Surface-Current Variability Statistics in the Tidally Dominated San Francisco Bay

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Abstract—**Drifter deployments were performed in the Central San Francisco Bay in order to evaluate performance of the high-resolution High-Frequency (HF) radars that are deployed there. The field study was designed to obtain drifter measurements in the radar coverage areas for comparison between the two measurements. Drifter radial velocities were computed along with statistics on surface-current subgrid-scale variability in the deployment areas. Removing the variability of the strong surface-currents from the estimate of instrument error gives a precise estimate of HF radar error in San Francisco Bay. An overall value of 8.45 cm/s for radar error is obtained by the comparison between surface drifters and the radar.**

Keyword; surface-current subgrid-scale variabilty; HF radar-drifter comparisons

I. INTRODUCTION

High-Frequency radar has become a well established and extensively validated ocean monitoring tool at the standard (~25 MHz and ~12 MHz) and long-range (~5 MHz) frequencies; however, the less ubiquitous 42 MHz short-range/high-resolution system has not undergone validation studies. Within the California Coastal Ocean Currents Monitoring Program (COCMP), over 50 radars (standard and long range) have been deployed along the coastal waters of California as a way to monitor the state's coastal currents; Central San Francisco (SF) Bay is the only region where the 42 MHz systems are presently deployed. This study is a first attempt to evaluate the performance of the 42 MHz radars that are situated in the SF Bay using GPS-tracked surface drifters as the comparison measurement. With the data collected by the drifters, it is possible to constrain the radar error by isolating it from the natural current variability that exists in the flow field. Doing this gives an estimate of actual radar error on the 42 MHz systems.

II. METHODS

The 42 MHz array in the SF Bay consists of four radar stations: at San Francisco's Crissy Field, (CRIS, center frequency = 43.69 MHz); at the Sausalito water treatment facility (SAUS, center frequency = 44.21 MHz); on the northwest side of Treasure Island (TRES, center frequency = 40.75 MHz); and on the Tiburon Peninsula (RTC1, center frequency = 41.48 MHz) (Figure 1). Hereafter the radars are referred to by their four letter site codes; CRIS, SAUS, TRES, and RTC1. Two locations (sampling boxes) in the radar coverage areas within SF Bay were chosen for drifter deployment; one at Southampton Shoals (SHS) and one at Harding Rock (HR) (Fig. 1). The SHS sampling box location includes the radial coverage areas of the TRES and RTC1 radars, while the HR sampling box includes the CRIS and SAUS radar coverage areas. The sampling areas for the comparison study needed to be outside of the major shipping channels and clear of vessel traffic, which constrained where they could be placed.

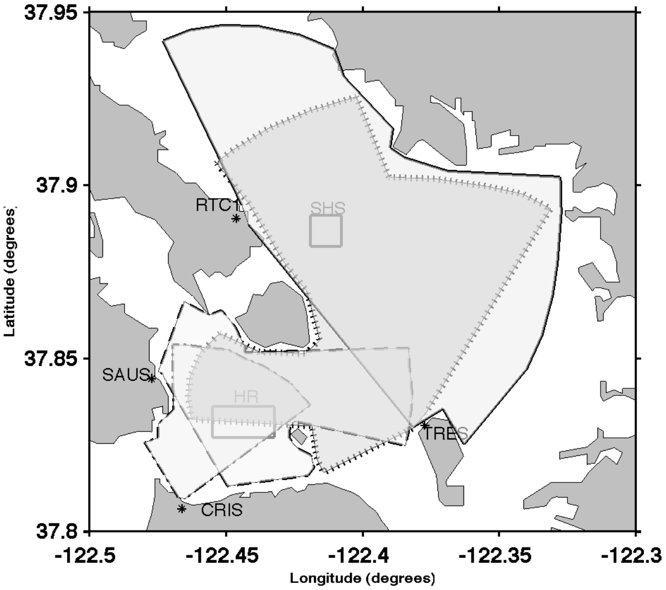

Figure 1. Central San Francisco Bay. Black stars represent radar stations starting from the bottom at Crissy Field (CRIS), then moving clockwise to Sausalito Water Treatment facility (SAUS), Romberg Tiburon Center for environmental studies (RTC), and Treasure Island (TRES). Grey filled areas represent radar measurement locations for each radar. Black boxes represent the two areas of drifter sampling, Southampton Shoal (SHS) to the North and Harding Rock (HR) in front of the Golden Gate.

In October of 2008, up to 17 drifters were deployed over six days from three San Francisco State University research vessels. During the six days of sampling, a total of 525 usable 10-minute drifter velocity observations were collected. Each box was sampled for three days; sampling days at SHS were October 8th, 9th, and 21rst, and October 15th, 16th, and 22nd for HR. The sampling strategy follows [1]. Where multiple drifter velocities within a sampling box were collected in order to bring the temporal and spatial measurement scales between drifters and radar closer together through averaging. Drifters were deployed so that the strong tidal current would move them through the sampling boxes; when drifters exited the sampling box, they were captured by the research vessels and redeployed along the up-current boundary of the sampling box.

Individual drifter tracks were visually inspected for errors. Suspect drifter measurements were identified based on abrupt angle changes or measurements with the opposing velocity or dramatically increased magnitude compared to the average measurement. Measurements with these attributes meant that the drifter was most likely being transported on a boat and still logging position. During the experiment, the upper limit set for radial current measurements on the Bay radars is 200 cm/s; drifter speeds above this limit were discarded. To account for the temporal discrepancy between the two measurements, drifter and radial binned velocity pairs with more than a twenty-minute time difference were discarded.

Measured antenna patterns were used for each of the antenna sites. A first level of quality control on the radar data happens within the software, no post-processing quality control was done on the radar data for this comparison, and all radar measurements that were paired with a drifter measurement meeting the criteria outlined above were used.

The drifter velocities were decomposed to obtain the radial component, V_{drif} that corresponded to the radar radial velocity bin measurement for the drifter being compared. Drifter velocities u (east-west) and v (north-south) components were transformed into the radial velocities using

$$V_{drif} = u \bullet \sin\theta + v \bullet \cos\theta. \ (1)$$

where u and v are the original east-west and north-south velocity components of the drifter movement, and θ represents the radial direction from the antenna measured clockwise from 0^o north . Radial current velocities were sampled both in the negative (moving away from the radar) and positive (moving towards the radar) direction for all the radars in the study. Positive radial velocity is defined moving towards the radar due to the positive doppler shift. Linear regressions along with basic statistics between drifter and radar radial velocities were calculated on a day-to-day basis as well as for the entire sampling period at each individual radar site.

The observed velocity field had a large dynamic range. In an attempt to minimize the difference between the temporal and spatial scales measured by the two instruments, HF radar and drifter velocity measurements were binned into 30 minute averages. This was done by taking all the HF measurements within the sampling box for a 30 minute sampling interval and calculating the average velocity and standard deviation of these measurements. Drifter velocities within the sampling box that fell on the 30 minute time stamp, as well as velocities 10 minutes before and after that 30 minute time stamp were averaged and the standard deviation was calculated. In Tables 1-5 the mean standard deviation of the two measurements has the tidal influence removed. This occurs because the 30-minute short-term mean which includes the tides is separated from the standard deviation estimate. We thus remove the variability from the strong tidal currents and ensure that this standard deviation better represents the instrument error as well as subgrid-scale variability as sensed by each instrument. Radar error is then isolated over the sampling periods for individual stations by defining it as

$$HFerror = \sqrt{RMS^2 - HFstd^2 - Drifstd^2}. \ (2)$$

where *RMS* is the root mean square difference between the radar and drifter, *HFstd* is the mean standard deviation over a sampling period for the radar, and *Drifstd* is the mean standard deviation of the drifter measurements over a sampling period. This estimation of radar error assumes that there are an infinite number of samples. In reality there are a finite number of samples, therefore, terms that go to zero when infinite samples are present do not in fact go to zero. This results in some of the radar error measurements to become negative when using (2) in Tables 1-5.

III. RESULTS

A. Harding Rock (HR) Radial Comparisons

For the HR sampling box (CRIS and SAUS) on October 15th sampling was performed during a tidal switch from flood to ebb, resulting in negative and positive radial velocities. On the 16th, sampling took place while the flood current was pushing through the Golden Gate (strong negative radial velocities for both CRIS and SAUS). Sampling on the 22nd occurred while tidal currents were mostly in the ebb phase, providing a sampling day of more positive radial velocities than the previous two days of sampling.

The best-fit line slope at CRIS on the 15th is 1.14 with a regression coefficient (r^2) value of 0.87. On the 16th the best-fit line slope is 1.1 and the r^2 value is 0.80. On the 22nd currents were moving towards the radar on an ebb current, less strong negative radial velocities were observed than on the first two days, and the best-fit line slope is 0.68 with an r^2 of 0.27. It is interesting to note that the results from the first two days come from flood currents (high negative radial velocities), and the last day of sampling results are from ebb tide currents (higher positive radial velocities than negative). When all three days are taken as a whole, slope of the best-fit line is 1.0 and the r^2 becomes 0.84 (Table 1). Current velocity ranges and radar error are the highest between drifter and radar measurement pairs at CRIS with a value of 10.80 cm/s. Results at CRIS for the entire experiment can be found in Table 1.

SAUS results are similar to CRIS, both radars are positioned to look at the Bay side of the Golden Gate where strong tidal currents exist (Fig. 1). On the first two days of sampling (flood current), SAUS has a best-fit line of 1.07 and r^2 value of 0.82 for the 15th; and a best-fit line of 0.91 with r^2 of 0.79 for the 16th. Similar to CRIS, agreement between drifter and radar measurements get weaker on the 22nd at

SAUS. Best-fit line slope is 0.50 with an r^2 value of 0.38. When all three days are combined SAUS has a slope of 0.94, an r^2 of 0.85, and a radar error estimate of 5.68 cm/s (Table 2).

B. Southampton Shoals (SHS) Radial Comparisons

The first day of sampling at SHS was performed primarily during ebb currents, orienting currents to flow southward towards the TRES radar (positive radial velocities) and nearly perpendicular to the RTC1 radar (positive radial velocities). The second day and final day of sampling capture the tide moving from ebb to flood, positive and negative radial velocities at both radars.

TABLE I. Table 1. Drifter comparison results for CRIS. Statistics in the table are; slope of the best-fit line, y-intercept, r2, root mean square difference, radar error (** indicate a negative result from Eq. (2)), radar mean radial velocity and mean standard deviation (mean standard deviations were calculated over the entire sampling day for both the radar and drifter), radar maximum radial velocity, radar minimum radial velocity, drifter mean radial velocity and mean standard deviation, drifter max radial velocity, drifter minimum radial velocity, and number of paired observations. All radial velocities are in cm/s.

Time	**Slope Of Best-fit line**	**y-intercept**	**r^2**	**RMS diff (cm/s)**	**Radar error (cm/s)**	**HF mean & mean std (cm/s)**	**HF max (cm/s)**	**HF min (cm/s)**	**Drif mean & mean std (cm/s)**	**Drif max (cm/s)**	**Drif min (cm/s)**	**# of obs.**
10/15/08	1.14	18.92	0.87	25.14	16.66	11.06 ± 17.43	82.66	-137.38	-6.92 ± 7.11	51.54	-103.96	41
10/16/08	1.1	11.18	0.80	16.78	8.18	-39.64 ± 12.48	26.32	-134.30	-46.76 ± 7.68	8.0	-122.73	76
10/22/08	0.68	9.31	0.27	15.63	9.81	21.38 ± 8.53	68.91	-14.59	17.83 ± 8.68	52.57	-11.29	98
Total for all three days	1.0	7.54	0.84	18.14	10.80	-2.16 ± 12.23	82.66	-137.38	-9.72 ± 7.93	52.57	-122.73	215

TABLE II. Drifter comparison results for SAUS, statistics are the same as table I.

Time	**Slope Of Best-fit line**	**y-intercept**	**r^2**	**RMS diff (cm/s)**	**Radar error (cm/s)**	**HF mean & mean std (cm/s)**	**HF max (cm/s)**	**HF min (cm/s)**	**Drif mean & mean std (cm/s)**	**Drif max (cm/s)**	**Drif min (cm/s)**	**# of obs.**
10/15/08	1.07	4.99	0.82	14.97	5.84	7.10 ± 12.43	46.83	-116.48	-1.97 ± 5.96	37.40	-79.51	42
10/16/08	0.91	-3.06	0.79	12.39	**	-29.89 ± 11.21	22.98	-102.05	-29.36 ± 5.91	21.88	-76.68	81
10/22/08	0.62	11.92	0.52	12.26	**	30.67 ± 10.27	68.91	-7.06	30.25 ± 7.81	75.18	-2.24	109
Total for all three days	0.94	1.13	0.85	14.22	5.68	5.69 ± 11.16	68.91	-116.48	-4.46 ± 6.74	75.18	-79.51	232

TABLE III. Drifter comparison results for TRES, statistics are the same as table I.

Time	**Slope Of Best-fit line**	**y-intercept**	**r^2**	**RMS diff (cm/s)**	**Radar error (cm/s)**	**HF mean & std (cm/s)**	**HF max (cm/s)**	**HF min (cm/s)**	**Drif mean & std (cm/s)**	**Drif max (cm/s)**	**Drif min (cm/s)**	**# of obs.**
10/8/08	0.57	12.28	0.11	12.25	8.62	22.41 ± 7.79	45.62	-8.63	17.66 ± 3.89	32.99	0.74	63
10/9/08	0.75	7.37	0.68	12.00	9.82	8.21 ± 4.72	37.76	-30.76	1.11 ± 5.03	34.52	-39.30	94
10/21/08	0.72	6.36	0.68	10.61	9.13	15.79 ± 3.99	43.01	-33.49	13.12 ± 3.65	47.75	-45.25	136
Total for all three days	0.73	7.26	0.64	11.41	9.25	14.69 ± 5.31	45.60	-33.50	10.13 ± 4.06	47.75	-45.25	293

TABLE IV. Drifter comparison results for RTC1, statistics are the same as table I.

Time	**Slope Of Best-fit line**	**y-intercept**	**r^2**	**RMS diff (cm/s)**	**Radar error (cm/s)**	**HF mean & mean std (cm/s)**	**HF max (cm/s)**	**HF min (cm/s)**	**Drif mean & mean std (cm/s)**	**Drif max (cm/s)**	**Drif min (cm/s)**	**# of obs.**
10/8/08	1.007	-1.08	0.34	9.0	**	3.93 ± 7.77	43.73	-22.54	4.97 ± 4.74	15.39	-7.75	60
10/9/08	0.62	1.45	0.29	8.17	**	10.71 ± 9.60	23.19	-26.90	14.97 ± 3.51	28.34	-9.46	90
10/21/08	0.64	1.54	0.22	10.90	7.93	3.39 ± 6.56	52.15	-21.04	2.89 ± 3.60	20.09	-20.54	136
Total for all three days	0.66	1.06	0.32	9.72	4.59	5.81 ± 7.63	52.15	-26.90	7.12 ± 3.90	28.34	-20.54	286

TABLE V. Drifter comparison results for the entire study, statistics are the same as table I.

Time	**Slope Of Best-fit line**	**y-intercept**	**r^2**	**RMS diff (cm/s)**	**Radar error (cm/s)**	**HF mean & mean std (cm/s)**	**HF max (cm/s)**	**HF min (cm/s)**	**Drif mean & std (cm/s)**	**Drif max (cm/s)**	**Drif min (cm/s)**	**# of obs.**
Entire sampling period	0.92	3.03	0.79	13.36	8.45	6.67 ± 8.8	82.66	-137.38	3.88 ± 5.44	75.18	-122.73	1026

Results for the first day of sampling, Oct 8th, show TRES having low correlation with a best-fit line slope of 0.57 and r^2 value of 0.11 (Table 3). Best-fit line slope on the 9th is 0.75 and r^2 value is 0.68. On the final day of sampling at TRES, best-fit line slope and r^2 are 0.72 and 0.68 respectively. TRES best fit line slope for the entire experiment is 0.73 with a r^2 of 0.64 and a radar error of 9.25 cm/s (Table 3).

The nearly perpendicular flow to RTC1 resulted in smaller radial velocity components observed by RTC1 overall, compared to those observed at TRES, CRIS, and SAUS. The RMS difference between all the drifter and radar measurement pairs at RTC1 is 9.72 cm/s (Table 4). Although RTC1 best-fit line slope for the entire experiment is 0.66 and r^2 is 0.32, error value is the lowest out of all three radars in the comparison with an overall value of 4.59 cm/s (Table 4).

IV. DISCUSSION/CONCLUSION

Results at the HR sampling area for the CRIS and SAUS radars are similar. Overall the radar and drifter correlation is high; however, a discrepancy becomes obvious when looking at results for each individual sampling day. On the first two days of sampling when the tidal current was in a flood phase moving into the Bay through the Golden Gate, correlation between drifter and radar measurements is high. On the last day of sampling at HR when both radars are mapping tidal currents that are in the ebb phase moving seaward through the Golden Gate, correlation between drifter and radar measurements is lower. These results indicate that dynamic tidal currents in SF Bay may be mapped more accurately at different phases of the tide by using varying settings rather than static settings in the radar data averaging routines. An area of future research will be to test different settings within the data processing software at different phases of the tide to confirm these findings and determine if better correlation with drifter measurements can be obtained.

The SHS results for RTC1 and TRES differ between the two radars and from the results at HR. Overall, TRES shows a strong correlation between drifter and radar measurements. The first day of sampling at TRES resulted in low correlation between the two measurements. This low correlation cannot be attributed to a difference in tidal phase like at HR, since the next sampling day the tide was in a similar phase and correlation at TRES increased. RTC1 did not show the same correlation trend as TRES. RTC1 had a consistently weaker correlation than TRES and the rest of the array. This is thought to be due to its location with respect to the sampling box. Within the SHS sampling box, the dominant current is nearly perpendicular to the radial direction being measured by RTC1. This results in smaller radial current measurements within the box compared to the other radars in the study. It was predominantly with these lower radial velocities where the lowest correlation between drifter and radar measurements occurred.

Mean standard deviations calculated from the half-hourly bins over sampling days show variability in instrument measurements for both radar and drifter that are generally in good agreement with one another. The mean standard deviation values are larger when the radial velocity ranges for the two instruments are greater. On the 15th, when radial velocity ranges are greatest for CRIS, radar mean standard deviation at CRIS is 17.43 cm/s while the drifters have a mean standard deviation of 7.11 cm/s. On the 22nd the range of radial velocities is smaller, CRIS radar mean standard deviation is 8.53 cm/s while the drifters mean standard deviation is 8.68 cm/s. Radar mean standard deviation for the entire sampling period at all stations is 8.88 cm/s, while drifter mean standard deviation is 5.44 cm/s. Radar error calculated from (2) gives a representation of the instrument error by removing the natural variability of the currents, as seen by the independent mean standard deviation estimates from both radar and drifter. The CRIS radar error is the highest for all the stations at 10.80 cm/s, RTC1 is the lowest at 4.59 cm/s, and the overall radar bias from all four 42 MHz radars used in this study the measurements is 8.45 cm/s.

The two main conclusions from this field project are: 1) the SF Bay short-range/high-resolution HF radar radial velocities and surface drifter radial velocities have a strong correlation with each other and 2) overall radar bias derived from Eq. (2) for the 42 MHz systems is 8.45 cm/s. In regards to the differences between correlation strength for different sampling days at HR, there is a need for further investigations on the accuracy of radial currents derived from empirical radar settings throughout different phases in the tide. At the RTC1 radar station, lower correlation corresponds with lower radial velocities at that site. In order to limit error sources between drifter and radar measurements in future experiments, for example, the user might choose sampling boxes to maximize radial current velocity at each individual radar station. It also would be useful to set the drifter sampling rate higher to shorten the differing temporal scales that the two instruments measure.

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