Final Report
Supplement to Remote Sensing and Modeling of Coherent Structures in River and Estuarine Flows

Andrew T. Jessup
Applied Physics Laboratory, University of Washington
1013 NE 40th St., Seattle, WA 98105-6698
phone: (206) 685-2609 fax: (206) 543-6785 email: jessup@apl.washington.edu

Robert L. Street, Stephen G. Monismith
Department of Civil and Environmental Engineering
Stanford University, Stanford, CA 94305-4020

Alexander R. Horner-Devine
Department of Civil and Environmental Engineering
University of Washington, Seattle, WA 98195-2700

Award Number: N00014-10-1-0425

This grant provided follow-on support for the FY05 MURI designated COHSTREX (award number N00014-05-1-0485). As such, this final report is similar to the COHSTREX final report.

LONG-TERM GOALS

The long-term goals of this research were to combine state-of-the-art remote sensing and *in situ* measurements with advanced numerical modeling (a) to characterize coherent structures in river and estuarine flows and (b) to determine the extent to which their remotely sensed signatures can be used to initialize and guide predictive models.

OBJECTIVES

Coherent structures are generated by the interaction of the flow with bathymetric and coastline features. These coherent structures produce surface signatures that can be detected and quantified using remote sensing techniques. Furthermore, a number of relationships between coherent structures and flow characteristics have been suggested that have the potential to allow flow parameters (e.g. mean velocity, bottom roughness, shear, and turbidity) to be inferred from remote measurements. The objectives were to test the following four hypotheses:

1. Flow parameters can be inferred from remotely sensed signatures of coherent structures.
2. Numerical models can be constrained with these inferred parameters.
3. The effect of stratification on the strength of coherent structures can be used to detect the presence or absence of stratification and the location of the fresh/salt water interface.
4. Numerical and field experiments can be used together to predict, interpret, characterize, and understand coherent structures.

APPROACH

The key to this project was an interactive process that blended sophisticated remote sensing, in-situ measurements, and numerical simulation. Our approach was to conduct closely coupled field and numerical model experiments to test the hypotheses listed above. We conducted two major field experiments with both *in situ* and remote sensing measurements – the first was in Year 2 and the second in Year 4. Preliminary experiments were conducted in Years 1 and 3 to aid in the design of the major field efforts. The research involved four main areas - (1) *in situ* measurements, (2) remote sensing, (3) modeling, and (4) physics and classification of coherent structures. The *in situ* field measurements were used to characterize the overall flow field to investigate the generation of coherent structures at specific sites, and initially, to provide boundary inputs for the numerical models. The surface signatures of coherent structures in the same region were detected using remote sensing techniques and compared with the *in situ* and model results. The numerical models served three roles, viz., (1) precursor simulations in which existing bathymetry and assumed regional forcing will allow us to guide the measurement plans, (2) detailed simulations of both the region and specific local areas for comparison to field-determined coherent structures, and (3) simulations to aid in characterizing the mechanisms by which observed coherent structures are formed, to evaluate the sensitivity of these generation mechanisms to variations in forcing, and to predict the surface signature that such structures generate. Results from the *in situ* field observations, remote sensing, and numerical model runs were synthesized into a classification scheme that included all observed coherent structures. Predictive scaling relationships were developed in order to generalize the results from this study to other systems. The result of this integrated approach were a thorough investigation of the mechanisms and evolution of coherent structures in rivers and estuaries in order to link their surface expressions to subsurface flow features.

The project participants were organized into teams identified by the main areas of interest listed above: <u>Remote Sensing</u>: A. Jessup, W. Plant (APL-UW),; <u>Modeling</u>: R. Street and O. Fringer (Stanford); <u>In situ Measurements</u>: S. Monismith and D. Fong (Stanford); <u>Physics and Classification:</u> A. Horner-Devine.

The project supported one MS student (Brownyn Hayward, UW-CEE), two PhD students (Sarah Giddings and Bing Wang, Stanford-CEE), and two postdoctoral fellows (Chris Chickadel, APL-UW, and Mike Barad, Stanford-CEE).

To date, the project has produced 7 published and 2 submitted peer-reviewed journal articles, 1 MS thesis, and 2 PhD theses. We anticipate that at least 3 additional manuscripts will be submitted to peer-reviewed publications within the next year.

The results of the project to date are summarized in the following publications:

<u>Articles in Peer-Reviewed Journals: Published</u>

1. Chickadel, C., S. Talke, A. Horner-Devine, and A. Jessup (2011), Infrared based measurements of velocity, turbulent kinetic energy, and dissipation at the water surface in a tidal river, *Geosci. Rem. Sen. Let., in press*.

2. Chickadel, C. C., A. R. Horner-Devine, S. A. Talke, and A. T. Jessup (2009), Vertical boil propagation from a submerged estuarine sill, *Geophysical Research Letters, 36*.

3. Giddings, S. N., D. A. Fong, and S. G. Monismith (2011b), Role of straining and advection in the intratidal evolution of stratification, vertical mixing, and longitudinal dispersion of a shallow, macrotidal, salt wedge estuary, *J. Geophys. Res.-Oceans*, *116*.

4. Plant, W. J., et al. (2009), Remotely sensed river surface features compared with modeling and in situ measurements, *J. Geophys. Res.-Oceans*, *114*.

5. Talke, S. A., A. R. Horner-Devine, and C. C. Chickadel (2010), Mixing layer dynamics in separated flow over an estuarine sill with variable stratification, *J. Geophys. Res.-Oceans*, 115.

6. Wang, B., O. B. Fringer, S. N. Giddings, and D. A. Fong (2009), High-resolution simulations of a macrotidal estuary using SUNTANS, Ocean Modelling, 28(1-3), 167-192.

7. Wang, B., et al. (2010), Modeling and understanding turbulent mixing in a macrotidal salt wedge estuary, J. Geophys. Res.-Oceans, 116.

Articles in Peer-Reviewed Journals: In Review

1. Giddings, S. N., et al. (2011a), Frontogenesis and frontal progression of a trapping-generated estuarine convergence front and its influence on mixing and stratification, *Estuaries and Coast*, *in review*.

2. Wang, B., G. Zhao, and O. Fringer (2011), Reconstruction of vector fields for semi-Lagrangian advection on unstructured, staggered grids, *Ocean Modelling*, *in review*.

Dissertations

1. Giddings, S. (2010), Dynamics of a shallow, macrotidal, strongly stratified estuary, PhD Dissertation, Stanford University.

2. Hayworth, B. (2007), Observations of Tidally Generated Coherent Structures in the Snohomish River Estuary, MS Dissertation, University of Washington.

3. Wang, B. (2011), Multiscale numerical simulation of a complex macrotidal tidal-river estuary, PhD Dissertation, Stanford University.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
19-05-2011	Final Report	1 January 2010 to 31 March 2011

4. TITLE AND SUBTITLE

Final Report Supplement to Remote Sensing and Modeling of Coherent Structures in River and Estuarine Flows

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-10-1-0425

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Andrew T. Jessup
Robert L. Street
Stephen G. Monismith
Alexander R. Horner-Devine

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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

Applied Physics Laboratory - University of Washington
1013 NE 40th Street
Seattle, WA 98105-6698

8. PERFORMING ORGANIZATION REPORT NUMBER

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

Office of Naval Research (ONR 32)
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

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

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

None

14. ABSTRACT

Coherent structures are generated by the interaction of the flow with bathymetric and coastline features. These coherent structures produce surface signatures that can be detected and quantified using remote sensing techniques. Furthermore, a number of relationships between coherent structures and flow characteristics have been suggested that have the potential to allow flow parameters (e.g. mean velocity, bottom roughness, shear, and turbidity) to be inferred from remote measurements. The objectives were to test the following four hypotheses: 1. Flow parameters can be inferred from remotely sensed signatures of coherent structures. 2. Numerical models can be constrained with these inferred parameters. 3. The effect of stratification on the strength of coherent structures can be used to detect the presence or absence of stratification and the location of the fresh/salt water interface. 4. Numerical and field experiments can be used together to predict, interpret, characterize, and understand coherent structures.

15. SUBJECT TERMS

Coherent Structures, Infrared, River, Estuary

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU		Andrew T. Jessup

19b. TELEPHONE NUMBER *(Include area code)*
206-685-2609

Reset

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.