High-Resolution Ocean Wave Estimation

David Walker
SRI International
2100 Commonwealth Boulevard, Third Floor
Ann Arbor, MI 48105
phone: (734) 926-4416 fax: (734) 926-4402 email: david.walker@sri.com

Award Number: N00014-12-C-0566
http://sri.com/esd/

LONG-TERM GOALS

The goal of this effort is to develop and validate an algorithm to provide high-resolution estimates of the sea surface in the area around a fixed sensor system. The purpose of this development effort is to improve environmental situational awareness for open-ocean Naval operations.

OBJECTIVES

The objectives of this project are to develop and refine a sea-surface estimation algorithm based on the Vortwave model (Nwogu 2009), to apply the algorithm to synthetic data and to stationary tower- or ship-mounted marine radar systems to obtain high-resolution estimates of the ocean wave field, and to validate these estimates against available independent field observations.

APPROACH

We use the Vortwave model to solve for the time evolution of the sea surface given initial data. Vortwave is a nonlinear wave model which computes the sea-surface elevation and surface-velocity fields in deep open water. The model solves the exact kinematic and dynamic free-surface boundary conditions, expressed as a set of nonlinear coupled evolution equations for the surface elevation and tangential surface-velocity components. The normal velocity at the surface is required to close the model, and this is done using an FFT-based closure relationship to express the normal velocity in terms of the surface elevation and tangential velocity components. The model is driven by initial surface elevation and velocity fields, and can be run with a specified mean surface current. The model enforces spatially periodic boundary conditions on the solution.

Since the surface elevation and velocities in the ocean are not spatially periodic, we implemented a "damping region" at the edges of our computational domain in which waves effectively propagate out of the domain and do not re-enter at the other edge. We then implemented a mass and momentum source function (wavemaker) just inside of this region that is capable of introducing "fresh" waves into the computational domain. The source terms, along with the initial wave/velocity fields and the mean surface current, are the main inputs to the Vortwave model when attempting to compute ocean waves for a region of interest.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **High-Resolution Ocean Wave Estimation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **SRI International,2100 Commonwealth Boulevard, Third Floor,Ann Arbor,MI,48105**	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
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Our estimation algorithm consists of a gradient-based minimization scheme to accomplish a least-squares fit of the estimated sea surface to the data. The gradient is computed by solving the continuous adjoint equations, which are derived within a variational framework. We solve the associated adjoint evolution equations and iteratively estimate initial conditions, boundary source terms, and mean surface currents using the computed gradient.

WORK COMPLETED

We have derived, implemented, and validated the implementation of an estimation algorithm as described above. We also applied the algorithm to observation data from the FLIP and Sproul 2010 HiRes experiments. Specifically, this consisted of:

- Parallelization and optimization of the original Vortwave model, including:
    - Implementation of a "damping region" to allow waves to propagate out of the domain regardless of the periodic boundary conditions.
    - Implementation of a wavemaker inside the damping region to bring "fresh" waves into the domain.
- Development and implementation of an algorithm to generate a solution from the Vortwave model that is a best-fit to sea-surface observation data, including
    - Derivation and parallel implementation of the adjoint equations.
    - Implementation of an assimilation algorithm that combines the forward model and adjoint model to estimate initial conditions, boundary source terms, and mean surface current that provide a best-fit to observation data
    - Derivation and implementation of a scheme to produce an initial estimate of the mean surface current solely from data.
- Validation of the algorithm implementation using synthetic data.
- Application of the algorithm to FLIP and Sproul 2010 HiRes experimental data from SIO, as well as analysis of the results.

RESULTS

Here we focus on results obtained using data collected during the HiRes Departmental Research Initiative provided by Eric Terrill from Scripps Institution of Oceanography (SIO). We were given data from the FLIP and Sproul 2010 HiRes data collections; the data are from a WaMoS marine radar system and have been band-pass filtered around the linear dispersion surface. The data span 2.5 hours, beginning at 2330 GMT on 07 June 2010, and are from a domain off the coast of northern CA with approximately 2 km x 2 km spatial extent at 7.5 m spatial resolution and 1.52 s temporal resolution. The FLIP and Sproul upwind and downwind domains are shown in Figure 1. SIO also provided HF radar surface-current data for the month of June 2010 (presumably) from the NOAA operational HF radar system. These measurements were given hourly at 16 points located near the FLIP and Sproul domains. Since we ran our assimilation on the upwind data at the beginning of the time history (06/07/2010 at 2330), we averaged the nearest hourly current measurements and plot this field in Figure 2 with the upwind domains. The maximum surface current was 55 cm/s. To produce mean surface-current values for the FLIP and Sproul upwind domains, we averaged the four closest vectors for the FLIP and the five closest vectors for the Sproul.

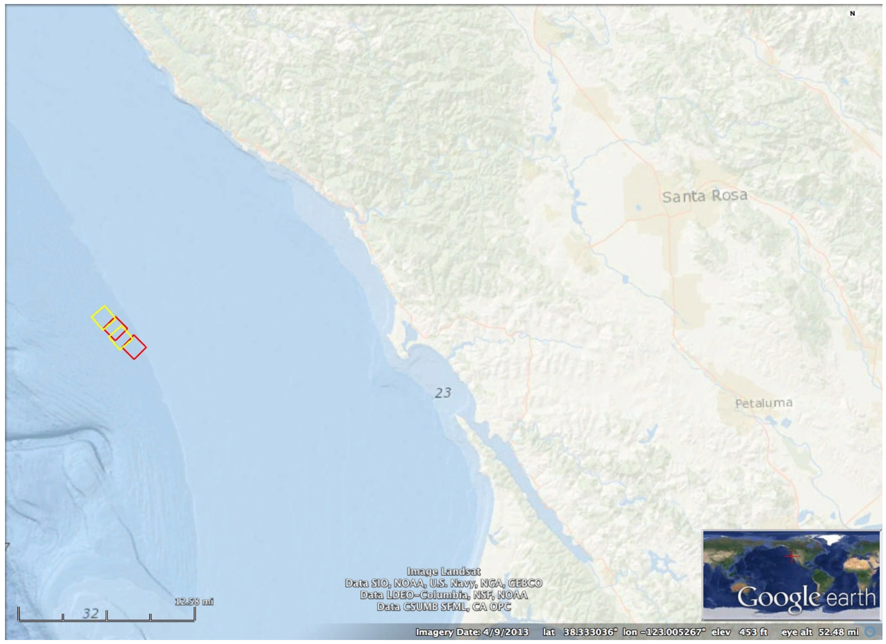

Figure 1 FLIP and Sproul domains. The image is set off the coast of northern California, about 110 km northwest of San Francisco. The FLIP domains are shown in yellow; the Sproul domains are shown in red. The northwest of each color is the upwind domain; the southeast of each color is the downwind domain.

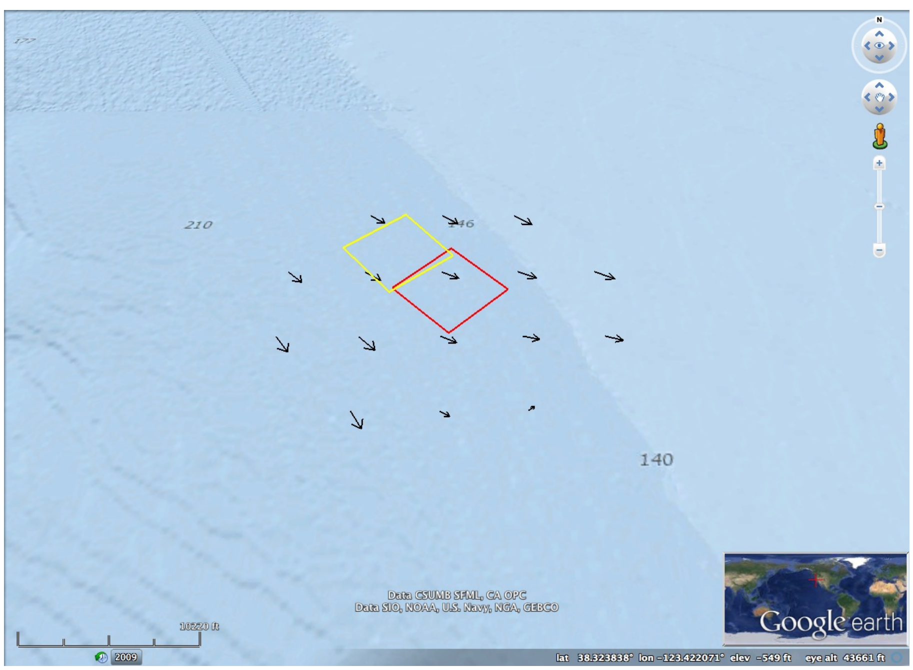

Figure 2. FLIP and Sproul upwind domains with surface-currents at 2330 on 06/07/2010. The current vector scaling is linear with the maximal speed of 55 cm/s. The FLIP upwind domain is shown in yellow; the Sproul upwind domain is shown in red (HF radar data provided by SIO).

We used 97 s of data from the FLIP upwind domain sea-surface data to estimate the sea surface at 0.05 s temporal resolution (the Vortwave time step) and 1.23 m spatial resolution for 97 s on the same spatial domain. The mean error for the entire resulting sea-surface time history is 0.0011 m and the RMS error is 0.21 m (comparable to about 11% of the energy in the observed wave field). Some results of the assimilation are shown in Figures 3 and 4. A comparison of the surface-current estimates and the HF radar data is shown in Figure 3. The initial guess is based on fitting the 3D spectrum of the data to the linear dispersion surface. The difference in magnitude between the initial guess (based solely on the data) and the HF radar data was 21.34 cm/s, while for the final estimate it was 9.10 cm/s. The difference in direction was 15.23 deg for the initial guess and 26.25 deg for the final estimate. It should be noted, however, that our final surface-current estimate correctly predicts the energy spectrum, whereas the observed current does not. This will be a subject of future investigation. Figure 4 presents the sea-surface data, the predicted sea surface from the Vortwave model, and the residual (i.e. the difference between the predictions and observations). The sea surface appears to be a good match, but residual wave fields appear to have high-frequency wavelike structure. This indicates that either there are high-frequency wave components in our estimate that do not appear in the data, or there are high-frequency wave components in the data that do not appear in our estimate. This will also be the subject of future investigations and ground-truth comparisons.

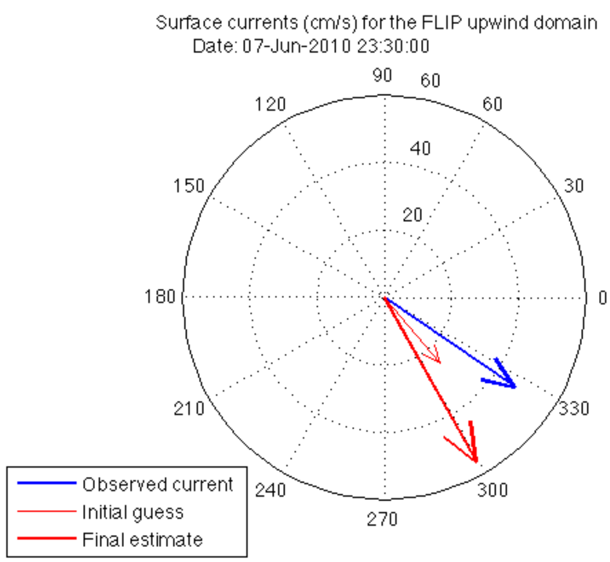

Figure 3 Comparison of the HF radar-derived and estimated surface current. The observed HF radar current (blue), the initial estimate (red), and the final estimate (thick red) are shown. The differences between the initial guess and the observation current were 21.34 cm/s in magnitude and 15.23 deg in direction. For the final estimate, the differences were 9.10 cm/s in magnitude and 26.25 deg in direction. However, our estimate of the current correctly predicts the energy spectrum of the data, which provides some validation to our estimate of the current.

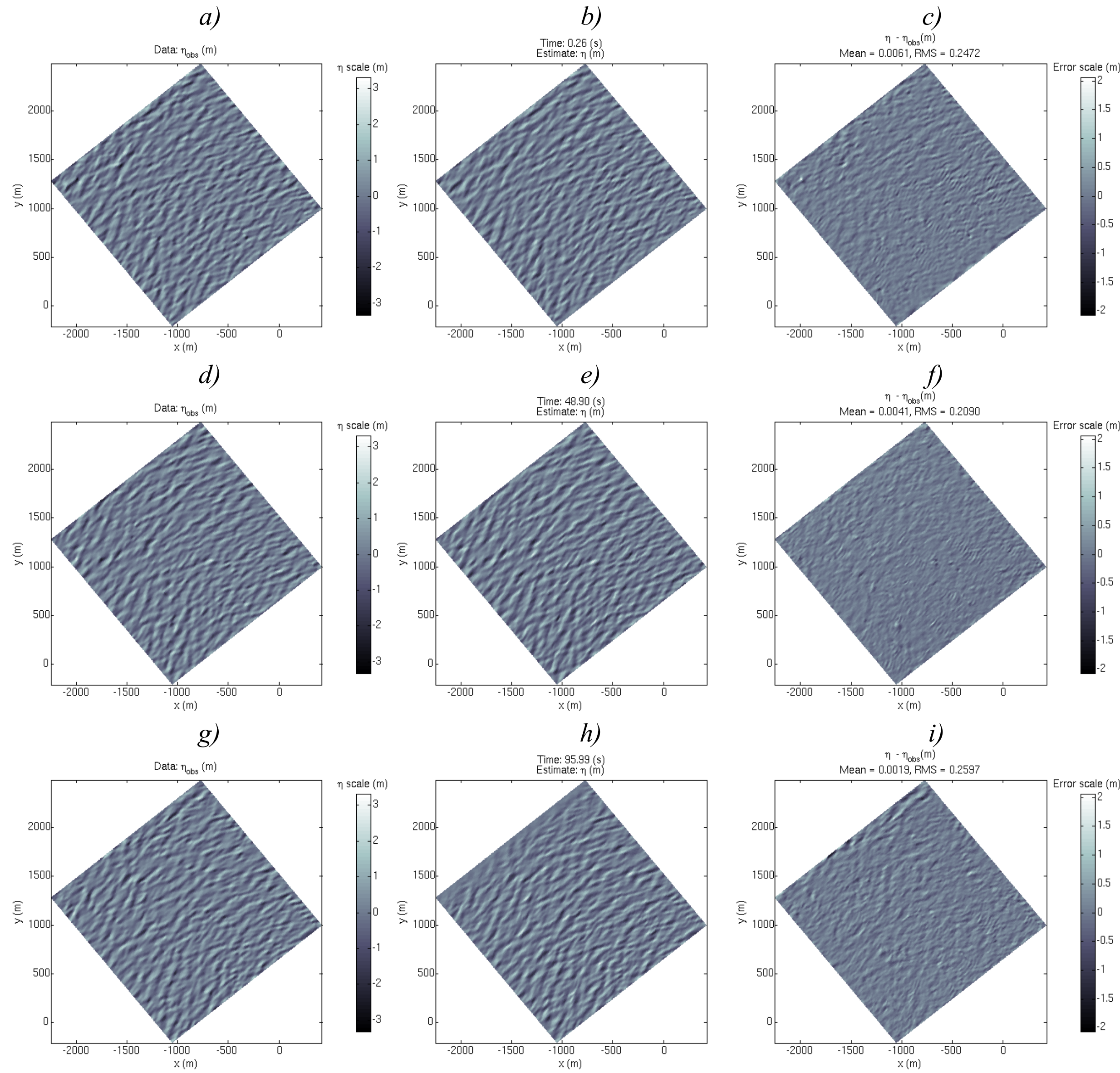

Figure 4 Results from the FLIP upwind domain assimilation for 97 s of data. Each row shows the data, the estimate, and the residual, respectively. The first row shows the first frame (mean frame time = 0.26 s), the second row shows the 33^rd^ frame (mean frame time = 48.9 s, and the third row shows the 64^th^ frame (mean frame time = 95.99 s). Note that the residual fields are shown on a different scale than the data and estimate fields. Also note that the residuals resemble high-frequency wave components.

IMPACT/APPLICATIONS

This program shows the use of variational inverse modeling for the estimation of detailed sea-surface characteristics from shipborne radar observation data.

RELATED PROJECTS

This project is related to the High Resolution Air-Sea Interaction Departmental Research Initiative. We have been provided the above data for application of our assimilation algorithm and expect to do further ground-truth comparisons to other data collected during the DRI.

REFERENCES

Nwogu, O.G. 2009 Interaction of finite-amplitude waves with vertically sheared current fields. *J. Fluid Mech.* **629**, 179 – 213.