REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
13/12/2006	FINAL	01/08/2002-30/09/2006

4. TITLE AND SUBTITLE

An Autonomous Glider Network for the Monterey Bay Predictive Skill Experiment / AOSN-II

5a. CONTRACT NUMBER

N00014-02-1-0846

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

03PR00097-00

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Woods Hole Oceanographic Institution
MS #21
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

See attached Final Report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: none			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	Seven	David M. Fratantoni
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An Autonomous Glider Network for the Monterey Bay Predictive Skill Experiment / AOSN-II

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LONG-TERM GOALS

Our long-term goal is to develop a relocatable, sustainable, infrastructure-free ocean observing system composed of low-cost, high-endurance vehicles with near-global range and a modular sensor payload. Particular emphasis is placed on the development of adaptive sampling strategies and the automated control of large glider fleets.

OBJECTIVES

This work was one component of a coordinated effort to demonstrate and quantify gains in predictive skill resulting from model-guided adaptive sampling using a network of autonomous vehicles. The objectives of this program were to (1) Construct and operate a ten-vehicle fleet of autonomous gliders during the AOSN-II field program, (2) Develop and test, in collaboration with colleagues, the necessary vehicle control protocols to enable model-driven repositioning of the glider fleet, and (3) Integrate observational results from a variety of platforms with nowcast and forecast products from several assimilating numerical ocean models. Ongoing work focuses on the analysis and synthesis of the observational and numerical results and dissemination of these findings via journal publications and meeting presentations.

APPROACH

The August 2003 Autonomous Ocean Sampling Networks (AOSN-II) experiment utilized ships, aircraft, and a heterogeneous group of 21 underwater vehicles with widely varying capabilities to investigate physical and biological processes associated with coastal upwelling along the central California coast. Central to this effort were two fleets of high-endurance autonomous underwater gliders operated by the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution. Gliders are torpedo-shaped winged vehicles which maneuver slowly through the ocean in a sawtooth-shaped trajectory. At predetermined intervals the vehicles surface to determine their geographic position, transmit collected data, and receive new instructions from a shore-based control system via Iridium satellite phone. During the month-long experiment a total of 15

gliders occupied more than 10,000 km of horizontal trackline in Monterey Bay and vicinity.

WORK COMPLETED

As part of the summer 2003 AOSN-II field experiment the WHOI glider fleet provided distributed measurements (Figure 1) of temperature and salinity, vertically-averaged velocity, chlorophyll fluorescence, optical backscatter, and PAR. We deployed and operated a 10-vehicle fleet, collected and quality-controlled the glider-derived oceanographic measurements in real-time, and perform basic interpretive analyses and syntheses with several numerical prediction systems. Adaptive reconfiguration of the fleet during the course of the experiment was directed by a synthesis of available observations and model results in combination with fleet control algorithms developed by Naomi Leonard (Princeton) and colleagues. We are presently completing the post-experiment analysis of the data collected by the gliders and, with our collaborators, synthesizing this information with data from other ongoing investigations. Preliminary results from this program have been reported at several national meetings including AMS, AGU and ASLO. Several publications describing the oceanographic observations, numerical modeling, and systems engineering aspects of AOSN-II are in preparation for a special issue of Deep-Sea Research II edited by the PI with colleague Steve Haddock (MBARI).

RESULTS

A unique dataset consisting of more than 10,000 vertical profiles was collected. Two complete upwelling/relaxation cycles were observed by the glider fleet and horizontal scales of variability ranging from a few hundred meters to 25+ km were simultaneously measured. Glider performance during the experiment was generally good with typical effective survey speeds of 20-25 km per day in an ocean environment characterized by strong (25-50 cm/s) tidal fluctuations. Iridium communications was both slow and energy intensive but generally robust. Preliminary results suggest that better than 90% of expected surface contacts via Iridium were completed. Our automated control and data management system worked flawlessly and enabled smooth interaction with numerical ocean prediction systems and external mission planning tools.

IMPACT/APPLICATIONS

Continued development of multi-vehicle network operations will improve measurement and understanding of transient ocean phenomena such as mesoscale eddies and fronts and streamline distributed environmental observations in remote or hostile locations. We have shown conclusively that a network of gliding vehicles can supply, in an efficient and cost-effective manner, high-quality, near-real-time environmental information for operational ocean/atmosphere forecasting and model validation.

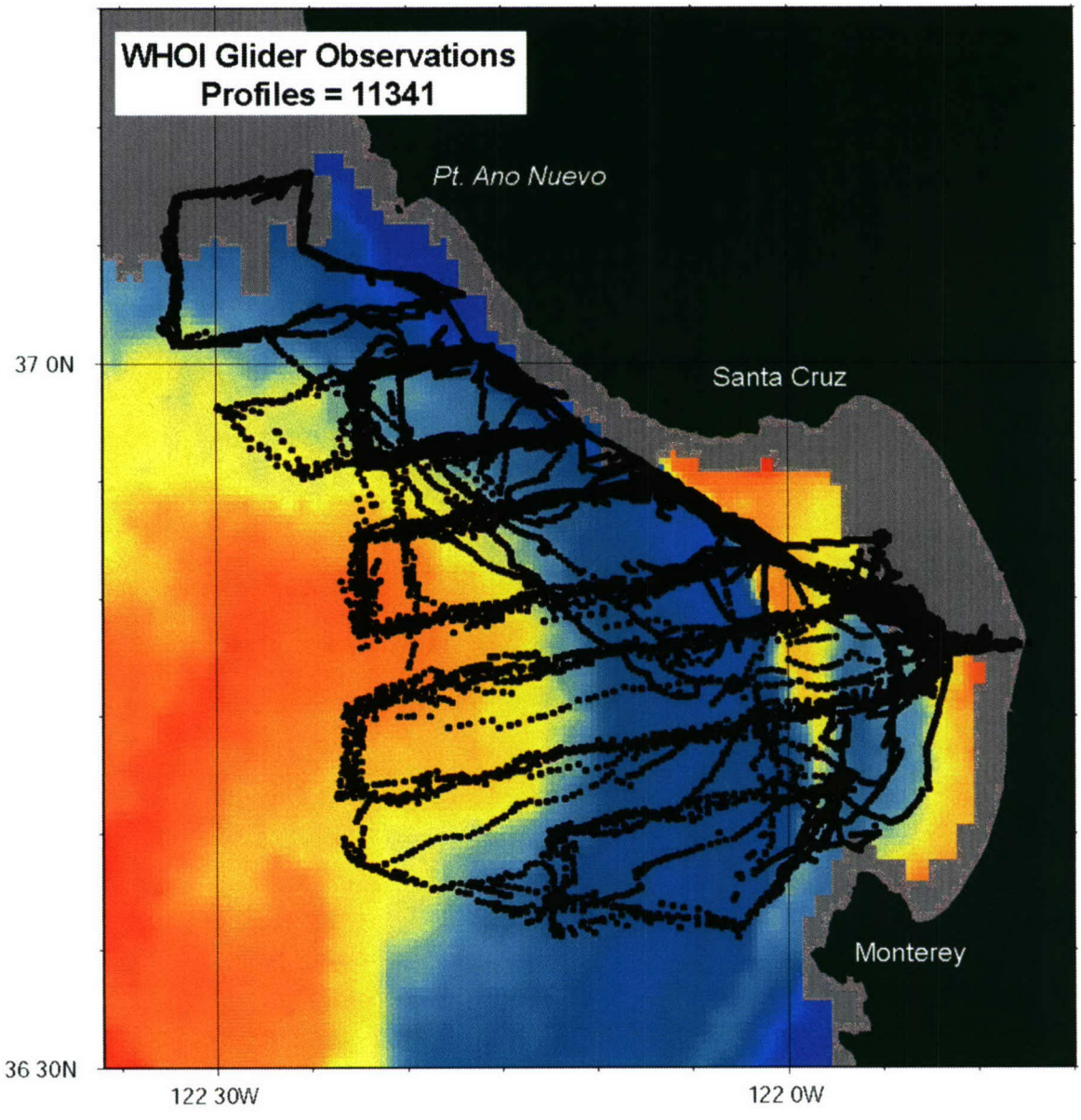

Figure 1: Location of profile data collected by WHOI glider fleet during AOSN-II superimposed on an AVHRR sea surface temperature image showing the relatively cool Ano Nuevo upwelling plume. Ten WHOI gliders collected hydrographic and vertically-averaged velocity data along five closed circuits spanning the Ano Nuevo upwelling plume and performed adaptive sampling experiments using multi-vehicle clusters. Dives were to 200 m or 5 m above the bottom. Data transmission consisted of approximately 75 Kbytes every 2 hours.

RELATED PROJECTS

The following is an exhaustive list of projects related to the AOSN-II effort:

Implementing FORMS (Feature oriented regional modeling system) for the Monterey Bay forecasting system using HOPS and ROMS.
Avijit Gangopadhyay.
N00014-1-0206

Development of a Monterey Bay Forecasting System Using The Regional Ocean Modeling System (ROMS)
Yi Chao
N00014-03-1-0208

Adaptive sampling during AOSN-II
PI: S. J. Majumdar
N00014-03-1-0559

Deep Autonomous Gliders for the "Autonomous Ocean Sampling Network II' Experiment
Russ E. Davis, Jeffrey T. Sherman
N00014-03-1-1049

Coastal Bioluminescence: Measurement and Prediction
J.F. Case
N00014-97-1-0424
Grant Supplement, Mod. 13

Aerial Surveys of the Atmosphere and Ocean off Central California
N0001403WR20002
N0001403WR20006
S. R. Ramp, J. D. Paduan, W. Nuss, and C. A. Collins

Hyperspectral Radiometer for Airborne Deployment
N0001403WR20209
S. Ramp

High-Resolution Measurement of Coastal Bioluminescence: II. Improving short-term predictability across seasons
Steven Haddock
N00014-00-1-0842

QUANTIFICATION OF LITTORAL BIOLUMINESCENCE STRUCTURE AND INDUCED WATER LEAVING RADIANCE
Mark Moline

N00014-03-1-0341

Use of a Circulation Model to Enhance Predictability of Bioluminescence in the Coastal Ocean
Igor Shulman
Naval Research Laboratory, Grant Number: N00014-03-WX-20882 and -20819
Leslie Rosenfeld and Jeffrey Paduan
NPS, Grant Number: N00014-03-WR-20009
Dennis McGillicuddy
N000140210853

Participation in AOSN II
A. Healey
N0001403WR20063

Autonomous Ocean Sampling Network II (AOSN II): System Engineering and Project Coordination
J. G. Bellingham and P. Chandler
N00014-02-1-0856

Underwater Glider Networks and Adaptive Ocean Sampling
Naomi Leonard, Clarence Rowley, and Jerrold Marsden
N000140210826

Underwater Glider Dynamics and Control
Leonard (PI)
N00014-02-1-0861

Autonomous Ocean Sampling Network II: Assessing the Large Scale Hydrography of the Central California Coast
Margaret A. McManus and Francisco Chavez
N000140310267

An Autonomous Glider Network for the Monterey Bay Predictive Skill Experiment / AOSN-II
David M. Fratantoni
N000140210846

Development of a Regional Coastal and Open Ocean Forecast System:
Harvard Ocean Prediction System (HOPS)
(Included under this are "Quantitative Interdisciplinary Adaptive Sampling OSSEs for Monterey Bay and the California Current System - AOSN-II" and "Adaptive Sampling OSSEs for Monterey Bay and the California Current System - AOSN-II")
A.R. Robinson
N00014-97-1-0239

PUBLICATIONS RESULTING FROM THIS SUPPORT

Rudnick, D. L., R. E. Davis, C. C. Eriksen, D. M. Fratantoni, and M. J. Perry, 2004, Underwater Gliders for Ocean Research. Journal of the Marine Technology Society.

Fiorelli, E., N. E. Leonard, P. Bhatta, D. Paley, R. Bachmayer, and D. M. Fratantoni, 2005 Multi-AUV control and adaptive sampling in Monterey Bay. IEEE Journal of Oceanic Engineering, submitted.

Leonard, N. E., D. Paley, F. Lekien, R. Sepulchre, and D. M. Fratantoni, 2005, Collective motion, sensor networks and ocean sampling. Proceedings of the IEEE, submitted.

Graver, J. G., R. Bachmayer, N. E. Leonard, and D. M. Fratantoni, 2003. Underwater glider model parameter identification. Paper presented at *The 13th International Symposium on Unmanned, Untethered Submersible Technology (UUST03), August 24–27, 2003, Durham, NH* (paper).

Bellingham, J. G., P. E. Chandler, Y. Chao, F. Chavez, R. E. Davis, D. M. Fratantoni, S. Haddock, N. E. Leonard, M. A. McManus, J. D. Paduan, S. R. Ramp, and A. Robinson, 2004. AOSN Monterey Bay Experiment: Observing and Predicting the Coastal Ocean. Presentation at the *84th American Meteorological Society Annual Meeting, Symposium on Forecasting the Weather and Climate of the Atmosphere and Ocean, 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction, 84th AMS Annual Meeting, January 10–15, 2004, Seattle, WA* (abstract).

Bellingham, J. G., D. M. Fratantoni, R. E. Davis, S. Ramp, F. Chavez, S. Haddock, M. McManus, M. Moline, J. Paduan, A. Healey, N. Leonard, P. Chandler, A. R. Robinson, Y. Chao, R. Bachmayer, J. F. Case, J. D. Doyle, P. Haley, H. Christy, S. Johnston, P. F. Lermusiaux, W. G. Leslie, S. J. Majumdar, J. Marsden, J. Ryan, J. Sherman, I. Shulman, and H. Thomas, 2004. AOSN in Monterey Bay: Observation and Adaptive Sampling with Multiple Platforms. Presentation at the *American Society of Limnology and Oceanography/The Oceanographic Society 2004, Ocean Research Conference, February 15–20, 2004, Honolulu, HI* (abstract).

Fiorelli, E., N. E. Leonard, R. Bachmayer, P. Bhatta, and D. M. Fratantoni, 2004. Adaptive Ocean Sampling Using Coordinated Autonomous Underwater Vehicle Fleets: The Autonomous Ocean Sampling Network in Monterey Bay 2002 and Beyond. Presentation at the *American Society of Limnology and Oceanography/The Oceanographic Society 2004, Ocean Research Conference, February 15–20, 2004, Honolulu, HI* (abstract).

Fratantoni, D. M., and R. E. Davis, 2004. Autonomous Underwater Glider Performance During AOSN-II. *Eos, Transactions, American Geophysical Union*, **84**(52), Abstract OS22D-01, 2003. *AGU Ocean Sciences Meeting, January 26–30, 2004, Portland, OR.*

Fratantoni, D. M., and R. E. Davis, 2004. Autonomous Underwater Glider Performance During AOSN-II. Presentation at the *American Society of Limnology and*

Oceanography/The Oceanographic Society 2004, Ocean Research Conference, February 15–20, 2004, Honolulu, HI (abstract).

Leonard, N. E., R. Bachmayer, P. Bhatta, E. Fiorelli, D. Paley, and D. M. Fratantoni, 2004. Design and Implementation of Multi-AUV Control Methodologies for Adaptive Sampling in a Dynamic and Uncertain Environment. Presentation at the *IEEE Oceanic Engineering Society, Autonomous Underwater Vehicles 2004, AUV 2004, June 17, 2004, Sebasco Estates, ME* (paper).

Robinson, A. R., J. G. Bellingham, Y. Chao, F. Chavez, R. E. Davis, D. M. Fratantoni, S. Haddock, N. E. Leonard, M. A. McManus, J. Paduan, S. Ramp, R. Bachmayer, P. Bhatta, P. Chandler, P. Choi, J. K. Fiorelli, P. J. Haley, P. F. Lermusiaux, W. G. Leslie, Z. Li, and J .E. Marsden, 2004. AOSN in Monterey Bay: Modeling and Predicting Multiple Scales for Adaptive Sampling. Presentation at the *American Society of Limnology and Oceanography/The Oceanographic Society 2004, Ocean Research Conference, February 15–20, 2004, Honolulu, HI* (abstract).

Bahatta, P., E. Fiorelli, F. Lekien, N. E. Leonard, D. A. Paley, F. Zhang, R. Bachmayer, R. Davis, D. M. Fratantoni, and R. Sepulchre, 2005. Coordination of an Underwater Glider Fleet for Adaptive Ocean Sampling. *International Workshop on Underwater Robotics. September 2005, Genoa, Italy*, (paper).