Toward an integrated HF radar network in the Mediterranean Sea to improve search and rescue and oil spill response: the TOSCA project experience

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ABSTRACT

High Frequency (HF) coastal radars measure current velocity at the ocean surface with 30-100km range and 1-3km resolution, every 0.25-1h. HF radars are well suited for many applications: search and rescue (SaR), oil spill mitigation and ecosystem management. Here we present a first organized core of 12 HF radars installed in five sites in four countries (Greece, Italy, France and Spain) within the European Med project TOSCA. Dedicated experiments tested radar capabilities to estimate transport driven by currents, which is the key feature for all the above applications. Experiments involved the deployment of drifters, ie floating buoys, acting as proxies for substances passively advected by currents. Using HF radars the search range is reduced by a factor 1.6 to 5.3 after 24h. The paper also underlines the importance of sharing common tools for HF radar data processing and the need to mitigate radio frequency interference. The effort can be regarded as an initial step toward the creation of a Mediterranean or European HF radar network, crucial for any European Integrated Ocean Observing System (IOOS).

INTRODUCTION

In the last two decades, the importance of Integrated Ocean Observing Systems (IOOSs) has been widely recognized, not only for scientific purposes but also in order to support societal needs such as management of coastal and marine environments, mitigation of accidents at sea, and planning for climate changes.[1-4] IOOSs are typically composed of monitoring instruments providing observations, numerical models assimilating data, and software infrastructures that guarantee real-time access to the products. Various types of monitoring instruments are used, with different sensors and platforms, ranging from remote satellites to *in-situ* instruments on fixed or moving locations.[5-7]

In particular, High-Frequency (HF) radars[8,9] are crucial in coastal areas for those applications related to transport by ocean currents, such as monitoring and predicting the spreading of pollutants and biological quantities[10] and Search and Rescue (SaR) operations.[11,12] Lagrangian instruments and HF radars are in many aspects complementary. Among the former, drifters[13] follow the current with good approximation, providing direct information on horizontal transport with small errors, typically within 1-3cm/s for current velocity.[14] Their drawback is that their coverage in a given region is often limited and dependent on dedicated releases. HF radars, on the other hand, provide autonomously continuous information in terms of two-dimensional surface velocity maps with typical range of 30-100km from the coast, spatial resolution of 1-3km, and integration time of 0.25-1h.[15] Although the combination of these values is unique among oceanographic instruments and is well suited for the aforementioned

applications, the unresolved spatial variability of velocity fields at subgrid scales may still be significant, so that the joint use of drifters and HF radars appears promising and advantageous.[16]

Integrated HF radar observatories providing real-time information with unified quality control have been operating in the United States as part of the US-IOOS[17] (http://www.ioos.noaa.gov/hfradar/) and in Australia through the dedicated Australian Coastal Ocean Radar Network (ACORN)[18] (http://www.ees.jcu.edu.au/acorn/), and they provide an important support for agencies in charge of SaR and pollution mitigation.[19] Following the same approach, the 1st Ocean Radar Conference for Asia (ORCA) has recently censused all the Asian HF radar installations.[20]

In Europe, a large number of individual HF radars is present, providing relevant scientific and technological advancements as well as practical applications.[16,21-27] Nevertheless, although some countries have started to devote a significant effort toward the implementation of national HF radar networks,[28,29] a unified HF coastal radar network has not been implemented yet, nor the parameters observed and derived from HF radars have been part of the main European IOOS projects such as Copernicus and MyOcean 2.[30] This issue has been recently addressed in the framework of EuroGOOS (http://eurogoos.eu/about-eurogoos/overview/) through an on-going initiative aimed at providing an inventory of existing HF radar systems and starting to organize a European coordinated HF radar group (http://eurogoos2014.hidrografico.pt/eurogoos-conference.php). The coordination will be most likely organized in terms of a distributed system built on EuroGOOS Regional alliances (ROOSes), providing a research and operational framework to develop and deliver observations and products, similarly to what has already been done for satellite and *in-situ* data.

In this paper, we present a first organized core of HF radar network in the Mediterranean Sea set up in frame of the European MED project TOSCA (Tracking Oil Spill and Coastal Awareness network, 2010-2013, http://www.tosca-med.eu/). TOSCA has focused on the identification of good practices based on science knowledge for the mitigation of accidents at sea, such as oil spills or SaR incidents, and one of its main achievements has been to experimentally test observational systems based on coastal HF radars and drifters, coupled also with numerical models.

The HF radar network consists of five installation sites with coverage within the main Mediterranean sub-basins, ie the Aegean, Adriatic, Tyrrhenian, Ligurian, and Balearic Seas (Fig 1). Although each site was operated independently from the others during TOSCA, common practices have been established and dedicated experiments have been carried out in the five locations using a similar methodology, involving the combined use of HF radar and drifters. The experiments had a number of goals, including *(i)* the validation and comparison of drifter and HF radar measurements, *(ii)* the investigation of optimal blending techniques of the two datasets[16], *(iii)* the validation of numerical circulation models,[31] *(iv)* the estimation of statistical

dispersion[16] and flow properties,[32] and *(v)* the assessment of the water/oil following capabilities of different types of surface drifters.

Here, we present the results of the TOSCA HF radar network and focus on the first objective. Comparisons are performed in two distinct ways. First, the HF radar so-called *radial* velocities, that is, 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. As radial velocities are the ones actually sensed by HF radars, this can be regarded as the rawest possible comparison, so that its interest lies in the direct validation of HF radar measurements and in the evaluation of their precision at distinct locations and/or dates. Then, drifter trajectories are compared with the synthetic ones obtained by numerically advecting point-like particles within the HF radar *vectorial* current field, built in turn by aggregating two or more overlapping radial velocity fields. This approach is well suited for practical applications such as oil spill monitoring, SaR, and connectivity, where trajectories are needed to estimate transport by surface currents. Therefore, since drifters can be considered as proxies for passive particles advected by currents, the comparison of trajectories provides a straightforward measure of the benefits that HF radars would offer in the aforementioned applications.

Because the five sites are very different from the geographical and dynamical point of view, as well as for the HF radar technology and signal processing techniques that have been used, we do not expect the results to be necessarily similar. Rather, the purpose of the comparison is to investigate on variability, practices, and possible existing problems and solutions. In this light, the results should provide an important scientific basis for the ongoing building process of an integrated HF radar system in the Mediterranean Regional alliance.

The TOSCA sites, experimental set-ups and methods are introduced, followed by the results. Finally a brief discussion is presented.

DATA AND METHODS

The TOSCA HF radar sites

HF radar systems transmit signals typically in the range 3-42MHz and rely on the backscattering of electromagnetic waves from resonant sea surface waves. Radial current velocities are retrieved over a distance/azimuth grid from the analysis of the Bragg peaks in the Doppler spectrum of the back-scattered signal.[8,33,34] Radial velocities are combined geometrically from at least two HF radar stations to produce vectorial maps of surface current.[35,36] Such recombination comes with geometric errors, indicated as Geometric Dilution of Precision (GDOP), that arise from deviations from the perpendicular of the relative angles between radial components.[37]

The locations of the TOSCA HF radar sites are shown in Fig 1, together with examples of instantaneous vector velocity fields from the HF radars during the TOSCA experiments. These fields are unaveraged snapshots chosen for their representativeness of coverage and local circulation during the experiments. All the sites are environmentally relevant and located in sensitive areas affected by intense ship traffic and/or presence of oil pipelines. Their oceanographic characteristics, though, are very different. Two of them are situated in gulfs, Trieste and Naples, located in the Adriatic and Tyrrhenian Sea, respectively. They are characterized by an average cyclonic circulation and by a very high variability in time and space induced by wind forcing and submesoscale dynamics.[22,31,38] The Ligurian Sea site is located in Toulon and covers the Northern Current[39] that flows cyclonically along the coast with significant mesoscale variability.[25,32] The Aegean site, situated on the East coast of the Lemnos Island, is characterized by a prominent westward surface flow from the Dardanelles modulated by a seasonal cycle.[40] In both Ligurian and Aegean sites, the patterns observed during the experiment are indeed well representative of the climatological flow (Fig 1). Finally, the Balearic site covers the Ibiza Channel, which is a critical point for the exchange of 'old' Mediterranean and 'new' Atlantic waters and is marked by a high mesoscale variability impacted by atmospheric forcing. [41,42]

The characteristics of the HF radar installations are summarized in Table 1. Three of them - Trieste, Naples and Balearic - use CODAR SeaSonde systems,[43] whereas for the Toulon and Lemnos sites the WERA technology[44] is employed. While the SeaSonde systems all consist of one emitting and three receiving, all co-localized antennas (Fig 2(a)), WERA is based on antenna arrays. Namely, in Lemnos the radar stations comprise one transmitting and one receiving square arrays with four antennas each as shown in Fig 2(b), whereas in Toulon either one or two transmitting and eight receiving antennas are used. The minimum separation distance between transmitting and receiving arrays is set to 300m. The radar operating frequency and bandwidth are chosen so as to obtain higher spatial resolution with reduced coverage in the Gulfs of Naples and Trieste, which are dominated by small-scale dynamics and have dimensions of ~30km, and less resolved but wider fields in the other sites. Current velocity maps are produced every 20-60min after averaging signals over a similar duration.

The measured antenna pattern[45] is used to compute radial velocities for all the sites except for Lemnos and Trieste, where the measurements have not been performed yet. Therefore, an additional error source has to be accounted for in these cases. Nonetheless, in Lemnos the ideal patterns are not expected to be sensibly different from the actual ones since both radars occupy empty areas without urbanization and metallic environments.

In all sites, direction finding algorithms are used for the azimuthal analysis. An adapted version of the MUSIC algorithm[46-48] is employed in all the SeaSonde systems as well as in the WERA system in Toulon, whereas the Least Squares single-source method[35] is used in the Lemnos WERA system. Vectorial velocity computations from radials are

all performed over a regular grid using local interpolation schemes based on Least Squares Minimization.[35] Although the grid step size should scale with the radar range resolution, its value is rather arbitrary due to the coarser resolution of the radial grids as the distance from the radar increases. Values ranging from 1 to 3km are commonly accepted in the HF radar community[15] and have been retained in the TOSCA sites. Finally, the GDOP is accounted for by discarding grid points with values larger than 2.5.

Radial and vectorial velocities are Quality-Controlled (QC) using thresholding methods based on first- and second-order finite differences in time and space.[49] Besides, the Signal-to-Noise Ratio (SNR) of individual Doppler lines and the energy of the MUSIC algorithm sources are also taken into account in Trieste and Toulon, respectively.

Finally, data gaps are partially filled through linear interpolation in space and time. However, for the Lemnos and Balearic sites the vectorial current fields are interpolated through the DINEOF method[50] that produces a uniform and constant coverage area based on an EOF analysis of the gappy field. This will be discussed further in the next sections.

Drifters deployments

In the framework of TOSCA, a set of experiments with similar methodology have been performed within the HF radar observation areas from winter 2011 to fall 2012 (Fig 3). Although two experiment each were conducted in Toulon, Lemnos and Trieste, given the qualitatively similar results only one has been selected for this work (Table 1).

Various types of drifters have been launched during the experiments, to investigate surface currents and wind effects. They include CODE-type drifters,[13,51] designed to follow currents from surface to 1m-depth, and 'oil spill' drifters[52] conceived to follow pollutants at the sea surface. Here we mostly concentrate on CODE drifters, since they are more suitable for HF radar comparison as discussed in the following section. They are drogued in the first meter below the surface and are designed to minimize slippage due to the direct action of wind and waves, whose impact has been quantified to 1-3cm/s.[14]

CODE drifters have been launched and used in all the sites, except for the Balearic one. There, only oil spill drifters were available, but some of them have been ballasted with an additional 2kg weight in order to reduce windage. Since only the latter have been retained in this study and since they had a low residence time within the radar coverage area (Table 1), the number of drifter points used for comparison is very limited. Therefore, any statistical inference presented in the results has to be considered with care for this site.

In some cases drifters were caught and re-launched during the experiments in order to

maintain coverage of the HF radar area. All drifters were equipped with Global Positioning System (GPS) receivers with an accuracy of approximately 5-10m. Drifter positions were edited to remove outliers and spikes[53,54] and interpolated at uniform 1h intervals,[55] and velocities along trajectories were computed from the positions by central finite differences. Considering the aforementioned GPS accuracy and for a duration comparable to the HF radar integration time, the drifter velocity accuracy is expected to be below 1cm/s.

The experiment period, the number and kind of drifters used, and the average time spent by drifters in the HF radar coverage are shown in Table 1 for all the sites. The atmospheric conditions during the experiments were rather calm (wind velocities smaller than 7m/s) in Lemnos, Trieste and Naples, with a typical summer breeze regime in the latter case. In Toulon, conditions were also calm except for a northwesterly wind episode with velocities up to 15m/s that lasted for 1.5 days. Finally, the Balearic experiment was performed under very energetic atmospheric conditions, with intense winds (velocities larger than 20m/s) and high waves (significant heights larger than 3m) during 2 days.

Considerations on HF radar and drifter velocity comparison

When comparing HF radar and drifter-based velocities, it is important to keep in mind the differences between the two types of instrument and sampling. While drifters feel the velocity at a scale corresponding to their physical horizontal and vertical size, of the order of 1m for the CODE type used here, HF radar velocities are quantities averaged over very different vertical and horizontal scales.

In the vertical, the HF radar velocity is the exponentially-weighted average of the upper ocean velocity profile, and it depends on the vertical shear of the horizontal current and on the HF radar frequency.[8,56-58] In the case of a linear shear, in particular, the measurement corresponds to an effective depth in the range between 50cm for a working frequency of 25MHz and 90cm for 13.5MHz.
Consequently, the comparison with CODE-type drifters, that provide the vertical average of the velocity in the upper 1m, is expected to be appropriate, unless very strong shears are present in the upper water column that can affect the two averages in a different way.

In the horizontal, on the other hand, there is clearly a mismatch of scales. Indeed, since the HF radar velocity is an average over the two-dimensional grid cell whose size is of the order of 1-3km for the TOSCA sites (Table 1), submesoscale variability associated to eg high horizontal shears is hard to resolve as the Rossby deformation radius in the regions considered is ~10km.[59] Therefore, the comparison between HF radar and drifters can only be considered satisfactory when it falls within the range of expected variability within the horizontal grid.[60] In our sites, specific estimates of such variability, that depends on both flow characteristics and grid size, are not available.

As a general guidance, results from the literature suggest that discrepancies of the order of 5-15cm/s can be considered acceptable and within the expected variability.[37,60-71]

RESULTS

HF radar and drifter velocities have been compared for all the sites, considering drifters within the HF radar coverage. Such comparisons are performed both on radial velocities and on the trajectories computed from vectorial velocities, and they are presented separately in the following.

Comparison between radial velocities

Radial velocities from HF radars (u_r^R) and those computed 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 for each drifter position the radar velocities corresponding to the nearest cells are bilinearly interpolated to obtain the radar velocity estimate. The difference between the two estimates of radial velocities, $\Delta u^R = u_r^R - u_d^R$, is then calculated, and its statistics is quantified in terms of bias $b_\Delta = \overline{\Delta u^R}$ and root mean square $rms_\Delta^2 = \overline{(\Delta u^R)^2}$, where overbars stand for averages over all drifters positions and times. For comparison, also the root mean square value of the drifter velocity is computed as $rms_u^2 = \overline{(u_d^R)^2}$.
Notice that this methodology differs slightly with respect to that of eg Ohlmann *et al.*[60], Molcard *et al.*[70], Rypina *et al.*[71], as in those cases HF radar velocities are compared with the average of all drifter velocities within each radar grid cell. To justify our choice, sensitivity tests performed for the Naples and Toulon sites, where the two approaches are compared, have shown that a slightly better matching is obtained with the methodology proposed here.

Results are summarized in Table 2 in terms of $rms_{\Delta,u}$ and b_Δ averaged among all the radar stations of each site. Furthermore, an example of drifter trajectory map with the associated Δu^R is shown in Fig 4 for one of the stations belonging to the Naples system. For the three sites of Trieste, Naples and Toulon, rms_Δ is within 5-10cm/s, ie well within the range of values expected from the literature, and it is smaller than the rms_u of the drifters by a factor 3.1 for Toulon, 2 for Naples and 1.3 for Trieste. Biases range from 0.4-0.5cm/s for Naples and Toulon to 2.1cm/s for Trieste. The relatively higher rms_Δ and b_Δ for Trieste might be due to at least two reasons. The first is the use of the measured antenna pattern for only one out of the three stations, confirmed by the fact that for this one station rms_Δ improve from 19.2cm/s to 9.6cm/s when computed with ideal and measured pattern, respectively. On the other hand, b_Δ is hardly changed by the measured pattern, corroborating the second possible cause of error, that is, the presence of a low salinity surface layer of about 1m at the time of the experiment, originating at the Isonzo river outflow and likely characterized by significant vertical

shear.[72] As mentioned in the previous section, the shear could indeed affect in a different way the effective depth of HF radar and CODE drifters, increasing the differences between the two velocity estimates.

The values of rms_Δ and b_Δ for the Balearic site are higher, reaching 16 and 5.5cm/s, respectively. As demonstrated in the next section, this is probabily related to the oil spill drifters used for the comparison, which are not CODE design and are consequently more directly influenced by the wind, which was very rough during the experiment. Such atmospheric conditions might as well explain the high rms_u value, confirming the fact that the flow is more energetic than in the other sites (Table 2).

Finally, in the Lemnos site very strong Radio-Frequency Interferences (RFI) occurred in the frequency spectrum (at the time of the experiment, voices speaking an eastern asiatic language could clearly be heard with an amateur AM radio receiver within the HF radar band!), characterized by a daily cycle with strong perturbations during the daytime and not during the night. The effect of RFI is both a reduced coverage, clearly visible in Fig 5 and the presence of outliers in the computed velocity field. Because of this, and considering the relatively small number of drifters, the comparison results are not significant and are therefore not reported in Table 2.

Comparison between drifter trajectories and synthetic HF radar-based trajectories

For each drifter trajectory within the HF radar coverage, synthetic trajectories have been computed using the vectorial velocity field from the HF radar. The numerical advection was performed using a fourth-order Runge-Kutta integration scheme. Synthetic trajectories were first initialized at the same launch time and location as the drifters, and then re-initialized at constant time intervals at the corresponding drifter positions. The comparison between synthetic trajectories $\boldsymbol{x}_r(t)$ and drifter trajectories $\boldsymbol{x}_d(t)$ is quantified computing their *mean separation distance* $D(t) = \langle \|\boldsymbol{x}_r(t) - \boldsymbol{x}_d(t)\| \rangle$ as a function of time *t* from deployment, where the mean is computed averaging over all the trajectories at time *t* and $\|\cdot\|$ is the Euclidean norm. The *mean absolute distance* $D_0(t) = \langle \|\boldsymbol{x}_d(t) - \boldsymbol{x}_d(0)\| \rangle$ travelled by the drifters is also computed. Indeed, in a number of previous papers (eg Ullman *et al.*[73], Molcard *et al.*[70]) it has been regarded as an estimate of the 'persistency error', ie of the error that would be made in SaR situations assuming that the target is not moving and there is no available information on ocean currents. When $D(t)$ is smaller than $D_0(t)$, this is an indication that the use of HF radar data allows to reduce the error of the estimated target position and the associated search range. As a consequence, we define the *Search Range Reduction Factor* (SRRF) as the ratio between $D(t)$ and $D_0(t)$ at the end of the advection time.

The results are shown in Figs 6-10 in terms of $D(t)$ and $D_0(t)$ for each site up to *t*=24h,

that corresponds to a typical correlation time scale in coastal regions,[74,75] except for Lemnos where due to insufficient data within the HF radar coverage t was reduced to 21h. Furthermore, in order to assess their variability, the standard deviations $\sigma_D(t)$ and $\sigma_{D_0}(t)$ associated to $D(t)$ and $D_0(t)$, respectively, are also shown as shaded areas around the mean values. Table 3 summarizes the final dispersion values together with the SRRF.

In the Gulfs of Trieste and Naples (Figs 6 and 7, respectively), the drifter travel distance $D_0(t)$ reaches a plateau after 12-14h, suggesting that the effects of boundaries and re-circulations become dominant after that time, corresponding to scales of ≈5km. $D(t)$ on the other hand increases almost linearly while being smaller than $D_0(t)$ at all times, especially for Naples. In the Toulon site (Fig 8), on the other hand, $D_0(t)$ keeps increasing and reaches approximately 10km after 24h, while $D(t)$ increases much more slowly reaching only 2km. In addition, $\sigma_{D_0}(t)$ is the smallest among all sites, and it practically does not increase with time as is the case in Trieste and Naples. This is probably due to a smaller space-time variability of the current fields in Toulon, whose covered area is mostly occupied by a boundary current.

For all these sites, the difference between $D(t)$ and $D_0(t)$ indicates a reduction on the position error and on the search range using HF radar data. Such reduction is especially evident for the Toulon site, where the SRRF is 5.3 after 24h. For the Gulfs, the flattening of $D_0(t)$ makes the comparison with $D(t)$ meaningful only in the first 12-14h, leading to a SRRF of 2.2 for Naples and 1.6 for Trieste.

For the Balearic site (Table 3), $D_0(t)$ increases almost linearly in time reaching almost 25km after 24h, in agreement with the fact that drifters moved under energetic conditions with rms_u=22cm/s (Table 2). $D(t)$ is significantly lower, reaching approximately 12km, giving a SRRF equal to 2. Yet, the very limited number of drifter points makes the statistics not completely reliable, as evidenced also by unusually large values of $\sigma_D(t)$, so that this result has to be taken with care. An interesting question, anyway, is to verify whether or not there is a significant wind influence on the drifter motion, as suggested in previous sections and keeping in mind that the drifters deployed in this site are of the oil spill type. A test is performed correcting the trajectories generated through the HF radar data by adding 2% of the wind from the HIRLAM model (~5km and 3h spatial and temporal resolution, respectively).[76] The results show a significant reduction of $D(t)$, that reaches only 6km at 24h, confirming that wind correction indeed reduces the error. An example of particle trajectories highlighting the impact of the wind correction is shown in Fig 11.

As already mentioned, the Lemnos site is characterized by significant daytime gaps due to RFI that are filled by DINEOF. Results in Fig 10, cut at 21h since no drifter stayed in the covered area for more than this duration, show that $D_0(t)$ increases up to almost 18km while $D(t)$ maintains smaller values, reaching approximately 10km and resulting in a SRRF equal to 1.7. This result suggests that even in presence of

significant errors or gaps in radial velocities, trajectory estimates can lead to an improvement in particle position using appropriate velocity reconstruction techniques, provided the velocity field is sufficiently persistent in space and time to allow for data gap filling. This is indeed the case in the Lemnos site during the experiment, when the flow showed the characteristic seasonal pattern flowing from the Dardanelles to the Aegean, with small variability between day and night-time.

SUMMARY AND CONCLUDING REMARKS

In this paper, the HF radar network operated during the TOSCA project is presented and results from the comparison between HF radar and drifter velocities during dedicated experiments are shown. In the three sites of Trieste, Naples and Toulon, where the comparison was performed using more than 20 CODE drifters drogued in the first meter under the sea surface, with average residence time within the radar coverage area of 2, 10 and 5 days, respectively, qualitatively similar results are found. In all cases, the rms value of the radial velocity difference between HF radar and drifters (rms_{Δ}) falls in the range 5-10cm/s, ie well within what is considered acceptable in the literature given the expected variability at the HF radar subgrid scale. The average difference $D(t)$ between drifter trajectories and synthetic ones computed from HF radar velocities is smaller than the mean distance travelled by drifters $D_0(t)$ by a factor ranging from more than 5 for Toulon to 1.6 for Trieste. Referring to SaR or oil spill applications using HF radar, we have interpreted these numbers as search range reduction factors (SRRF) to stress the reduction on the position error with respect to the persistency error quantified by $D_0(t)$. The quantitative differences between the sites can be due to several factors, including vertical shear in the surface layer that is likely to be more pronounced in Trieste at the time of the experiment. The Balearic site has a higher rms_{Δ} of 15cm/s, but it should be considered that during the experiment, because of very strong winds (>20m/s), the flow is the most energetic, and that the drifters used for comparison are not CODE and are more directly affected by winds. Nevertheless, the SRRF amounts to 2, and the improvement raises to a factor 4 when numerical trajectories are computed adding a direct wind influence in terms of correction. Lemnos results are strongly influenced by RFI that affects the radial velocities during daytime. Even in this case, though, when the vector velocity field is reconstructed using the DINEOF technique, that exploits EOF information to fill the gaps and smooth the field, the trajectory results show a reduced position error, with a SRRF of 1.7. Notice finally that the lowest SRRFs (Table 3) have been obtained in the two sites, Trieste and Lemnos, where ideal antenna patterns were used, at least partially for the former one. Therefore, a larger SRRF might be expected even in these cases provided measured antenna patterns were properly employed.

In summary, despite the differences in oceanographic sites, installations and data analysis, the results consistently show that the use of HF radar data allows to decrease

position errors and range of search by a factor varying between 5.3 and 1.6. At the same time, the results point to a number of important issues that should be considered in future studies and applications.

First of all, the comparison between drifters and HF radar appears to be influenced by the details of vertical shear and by air-sea interaction, implying that transport in the surface layer is very complex and can vary significantly with depth. Indeed, the knowledge of the response of the ocean in the first meter of water is still largely unknown and these results contribute to indicate the implications of this lack of knowledge. While HF radar fields provide important information on current velocity, they need to be complemented by wind knowledge, estimates of current shear, and buoyancy and drags of floating bodies in order to be used in the most effective way in practical applications such as SaR or pollution mitigation.

The other important issue highlighted by the TOSCA experiments is the problem of radio interference and its consequence on HF radar performance. The presence of RFI is indeed a well-known phenomenon in the HF band below ~30MHz (see The American Radio Relay League[77]), and it is due to the remote propagation of electromagnetic waves thanks to the excitation of the ionosphere by sun radiation, which in turn justifies its daily cycle. RFI has been observed particularly in 13 and 16MHz systems, including Lemnos, Toulon, Balearic, and the Calypso system installed between Malta and Sicily (A. Drago, personal communication). As shown for the Lemnos case, this problem can be alleviated *a posteriori* using dedicated signal processing methods able to reconstruct the velocity field by smoothing and filling the gaps, but this is likely to be acceptable only for flows with relatively low variability. On the other hand, only a few exploratory works have tackled the problem of suppressing RFI from the measured signals *before* computing velocity maps.[78-81] Given also the diverse nature of all possible interferences (pure carrier or modulated signal, transient or continuous, etc), which cannot be handled with a universal method, an effort at the international HF radar community level should be put forth in developing and sharing signal processing techniques for RFI mitigation.

In parallel, the presence of RFI should be avoided by a global coordination plan for the occupation of the frequency spectrum. Such plan can only marginally rely on national or border policies, as electromagnetic waves in the HF frequency band can easily propagate up to distances of thousands of kilometers thanks to the conducting properties of the ionosphere.[77] On this purpose, only very recently at the World Radiocommunication Conference held in Geneva, Switzerland in 2012 (WRC-12), the International Telecommunication Union (ITU) has officially allocated frequency bands to the use of HF radars. Yet, this allocation is not even exclusive or primary, especially in Europe, and today such bands are far from being emptied out by other official and non-official radio services. Even more importantly, each of these bands can host only one or two HF radars without frequency overlapping. Coordination is therefore mandatory even among HF radar manufacturers and users, in order to employ time or

modulation division duplexing or possibly orthogonal codes to have many systems sharing the same frequency band without interfering with each other.

Finally, the TOSCA project has allowed a useful exchange of different HF radar practices, implementations and data analyses. This has provided an interesting survey and has led to general results in terms of comparison and applications. On the other hand, the many differences between sites did not allow a systematic comparison of specific issues, eg QC and RFI suppression. In order to do that, a specific experiment should be chosen and the results treated and compared with different methodologies.[36] An effort in this direction is presently carried out, and the TOSCA results are available in a common format within a web-based GIS (http://toscagis.univ-tln.fr/) and proposed as a common open benchmark for testing.

The TOSCA network presented here includes Mediterranean installations that were active at the beginning of the project in 2010. Today, other installations and HF radar projects are active or in preparation (eg the aforementioned Calypso system or the SICOMAR installation in the Tuscan Archipelago), and there is a clear need to include them and proceed toward building an effective network for real time HF radar data with common standards in data format, QC, and signal processing.

Coherently with one of the main goals of the TOSCA project, we conclude suggesting that the installation of HF radars and the establishment of pollution mitigation facilities equipped with CODE and oil-spill drifters should be required to obtain the permission to build new offshore mining facilities. This claim is justified by the present context of developments in the exploration and prospective exploitation of deep-sea oil resources in the Mediterranean. In this framework, besides confirming the effectiveness of these instruments and methodologies, the study presented herein documents the existence of a first core of a European HF radar alliance, and stresses the need for a unified network that would be mandatory to obtain, among others, the aforementioned objective.

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Tables with captions

Site name	Installation set-up	Operating frequency (MHz)	Range resolution (km)	Experiment date (2012)	Drifters (res. time, days)
Trieste	3 SeaSonde	25	1	Apr	37 CODE (2)
Naples	3 SeaSonde	25	1	Aug	22 CODE (10)
Toulon	2 WERA	16.1	3	Aug	23 CODE (1)
Lemnos	2 WERA	13.5	3	Oct	8 CODE (1)
Balearic	2 SeaSonde	13.5	1.7	Oct	4 oil spill (1)

Table 1: Characteristics of the TOSCA sites in terms of HF radar installations and drifter deployments. The residence time indicated for each site corresponds to the average number of days spent by drifters within the HF radar coverage during the experiments.

Site name	rms_u (cm/s)	rms_Δ (cm/s)	b_Δ (cm/s)
Trieste	12.9	9.6	2.1
Naples	9.6	4.7	0.4
Toulon	15.5	5	0.5
Lemnos	24	X	X
Balearic	22	16	5.5

Table 2: Results of the comparison between radial velocities. Values are computed for each site as averages over all the HF radar stations. rms_u is computed from radial drifter velocities, whereas rms_Δ and b_Δ are computed from differences between HF radar and drifter radial velocities.

Site name	Advection time (h)	$D_0(t)$ (km)	$D(t)$ (km)	SRRF
Trieste	12	5.2	3.3	1.6
Naples	14	3.3	1.5	2.2
Toulon	24	9.6	1.8	5.3
Lemnos	21	17.9	10.3	1.7
Balearic	24	24.4	12.2 (6.1)	2 (4)

Table 3: Results of the comparison between drifter trajectories. For the Balearic site, values within parentheses are obtained with a 2% wind correction.

Figure captions

Fig 1: Location of the TOSCA HF radar installation sites with a snapshot of current velocity field measured during the TOSCA experiments. For each site, locations of HF radars are indicated using the following symbols: '□' for CODAR SeaSondes, '○' for quasi-monostatic WERAs and '×' and '+' for WERA transmitters and receivers, respectively in bistatic configuration.

Fig 2: Examples of HF radar systems belonging to the TOSCA network. (a) A CODAR SeaSonde installation in Formentera (Balearic site). The TX/RX monopole is installed above a closed dome containing two crossed-loop magnetic RX antennas. (b) A WERA transmitting array made of four monopoles in Plaka (Lemnos site).

Fig 3: Timeline of the TOSCA experiments.

Fig 4: Drifter trajectories for the Portici radar (square black dot) of the Naples site. The color associated to the positions of drifters is the difference Δu^R between the drifter and the radar radial velocities.

Fig 5: HF radar radial coverage as a function of time for the Plaka radar of the Lemnos site during the days of the experiment (very similar results are obtained for the other radar of the site). The coverage is computed as the number of valid radial velocities normalized by its largest value. The gray-shaded areas correspond to daytime (between sunrise and sunset). It can be clearly observed how the coverage drops dramatically during daytime, with almost zero coverage spikes due to extremely strong RFI.

Fig 6: Comparison between drifter trajectories for the Trieste site. Mean absolute distance $D_0(t)$ covered by the drifters and mean separation distance $D(t)$ between drifter and radar-based trajectories. The shaded regions correspond to the confidence intervals at ± one standard deviation. The vertical dashed line at 12h indicates the time after which recirculation effects in the Gulf become dominant.

Fig 7: Same as Fig 6 for the Naples site. The vertical dashed line at 14h indicates the time after which recirculation effects in the Gulf become dominant.

Fig 8: Same as Fig 6 for the Toulon site.

Fig 9: Same as Fig 6 for the Balearic site.

Fig 10: Same as Fig 6 for the Lemnos site. The comparison is shown only up to 22h since no drifter remained in the area covered by the HF radar for a longer time.

Fig 11: Trajectory of one among the four drifters of the Balearic site. The red dot indicates the deployment point; the two black squares in the Ibiza and Formentera islands on the right represent the location of radar stations.