Adaptive Sampling for MB'03 – Preliminary Update for Discussion

Naomi Ehrich Leonard
Mechanical and Aerospace Engineering
Princeton University

and the Adaptive Sampling Working Group

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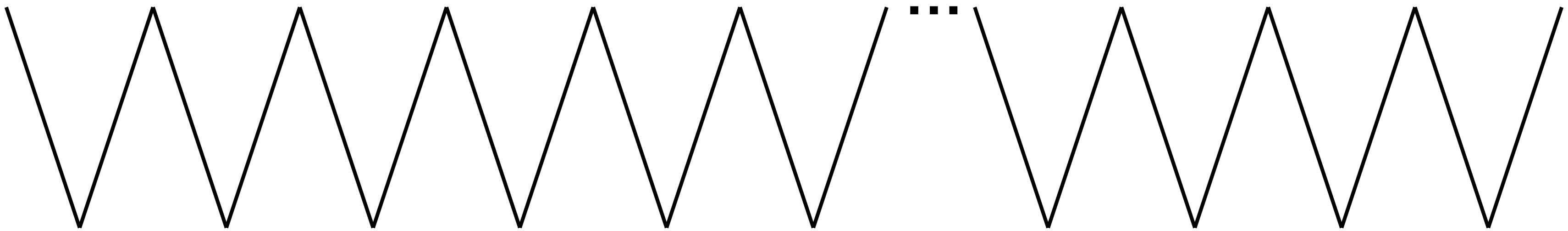
Some of the Adaptive Sampling Objectives

- Use tools to help direct the glider network along feasible and possibly efficient path to sampling hotspots: features of interest/places of greatest model uncertainty.
  - Output from modellers (e.g., identification by HOPS of sites to visit or even a proposed path or series of waypoints) provides input to Princeton/Caltech tools.
  - Princeton/Caltech tools may be helpful in refining initial (open-loop) path plans.
  - Feedback used to provide “real-time” adaptation/refinement of paths. Both model prediction data and observational data can be fed back.
- Use these tools to direct glider network to study features efficiently.
  - For example, 3 vehicles in a triangle “roll” along front. Again use feedback of prediction data and observational data as much as possible.
- Test these strategies in simulation and in experiment (w. D. Fratantoni).
  - Define appropriate metric.
- Use glider dynamic model to improve low-level control, dead reckoning (and therefore average flow calc.).

At Least Three Important Time Scales for Gliders



On the order of 1 day -- Open-loop, ensemble forecasts, optimization, Lag.structures

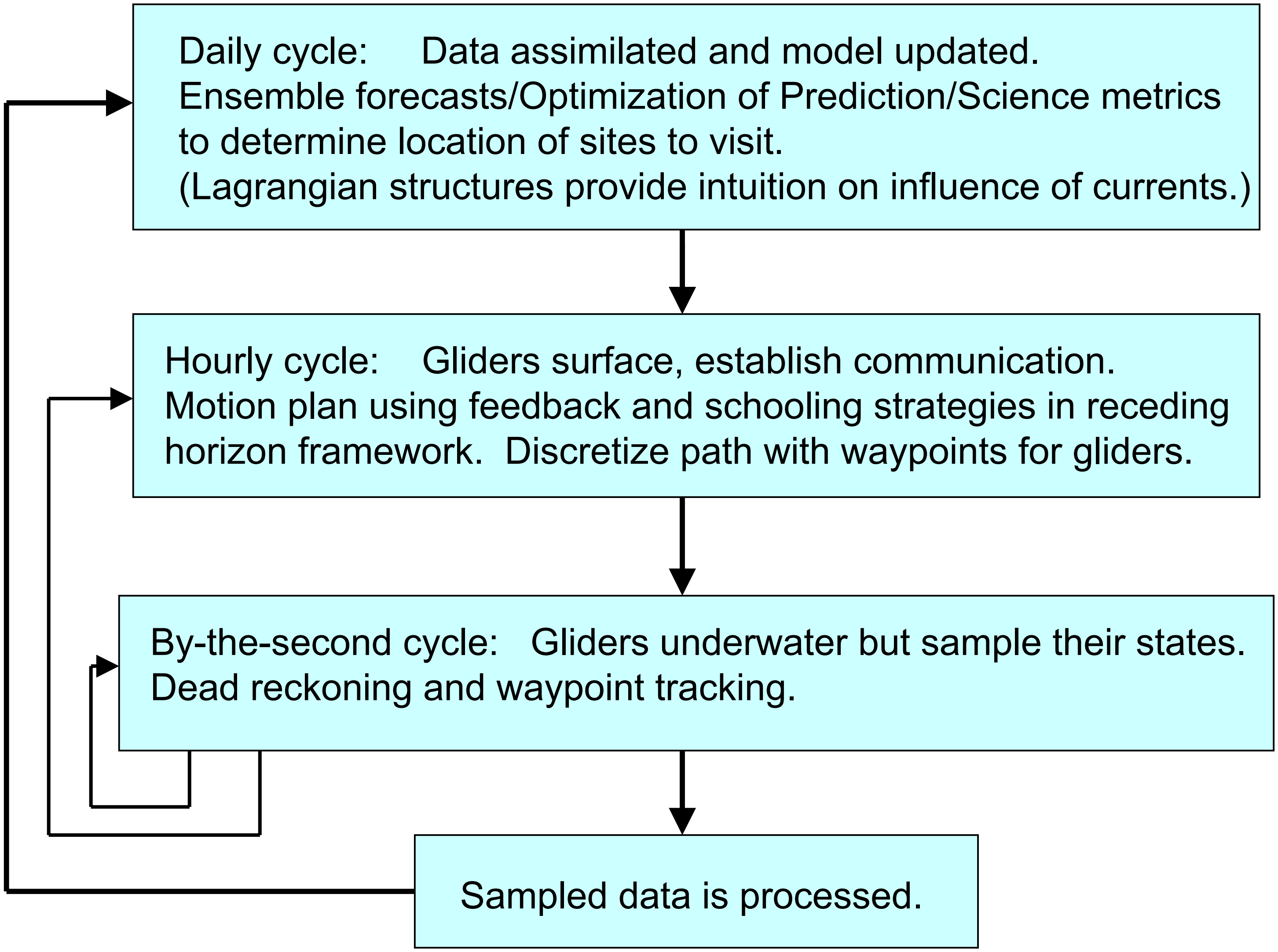
Coarse waypoints define areas of greatest uncertainty and scientific interest.
Distribute waypoints/feature sites to different glider subgroups if appropriate.

On the order of 1 hour -- Feedback measured relative glider positions, observational and state data, model prediction data.

Use schooling strategy (with Lagrangian structure computations if appropriate) to compute refinement of waypoints (for each glider) over next hour-long period.

On the order of 1 second – Low-level feedback control of gliders to follow waypoints.

Integration in Multi-Time Scale Setting



Daily cycle: Data assimilated and model updated. Ensemble forecasts/Optimization of Prediction/Science metrics to determine location of sites to visit. (Lagrangian structures provide intuition on influence of currents.)

HOPS,ROMS
- Majumdar
(Princeton/Caltech)
Input from Ecologists?

Hourly cycle: Gliders surface, establish communication. Motion plan using feedback and schooling strategies in receding horizon framework. Discretize path with waypoints for gliders.

Princeton/Caltech

By-the-second cycle: Gliders underwater but sample their states. Dead reckoning and waypoint tracking.

Fratantoni
Princeton/Caltech

Sampled data is processed.

Note: 5 gliders to be used for regional-scale surveys (repeated transects) and 5/6 to be used for adaptive sampling of frontal structures.

Some Important New Tools and Contributions

- To improve efficiency of adaptive sampling, complement existing strategies with the following:

  - Feedback control (control law -- a function of measurements/predictions, provides robustness).

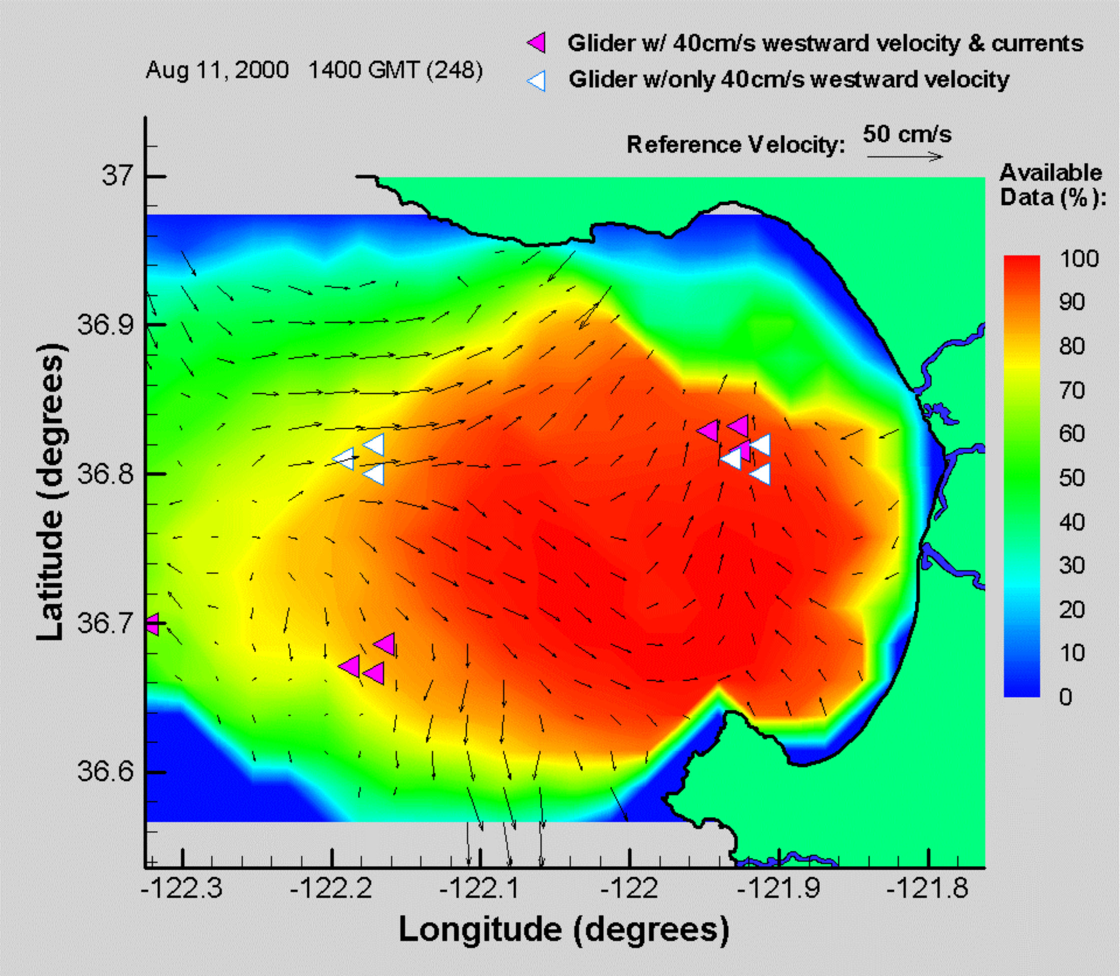
  - Schooling-like strategies (coordinated glider maneuvers, efficient gradient climbing, adaptation, multi-vehicle interactions).

  - Dynamical systems and Lagrangian structure computations (exploit natural dynamics for efficient navigation and sampling).

  - Detailed glider dynamic model (use to improve low-level control, dead reckoning, flow estimate).

  - Integration in multi-scale setting.

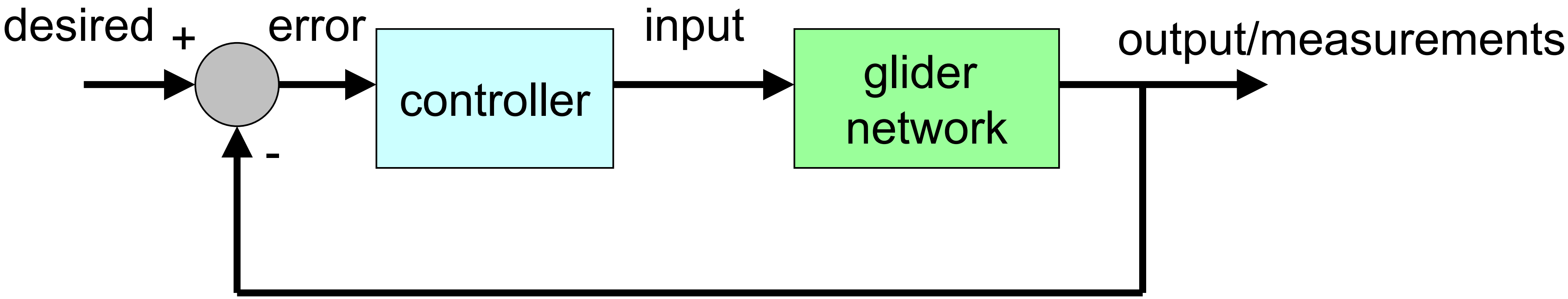
Influence of Current on Gliders in Monterey Bay



- Gliders are slow, the currents have a significant effect and dead reckoning is inefficient

- On the other hand, influence of the currents could be used to advantage.

Feedback Control



- Output/measurements could include model predicted data as well as directly measured data. (Relative position is key measurement.)

- Ideally want to use both.

- Limited communication capabilities constrain feedback sampling rate.

- Feedback provides robustness to uncertainties, disturbances, noise, etc.

Natural Schools

Group-level characteristics exhibited as “emergent properties” from individual-level behaviors.

Individuals respond to sensed environment constrained by behavior of neighbors.

Photos by Norton Wu

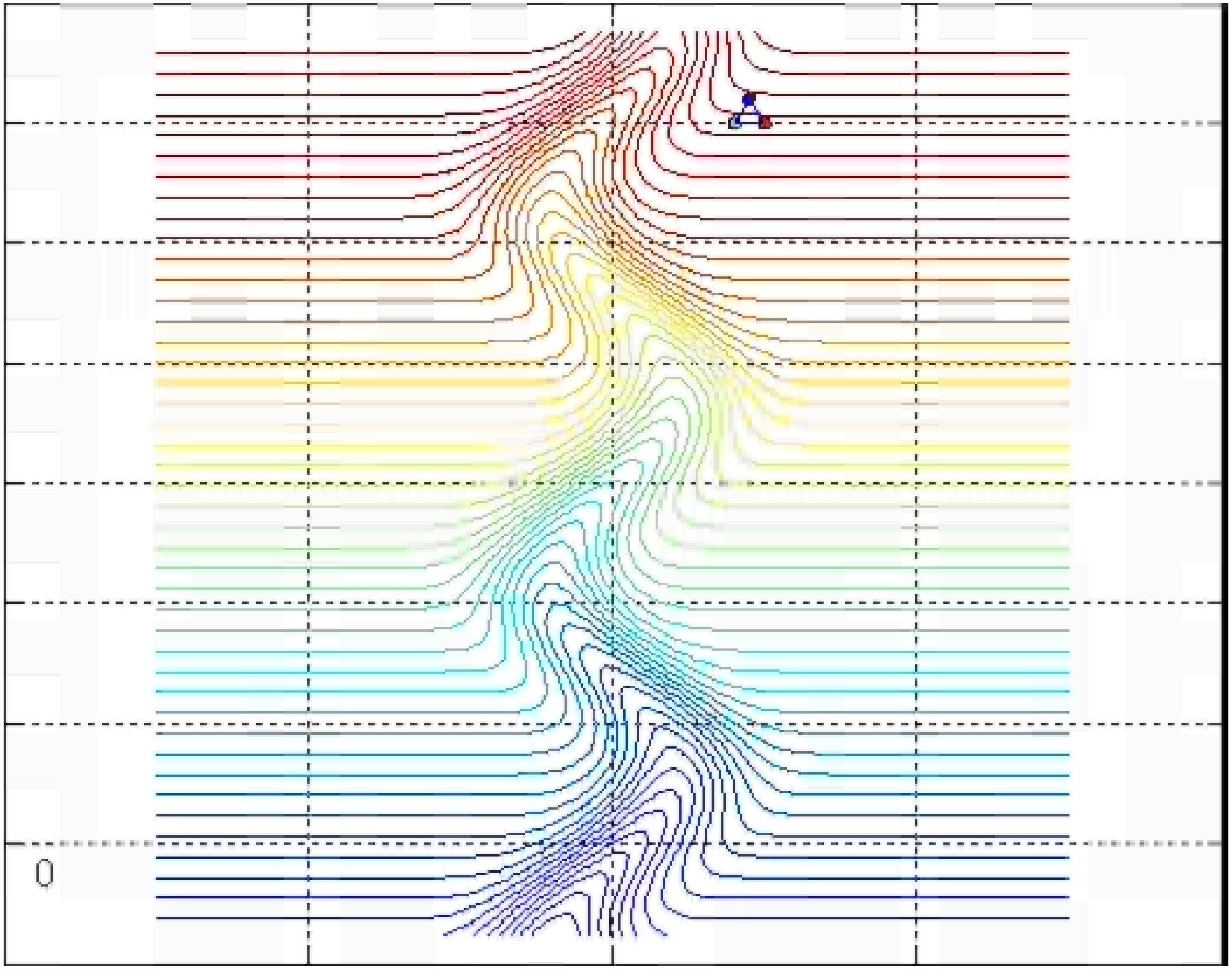
- Environmental signals received only by some members.
- Transduced via social pathways to others.
- Result is interacting array of sensors.
- Decision-making ability of group significantly more accurate than that of individual.

Why Schooling Strategies for Gliders?

- New opportunities for sampling patterns, e.g., coordinated sampling at fronts:
  - Mobile sensor "arrays" can provide local spatial and temporal gradient information.
  - Patterns for coordinated passes through front can be designed.
  - Sensor array resolution can be programmed to adapt to measurements.
  - Use formations to measure flow features (e.g., deformation of triangle formation).
  - Redundancy
- New opportunities for guiding gliders efficiently to fronts/features of interest:
  - Schools can cooperate to climb gradients (e.g., perform searches) (will discuss how this can not only help to find fronts but also to find "navigation channels" that take advantage of currents).
  - Simultaneous deployment at front.
  - Cooperative front tracking.

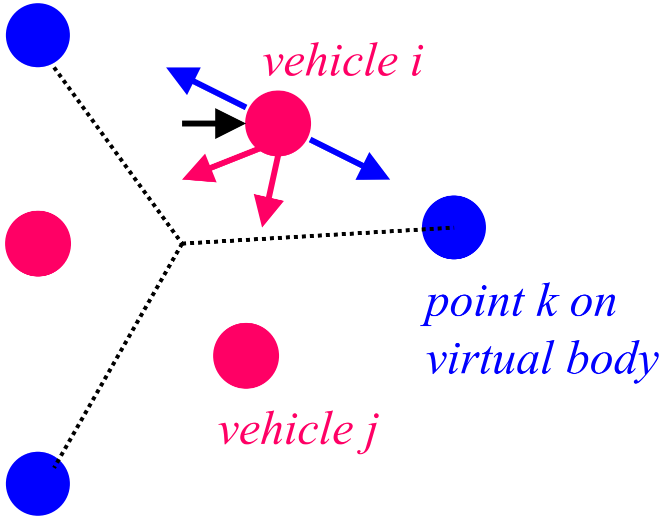
Vehicle Group in Descending Gaussian Valley

$$T(x,y) = ay + b\left(1 - e^{-(x-\sin(y/10))^2}\right)$$



Simulation by R.Bachmayer

Approach to Schooling Control Design:



- Manipulate collective dynamics via artificial potentials and virtual body.

- Keep track of position, orientation and size of formation.

- Because of artificial potentials, vehicles in formation will translate, rotate, expand and contract with virtual body.

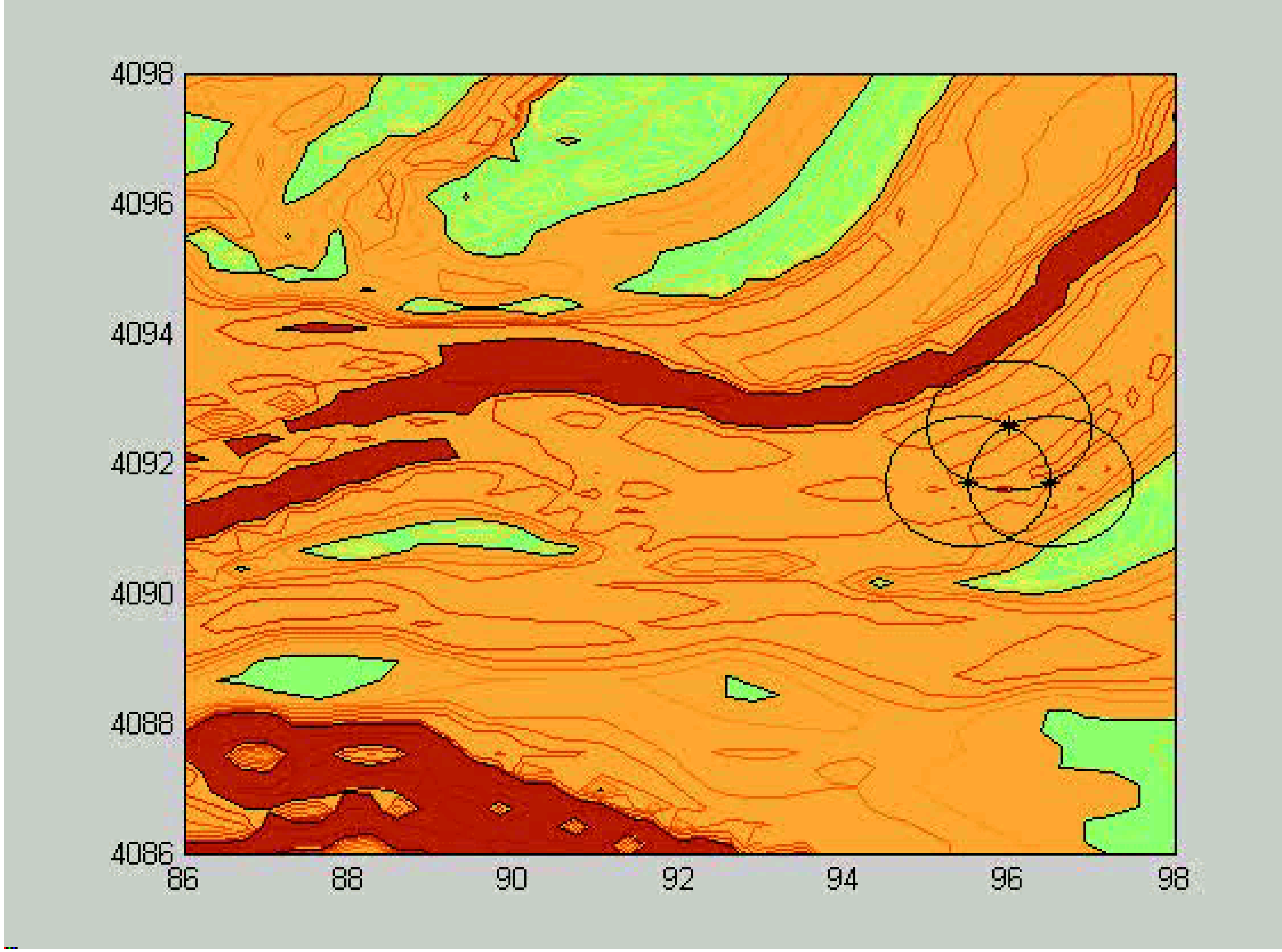
- To ensure stability and convergence, prescribe virtual body dynamics so that its speed is driven by a formation error.

- Define direction of virtual body dynamics to satisfy mission.

- Partial decoupling: Formation guaranteed independent of mission.

- Prove convergence of mission, e.g., gradient climbing.

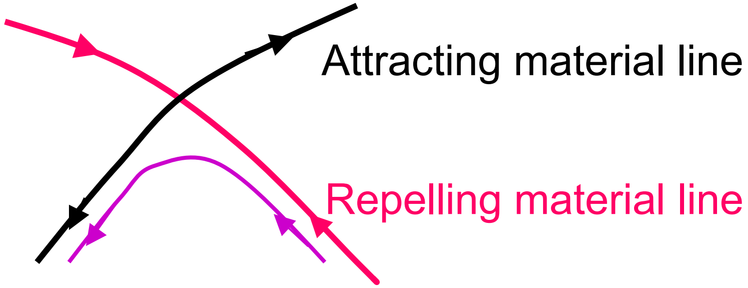
Rolling along a DLE ridge



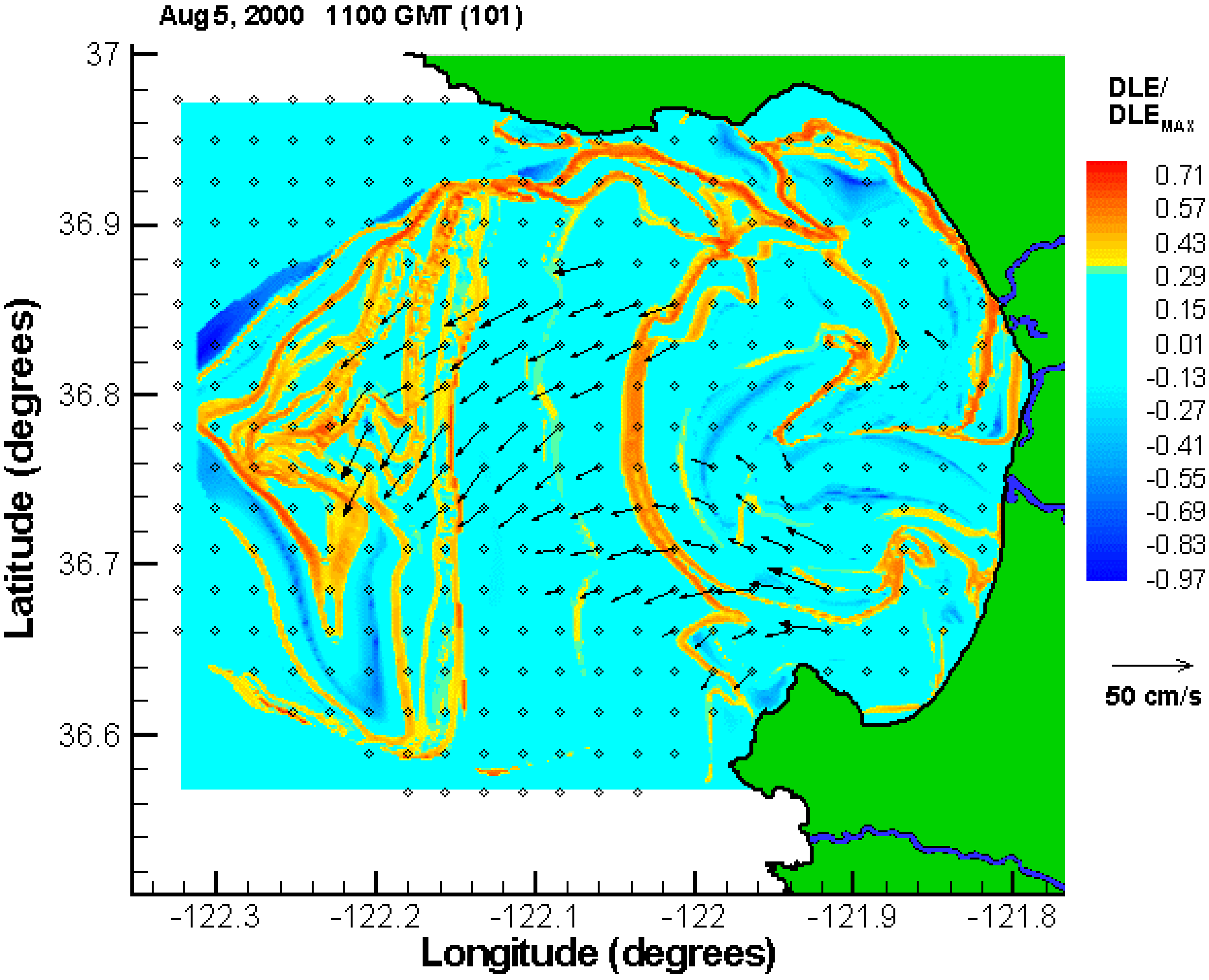
Define rules for using schooling behaviors: translation, rotation and expansion provide new and useful ways of collecting data at features of interest.

Lagrangian Structures

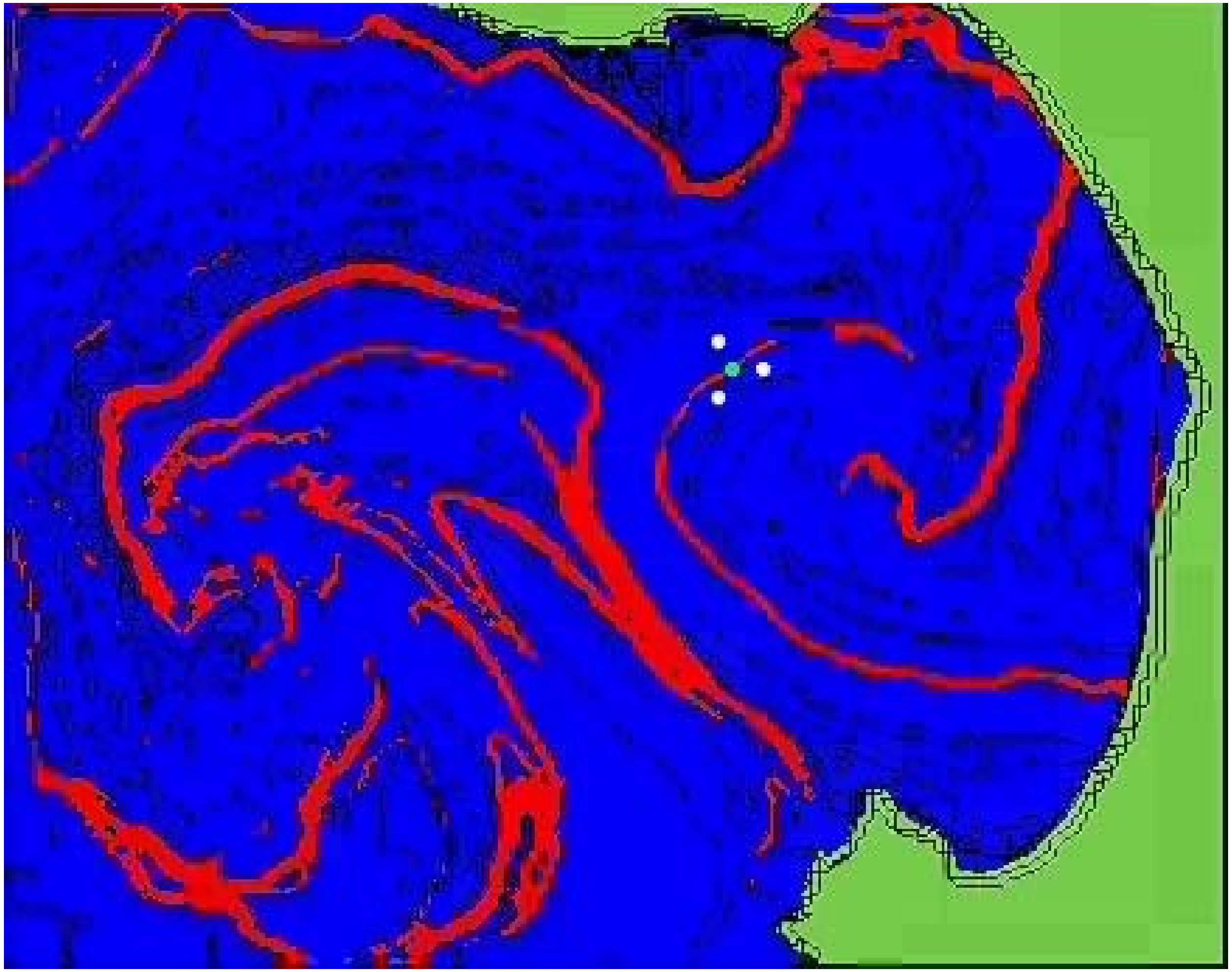
- From model prediction flow data (or measured, e.g., HF radar data), compute hyperbolic trajectories and repelling/attracting material lines (MANGEN).
- Use direct finite-time Lyapunov exponent (DLE) approach.
- Algorithms to automate glider path planning and control so that gliders get to fronts of interest efficiently – exploit natural dynamics.
- Repelling material lines <---> navigation channels;
- Attracting material lines <---> fronts
- Algorithms to exploit correlation of attracting material lines (computed in backwards time) to fronts.



Lagrangian Structures Computed in Monterey Bay



Integration of Lagrangian Structure Computations with Schooling Strategies



Glider Model and Control

- 3D rigid body model of glider dynamics with buoyancy engine, moving mass and rudder (if applicable).
  - Explore glider dynamics with analysis and computation.
  - Experimentation for system identification and verification of dynamic behavior

- Observer designed to estimate states, notably linear velocity (relative to the flow) from which one can get position by integration.
  - Improve current scheme for dead reckoning.
  - Improve "average" current estimate over glide cycle.

- Low-level control laws using model for improved performance and robustness
  - Waypoint following in horizontal plane.
  - Tracking in vertical plane.
  - Controlled gliding through density change across front. (Test in Buzzard's Bay)

- Experiments: Buzzard's Bay '02-'03, Bahamas Jan. '03 with D. Fratantoni, WHOI.

Integration

- Intermediate (Hour-Long) Time Scale:
  - Motion plan computed using schooling strategies, predicted data and observational data (as possible).
  - Glider paths recomputed for dead reckoning context.
  - Paths discretized for waypoint specification to gliders.

- Simulator tools to run integrated adaptive sampling approach using HOPS (beginning with Mass Bay data).

- Investigation of synchronization and other issues related to constrained communication.

- Experimental plan prior to MB’03 with D. Fratantoni to support development and testing of strategies.

Some Questions – More to Come!

- What are the relevant spatial scales for data collection by the gliders?

- What are some particularly useful patterns for sampling across a front?

- How is the daily time-scale strategy effort going to be consolidated among the different participating groups?

- What is the most effective communication strategy?

- Longer Range: How should we plan things with the various components to eventually provide an autonomous system?