Vector Field Mapping and Analysis Using Finite Sensor Swarms

DARTMOUTH
UNDERGRADUATE
CREEK
SURVEYOR

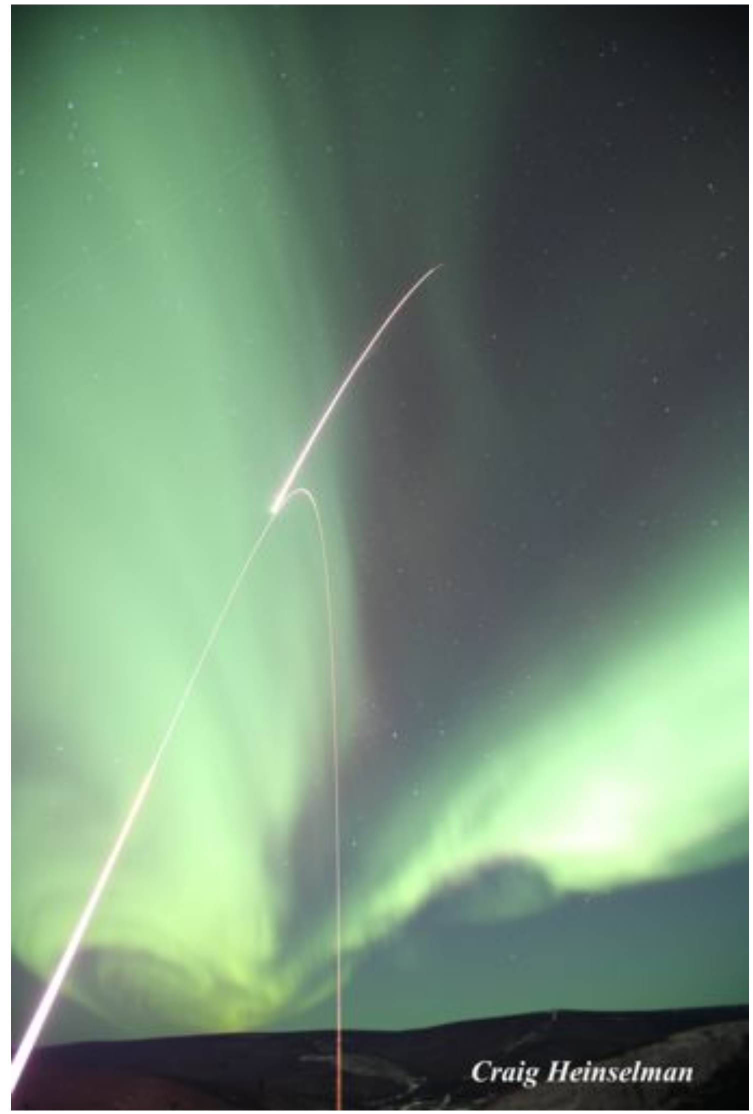
Amanda Slagle
May 28, 2012

Outline

- Introduction
  - Auroral physics motivation
  - Divergence, curl, and continuity
  - Rivers: a nearby vector field
  - GreenCube's history with low-resource technology
- Statement of Thesis
- Methodology
  - Payload Overview
  - Electronics Details
  - Mission management and the student team
  - Field Work
- Data
- The future for DUCKS

Introduction

- Auroral physicists study movements of ions, electrons, and the E and B fields associated with them
- Ultimate goal: use a swarm of payloads to map the vector and scalar fields associated with plasmas
- This thesis focuses on what can be learned about multipoint instrumentation and methods using ground-based experiments



River flow as a 2D scalar and vector field

Similarities to aurora:

- Both are vector fields
- Both describe the behavior of fluids

Differences:

- Payloads floating downstream move with the flow field rather than through it
- Rivers are neutral rather than charged
- Rivers are more or less time stationary for the duration of a mission, which hugely simplifies data analysis

Vector operations with neutral fluids

- Continuity equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0$$

  - Density of water in a river is constant, so it can't bunch up anywhere.

- Divergence

$$\operatorname{div}\,\mathbf{F} = \nabla\cdot\mathbf{F} = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z}.$$

  - In 3D, there should be no divergence, but since we are taking a 2D cut, any divergence would indicate an upwelling

- Curl

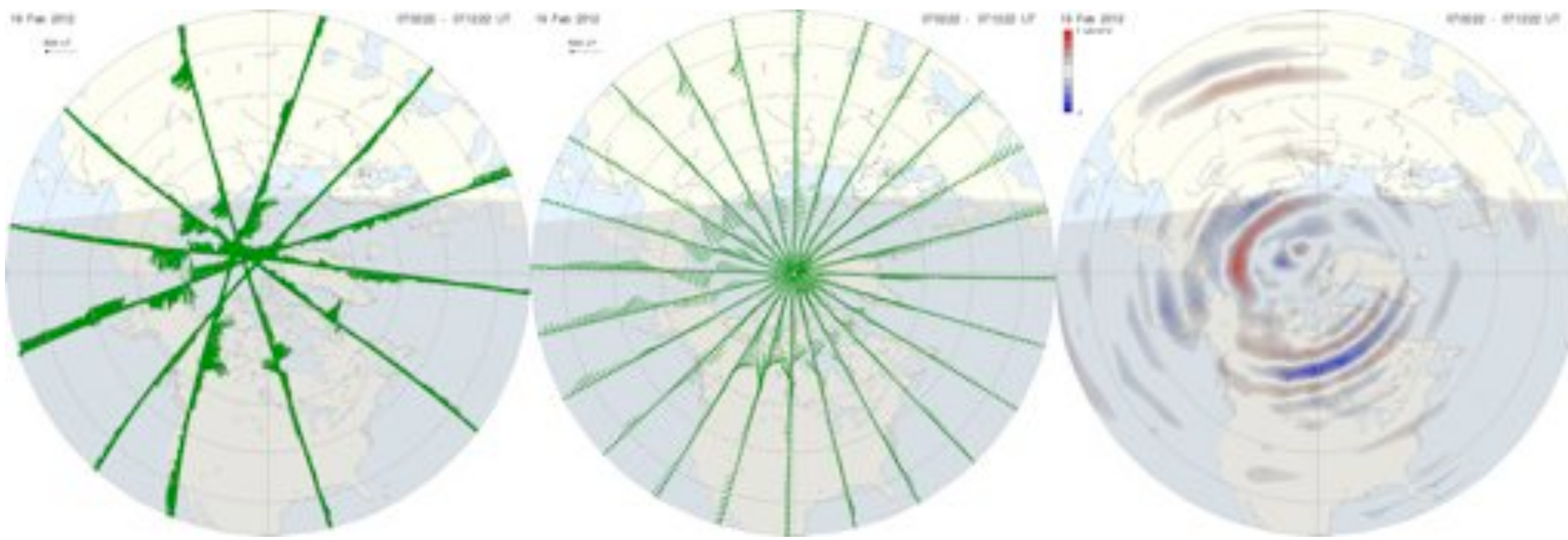
$$\left(\frac{\partial F_z}{\partial y} - \frac{\partial F_y}{\partial z}\right)\mathbf{i} + \left(\frac{\partial F_x}{\partial z} - \frac{\partial F_z}{\partial x}\right)\mathbf{j} + \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}\right)\mathbf{k}$$

  - Curls should occur in spots where a payload spins around in eddies or where the course of the river bends

Equation images from wikipedia

Plasmas

- Continuity equation still applies
- Can have curls of E-fields, Faraday's Law
- Or curls of B-fields, Ampere's Law



http://ampere.jhuapl.edu/

Large Woody Debris

- Logs at least 4 inches in diameter and 6 feet long
- Trapped LWD creates low-velocity pockets of water that serve as fish habitats

"Large Woody Debris Fact Sheet", CT DEP

- LWD stabilizes river banks and helps control erosion due to flooding

Recap

- River flow is both a useful proxy for aurora and interesting for environmental science reasons
- Now that we've chosen a suitable vector field, we just need a swarm with which to measure it.
- How do we build one?
  - Fortunately, the GreenCube group has a history of using low-resource technology for science missions, including taking multipoint measurements.

GreenCube history

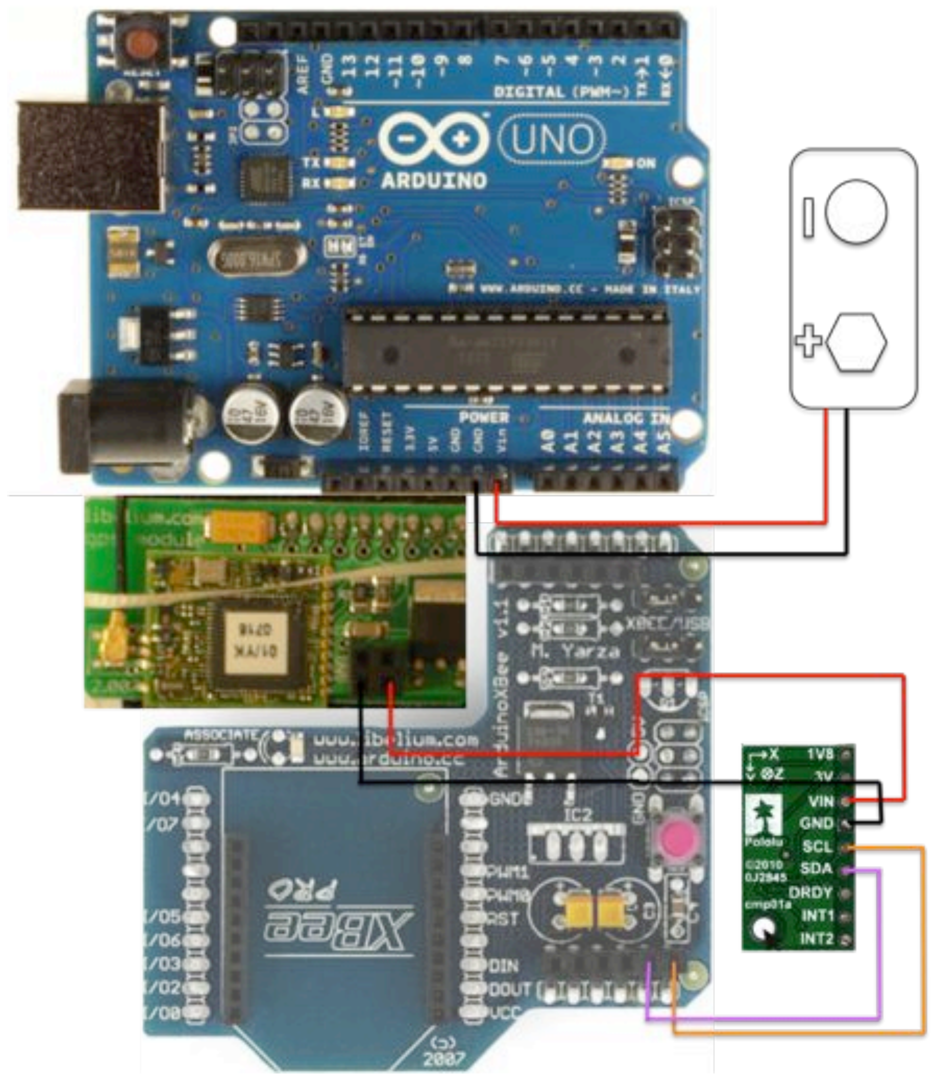
- GreenCube2 (2009): first attempt at multipoint measurements, studying gravity waves over New Hampshire
- GreenCube3 (2010): telescope tracking using real-time GPS coordinates; first work with radio systems intended for networking
- GreenCube4 (2011 - 2012): solar panels, first use of Arduino

Knowledge gained from GreenCube

- Mass production
- Use of Arduinos and networked radios
- Fielding a team of students for a mission
  - Launch procedures modeled after a rocket launch
  - Mission Readiness Review document

Commercially available technology

- Can be put together and used with relatively little additional design work or fabrication time
- Ability to build the swarm in 7 months



Statement of Thesis

The GreenCube team has built 20 “Duck” payloads out of low-resource, commercially available technology that can measure position, acceleration, and magnetic field. These are capable of taking measurements to map and analyze the flow fields of the Connecticut and Ompompanoosuc Rivers, the results of which can be used both to inform LWD studies and to explore issues related to the development and use of payload swarms.

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  - Electronics Details
  - Mission management and the student team
  - Field Work
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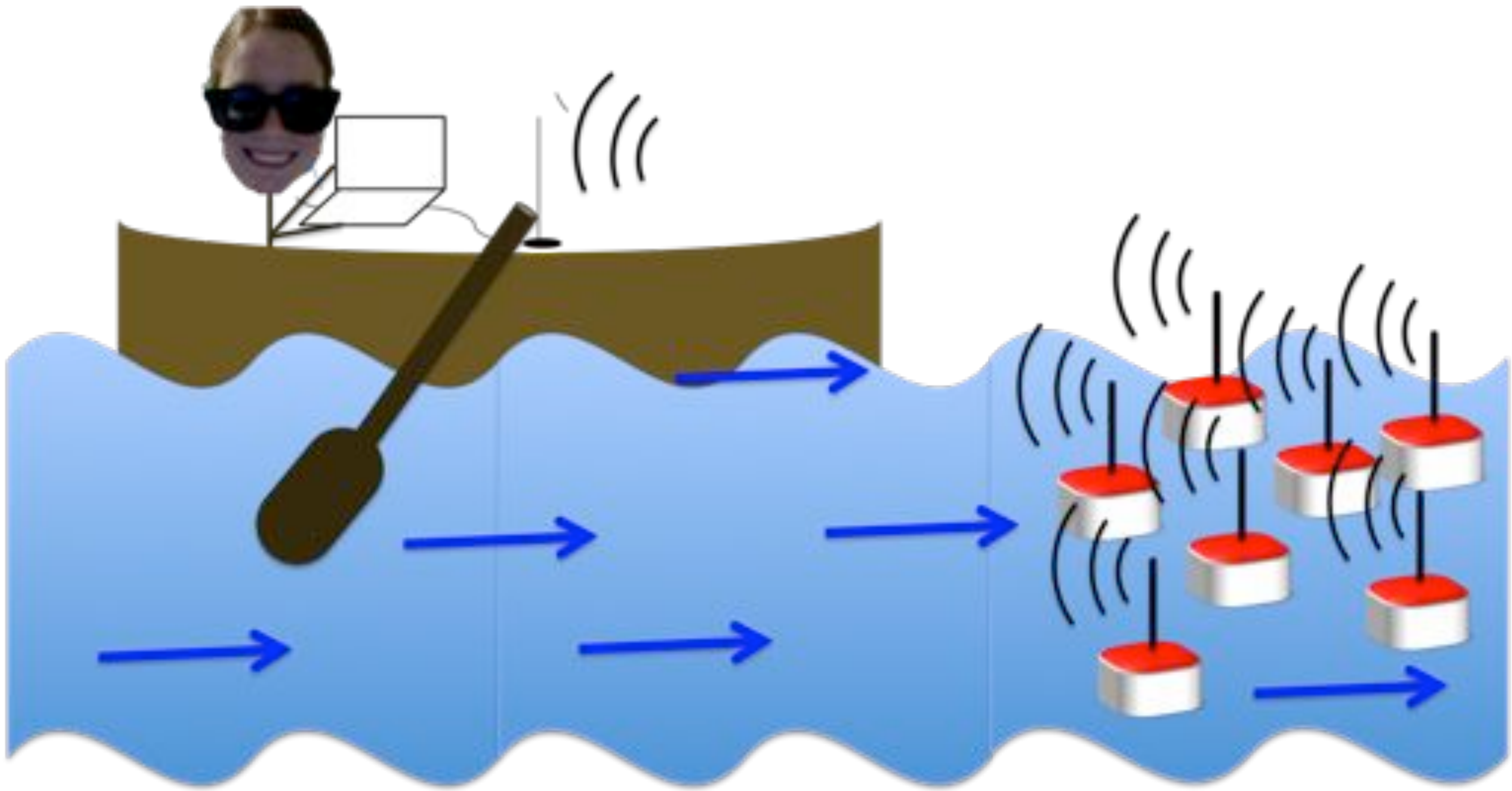
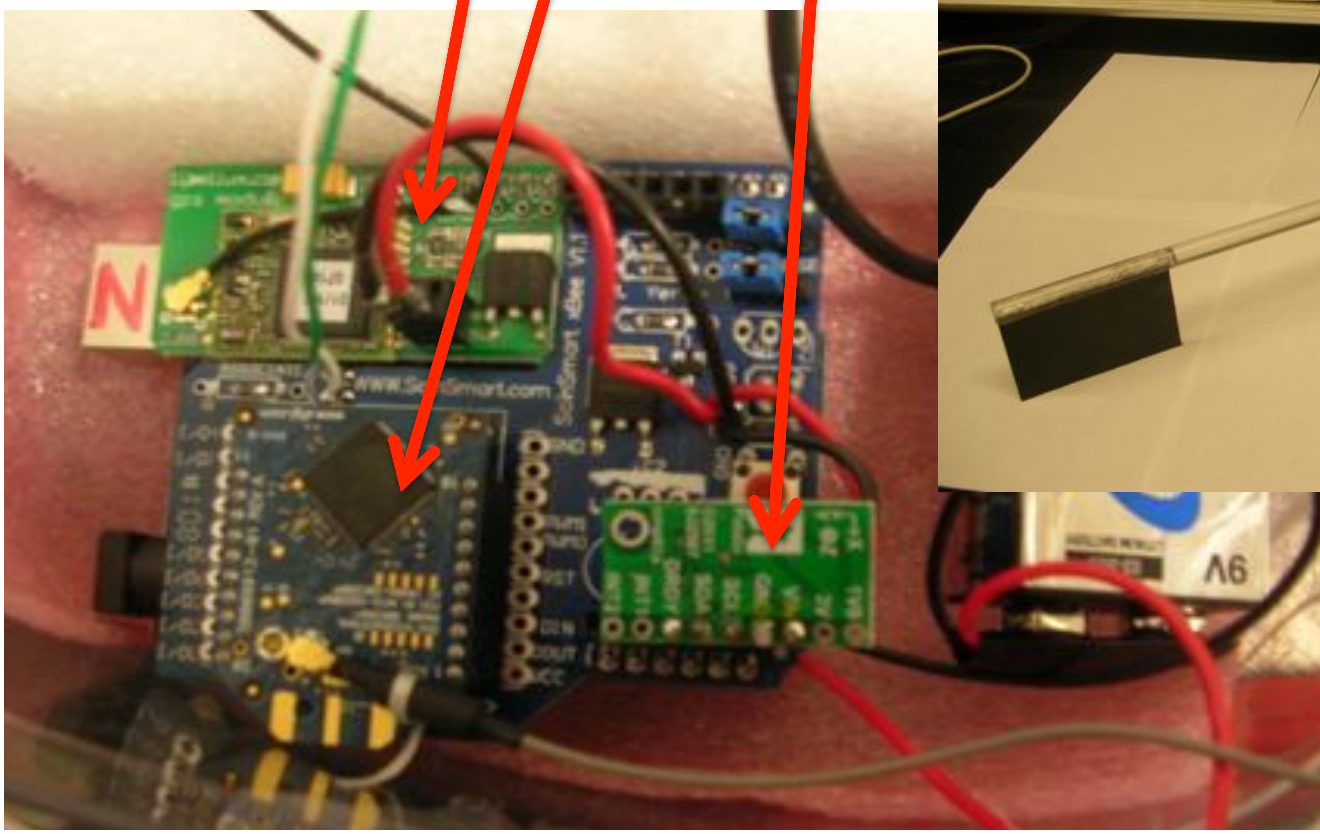
Methodology overview

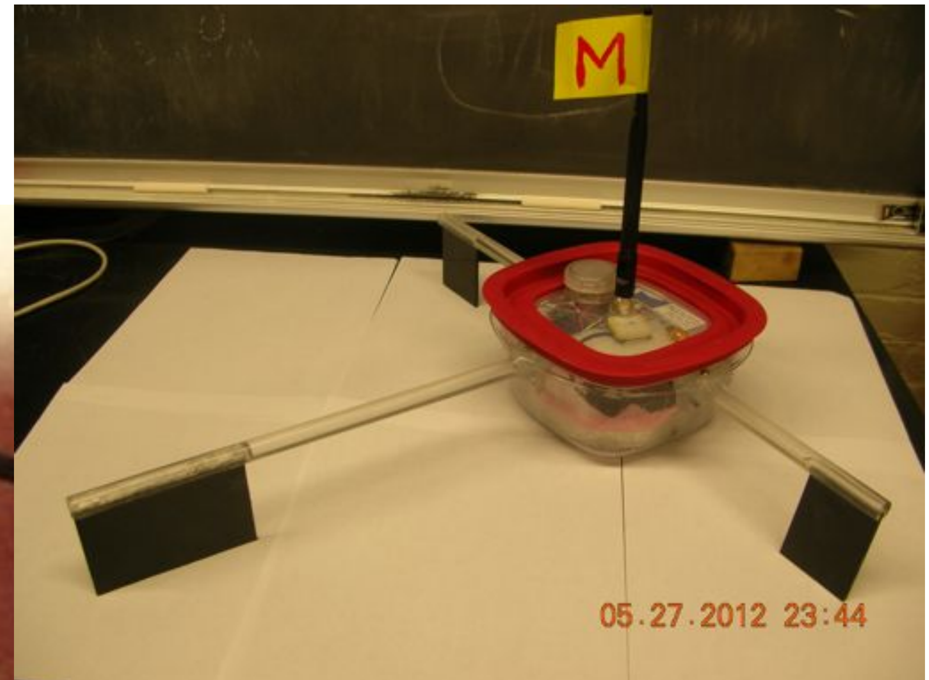
- Missions last for a few hours, a few miles
- Payloads transmit once/second



Payload overview

- Electronics stack: Arduino UNO, compass board, GPS, radio
- Battery
- Weight





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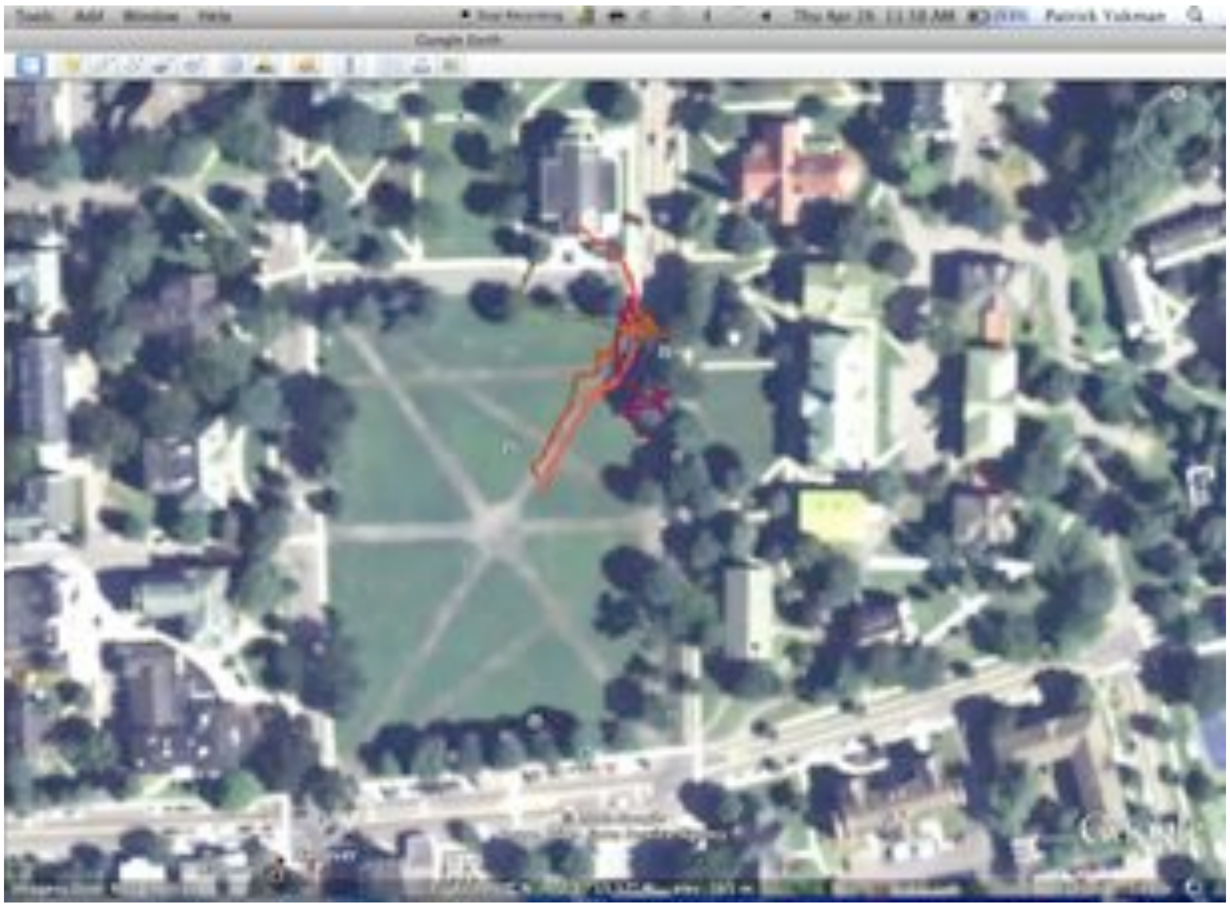
Arduino UNO

- Open source
  - Quick and easy to learn!
- Fast and low power
- Atmel microprocessor, wrapper for C language
- Analog and digital inputs for sensors

www.arduino.cc

GPS

$GPGGA,171034.000,4346.480,N,07215.306,W ,1,05,2.4,0134.7,M,-32.5,M,, B

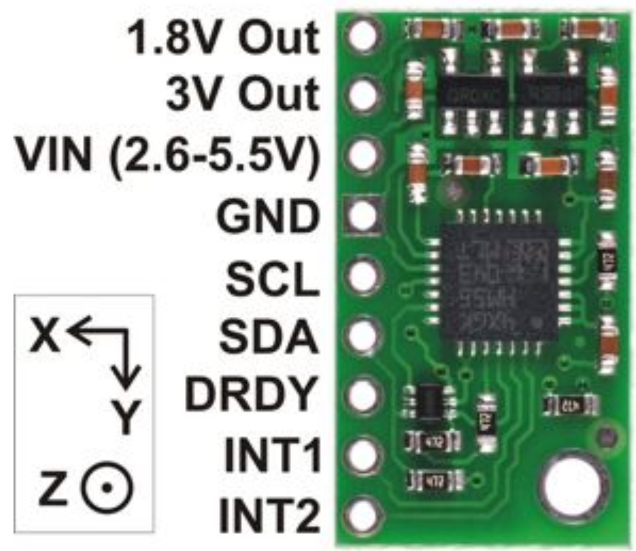


www.cooking-hacks.com

Compass board

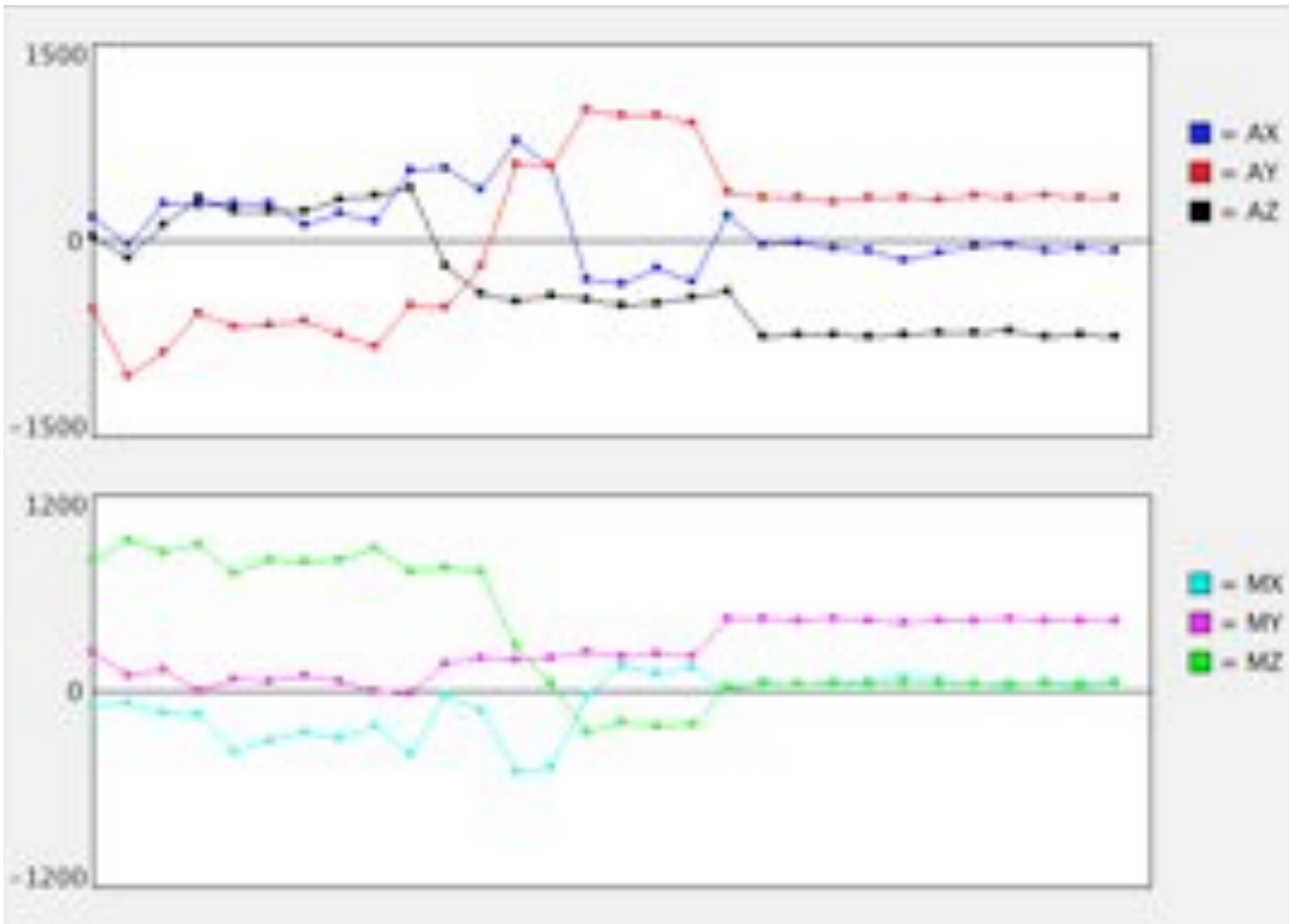
A X: -0001 Y: -0012 Z: -1038 M X: -0017 Y: +0474 Z: +0001 1971 J

- Measures Earth's magnetic field and acceleration due to gravity
- Used to determine payload orientation
- From NOAA's magnetic field property calculator, Earth's magnetic field in Hanover is approximately:
    - 0.498 gauss in the vertical (downward) direction
    - 0.186 gauss in the northward direction
    - -0.049 gauss in the eastward direction
- Our compass board has an input range of +/-1.3 gauss and a gain of 1100 LSB/gauss



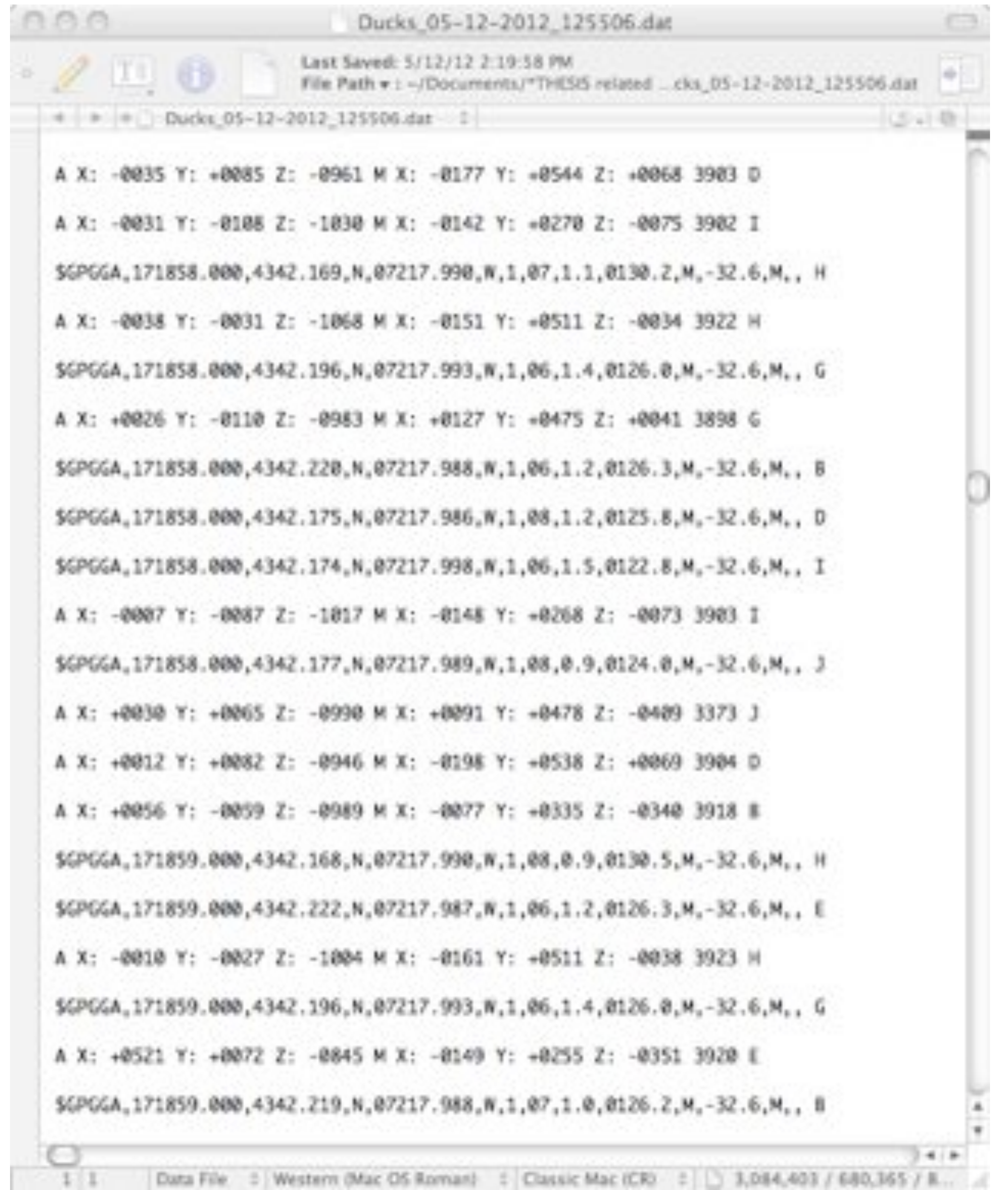
www.pololu.com

Magnetometer/Accelerometer Data



Radios

- One mile maximum range
- Easy to interface with Arduino
- Star network configuration



Testing

- One complete duck was taken to the river and allowed to float and transmit data while attached to a tether
- All ducks were taken outside and allowed to run until they acquired a GPS lock.
- All ducks were rotated through 180° in each axis to confirm magnetometer and accelerometer functioning

Mission Management

In a nutshell, making sure that everything about the mission comes together properly.

- Do all the team members have jobs?
- Will all the parts fit together and work as a whole?
- Do we have all the equipment and personnel needed for a launch?
- Once we are ready for a launch, what do we do?

Student Team

- DUCKS project involves students at a variety of experience levels, for example:
  - Presidential scholar student Jon Guinther
  - Sophomores Patrick Yukman, Tom Whalen
  - Women In Science Project interns Ellen Weburg and Ha Nguyen
  - And many others! (currently a total of 13 students)

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Field Work

Two launches:

- May 12, 2012 Connecticut River
- May 19, 2012 Ompompanoosuc River

Procedures

- GreenCube group launch procedures are based on a rocket launch
- MRR document details all actions that should be completed during a launch, such as:
  - Pre-launch sensor and telemetry testing
  - Duck deployment
  - Protocol for stuck ducks
  - Duck retrieval

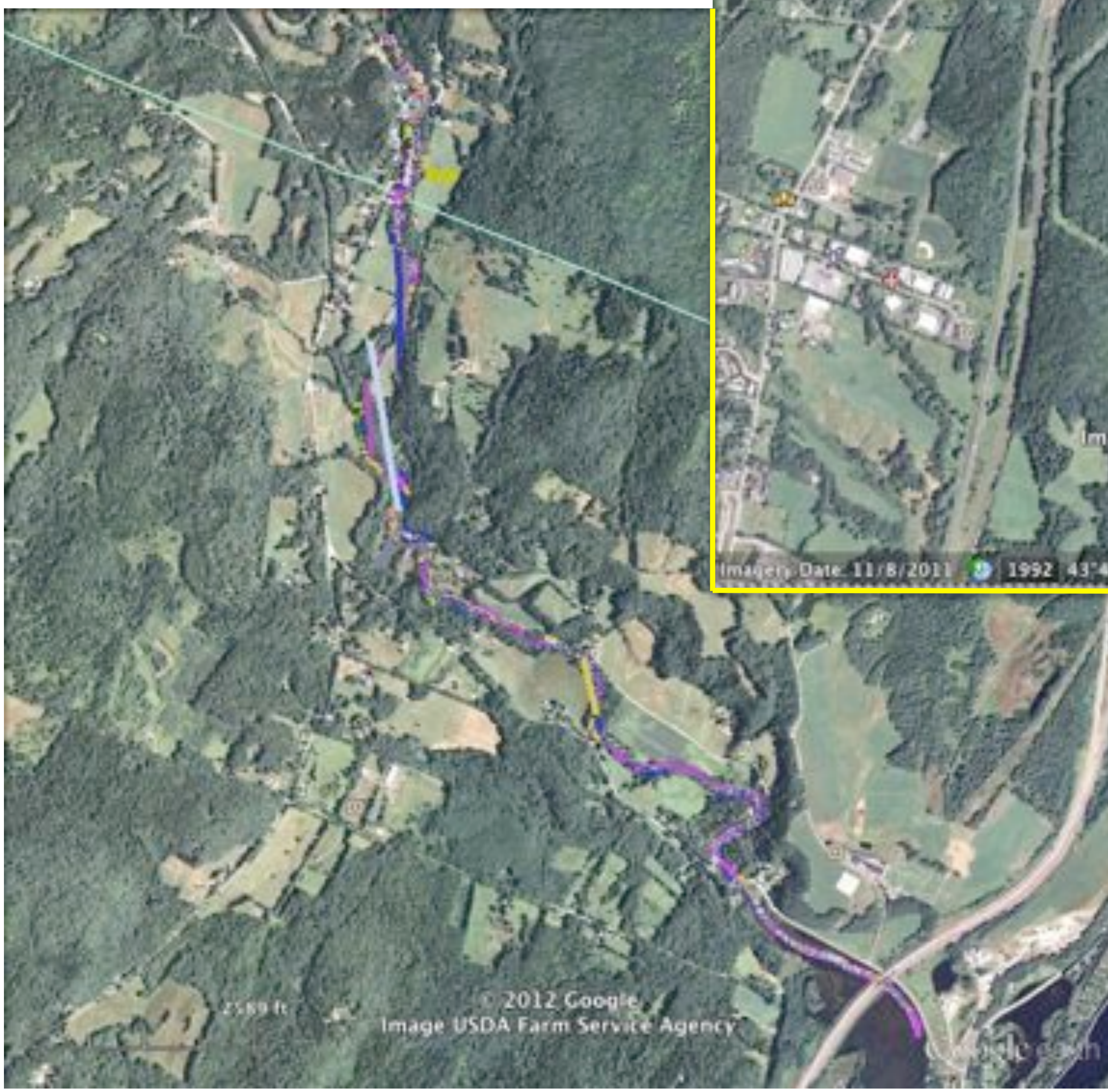
Real-time data display

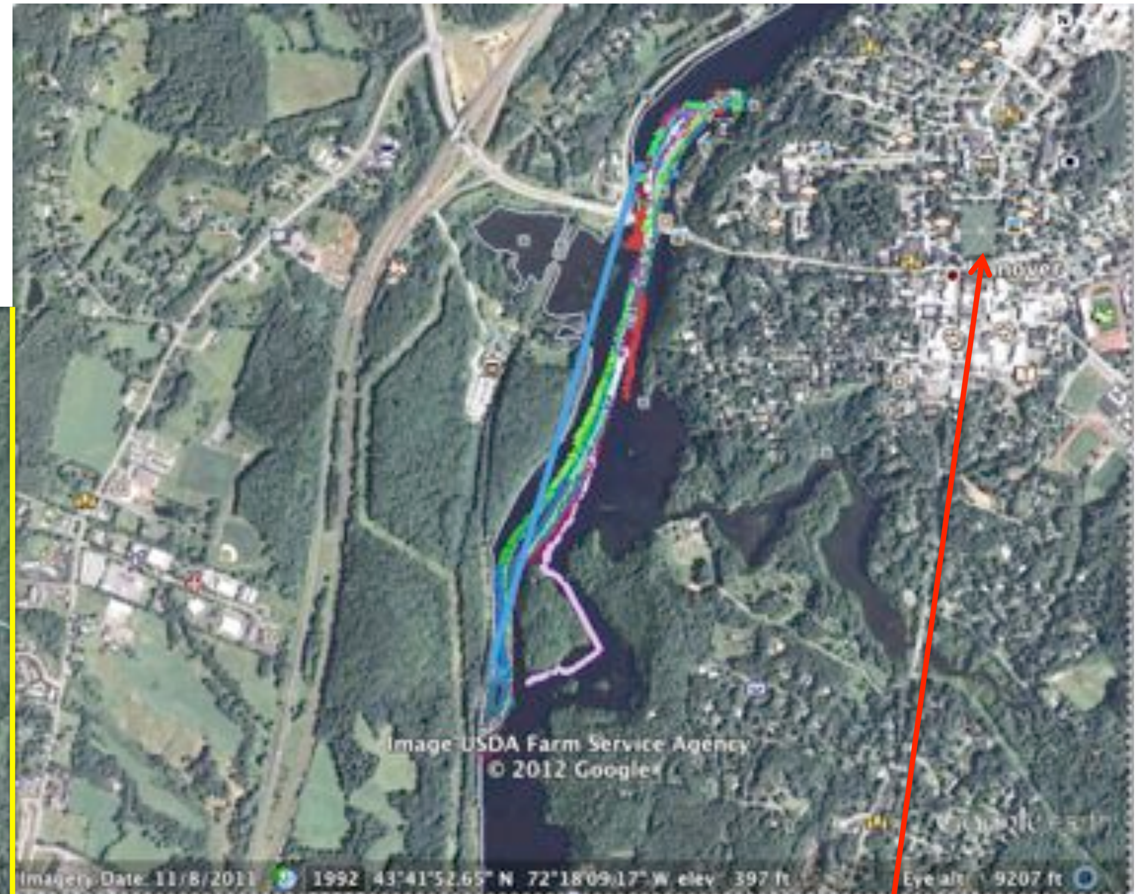
	#Sats	Lat.	Lon.	Acc. Z	Valid?
Axl	6	43.790883	-72.25545	-132	
Buddy	6	43.7909	-72.25565	-585	
Chuck	5	43.790883	-72.255517	-230	
Diana	5	43.790867	-72.255583	-115	
Ella	6	43.790883	-72.255483	-86	
Freddie	5	43.790917	-72.255567	-264	
George	6	43.790917	-72.2556	-103	
Hendrix	6	43.79085	-72.255533	-459	
Iggy	4	43.7909	-72.255483	-34	
Janis	6	43.790867	-72.255583	-1021	
Kurt	5	43.79095	-72.25565	-871	
Lynyrd	6	43.790883	-72.255417	-264	
Madonna	7	43.79095	-72.255633	-323	
Norah	0	0.0	0.0	0	
Ozzy	5	43.790783	-72.255433	-1025	
Page	3	43.826367	-72.363833	117	
Queen	1	0.0	0.0	-950	
Ricky	5	43.79085	-72.255467	-691	
Stevie	6	43.7909	-72.255567	-616	
Tina	6	43.790883	-72.25555	-77	

Darkwing DUCKS software created by Patrick Yukman

Break for duck slideshow

GPS tracks made in Google Earth





Dartmouth College Green

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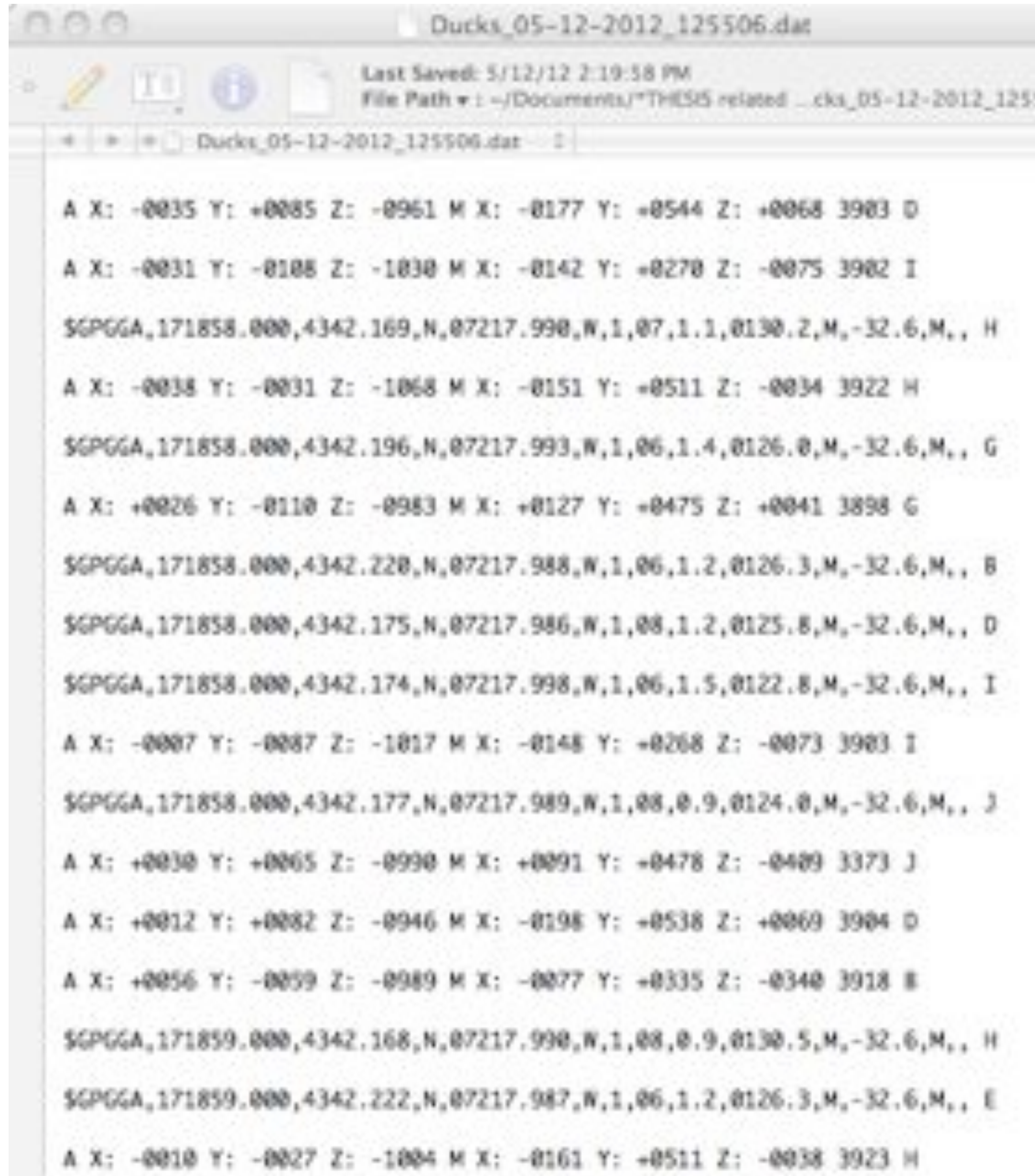
Data overview

- Data sent from the ducks gets written into a giant file, see right
- Then transmissions from each individual duck must be separated from each other
- GPS and mag/accelerometer data must be separated
- Position data from GPS must be converted into velocities


Ducks_05-12-2012_125506.dat
Last Saved: 5/12/12 2:19:58 PM

```
A X: -0035 Y: +0085 Z: -0961 M X: -0177 Y: +0544 Z: +0068 3903 D
A X: -0031 Y: -0108 Z: -1030 M X: -0142 Y: +0270 Z: -0075 3902 I
$GPGGA,171858.000,4342.169,N,07217.990,W,1,07,1.1,0130.2,M,-32.6,M,, H
A X: -0038 Y: -0031 Z: -1068 M X: -0151 Y: +0511 Z: -0034 3922 H
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A X: +0026 Y: -0110 Z: -0983 M X: +0127 Y: +0475 Z: +0041 3898 G
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A X: +0030 Y: +0065 Z: -0990 M X: +0091 Y: +0478 Z: -0409 3373 J
A X: +0012 Y: +0082 Z: -0946 M X: -0198 Y: +0538 Z: +0069 3904 D
A X: +0056 Y: -0059 Z: -0989 M X: -0077 Y: +0335 Z: -0340 3918 B
$GPGGA,171859.000,4342.168,N,07217.990,W,1,08,0.9,0130.5,M,-32.6,M,, H
$GPGGA,171859.000,4342.222,N,07217.987,W,1,06,1.2,0126.3,M,-32.6,M,, E
A X: -0010 Y: -0027 Z: -1004 M X: -0161 Y: +0511 Z: -0038 3923 H
```
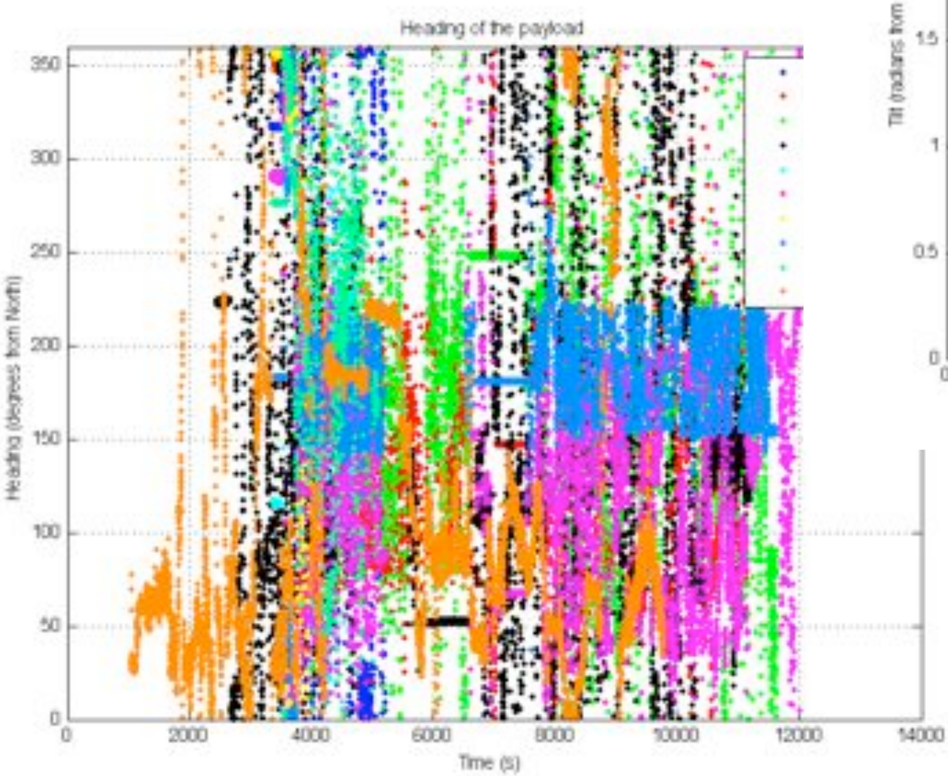
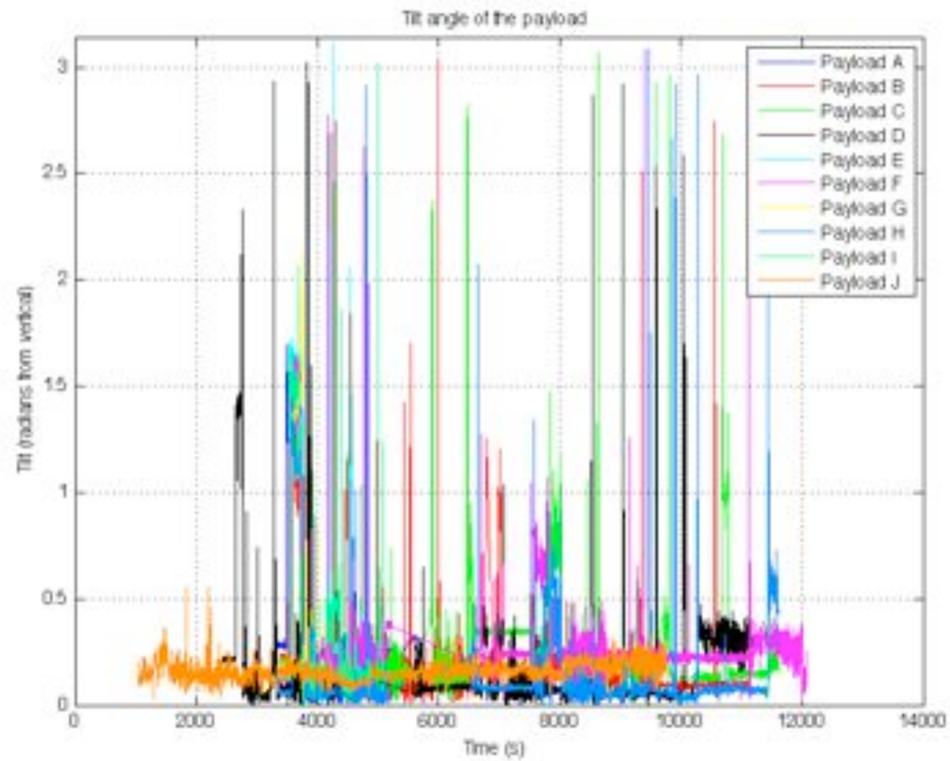

Tilt and Heading Data

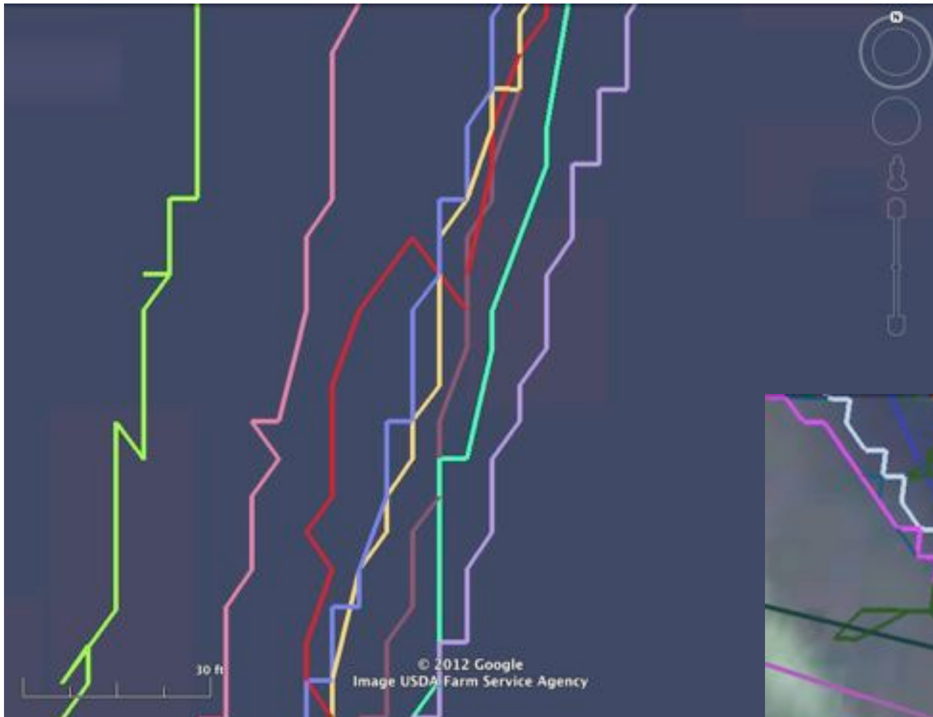
Right: angle of payload tilt from vertical vs time. Note that payloads sit in the water at approximately a 10 degree angle.



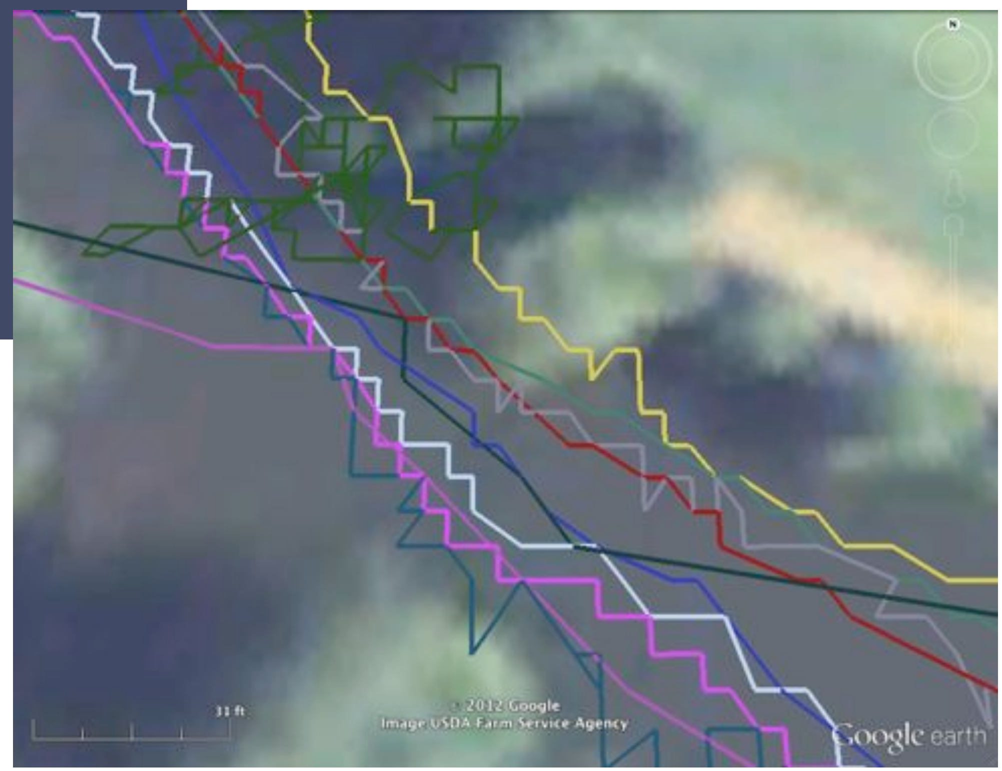


Left: payload heading in degrees from north vs time. Payloads do not display a preferred orientation.
Plots created by Tom Whalen

GPS jitter



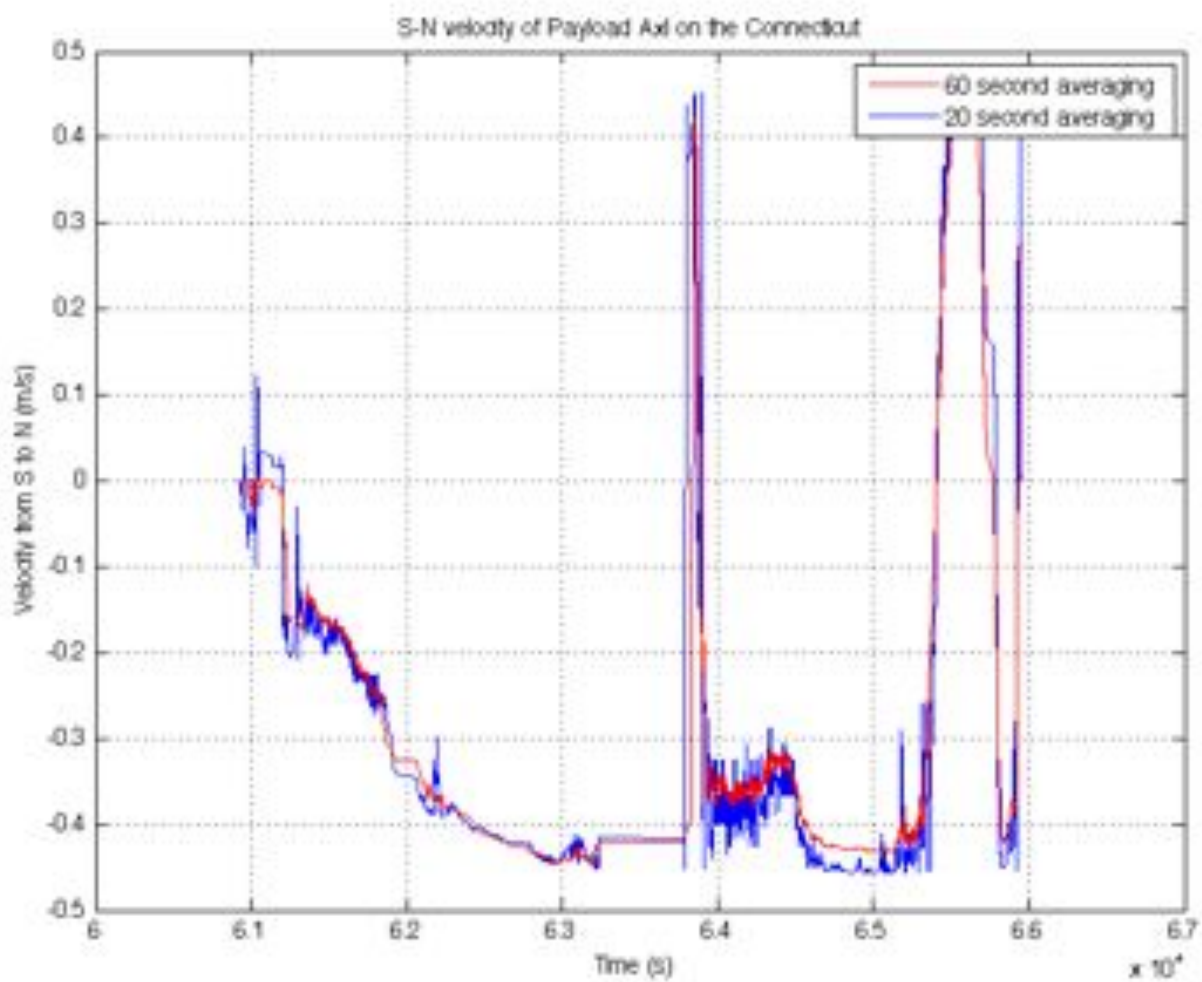
- Jitter is worse for the Ompompanoosuc than the Connecticut
- For both jitter is greater than a payload's downstream movement between measurements



These images show closeups of the GPS tracks from before. The Connecticut is above and the Ompompanoosuc to the right. For scale, the green and pink tracks above are approximately 10 meters apart.

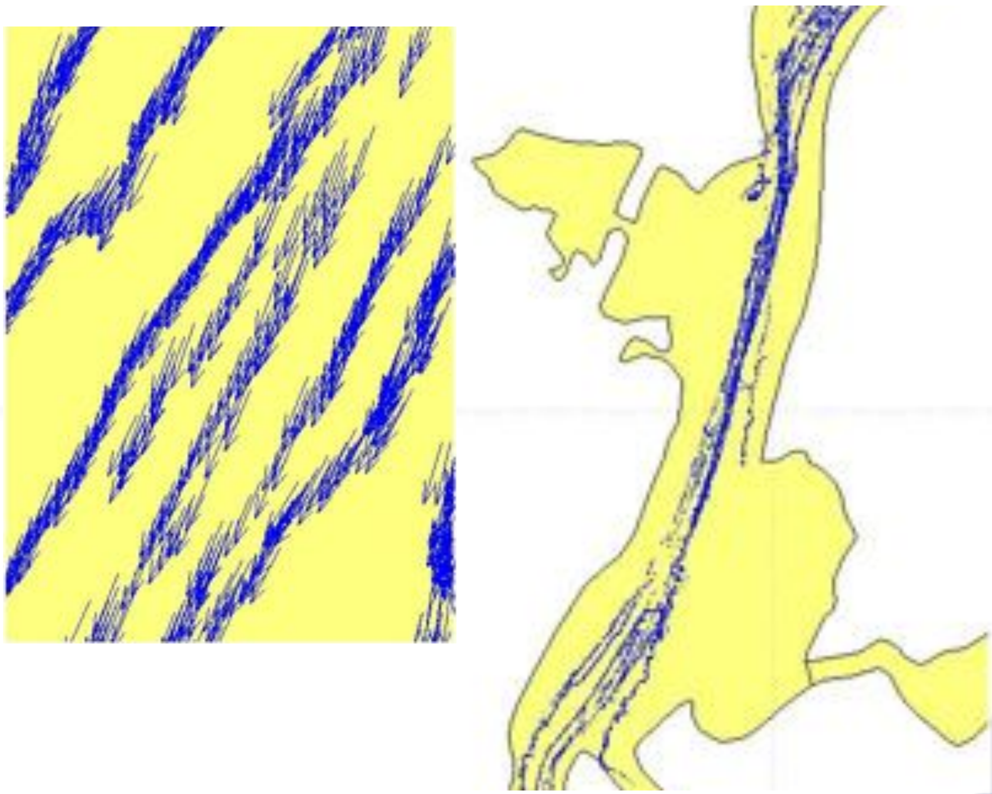
Time averaging in velocity calculations

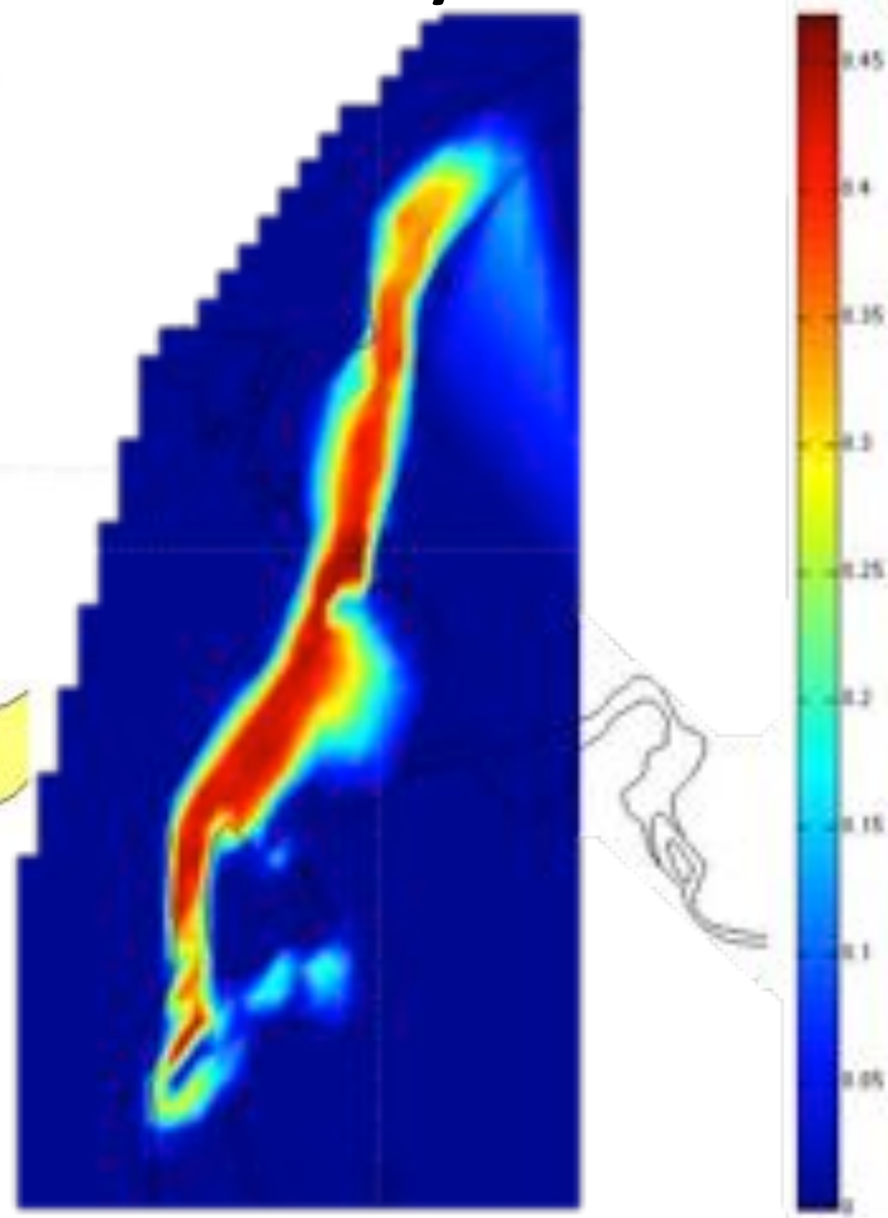
- Velocity for a point was calculated by evaluating the distance traveled by the payload during a time interval surrounding that point.
- No dramatic difference between 20 second and 60 second averaging
- But 60 second averaging is smoother



Plot by Tom Whalen

Connecticut River Velocity Plots

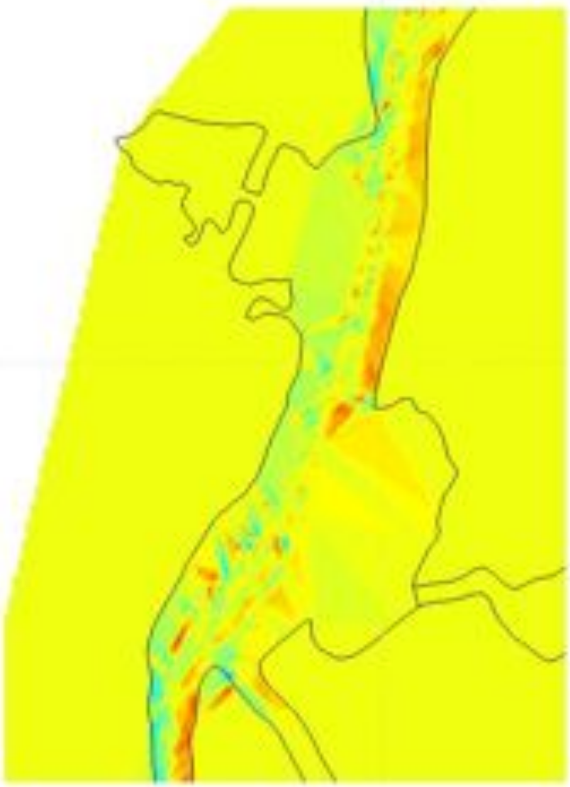




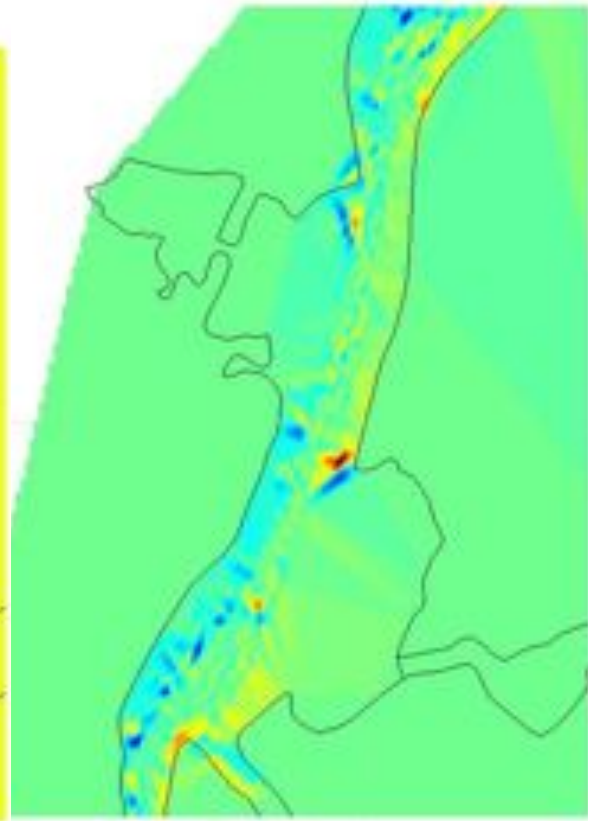
Above: quiver plot of velocities for all payloads on the Connecticut River

Right: Map of scalar magnitude of velocity interpolated from above data; color scale ranges from 0 to 0.45 m/s
Plot by Jon Guinther

Divergence and Curl from Connecticut

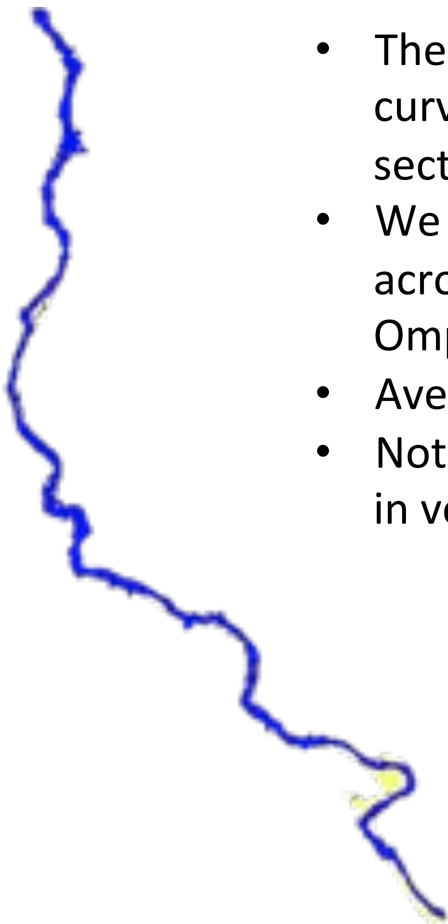


Divergence



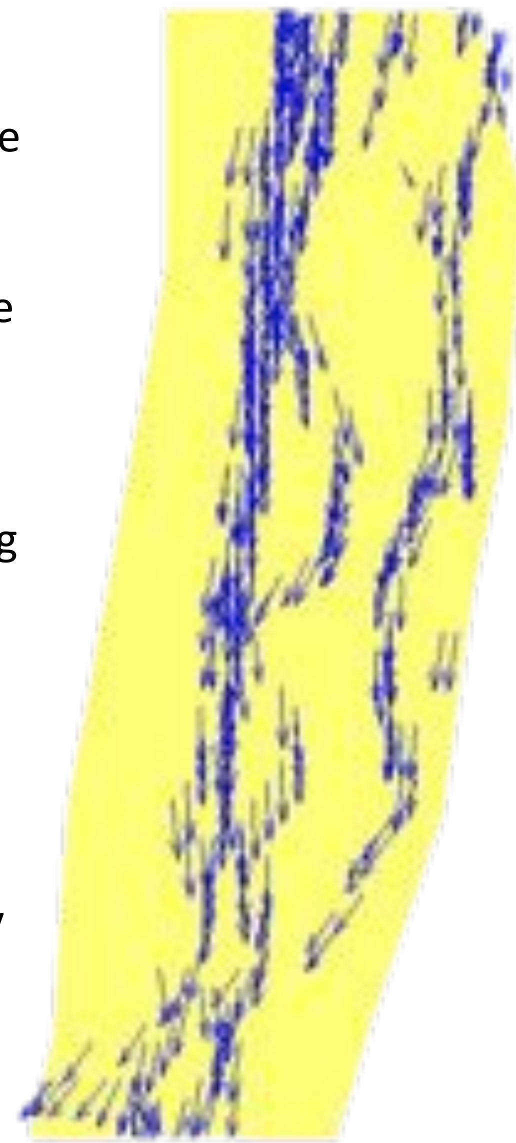
Curl

Ompompanoosuc River Velocities

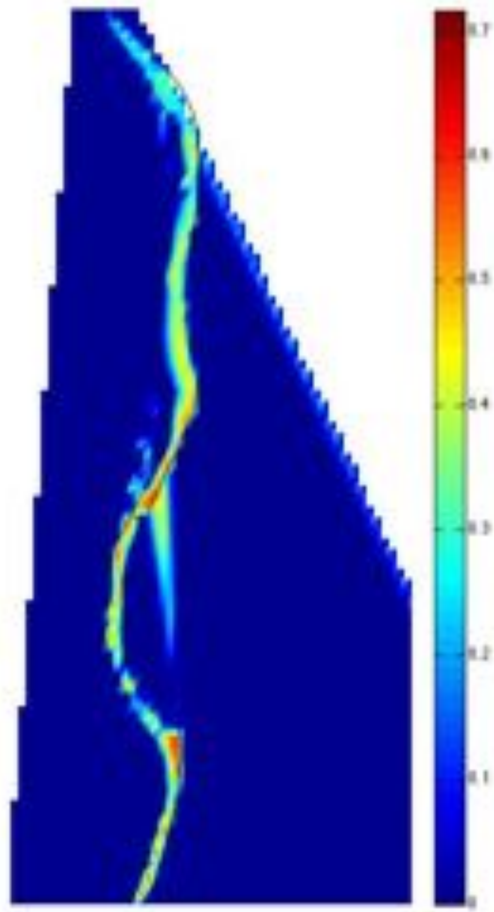


- The Ompompanoosuc has many more curves than the Connecticut for the sections we traveled.
- We achieved better payload coverage across the width of the river with the Ompompanoosuc
- Average velocity is around 0.5 m/s
- Note the sinusoidal pattern appearing in velocities on the far right

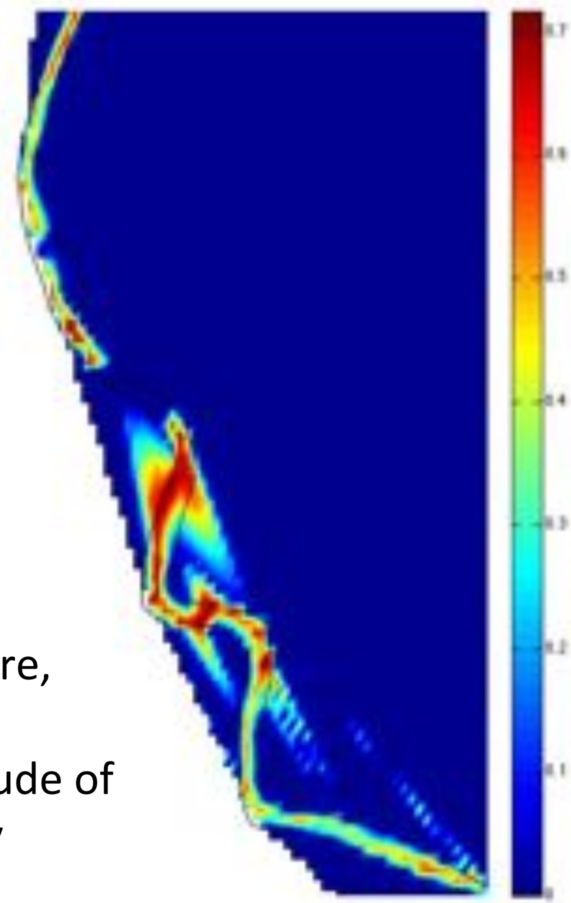
Left: the entire 3.5 mile stretch of the Ompompanoosuc traversed by ducks
Right: Close-up view of velocity vectors on a small section of the river



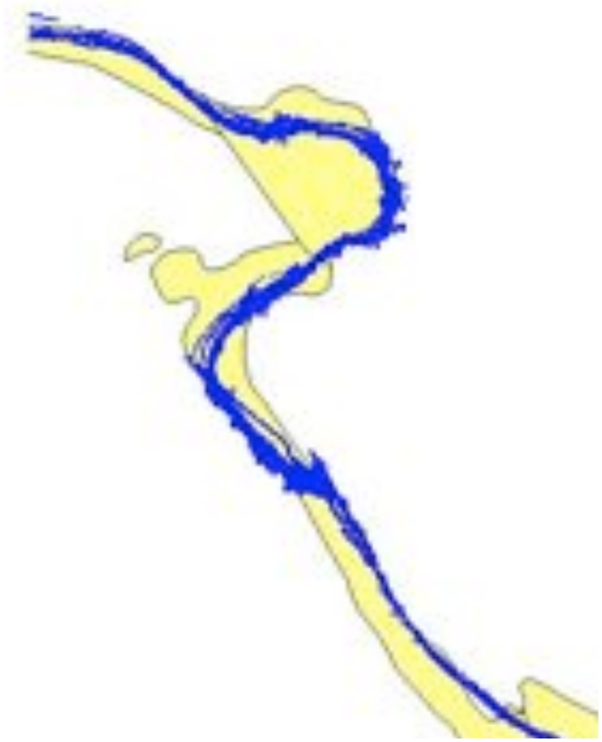
Ompomp River Velocities cont.

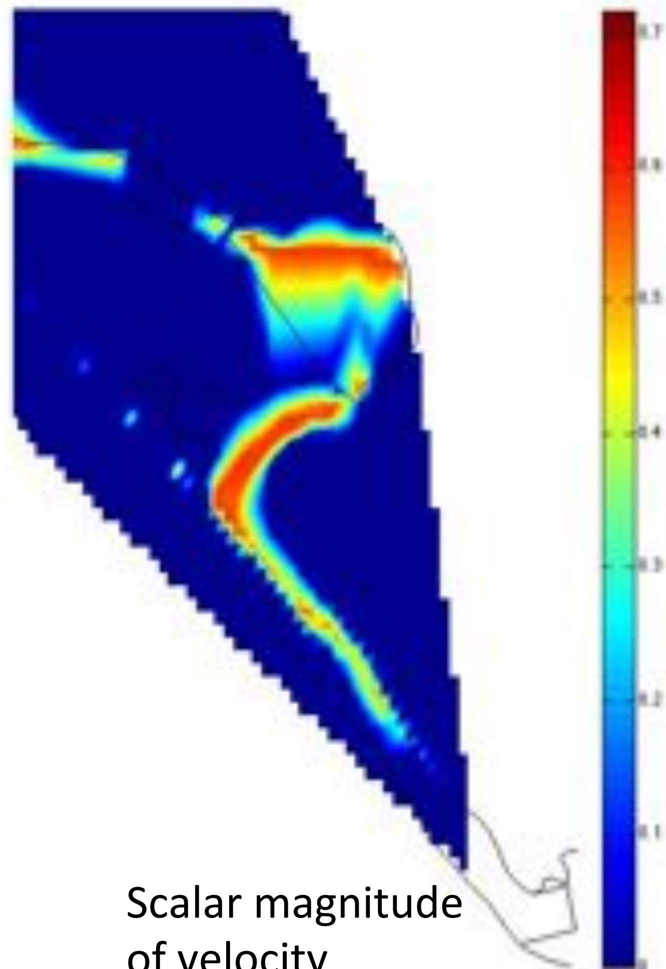


As before, scalar magnitude of velocity



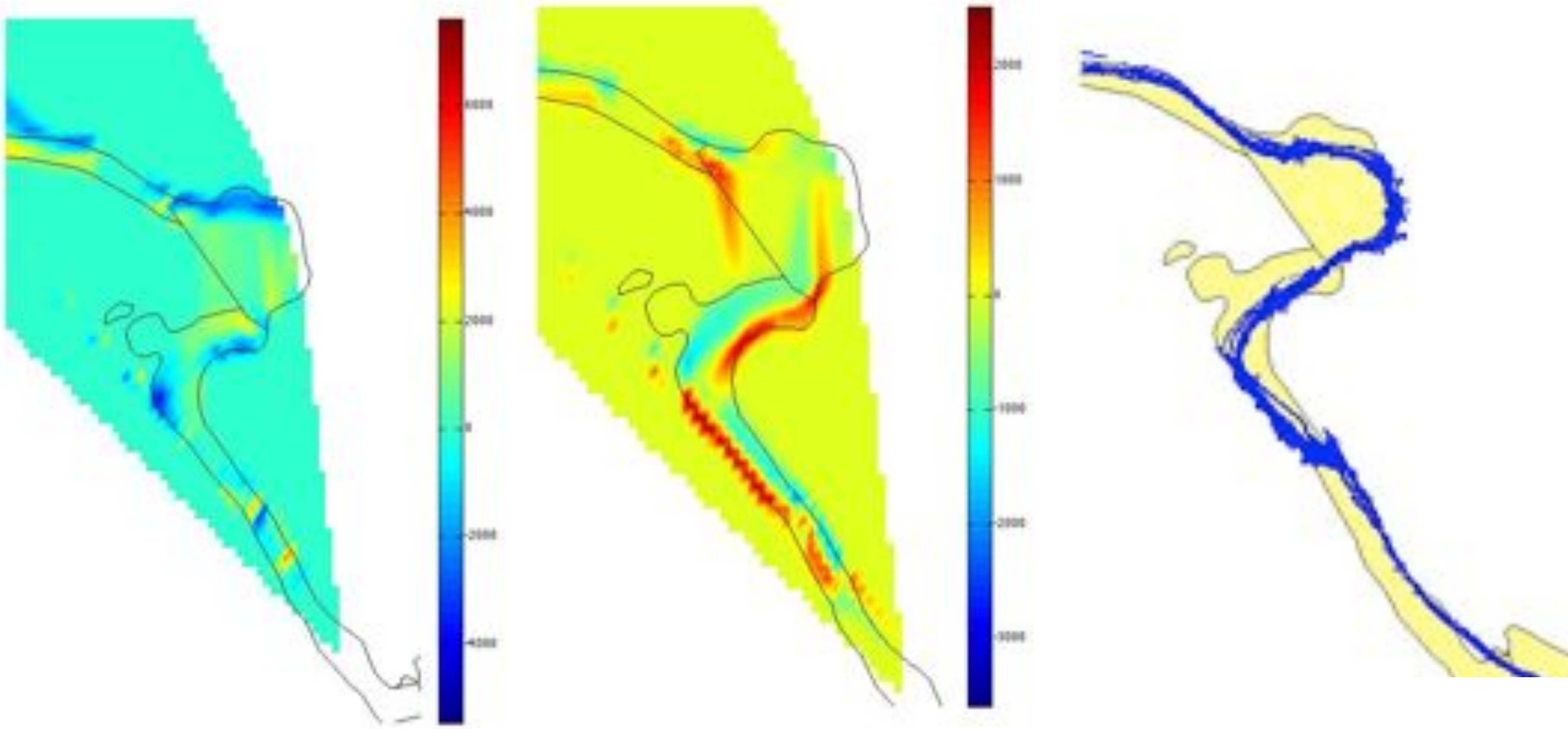
Ompomp River Velocities cont.





Scalar magnitude
of velocity

Divergence and Curl



Conclusions for data

- Data analysis is still ongoing
- LWD investigations with Professor Magilligan: how useful is our river flow data?
- It would be interesting to plot magnitude of velocity across a cross section of the river
- Further study of sinusoidal patterns in flow

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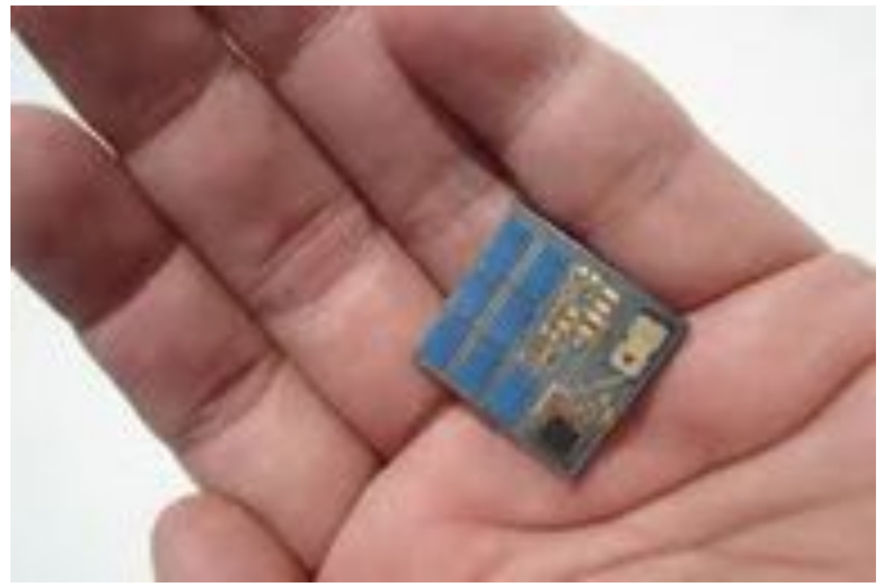
The Future for DUCKS

Other LWD experiments:

- Long term (days to weeks) mission with fewer payloads
- Intentionally launching into a river with many obstructions to study getting stuck
- Payloads should be redesigned to resemble LWD more closely
- Reexamine bridge abutments data

GreenCube4 and Chipsats

- Summer 2012
- We will collaborate with Cornell Space Systems Design Studio
- GreenCube will help them test the behavior of their satellites while hanging from a high altitude balloon and while tumbling after falling from a balloon.



www.engineering.cornell.edu

- GreenCube will also use the opportunity to learn about the Cornell group's software radio.

Small Rockets and Beyond

- 2012 – 2013: the group will adapt duck technology for use with small rockets
  - Vibration-safe housing and high power radios will be needed
- Long term: preparation for orbital missions
  -- Solar power
  -- Additional sensors for auroral physics

Summary

- Thanks to a dedicated group of students and their mentors, DUCKS grew from an interesting idea to a fully operational swarm in the space of one school year.
- The team has made great strides in developing an easily reproducible, low-resource electronics package for a swarm payload, and in learning about mapping vector fields from sparse measurements.
- The knowledge base the group has built through DUCKS will serve as a strong foundation as they continue to work towards truly multipoint ionospheric science.

Acknowledgements

Funding provided by:

- National Science Foundation Outreach;
- JPL Director's Research and Development Fund: Strategic University Research Partnerships

Thanks also to my committee and to the entire GreenCube/ DUCKS team. This project has been a group effort and without their hard work it would not have happened:

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