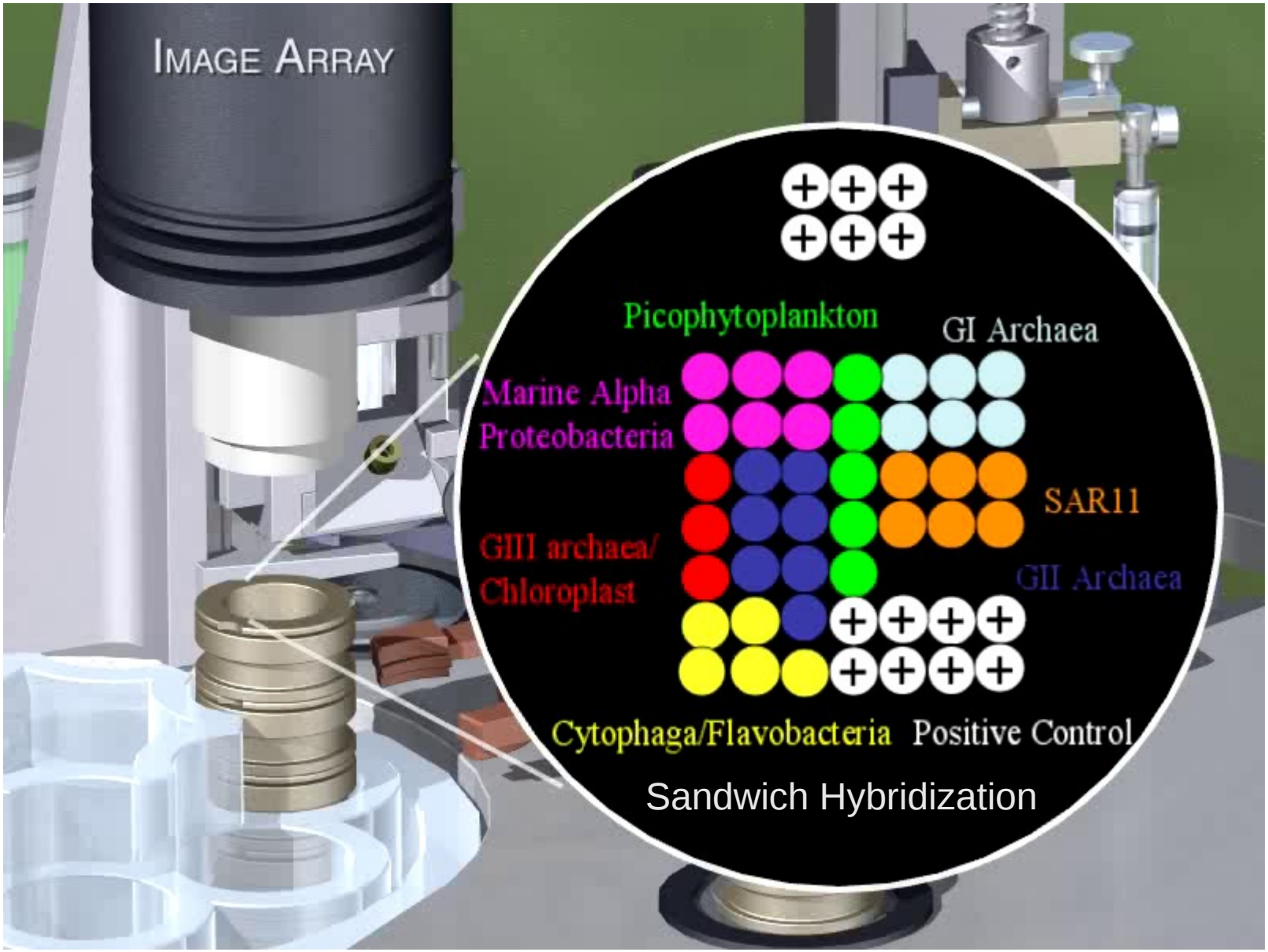
Detergent & Heat break open cells

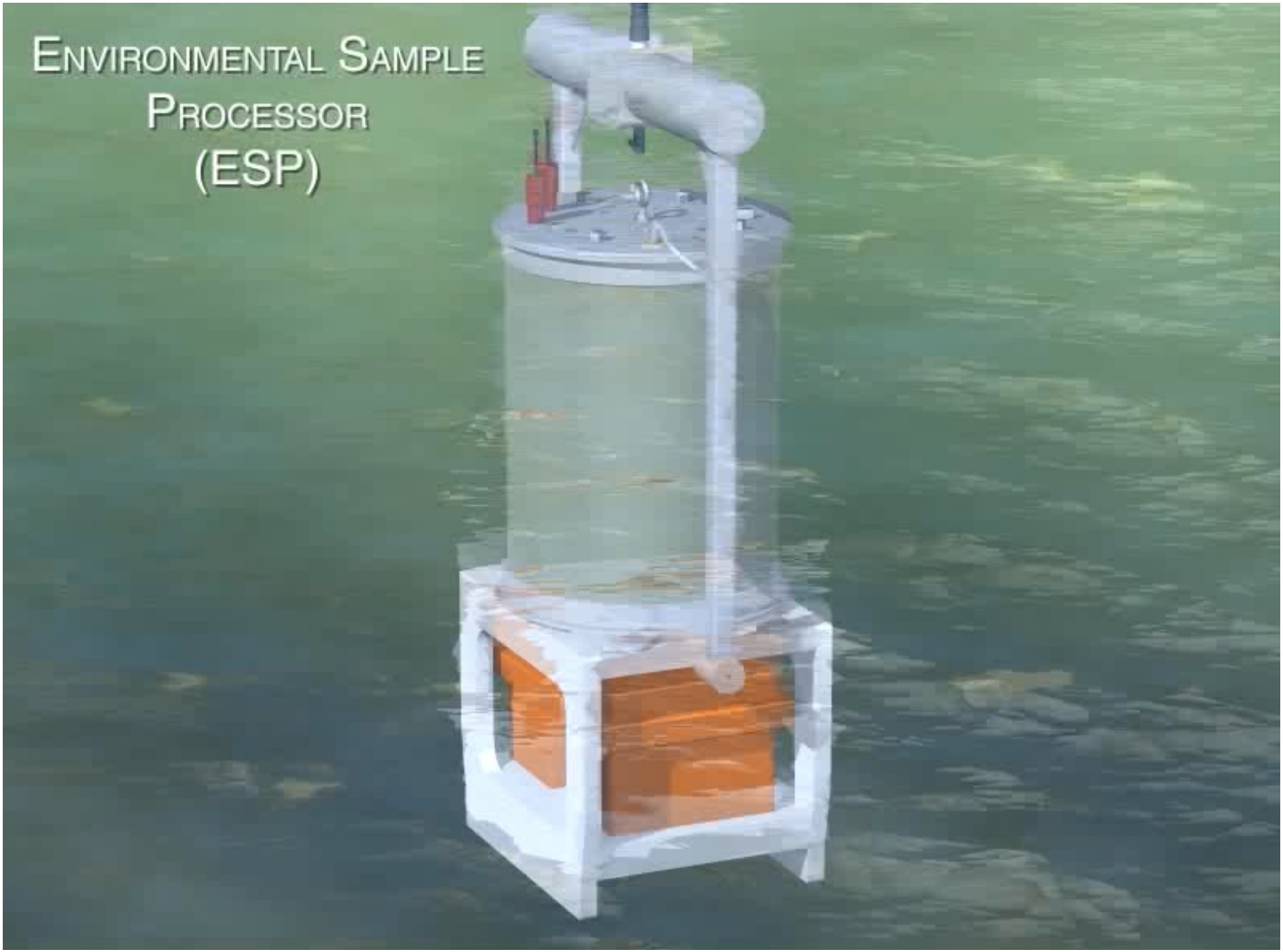


Pump Extract into Imaging Puck



Glowing spots indicate specific DNA/RNA



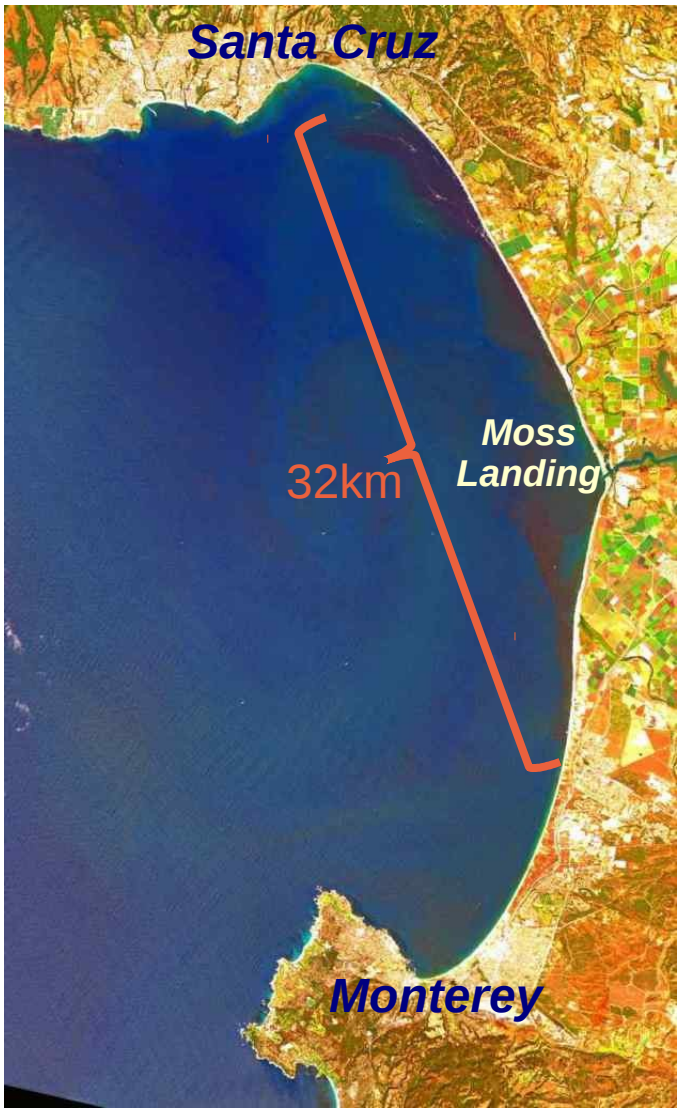

Environmental Sample
Processor
(ESP)

Harmful Algal Blooms (Red Tides)

- Poison accumulates in shellfish
- Kills fish, birds and mammals
- Closes fisheries and beaches
- Traditional detection takes days
  - ESP identifies HABs in 3 hours

Not all Red Tides are Toxic

- Algae often bloom...
  - Without producing toxin
    - No one is sure why
- ESP directly detects algal toxins
  - Domoic acid
    - amnesic shellfish poisoning
  - Saxitoxins
    - paralytic shellfish poisoning
  - Toxins bind to antibodies
    - Independent of DNA
  - Using a procedure called
    “Competitive ELISA”



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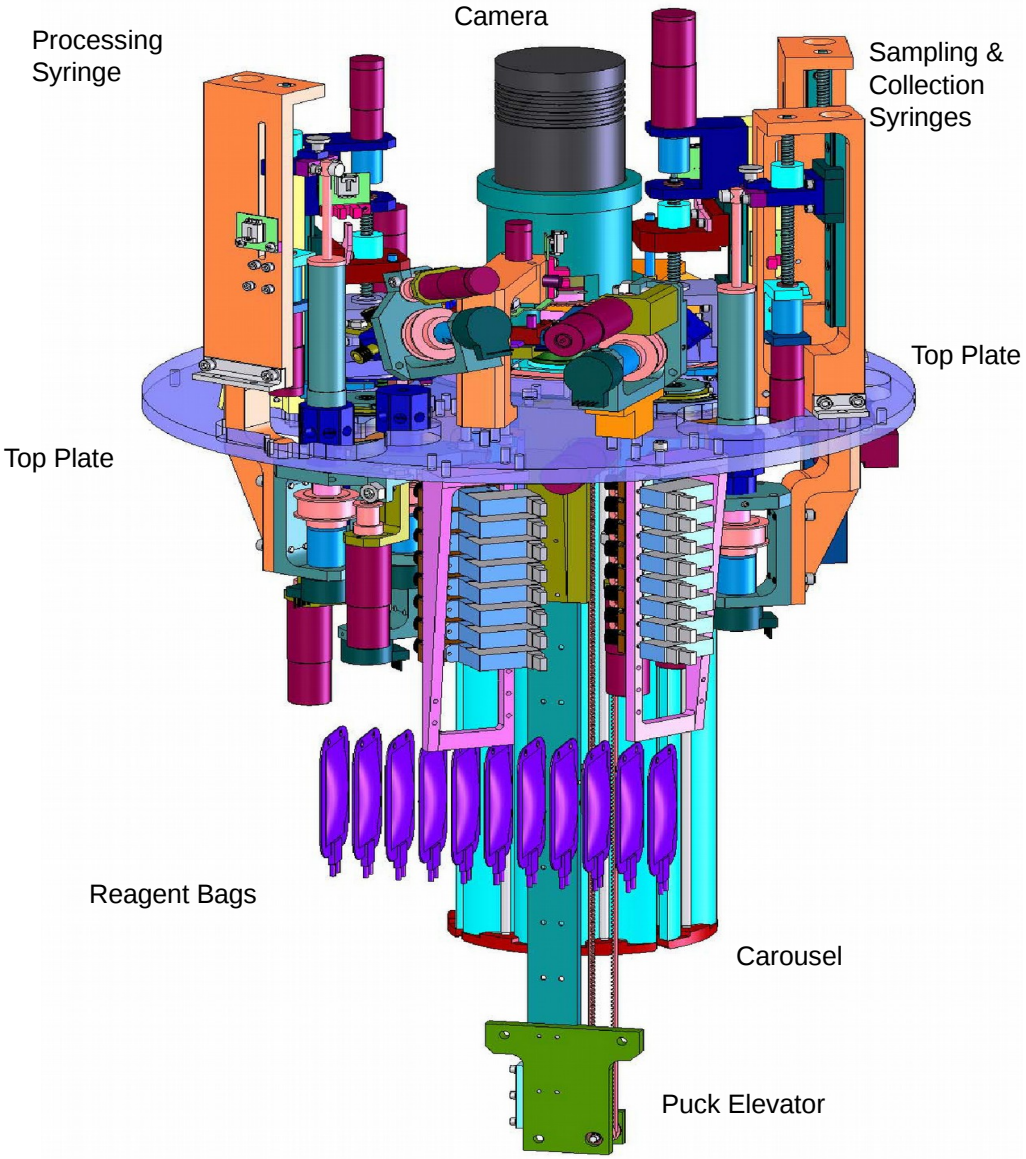
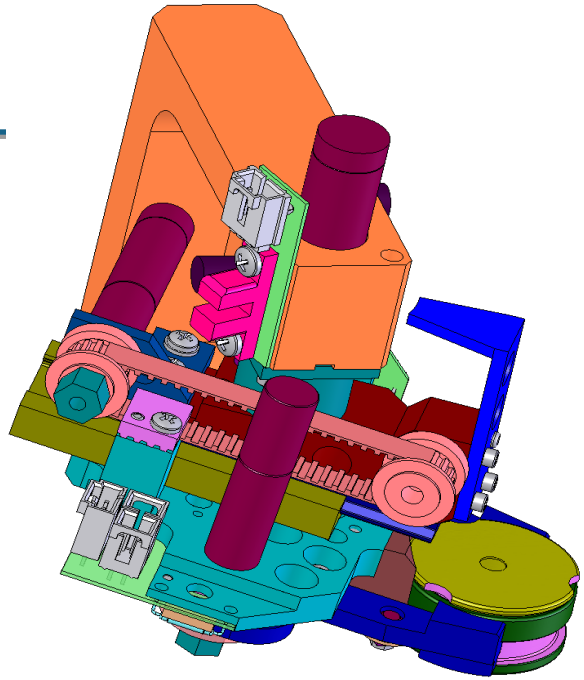
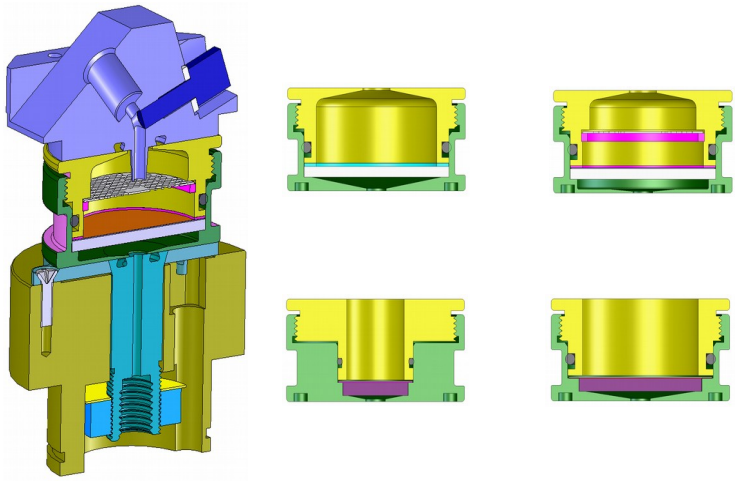
ESP Core robotics

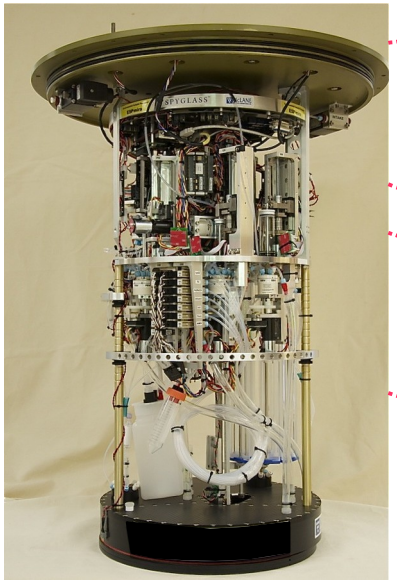




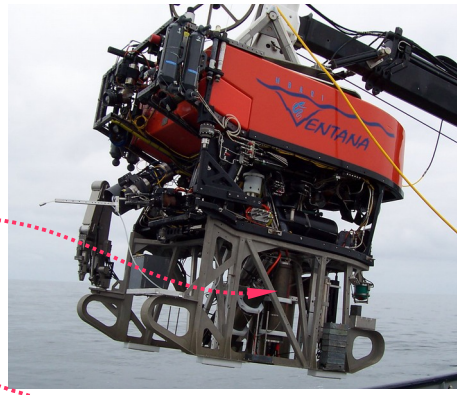


Deployment Platforms

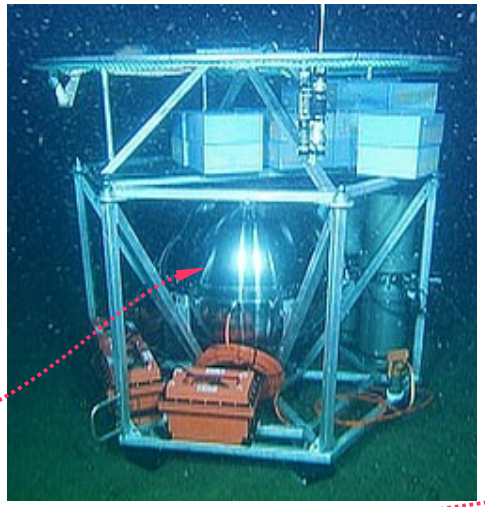
ESP Core



ROV tool sled



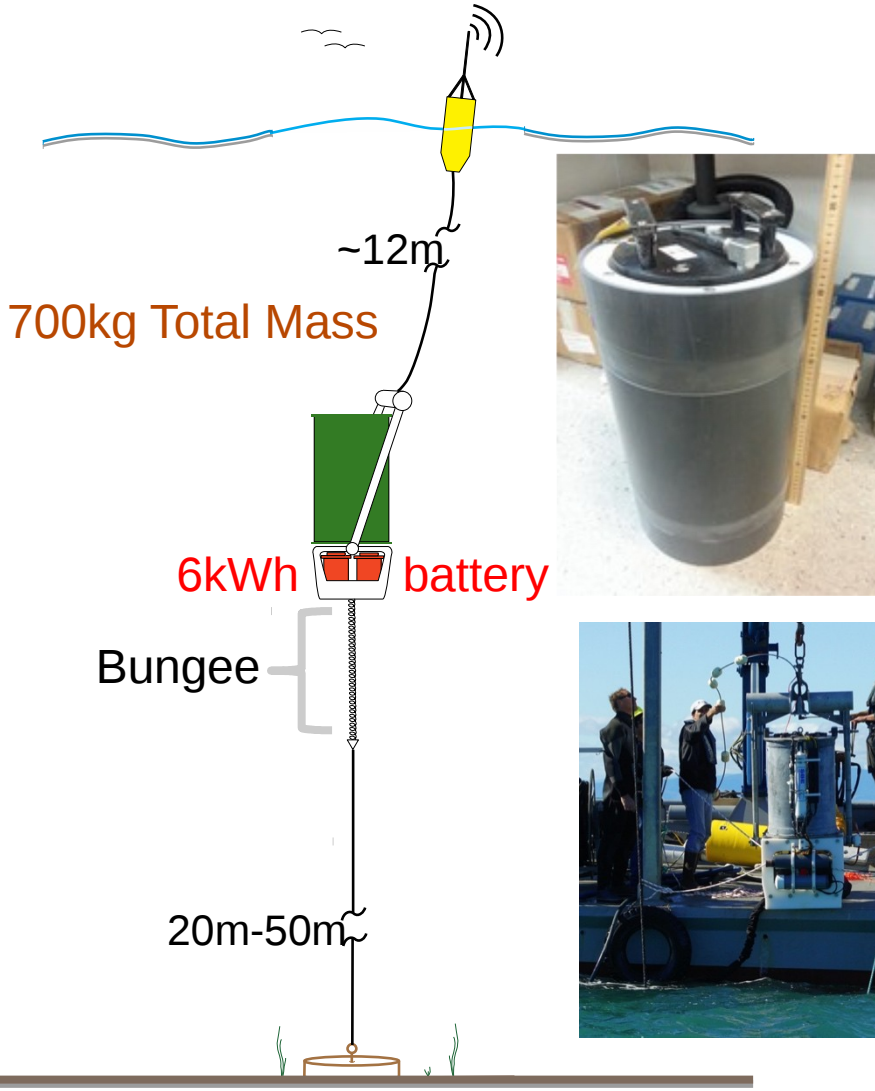
Ocean Bottom

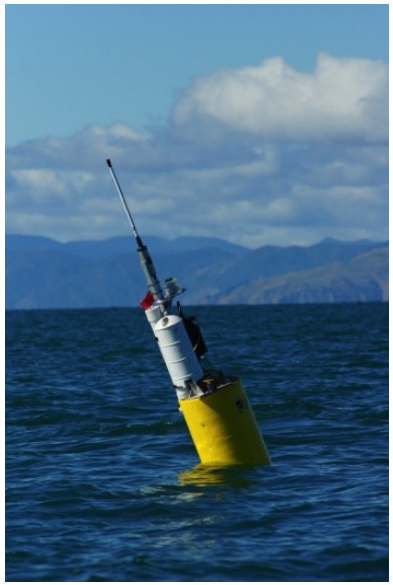


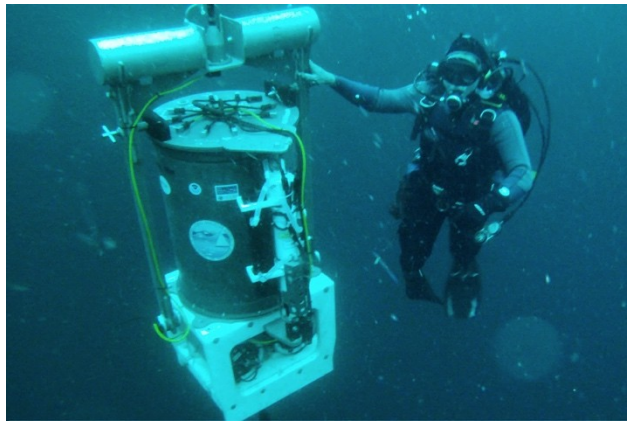
Surface Drifter

Pier

Shallow Moored Deployments







360 Alkaline 'D' Cells

+ As energy dense as Li-Ion, but much safer
+ Very inexpensive
- Not rechargable

76kg including waterproof housings

Low Power DC Servo Microcontrollers

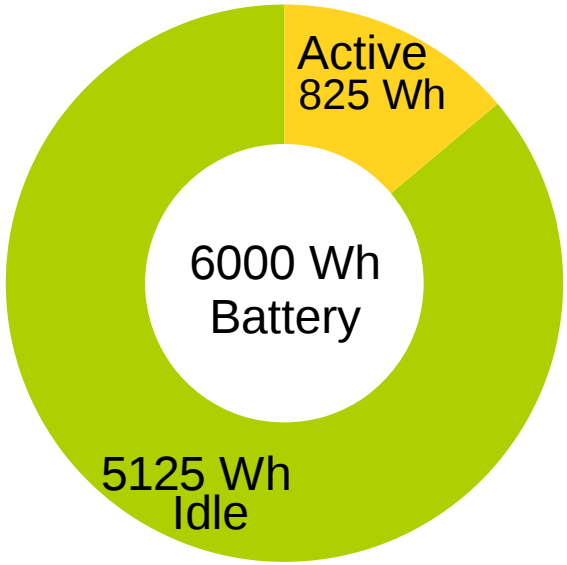
- Multi-Master I^2C bus
  - Allows easy expansion
  - Lower power than CAN or RS-485
  - Eliminates polling
- TI MSP430F169 consumes < 1mW
  - But provides only 2kBytes RAM
  - I^2C silicon bugs cost 4 man months
- Controller Board total quiescent draw = ~70mW
  - Designed in 2002

In retrospect...

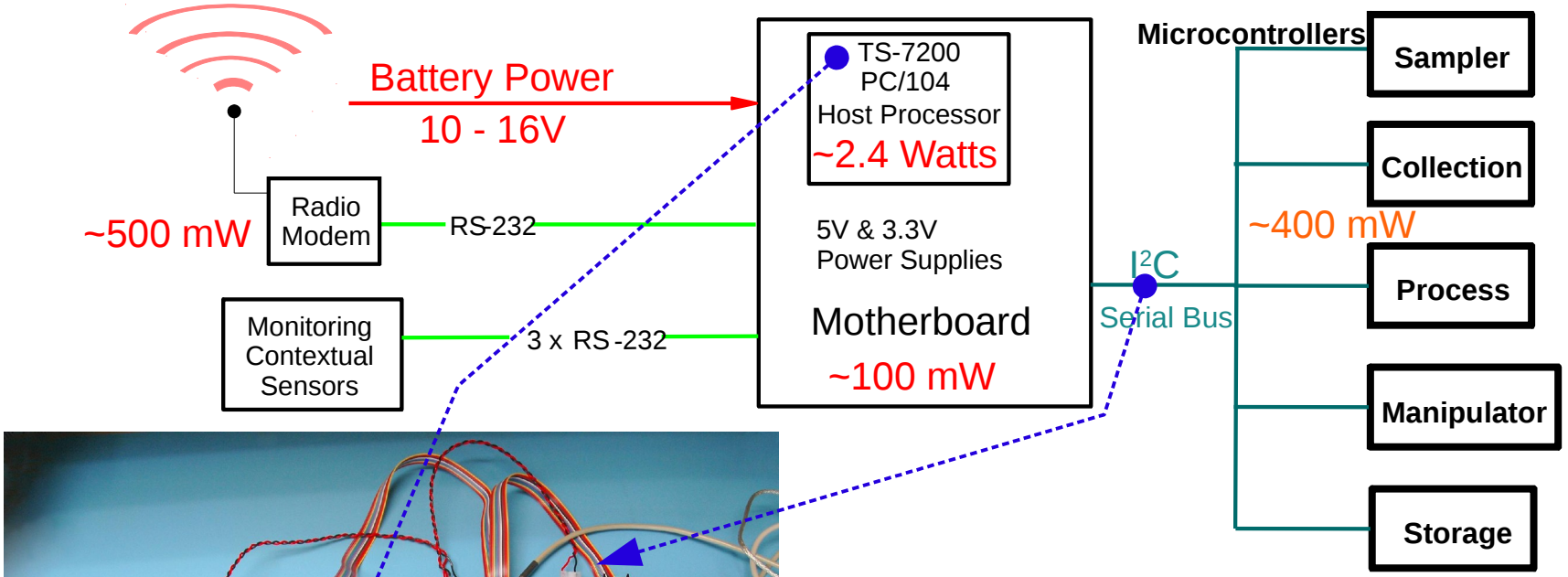
➔ More kB RAM would have been worth added mWs

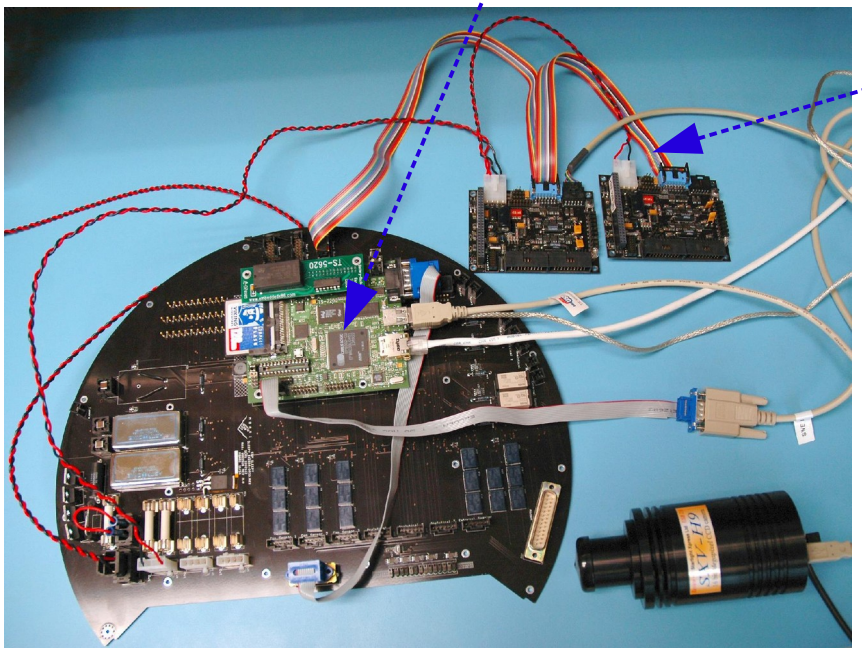
Energy Required to actively Process Pucks

- 25 Watt / hrs to process each set of 4 pucks
  - For typical HAB species identification
- Deployment consists of 33 such puck sets
- 25 Watt / hrs / puck set * 33 puck sets = 825 Wh
  - To process all 132 pucks
- Battery has 6000 Wh capacity
- So, we have plenty of energy...
- Right?



Baseline Load as designed in 2002





Technologic Systems TS-7200 200Mhz ARM9
64MB RAM, 16MB NOR flash, 2.4 Kernel

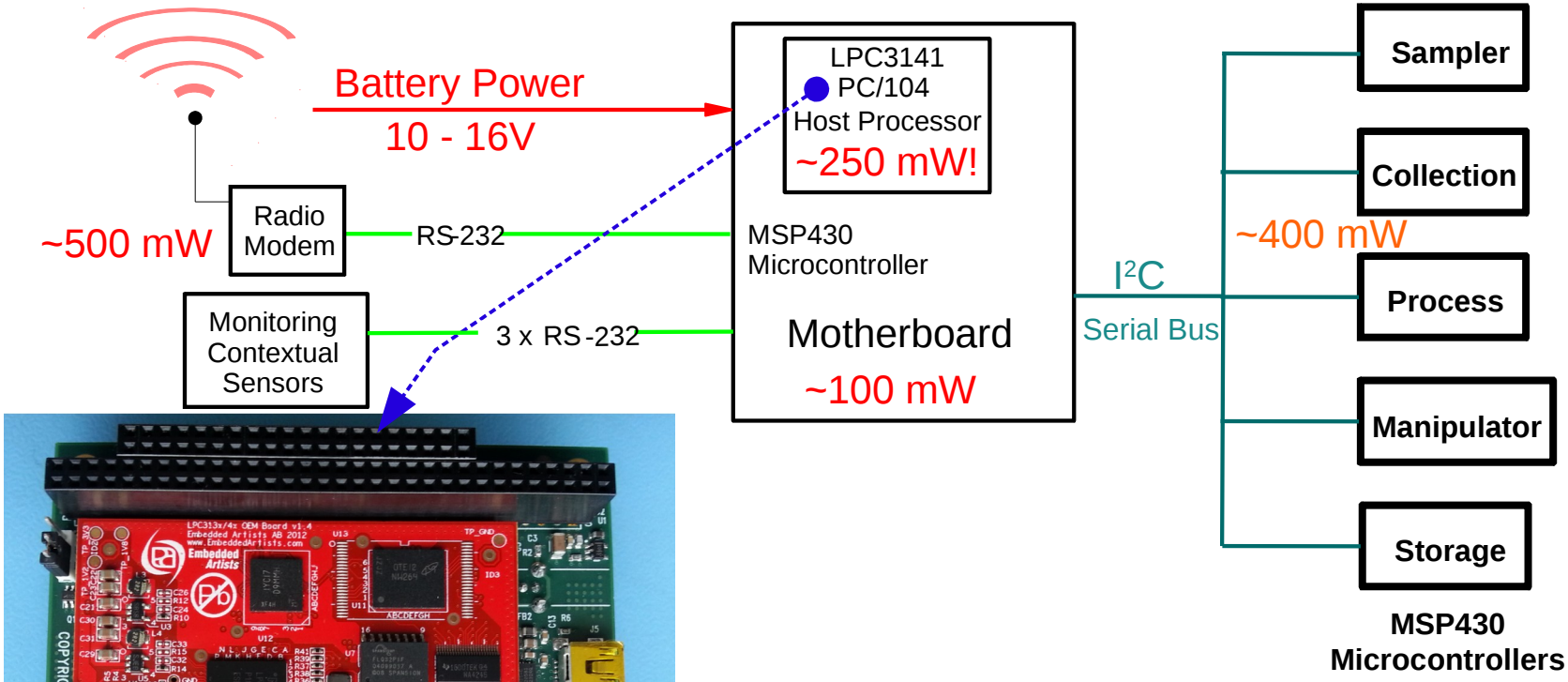
With Microcontrollers powered off

~3 Watt total "monitoring mode" load
= 75 Wh/day
= 2250 Wh/month

5125 Wh depleted in only 68 days

But, reagents good for >180 days

Baseline Load after electronics redesign in 2014



Embedded Artists LPC3141 270Mhz ARM9
64MB RAM, 256MB NAND flash, 2.6 Kernel

With Microcontrollers powered off

~1 Watt total "monitoring mode" load
= 25 Wh/day
= 750 Wh/month

5125 Wh depleted in 205 days !

Mission Accomplished?

High Speed Over Long Wires Saps Power

Ethernet:

- 100BaseT link uses 1 watt
- 10BaseT uses only 400mW

Old, slow tech saves power!

DSL

Symmetric Digital Subscriber Line:

- Pushes Mb/s over most any cable
- But, links typically use >4 watts

With today's low power Linux processors, such links dominate the power budget

WHOI Stretch Hose ESP Mooring

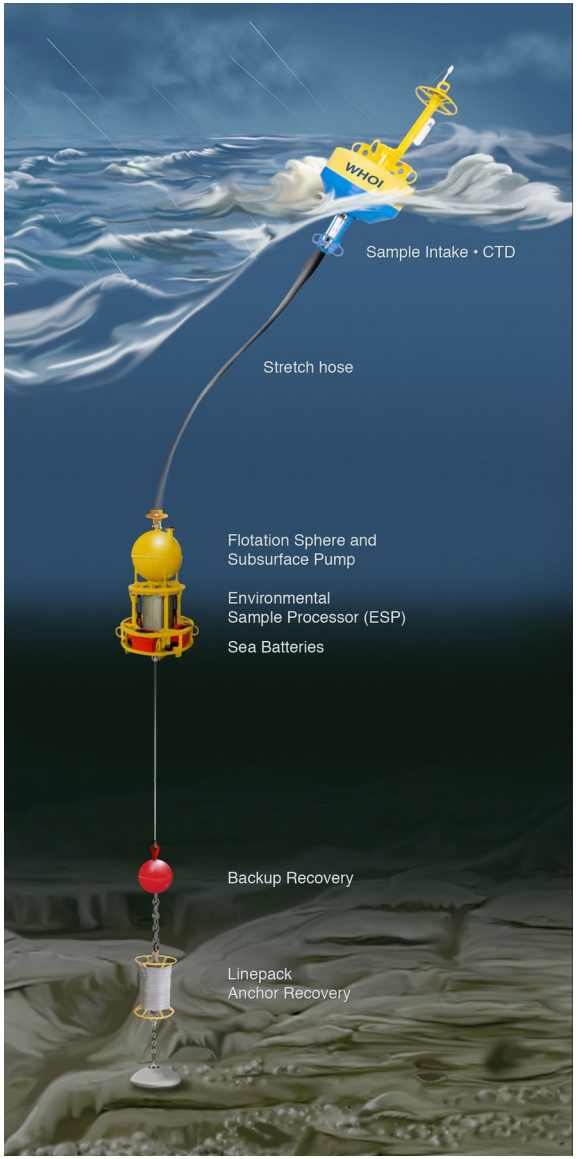
- Designed to survive Atlantic Ocean storms
- 3200kg mass
- No Divers Required

- Wires in stretch hose are 65 meters
  No twisted pairs!
- DSL links radio in float with ESP below
- Uses ethernet internally

- Monitoring Mode load increased to >8 W
- Max deployment duration <60 days
  Even with >3x battery capacity

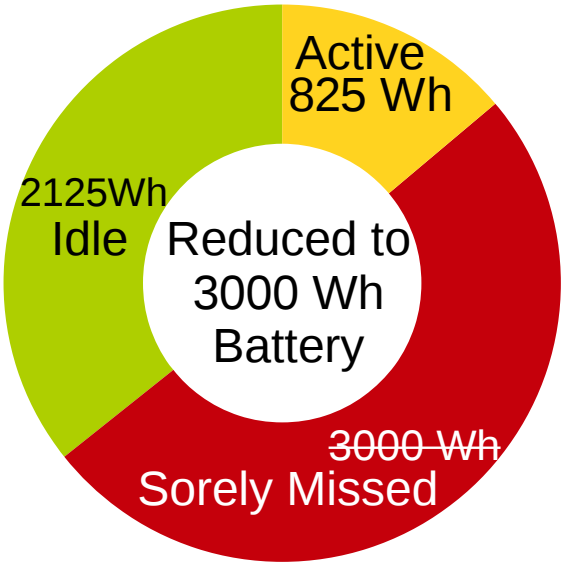
- Retrofitting with new 250mW CPU board
  Does not change much

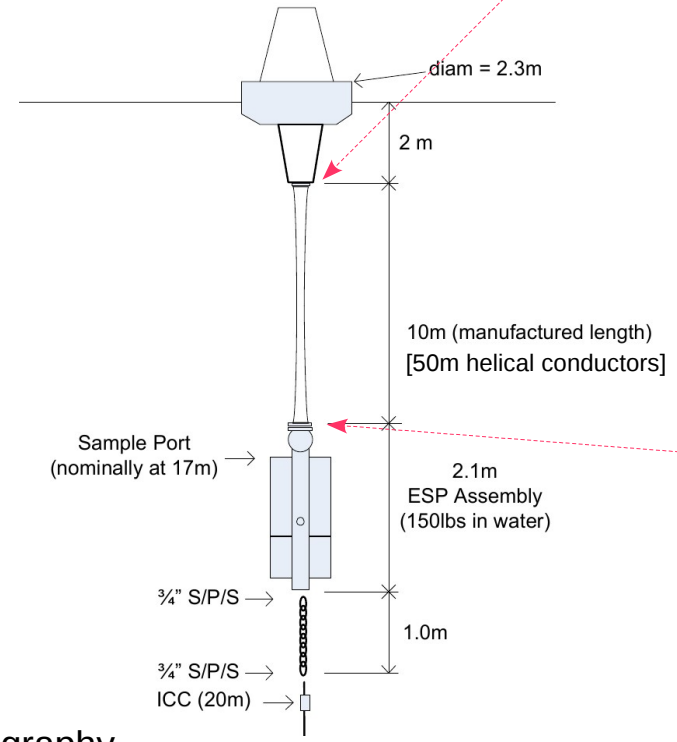
WHOI = Woods Hole Oceanographic Institution

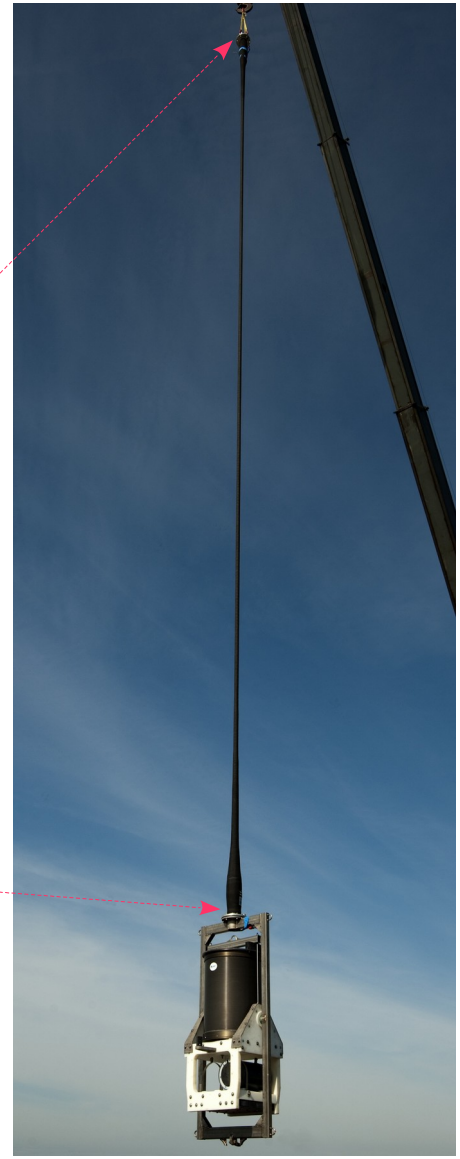


SCRIPPS Stretch Hose Mooring

- ESP hangs from 10m stretch hose
  - Can stretch to 15m in waves
- One battery removed to reduce mass
  - Capacity halved to 3000 Wh
- Still want 6 month mission duration







➔ Depleted in 85 days

➔ With just 1W load

SCRIPPS = Scripps Institution of Oceanography

Why not Suspend-to-RAM ?

- Lowers host CPU power by only 100mW
  - Reducing monitoring mode load to 0.85W
  - Increasing deployment by only 15 days

Why not Suspend-to-Disk ?

- Concern about SD card flash
  - Slow write speed for image saves
  - Flash wear over 100s of hibernate cycles

- Hibernate not implemented in 2.6 ARM kernels

Rethinking Requirements

- If all activity is triggered only by time...
  - No need to monitor sensors
  - Host CPU could be powered off
    - Until switched on again by motherboard

- Even this yields only enough power for 140 days
  - Radio has become the power hog
  - If it must also shutdown, how would unscheduled access be possible?

Deep sleep while allowing remote wakeup

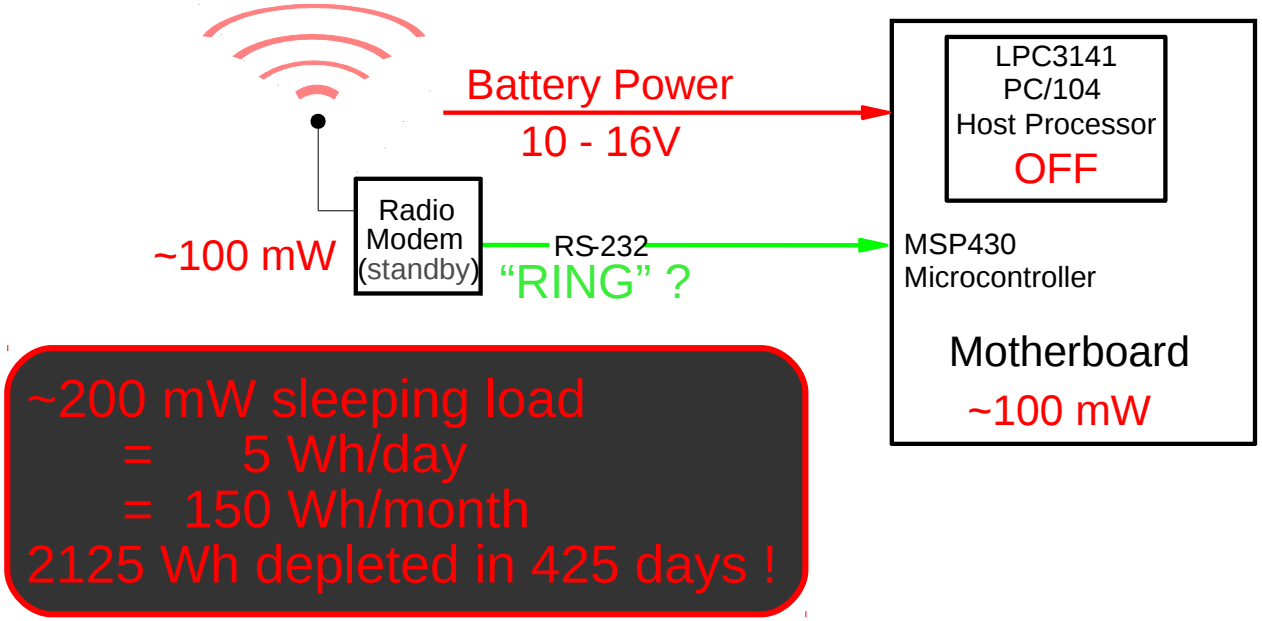
Utilizing modem's “low-power standby” mode

- Drop the data connection
- Modem functions as a pager.
- Outputs

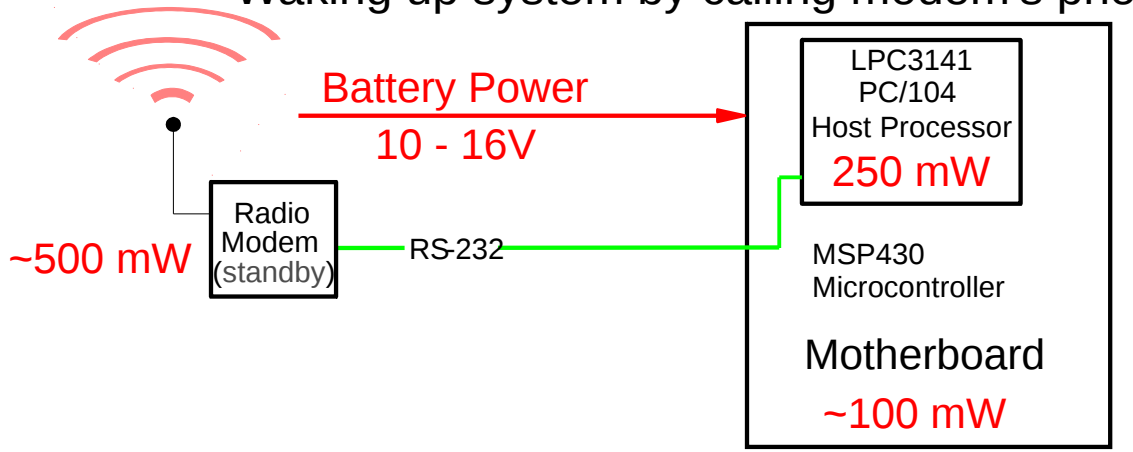
  “RING”

  when it detects an incoming phone call.
- Draw reduced from 500mW to 100mW

Year long deployments possible on 3kWh

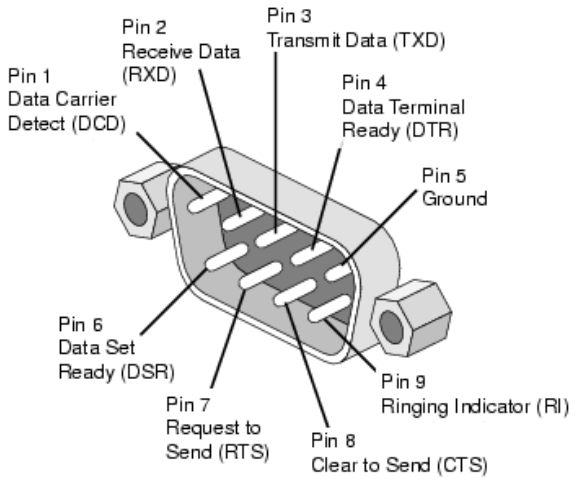


Waking up system by calling modem's phone #



Oceanographers still use RS-232 serial

25-pin RS-232 standard was introduced in 1962
9-pin connector appeared first on original IBM PC

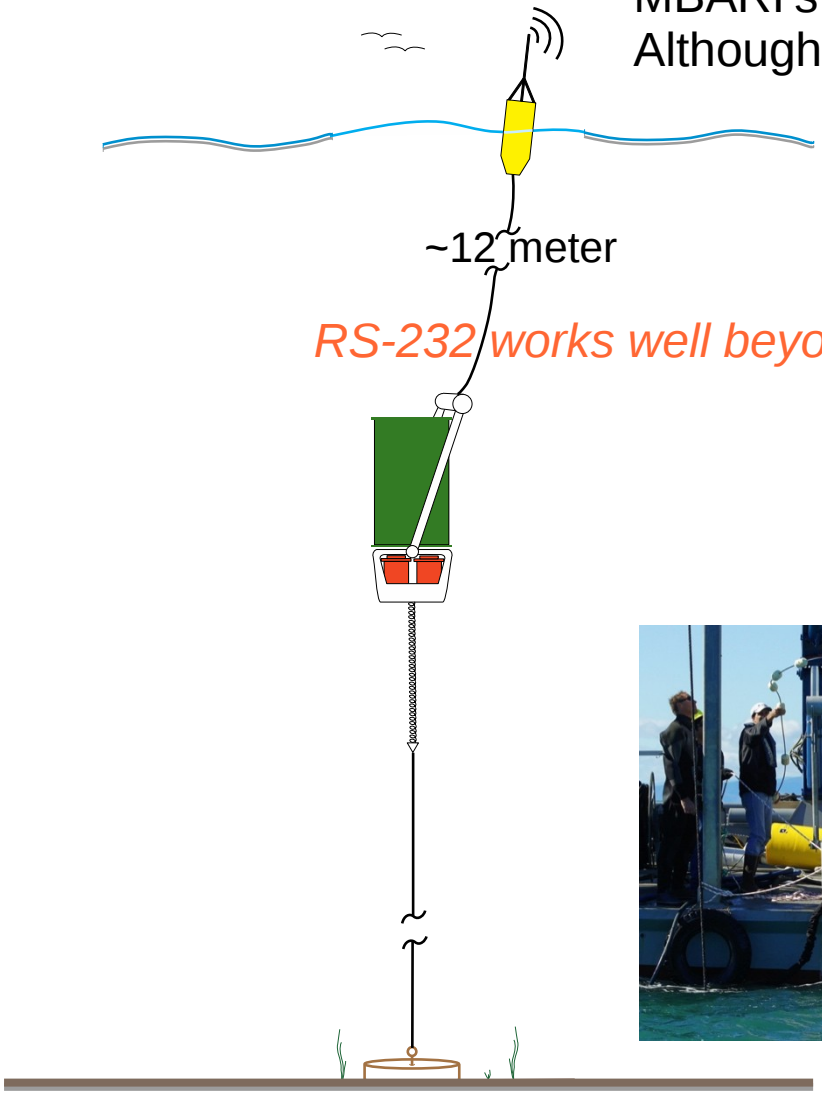


+ Often lowest power option
+ Compatible with every processor
+ No (fixed) length limit

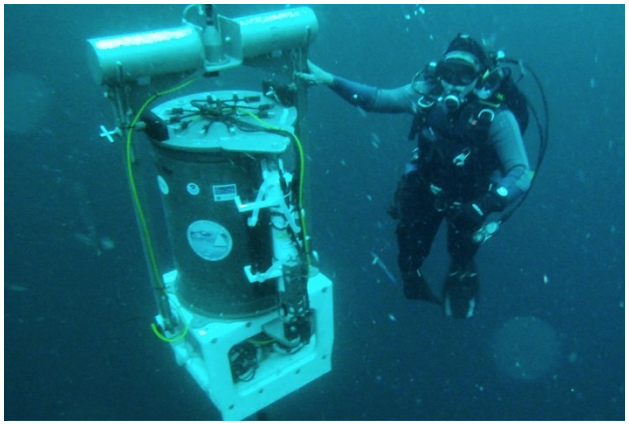
- Relatively high signal voltages
- Poor standards for flow control
- Many conductors
- No multiplexing
- Slow (especially on long links)

RS-232 cable length vs max speed

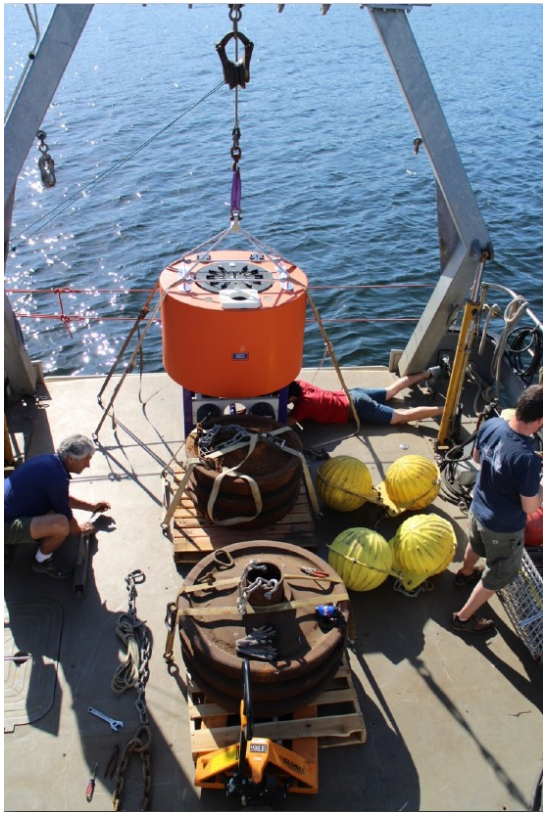
MBARI's ESP mooring runs 115 kBaud over 12m cable
Although RS-232 spec would suggest ~19.2kBaud limit

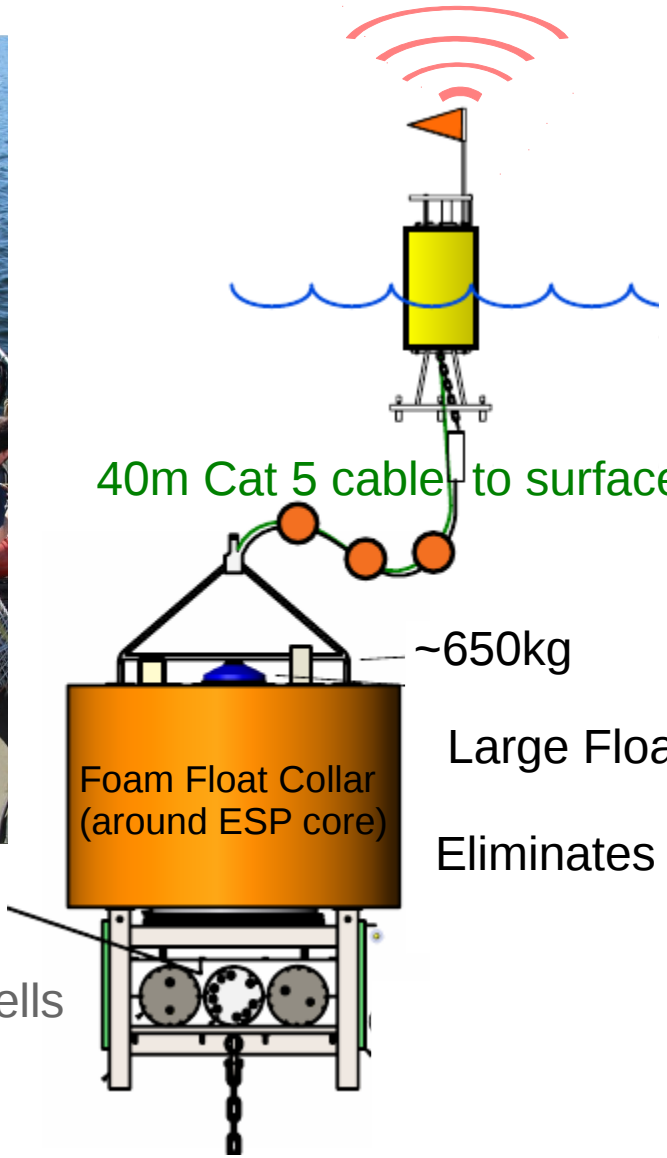


RS-232 works well beyond its recommended speed/length limit



University of Washington's ESP Mooring





+ Suitable for open ocean
+ No Divers Needed
+ Relatively inexpensive

- Requires larger ship

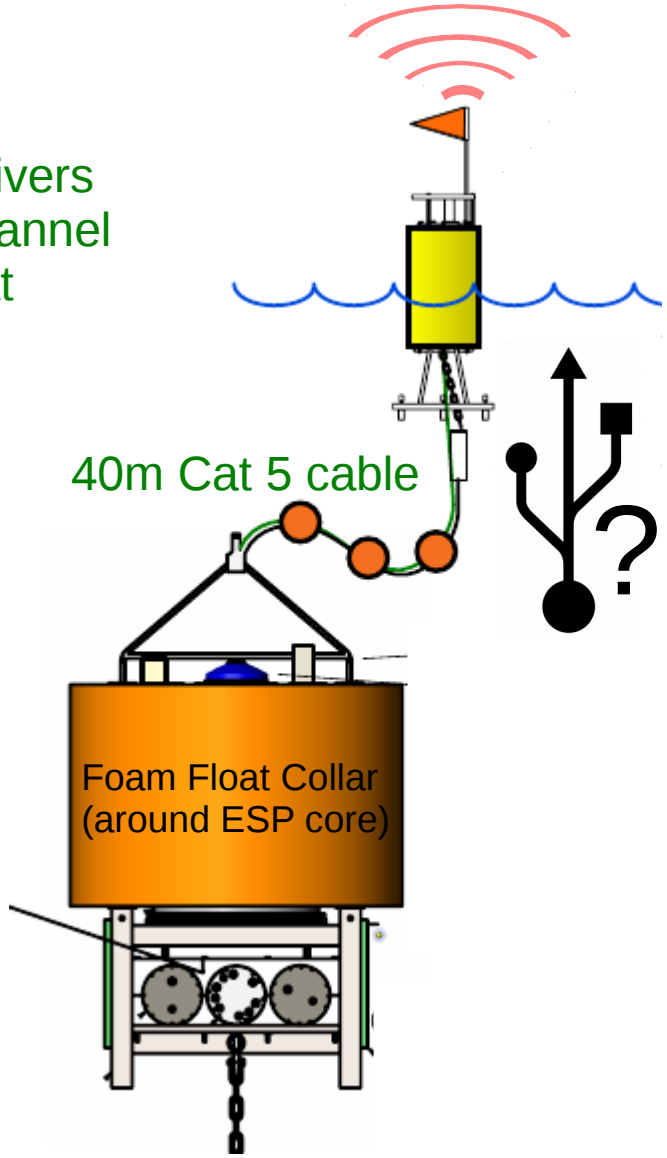
Large Float collar protects ESP
and
Eliminates need for rotating bale

Replace RS-232 with USB?

+ >100 times faster than RS-232 to modem
+ Linux kernel includes many USB class drivers
+ Hubs multiplex 100+ devices per USB channel
+ Can support additional devices in the float
  Weather instruments, WiFi, etc.

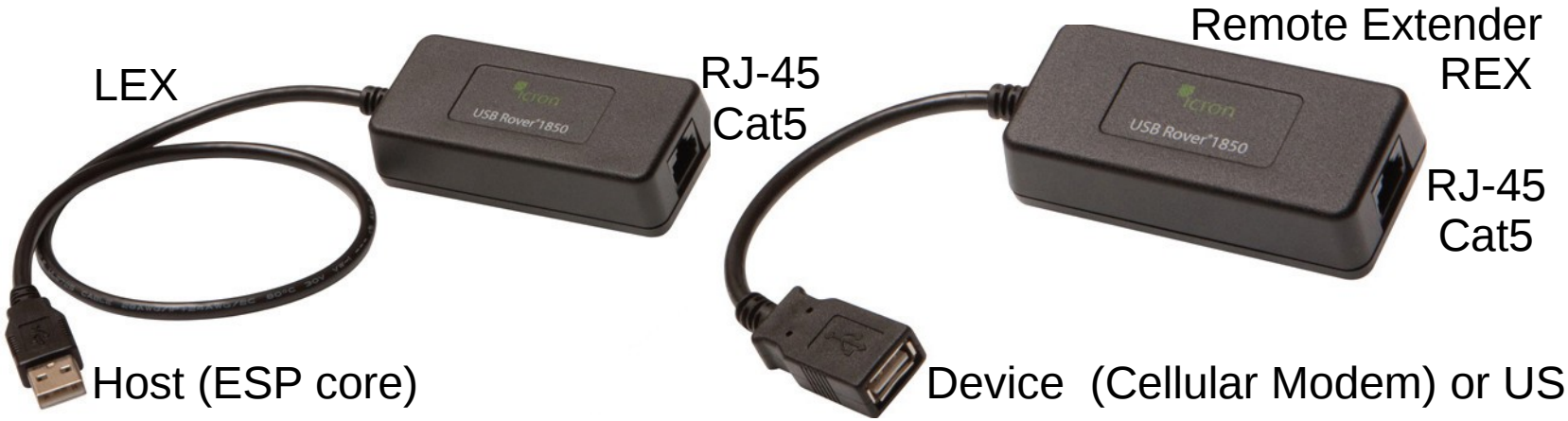
- Adds about 30mW per device
- Hubs draw 150mW each!
- Segment length limited to 5 meters

➔ But, we need to span 40 meters.



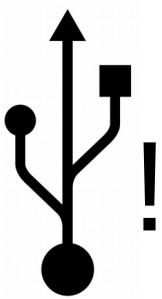
USB on Cat5 cable

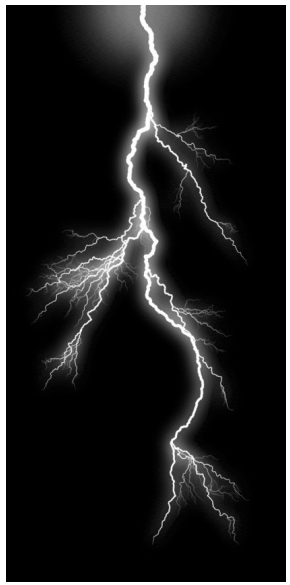
Many Cat5 USB extenders available...
Icron 1850 works reliably over up to 50 meters of cable:



- Full Speed (12Mb/s) and Low Speed (1.5Mb/s) only
- Supports remote hubs, transparent to software
- 12Mb/s link burns 500mW
- *Newer designs support 480Mb/s, burn >2W*

➔ Precludes low power sleep in current ESP design
➔ Would require a dedicated RING signal from modem





Note: Many other vendors rebrand Icron USB extenders

USB 2.0 Power Management Theory & Practice

- Devices may be put into a “suspended” power state
  - Most devices ignore requests to suspend
  - Suspended devices still draw many mWs
- Individual Ports may be powered down
  - Vast majority of hubs don't support this
- Laptop users simply unplug unused USB devices
  - ➔ **Embedded systems can do the same**
- Power USB devices via software controlled switches
  - USB stack sees usual dev disconnect / connect
  - No need to splice high speed data lines

Energy Harvesting

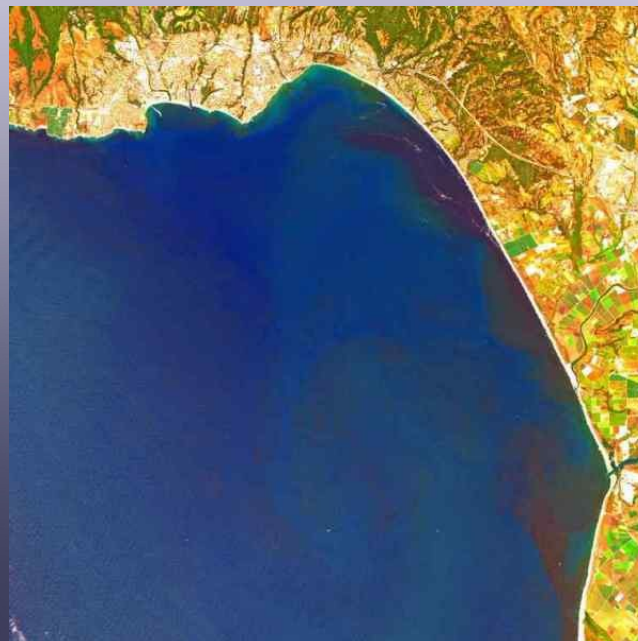
- Lots of available energy at ocean's surface
- Need only 50 Wh/day ~= 2W continuous
- Solar probably requires least maintenance
- Relying on only 3 hrs sunlight/day
  - Need panel w/peak rating of ~25W
  - 25W panel area ~= 0.25 square meters
- Might blow over existing small surface floats
  - Tipping > 30 degrees interferes with radio
- Rechargeable battery & new float design required
  - But very doable and worth investigating...

3G ESP/Long-Range AUV

makai

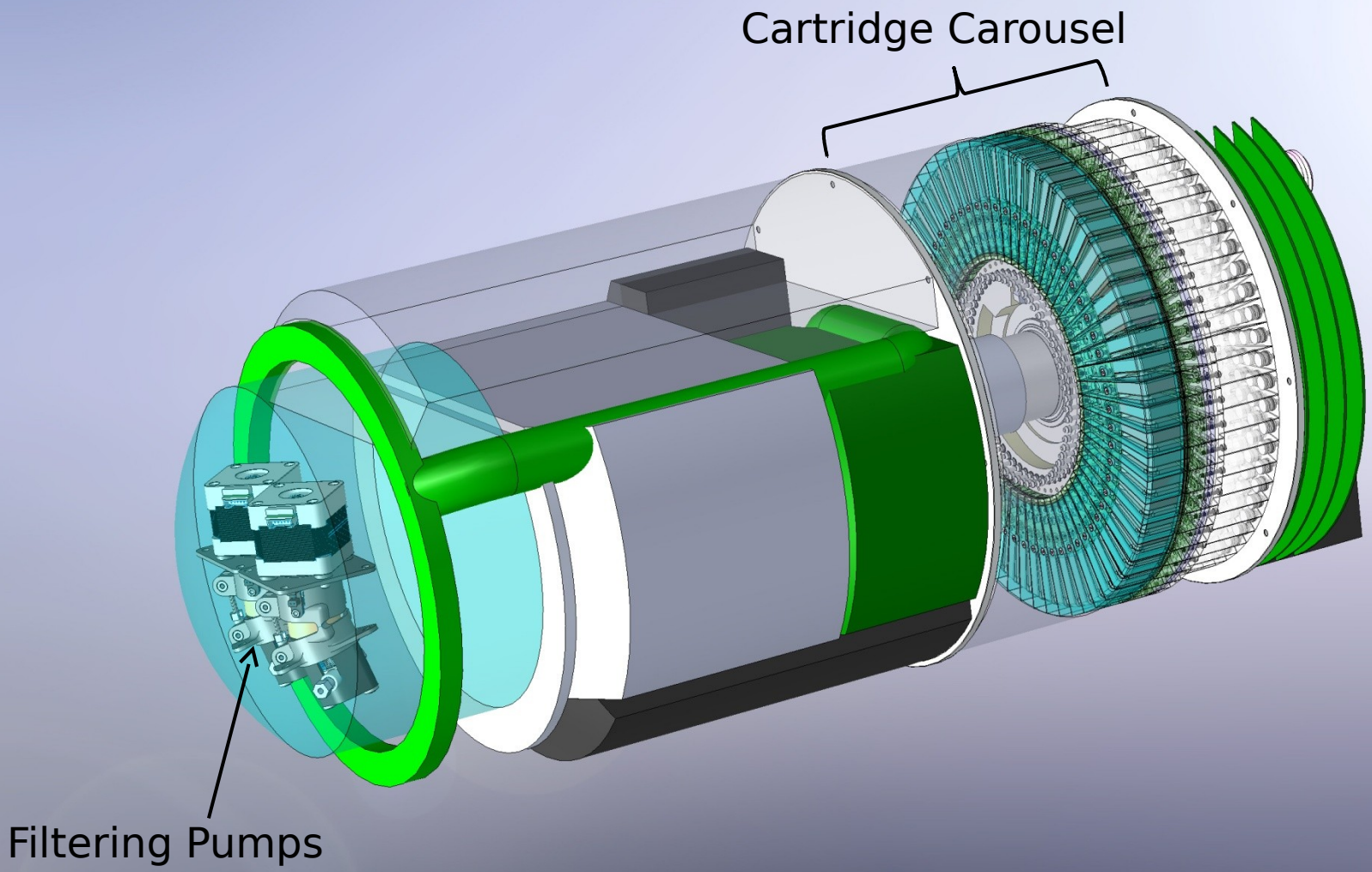
700cm

3 meters



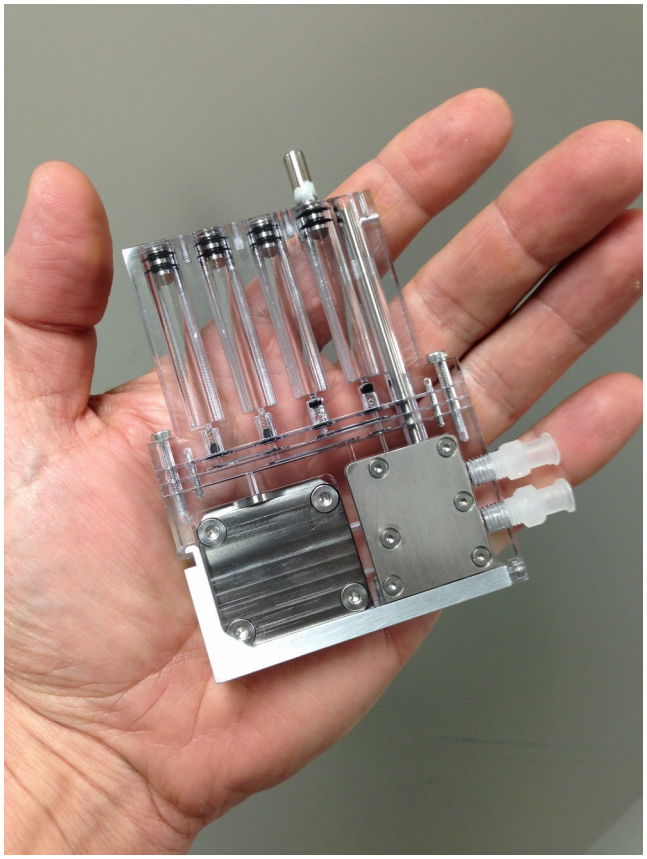
C-MORE
Center for Microbial Oceanography: Research and Education
Science
Technology
Education and Training
Communication and Outreach
Explore-Experiment-Educate

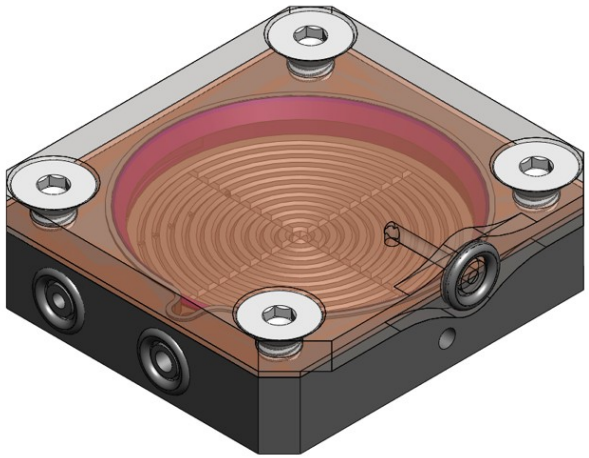
3G ESP Instrument

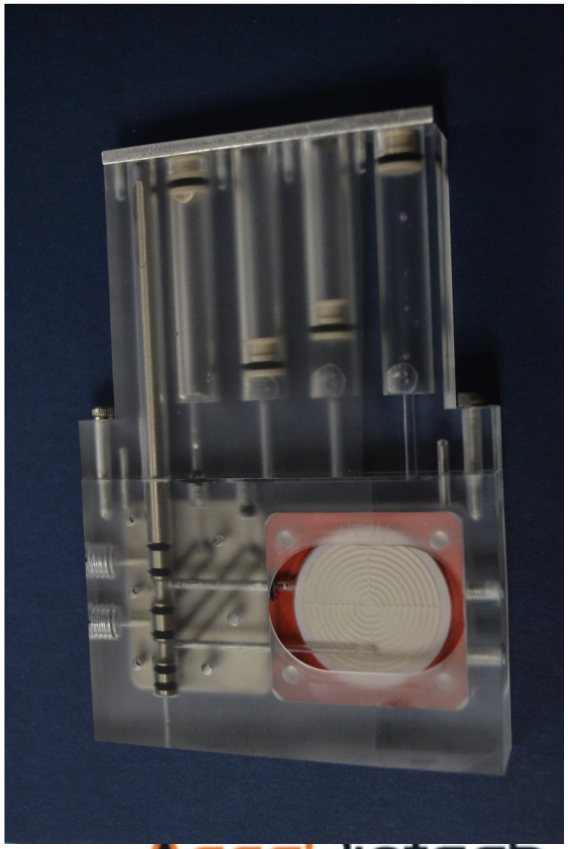


Integrated Cartridge Concept

- All reagents carried onboard cartridge
- Two types of cartridges
  - Archival
  - Lyse-n-go





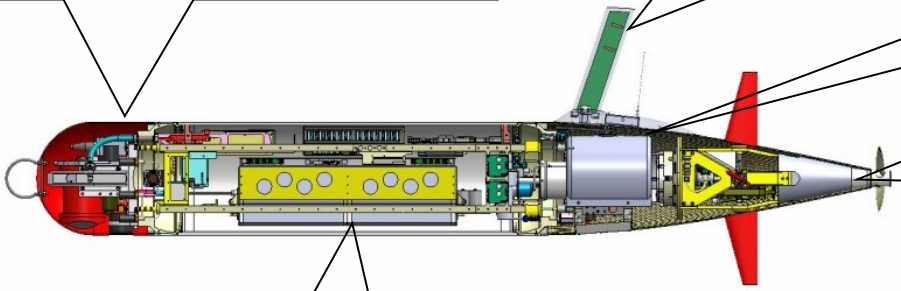


MBARI Long Range Underwater Vehicle

Core sensors: DVL/ADCP (Rowe), Fluorometer/ Backscatter (WetLabs), CTD (Seabird), PAR, O2 (Aanderaa)

Iridium, GPS, WiFi and Cellular in mast
Backup argos and VHF

Buoyancy Engine allows neutral drift in water column



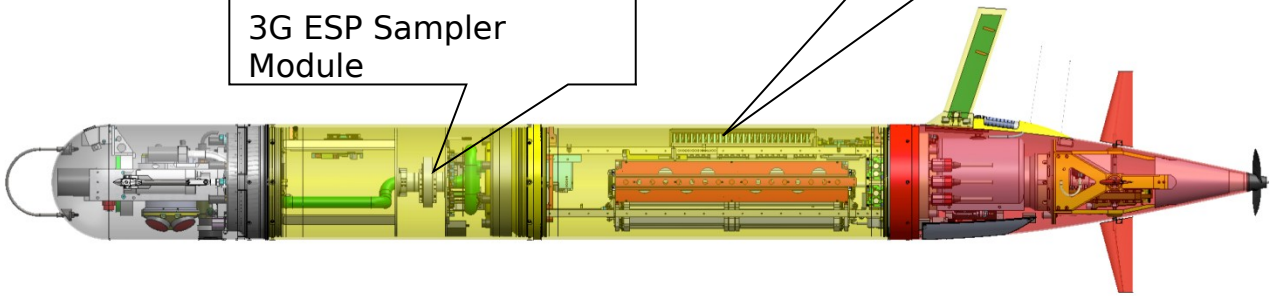
Efficient low-speed propeller
Paired Rudder and Elevator Control Surfaces

Load Control System
18 configurable channels
Isolates load, circuit breaker, ground fault detection

NXP LPC3250 running 2.6 kernel

6 kWh rechargeable,
11 kWh expendable
Shifting Mass allows controlled angle of attack during flight

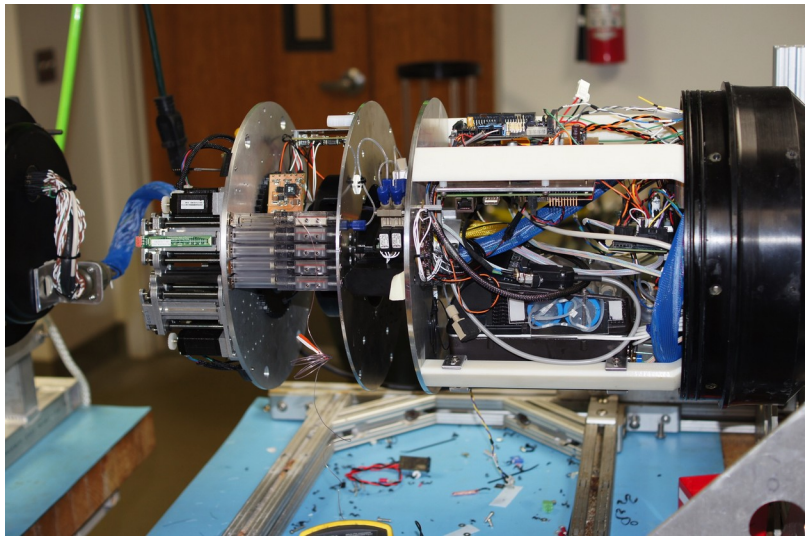
3G ESP Sampler Module



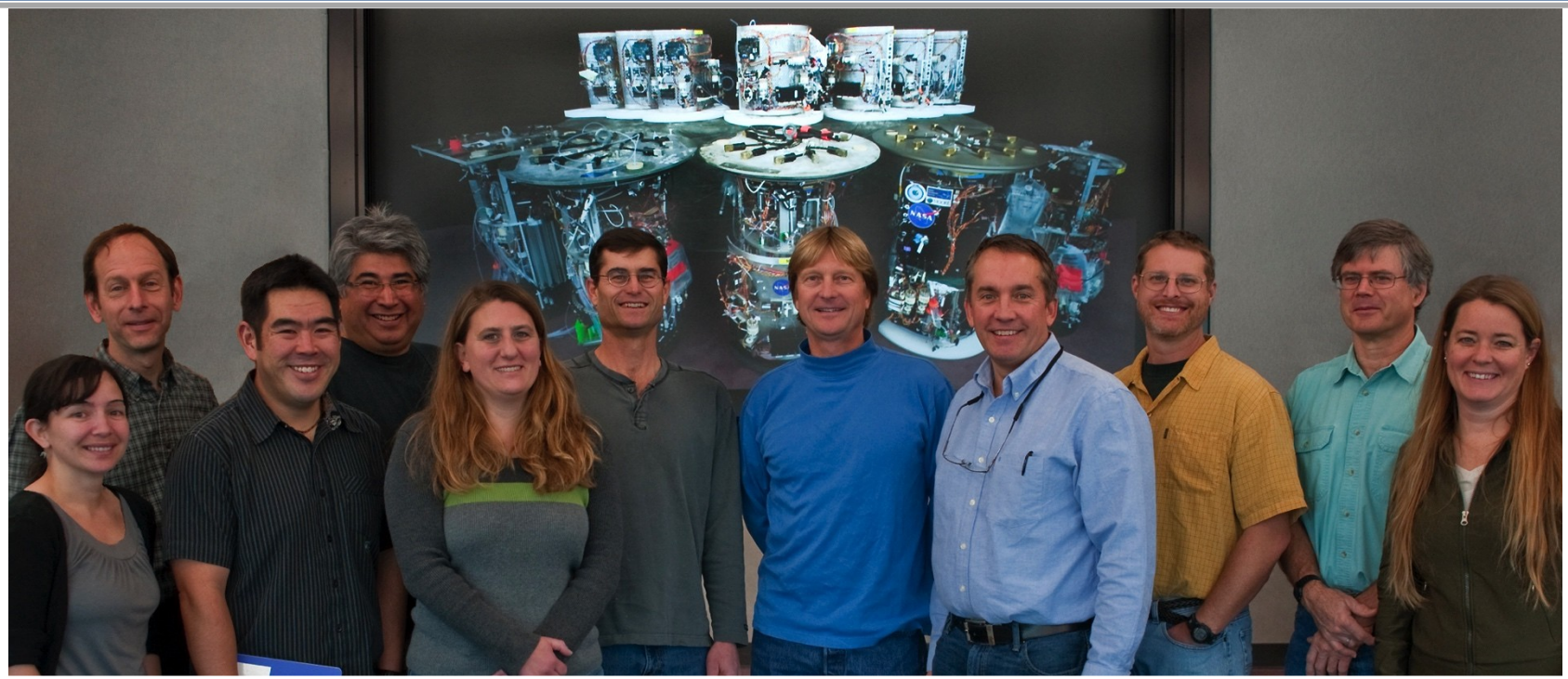
	Short Nose	With 3G ESP Nose
Mass:	110 kg (240lb) dry weight	160 kg (354 lbs)
Size:	0.3m (12”) diameter, 2.47m long	3.18 m long
Speed:	0.5 – 1.2 m/s plus hover	

Long Nose Range Est.: 400 Ah energy, ~1 Ah/h rate, ~3km/h:
~**13 days, 945 km at full speed**

3G ESP/Long-Range AUV



Acknowledgements



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