The ISMAR High Frequency Coastal Radar Network: monitoring surface currents for management of marine resources

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Abstract*—The Institute of Marine Sciences (ISMAR) of the National Research Council of Italy (CNR) established a High Frequency (HF) Coastal Radar Network for the measurement of the velocity of surface currents in coastal seas. The network consists of four HF radar systems located on the coast of the Gargano Promontory (Southern Adriatic, Italy). The network has been operational since May 2013 and covers an area of approximately 1700 square kilometers in the Gulf of Manfredonia. Quality Assessment (QA) procedures are applied for the systems deployment and maintenance and Quality Control (QC) procedures are performed on the data generation pipeline. The network provides hourly sea surface velocity data in real-time mode, that are published for visualization and access. In order to produce data in interoperable formats, according to the standards of Open Geospatial Consortium (OGC) for the access and delivery of geospatial data, a netCDF architecture has been defined on the basis of the Radiowave Operators Working Group (US ROWG) recommendations and compliant to the Climate and Forecast (CF) Metadata Conventions CF-1.6. The hourly netCDF files are automatically attached to a Thematic Real-time Environmental Distributed Data Services (THREDDS) catalog supporting OGC compliant distributions and protocols for data visualization, metadata interrogation and data download. HF radar data have been validated by comparison with velocities measured by drifters deployed within the radar coverage. The data produced by the ISMAR HF radar network are presently used in a number of applications, ranging from oil spill and SAR to fishery and coastal management applications.

I. INTRODUCTION

High Frequency (HF) Radar became a well established and widely used instrument for measuring surface currents and wave parameters [1], providing effective coverage of large coastal areas, where observing and modeling marine transport and dispersion processes are still difficult tasks. The comprehensive understanding of these phenomena is crucial for protecting marine biodiversity and mitigating anthropogenic hazards, especially in nearshore areas, as the coastal sea is especially sensitive in terms of ship traffic, port activity, border security and mineral exploitation.

HF radar uses ground wave propagation and the relationship between the transmitted signal (in the High Frequency range $[3 - 30]$ MHz, with corresponding wavelengths in the range $[100 - 10]$ m) and the signal backscattered by surface ocean waves with half the transmitted wavelength, referred to as Bragg scattering [2]. Through the analysis of the Bragg peaks in the backscattered signal, it is possible to obtain information on the sea water velocity [3]. These peaks are generated by the coherent summation of the signals backscattered by surface gravity waves with half wavelength of the emitted signal and moving in a radial path either away from or towards the radar. The backscattered signal is Doppler-shifted depending on the speed of the scattering surface. In the absence of ocean currents, the Doppler contribution would always arrive without shift, i.e. at a known position, in the frequency spectrum. The shift due to the phase speed of surface waves can be separated from the total frequency shift, thus the shift due to surface current components in the direction of the antenna to be isolated. From the frequency shift in the first-order backscatter, the surface current velocity is retrieved, while from both the first-order and the second-order backscatter the waves parameters are evaluated [4]. HF radars provide continuous information in terms of two-dimensional surface velocity generating maps of the velocity radial components over a range of [30-100] km from the coast, with typical spatial resolution of $[1 - 6]$ km, angular resolution of $5°$ [5] and integration time of [0.25-1] h [6]. The spatial horizontal averaging in range and azimuth depends on the radar configuration, while the vertical averaging occurs from the surface to a depth of $\frac{\lambda}{8\pi}$, where λ is the transmitted wavelength [7]. Since the Doppler shift only resolves the current components moving along radial directions (toward or away) with respect to the antenna, total surface velocity maps can be obtained by geometrically combining data from at least two radar sites, provided some geometrical constraints are satisfied. The main uncertainty source in the combination of radials into total velocities is the geometry of the radar network (i.e. reciprocal positions of the contributing sites). The geometric error is based on the incidence angles between the radial component vectors at the grid point of the total vectors map, commonly referred to as Geometric Dilution Of Precision (GDOP) [8]. The more the relative angles between radials

978-1-4799-8736-8/15/$31.00 ©2015 IEEE

moves away from orthogonality, the higher is the geometric error. Other unavoidable error sources affecting radial data, are related to electromagnetic interferences, sea clutter, and antenna pattern distortion due to environmental issues. All these factors result in a decreased signal-to-noise ratio SNR. SNR variations cause variability in time and space of the available radial data. Many interpolation techniques have been developed to overcome this problem, based on 2D variational approach [9], open-boundary modal analysis [10], normal modes [11], statistical mapping [12] and weighting based on the decorrelation scale [13].

Over the years different types of HF radars have been developed and presently two are the mostly spread instruments: the Coastal Ocean Dynamics Applications Radar (Codar SeaSonde) [3], [14] and the WEllen RAdar (WERA) [15] systems. Direction finding radars use a n-element antenna mounted in a single post for the determination of the direction of the incoming signals. Phased array radars use beamforming for the determination of the bearing angle and their receive antenna is typically composed of linear phased array whips with $\frac{\lambda}{2}$ spacing, where λ is the transmit wavelength [7]. HF radars are widely used in coastal area applications related to ocean current transport, such as monitoring and predicting the spreading of pollutants and biological quantities [16], and Search And Rescue (SAR) activities [12]. From the modeling perspective, HF radar data offer great benefits, as they cover significant portions of coastal ocean model domains and can be used for blending and assimilation [17].

Integrated HF radar observatories providing real-time information with unified Quality Assessment and Quality Control standards are operating in the United States as part of the US-IOOS17 (http://www.ioos.noaa.gov/hfradar) [1] and in Australia within the Australian Coastal Ocean Radar Network (ACORN) [18] (http://www.ees.jcu.edu.au/acorn). These networks support agencies for SAR applications and pollution mitigation [19]. The HF radar networks operating in Asia and Oceania countries were recently censused by the 1st Ocean Radar Conference for Asia (ORCA) [20]. A large number of individual HF radar systems are active in Europe, operating in a wide range of applications, such as the study of transport of passive tracers and pollutants, of water renewal mechanisms, of coastal/offshore exchanges [**?**], [21], validating ocean circulation models [22], forecast of sea-surface currents [23], data blending [24] and assimilation [25] in forecasting models. Recently some countries have started spending significant efforts toward the establishment of national HF radar networks [26], but a unified European HF coastal radar network has not been implemented yet. EuroGOOS (http://eurogoos.eu/about-eurogoos/overview) is currently addressing this issue by promoting an initiative aimed at providing an inventory of existing HF radar systems, at organizing a European coordinated HF radar group (http://eurogoos2014.hidrografico.pt/eurogoos-conference.php) and at defining homogenized standards for the development and the delivery of data and products.

In this paper the ISMAR HF radar network is presented, detailing the infrastructural core and the processing methods, reviewing recent developments in interoperability and describing innovative ongoing applications. The network is part of the Italian coastal radar network established within the flagship project RITMARE (www.ritmare.it) and the ISMAR radar group is part of the EuroGOOS HF radar Task Team in charge for setting up the foundation of the European network.

In the following, Section II describes the ISMAR HF Radar network and the interoperability framework of data production, Section III presents the results of the validation procedures carried on to assess the network operational regime and Section IV illustrates the applications of HF radar data. Finally, in Section V conclusions are given and future developments of the network are discussed.

II. THE HF RADAR NETWORK

The Institute of Marine Sciences (ISMAR) HF Radar Network is composed of four HF radar systems located on the coast of Gargano (Puglia, Italy) and covering the Gulf of Manfredonia (Southern Adriatic Sea), as shown in Figure 1. The network has been designed and developed within Co.Co.Net (www.coconet-fp7.eu), SSD-Pesca and RITMARE (www.ritmare.it) projects, with the aim of studying connectivity between Marine Protected Areas in the Southern Adriatic and monitoring fish larvae spawning dynamics in the Gulf of Manfredonia, with particular focus on anchovies and sardines. The network has been established and is operated through the joint efforts of the two ISMAR detached institutes of La Spezia and Lesina. The four sites are located along the Gargano coast and they have been selected, given some constraints by the shape of the coastline, with the best available spacing, in order to optimize the coverage on the interest area, that is the Gulf of Manfredonia and the western coast of Gargano. The HF radar system covers an area of approximately 1700 square kilometers. The four nodes of the network are situated in Vieste (site code VIES) at the lighthouse on the S. Eufemia island, at the lighthouse Torre Preposti in Pugnochiuso (site code PUGN), on the coast of Mattinatella (site code MATT) and at the entrance lighthouse of the port of Manfredonia (site code MANF). Table I lists the geographic coordinates of the four installations.

TABLE I
GEOGRAPHIC COORDINATES OF THE ISMAR HF RADAR NETWORK NODES.

Site code	**Site location**	**Latitude**	**Longitude**
VIES	Vieste	$41°53'19.87"N$	$16°11'5.49"E$
PUGN	Pugnochiuso	$41°46'57.24"N$	$16°11'31.86"E$
MATT	Mattinatella	$41°43'51.96"N$	$16°6'58.32"E$
MANF	Manfredonia	$41°37'14.41"N$	$15°55'30.95"E$

The HF Radar ISMAR network architecture consists of three operational layers, as shown in Figure 2. The Ground Layer consists of the infrastructural components, the acquisition instruments and the data management and storage modules. The Processing Layer is responsible for the data processing, in

Fig. 1. Map of the ISMAR HF radar network node locations. The highlighted area indicates the coverage of the radar network.

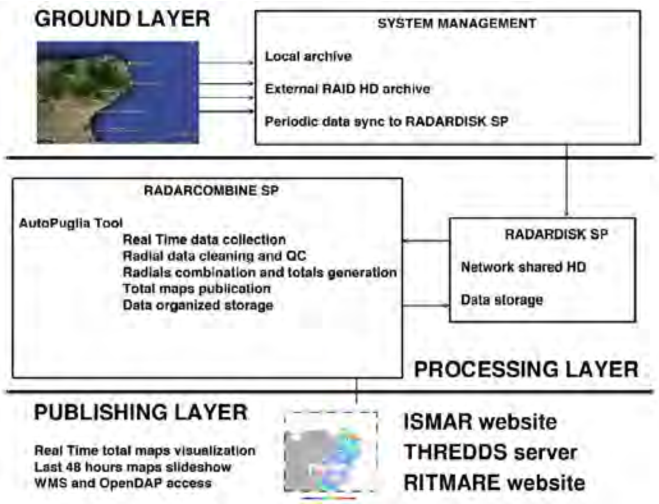

Fig. 2. Architectural scheme of the ISMAR HF radar network.

particular radial data combination into total vectors, data storage and data dissemination. The Publishing Layer visualizes the total velocities maps and distributes the data in different interoperable formats.

A. The Ground Layer

The HF radar sites of the ISMAR network are all SeaSonde direction finding systems manufactured by Codar Ocean Sensors [14]. All the devices operate in the high resolution frequency band of 25 MHz. Each SeaSonde HF radar station is equipped with co-located receiving and trasmitting antennas. The antennas are connected to the radar transmit device and receive device, which are controlled by a desktop computer. The transmitting antenna is omni-directional and the receiving antenna consists of three colocated antenna elements, oriented with respect to each other on the x, y, and z-axes. The system is thus able to receive and separate returning signals in all 360 degrees.

The radars process time series of the received sea echoes to determine bearing, range and speed of the scattering source, in order to retrieve the current data. The received backscatter time delay is converted to a frequency shift in the echo signal through a modulation/demodulation pipeline. The first digital spectral analysis of the signal extracts the distance of the sea-surface scatterers, and sorts it into range bins, typically set between 1 and 12 km in width. A second spectral processing of the signals from each range bin retrieves the Doppler-frequency shifts due to the motion of the scattering ocean waves, thus obtaining their velocity. The length of the time series used for this processing determines the velocity resolution: at 25 MHz for a 256-second time-series sample, this corresponds to a velocity resolution of ~ 2 cm/s. By analyzing and comparing data collected from the co-located directional elements in the receiving antenna at each spectral point (i.e. range and speed), the bearing angle of the scatterers is finally determined. This process is operated by the patented direction finding algorithm MUSIC [27], which has been optimized for SeaSonde instruments. At the end of the signal-processing steps, maps of surface current radial velocity are available in polar coordinates. These radial data are outputted every 10 minutes (short term radials) and are then averaged over a time period of one hour to create the radial vectors maps. Radar antenna patterns [28] have been measured for each system (antenna calibration procedure), so that the processing pipeline takes into account possible pattern distortions due to the antenna surroundings and therefore radial data can be considered more reliable.

For a given transmitting power, the central emitted frequency determines the coverage range, which is typically between 35 and 50 Km in the 25 MHz frequency band. The signal bandwidth dictates the spatial resolution: it is set in all the stations at 150 kHz, thus yielding a spatial resolution of 1 km. Within the radar duty cycle, the time interval in which the antenna does not transmit and listens to backscatter echoes is defined as blanking period and determines the range cut-off. In the ISMAR network installation the blanking period is set at 486 μs, i.e. a range cut-off at approximately 44 km. The antennas sweep rates dictates the Spectral Doppler Range and then the Doppler resolution. The four systems work with a sweep rate of 2 Hz, which means a Doppler resolution of 0.5 Hz. The transmitted power of the four systems ranges in the interval $[36 - 42]$ W. Table II summarizes the configuration parameters of the four network nodes.

At each installation, all produced data (diagnostics, log, configurations, spectra, radial velocities) are automatically recorded in the internal hard drive of the controlling desktop computer and in an external RAID hard drive for the local redundant storage. The local computer also runs scripts for the automatic syncing of data to the central Network Attached Storage (NAS), referred to as RadarDisk and located in the

TABLE II
OPERATIONAL SETTINGS OF THE ISMAR HF RADAR NETWORK.

	VIES	PUGN	MATT	MANF
Transmit Frequency [MHz]	25	25	25	25
Bandwidth [kHz]	150	150	150	150
Spatial Resolution [km]	1	1	1	1
Angular Resolution [deg]	5	5	5	5
Blanking Period [μs]	486	486	486	486
Range Cut-off [km]	44	44	44	44
Sweep Rate [Hz]	2	2	2	2
Doppler Resolution [Hz]	0.5	0.5	0.5	0.5
Transmit Power [W]	33	38	44	35

ISMAR institute in La Spezia. Each site is equipped with a communication module based on a GPRS/UMTS modem with high gain omni-directional external antenna, capable to provide enough bandwidth to perform main data backup to the RadarDisk and remote management (diagnostic checks and re-programming tasks).

The installations are organized with the outdoor antenna post and the indoor control room, where all the measuring and controlling devices are hosted in a rack cabinet. The temperature and humidity conditions of control rooms in the most critical sites are kept in adequate status by an air-conditioning system. Electrical safety of all the instrumentation is guaranteed by an Uninterruptible Power Supply (UPS), which provides voltage stability and a short emergency power to all the loads when the main power fails. The emergency power is provided with a scheduled timing scheme in order to comply with the timing needs of the transmit and the receive devices shut-down.

B. The Processing Layer

The core of the Processing Layer are the central calculation server RadarCombine and the RadarDisk NAS, both located in the ISMAR institute in La Spezia. The RadarCombine server runs the AutoPuglia software tool responsible for the automatic real-time data processing, storage and dissemination. All the data processing and data management modules have been developed by the radar research group of the ISMAR institute in La Spezia.

AutoPuglia operates the real-time collection of the hourly radial data, the organization in working data structures, the cleaning and QC processing, the radial combination in total vectors, the data distribution, and the organized data storage. The tool has been developed in the Matlab language, as it is based on the open source libraries HFR_Progs 2.1 (cencalarchive.org/~cocmpmb/COCMP-wiki/index.php/MainPage) [29] and M_Map (www2.ocgy.ubc.ca/~rich/map.html) [30], which are suited for Matlab environment. AutoPuglia automatically accesses the folder on RadarDisk where radial data are synced from all the network nodes, and organizes them into a proper data structure. Each element of the structure gathers the file names of the radial data of the same timestamp and has fields containing the related timestamps and flags indicating whether some of the expected file is missing or if the processing of the data is complete or corrupted. Due to eventual limitations on the communication systems at the radar sites, it can happen that not all the radial data from the four sites were synced at the time of the query made by AutoPuglia. The *Missing_File* flag tells the system not to stop processing data related to that timestamp and to attempt processing during the next queries, in case the late radial file was synced at that time. The *Corrupted_Process* flag allows the system to avoid closing the data processing of that timestamp if some task went wrong, e.g. the saving of the total file on the remote distribution centers or the loading of some of the radial files. If both the *Corrupted_Process* and the *Missing_File* are disabled, the *Process_Complete* flag is enabled and the radial data of the specific time stamp is not reprocessed during later queries. Once the data structure is built, AutoPuglia proceeds in loading the radial data (referred to the file names in the structure), cleans them and combines them into total vectors. The combination process is performed on a geographic grid with a spatial resolution 1.5 km and a Transverse Mercator projection. The grid has 61 cells in longitude, in the range $[15.6° - 16.7°]E$ and 52 points in latitude, in the range $[41.4° - 42.1°]N$. Radial velocities are cleaned by eliminating vectors with amplitude bigger than 120 cm/s, according to the expected sea state statistics in the area. For each grid cell, a total vector is generated if at least 3 radial vectors are found within a search radius of 3 km and they comply with the set GDOP limitation. A GDOP threshold equal to 2 is set for the radial combination. As GDOP is the square root of the trace of the covariance matrix of incidence angles between radial vectors [8], introducing GDOP cut-offs imply combining radial vectors only if their incidence angles lie in a specific range. Setting GDOP ≤ 2 means that the incidence angles between radial vectors lie in the range $[45° - 135°]$.

A first QC for total velocities is active and is based on GDOP thresholding and linear interpolation in space. As part of the activities of the RITMARE project, more sophisticated QC procedures for radial velocities are now in the process of being defined and proposed as a national standard. The new QC techniques will implement further enhancements in the standard SNR filtering on spectra, in the data cleaning and in the interpolation methods.

AutoPuglia creates total vectors in the *.tuv* Codar format, in netCDF format and, as maps, in image format. Figure 3 shows an example of total velocity map.

The generated total velocity files are then automatically disseminated and stored. AutoPuglia records all the created output on the RadarDisk, according to a file system structure adherent to Codar's. Furthermore, AutoPuglia saves the hourly total velocity maps on the ISMAR website server and the netCDF files on the Thematic Real-time Environmental Distributed Data Services (THREDDS) server responsible for data distribution. AutoPuglia is continuously running and provides a permanent service in visualizing and distributing data. The reliability of the service is guaranteed by the redundant architecture of the RadarCombine server and by an UPS avoiding power failures

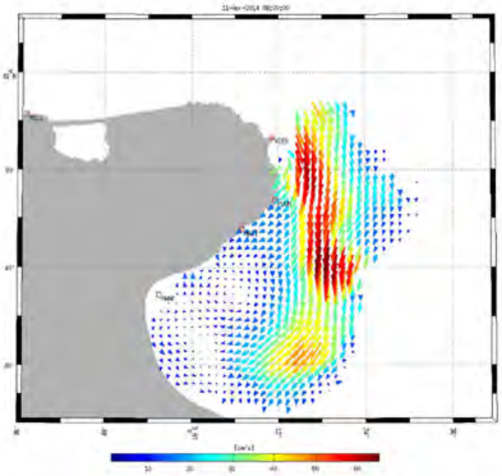

Fig. 3. Surface water currents around Gargano area as measured by the ISMAR HF radar network. A boundary current flowing south along the Italian coast and detaching from the Gargano Cape, and an anticyclonic recirculation in the interior of the Gulf are visible.

and operations interruptions.

C. The data interoperability framework

In order to produce data in interoperable formats, according to the standards of Open Geospatial Consortium (OGC) [31] for the access and delivery of geospatial data, a netCDF file structure has been built according to the Radiowave Operators Working Group (US ROWG) standard [1], [32] and compliant to the Climate and Forecast (CF) Metadata Conventions CF-1.6 [33]. The netCDF format contains the following information: the current variable fields (Eastward and Northward Sea Water Velocity, Surface Sea Water Velocity), the error fields (Surface Eastward and Northward Sea Water Velocity Standard Deviation, Surface Sea Water Velocity Standard Deviation, Covariance of Surface Sea Water Velocity and Geometrical Dilution of Precision) and all metadata related to site installations, sensors specifications, operational settings, geospatial information and dissemination policy.

D. The Publishing Layer

The Publishing Layer of the network relies on (a) the ISMAR HF Radar network website, (b) the THREDDS server and (c) the RITMARE project website. As it is automatically fed by the Processing Layer, the ISMAR HF Radar website (a) (radarhf.ismar.cnr.it) presents on its home page the real-time visualization of the total velocities maps of the last 48 hours. Through a search pane, it is possible to navigate within the maps and to create animations of the selected period. The other sections of the website describe the nodes installations and the network architecture and present an overview of the principles of HF radar technology.

The produced surface water current data in netCDF format are automatically attached in real-time mode to a THREDDS catalog (b) which provides metadata and data access. The catalog offers different remote-data-access protocols such as Open-source Project for a Network Data Access Protocol (OpenDaP), Web Coverage Service (WCS), Web Map Service (WMS) (OGS standards), as well as pure HTTP or NetCDF-Subsetter. They allow for metadata interrogation and data download (even sub-setting the dataset in terms of time and space) while embedded clients, such as GODIVA2, NetCDF-JavaToolsUI and Integrated Data Viewer, grant real-time data visualization directly via browser and allow for navigating within the plotted maps, saving images, exporting-importing on Google Earth, generating animations in selected time intervals. The data on the THREDDS catalog are organized in two folders, collecting the hourly current files of the last five days and grouping all the historical data. The two folders are accessible both in aggregated and in non-aggregated configuration. The ISMAR HF Radar network catalog is managed by the Institute of Atmospheric Sciences and Climate of the National Research Council of Italy (CNR-ISAC) and is available at http://ritmare.artov.isac.cnr.it/thredds/ritmare/CoastalRadarOS/RADAR_HF/Gulf_of_Manfredonia/catalog.html.

The RITMARE website (c) (http://www.ritmare.it/articolazione/sottoprogetto-5/sp5-wp2/sp5-wp2-azione3) presents the ISMAR HF radar network in the section related to the coastal radar applications and gives access to the surface water current maps and data files through a link to the ISMAR website and to the THREDDS catalog.

III. VALIDATION

The HF radar data produced by the network have been validated by comparing the surface velocities measured by the radar nodes with the velocities measured by drifters deployed within the radar coverage. Drifters [34] are Lagrangian instruments following the surface current with good approximation, providing direct information on horizontal transport with small errors, typically within 1-3 cm/s for current velocity [35]. The CODE drifters [34] have been chosen for the validation experiments, as they are the most suitable for comparison with radar data. In fact they are designed to follow currents from surface to 1m-depth and are drogued in the first meter below the surface in order to minimize slippage due to the direct action of wind and waves [35].

Six CODE-based drifters were launched within the radar coverage region in November 2013. All the drifters were equipped with Global Positioning System (GPS) receivers with an accuracy of approximately 5-10 m. Drifter positions were processed to remove outliers and spikes [36] and interpolated at uniform 1 h intervals [37]. Their velocities along trajectories were computed from the positions by central finite differences. In order to validate HF radar data, the surface radial velocities measured by the radars, i.e. the projection of current velocities along the line-of-sight of each radar station, are compared with the velocities measured by drifters projected along the same direction. This approach guarantees a direct validation of HF radar measurements, as radial velocities are actually sensed by HF radars. It should be noted that radar and drifters sample velocity at different scales, so that some caution must be used when interpreting comparison results. CODE drifters feel the current velocity at a scale corresponding to their physical horizontal and vertical size, that is of the order of 1 m. As for HF radar, velocity information are integrated over different vertical and horizontal scales. In the vertical, the velocity is an exponentially-weighted average that depends on the vertical shear of the horizontal current and on the HF radar frequency [7]. For HF radars operating in the 25 MHz frequency band and in the case of a linear shear, the measurement corresponds to an effective depth of the order of 50 cm. As CODE drifters provide the vertical average of the velocity in the upper 1 m, the comparison of the two velocities can be considered appropriate, unless very strong shear is present in the upper layers. In the horizontal direction, on the other hand, a clear mismatch of scales is expected, since HF radar based velocity is averaged over the two-dimensional grid cell with a size of 1 km, while drifter velocity is averaged over 1 m scales. As a consequence, the comparison between HF radar and drifters can be considered satisfactory when it falls in the range of expected variability within the horizontal grid [38]. Results from the literature suggest that differences of the order of [5-15] cm/s can be considered acceptable and within the expected variability at the HF radar sub-grid-scale [39], [40].

For the validation experiments, HF radar-based radial velocities from HF radars (u_r^R) and radial velocities from drifter data (u_d^R) are compared at the same time and locations. Drifter data are resampled on the uniform radar time grid, and the radar velocity is estimated through bilinear interpolation of the radar velocities corresponding to the cells closest to each drifter position. The difference between the two estimated radial velocities is then calculated as $\Delta u^R = u_r^R - u_d^R$. The statistics of the comparison are evaluated by averaging over all drifter positions and times (the overbars stand for the average) in terms of bias $\mu = \overline{\Delta u^R}$, root mean square (RMS) $rms_R^2 = \overline{(\Delta u^R)^2}$ and correlation coefficients ρ^2 [41]. In order to validate the effectiveness of antenna calibrations, the same statistics have been evaluated for radar radial uncalibrated velocities, i.e. surface sea water radial velocities measured without applying the measured antenna patterns. These quantities have been compared to the ones computed for the radial velocities sensed with applying the measured antenna patterns (calibrated).

The validation results are summarized in Table III, where rms_R^2, μ and ρ^2 averaged among all drifters and all times are presented for each radar station. For each value, the corresponding value evaluated without applying the measured antenna pattern is reported. Figures 4 to 7 shows the regressions between drifter velocities and radar velocities sensed with and without applying the measured antenna patterns at each site.

TABLE III

RESULTS OF THE COMPARISONS BETWEEN RADIAL VELOCITIES. rms_R^2, μ AND ρ^2 ARE COMPUTED FROM DIFFERENCES BETWEEN HF RADAR AND DRIFTER VELOCITIES. FOR EACH VALUE, THE CORRESPONDING VALUE EVALUATED WITHOUT APPLYING THE MEASURED ANTENNA PATTERN IS REPORTED IN PARENTHESIS.

Site code	rms_R^2 [cm/s]	μ [cm/s]	ρ^2
VIES	4 (17)	0 (1)	0.93 (-0.13)
PUGN	7 (9)	2 (3)	0.90 (0.86)
MATT	3 (4)	0 (1)	0.97 (0.95)
MANF	6 (5)	0 (2)	0.86 (0.93)

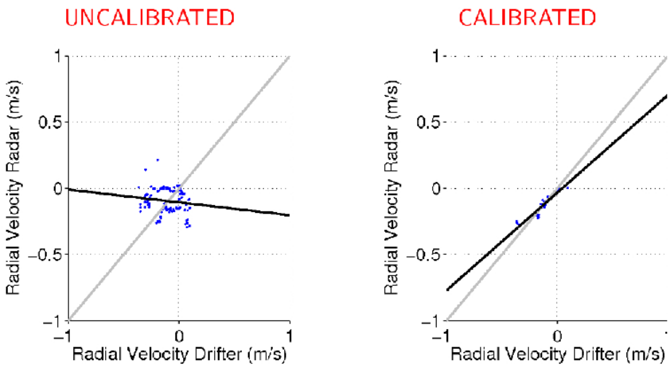

Fig. 4. Regressions between radar velocities sensed without (uncalibrated) and with (calibrated) applying the measured antenna patterns and drifter velocities at VIES site.

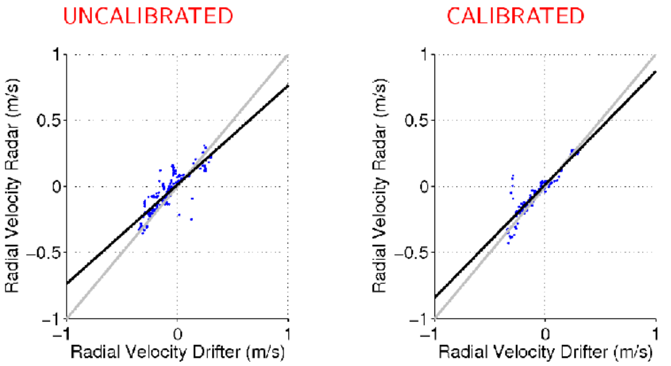

Fig. 5. Regressions between radar velocities sensed without (uncalibrated) and with (calibrated) applying the measured antenna patterns and drifter velocities at PUGN site.

For all sites the RMS of the differences between the radial velocities estimated from radars and drifters lie in the range [3-7] cm/s, well within what is considered acceptable in literature, given the expected variability at the HF radar sub-grid-scale. Biases are 0 cm/s for three out of four sites, namely VIES, MATT and MANF. For the PUGN site it is slightly higher (2 cm/s), but anyway reasonably small. The correlation coefficients show an excellent agreement in all sites between the velocities from radar and drifters and, together with the other comparison indicators, highlight the very satisfactory level of accuracy of the surface currents measured by the HF radar network.

The evaluation of the effects of the antenna calibration confirms the expected improvement of the measuring reliability of the radar devices in three out of four sites, namely VIES, PUGN and MATT. For the MANF site a light worsening has been recorded when applying the measured antenna pattern,

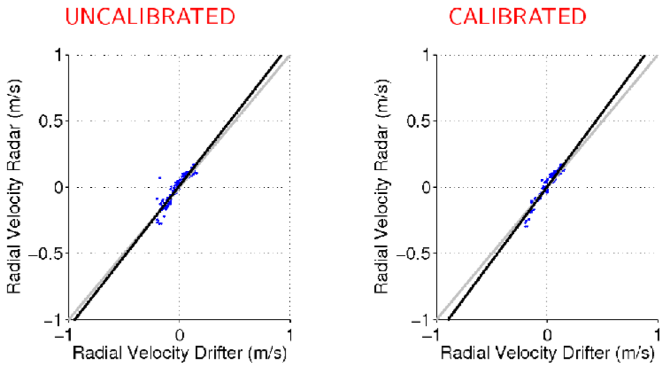

Fig. 6. Regressions between radar velocities sensed without (uncalibrated) and with (calibrated) applying the measured antenna patterns and drifter velocities at MATT site.

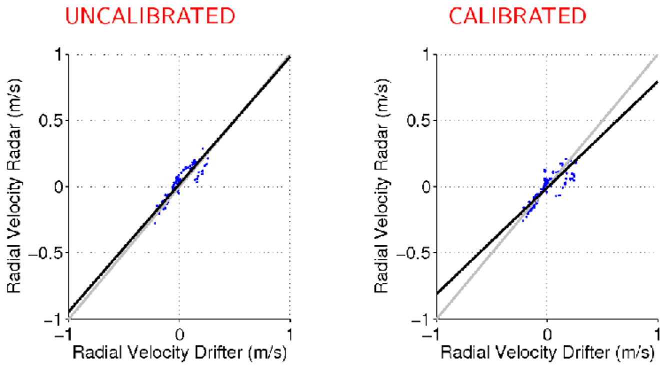

Fig. 7. Regressions between radar velocities sensed without (uncalibrated) and with (calibrated) applying the measured antenna patterns and drifter velocities at MANF site.

while the bias is consistently reduced.

IV. APPLICATIONS

HF radar based surface current velocities proved to be a fundamental instrument for performing the hindcast of oceanic transport and are thus successfully applied in the analysis and the forecasting of particle trajectories. In particular, they are widely employed in the fields of oil spill management, SAR, biological quantities and sediment transport. The data produced by the ISMAR HF radar network are presently used in a number of applications, ranging from oil spill and SAR to fishery and coastal management applications. Specifically, the Manfredonia Gulf is a known nursery area for small pelagic species (anchovies and sardines) and HF radar and drifter data are utilized for understanding the origins of larvae [42]. Data are also used to provide information on biological connectivity between Marine Protected Areas and other relevant ecological regions in the Adriatic Sea [42]. Furthermore, HF radar velocity fields are employed in validating ocean circulation models for the optimization of the forecast of the trajectories of oil spills [24], [42]. HF radar measurements, together with satellite ocean colour data, are also used to understand sediment transport and impact of flood events in the Gargano area.

V. CONCLUSION

The ISMAR HF radar network for the measurement of the velocity of surface currents in coastal seas is presented. It was established on the coast of Gargano (Puglia, Italy). It has been operational since May 2013 and covers an area of approximately 1700 square kilometers in the Gulf of Manfredonia, in the Italian Southern Adriatic Sea. The measurement and data production pipelines operate under QA/QC procedures. The network provides hourly surface velocity fields in real-time mode and data are produced in interoperable formats, according to the standards of OGC for the access and delivery of geospatial data, adherent to the US ROWG recommendations and compliant to the Climate and Forecast (CF) Metadata Conventions CF-1.6. Data are distributed via a THREDDS catalog supporting OGC compliant distributions and protocols for data visualization, metadata interrogation and data download. When validated through the comparison with velocities measured by drifters deployed within the radar coverage, the data produced by the network proved to have very satisfactory level of accuracy, with errors lying within the range considered acceptable in literature, given the expected variability at the HF radar sub-grid-scale. The data produced by the ISMAR HF radar network are presently used in a number of applications, ranging from oil spill and SAR to fishery and coastal management applications.

The ISMAR network is part of the RITMARE Italian Coastal Radar Network and CNR-ISMAR represents the Italian partners as a member of the EuroGOOS HFR Task Team, responsible to set the foundation of the European network. Within these two frameworks, more sophisticated QC procedures for radial velocities are now being defined as national and European standards. The new QC techniques will implement further enhancements in the standard signal-to-noise filtering on spectra, in the data cleaning and in the interpolation methods.

In order to enrich the surface current products and to implement a tool for data analysis, an Interactive Virtual Particle Tracking system is now under development. The goal is to develop a real-time interactive module for online virtual particle tracking, in order to address support applications for safe navigation in densely operated areas, sea accident fast response, oil spill monitoring, Search and Rescue.

ACKNOWLEDGMENT

The authors would like to thank the RITMARE, Co.Co.Net and SSD Pesca projects, the Institute of Atmospheric Sciences and Climate of the National Research Council of Italy (CNR-ISAC) and the Physical and Chemical Oceanography Group of Department of Marine Sciences at University of the Aegean, Mytilini for the support to the research.

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