Adaptive Velocity Estimation System

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Introduction: Knowledge of the velocity field in littoral waters is crucial to specifying the battlespace and is important in oceanographic studies as well. In many areas, however, direct measurement of surface velocity requires a large amount of in situ data from ships or current meters, which may not possible if the region is denied or otherwise inaccessible. Instead, successive spaceborne or airborne images are being used more extensively to extract surface velocity information in oceans, rivers, and littoral areas.

The general topic of velocity estimation from an image sequence is a well-known inverse problem in computer vision, geosciences, and remote sensing. It has been of fundamental interest in many diverse fields such as velocity estimation from large and small displacements, object tracking, advanced video editing, and deriving surface currents for ocean dynamics studies.

Almost all existing velocity estimation models and algorithms assume that the image intensity recorded from different physical sensors obeys a conservation equation for tracer, heat, or optical flow in space and time. The inverse problem was believed to be underconstrained, however, because the two unknown velocity components must be derived from this single conservation equation at each of these pixel points. To solve the underconstrained problem for the intensity conservation equation from an image sequence, different models or frameworks with additional constraints have been reported in literature.

Adaptive Velocity Estimation System: Our strategy[1,2] converts the underconstrained system to an overconstrained one by modeling the velocity field as a set of tiles or blocks. Within each block, the velocity is specified as a binomial or B-spline. By collectively constraining the set to obey the above conservation equation in a least-squares sense, we derive a global optimal solution (GOS) for the velocity field. We can adjust the tile (block) size to control the degree of the overconstrained system and its robustness to noise. To obtain higher accuracy in velocity estimation, especially in larger scale displacement motion, a temporal integral form of the conservation constraint equation (the nonlinear inverse model) has been created to replace a differential form of the equation (the linear inverse model).

In addition, we have proven that this inverse problem for motion determination is generally not underconstrained based on an innovative approach.

The motion fields are identified by the velocity field and displacement field. In general, the velocity determination is an ill-posed problem, because the information about the path and rate is lost after a temporal sampling. However, the problem of the displacement field determination is well-posed because the initial and final configurations of a textured moving particle can be physically determined and observed by an image sequence. A fully constrained nonlinear system of equations combing the Displacement Vector Invariant (DVI) equation is presented without any approximation and imposing additional constraint and assumption. An adaptive framework for resolving the displacement or average velocity field has been developed.

NRL's Adaptive Velocity Estimation System (AVES) has been developed based on these fully constrained nonlinear systems of equations, velocity field modeling, GOS strategies, Gauss–Newton and Levenberg–Marguardt methods, an algorithm of the progressive relaxation of the pyramid constraint, and adaptive frameworks.

Demonstration: We test the performance of the new inverse model and algorithms by experimental results synthesized from a numerical simulation[1] and actual thermal images. The synthetic tracer (i.e., the two background images in Figs. 1(a) and 1(b)) in a square box with dimension $L = 50$ km has been deformed by an initial velocity distribution and is significantly different from its original tracer field. The average benchmark velocity vectors for $t = 18$ h and 20 h as given by the numerical simulation are shown in Fig. 1(a). For comparison, the velocity field estimated by the AVES from the tracer fields at 18 h and 20 h is shown in Fig. 1(b). Average values of angular and magnitude measures of error[2] are applied to evaluate the performance of the velocity estimations, as shown in Fig. 2.

Finally, we demonstrate the utility of AVES by deriving a velocity map from actual satellite-borne NOAA Advanced Very High Resolution Radiometer (AVHRR) images taken in the New York Bight, east of the New Jersey coast and south of Long Island, New York, on May 25, 2007 (Fig. 3(b)). For a comparison, a measured velocity array by the Coastal Ocean Dynamics Application Radar (CODAR) is shown in Fig. 3(a).

Summary: The inverse problem of velocity estimation from an image sequence had been considered as an underconstrained problem for several decades. Previous models for solving the inverse problem have done so by imposing unphysical constraints, which yields sparse and often inaccurate velocity fields.

The inverse problem for displacement or average velocity determination based on two successive frames has been proven to be fully constrained without any
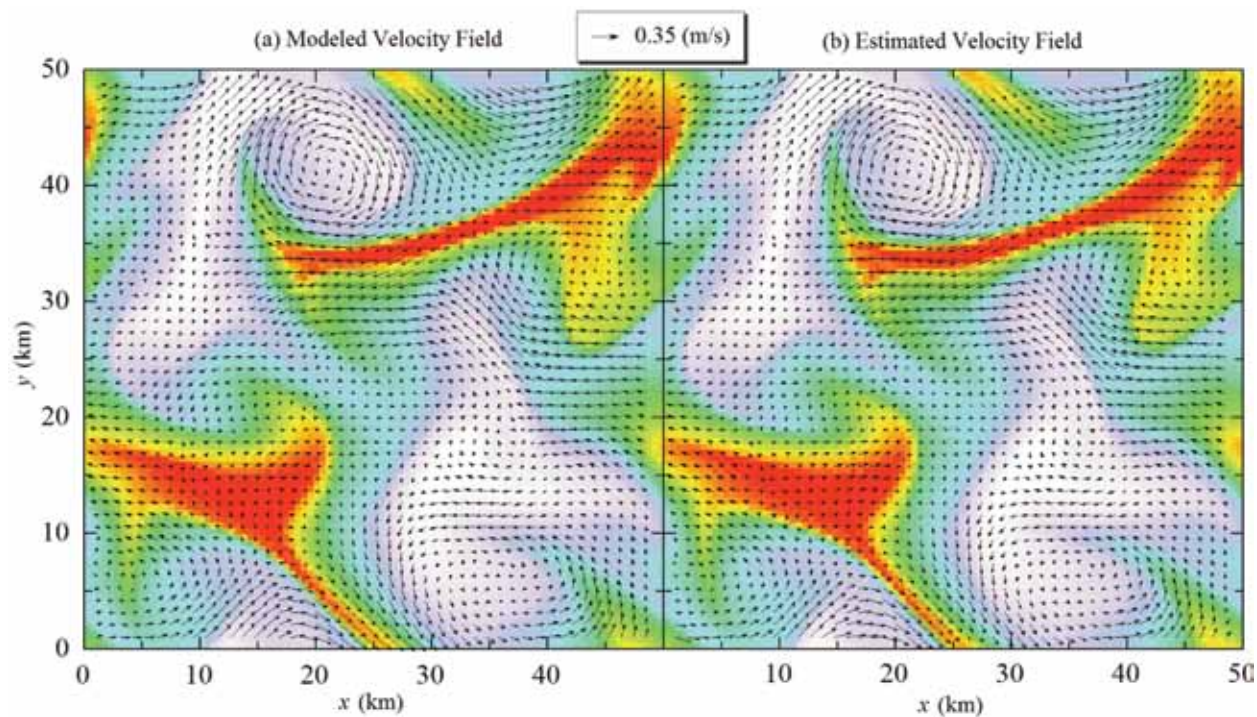
FIGURE 1
Velocity fields: (a) Velocity field generated by averaging numerical model results at times t_1 = 18 h and t_2 = 20 h; (b) Velocity field estimated by the AVES between times t_1 = 18 h and t_2 = 20 h. The background images shown in (a) and (b) are the tracer fields at t_1 = 18 h and t_2 = 20 h, respectively.
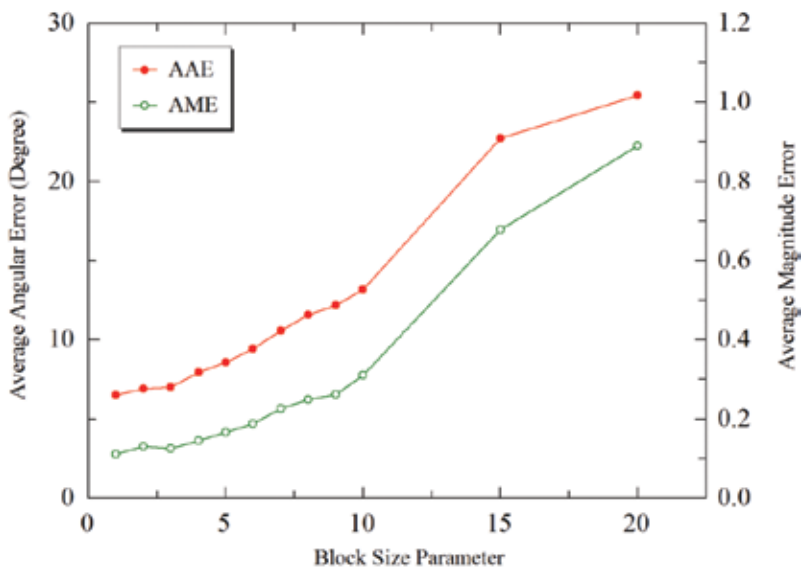

FIGURE 2
Quantitative measurements of average angular and magnitude errors (AAE and AME) vs block size parameter for the AVES estimator with ocean simulation model data are plotted.
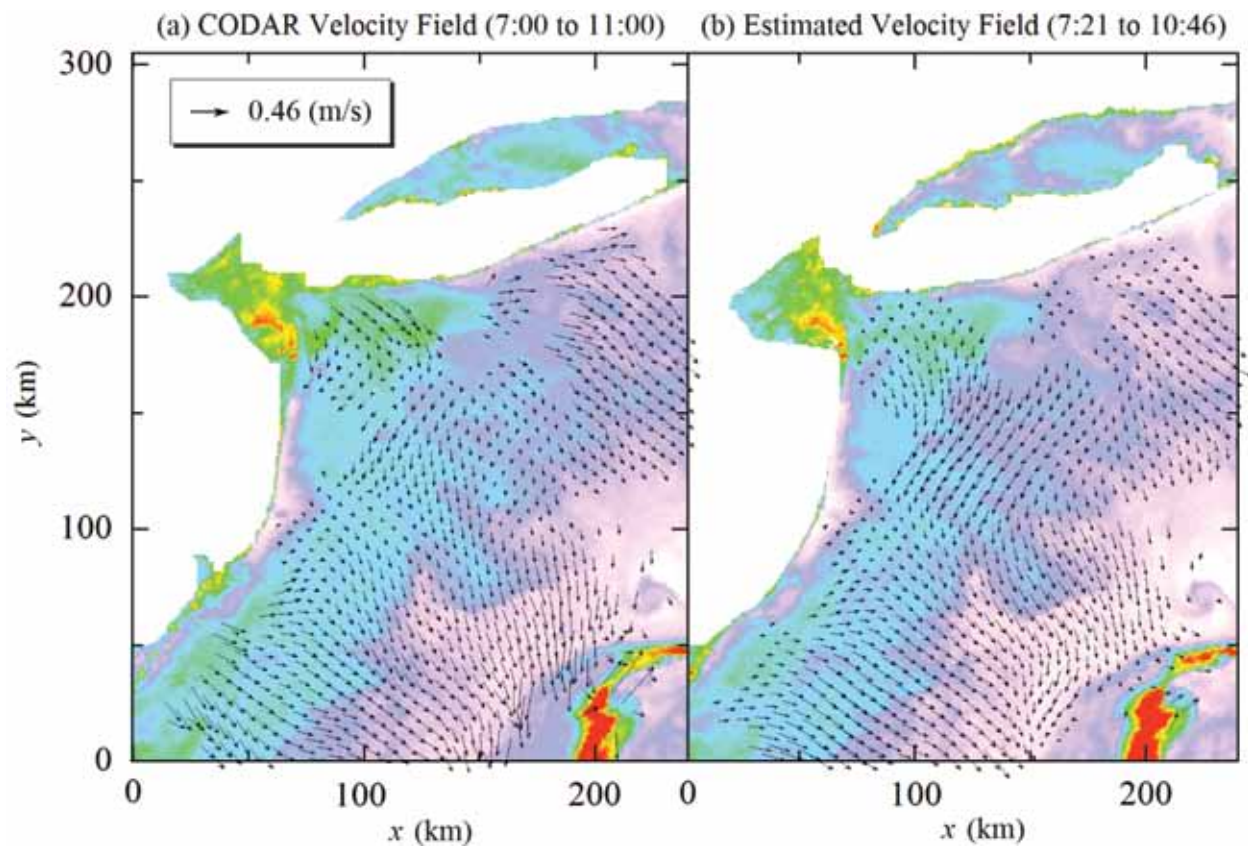
(a) CODAR Velocity Field (7:00 to 11:00)   (b) Estimated Velocity Field (7:21 to 10:46)

FIGURE 3
The velocity vectors are superimposed on the AVHRR image pair at time 7:21 and 10:46 UT on May 25, 2007 (false-color representation). (a) Average of the CODAR velocity field from 7:00 to 11:00 (the background image at t_1 = 7:21 UT). (b) Estimated velocity field obtained from the AVES (the background image at t_2 = 10:46 UT).

additional unphysical constraints. The Remote Sensing Division has developed the powerful AVES to retrieve velocities from image sequences based on this fully constrained system. NRL's AVES is an integration of models, methodologies, and state-of-the-art techniques. It is suited for motion field estimation from visible-band, thermal, or hyperspectral image sequences with complicated coastal land boundaries in ocean/river dynamics studies. The AVES framework has a wide variety of applications in both computer vision and remote sensing fields.

[Sponsored by ONR]

References
[1] W. Chen, R.P. Mied, and C.Y. Shen, "Near-Surface Ocean Velocity from Infrared Images: Global Optimal Solution to an Inverse Model," *J. Geophys. Res.* **113**, C10003 (2008), doi:10.1029/2008JC004747.
[2] W. Chen, "A Global Optimal Solution with Higher Order Continuity for the Estimation of Surface Velocity from Infrared Images," *IEEE Trans. Geosci. Rem. Sens.* **48**(4), 1931–1939 (2010).

Coupling Satellite Imagery and Hydrodynamic Modeling To Map Coastal Hypoxia

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Introduction: The frequency, extent, and severity of coastal hypoxic events are increasing worldwide due to increasing eutrophication. Hypoxia occurs when dissolved oxygen levels in the water column drop below 2 mg/l, and these low oxygen levels can potentially impact local fisheries and benthic organisms, with important ecological and economic consequences. A "dead zone" off the coast of Louisiana forms every summer and is the second largest hypoxic zone in the world (only the Baltic Sea hypoxic zone is larger). It is generally thought that agricultural fertilization upstream and runoff delivered via the Mississippi-Atchafalaya river

basin leads to the increased nutrient loading on the Continental Shelf, stimulating a phytoplankton bloom. As the bloom stimulated by this nutrient-rich discharge of the Mississippi and Atchafalaya Rivers sinks and decays, oxygen levels near the bottom become depleted. In addition to the bloom decay, water column stratification is also a required condition for hypoxia development, to prevent mixing with surrounding oxygen-replete waters.

TABLE 1 — Size of Coastal Louisiana Hypoxic Zone, as Determined by Mid-Summer Ship Surveys[1]

Year	Hypoxia Size (km²)
1998	12,400
1999	19,750
2000	4,000
2001	20,720
2002	22,000
2003	8,560
2004	15,040
2005	11,840
2006	17,280
2007	20,500
2008	20,720
2009	8,000
2010	20,000

Ship-based surveys have been conducted each summer since 1985 by the Louisiana Universities Marine Consortium (LUMCON) to map the spatial extent of the bottom hypoxic waters (Table 1); this measurement represents the officially reported size of the hypoxic zone.[1] Ten other cruises covering the Louisiana shelf from 2002 to 2009 by the U.S. Environmental Protection Agency (EPA) provided additional physical oceanographic data. There is currently a national mandate to decrease the size of the hypoxic zone to 5,000 km² by 2015, mostly by a proposed 40% reduction in annual nitrogen discharge into the Gulf of Mexico. A monitoring program is required to assess whether these goals are being met. However, ship sampling is expensive and is not spatially or temporally synoptic. Our goal is to develop a technique to more effectively map coastal hypoxia.

Can We Combine Surface Satellite Imagery and 3D Hydrodynamic Modeling To Map the Spatial Extent of Bottom-Water Hypoxia? To answer this question, NRL first collected, processed, and archived a 13-year time series of satellite ocean color imagery covering the northern Gulf of Mexico from 1998 to 2010. All imagery was processed using the NRL automated satellite processing system (APS) to derive water optical properties.[2] APS is a complete end-to-end system
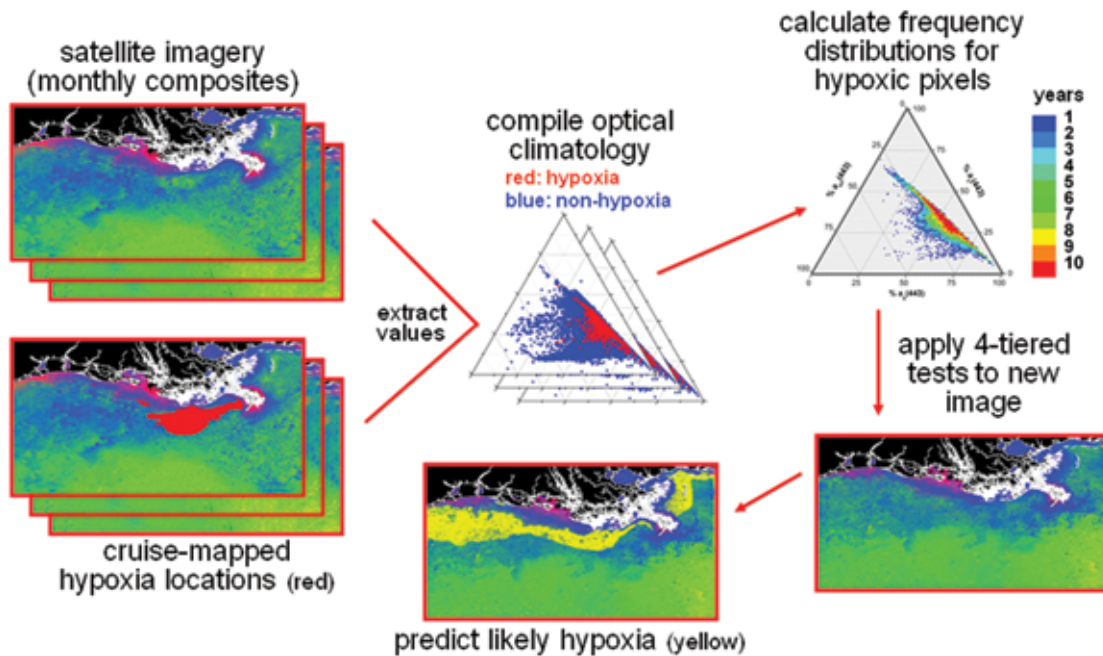
that includes sensor calibration, atmospheric correction (with near-infrared correction for coastal waters), and bio-optical inversion. APS incorporates the latest NASA algorithms, as well as NRL algorithms tailored for Navy-specific products. We then applied an optical water mass classification (OWMC) system developed at NRL to the imagery to characterize the absolute and relative surface optical conditions.[3] Using this satellite climatology, we extracted optical properties at hypoxic locations (delineated by the mid-summer ship surveys) for each year to develop frequency distributions to characterize expected optical conditions of hypoxic waters.

As mentioned, water column stratification is also required for hypoxia development. A real-time ocean nowcast/forecast system (ONFS) has been developed at NRL.[4] The NRL ONFS provides short-term forecasts of ocean current, temperature, salinity, density, and sea level variation including tides. It is based on the Navy Coastal Ocean Model (NCOM) hydrodynamic model, but has additional components such as data assimilation for sea surface height (SSH) and sea surface temperature (SST) and improved forcing with actual river discharge data. A nested model with 2-km horizontal resolution and 40 vertical layers has been implemented in the northern Gulf of Mexico, and we use the surface-to-bottom vertical density gradient derived from this model as our stratification index. Based on the in situ and model data, we estimated a minimum stratification threshold required for hypoxia development.

To determine likely hypoxic areas in an image, we compare the observed satellite-derived optical properties (absolute and relative water composition) to the expected conditions (from the optical climatology). We couple this with the model-derived stratification index and the bathymetry in a four-tiered testing approach to provide a spatial estimate of possible hypoxic areas. A pixel is flagged as potentially hypoxic if all four of the following criteria are satisfied:

(1) the relative optical properties match the historical hypoxic properties in at least 8 years and occur at least 500 times (i.e., in at least 500 pixels over the 10 years);

(2) the absolute optical properties match the historical hypoxic properties in at least 8 years and occur at least 500 times;

(3) the water depth is shallower than 50 m;

(4) the surface-to-bottom density difference from the model is greater than 1.5 kg/m³ (i.e., the water column is stratified).

The premise is that by comparing current optical conditions to those observed during past hypoxic events, we can "predict" where hypoxia is most likely to occur. Figure 4 shows a schematic of the process.

satellite imagery
(monthly composites)

extract values

compile optical climatology
red: hypoxia
blue: non-hypoxia

calculate frequency distributions for hypoxic pixels

years
1 2 3 4 5 6 7 8 9 10

cruise-mapped hypoxia locations (red)

apply 4-tiered tests to new image

predict likely hypoxia (yellow)

four-tiered optical and physical testing:
- relative optical composition
- absolute optical properties
- water-column stratification index
- bathymetry

FIGURE 4
Schematic illustration showing the steps involved in the estimation of hypoxic locations, using a combination of satellite ocean color imagery and hydrodynamic modeling. A four-tiered test based on both the optical and physical properties of the water is applied; if all four criteria are met, an image pixel is flagged as hypoxic.

Validation: To validate the approach, we can compare the cruise-mapped and the satellite-estimated hypoxia regions. Figure 5 shows example results for one year (2006). Following extraction of the optical values from the 2006 satellite OWMC image, comparisons were made with the past hypoxia optical conditions as prescribed by the frequency plots. The four-tiered test described above, coupling the optical and physical conditions, was then applied; the intersection of the resulting four regions determined the final prediction (red and yellow pixels in Fig. 5). Note the close correspondence between the estimated and observed hypoxic regions. Why can we successfully use surface optical imagery to represent a bottom hypoxic process? We believe that the success of this approach is due to the causative linkage between the bottom hypoxia and the prior surface phytoplankton bloom, which can be detected by satellite.

Impact: Our research has led to the development of a novel approach that combines satellite ocean color imagery and hydrodynamic modeling to estimate both the size and location of coastal hypoxia. This approach can be used to augment ship surveys and delineate areas of expected hypoxia in near-real time, reducing costs and providing coastal managers with a new monitoring and predictive tool. In addition, this approach can be extended to a variety of other applications, such as mapping, tracking, and forecasting of harmful algal blooms and other coastal processes that impact both Navy and civilian operations.

References
[1] Louisiana Universities Marine Consortium. "Hypoxia in the Northern Gulf of Mexico," http://www.gulfhypoxia.net, 2009.
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[3] R.W. Gould, Jr., and R.A. Arnone, "Optical Water Mass Classification for Ocean Color Imagery," in *Proceedings: Second International Conference, Current Problems in Optics of Natural Waters*, I. Levin and G. Gilbert, eds., St. Petersburg, Russia, 2003.
[4] D.S. Ko, P.J. Martin, C.D. Rowley, and R.H. Preller, "A Real-Time Coastal Ocean Prediction Experiment for MREA04," *J. Marine Systems* **69**, 17–28 (2008), doi:10.1016/j.jmarsys.2007.02.022. ■
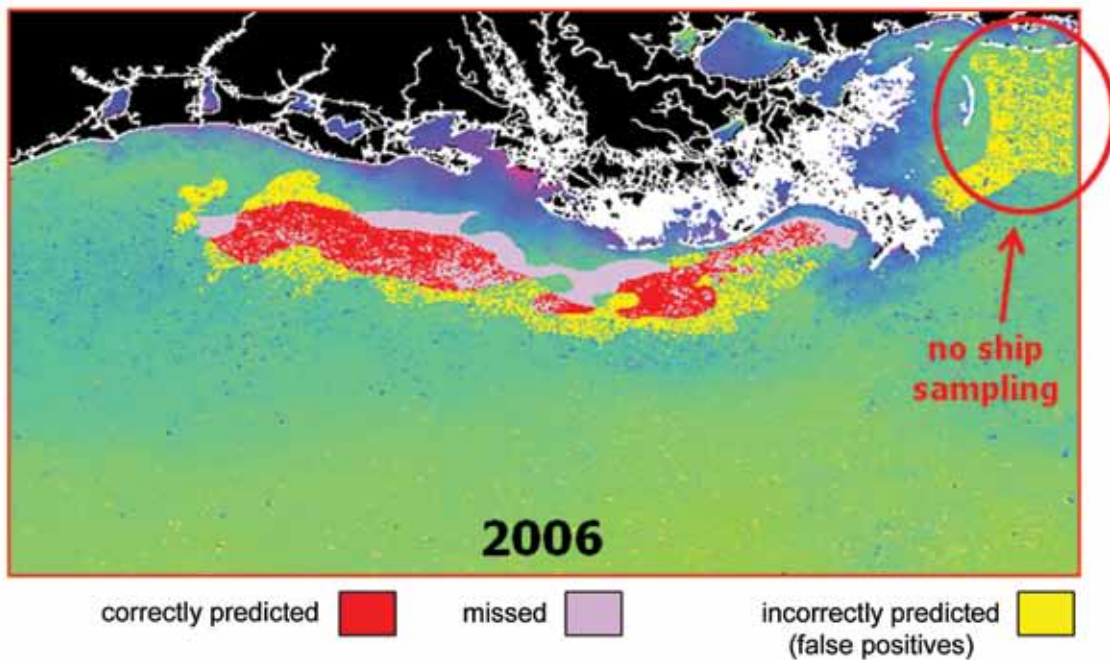
FIGURE 5
Estimated hypoxic locations for coastal Louisiana in 2006, compared to observed hypoxia locations as determined by the mid-summer cruise. Red pixels indicate correctly predicted locations using our approach, pink pixels indicate "missed" locations (i.e., the cruise survey observed hypoxia but our approach failed to highlight these areas as hypoxic), and yellow pixels indicate "false positives" (i.e., our approach indicated likely hypoxia but the cruise sampling did not observe hypoxia). Note the large area of yellow pixels east of the Mississippi River delta. These are better described as "uncharacterized" rather than "false positives" because this region was not sampled by any of the mid-summer surveys. However, some work has indicated that this area experiences sporadic hypoxia, and our approach also indicates that hypoxia is likely there. Plans are under way for future sampling in that area.

MIS Sensor Program Endures Turbulent Year

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[2] *Remote Sensing Division*

MIS Progress: The imaging of the Earth's surface and the sounding of the atmosphere using passive sensing of microwave and millimeter-wave frequencies has become a critical piece of Earth observations. Measurements in the 6 to 184 GHz frequency range provide information and insight into soil moisture, sea surface winds, atmospheric temperature, atmospheric moisture, sea surface temperature, water vapor, and precipitation. The Microwave Imager/Sounder (MIS) will be the first instrument to measure across all of these frequencies with a single sensor. Figures 6 through 8 depict its planned deployment aboard the spacecraft.

The MIS combines the capability of an imaging microwave radiometer, a lower and upper atmosphere micro/millimeter-wave sounder, and a polarimetric radiometer. Using algorithms developed in conjunc-

tion with the flight hardware and software, sensed data will be processed to produce microwave imagery and other specialized meteorological and oceanographic products. These products will be disseminated to users worldwide by the DoD in the form of raw data records (RDRs), temperature data records (TDRs), sensor data records (SDRs), and environmental data records (EDRs). To provide this unique capability for our nation, the Naval Center for Space Technology's Spacecraft Engineering Department has teamed with the Remote Sensing Division to develop an operational sensor for the Defense Weather Satellite System. The Electronics Science and Technology Division is providing their expertise to support the program's sounding channels.

From WindSat to MIS: In 2003, the NRL-built WindSat instrument was launched aboard the Coriolis Mission spacecraft. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) and the United States Navy jointly sponsored the WindSat sensor. To build WindSat, NRL put together a science and engineering team drawn from the Spacecraft Engineering Department and the Remote Sensing Division.
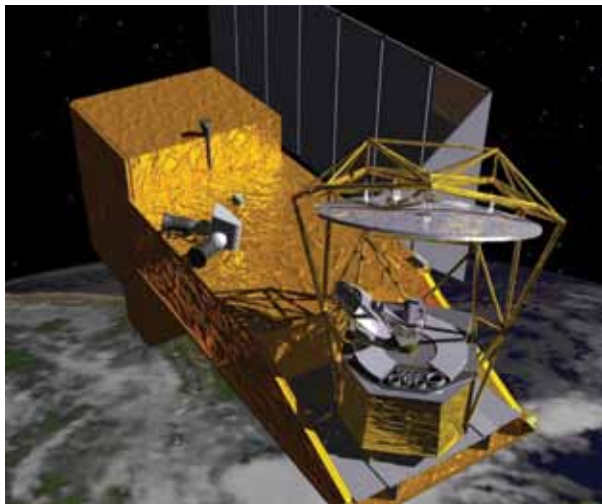
FIGURE 6
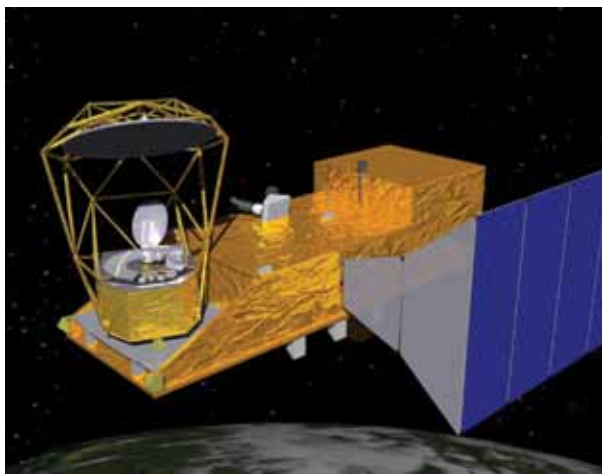Microwave Imager/Sounder depicted on the spacecraft bus.

FIGURE 7
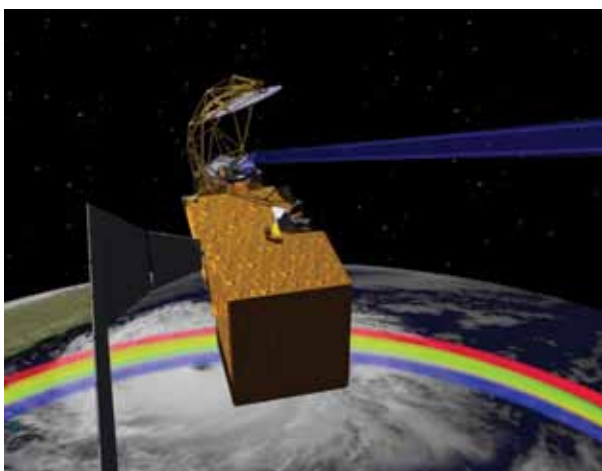Microwave Imager/Sounder depicted on the spacecraft bus (view 2).

FIGURE 8
Microwave Imager/Sounder showing cold sky scene (for calibration) and operational sensor sweep.

The WindSat sensor brought together the long national heritage of Scanning Multichannel Microwave Radiometers from Seasat and Nimbus-7 through the Special Sensor Microwave Imager with advances in polarimetric science to create the first conical scanning polarimetric microwave radiometer. More than 8 years later, the "operational leave behind" capability of an on-orbit WindSat continues to provide data to military and civilian users.

The NPOESS IPO competitively selected NRL to build MIS because of the Laboratory's demonstrated experience and knowledge. In July 2008, the NPOESS IPO tendered an Economy Act order to NRL's Naval Center for Space Technology to design, develop, build, and transition to industry production a conical scanning polarimetric microwave radiometer based on the highly successful WindSat project. The 41-channel MIS instrument would be an operational sensor and would include an atmospheric sounding capability.

This MIS Program team completed a successful System Requirements Design Review (SRDR) in May 2009. On November 24, 2009, the MIS Program completed its Integrated Baseline Review (IBR), which validated the technical scope of work, verified the program's budget and schedule as articulated in the Performance Measurement Baseline (PMB), and assessed program risk. Upon exiting the review, the program sponsor and Program Manager mutually agreed to the executability of the program. A successful IBR is a significant milestone for the Earned Value Management (EVM) process for program cost and schedule oversight.

From NPOESS to DMSG: In February 2010, the President directed the dissolution of the Tri-Agency managed NPOESS. The dissolution of NPOESS returned to the Defense Meteorological System Group (DMSG) the responsibility for the space-based satisfaction of military weather-forecasting, storm-tracking, and climate-monitoring requirements per a March 17, 2010, Acquisition Decision Memorandum (ADM). DMSG is managed by the Space and Missile Systems Center (SMC) at Los Angeles Air Force Base, California.

On April 8, 2010, the MIS program successfully completed its Preliminary Design Review (PDR) for the 41-channel MIS on the NPOESS spacecraft bus. The MIS PDR was the second in a series of event-driven Systems Engineering Technical Review (SETR) milestones that are rigorously adjudicated by independent technical experts and review teams. The PDR validated the preliminary design performance meets the requirements and also verifies necessary technical processes and documentation. The NPOESS IPO approved the MIS Program to proceed to the Complete Design Phase.

Since PDR and during sponsor transition, the MIS Program continued to perform design, development, and risk reduction for both 23- and 43-channel conically scanning microwave radiometer options, based heavily on the NPOESS MIS. On November 1, 2010, management of the MIS Program was officially transferred from the NPOESS IPO to the Defense Weather Satellite Systems (DWSS) System Program Office (SPO).

During the sponsor transition analysis of alternatives (AOA), the transition of the MIS technology to industrial production was eliminated. The MIS sensor will be the microwave remote sensing instrument of record for the future Major Defense Acquisition Program (MDAP) Defense Weather Satellite System. DWSS has asked NRL to produce two MIS instruments. The NRL-built MIS will be used operationally from 2018 through 2028.

[Sponsored by NRL and DWSS]

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