Validation of HF Radar-Derived Currents in the Gulf of Naples With Lagrangian Data

Alkiviadis Kalampokis, Marco Uttieri, Pierre-Marie Poulain, and Enrico Zambianchi

***Abstract*—A massive drifter deployment in the Gulf of Naples (Southern Tyrrhenian Sea, Western Mediterranean Sea) over a ten-day multidisciplinary *in situ* experiment in Summer 2012 provided sea-truth data for validating the performance of a high-frequency (HF) radar network. The buoys were frequently retrieved and relaunched to ensure an optimal coverage of the domain. The total velocity of the drifters, together with the associated zonal and meridional components, was compared with the HF radar surface current estimates. Divergence between virtual and real drifter trajectories, and also the simulated movement of clouds of particles give useful insights for scenarios of search and rescue. All comparisons were performed, considering both ideal and antenna radiation pattern-corrected fields. The results of the investigation testify the high precision of HF radars and confirm the necessity of periodically verifying the antenna pattern to ensure the optimal functionality of these systems.**

***Index Terms*—Drifters, Gulf of Naples, high-frequency (HF) radar, ideal pattern, measured pattern, search and rescue, validation.**

I. INTRODUCTION

OVER the last decades, land-based high-frequency (HF; 3–30 MHz) coastal radars have represented one of the most significant breakthroughs in ocean science [1]. In contrast to classical Eulerian (i.e., fixed point) instruments (e.g., moored current profilers and wave buoys), these land-based remote sensing systems provide a synoptic reconstruction of the surface current and wave fields over basins of interest, with high spatial [O (1 km)] and temporal [O (1 h)] resolutions. By combining Bragg scattering coherent resonance and Doppler shift, HF radars can extract details on surface currents acting beneath the gravity waves [1].

Like any scientific apparatus, HF radars require careful setting and calibration for accurate measurements. Surface current estimates refer to a portion of the water column extending between 50 cm and 3 m, depending on the operating frequency; thus, near-surface sea-truth instruments must be used for comparative purposes for an appropriate validation. Acoustic Doppler current profilers (ADCPs) have been frequently used for side-by-side validations, indicating good agreement with reduced root-mean-square differences between the two estimates (e.g., [2]–[10]).

A more effective validation procedure is based upon the intercomparison between HF radars and drifting buoys (e.g., [6], [11], and [12]). Contrary to ADCPs, surface drifters reconstruct the motion of the very first meters of the water column, making the validation between the two platforms more robust. Obviously, discrepancies between the two estimates may exist, as discussed in [11], and attention must be exercised for a proper validation. The comparison with drifting buoys is often corroborated by computer-based simulations of virtual drifters moved by the HF radar-derived current fields (e.g., [6], [11], and [13]), permitting a time-evolving analysis of the separation between the real track and the simulated ones.

As HF radar-derived current measurements may suffer from a number of errors (e.g., [14] and the references therein), the accuracy of those estimates can be significantly improved through the adoption of fine tuning and best practice procedures. One of the major sources of disturbance is attributable to electromagnetic distortions in the vicinity of receiving antennas, altering the pattern of the antenna from an ideal case (as would be the case in an obstruction-free condition) and introducing angular biases up to 35° [15]. To tackle this issue, an optimization protocol is the realization of antenna pattern measurements recording the real antenna pattern, which is subsequently used by the reprocessing software eliminating—or at least minimizing—environmental distortions. Current fields estimated this way (“measured” current maps, AP heretofore) produce better results when compared with both ADCPs and drifters (e.g., [5], [8], [9], and [16]–[18]), thus providing a more reliable approach to resolve surface dynamics than “ideal” current maps, which are acquired without any antenna pattern correction (ID heretofore).

In this letter, we present the results of the validation of HF radar surface current measurements in the Gulf of Naples (Southern Tyrrhenian Sea, Western Mediterranean Sea; see, e.g., [19] and [20]; henceforth GoN) through comparison with Lagrangian drifters deployed in the GoN in the framework of the MED TOSCA (Tracking Oil Spill and Coastal Awareness network) project [21]. The results presented provide a validation of the system operating in the GoN and confirm the superior performances of AP fields in evaluating the surface dynamics of coastal basins.

Manuscript received June 7, 2016; accepted June 27, 2016. Date of publication August 2, 2016; date of current version September 16, 2016. This work was supported in part by the MED TOSCA Project, by the Italian Flagship Project RITMARE, and by the European Community’s 7th Framework Program Project COCONET (Grant agreement No. 287844).

A. Kalampokis is with Hellenic Center for Marine Research, 71003 Heraklion, Greece (e-mail: alkiviadis.kalampokis@hcmr.gr).

M. Uttieri and E. Zambianchi are with CoNISMa, 00196 Roma, Italy, and also with the Department of Science and Technology (DiST), “Parthenope” University, 80143 Napoli, Italy (e-mail: uttieri@uniparthenope.it; enrico.zambianchi@uniparthenope.it).

P.-M. Poulain is with Istituto Nazionale di Oceanografia e Geofisica Sperimentale, 34010 Trieste, Italy (e-mail: ppoulain@inogs.it).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LGRS.2016.2591258

II. MATERIALS AND METHODS

A. *HF Radar Network in the Gulf of Naples*

The surface circulation of the GoN has been monitored since October 2004 through a network of SeaSonde radars manufactured by CODAR Ocean Sensors (Mountain View, USA). These are monostatic direction-finding transceiving antennas using a three-element crossed loop/monopole. In our study, the proprietary software workflow was used, with the MUSIC direction-finding algorithm [22] and a CODAR combine tool to merge radial contributions from each remote site into one total current map using an unweighted least squares method [23].

The system consists of three transceiving antennas located along the coasts of the Gulf of Naples. The three-site configuration retrieves hourly data over a regular square grid with a spatial resolution of 1 km. The antennas operate at a frequency of ∼25 MHz, resulting in an integrating surface depth of ∼1 m. The system is configured to monitor both the surface current and wave fields [24], [25], and the HF radar measurements have been preliminarily validated through comparison with satellite data [26] and with sea-truth data from drifters deployed in Summer/Fall 2009 (unpublished data). The use of HF radar data has allowed the analysis of typical circulation patterns in the GoN [27], [28], as well as of transport mechanisms and coast-offshore exchanges [26], [29]–[31].

Each antenna underwent frequent and regular tuning and maintenance procedures, including antenna pattern measurements [15].

B. *Drifter Data*

The drifter data utilized for this validation study are a subset of Lagrangian instruments deployed in the GoN during the GELaTO (Gulf of Naples Eulerian/Lagrangian TOsca) experiment, carried out in the framework of the MED TOSCA project (E. Zambianchi, unpublished data), in which the dynamics and evolution of the surface field were measured synoptically through the HF radar network, while a sea-truth Lagrangian reconstruction was obtained through the deployment of 46 drifters of different shapes and designs.

In this letter, we focus on the tracks described by 22 CODE drifters [32], [33], whose drogues were located within the first meter below the surface, thus allowing direct estimates with the HF radar sampled layer. It is worth noticing that, for this kind of instrument, direct wind effects have been estimated to be within 1–3 cm s^{-1} for winds up to 10 m s^{-1} [34]. The drifters were localized using GPS and reported either by satellite communication (Iridium) or GSM network every 15 min. The drifter data were processed for spikes and gaps and interpolated at 1-h intervals. Velocities along trajectories were computed from the positions by central finite differences (see the following section).

As in [17], in order to keep a spatially uniform distribution of observations and to provide more robust current estimates, drifter buoys were frequently retrieved and redeployed on the basis of the HF current field estimates.

In agreement with previous studies [26], [28], see also [35], the overall circulation of the GoN during the investigation responded to a typical breeze wind regime and a stable high-pressure system, with an anticyclonic turn of the surface current field over a daily period.

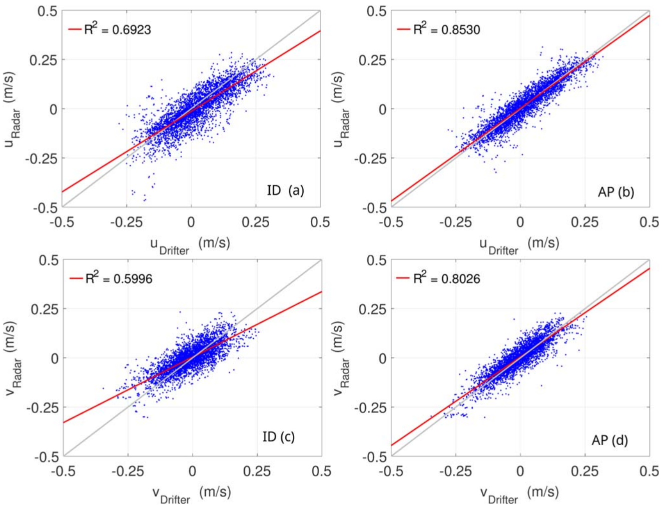

Fig. 1. Comparison of drifter and radar u and v velocity components in the ID and AP cases (the gray line represents the coincidence between radar and drifter data, and the red line represents the regression). (a) ID uRadar versus uDrifter. (b) AP uRadar versus uDrifter. (c) ID vRadar versus vDrifter. (d) AP and vRadar versus vDrifter (best view in color).

III. RESULTS

A. *Comparison Between Drifter- and Radar-Measured Velocities*

In the first part of this study, current velocities as measured by the HF radar were compared to the velocities of the CODE drifters. For this purpose, the drifter velocities were interpolated to 1-h intervals so as to temporally coincide with the velocity field measured by the radar measurements, and the radar-measured velocity was spatially interpolated at the position of each drifter. The u (zonal) and v (meridional) components of the velocities were used for the comparison, using radar velocity fields produced in ID and AP modes (Fig. 1). In all comparisons, the results are statistically robust, and for both components, the AP results [Fig. 1(b) and (d)] show a better agreement between radar and drifter estimates than ID [Fig. 1(a) and (c)]. This is shown by the scatterplots as well as by the linear regression lines, which, in the AP cases, are much closer to the coincidence between the two data sets, and by the associated regression coefficient R^2.

The spatial distribution of the deviations between the drifter- and radar-measured components of the velocity Δu and Δv is presented in Fig. 2. In the ID case, we note high error values even in areas with good radar coverage, like the center of the GoN [Fig. 2(a) and (c)]. By contrast, in the AP case, high errors are encountered mainly at the outer edge of the radar coverage or very close to coastal areas, both cases that may prove problematic for accurate HF radar measurements.

The results of the comparison can be summarized as follows: rms_u and rms_v amount to 10.60 and 8.44 cm s^{-1}; the bias $\mathrm{b}_{\Delta u} = \langle \Delta u \rangle$ results to 1.69 and -0.12 cm s^{-1} for the ID and the AP case, respectively; $\mathrm{b}_{\Delta v} = -0.69$ and -0.54 cm s^{-1} for the ID and the AP case; $\mathrm{rms}_{\Delta u} = 6.23$ and 4.13 cm s^{-1} and

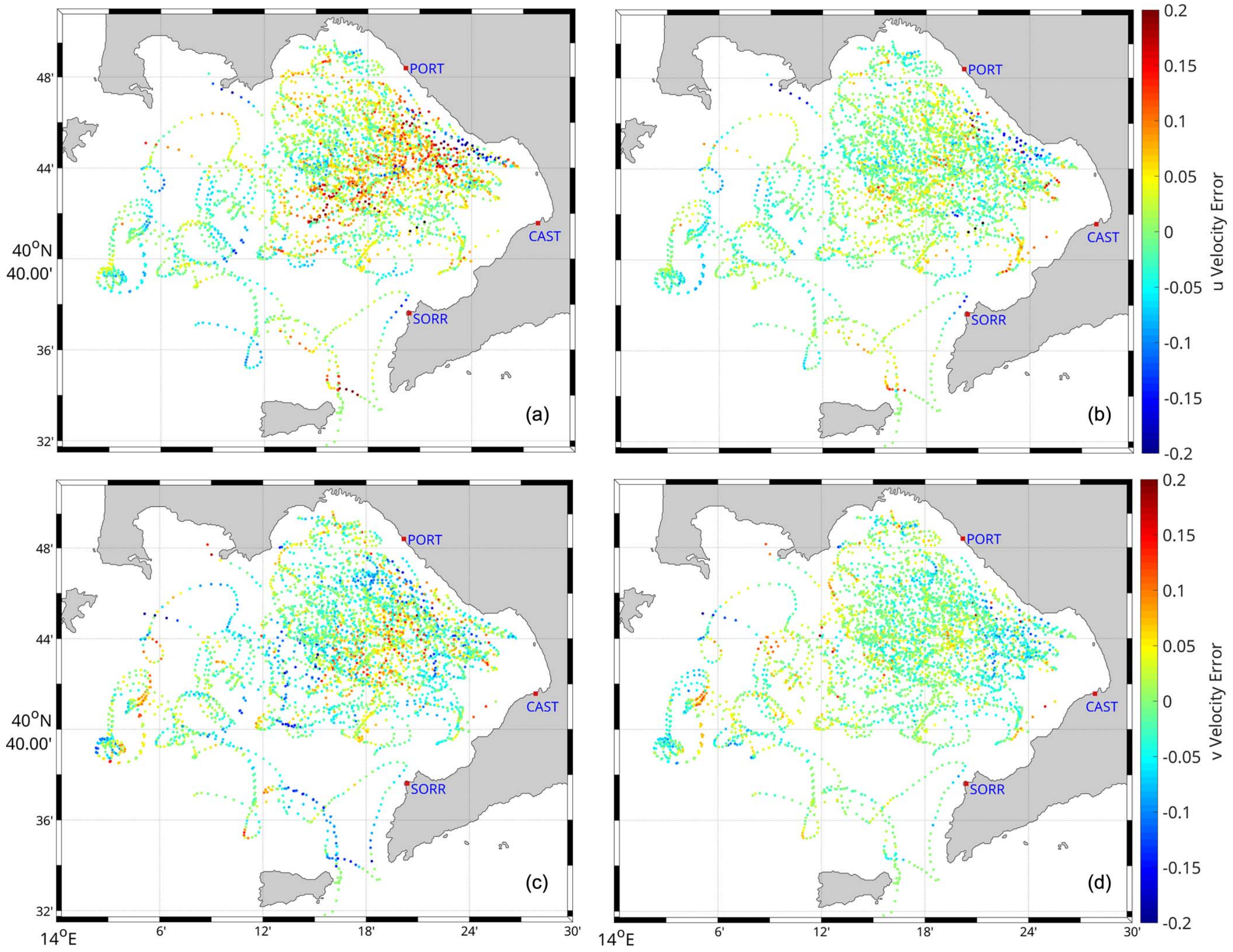

Fig. 2. Maps of the Gulf of Naples depicting the deviations between the u and v velocity components as measured by the HF radar and the drifters. (a) u component in the ID case. (b) u component in the AP case. (c) and (d) Same as (a) and (b) for the v component (best view in color).

for $\mathrm{rms}_{\Delta v} = 5.37$ and 3.85 cm s^{-1} for the ID and the AP case, respectively.

In all cases, the results show a very good agreement between the drifter and radar current estimates, with the rms errors being slightly higher than 5 cm s^{-1} for the ID case and less than 5 cm s^{-1} for the AP one. The rms errors are less than half of the values of the rms drifter velocities, and the bias errors are also very small in all cases.

B. *Comparison Between Real Drifter Trajectories and Synthetic Trajectories*

Synthetic drifter trajectories were computed using the HF radar velocities as the advective field in both ID and AP modes. For each real drifter deployment, a synthetic one was initialized in the same coordinates and time, and the trajectory was computed for 1-h steps, using fourth-order Rung–Kutta integration. Following other authors [11], [36], the synthetic drifters were reinitialized every 24 h by setting their coordinates to the coordinates of the real drifter, a scale typical of the Lagrangian predictability near the sea surface [37]. For every time step, the distance between the synthetic drifter and the real one was computed, and the mean separation distance, i.e., the average over all trajectories [Fig. 3(a)], was calculated. After 24 h, the mean distance is about 2 km for the drifters produced with the AP-corrected radar velocity fields and almost 3 km for the ID ones. At all times, the distance between drifters simulated using AP radar data and real drifters is about 40% less than that of the ideal ones.

We also computed the mean absolute distance, i.e., the mean displacement from the point of deployment. As shown in Fig. 3(b), the displacement reaches a plateau after about 10 h, most likely related to the breeze conditions as well as to the geometry of the GoN. The trajectories of the synthetic drifters follow the behavior of the real drifters quite accurately, with the AP drifters showing again better accuracy.

C. *Time Spent in the Envelope*

The trajectories of the synthetic drifters are very sensitive to the initial conditions, as small errors in the velocities integrated over time may very quickly lead to a trajectory totally different than the real one. Given that, by its nature, the HF radar averages over an area on the order of 1 km^2 while the drifter "feels" the local currents in a range of a few meters, it can be easily seen how errors can propagate rapidly. For this reason, we tried to better sample the velocity field by initializing a number of synthetic drifters surrounding in equal distances the deployment point of the real one and calculating how much time the real drifter spends in the envelope formed by the synthetic

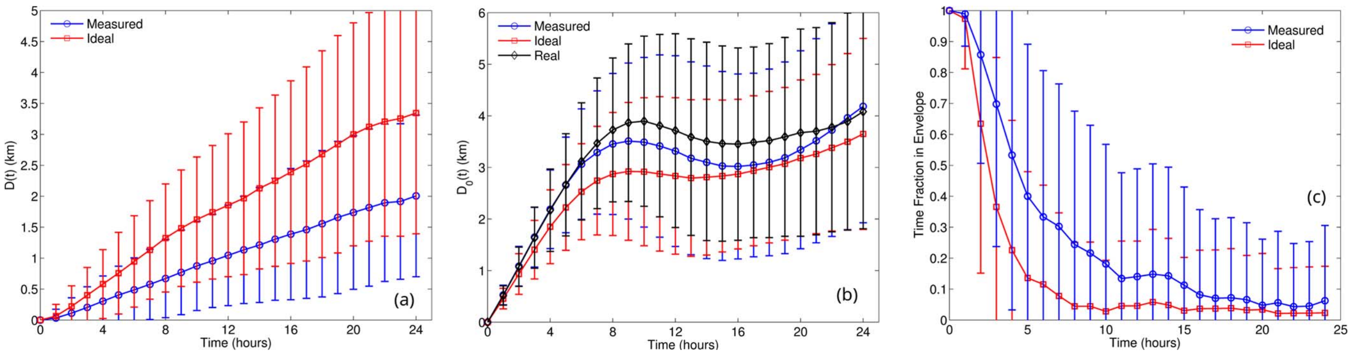

Fig. 3. (a) Mean separation distance $D(t)$ between synthetic and real drifters versus time in the ID (red squares) and AP (blue circles) cases. (b) Mean absolute distance $D_0(t)$ (distance from the deployment point) for real drifters (black diamonds) and synthetic drifters based on ID (red squares) and AP fields (blue circles). (c) Mean fraction of time spent by real drifters in the envelope created by a group of 121 synthetic drifters following HF radar-measured currents using ID (red squares) and AP fields (blue circles). Error bars represent one standard deviation (best view in color).

ones. This can be especially useful in scenarios of search and rescue to help establish a most probable search area.

In our realization, we used 121 synthetic drifters equidistantly spaced every 100 m to form a square with a side of 1 km, the center of which was the real drifter's deployment point. In both ID and AP cases, the drifter tends to move out of the envelope quite fast, which means that the prediction accuracy decreases after the first hours [Fig. 3(c)]. Specifically, after 6 h, the mean percentage of time the drifter is found inside the envelope is only around 12% for the ID case, while it is more than doubled (around 30%) for the AP case.

IV. DISCUSSION AND CONCLUSIONS

In their paper focused on the validation of HF radars, [2] raised the question of their accuracy. Such an issue is critical for appropriate uses and applications of HF radar-derived surface current measurements and has motivated numerous studies over the last two decades. In this letter, the accuracy of the coastal radar network installed in the GoN has been assessed through the comparison with Lagrangian drifters released in the basin during massive deployment experiments conducted in Summer 2012.

With the specific aim of permitting direct comparisons with available literature, the analytical approach used in the present research follows that discussed by other authors [11], [17], [38], [39]. The results of the validation indicate that both ID and AP radar current estimates are in relatively good agreement with the drifter velocities. In particular, the values for the GoN (particularly the AP ones) are comparable with the lowest records scored in previously published reports both in terms of rms and $D(t)$. Previous studies demonstrated that AP fields provide more reliable estimates of the currents than ID ones in comparative studies with Lagrangian drifters [16]–[18]. A similar conclusion was achieved also when using moored current meters, even though some sites of the same network might work better in the ID case (e.g., [5], [8], and [9]), possibly owing to imperfect calibration and/or hardware problems (as proposed by [8]). The use of pattern-corrected measurements, however, comes at the cost of a less constant spatial and temporal coverage of the basin, and for such reason, ID fields are sometimes elected as study tools (e.g., [6]). Our results confirm the superior quality of the measurements accounting for the amendment of local electromagnetic disturbance, as both rms and $D(t)$ attain lower values when pattern-corrected fields are taken into account.

An important issue to consider in the validation of HF radars is the typology of buoys used for the comparison. CODE-type drifters represent to date the best comparative platform for HF radar measurements, as both instruments measure the current field acting in the first meter of the water column. Reference [6] noticed that, using modified WOCE drifters with drogues extending between 4.5 and 10.5 m below the surface, speeds recorded by the buoys were systematically lower than the corresponding HF radar ones. Reference [12] compared different kinds of drifters (CODE-type instruments, along with Argospheres for oil spill simulations) and found that, when only surface drifters were compared to HF radar measurements, the angular difference was reduced, most likely due to the different Ekman drift experienced by surface and subsurface buoys.

The type of drifters is also a determinant in the estimation of the mean separation distances $D(t)$ between real and synthetic buoys. The high $D(t)$ values recorded by [40] may be attributed to the use of drifters with drogues positioned at $\sim$15 m depth, as well as to the resolution of the radar system employed in the study (5 km). The proper accounting of both wind stress and surface current is clear in [36], where a PTR surface drifting buoy was used to mimic an oil spill event, therefore focusing on the sea–air interface.

Another critical factor is the geometry of the network of radar sites [13], [17]. Our results indicate that, using pattern-corrected measurements, the three-site configuration installed in the GoN spatially resolves the domain efficiently, even though errors are obviously more pronounced at the external edges of the basin (where the echo might be reduced) and near the coast. This evidence makes resorting to filtering current vectors associated with high GDOP for the GoN HF radar system unnecessary, as was done by other authors (e.g., [13], [37], and [38]) to improve the spatial coverage of their current field.

The calculation of $D(t)$ has so far been used to assess the reliability of HF radar systems for search and rescue applications (e.g., [13]). In the present work, we also calculated the time spent by the real drifter in a cloud of virtual buoys creating a regular grid around the deployment position. Such an approach allows defining an operational time-evolving search area supporting rescue operations, rather than only estimating an uncertainty region. While the time fraction in the envelope quickly drops down when using ID current fields, the adoption of AP measurements returns more robust outcomes. In this latter circumstance, the modeled search area ensures high rescue success for longer times (up to 7 h). This underlines that, for operational purposes and for the management of the coastal zone, relying upon an efficient network of HF radars is fundamental, as these tools might be invaluable in raising the probability to find castaways and thus save human lives.

REFERENCES

[1] J. D. Paduan and L. Washburn, "High-frequency radar observations of ocean surface currents," *Ann Rev Mar Sci.*, vol. 5, pp. 115–136, 2013.

[2] R. D. Chapman and H. C. Graber, "Validation of HF radar measurements," *Oceanogr.*, vol. 10, no. 2, pp. 76–79, 1997.

[3] R. D. Chapman *et al.*, "On the accuracy of HF radar surface current measurements: Intercomparisons with ship-based sensors," *J. Geophys. Res.*, vol. 102, no. C8, pp. 18 737–18 748, 1997.

[4] S. Cosoli, M. Gačić, and A. Mazzoldi, "Surface current variability and wind influence in the northeastern Adriatic Sea as observed from high-frequency (HF) radar measurements," *Cont Shelf Res.*, vol. 33, pp. 1–13, 2012.

[5] S. Cosoli, A. Mazzoldi, and M. Gačić, "Validation of surface current measurements in the Northern Adriatic Sea from high-frequency radars," *J. Atmos. Oceanogr. Technol.*, vol. 27, no. 5, pp. 908–919, 2010.

[6] D. M. Kaplan, J. Largier, and L. W. Botsford, "HF radar observations of surface circulation off Bodega Bay (northern California, USA)," *J. Geophys. Res.*, vol. 110, 2005, Art. no. C10020.

[7] Y. Liu, R. H. Weisberg, and C. R. Merz, "Assessment of CODAR SeaSonde and WERA HF radars in mapping surface currents on the West Florida Shelf," *J. Atmos. Oceanogr. Technol.*, vol. 31, no. 6, pp. 1363–1382, 2014.

[8] P. Lorente, S. Piedracoba, and E. Álvarez-Fanjul, "Validation of high-frequency radar ocean surface current observations in the NW of the Iberian Peninsula," *Cont Shelf Res.*, vol. 92, pp. 1–15, 2015.

[9] P. Lorente, J. Soto-Navarro, and E. Alvarez-Fanjul, "Accuracy assessment of high frequency radar current measurements in the Strait of Gibraltar," *J. Oper. Oceanogr.*, vol. 7, no. 2, pp. 59–73, 2014.

[10] A. M. Robinson and L. R. Wyatt, "A two year comparison between HF radar and ADCP current measurements in Liverpool Bay," *J. Oper. Oceanogr.*, vol. 4, no. 1, pp. 33–45, 2011.

[11] A. Molcard *et al.*, "Comparison between VHF radar observations and data from drifter clusters in the Gulf of La Spezia (Mediterranean Sea)," *J. Mar. Syst.*, vol. 78, pp. S79–S89, 2009.

[12] J. D. Paduan and L. K. Rosenfeld, "Remotely sensed surface currents in Monterey Bay from shore-based HF radar (Coastal Ocean Dynamics Application Radar)," *J. Geophys. Res.*, vol. 101, no. C9, pp. 20 669–20 686, 1996.

[13] D. S. Ullman, J. O'Donnell, J. Kohut, T. Fake, and A. Allen, "Trajectory prediction using HF radar surface currents: Monte Carlo simulations of prediction uncertainties," *J. Geophys. Res.*, vol. 111, 2006, Art. no. C12005.

[14] K. Laws, J. D. Paduan, and J. Vesecky, "Estimation and assessment of errors related to antenna pattern distortion in CODAR SeaSonde high-frequency radar ocean current measurements," *J. Atmos. Oceanogr. Technol.*, vol. 27, no. 6, pp. 1029–1043, 2010.

[15] D. E. Barrick and B. J. Lipa, "Correcting for distorted antenna patterns in CODAR ocean surface measurements," *IEEE J Ocean Eng.*, vol. 11, no. 2, pp. 304–309, Apr. 1986.

[16] J. T. Kohut and S. M. Glenn, "Improving HF radar surface current measurements with measured antenna beam patterns," *J. Atmos. Oceanogr. Technol.*, vol. 20, no. 9, pp. 1303–1316, 2003.

[17] C. Ohlmann, P. White, L. Washburn, E. Terrill, B. Emery, and M. Otero, "Interpretation of coastal HF radar-derived surface currents with high-resolution drifter data," *J. Atmos. Oceanogr. Technol.*, vol. 24, no. 4, pp. 666–680, 2007.

[18] J. D. Paduan, K. C. Kim, M. S. Cook, and F. P. Chavez, "Calibration and validation of direction-finding high-frequency radar ocean surface current observations," *IEEE J. Oceanogr. Eng.*, vol. 31, no. 4, pp. 862–875, Oct. 2006.

[19] E. Rinaldi, B. Buongiorno Nardelli, E. Zambianchi, R. Santoleri, and P.-M. Poulain, "Lagrangian and Eulerian observations of the surface circulation in the Tyrrhenian Sea," *J. Geophys. Res.*, vol. 115, 2010, Art. no. C04024.

[20] P. Falco, M. Trani, and E. Zambianchi, "Water mass structure and deep mixing processes in the Tyrrhenian Sea: Results from the VECTOR project," *Deep Sea Res. I, Oceanogr. Res. Papers*, vol. 113, pp. 7–21, Jul. 2016.

[21] L. Bellomo *et al.*, "Toward an integrated HF radar network in the Mediterranean Sea to improve search and rescue and oil spill response: The TOSCA project experience," *J. Oper. Oceanogr.*, vol. 8, no. 2, pp. 95–107, 2015.

[22] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Trans. Antenna Propag.*, vol. 34, no. 3, pp. 276–280, Mar. 1986.

[23] B. J. Lipa and D. E. Barrick, "Least-squares methods for the extraction of surface currents from CODAR crossed-loop data: Application at ARSLOE," *IEEE J. Oceanogr. Eng.*, vol. 8, no. 4, pp. 226–253, Oct. 1983.

[24] P. Falco *et al.*, "Dynamics and sea state in the Gulf of Naples: Potential use of HF radar data in an operational oceanographic context," *J. Oper. Oceanogr.*, vol. 9. no. S1, pp. s33–s45, 2016.

[25] F. Serafino *et al.*, "REMOCEAN: A flexible X-band radar system for sea-state monitoring and surface current estimation," *IEEE Geosci. Remote Sens. Lett.*, vol. 9, no. 5, pp. 822–826, 2012.

[26] M. Uttieri *et al.*, "Multiplatform observation of the surface circulation in the Gulf of Naples (Southern Tyrrhenian Sea)," *Ocean Dyn.*, vol. 61, no. 6, pp. 779–796, 2011.

[27] D. Cianelli, M. Uttieri, B. Buonocore, P. Falco, G. Zambardino, and E. Zambianchi, "Dynamics of a very special Mediterranean coastal area: The Gulf of Naples," in *Mediterranean Ecosystems: Dynamics, Management and Conservation*, G. S. Williams, ed. New York, NY, USA: Nova Sci., 2012, pp. 129–150.

[28] D. Cianelli *et al.*, "Land-based remote sensing of coastal basins: Use of an HF radar to investigate surface dynamics and transport processes in the Gulf of Naples," in *Remote Sensing: Techniques, Applications and Technologies*, E. Alcântara, ed. New York, NY, USA: Nova Sci., 2013, pp. 1–30.

[29] M. Menna, A. Mercatini, M. Uttieri, B. Buonocore, and E. Zambianchi, "Wintertime transport processes in the Gulf of Naples investigated by HF radar measurements of surface currents," *Nuovo Cimento*, vol. 30 C, no. 6, pp. 605–622, 2007.

[30] D. Cianelli *et al.*, "Inshore/offshore water exchange in the Gulf of Naples," *J. Mar. Syst.*, vol. 145, pp. 37–52, 2015.

[31] I. Iermano, A. M. Moore, and E. Zambianchi, "Impacts of a 4-dimensional variational data assimilation in a coastal ocean model of southern Tyrrhenian Sea," *J. Mar. Syst.*, vol. 154, pp. 157–171, 2016.

[32] D. F. Carlson *et al.*, "Observed and modeled surface Lagrangian transport between coastal regions in the Adriatic Sea with implications for marine protected areas," *Cont Shelf Res.*, vol. 118, pp. 23–48, 2016.

[33] A. Pisano *et al.*,"An oceanographic survey for oil spill monitoring and model forecasting validation using remote sensing and *in situ* data in the Mediterranean Sea," *Deep Sea Res II*, doi: 10.1016/j.dsr2.2016.02.013, 2016, to be published.

[34] P.-M. Poulain, R. Gerin, E. Mauri, and R. Pennel, "Wind effects on drogued and undrogued drifters in the Eastern Mediterranean," *J. Atmos. Oceanogr. Technol.*, vol. 26, no. 6, pp. 1144–1156, 2009.

[35] L. Grieco, L.-B. Tremblay, and E. Zambianchi, "A hybrid approach to transport processes in the Gulf of Naples: An application to phytoplankton and zooplankton population dynamics," *Cont. Shelf Res.*, vol. 25, pp. 711–728. 2005.

[36] A. J. Abascal, S. Castanedo, R. Medina, I. J. Losada, and E. Alvarez-Fanjul, "Application of HF radar currents to oil spill modelling," *Marine Pollution Bull.*, vol. 58, no. 2, pp. 238–248, 2009.

[37] M. Berta *et al.*, "Estimating Lagrangian transport blending drifters with HF radar data and models: Results from the TOSCA experiment in the Ligurian Current (North Western Mediterranean Sea)," *Prog Oceanogr.*, vol. 128, pp. 15–29, 2014.

[38] Z. Kokkini, M. Potiris, A. Kalampokis, and V. Zervakis, "HF radar observations of the Dardanelles outflow current in the North Eastern Aegean using validated WERA HF radar data," *Mediterranean Marine Sci.*, vol. 15, no. 4, pp. 753–768, 2014.

[39] I. I. Rypina, A. R. Kirincich, R. Limeburner, and I. A. Udovydchenkov, "Eulerian and Lagrangian correspondence of high-frequency radar and surface drifter data: Effects of radar resolution and flow components," *J. Atmos. Ocean. Technol.*, vol. 31, no. 4, pp. 945–966, 2014.

[40] A. Rubio *et al.*, editors. "Surface circulation and Lagrangian transport in the SE Bay of Biscay from HF radar data," in *Proc. MTS/IEEE OCEANS—Bergen*, Jun. 10–14, 2013, pp. 1–7.