Delivery and Quality Assurance of Short-Term Trajectory Forecasts from HF Radar Observations

A Final Report Submitted to

The Coastal Response Research Center

Submitted by

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Abstract

Surface current mapping data from a network of coastal high frequency (HF) radar instruments were examined for the region offshore central California. In the first phase of the project, year-long surface current data from the Gulf of the Farallones were examined to compare predicted and observed particle trajectories. Short term forecast skill after twenty four hours was shown to be typically better than 10 km with occasional spikes up to 30 km. These results are based on the standard forecasting procedures in place for California's Coastal Ocean Currents Monitoring Program (COCMP), which involves projecting tidal constituents and mean currents observed over the past 48 hours at each radar grid point. Extensions to the standard forecasting procedures were investigated. In particular, tests were conducted using a linear transfer function between observed wind and HF radar-derived surface current to determine the degree to which explicit treatment of wind changes during the forecast period can improve the forecast currents. The transfer function was developed using eighteen-month-long records of wind and HF radar-derived currents at the site of NOAA's NDBC buoy 46042 offshore Monterey Bay. The resulting transfer function recommends surface current values with magnitudes that are 2% of the wind speed and directions that are 50 degrees to the right of the wind vector. Applying the linear wind correction to the difference between wind observations during the forecast period and wind observations during the previous day leads to improvements in forecasted currents on the order of 10% (~1 km in position accuracy after 24 hours). The results suggest that more significant improvements in forecast skill will depend upon the development of new algorithms that take account of the spatial information available in the HF radar-derived surface current maps. i.e., single-point projections derived from time series techniques appear to be limited in their accuracy to the order of magnitude documented here. This study also supported in situ observations of surface currents through deployment of 32 GPS-tracked microstar drifting buoys. The instruments were deployed in the Gulf of the Farallones in April 2008. The data were used to establish background velocity uncertainty levels for the several CODAR-type HF radar systems deployed in the region, which ranged between 9 cm/sec and 17 cm/sec. Performance differences between individual radar stations are pronounced and should lead to better understanding of the impact of site-specific antenna pattern distortions and noise sources on HF radar performance. Finally, recommendations were developed and documented that allow HF radar-derived data to be routinely formatted for use by two important communities: 1) oil spill responders using NOAA's GNOME trajectory model (a NetCDF file format) and 2) responders using various GIS tools (a set of shape files).

Keywords: HF radar, oil spill response, ocean currents, air-sea interaction

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1.0 Introduction

This project involved development and assessment of operational products based on real-time surface current mapping data collected from coastal high frequency (HF) radar monitoring systems. HF radar instruments for ocean monitoring consist of radio wave transmitters and receivers mounted along the shoreline together with the processing algorithms required to convert backscatter data into estimates of helpful environmental parameters. Those parameters include ocean surface currents, significant wave heights, and wind directions (Paduan and Graber, 1997). The instruments and their associated algorithms have been steadily improving since their introduction in the 1980s (e.g., Barrick et al., 1977). In addition, the number of deployed instruments and the coastal ocean area covered by real-time measurements have greatly increased in recent years. In order to exploit these new data sources for applications such as optimally containing spilled oil, it is necessary to both expand the types of applications using HF radar data and to quantify the errors or uncertainties inherent in the data. This project focused on the requirement to produce short-term (24 hour) forecasted surface current data fields in support of spill mitigation and search and rescue operations. While that problem is well defined, success involves knowledge of all aspects of instrument (or algorithm) errors combined with identification of the many natural modes of variability in the coastal ocean and atmosphere systems.

In terms of instrumentation, the project focused on the most commonly deployed HF radar system, which is the direction-finding, CODAR-type HF radar (Figure 1). Those instruments, which also go by the brand name SeaSonde™, operate using three co-located receive antennas and, in most instances, a separate whip antenna for transmit. The key to the small footprint of the SeaSonde™ units is the use of direction-finding techniques, which also gives rise to much of the uncertainty in the surface current estimates. A recent in situ validation study by Paduan et al. (2006) helps to bound those errors, as does the very nice drifter-based study of Wright (2008), which was part of this project. In addition, the simulation work of de Paolo and Terrill (2007a,b) goes a long way toward understanding how the direction-finding algorithm (MUSIC) produces position and, ultimately, velocity errors under a variety of ocean conditions. Most of the literature related to SeaSonde™ systems is cataloged on the web site of the instrument manufacturer, Codar Ocean Sensors, Ltd. (http://codaros.com). For completeness, it is important to recognize that other types of HF radar systems are in use that utilize the very well established but much larger phased array (or beam forming) antenna configuration. Surface current data deriving from these systems is also useful in real time applications. To that end, the forecast algorithms tested and recommended by this project can be applied directly to the output of phased array HF radar systems. An excellent example of an operational phased array system is the network of WERA-type HF radar systems deployed off the southeast coast of Florida (Shay et al., 2007).

An important factor in the focus and timing of this project was the existence of the state-wide program to install CODAR-type HF radar systems along the entire coast of California. The project, known as the Coastal Ocean Currents Monitoring Program (COCMP) was funded by the State of California and has as its goal the installation and initial operation of a state-wide, real-time surface current mapping network. That goal was realized in the later half of 2008 (Figure 2). Even earlier, wide-area surface velocity coverage became operational in the area of central

California between San Francisco and Monterey Bay, which is the focus area selected for this project.

Figure 1. View of the receive (foreground) and transmit (background) antenna elements for the SeaSonde™ HF radar system deployed above the lighthouse at Pt Sur, California. The system and communication electronics are deployed in a small, weatherproof enclosure below the transmit antenna.

Access to COCMP data, and to collaborations with its principal investigators and HF radar technicians, made this project extremely timely and efficient. While COCMP researchers were maintaining the wide-area network of HF radar systems and real-time communications, researchers involved with this project were able to focus on the data and applications required to provide short term forecasts. Collaboration with COCMP also included joint work to conduct an extensive drifter-based validation experiment in the waters offshore San Francisco. Without the personnel and vessel support from COCMP, such a field program would not have been possible as part of this project.

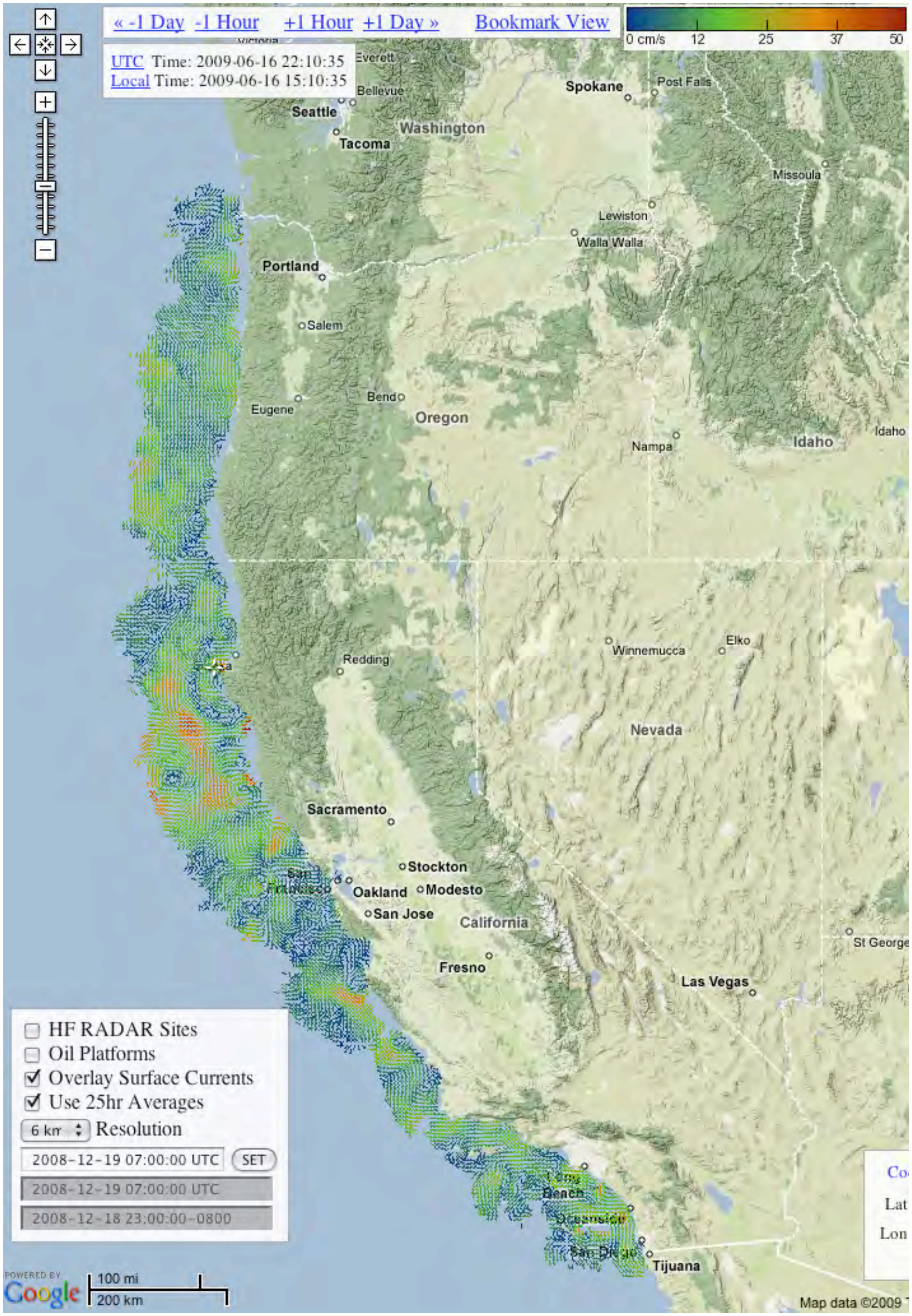

Figure 2. HF radar-derived surface current coverage along the U.S. west coast on the day COCMP operations were suspended (19 December 2009).

2.0 Objectives

The objectives of this project were both specific and several in number. They included:

1) Quantification of the position uncertainties for the short-term trajectory forecasts being produced by COCMP and other quasi operational HF radar network programs.

2) Recommendations for improved short-term trajectory forecast algorithms.

3) Documentation of the specific netCDF-based file format requirements for use of HF radar-derived surface velocity mapping data and forecasts within NOAA's GNOME trajectory modeling framework.

4) Recommendations for alternative formatting options that will also make HF radar-derived surface velocity mapping data easily ingestible into standard Geographical Information System (GIS) analysis tools.

5) Widespread dissemination of the results obtained and recommendations developed within the HF radar user community.

3.0 Methods

The primary methods proposed and employed in this project for meeting the above objectives were to:

1) Collect and organize representative surface current mapping data from the HF radar network in the region of central California.

2) Compare HF radar-derived surface velocity estimates between radar sites and against in situ, drifter-derived velocity estimates to establish baseline uncertainty levels.

3) Compare forecasted trajectory positions after 24 hours with trajectory positioned based on observed HF radar velocity values during the same forecast period to quantify position uncertainty levels.

4) Compare long-term surface wind and HF radar-derived surface velocity time series to establish an HF radar-specific transfer function between wind and currents.

5) Alter the existing trajectory forecast algorithms to include explicit corrections for forecasted wind changes and compare forecasted position error statistics with and without wind corrections.

6) Consult with NOAA hazardous spill response coordinators and California's Office of Spill Prevention and Response (OSPR) to develop surface velocity mapping data file formats compatible with GNOME and GIS tools, respectively.

7) Implement parallel, automated data formatting scripts within the real-time processing protocols using by COCMP to create online GNOME- and GIS-compatible HF radar data files.

8) Produce specific user manuals to document the formatting requirements for GNOME- and GIS-compatible HF radar data files.

9) Advise and assist NOAA personnel in the creation of HF radar user workshop(s) devoted to matching HF radar data producers and users, and to the explanation of the GNOME- and GIS-compatible file formatting requirements.

4.0 Results

Clear results have been obtained for all of the above objectives as described in this section. Of the many methods employed, all but the final method related to the creation of HF radar user workshop(s) have been followed to some logical conclusions. As described in the Technology Transfer section below, the primary participants in this project will continue to work with these data and data formats and will continue to be available to work with NOAA personnel to create working groups around the topic of effective use of real time HF radar data.

The main technical results achieved in this project have been described sequentially in the semi-annual reports to NOAA/CRRC. For completeness, the critical results are outlined here. The first stage of the project involved reviewing available HF radar data sources, selecting a primary geographic region of interest, and collecting long-term (months to years) HF radar data and ancillary wind data for the primary region of interest. The region selected was the Gulf of the Farallones offshore San Francisco. That region has many important benefits, including existing HF radar data from multiple locations over many months and overlap with the NOAA Safe Seas 2006 oil spill response exercise location. (The region also turned out to have the unfortunate overlap with impacts of the 7 November 2007 oil spill from the *Costco Busan*, which occurred inside San Francisco Bay but quickly introduced oil into the coastal ocean areas of the Gulf of the Farallones.) The region of interest is shown in Figure 3 together with a nominal test grid used to produce surface trajectory estimates from observed and forecasted HF radar data. This region was also the site for the drifter-based field experiment, which took place in April 2008. An example that establishes forecast trajectory position uncertainty for the standard processing algorithms used by COCMP is given in Figure 4 based on one full year of HF radar observations in the Gulf of the Farallones. These results were produced by comparing the endpoint locations of trajectories produced using forecasted surface currents with those of trajectories produced using observed surface currents starting at the same grid point locations and times. The test duration (i.e., forecast time) was 24 hours. For the individual trajectory's position separations to be included in the hour-by-hour computation of root-mean-square (RMS) position difference, end points for both the forecasted and observed trajectories must have remained within the area of the radar data coverage.

This initial study showed that position uncertainties of standard COCMP forecast procedures are on the order of 10 kilometers after 24 hours. Occasional larger rms errors tended to be associated with periods of stronger currents when a larger fraction of the surface particles exited the coverage area during the 24 hour window.

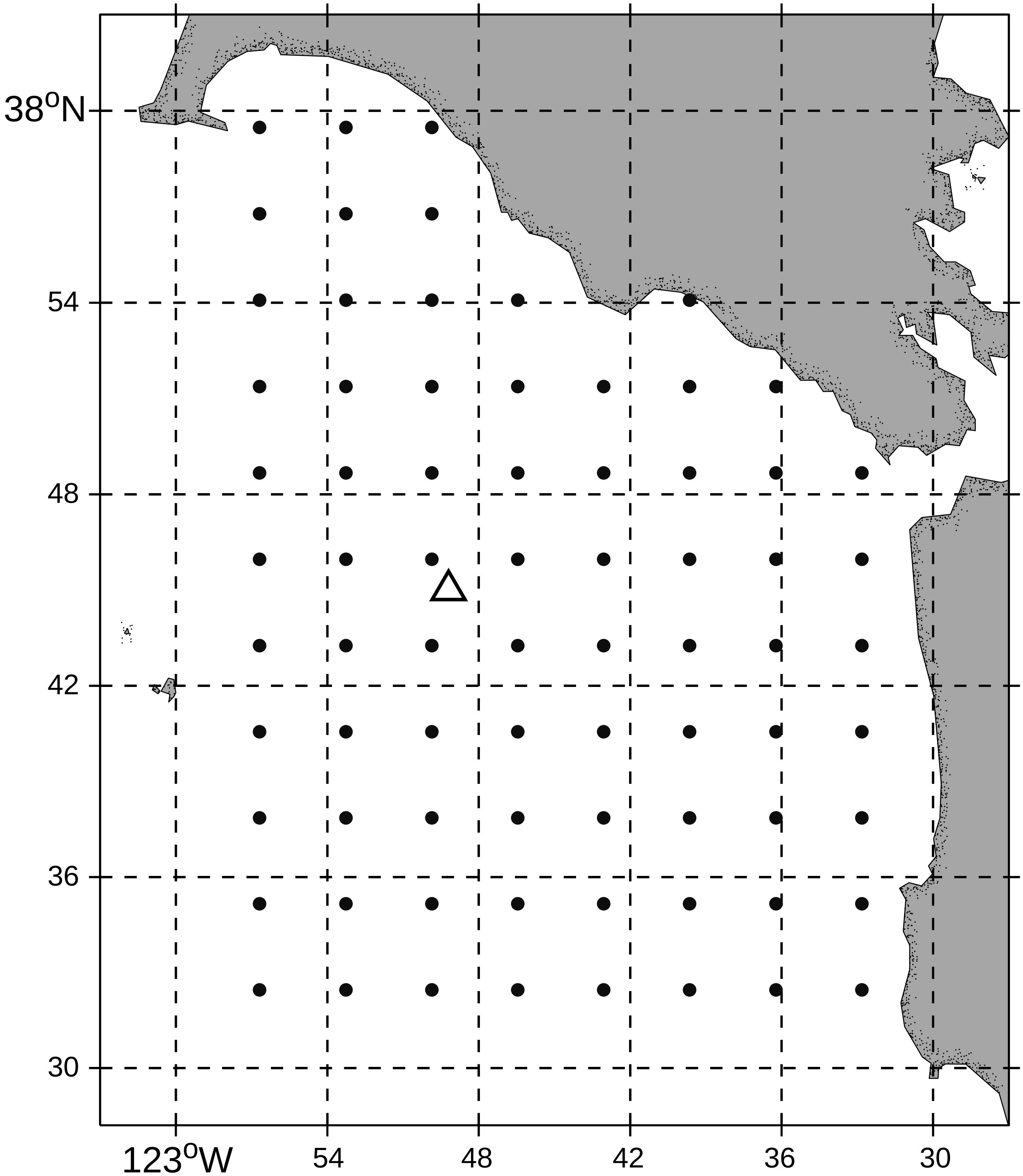

Figure 3. Region of the Gulf of the Farallones offshore San Francisco and the Golden Gate showing the initial locations (•) of surface particle trajectories computed from HF radar-derived currents together with the location NOAA/NDBC buoy 46026 (triangle).

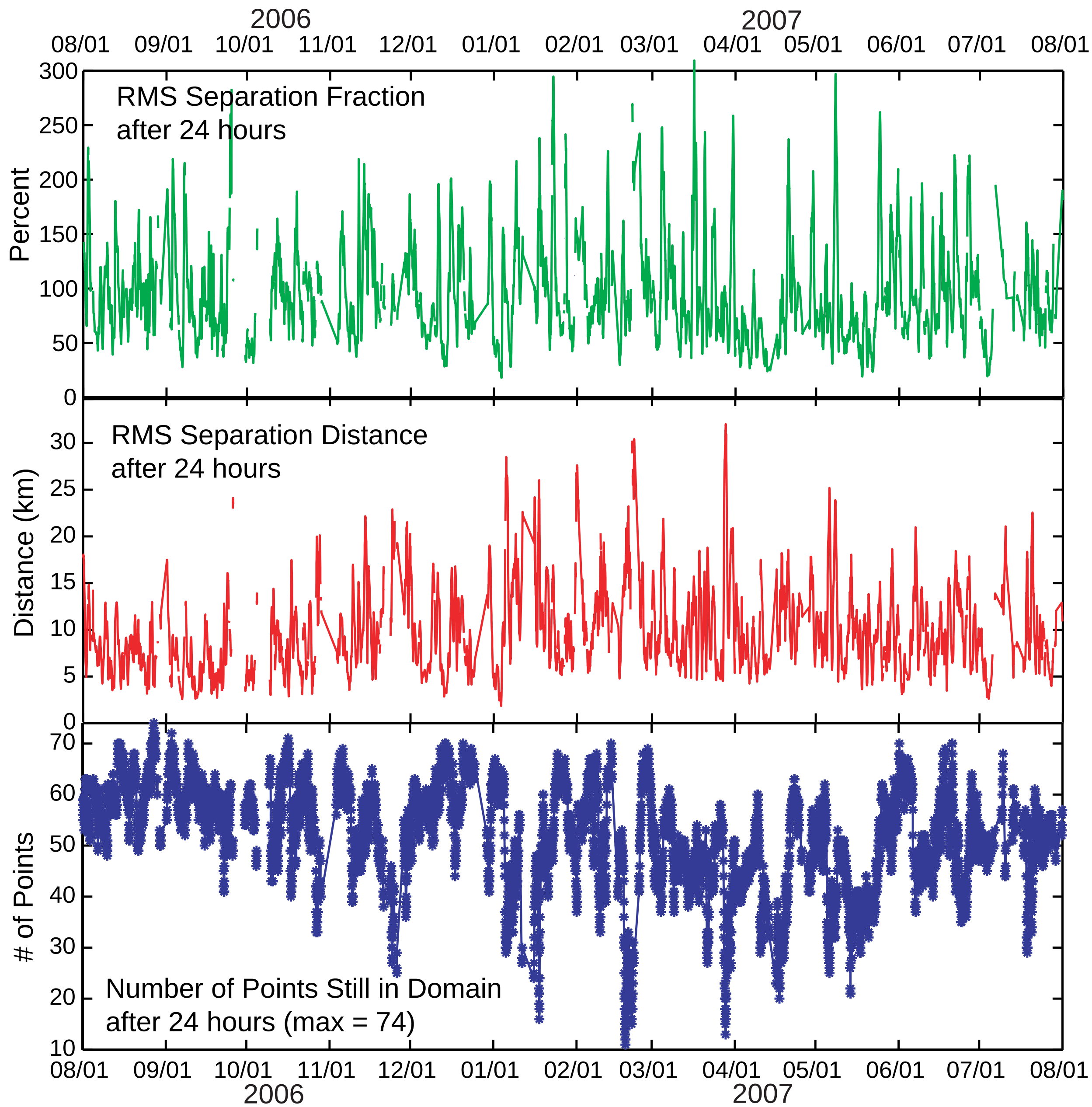

Figure 4. Hourly statistics of the RMS separation distance after 24 hours between the positions of forecasted and observed particle trajectories (middle) for the analysis grid in Figure 3. The fractional separation as a function of the RMS movement in the trajectories based on observed currents (upper) and the number of matching points remaining in the analysis domain after 24 hours (lower) are also shown.

The next phase of the project included a dedicated field experiment designed using GPS-tracked surface drifting buoys. The goal of the experiment was to provide a large number of independently determined surface trajectories in an ocean region covered by several coastal HF radar installations. To that end, 32 microstar-type surface drifting buoys were deployed and tracked in the Gulf of the Farallones during the period 31 March through 4 April 2008. The drifter (insert) used and the composite trajectories (black traces) obtained are shown in Figure 5 together with additional trajectories from a NPS student cruise in January 2008 (blue traces). The student cruise was conducted from the *R/V Pt Sur*. Four microstar drifters were deployed in Monterey Bay and recovered offshore San Francisco as shown in the figure.

The drifting buoys, research vessels, and research participants all performed exceptionally well during the field experiment. The weather, on the other hand, was well outside the seasonally expected conditions. The winds and sea state were very much lower than normal, which lead to weak surface currents and more limited drifter movements than were expected. Nonetheless, the experiment produced one of the most extensive HF radar ground truth data sets anywhere. And it added considerably to the identification and quantification of error sources for the HF radar-derived surface current mapping data.

The drifter-based validation study was carried out by M.S. student George Wright at the Naval Postgraduate School. In his thesis (Wright, 2008), extensive radar-to-drifter comparisons were documented using the radial surface current estimates from individual radar sites (i.e., the component of the drifter motion along the line between the drifter and the radar site). Details of the radial current matching process at a fixed radar grid cell are illustrated in Figure 6. Overall, these results extend and complement other recent studies, such as those of Paduan et al. (2006) and Emery et al. (2004). The CRRC data set includes not only data from a large number of drifting buoys, but it also includes comparison opportunities from a large number of coastal HF radar sites as shown in Figure 5. The thesis presents validation results for each radar site overall and as a function of look angle. Although results are consistent between radar stations, clear differences were found that are now guiding investigations into the different sources of error that can be attributed to site-specific characteristics, such as distortion of the receive antenna patterns (e.g. Laws et al., 2009).

The overall HF radar performance results compared with the microstar drifting buoy observations are shown in Figure 7. The radar versus drifter scatter from the many distributed radial current estimates indicates rms differences in the range 10-17 cm/sec. The larger value from the student cruise data set clearly is skewed by a small set of highly erroneous observations, the source of which is still being investigated. These values provide very general guidelines for HF radar velocity errors, which can also be translated into uncertainty values for radar-derived trajectory estimates.

The instrument-level (or algorithm-level) HF radar errors clearly explain a part of the position errors shown in Figure 4, but additional errors also arise from the physical processes missing from the standard COCMP forecast model. One set of missing physical processes are those related to changes in wind forcing that occur during the forecast period relative to the analysis period, which is the previous 48 hours in the case of the standard COCMP forecast model set up. The thesis work of LCDR Francisco M.S.C. de Almeida (2008) focused on this question of the influence of wind variations on the quality of short-term trajectory forecasts. That thesis was completed as part of this project. The results include insights into the basic relationship of HF radar-derived surface currents and wind stress as well as insights into the major factors controlling forecast trajectory errors.

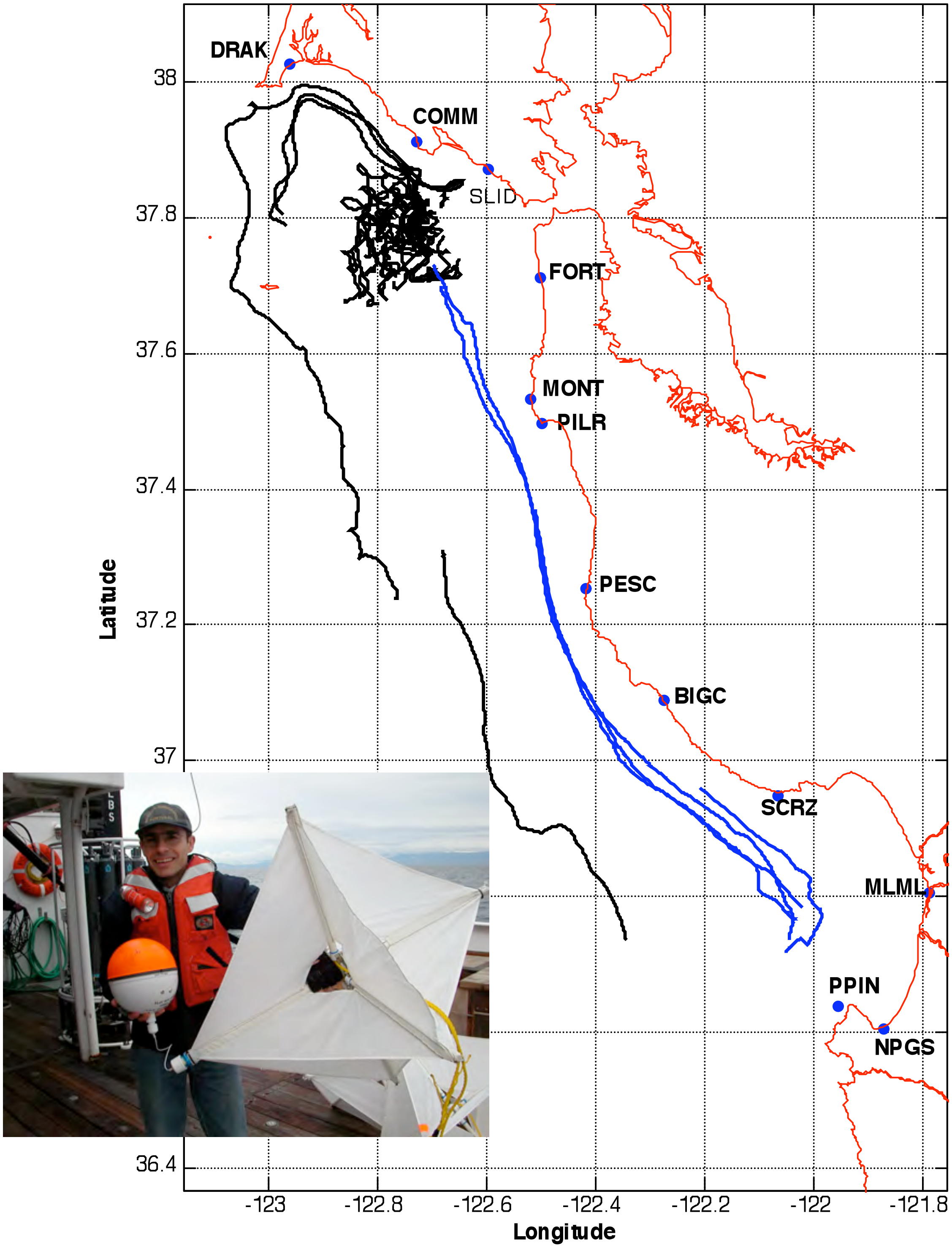

Figure 5. NPS thesis student Francisco Almeida holding a Pacific Gyre Microstar surface drifting buoy, including the electronics-housing surface float, tether, and tristar drogue element (inset), surface trajectories from the April CRRC (black) and January NPS student (blue) experiments, and the locations of shore-based HF radar sites (4-letter codes).

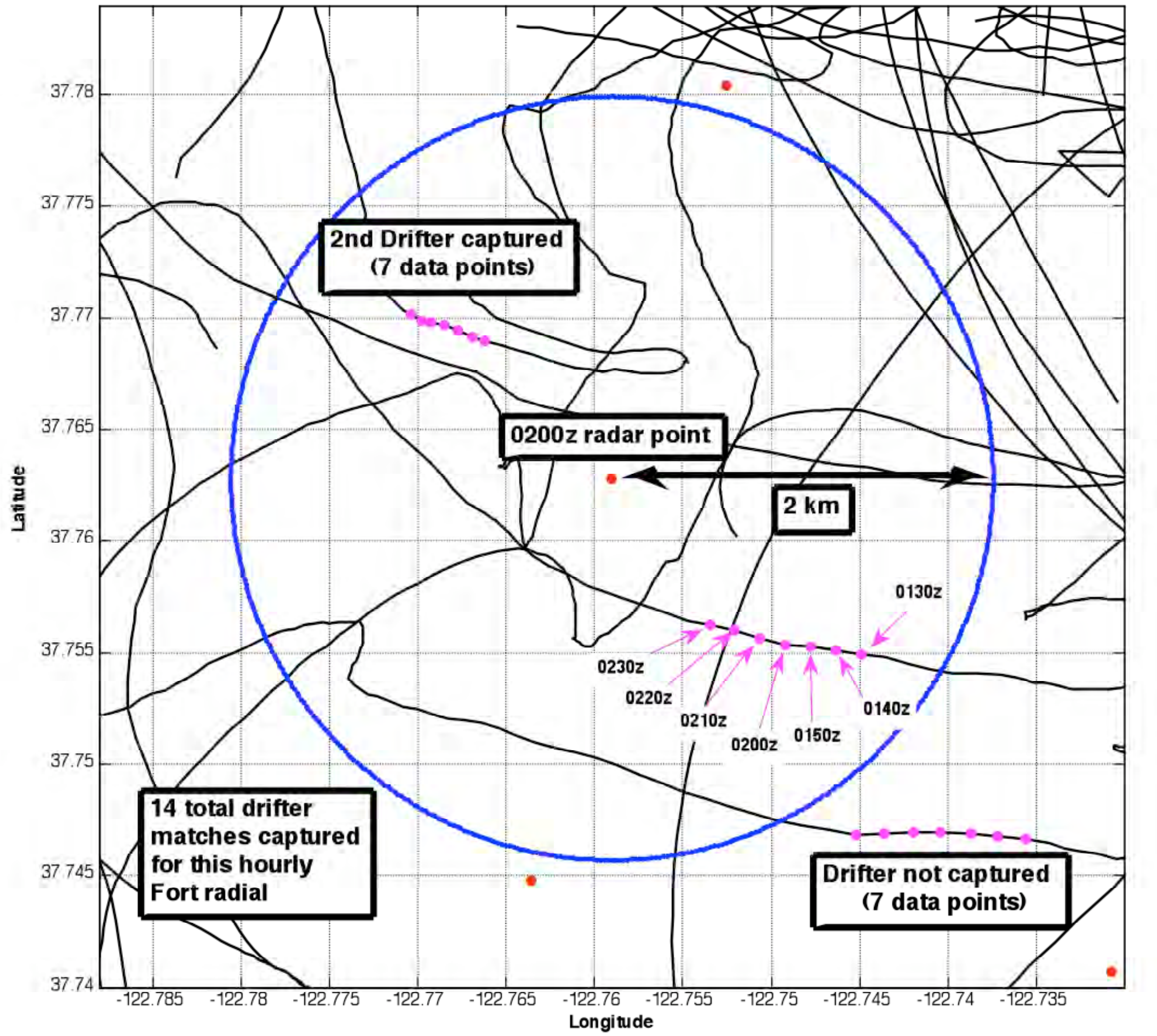

Figure 6. Example radar versus drifter data pairing. For each hourly radar grid point, such as the center symbol highlighted here for 0200Z, drifter data points corresponding to plus or minus 30 minutes and less than 2 km away from the center of the radar grid point were captured (magenta points inside blue circle for this example). This example has 14 total 10-minute velocity observations from drifter matches.

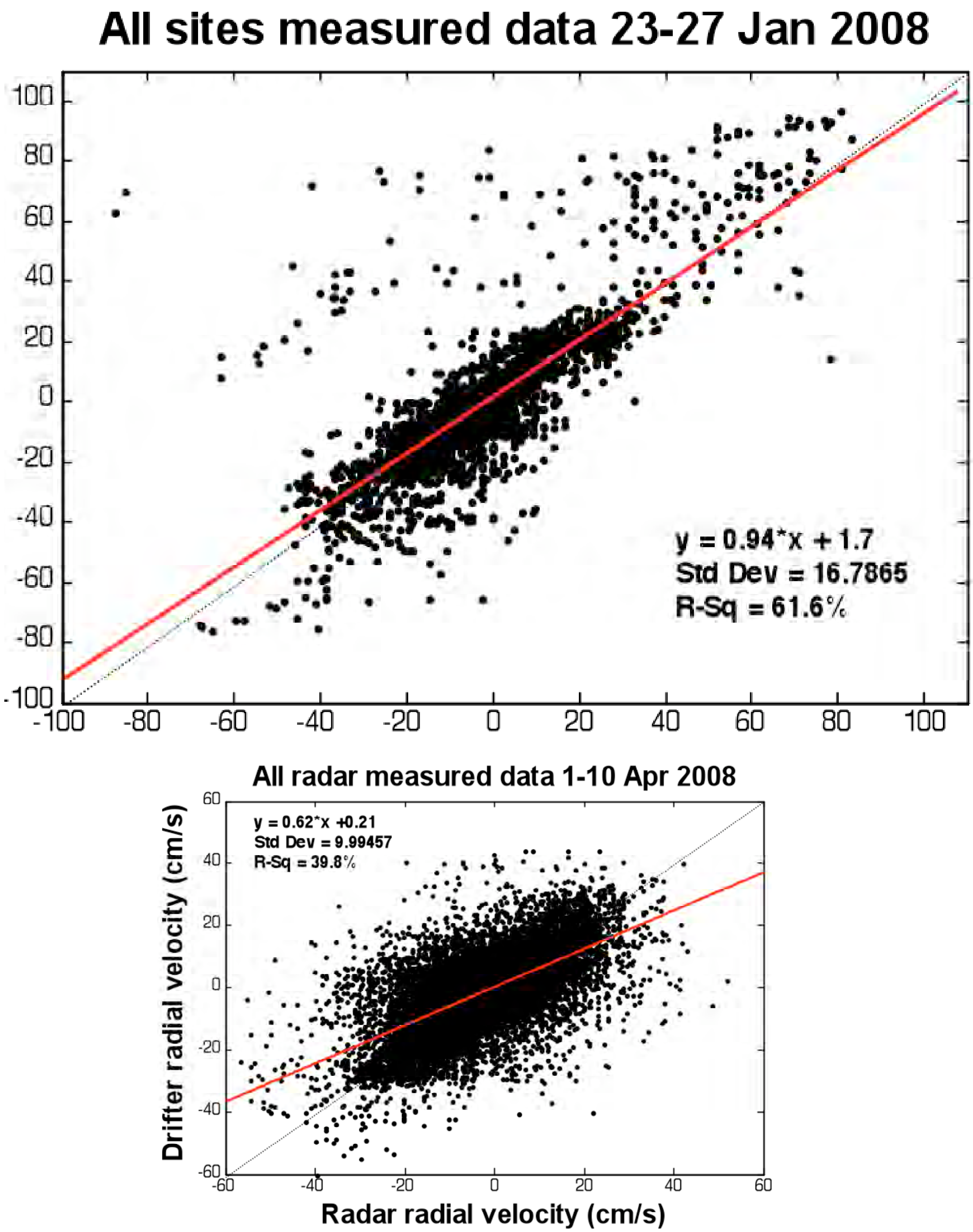

Figure 7. Combined drifter- versus HF radar-derived radial current comparisons for all radar sites for the NPS student cruise (upper) and CRRC drifter experiment (lower). The best-fit lines (red bold) are shown for each experiment along with the standard deviation about those lines.

LCDR Almeida investigated the correlation and coherence between winds and HF radar-derived surface currents by focusing on the period June 2006 through December 2007 at the NDBC 46042 mooring location offshore Monterey Bay. For the entire data set, the vector correlation magnitude is 0.5 with the surface currents 34 degrees to the right of the wind. Spectral coherence methods allow for a more precise description of those fluctuating components for which the vector winds and currents are most closely related. The complex coherence and phase results for the NDBC46042 mooring location are shown in Figure 8. It is clear from these results that HF radar-derived currents follow closely the local wind forcing for low frequencies extending out to fluctuations at the diurnal frequencies (i.e., one cycle per day). In the Monterey Bay region, the energy in the wind and currents is primarily in the positive frequencies, which are the clockwise rotating components. For those components, the winds and currents are highly coherent and their phase indicates that the surface current vector rotates, approximately, 50 degrees behind the wind vector.

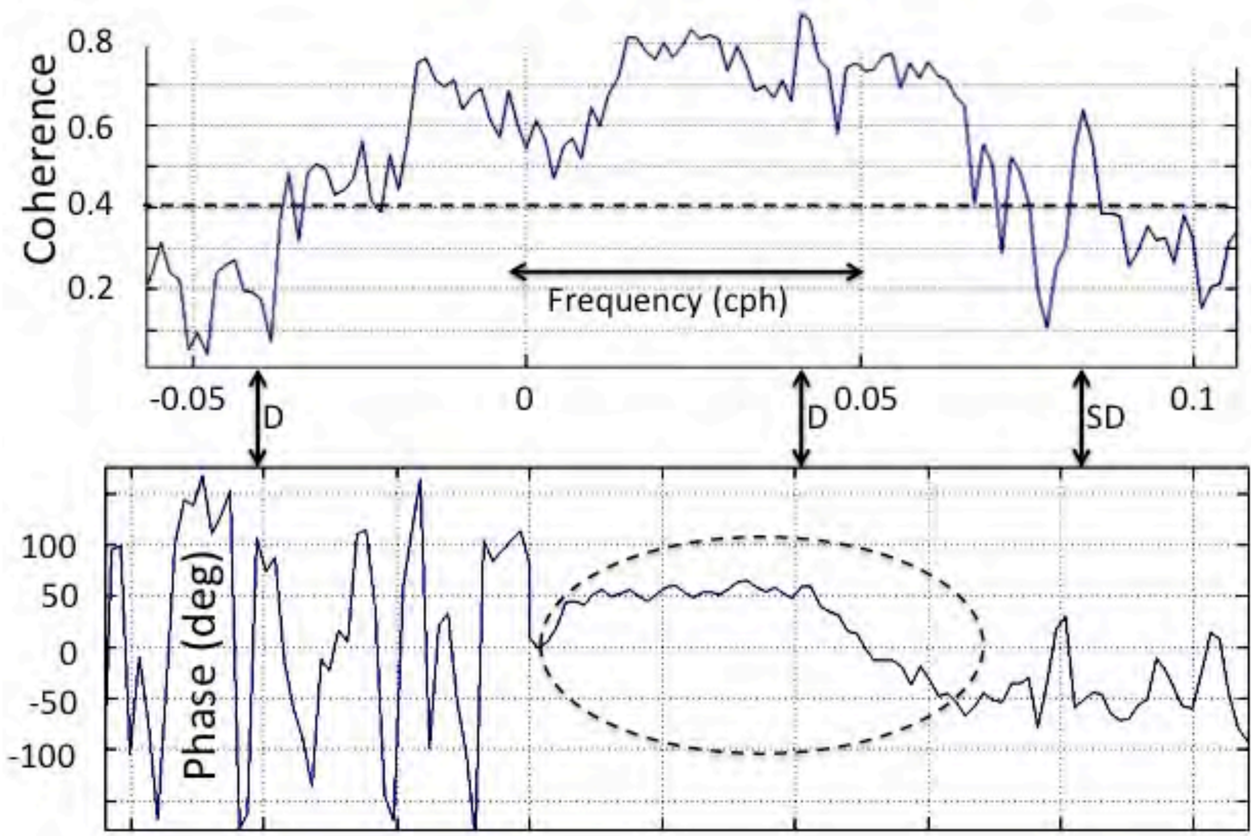

Figure 8. Coherence (upper) and phase (lower) between vector wind and HF radar-derived surface currents at the NDBC 46042 mooring location offshore Monterey Bay. The signals are coherent above the 95% confidence level (dashed line) over a broad frequency range from subtidal frequencies up to, approximately, diurnal frequencies. The phase offset in this band is consistently 50 degrees for the clockwise fluctuations with HF radar-derived surface current to the right of the wind forcing.

Although some variation exists, the vector comparisons between currents and winds indicate that a simple transfer function can be used for HF radar-derived surface currents. The surface currents are, approximately, 2% of the wind speed and between 35 and 50 degrees to the right of the wind vector. Almeida (2008) suggests the following optimal linear transfer function:

$$\left|\vec{V}\right|_{HF} = 0.018\vec{W}_5 + 0.018$$
$$ang(\vec{V})_{HF} = ang(\vec{W}_5) - 50\deg$$

where, $\vec{V}_{HF}$ is the HF radar-derived surface current and $\vec{W}_{HF}$ is the wind vector 5 m above the sea surface. Testing was conducted with this transfer function that added wind-based corrections to the short-term surface current forecasts made from the HF radar observations. It is proposed that the simple, linear wind transfer function be used in a very specific way to improve the forecast results. That is, the linear transfer function should be applied to the *difference* between today's wind and tomorrow's forecast wind and then the resulting surface current correction should be added to the results of the standard forecast model. An example of this approach is shown in Figure 9 where the linear wind correction helps to bring the forecasted current at a single test point closer to the observations. The results from Almeida (2008) also suggest that alternative methods for projecting HF radar surface current observations forward in time may be superior to the tide-based method presently in use, although more in-depth testing is needed. It appears that simple persistence of the (variable) daily HF radar observations one day forward may be a more accurate forecast model than computing the best-fit tidal constituents over the same short data records and projecting them forward.

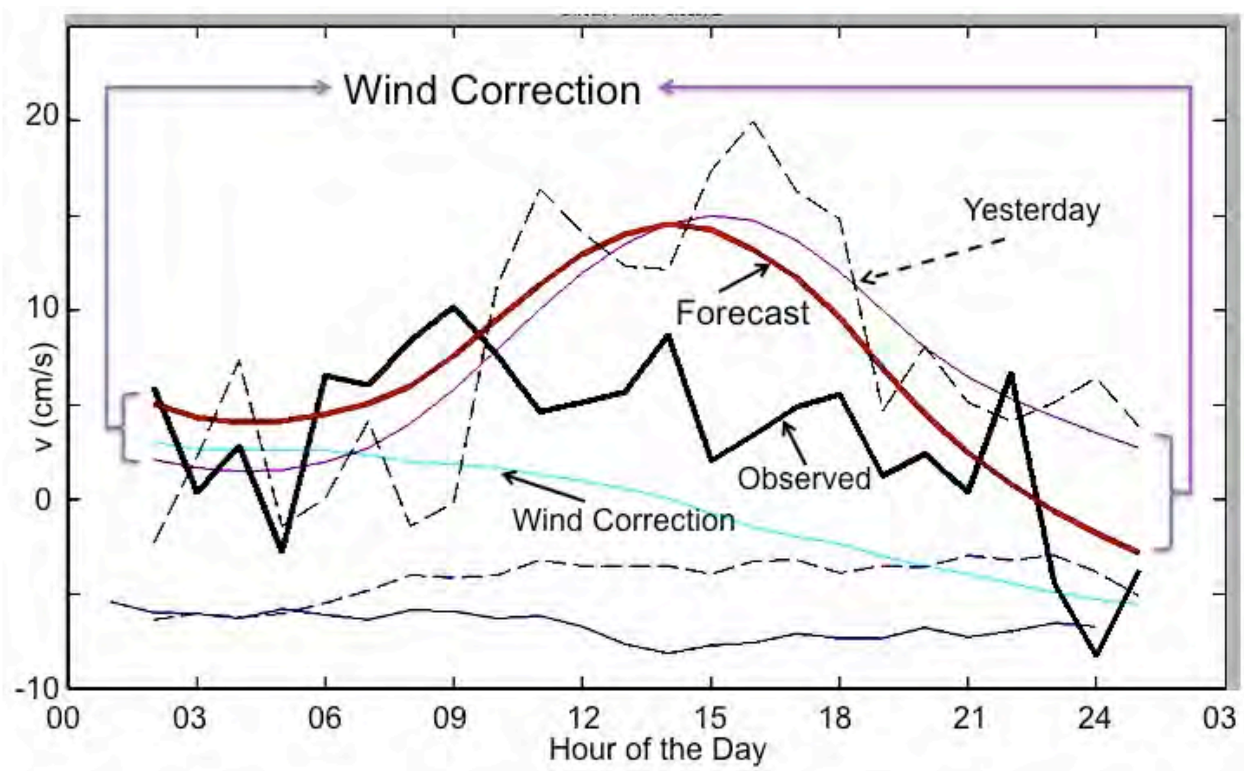

Figure 9. Sample surface current forecast results for 1 July 2006 for which a low-pass-filtered version of the observed north-south surface currents for the day prior have been persisted forward and corrected using the linear wind transfer function model applied to the difference between observed and forecast winds.

5.0 Discussion and Importance to Oil Spill Response/Restoration

This study has helped to further the use of real-time surface current mapping data from HF radar installations in a number of important ways. In terms of the primary goal of identifying spatial uncertainty for short-term trajectory forecasts based on HF radar observations, the study has shown that position errors are bounded with typical values less than 10 km and extreme values up to 30 km for the twenty four hour forecast time. This project tested wind-based corrections by first documenting the optimal transfer function between wind and HF radar-derived surface currents. The results show a statistical improvement in the twenty four hour forecast positions when the linear wind model is applied to observed wind variations at the radar grid point. However, the wind-based improvements account for less than 10% of the position error (Almeida, 2008). The important conclusion from the wind study is that substantial forecast improvements will depend on the development of pattern-based correction algorithms. That is, forecast algorithms based on time series analyses at single grid points appear to be limited to the position accuracies documented in this study. Knowing the wind during the forecast period (from observations as in this hindcast study or from wind models as in an operational setting) is not sufficient to account for advection of surface current features past the radar grid point. The HF radar-derived surface current mapping data, on the other hand, contain information about horizontal velocity gradients that, in principle, can be used to improve the projections. Such two-dimensional information was not exploited in this study. Doing so in future HF radar-based forecast products is a strong recommendation of this study.

This study also added significantly to the in situ validation data for HF radar systems. The April 2008 experiment was the largest anywhere in terms of the number of GPS-tracked surface drifters deployed within range of several HF radar installations. The initial validation results were presented by Wright (2008). The data set itself is available for others to use for additional tests, such as validation of the bi-static HF radar radial currents simultaneously produced by a number of the HF radar instrument pairs. The site-to-site and angle-by-angle variations in radar performance presented by Wright (2008) also form a strong constraint for researchers investigating the performance of the MUSIC direction-finding algorithm as it is used by the SeaSonde™ HF radar systems.

This study critically advanced the practical utility of real-time HF radar-derived surface current mapping data by testing and documenting specific formatting specifications for GNOME model applications and GIS programs. The formats required for those applications are described in Appendix A and Appendix B, respectively. The descriptions include sample matlab programming functions that transform surface current mapping data from the format used by the vast majority of data producers into the formats that are required for direct importing into GNOME (a NetCDF file) and GIS (a set of shape files).

The numerical error bounds, algorithm suggestions, and data formats produced in this study all help to make HF radar data much more accessible to technicians and managers involved with oil spill response. Even as the number of HF radar systems grows around the country, the use of data from those systems depends on studies such as this one to bridge gaps between producers and users.

6.0 Technology Transfer

This study has not produced a new type of technology transfer. However, it is hoped and expected that the results of this study will greatly speed up technology transfer that is underway between scientific groups using HF radar instruments to produce surface current maps and management and response groups responsible for reacting as quickly and effectively as possible to the hazardous material spills in our coastal ocean. The study produced statistical results that are described in its publications and reports. It also produced explicit computer programs and format descriptions that are required for HF radar-derived surface current mapping data to be used by the most important response tools. Those technical products are included in the appendices below.

Relevant and helpful facts and behaviors have been uncovered in this study. The effective technology transfer that occurs because of the study will depend also on the dissemination efforts described below.

7.0 Achievement and Dissemination

This study has achieved the vast majority of its initial goals, including documenting errors in forecast trajectories and creating explicit recommendations for data formats to make HF radar-derived surface current mapping data more reliably available to and used by the primary oil spill response agencies. Critical goals that are ongoing are to: 1) publicize these results and recommendations among the HF radar user community and 2) ensure widespread adoption of these results and recommendations among the HF radar user community. To date, dissemination has been through the efforts of the project investigators working through scientific conferences and within the relatively small HF radar science community. Presentations were made throughout the course of this project, including Garfield et al. (2007a; 2007b; 2008), Almeida et al. (2008), and two M.S. theses were published as a direct result of this study (Wright, 2008; Almeida, 2008). In addition, results were discussed at the NOAA/IOOS HF radar national planning workshop in Keystone, Colorado on 22-24 August, 2008, at the 8th and 9th International Radiowave Oceanography Workshops (see http://radiowaveoceanography.org), and at the 3rd and 4th Radiowave Operators Working Group meetings (see http://www.rowg.org). The results were a necessary step toward a recently funded NOAA project (Chao et al., NSF funded proposal) that uses a similar paradigm with the addition of a ROMS component.

Going forward, it is recommended that results from this study be even more widely disseminated and adopted. The investigators will continue to work with CRRC advisors inside NOAA/ERD and NOAA/IOOS as well as within California's Office of Spill Prevention and Response (OSPR) to see that the recommendations are strongly encouraged, particularly those relating to formatting for GNOME and GIS applications (see appendices). A specific follow-on goal that can reasonably be adopted is to create specific sessions at next year's ROW and ROWG meetings devoted to presenting and discussing these recommendations. Whether or not a dedicated workshop for the dissemination of these results between HF radar scientists and users is called for should be the topic of a continuing dialogue between the project investigators, CRRC program managers, and the technical experts within NOAA and OSPR.

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Appendix A
NetCDF File Formats for GNOME Applications

Surface current mapping data are an important information source to the spill mitigation procedures used by NOAA's Emergency Response Division (ERD). In most response cases, NOAA/ERD personnel utilize the General NOAA Oil Modeling Environment (GNOME) framework, which has been developed over many years to facility trajectory modeling for a wide variety of oil types and environmental conditions. The GNOME modeling framework accepts (requires) ocean surface current data in a particular version of the NetCDF file format. This project collaborated closely with NOAA/ERD to create and test a tailored NetCDF file format for GNOME importing of HF radar-derived surface current mapping data. This appendix describes the NetCDF specifications and procedures used to produce these GNOME-compliant data files.

The code used in this project was written in the matlab programming language (http://www.mathworks.com), although other methods could be used to produce the NetCDF file format. The computations were performed on an Apple Xserve computer with OS X 10.4 and running matlab version 7.5. Additional software utilized to produce the GNOME NetCDF files were: the T_Tide Harmonic Analysis Toolbox (http://www2.ocgy.ubc.ca/~rich/#T_Tide), HFR_Progs Toolbox (http://www.cencalcurrents.org/ProgsRealTime), and the NetCDF Toolbox for Matlab (http://mexcdf.sourceforge.net/index.html).

Each NetCDF file contains 72 hours of surface current data assembled from two sources: 1) 48 hours of actual radar-derived surface current observations on a rectangular grid from 49 hours in the past to the current hour minus one and 2) 24 hours of predicted, or forecasted surface currents on the same grid from the current hour to 24 hours into the future. The methods used to produce the forecasted currents can vary and, in fact, investigating those methods and their accuracies has been a central focus of this project. Different methods also exist for gridding the often gappy HF radar-derived velocity fields. In this project, the spatial filtering technique known as Open Modal Analysis (OMA; Kaplan and Lekien, 2007) was used to produce spatially complete mapping data every hour based on both observed and forecasted data. This step is critical because the behavior of GNOME is such that data gaps within the rectangular mapping grid are treated as zero velocity locations, which would cause computed trajectories to erroneously stop at those locations.

GNOME has the ability to import data from more than one mapping grid in support of large-area trajectory computations. In those situations, it is important to utilize mapping grids for adjacent domains that neither overlap or contain gaps between grids. If careful domain choices are not made, GNOME trajectory computations may again produce erroneous results at the domain boundaries. For this reason, it is recommended that HF radar processing domains are chosen a priori to carefully abut one another for GNOME purposes. In this way, NOAA/ERD spill responders can quickly import surface current mapping data from multiple domains and more accurately predict spill trajectories within and between those domains. An example of the analysis domains in use by COCMP in the region offshore central California is shown in Figure A1.

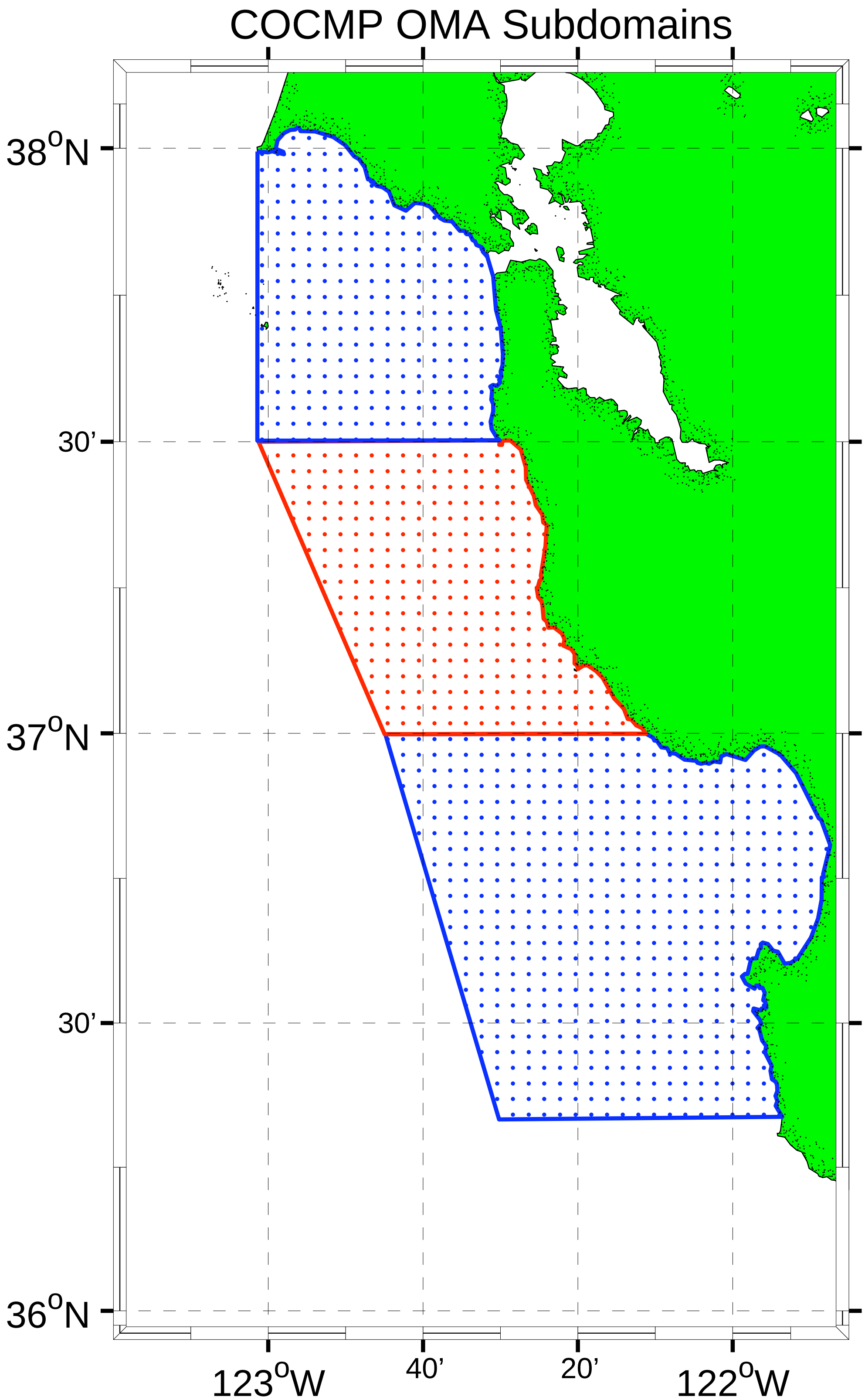

Figure A1. Surface current analysis domains carefully constructed to provide seamless import of data into GNOME.

The end-to-end surface current forecast procedure used in this project is as follows: Hourly radial data from each radar field site were transferred to the central site in Santa Cruz, CA. Radial data were quality controlled and radials from all sites combined to form total surface currents. Tidal analysis of surface currents was computed for each grid point using the last 48 hours of actual total currents where the temporal coverage was 80% or better. Tidal predictions based on the 48 hour analysis were made for next 24 hours. The forecast current was the computed as the mean current at each grid point for the last 48 hours plus the tidal prediction. Each hour's spatial data were then filled in using the OMA procedure and observed and predicted current fields were combined and written to a single, NOAA/GNOME-compliant NetCDF file every hour as part of the automated process. i.e., for every hour there exists a NetCDF file that itself contains 72 hours of filled-in velocity grids. The NetCDF file naming convention was:

GNOME_SSSS_yyyy_mm_dd_hh00.nc

where:

SSSS is the site designator

yyyy_mm_dd_hh00 is the year_month_day_hour of the last actual surface current field.

These GNOME-compliant data files are available for all users via the web page:

http://cencalcurrents.org/DataRealTime/Gnome

In addition to the careful filling of data grids and selection of adjacent domains described above, GNOME compliance depends on use of a specific variable naming convention. That convention is specified in the matlab function provided below. Data definitions and conventions follow the methodology laid out in the data report entitled: “GNOME Data Formats,” April 2005, which is available online from:

http://response.restoration.noaa.gov/book_shelf/714_file_formats.pdf

The matlab GNOME formatting function is:

```
function [ ] = writeGnomeNetCDF(dom,lon,lat,times,U,V,file_netcdf, ...
                                netcdfFlag,timeNow,desc,author)
%WRITEGNOMENETCDF  Write current data to NetCDF file following NOAA's
%                  GNOME format
%
% NOTE:  Requires the free netCDF matlab toolbox.
%
%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
%
%      $Id: writeGnomeNetCDF.m 583 2008-01-26 00:24:27Z cook $
%        AUTHOR: Michael S. Cook, Naval Postgraduate School%
%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

%% NOTES for future modifications:
% 1) Document: At a minimum, we need to properly establish dimensionality
%    of lon, lat, times, U, V, etc.
% 2) lon, lat, times, U, V should be basic input arguments.
% 3) Other arguments should be param,val pairs following model of
%    makeTotals.  These should take appropriate default values.  Also
%    need to add additional parameters such as description, author.
% 4) All references to us should be removed - generalize.
% 5) Add possibility of including error estimates

%% Set default values if necessary.
```

```
if ~exist('timeNow','var') || isempty(timeNow)
  disp( 'Using time=now for creation TimeStamp.' );
  timeNow = now;      % TIMESTAMP
end
if ~exist('desc','var') || isempty(desc)
    desc = 'HF Radar Derived Surface Currents'
end
if ~exist('author','var') || isempty(author)
    author = 'anonymous'
end


[y,m,d,h,mm,s] = datevec(timeNow);
if ~exist('file_netcdf','var')
  file_netcdf = sprintf('GNOME_%s_%04d_%02d_%02d_%02d00.nc', ...
                        dom,y,m,d,h);
  disp([ 'Attempting to write DEFAULT file named ', ...
          file_netcdf ' in the current directory' ])
end
if ~exist('netcdfFlag','var')  || isempty(netcdfFlag)
  netcdfFlag = -9999;
  % netcdfFlag = -9.9999e+32;
  fprintf('Using default flag of: %g\n',netcdfFlag);
end

% base_stamp appears to be the year, month, day, hour of the 1st TUV file
[year,mon,day,hr,mn,sec] = datevec(times(1));
base_stamp = sprintf('%.4d, %.2d, %.2d, %.2d',year,mon,day,hr);
% time_units appears to be "hours since the first TUV time
time_units = sprintf('hours since %.4d-%.2d-%.2d %.2d:%.2d:%.2d', ...
                     year,mon,day,hr,mn,0);

numTimes = size(times(:),1);

% ------------------- DEFINE THE NetCDF FILE ATTRIBUTES------------------ %

ncquiet                                         % No NetCDF warnings.

try
    nc = netcdf(file_netcdf, 'clobber');        % Create NetCDF file.
    fprintf('%s - GNOME netCDF file named:\n\t%s has been created\n', ...
            mfilename, file_netcdf);
catch
    fprintf('########## PROBLEM opening %s, ##########\n%s exiting WITHOUT WRITING
FILE.\n', ...
            file_netcdf, mfilename);
end

% Create time, the RECORD VARIABLE.  The RECORD VARIABLE is the dimension
% in any array that you can append to if subsequent opens on this netCDF
% file are desired.  This is what is referred to at the UNLIMITED variable,
% or dimension, in the GNOME documentation.
nc('time') = 0;

% Define global attributes
nc.description = desc;
nc.author = author;
% Not sure about this one
nc.date = datestr(timeNow);
nc.base_date = base_stamp;
% Grid type
nc.grid_type = 'REGULAR';

% Define variables dimensions - time (RECORD VARIABLE) defined above.
nc('lon') = length(lon);  % lon should be 1 x n
```

```
nc('lat') = length(lat);  % lat should be n x 1

% Define variables and dimensions
nc{'time'} = 'time';
nc{'lat'} = {'lat'};
nc{'lon'} = {'lon'};
nc{'water_u'} = {'time','lat','lon'};
nc{'water_v'} = {'time','lat','lon'};
nc{'u_error'} = {'time','lat','lon'};
nc{'v_error'} = {'time','lat','lon'};

% Define long name attributes
nc{'time'}.long_name = 'Valid Time (GMT)';
nc{'lat'}.long_name = 'Latitude';
nc{'lon'}.long_name = 'Longitude';
nc{'water_u'}.long_name = 'Eastward Water Velocity' ;
nc{'water_v'}.long_name = 'Northward Water Velocity' ;
nc{'u_error'}.long_name = 'Eastward Water Velocity Error' ;
nc{'v_error'}.long_name = 'Northward Water Velocity Error' ;

% Define base date for time (attributes)
nc{'time'}.base_date = base_stamp;

% Define variable units (attributes)
nc{'time'}.units = time_units;
nc{'lat'}.units = 'degrees north';
nc{'lon'}.units = 'degrees east';
nc{'water_u'}.units = 'm/s';
nc{'water_v'}.units = 'm/s';
nc{'u_error'}.units = 'm/s';
nc{'v_error'}.units = 'm/s';

% Define variable standard names (attributes)
nc{'time'}.standard_name = 'time';
nc{'lat'}.standard_name = 'latitude';
nc{'lon'}.standard_name = 'longitude';
nc{'water_u'}.standard_name = 'eastward_sea_water_velocity';
nc{'water_v'}.standard_name = 'northward_sea_water_velocity';
nc{'u_error'}.standard_name = 'eastward_sea_water_velocity_error';
nc{'v_error'}.standard_name = 'northward_sea_water_velocity_error';

% Define variable fill values (attributes)
nc{'water_u'}.FillValue_ = netcdfFlag;
nc{'water_v'}.FillValue_ = netcdfFlag;
nc{'u_error'}.FillValue_ = netcdfFlag;
nc{'v_error'}.FillValue_ = netcdfFlag;

% Write the grid information to the netcdf file
% % nc{'time'}(:) = 0:number_files-1;
nc{'time'}(1:numTimes) = 0:numTimes-1;
% lat, lon, and mask may have to be transposed!  If so make sure the
% u,v,uerr, and verr are also TRANSPOSED!
nc{'lat'}(:) = lat;
nc{'lon'}(:) = lon;
% nc{'mask'}(:) = maskInd;

% Now convert everything from cm/s to m/s
U = U ./ 100;
V = V ./ 100;
% grid_Uerr = grid_Uerr ./ 100;
% grid_Verr = grid_Verr ./ 100;

% Replace NaN's (matlab flags) with NetCDF flags - do this after
% converting from cm/s to m/s or -9999 will become -99.99!
U(isnan(U)) = netcdfFlag;
```

```
V(isnan(V)) = netcdfFlag;

nc{'water_u'}(:) = U;           % Write velocity data to the NetCDF file
nc{'water_v'}(:) = V;
% % nc{'u_error'}(:) = grid_Uerr;
% % nc{'v_error'}(:) = grid_Verr;

disp('closing netCDF file ...')
nc = close(nc);                    % Close the file
```

Appendix B
GIS File Formats

In addition to special formatting for GNOME importing, special formatting is required to be able to directly import HF radar-derived velocity maps into Graphical Information System (GIS) programs. Such programs are critical tools for many users, including hazardous spill response managers, water quality monitoring officials, and coastal zone managers. Because of the growing importance of GIS applications in coastal programs, this project worked to develop a standard product that provides for direct importing of surface current mapping data by GIS applications. The formatting protocol developed here depends on matlab analysis routines. Importantly, those routines also require that geographic projection information be established and written out together with the basic vector mapping data. The exact procedure and file naming convention used is described in the matlab function below.

The procedure that was developed in this project and incorporated into the real-time processing stream for COCMP takes radar-derived surface current data on a rectangular grid for one time instance and creates a set of files necessary for direct import into standard GIS programs. Prior to that step, the data are first written into U and V arrays and stored in a matlab binary formatted "`mat`" file using routines from the HFR_Progs Toolbox. Then a set of matlab programs load the "`mat`" file and convert the U/V data into GIS `.dbf`, `.shp`, and `.shx` files. A time-invariant `.prj` file containing projection information necessary to render the vectors correctly is then bundled with the hourly data files, and the four files are zipped together and made available on the web (see: http://www.cencalcurrents.org/DataRealTime/Totals). This process is automatically repeated every hour.

The matlab code that converts matlab U/V arrays to GIS-compatible files is the following (note: this code requires shapewrite.m, which is part of the matlab Mapping Toolbox): The routines can be obtained as part of HFR_Progs at: http://www.cencalcurrents.org/ProgsRealTime

```
function TUVstruct2shape(TUV,pathFile)

% USAGE:
%    TUVstruct2shape(TUV,pathFile)
%    will take the TUV struct, remove any NaN U,V currents, and write the
%    rest to a shapefile for use in GIS programs like ArcView.
%
%    AUTHOR: Michael S. Cook, Naval Postgraduate School

% No NaN's allowed in shapewrite function - id all
ind = ~(isnan(TUV.U)  |  isnan(TUV.V));
if sum(ind) == 0
    fprintf('No data in this TUV struct, no shape files written')
    return;
end

[Lon,Lat,U,V] = deal(TUV.LonLat(ind,1),TUV.LonLat(ind,2), ...
                     TUV.U(ind),TUV.V(ind));

writeShapePoints(Lon,Lat,U,V,pathFile,TUV.Type);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function writeShapePoints(Lon, Lat, U, V, pathFile, Type)

% writeShapePoints  Write HFR surface currents to shapefile format
```

```
% USAGE:
%   writeShapePoints(Lon, Lat, U, V, pathFile) generates a shapefile
%   containing latitude, longitude, magnitude and bearing of HFR
%   derived surface currents.  THERE MUST BE NO NAN's IN THE INPUT
%   VARIABLES.  All 5 inputs are required.
%
%   (U,V) are eastward and northward velocities which are
%   converted to magnitude and bearing (deg, cw from true North)
%   The shapefile is written out to pathFile.  Actually 3 files (.dbf,
%   .shp, and .shx) with the same file prefix will be created.
%
%   Input:
%      Lon    m x 1
%      Lat    m x 1
%      U      m x 1
%      V      m x 1
%      pathfile     string
%
%   Important NOTES:
%       - All input fields MUST be NaN free.
%       - shapewrite is part of the matlab mapping toolbox
%       - The file shpProjTemp.prj contains projection information, and
%           will be included as a 4th output file if it can be found on the
%           search path.
%
%   A modification of the program hfr_npred_mat2shp.m by Mark Otero.
%
% AUTHOR: Michael S. Cook, Naval Postgraduate School


if ~exist('shapewrite.m','file')
    fprintf('shapewrite not found, mapping toolbox probably not ')
    fprintf(' installed ...\n')
    fprintf('no shape files created, %s exiting\n',mfilename)
    return;
end

% Convert from Cartesian to polar coordinates and report bearing
% in geographic convention (cw from North)
[Bear, Mag] = cart2pol(U,V);
Bear        = mod(90-Bear*180/pi, 360);
MagKtsHr    = Mag.*0.01944;

% Create geostructure
m = length(U);
[S(1:m).Geometry] = deal('Point');
[S(1:m).Type] = deal(Type);
for I = 1:m
    S(I).Lat              = Lat(I);
    S(I).Lon              = Lon(I);
    S(I).Mag_cmSec        = Mag(I);
    S(I).Mag_ktsHr        = MagKtsHr(I);
    S(I).Bearing          = Bear(I);
end

% Write to shapefile
shapewrite(S, pathFile);

% Copy projection file template for new file set if it can be found
projTemp = 'shpProjTemp.prj';
if exist(projTemp,'file')
    projTemp = which(projTemp);
    projFile = strrep(pathFile,'.shp','.prj');
    copyfile(projTemp, projFile);
else
```

```
    fprintf('Can''t find %s in search path - no .prj file written\n', ...
             projTemp);
end

% Create a zip file of all shape file parts created in this hour
% Make the wildcard list of all the files for this hour.
zipList = strrep(pathFile,'.shp','.*');
zipName = strrep(pathFile,'.shp','');
% Now get rid of the file name
system(['zip -j ',zipName,' ',zipList]);

% Delete the shape files and keep only the zip file
shapeTypes = {'dbf','prj','shp','shx'};
for j = 1:numel(shapeTypes)
    if exist([zipName,'.',shapeTypes{j}],'file')
        delete([zipName,'.',shapeTypes{j}]);
    end
end
```

A similar process was developed to convert a “`mat`” file containing trajectories initialized on a rectangular grid 25 hours in the past and allowed to evolve for 24 hours into a set of GIS files. In the real-time COCMP processing stream, a `.prj` file containing projection information is bundled with the three required data files and all four files are zipped together and made available on the web each hour (see: http://www.cencalcurrents.org/DataRealTime/Trajectories). This process is automatically repeated every hour for observed trajectories. The same process can be used to format forecasted trajectories. An example of a GIS trajectory view of forecasted positions is shown in Figure B1 for a period during the Costco Busan oil spill incident.

The matlab code that converts matlab trajectory locations to GIS files is the following (note: this code requires shapewrite.m, which is part of the matlab Mapping Toolbox):

```
function TRAJstruct2shape(TRAJ,pathFile)

% USAGE:
%    TRAJstruct2shape(TRAJ,pathFile)
%    will take the TRAJ struct, remove any NaN's at the end of
%    tracks, and write the
%    rest to a shapefile for use in GIS programs like ArcView.
%    AUTHOR: Michael S. Cook, Naval Postgraduate School


% Time is calculated every 7 1/2 minutes, decimiate to every 1/2 hour.
time = TRAJ.TimeStamp(1:4:end);
Lon = TRAJ.Lon(:,1:4:end);
Lat = TRAJ.Lat(:,1:4:end);

% Eliminate trajectories with no duration.
ind = TRAJ.TrajectoryDuration < eps;
Lon(ind,:) = [];
Lat(ind,:) = [];

if isempty(Lon)
    fprintf('No data in this TRAJ struct, no shape files written')
    return;
end


writeShapeLines(Lon,Lat,pathFile,TRAJ.Type,time);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function writeShapeLines(Lon,Lat,pathFile,Type,time)
```

```
% Lon = 2-D matrix, #drifters x #times
%
% NOTES:
%     Lon and Lat should have no rows with all NaN's, ie. any drifter track
%     with all NaN's should have already been removed.


if ~exist('shapewrite.m','file')
    fprintf('shapewrite not found, mapping toolbox probably not installed ...\n')
    fprintf('no shape files created, %s exiting\n',mfilename)
    return;
end


% Loop over every remaining drifter (row) and trim off any nan's
numDrift = size(Lon,1);
for i = 1:numDrift
    ind = find(~isnan(Lon(i,:)));
    tmpLon = Lon(i,ind);
    tmpLat = Lat(i,ind);
    S(i).Lon = tmpLon';
    S(i).Lat = tmpLat';
    % Compute the start and stop times.
    S(i).StartTime = datestr(time(ind(1)),31);
    S(i).EndTime = datestr(time(ind(end)),31);
end

[S(1:numDrift).Geometry] = deal('PolyLine');
[S(1:numDrift).Type] = deal(Type);


% Write to shapefile
shapewrite(S, pathFile);

% Copy projection file template for new file set if it can be found
projTemp = 'shpProjTemp.prj';
if exist(projTemp,'file')
    projTemp = which(projTemp);
    projFile = strrep(pathFile,'.shp','.prj');
    copyfile(projTemp, projFile);
else
    fprintf('Can''t find %s in search path - no .prj file written\n', ...
             projTemp);
end

% Create a zip file of all shape file parts created in this hour
% Make the wildcard list of all the files for this hour.
zipList = strrep(pathFile,'.shp','.*');
zipName = strrep(pathFile,'.shp','');
% Now get rid of the file name
system(['zip -j ',zipName,' ',zipList]);

% Delete the shape files and keep only the zip file
shapeTypes = {'dbf','prj','shp','shx'};
for j = 1:numel(shapeTypes)
    if exist([zipName,'.',shapeTypes{j}],'file')
        delete([zipName,'.',shapeTypes{j}]);
    end
end
```

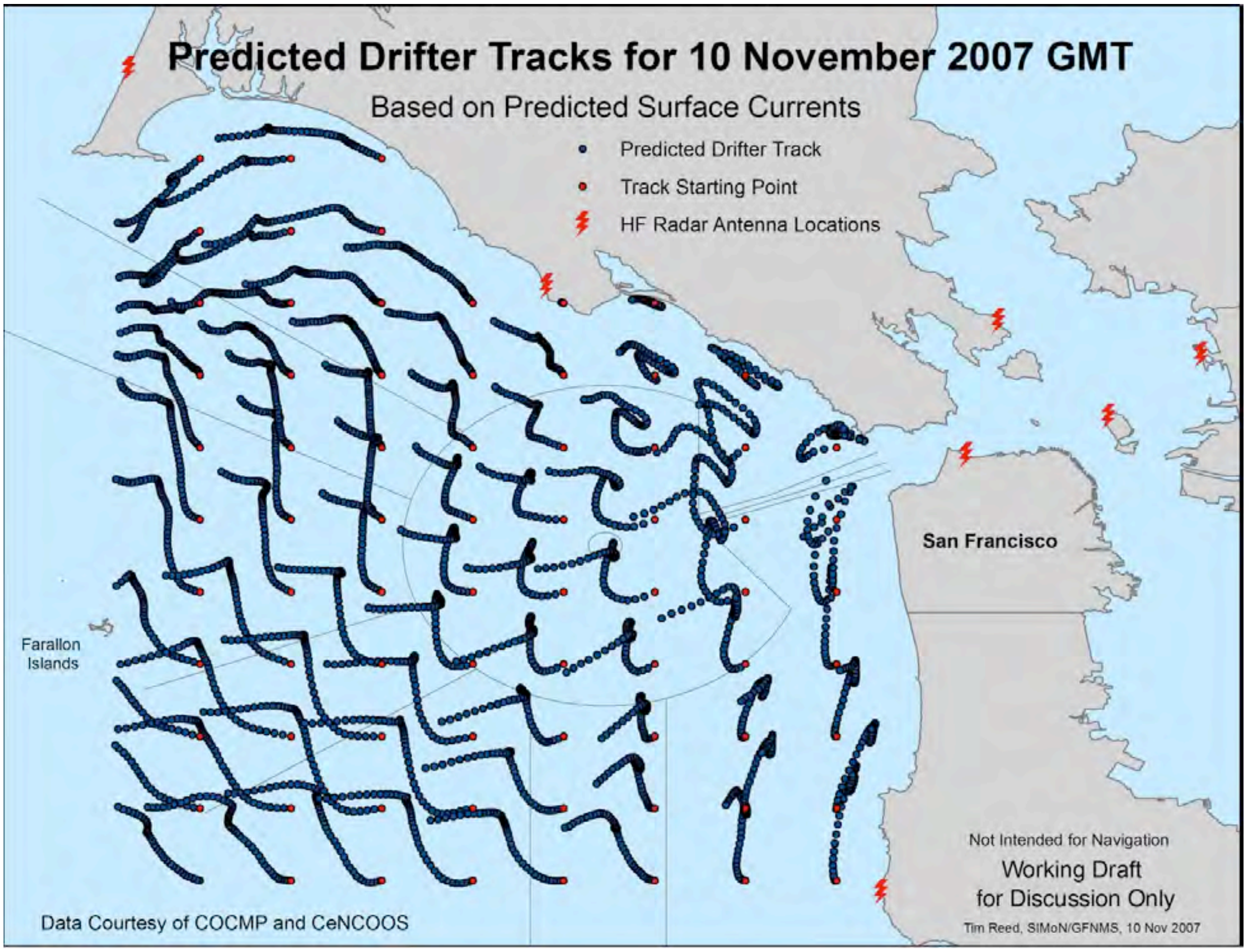

Figure B1. Example forecasted particle trajectories over a twenty four hour period from HF radar-derived surface currents plotted using a GIS program.

The GIS file naming convention is:

NNN_SSSS_yyyy_mm_dd_hh00.zip

where:

NNN is either trj, for 24 hour trajectories, or tuv for a velocity vector field.
SSSS is the site designator.
yyyy_mm_dd_hh00 is the year_month_day_hour of the last actual surface current field.

Unpacking the zip file will yield a folder of the name NNN_SSSS_yyyy_mm_dd_hh00 which will contain 4 files: NNN_SSSS_yyyy_mm_dd_hh00.dbf, NNN_SSSS_yyyy_mm_dd_hh00.prj, NNN_SSSS_yyyy_mm_dd_hh00.shp, and NNN_SSSS_yyyy_mm_dd_hh00.shx