Cooperative AUV Navigation using MOOS: MLBL

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Cooperative ASV/AUV Navigation

- AUV Navigation is not error bounded:
  - Even with a $300k RLG, error will accumulate
  - GPS and Radio Comms absorbed
  - Visual or Sonar Sensor ranges too great

- LBL: requires stationary installed beacons
- USBL: Doesn't scale well to multiple vehicles

- Cooperative Navigation Aid:
  - Example: Autonomous Scout Kayak
  - Computer and servo controlled prop
  - Acoustic Modem and GPS sensor
  - **<u>Or any surface acoustic source:</u>** Gateway Buoy, Research Vessel w/ GPS

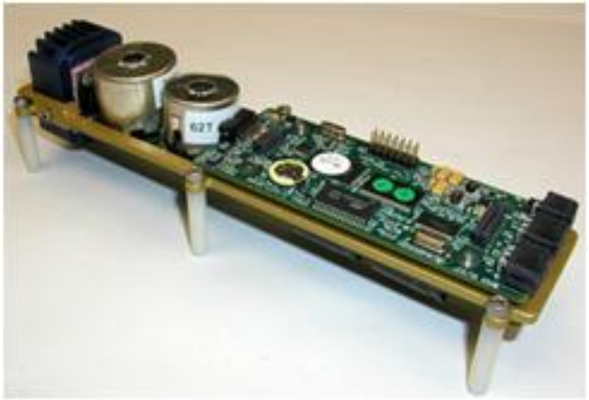
Kayak - AUV Nav.
-Concept
-Acoustic Ranging
-MOOS Arch

Coop Navigation:
-Algorithm Overview
-Illustrative Example

AUV Experiments:
-Iver 2
-REMUS 100

Combined w/ Sonar
-Sensor Fusion

Acoustic Marine Communication



- Acoustic Modem:
  - Designed by WHOI
  - Range: Up to 2km in open ocean
  - One 32 byte packet per 10 seconds
  - One-Way Range Estimate via globally sync'ed clocks (using board by Ryan Eustice, U Mich)
  - Already installed on AUVs for command and control
  - **NO (EXTERNAL) MODIFICATION OF EXISTING AUVs REQUIRED**
- Share the kayak position estimate and range measurement with the AUV so that it can improve its own navigation
  - Share the AUV's position estimate with the kayak so that the kayak can path its path to best inform the AUV in future
  - AIM: mobile, bounded error AUV navigation for **<u>any number of AUVs</u>**

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Cooperative Navigation: AUV Overview

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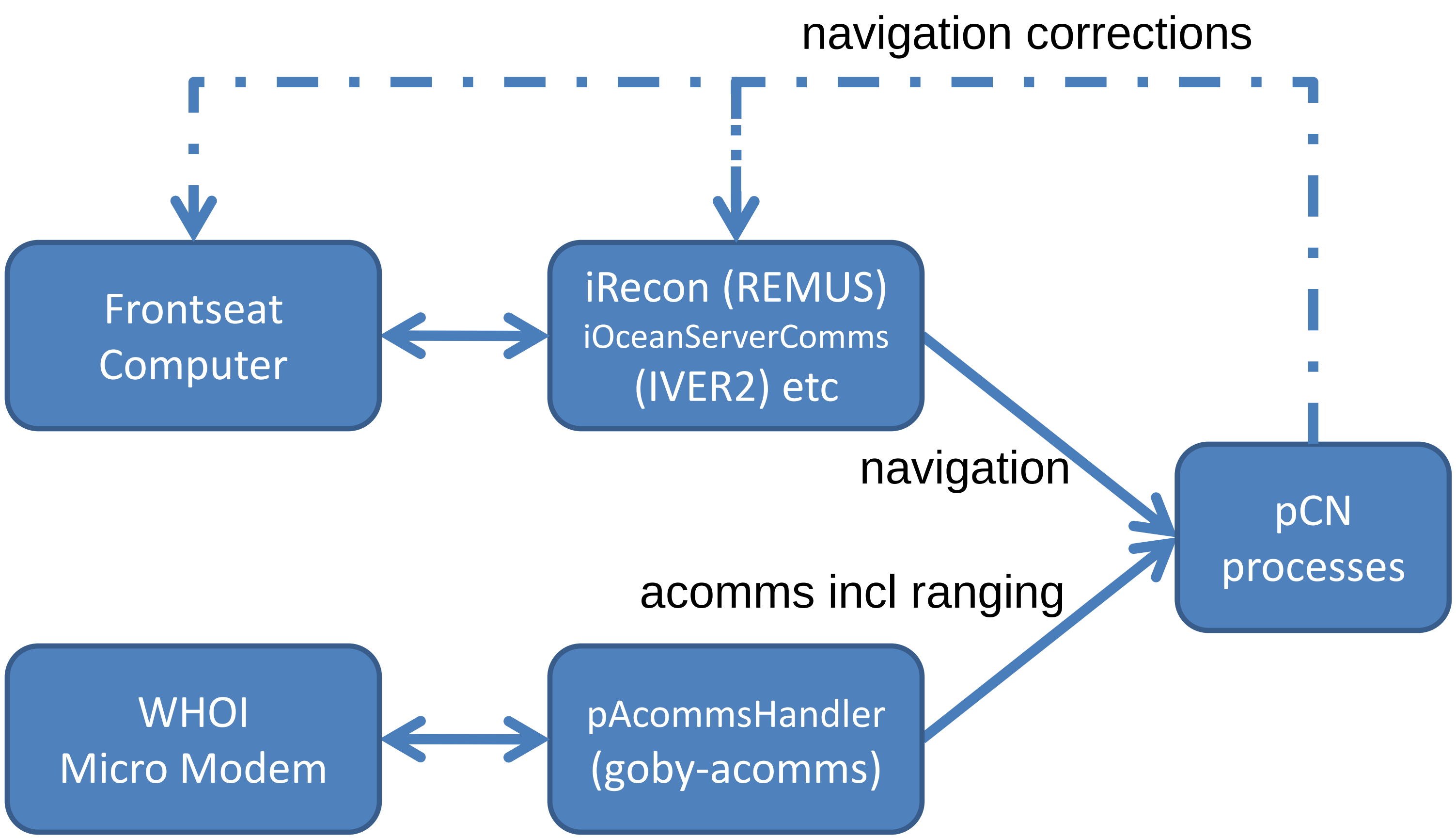

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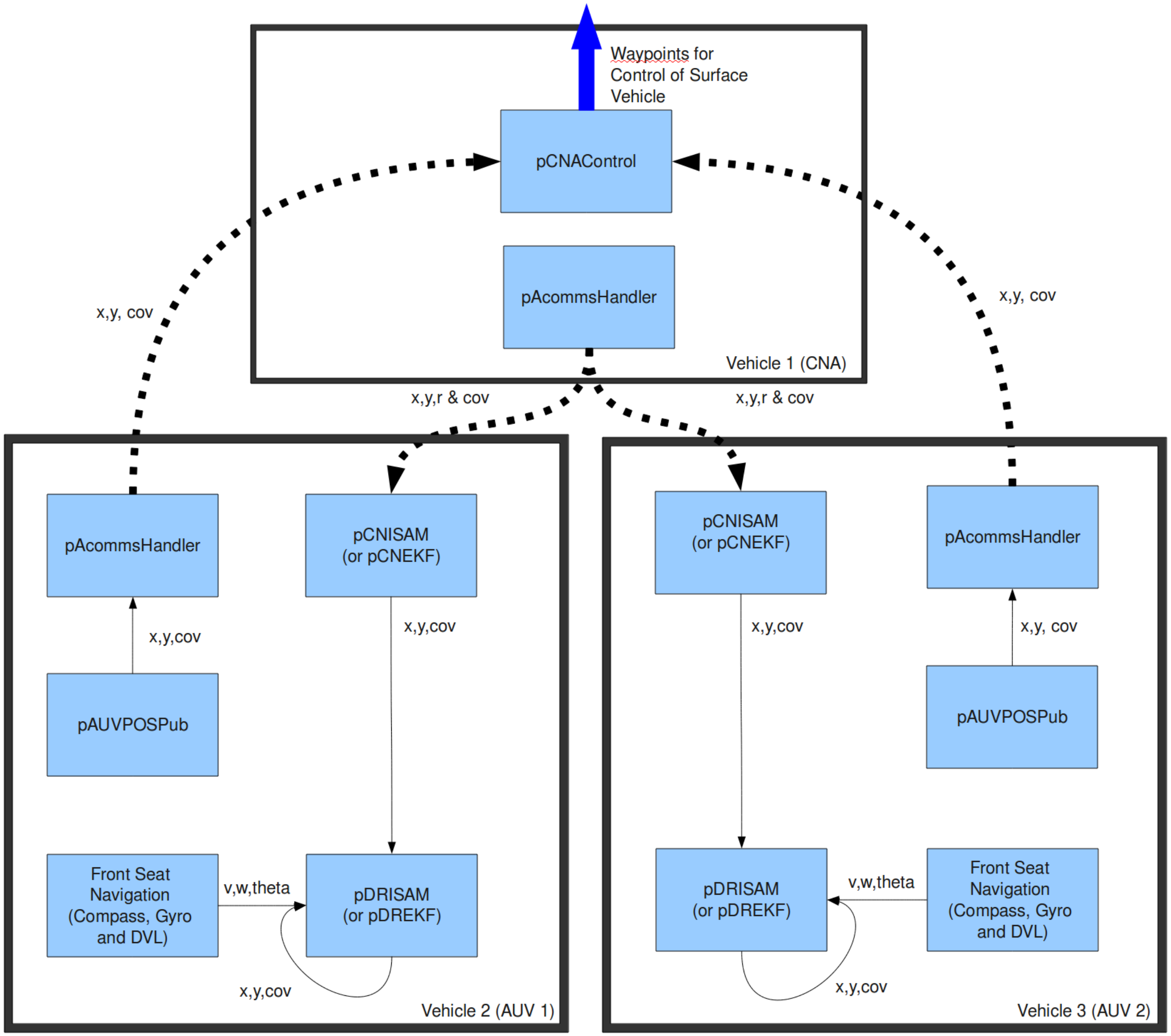
Full CNA and AUV Overview



Any number of AUVS

Algorithm Details

1. **AUV(s) initializes** with known position and propagates uncertainty using a filter (typically at dive)

2. Each period (10 seconds) either **an AUV(s) or the CNA transmits** using the modem:
   - CNA sends: GPS position and a time stamp
   - AUV(s) sends: current position estimate and covariance

3. **If the AUV(s) receives CNA message:** corrects position and uncertainty via a full-trajectory NLS optimization (using iSAM, Kaess et al, TRO 2008)

4. **If the CNA receives AUV(s) message:** it uses the estimate to plan its path, to best aid the AUV(s)
   - Two motion strategies for CNA: Encirclement or Zig-zagging

Proof of Concept, 2 kayaks [Nov 2008]

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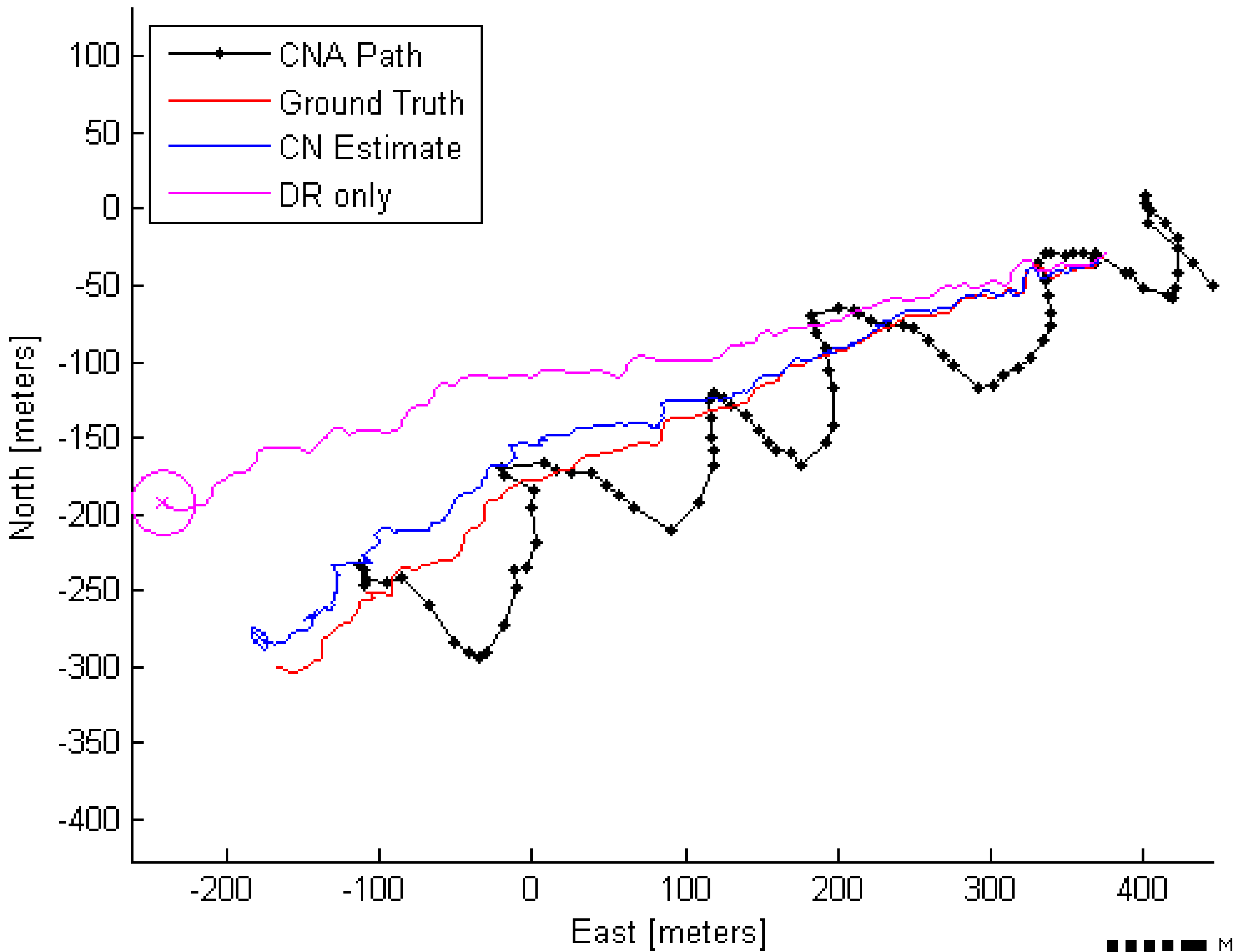
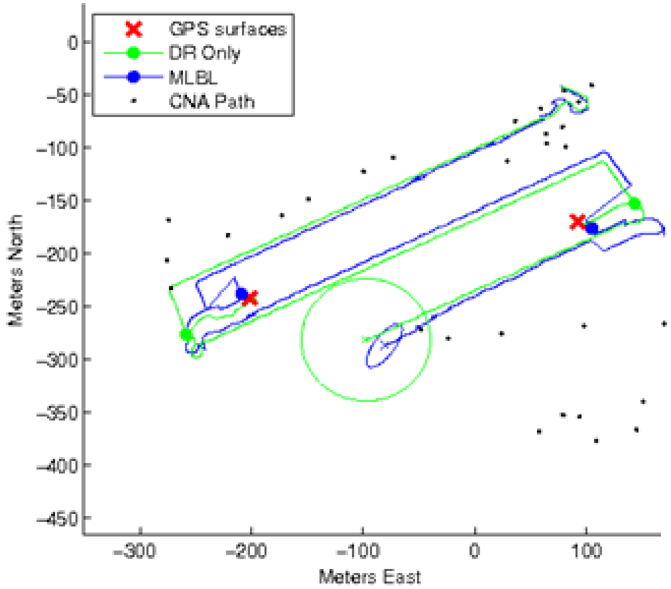


Iver2 Test: Charles River at MIT [EKF]

- Real Time Experiment using an OceanServer Iver2 with a kayak
  - One-Way-Ranging tested online
  - Successfully tested precision timing board
  - Travelled 2km, 5m below surface
  - Supported by one CNA kayak
  - With Scott Sideleau and Don Eickstedt (NUWC Newport)
- 30 min experiment, 200 transmissions [about 50% successful]
- CNA Kayak adaptively followed AUV using CNA's own position estimate (transmitted back to the surface)
- Position Error of 11m measured when AUV surfaced (twice). [60m without CNA]



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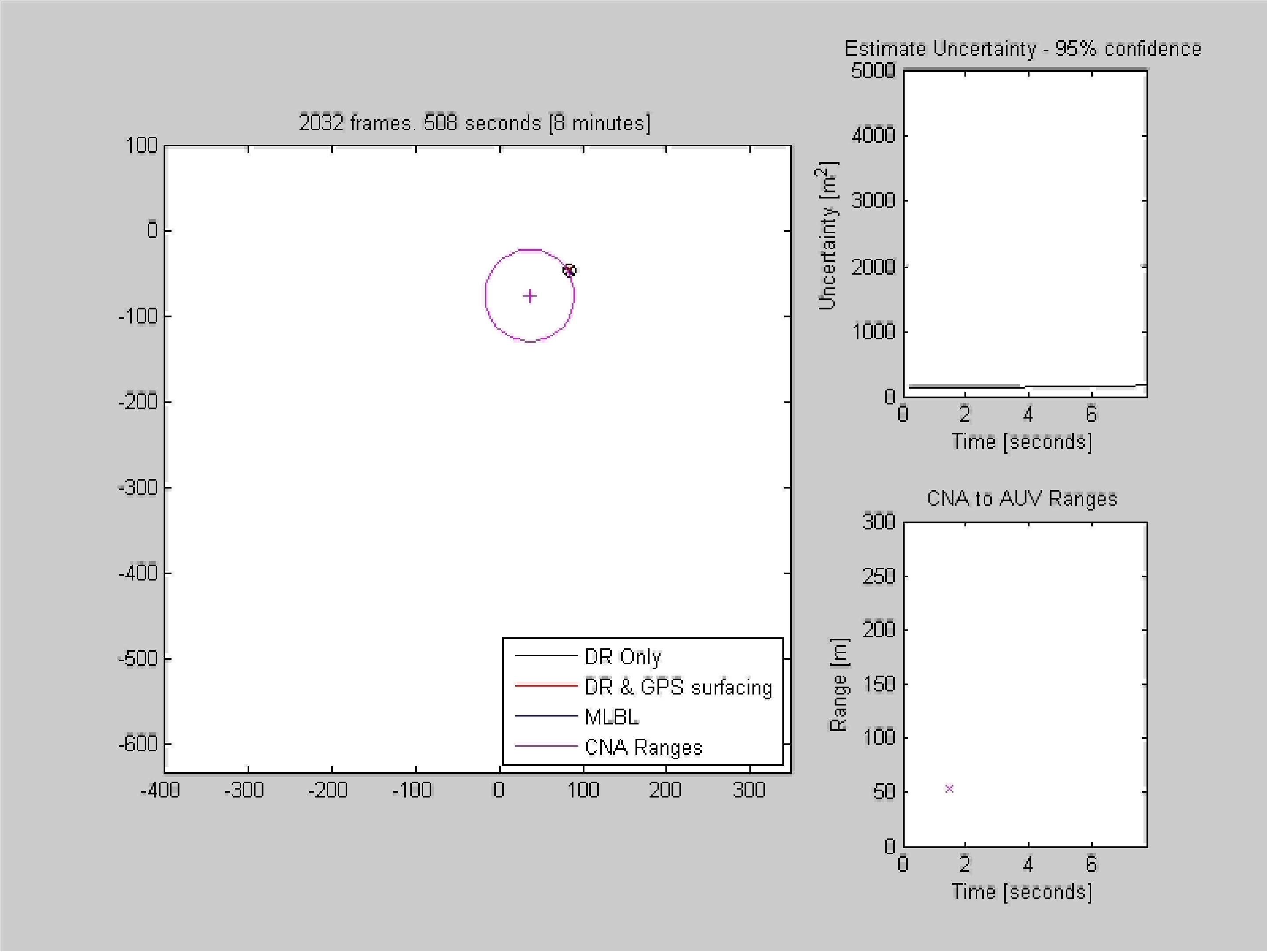
Iver2 Test: Results [EKF Version]



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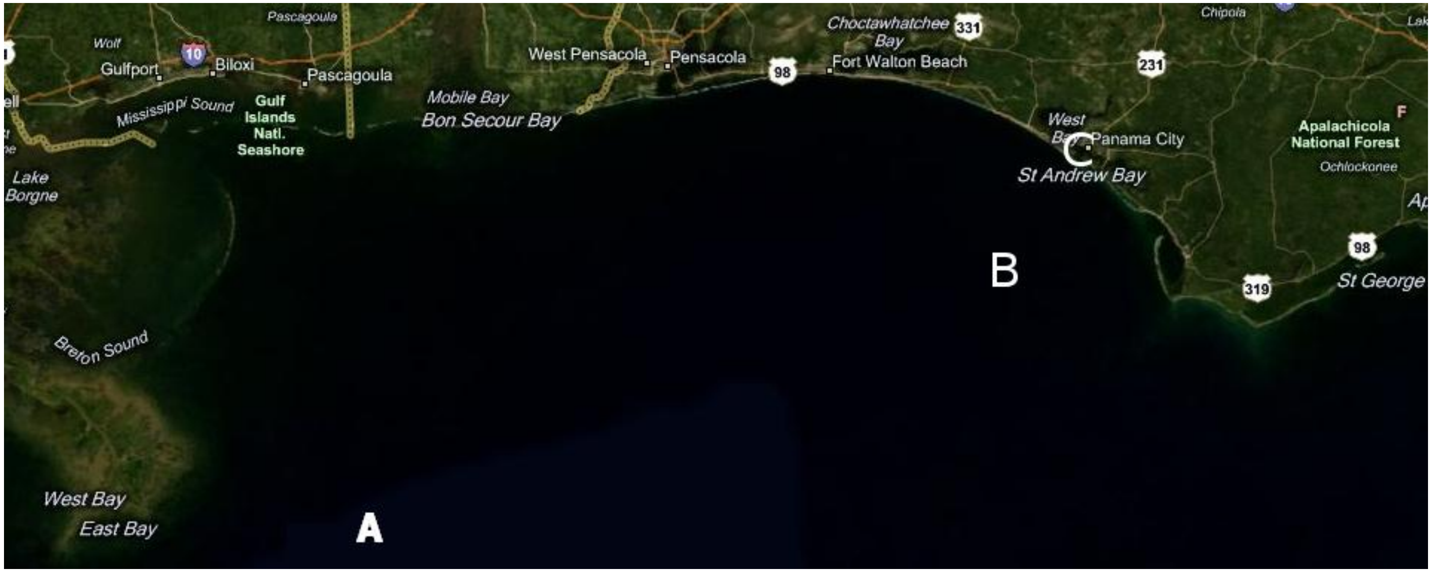
Field Tests June 2010: Panama City Florida



- Hydroid REMUS 100 [with RLG]
- An MIT SCOUT kayak or Deckbox
- With Andrew Bouchard, Jason Price et al. (NSWC, Panama City)

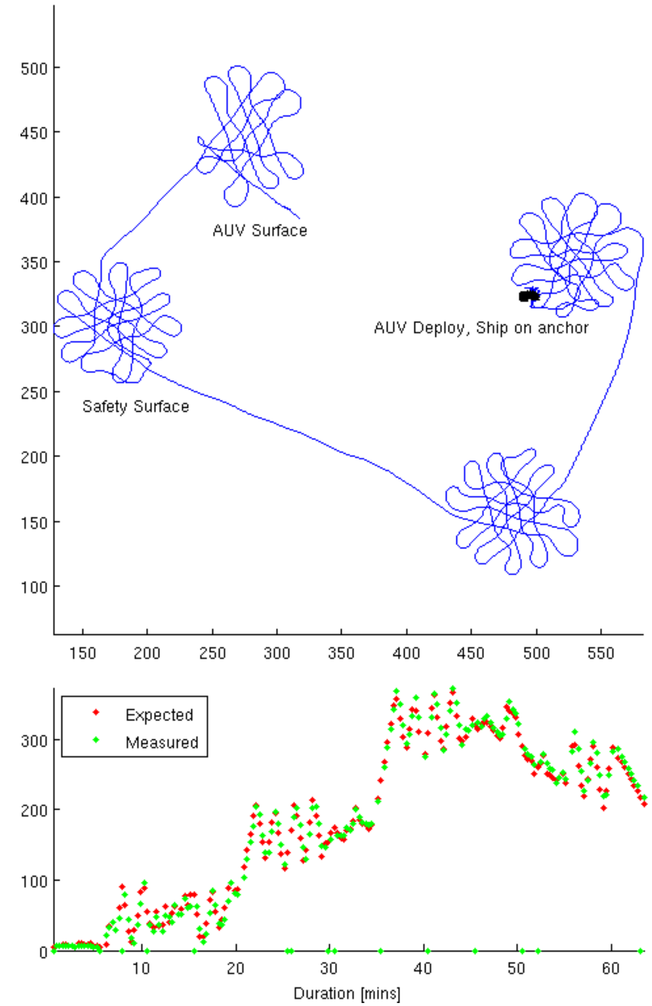
Acoustic Ranging Only Results [iSAM]

Aim:

- Extend duration of MCM missions, avoiding vehicle GPS surfaces.
- Minimal change to current operating procedure

Experiment:

- Transmission to AUV every 20seconds (v high frequency)
- Round Trip Ranging Used
- Ship operated as an approx. **<u>stationary</u>** beacon on anchor
- Observability due to **<u>AUV</u>** motion
- Back seat estimation – no active control



Acoustic CoopNav: Where can it help?

Lower-cost Prop-count or DVL with basic compass **Iver 2** (several % error)	**Applicable**	**Applicable**
High-end Ring Laser Gyroscope/DVL Combination **REMUS 100** (<1% error)	**Current Navigation Sufficient**	**Applicable**
	Short (20-40mins between surfacing)	Long (several hours+)

- Almost every AUV operation has at least one surface acoustic modem in the water
    - Why not consider it?

Combined Acoustic Ranging and Side-scan Sonar

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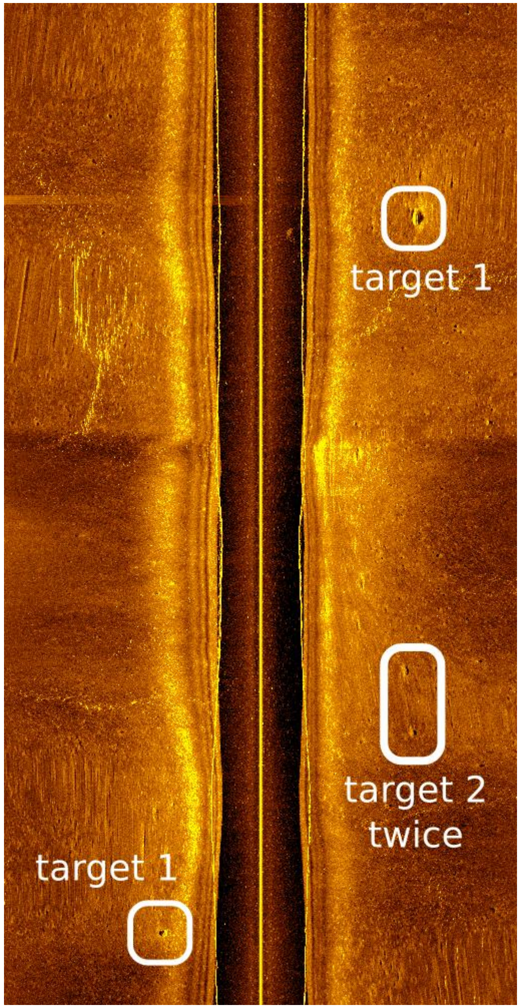
Ongoing/Upcoming Work:

- Sonar Targets repeatedly visible during operation.
- Much research on side-scan sonar based SLAM:
  - Newman ISRR03, Aulinas Oceans10 etc
- Detect target re-observations and treat as a SLAM loop closure
  - re-adjust entire pose graph

Same Mission as before:

- Use original acoustic Ranges
- Multiple observations of (artificial) targets in side-scan sonar
- Efficient online optimization using iSAM
- Towards an online multiple AUV, distributed localization system



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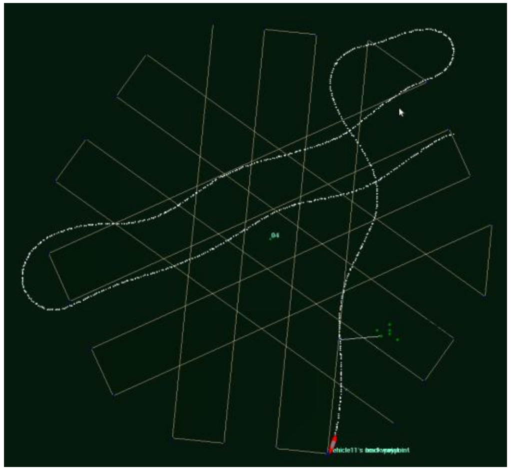

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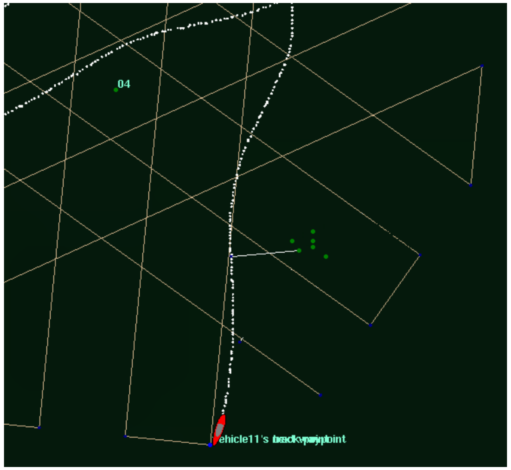
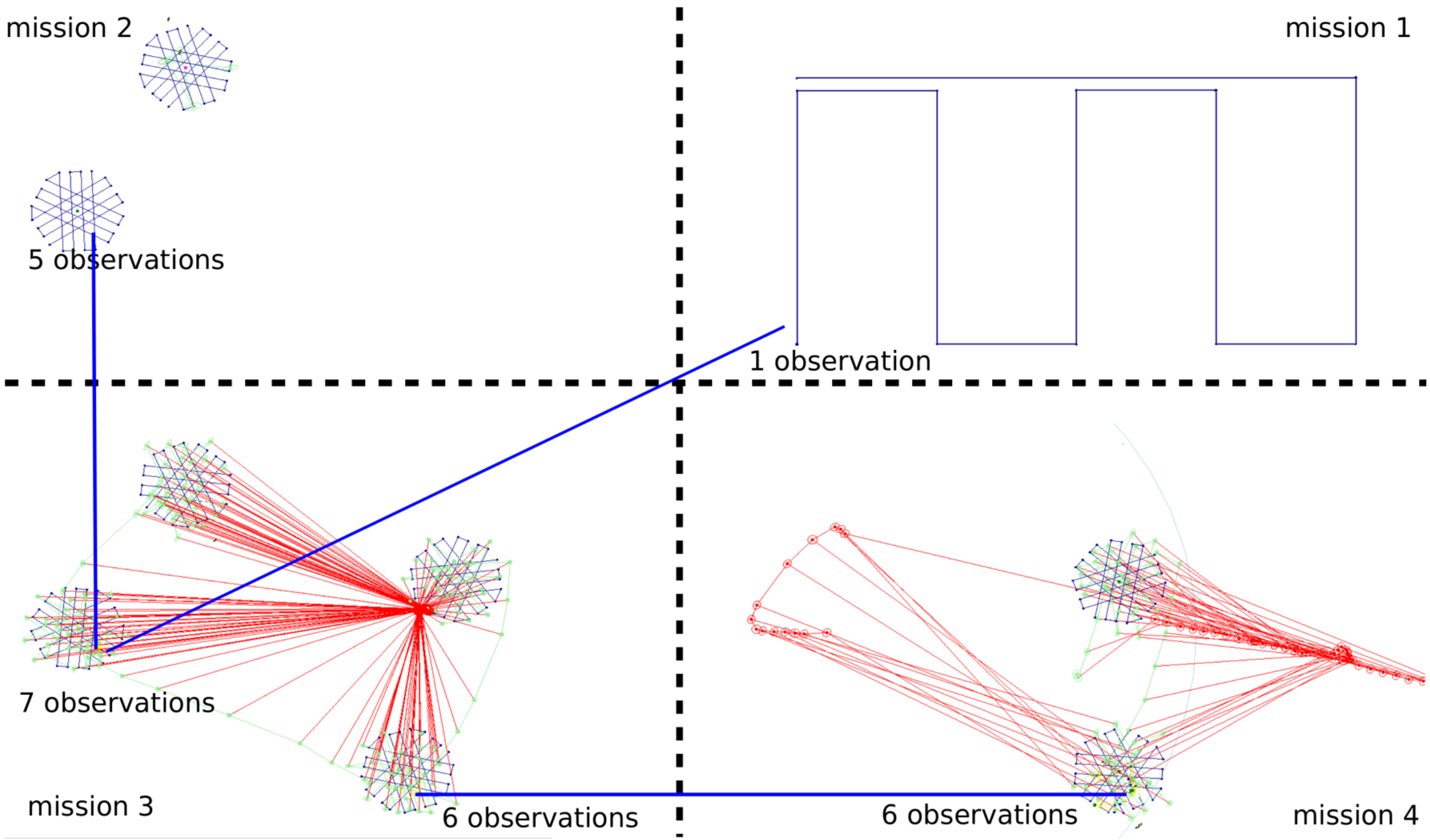


Multisession Combined Acoustic Ranging and Side-scan Sonar



- Target observation constraints drawn across 4 missions to optimize joint map (including eventual sonar mosaic)

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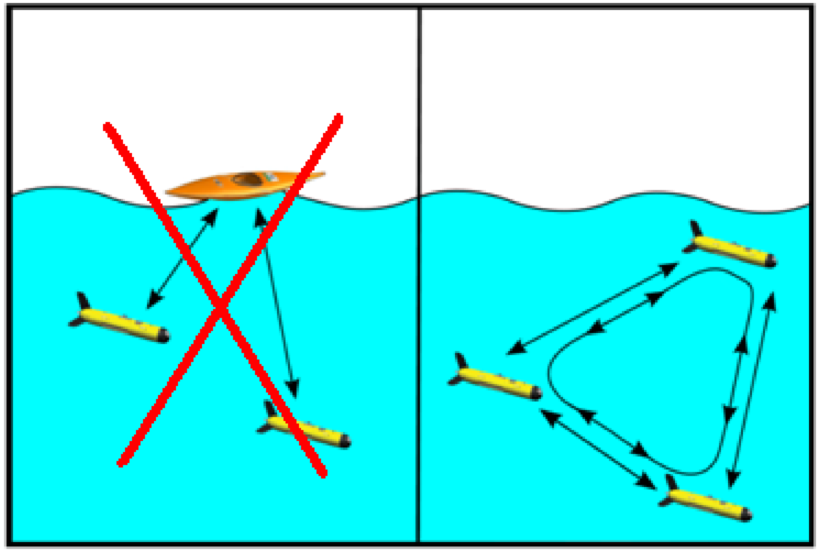
Inter AUV Cooperative Navigation

- Large Heterogeneous Fleet
  - Expensive AUV working with a group of cheaper vehicles



- **Mission 1:** Expensive INS-enabled AUV doesn't surface, cheap AUV surfaces occasionally and reports an accurate position

- **Mission 2:** Expensive AUV encircles a large set of cheaper AUVs and shares it's accurate position information
  - The cheap AUVs can operate as though they have the expensive navigation abilities.

- Distributed knowledge of other AUVs accurate positions
- ICRA 2010 Paper on designing a scalable network protocol for navigation

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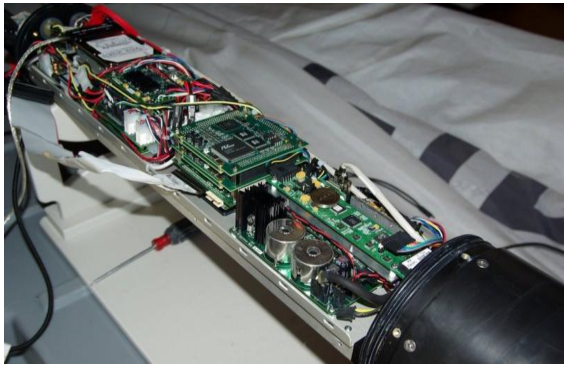
Future Work and Thanks

Summary:

- Suite for cooperative navigation nearing maturity
  - Surface range measurements from **any acoustic source**
  - Easily combined into existing systems
- iSAM Library released **this week**: http://people.csail.mit.edu/kaess/isam/
- Contributions from: Alex Bahr, Georgios Papadopoulos, Toby Schneider, Joe Curcio, Andrew Patrikalakis, Michael Kaess, Taylor Gilbert
- Sponsored by the Office of Naval Research (Dan Dietz and Mike Benjamin)



Speaker Tracking
-Steered Beamformer
-Particle Filtering
-Examples

Kayak AUV Nav.
-Concept
-Illustration
-Sea Tests

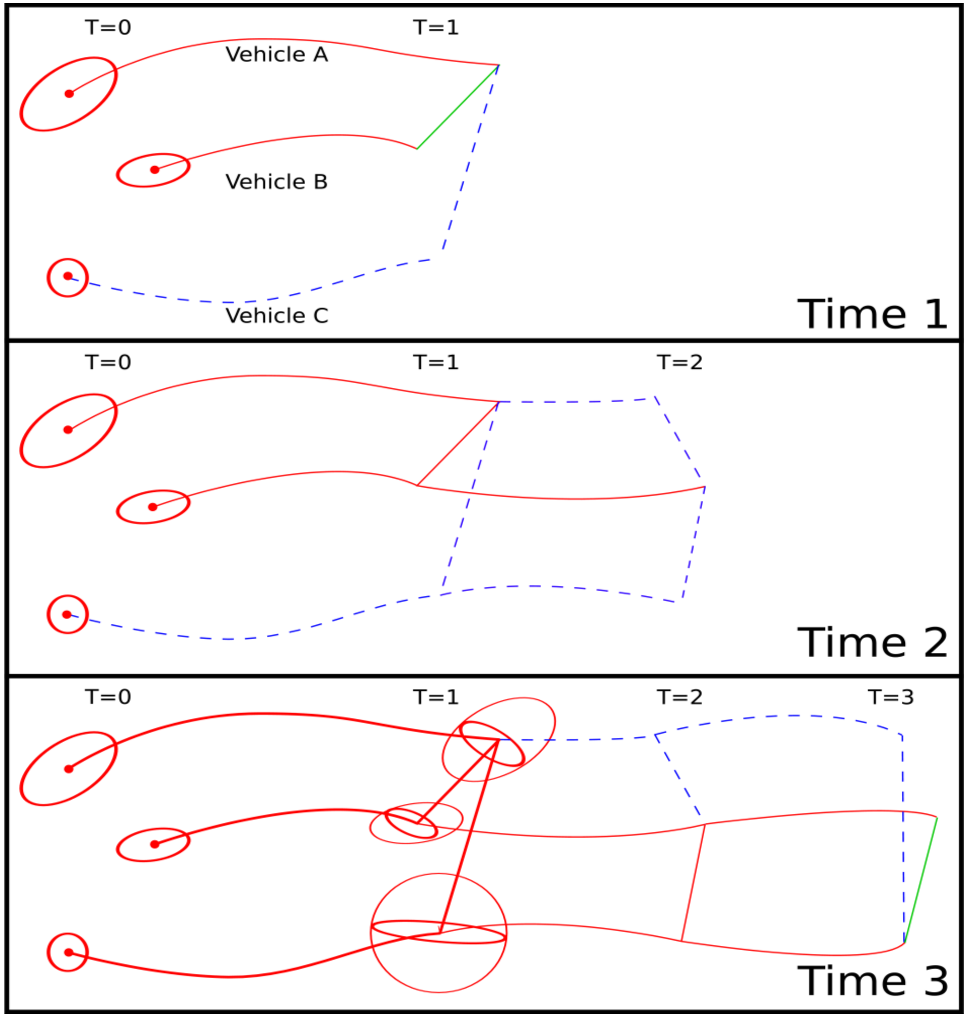
River Exploration
-DGC
-Bridge Mapping
-Obstacle Detection

Example Scenario for AUV B

AUV A transmits msg
AUV B receives it

AUV B transmits msg
But receives nothing

AUV C transmits msg
AUV B receives it



Red: Known
Black: Rx
Blue: Unknown
Green: Measured Range

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Inter AUV Navigation: Algorithm

- Each AUV transmits request for unknown messages
- Using similar messages from other vehicles:
  - AUV maintains a log of messages required by other AUVs
  - Uses it to choose what to send
- If AUV has a full set of Dead Reckoning/Range messages:
  - Do filter correction or optimization

Notes:

- Flexible to any filter or NLS solution
  - Currently Implemented: EKF
  - Future: Efficient full-trajectory NLS using iSAM (**Kaess et al 2008**)
  - Related to Online Bundle Adjustment

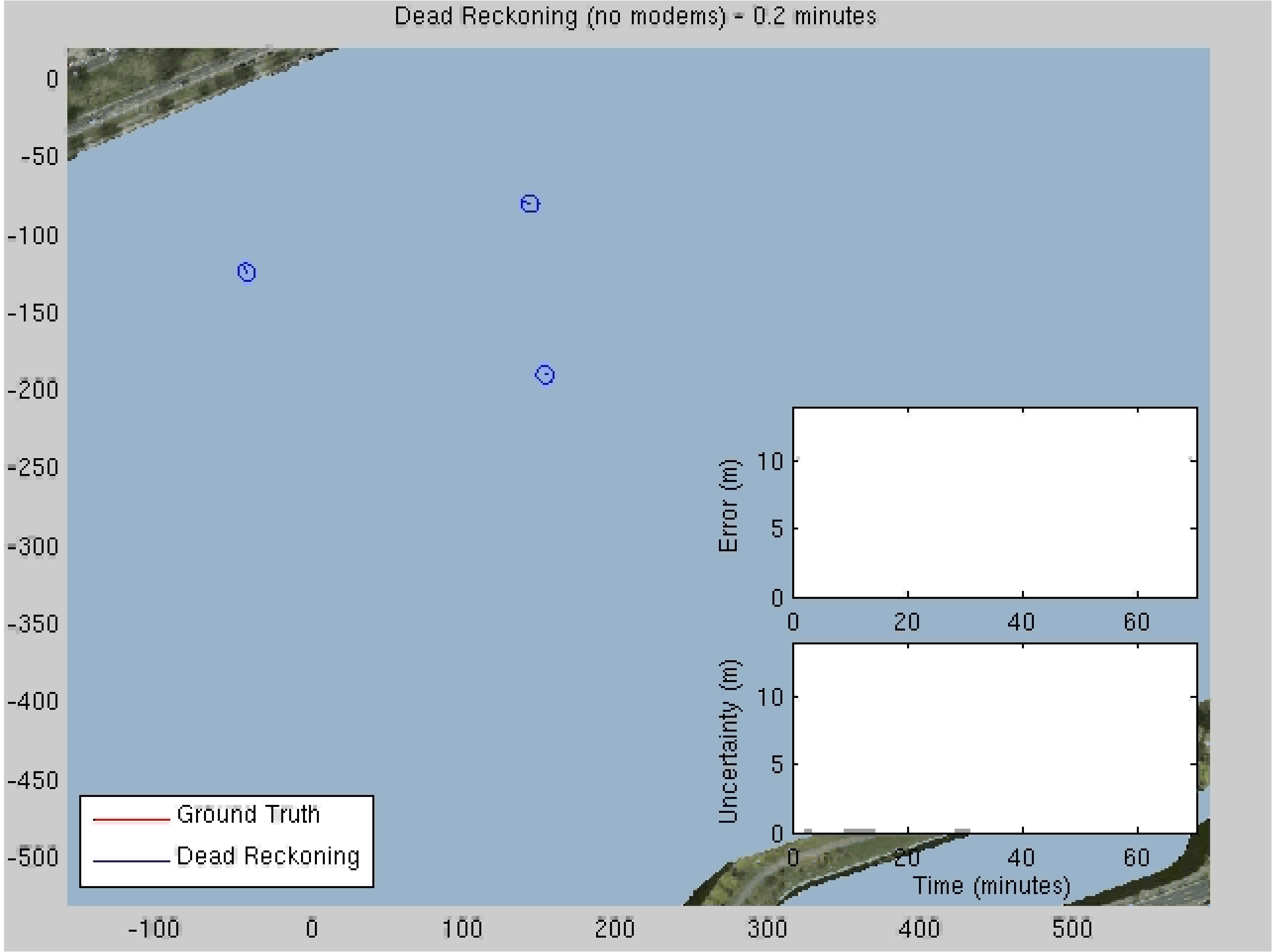
Background
-Other Approaches
-Acoustic Modems
-CNA and AUV Coop

Inter AUV Navigation
-Concept
-Illustration

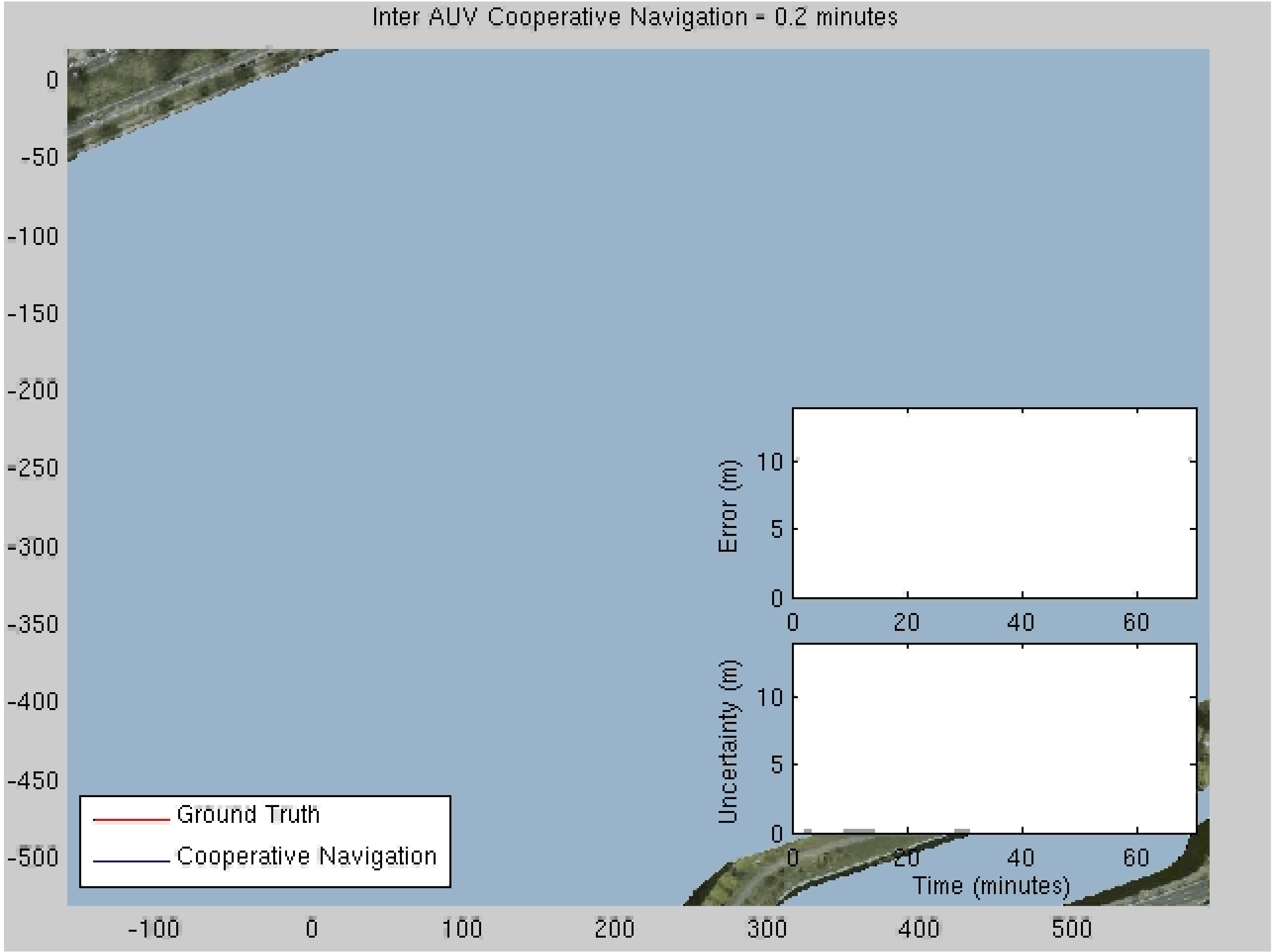
Experimental Validation

Future Work

Dead Reckoning Only



Using Inter AUV Communication



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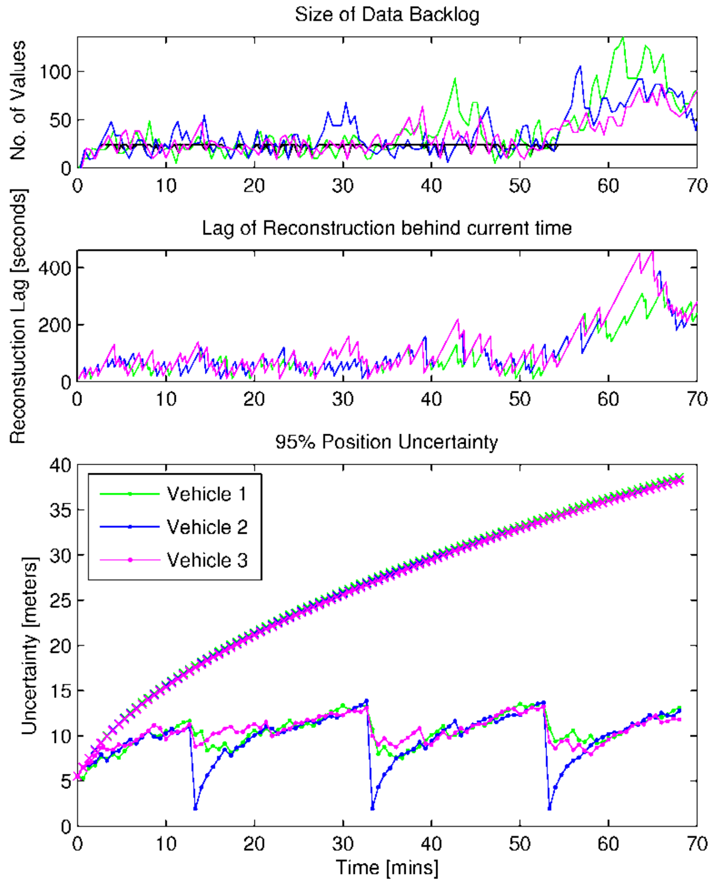
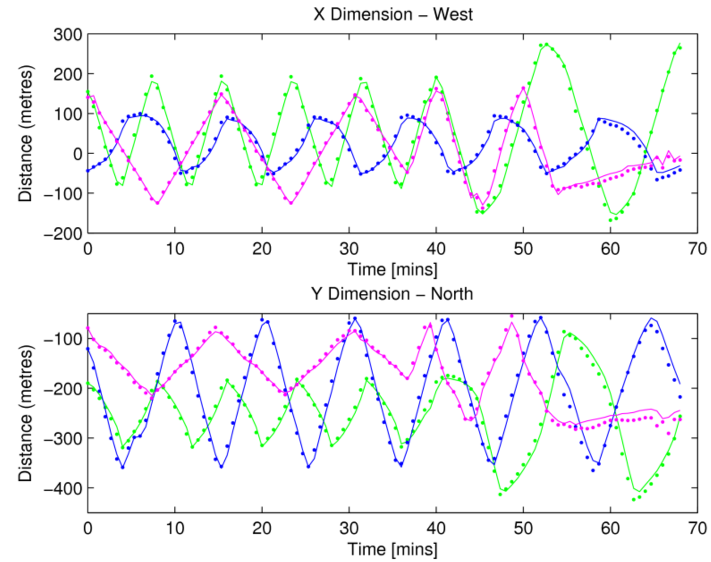
Inter AUV Navigation: Results





x - without cooperation

o - using cooperation

- Three Vehicles
- Duration: 70 mins
- 16 km travelled in total
- 420 message Tx's
  - 332 Successful (80 %)