Surface Current Measurements During Safe Seas 2006: Comparison and Validation of Measurements from High-Frequency Radar and the Quick Release Estuarine Buoy

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Abstract - The National Oceanographic and Atmospheric Association's (NOAA) 2006 Safe Seas Oil Spill Drill, conducted just outside the Golden Gate, was a prime opportunity to test the value and effectiveness of three recently deployed 13 MHz coastal radars that are part of the Central and Northern California Ocean Observing System. These Coastal Ocean Dynamic Application Radar (CODAR) systems were deployed by the Coastal Ocean Currents Monitoring Program (COCMP) to measure surface currents up to 85km offshore from Point Reyes to just north of Half Moon Bay. CODAR systems measure surface currents by transmitting radio waves over the ocean and use the Doppler-shifted return sea echo to extract surface current velocities. Safe Seas 2006 was the first demonstrated use of High-Frequency Radar (HFR) to assist in oil-spill response in real time. Surface current maps were posted to the web hourly during the simulated oil spill to monitor surface current structure during the 48-hour exercise. NOAA's Quick Release Estuarine Buoy (QREB) was also deployed at the location of the simulated oil spill to obtain oceanographic environmental data in real time. The QREB is equipped with an Acoustic Doppler Current Profiler (ADCP), which provided a vertical profile of currents near the location of the simulated spill. In an effort to determine the reliability of the data produced from both measurement devices during the exercise, HFR total vector data from the three coastal systems were compared to the data acquired by the QREB surface bin located at approximately 3m depth. Also, to verify individual HFR site performance, radial data from each site were compared with their respective radial components from the QREB data. Total-vector comparison results reveal strong correlation in both the cross-shore ($R^2 = 0.69$) and along-shore ($R^2 = 0.90$) components with RMS differences of less than 0.09m/s. Both instruments also observed the same dramatic shift in along-shore current direction during the two-day exercise. Radial comparisons revealed strong correlation as well for the two HFR systems that acquired data at the QREB location. Endpoints of recovered drift cards released during the exercise also qualitatively correlate with trajectories produced from the HFR current maps. Further, tidal analyses were performed on the QREB and HFR data, utilizing Pawlowicz's widely accepted T-Tide algorithm, to further validate measurements made by these instruments. Despite the short data set, these analyses showed pronounced signals of K_1 and M_2 constituents in good agreement between the QREB and HFR instruments. The consistent comparison results described in this paper show that HFR can add significantly to the effectiveness of surface current mapping over a large area during oil spills and can complement the QREB measurements to enhance oil-spill response.

I. Introduction

Several recently deployed Coastal Ocean Dynamic Applications Radar (CODAR) systems, as a part of the Coastal Ocean Currents Monitoring Program (COCMP) and the Central and Northern Ocean Observing System (CeNCOOS), were given the opportunity to test their value and effectiveness during the 2006 Safe Seas Oil Spill Drill conducted by the National Oceanographic and Atmospheric Association (NOAA) in August 2006.

The Quick Release Estuarine Buoy (QREB) has been used in previous Safe Seas exercises as the sole source of current measurements in the vicinity of the simulated spill; but results here suggest that high-frequency radar (HFR) can add significantly to oil spill response by adding to surface current area coverage, accuracy and trajectory simulations.

These two devices operate differently and provide different sets of data, both useful for predicting and monitoring a simulated – or real – oil spill. This study was conducted in an effort to justify surface current measurements recorded by both instruments during the 2006 Safe Seas exercise and to show that HFR can contribute to the effectiveness of surface current mapping over a large area during oil spills, complementing the QREB measurements to enhance oil-spill response.

Three comparisons between HFR and QREB measurements were conducted: 1) Total vector comparison of real-time data produced during the Safe Seas exercise; 2) radial vector comparisons between the QREB and two HFR sites that collected data at the simulated spill location; and 3) comparison of tidal constituents resolved from a short tidal

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analysis on each data set. In addition, trajectories were created from HFR data to show drifter tracks released from the location of the spill. Trajectories produced using HFR data coincide with reported locations of recovered drift cards released during the exercise.

Results from all comparisons revealed good correlation, suggesting that both systems were indeed producing valid measurements of the current field during the simulated oil spill. Further, positive and correlated results seen here show that utilizing HFR for oil spill response, in addition to the QREB, together give an unprecedented view of the current field in real-time during an oil spill crisis.

II. Location and Instruments

A. Location

The 2006 Safe Seas simulated oil spill was conducted just outside the Golden Gate in an effort to exercise oil spill response preparedness in the Monterey Bay and Gulf of the Farallones National Marine Sanctuaries [1]. The simulated spill scenario had an incoming container ship, the M/V Blue Harp, collide just east of the Farallone Islands with an outgoing oil barge, Dottie. Barge Dottie sank at 37° 39’N, 122° 38’W and leaked oil; the M/V Blue Harp anchored north of the simulated collision site (37° 49.5’N, 122° 41.5’W) and also leaked oil (see Fig. 1). Several CeNCOOS CODAR HFR contributed to mapping surface currents in this region from north of Point Reyes to Monterey Bay.

B. High-Frequency Radar

Three Standard Range (12-13MHz) CODAR systems, operated by San Francisco State University, covered the spill focus area just outside the Golden Gate; they are located at (1) Bolinas; (2) Fort Funston, San Francisco, referred to as FORT; and (3) Montara, referred to as MONT (Fig. 1).

CODAR HFR operate on land and measure surface currents by transmitting radio waves over the ocean and use the Doppler-shifted return sea echo to extract surface current velocities [2]. Each system measures currents moving toward or away from the radar, referred to as “radial currents.” By combining two or more radial vectors at a grid point, a total current containing u and v components is produced.

The measurement depth of CODAR systems varies dependent upon the operating frequency; the systems utilized during this experiment measure ocean currents from the surface down to approximately 1m depth. Real-time HFR radial data produced during this experiment were configured to average data over 75 minutes and output radial vectors every 60 minutes.

B. Quick Release Estuarine Buoy

The QREB is an in-situ device that includes an Acoustic Doppler Current Profiler (ADCP) and meteorological equipment. The RD Instruments ADCP is mounted on the bottom of the buoy and looks downward operating at 307kHz.

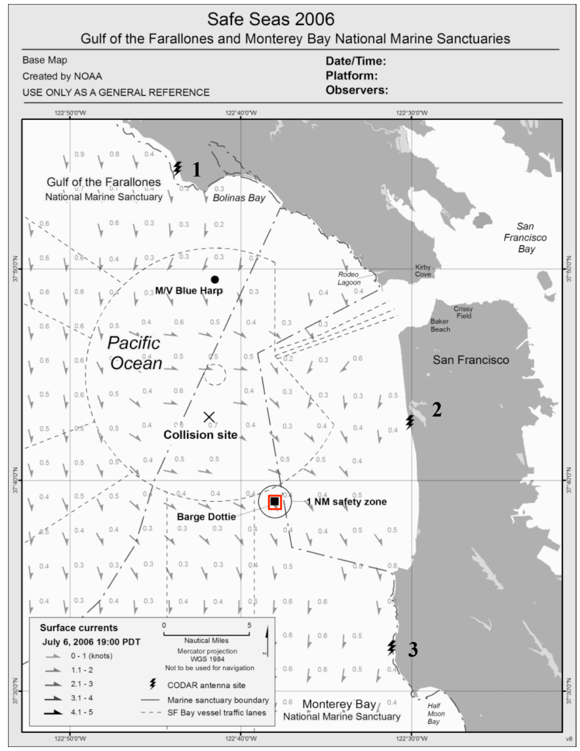


Fig. 1. Safe Seas base map, including collision site, locations of Barge Dottie (co-location of QREB, identified by red square), the M/V Blue Harp and three HFR sites focusing on the simulated spill area.

The ADCP measures the vertical profile of currents in one-meter increments, with the shallowest bin located at approximately 3m depth. The ADCP samples the water column every second for six minutes and calculates the average speed and direction for the interval [3]. A vertical current profile was collected every six minutes from approximately 3m (top bin) to 30m depth.

The QREB was deployed for the Safe Seas exercise on August 8, 2006, at the location of the simulated Barge Dottie to track currents at the source of the simulated spill (red square in Fig. 1). The buoy was operational in-situ for approximately 48 hours, and measurements collected during Safe Seas 2006 are used in comparisons here. QREB six-minute data outputs were hourly averaged for comparison with HFR hourly averaged data.

III. Data Analysis

The comparison data set is limited to 47 hours – the length of the QREB deployment during the Safe Seas 2006 exercise. A HFR total vector time series was created at a grid point corresponding to the location of Barge Dottie, also the location of the simulated spill. The time series was calculated to include data that fell on the grid point and data within a 6km radius of the grid point. Correlation coefficients and RMS differences were calculated for cross-shore (u) and along-shore (v) comparisons as well as radial and tidal comparisons.

A. Total Vector Comparison

A plot of the HFR hourly total vector data (along-shore and cross-shore) versus the QREB data during Safe Seas 2006 is shown in Fig. 2. Cross-shore correlation and RMS differences were calculated, revealing R^2 = 0.69 and 8.98cm/s, respectively. Along-shore correlation revealed good results of R^2 = 0.90 and RMS difference of 7.66cm/s.

Total vector comparison results reveal strong along-shore correlation and good cross-shore correlation. Some variation in cross-shore is observed between the two data sets, likely because the dominant flow along this area of the California coast is along-shore (north/south) [4]. Along-shore currents observed during this 47-hour period ranged from +/- 35cm/s and averaged closer to -30cm/s, while cross-shore currents were less dominant, reaching a maximum of -29cm/s.

B. Radial Comparisons

Comparisons of radial vectors at the location of the simulated oil spill from each contributing HFR are described below. Radial vectors from each site were compared to the respective radial component extracted from the QREB total vector.

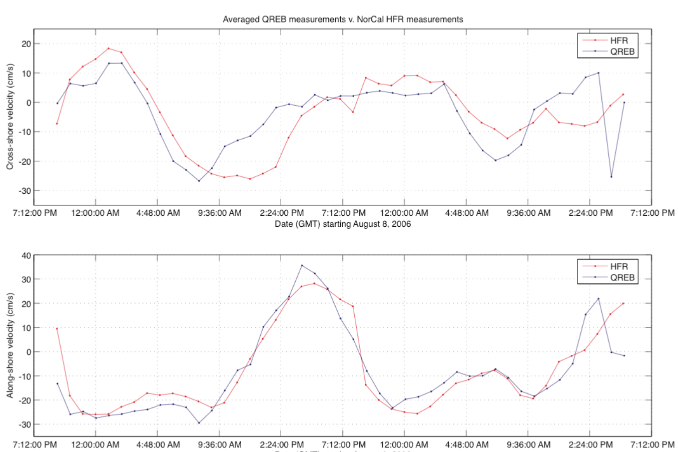
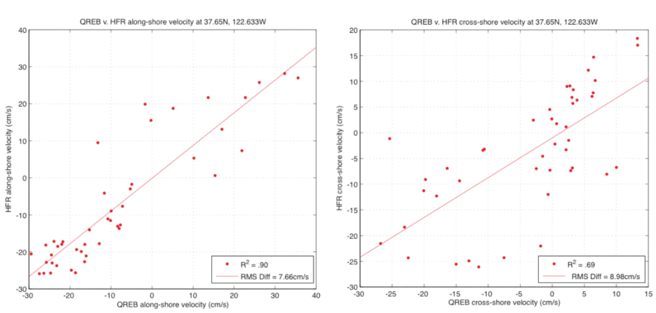


Fig. 2. Total vector comparison of HFR data and QREB data; cross-shore velocities on top, along-shore velocities on bottom.



a. b.

Fig. 3a and 3b. Linear scatter plots of QREB along-shore currents v. HFR along-shore currents (a.) and QREB cross-shore currents v. HFR cross-shore currents (b.)

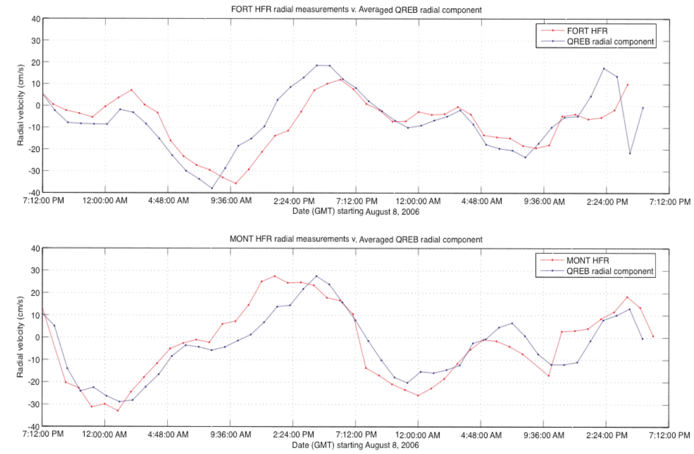
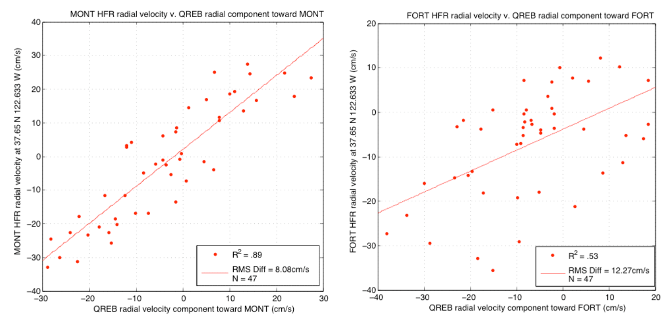


Fig. 4. Hourly radial vector comparison; FORT comparison on top, MONT comparison on bottom.



a. b.

Fig. 5a and 5b. Linear scatter plots of radial comparisons: QREB v. MONT (a.) and QREB v. FORT (b.)

Three radial comparisons were attempted, however, the Bolinas site did not consistently achieve radial coverage at the QREB location. Therefore, two radial comparison results are shown above.

A time series plot of the FORT v. QREB comparison is shown at the top of Fig. 4. General current trends between the two instruments are clearly observed, giving a correlation of R^2 = 0.53 and RMS difference of 12.27cm/s. The bottom of Fig. 3 shows the MONT v. QREB time series comparison. Here we see a strong correlation of R^2 = 0.89 and RMS difference of 8.07cm/s.

Of note is the location of these systems with respect to the QREB buoy. The MONT HFR site is located to the south-southeast of the simulated spill (~142°T). The radial currents from MONT at the location of the buoy are somewhat representative of an along-shore flow. The FORT HFR is located to the west-northwest of the buoy (~60°T). Therefore, the radial currents from FORT are more representative of the cross-shore flow in the region. We can see that this coincides with the total vector comparison results, showing a higher correlation and lower RMS differences in the stronger, along-shore flow and the lower correlation with the less dominant, cross-shore flow.

TABLE I
K1 and M2 tidal constituents derived using T-Tide

	K1				M2			
	K1 MAJOR	K1 MINOR	K ø	K1 S/N	M2 MAJOR	M2 MINOR	M2 ø	M2 S/N
Total								
HFR	19.54cm/s	-11.55cm/s	109°	380	13.26cm/s	3.79cm/s	150°	190
QREB	18.23cm/s	-7.79cm/s	120°	100	11.56cm/s	6.52cm/s	152°	41
Radial								
HFR FORT	11.67cm/s	----	164°	150	8.24cm/s	----	99°	75
HFR MONT	19.22cm/s	----	87°	1600	9.25cm/s	----	159°	360
QREB FORT	13.22cm/s	----	146°	110	7.43cm/s	----	98°	36
QREB MONT	13.60cm/s	----	95°	250	10.62cm/s	----	169°	150

C. Tidal Analysis Comparisons

Given that this data set is extremely short (~48hrs), one would not expect to develop a complete tidal analysis using this data. However, out of curiosity and in the spirit of trying to find yet another comparison point for the QREB and HFR data, both data sets were run through CODAR's SeaTides MATLAB Suite, which solely utilizes Pawlowicz's T-Tide MATLAB code [5] to extract major tidal constituents from an applied data set. In both the total vector data sets and radial data sets from the HFR and QREB, K1 and M2 constituents revealed strong signal-to-noise ratios (S/N), see Table 1.

The K1 and M2 major and minor axes and phase were resolved from the total vector data from both the QREB and HFR data sets. In addition, the K1 and M2 major axes and phase were resolved from the two HFR radial sites that collected data at the QREB location. The QREB total data was resolved to radial components in the direction of FORT and MONT to complete similar radial tidal analyses on the QREB data; K1 and M2 major axes and phase were resolved and are compared below with HFR K1 and M2 results.

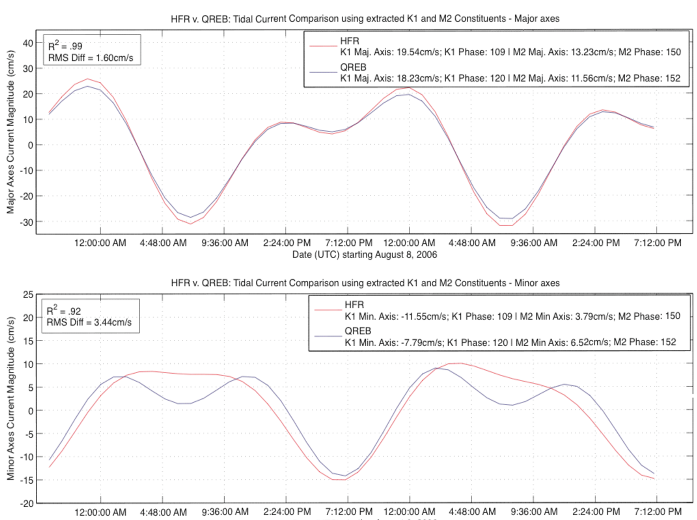


Fig. 6. Tidal time series created from T-Tide derived tidal amplitudes from HFR and QREB total vector data for K1 and M2 constituents.

Utilizing the K1 and M2 tidal frequencies, tidal amplitudes and phase resolved from T-Tide, tidal time series plots were created for the HFR and QREB data (see Fig. 6). Correlation and RMS difference were calculated for the tidal series, giving $R^2 = 0.99$ and RMS difference = 1.60cm/s, for the K1 and M2

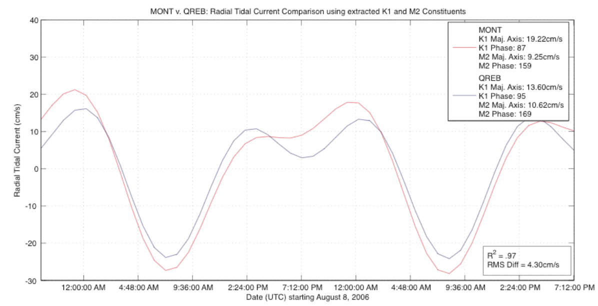


Fig. 7. Radial tidal time series of MONT HFR radial data and QREB data resolved in the direction of MONT. The radial tidal time series are derived from K1 and M2 frequencies and tidal amplitudes and phases derived using T-tide.

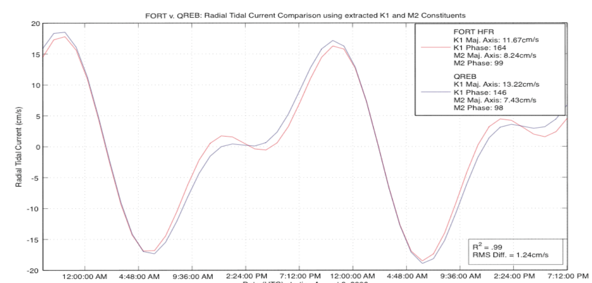


Fig. 8. Radial tidal time series of FORT HFR radial data and QREB data resolved in the direction of FORT. The radial tidal time series are derived from K1 and M2 frequencies and tidal amplitudes and phases derived using T-Tide.

major axes amplitudes and $R^2 = .92$ and RMS difference = 3.44cm/s for the minor axes amplitudes.

K1 and M2 major axes amplitudes were also resolved from HFR radial data from MONT and FORT. A tidal time series utilizing tidal frequencies and derived major axes and phase were created for the MONT and FORT sites for comparison with a tidal time series created from tidal constituent data derived from the resolved QREB radial data for MONT (Fig. 7) and FORT (Fig. 8).

Radial tidal time series comparisons are positive. Correlation between QREB and HFR data in the direction of FORT is good with a correlation of 0.99 and RMS difference of 1.24cm/s. Correlation between tidal time series derived from MONT HFR and QREB data in the direction of MONT gives $R^2 = .97$ and RMS difference of 4.30cm/s.

IV. Discussion

A. Total Vector Comparison

Total vector comparisons reveal strong along-shore correlation, but some cross-shore variation is observed between QREB and HFR measurements. Cross-shore currents observed by both QREB and HFR show similar trends: an onshore flow starting ~Aug. 9 0000 UTC to an offshore flow by 1200 on Aug. 9. By 1800 on Aug. 9, both instruments show cross-shore currents reduce and hover around +/- 15cm/s for the remainder of the exercise. Given that the cross-shore current strength measured by both systems is < 15cm/s for half of the exercise, it is not surprising that the cross-shore current correlation between the two instruments is lower than the along-shore current correlation – where measured current magnitudes rarely drop below 25cm/s.

Significant along-shore direction change was observed in total vector data by both instruments (Fig. 2). Just after deployment of the QREB on Aug. 8 at approximately 1900 UTC, along-shore currents were consistently moving southward at ~30cm/s; this was also observed by HFR instruments. Starting around 1200 on Aug. 9 and over the course of six hours, the along-shore current direction changes dramatically to a 30cm/s - northward flow. At approximately 1800 UTC on Aug. 9, we see the current begin to change direction again. By Aug. 10, 0000 UTC, currents have swung back to a southward flow, moving at ~30cm/s. This 360° change in current direction over 12 hours is observed in measurements by both instruments. This gives good confidence that both instruments are indeed measuring the true surface current field during the Safe Seas 2006 exercise.

B. Radial Comparisons

Radial comparison of the MONT radial vectors and the QREB radial component in the direction of MONT showed strong correlation ($R^2 = 0.89$). The FORT radial comparison reveals a lower correlation, again likely due to the fact that flow on the shelf during this experiment is consistent with typical flow in the region – a dominating along-shore flow. FORT aligns closely with the cross-shore current and MONT aligns with the along-shore current, hence we see similar correlations between MONT and the total vector along-shore flow, and similar correlations between FORT and the total vector cross-shore flow.

RMS differences calculated from comparisons between QREB radial components (resolved in the directions of MONT and FORT from total vector data) and HFR radial data are acceptable, with lowest RMS differences resulting from the MONT radial comparison (8.07cm/s).

C. Tidal Analysis Comparison

Tidal comparisons reveal surprisingly good correlation and low RMS differences between tidal time series derived from resolution of K1 and M2 tidal constituents from total and radial data from HFR and QREB data sets. Radial tidal comparisons show stronger S/N for the K1 and M2 constituents from both QREB and HFR data sets, and therefore good agreement is seen in the tidal time series for both QREB and HFR FORT and MONT radial comparisons.

Strong agreement between QREB and HFR is seen when comparing tidal time series derived from the K1 and M2 major axes and phases. The K1 near-surface tidal structure has been theorized to be oriented along-shore and to be dominant in this region [6], which agrees with results from this study. The M2 tidal ellipse has been theorized to be oriented cross-shore near the Farallones at-depth [7], but in this region – near-shore and south of the Farallones – we see both QREB and HFR measurements reveal the M2 ellipse orientation is closer to an along-shore orientation at/near the surface (~150°). A surface current tidal analysis in this region has not been previously conducted, and would shed more light on long-term surface tidal features in the region.

D. HFR Trajectories and Drift Card Recovery Locations

One advantage of HFR is the ability to create trajectories from the measured HFR current field. During Safe Seas 2006, several drift cards were released from the two simulated vessel locations. Yellow cards were released on Aug. 9 at 0900 from simulated Barge Dottie and orange cards were released on Aug. 9 at 1200 from the M/V Blue. The drift cards included instructions for reporting the time, date and location of the found drift card on the Safe Seas website. A drift card study conducted by NOAA [8], indicates that orange cards released from the Blue Harp were reportedly recovered on Aug. 9 and Aug.10 near Stinson Beach, north of the Golden Gate (see orange oval in Fig. 9). Yellow cards released from Barge Dottie were recovered south of Pacifica after Aug. 12 (see yellow oval in Fig. 9).

Trajectories created from HFR data, starting at the two vessel locations, were created from data starting Aug. 9 at 1300 UTC and ending Aug. 14 at 2300 UTC. HFR trajectories beginning at the Blue Harp show drifters reaching land near Stinson Beach on Aug. 9 at 2300 UTC, then trajectories continue north. Trajectories starting near the location of Barge Dottie show drifters hovering offshore for several days before actually hitting land near Pacifica (Fig. 10).

V. Conclusion

The Safe Seas 2006 exercise was a perfect opportunity to test the effectiveness of three recently deployed HFR systems in the Gulf of the Farallones outside the Golden Gate during an oil spill simulation.

Having two very different instruments collecting surface current data during this experiment gave the Safe Seas 2006 Command Center a large data set to help determine the evolution of current features during a simulated spill event. In

Fig. 9. Recovered drift card locations from Safe Seas 2006. Note: most card locations shown on this map near the Golden Gate are cards planted on beaches by Safe Seas 2006 personnel (see Drift Card Results website) [7]. Yellow cards were found within the yellow oval superimposed on map; orange cards were found within the orange circle on the map.

turn, this created a fantastic opportunity to validate both instruments by comparing data collected by each to determine if they both captured the same current field during the exercise.

Total vector comparisons revealed low RMS differences and good correlation, especially in the dominant along-shore direction. In particular, both instruments measured a 360° current shift from a strong northerly flow, to a strong southerly flow, and back to a northerly flow over the course of 12 hours. These comparisons show that both the QREB and HFR were measuring the same dominant current field during the spill exercise.

Further, radial vector comparisons between the QREB and two HFR sites revealed strong correlation, especially from the MONT site, which is closely aligned with along-shore flow. These positive radial comparisons show that both HFR systems were operating properly, and further show that QREB measurements in the direction of the respective radar sites were very similar to the HFR measurements.

Tidal analysis comparisons were conducted on the short data set to add another comparison point for the QREB and HFR surface current measurements. Tidal constituents resolved using Pawlowicz's T-Tide showed strong S/N in both the K1 and M2 tidal frequencies in total vector and radial vector data sets from both instruments. Total tidal time series plots created using extracted major and minor tidal ellipse

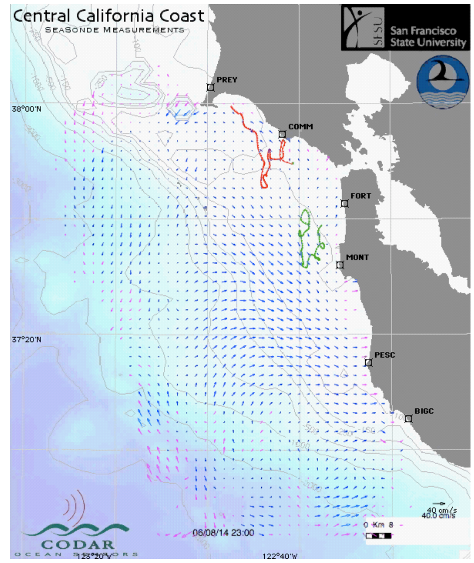


Fig. 10 . HFR-derived trajectories starting at locations of simulated Blue Harp (red trajectory) and simulated Barge Dottie (green trajectory).

parameters showed low RMS differences and good correlation. Radial tidal time series comparisons between two HFR sites and their respective QREB radial components revealed strong correlation and low RMS differences for both FORT and MONT comparisons. The tidal comparisons shown here are to substantiate and strengthen other comparison results discussed in this paper and could be informational for a future, more substantial (longer-term) surface current tidal analysis using HFR (or other surface current meters) in this region.

Different levels of comparisons described here and simulated HFR trajectories validate surface current measurements collected by both instruments during the Safe Seas 2006 exercise and show the importance of having both types of instruments deployed in an oil spill to track current features over a large area, at-surface and at-depth. Both instruments are extremely important for effectively mapping surface currents and predicting oil movement resulting from an oil spill.

ACKNOWLEDGMENT

The QREB and drift card data used in this study were provided by NOAA/NOS/CO-OPS. HFR data used in this study were collected by the COCMP program, and are available online. Many thanks to Tim Reed of NOAA for producing the Safe Seas 2006 basemap and including HFR site locations. And, thanks to Sarah Fenson for her feedback and editing expertise.

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