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1 **New signal processing techniques for phased-array oceanographic radars:**
2 **self-calibration, antenna grouping, and denoising**

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6 ABSTRACT: Original techniques are proposed for the improvement of surface current mapping
7 with phased-array oceanographic High-Frequency Radars. The first idea, which works only
8 in bistatic configuration, is to take advantage of a remote transmitter to perform an automatic
9 correction of the receiving antennas based on the signal received in the direct path, an adjustment
10 that is designated as “self-calibration”. The second idea, which applies to both mono- and bistatic
11 systems, consists in applying a Direction Finding (DF) technique (instead of traditional Beam
12 Forming) not only to the full antenna array but also to subarrays made of a smaller number of
13 sequential antennas, a method which is referred to as “antenna grouping”. In doing this, the number
14 of sources can also be varied, leading to an increased number of DF maps that can be averaged, an
15 operation which is designated as “source stacking”. The combination of self-calibration, antenna
16 grouping, and source stacking makes it possible to obtain high-resolution maps with increased
17 coverage and is found robust to damaged antennas. The third improvement concerns the mitigation
18 of noise in the antenna signal. These methods are illustrated with the multistatic High-Frequency
19 Radar network in Toulon and their performances are assessed with drifters. The improved DF
20 technique is found to significantly increase the accuracy of radar-based surface current when
21 compared to the conventional Beam Forming technique.

22 1. Introduction

23 High-Frequency Radars (HFR) are routinely used for the mapping of coastal surface currents.
24 The main physical principle underlying this detection has been unveiled in the pioneering works
25 of Crombie (Crombie 1955) and Barrick (Barrick 1972). It relies on measuring the Doppler shift
26 induced by the radial surface current on the backscattered sea echo. This is made possible by the
27 presence of a couple of very marked peaks in the Doppler spectrum, referred to as the “Bragg lines”.
28 This terminology alludes to a grating effect that is observed in HFR scattering from gravity waves
29 and which is similar to the resonant mechanism observed in X-ray Bragg diffraction from crystals.
30 There is abundant literature on the estimation of surface currents from HFR and the associated
31 applications (see e.g. the review papers Paduan and Graber (1997); Headrick and Thomason
32 (1998); Paduan and Washburn (2013); Wyatt (2014); Roarty et al. (2019); Reyes et al. (2022);
33 Lorente et al. (2022)) and there is no need to go into details. It is sufficient to say that the extraction
34 of surface current maps from HFR antenna voltage results from a complex but universal chain of
35 signal processing steps. Most HFR systems are monostatic, that is have co-located transmitters
36 and receivers, and use pairs of radar to infer two radial components from which the surface current
37 vector can be recombined. In some cases, it is advantageous to operate in a bistatic configuration
38 (e.g. Grosdidier et al. (2014)) in which the transmitter and receiver are located remotely or even
39 multistatic systems, which are a combination of remote transmitters and receivers (e.g. Dumas
40 et al. (2020)).

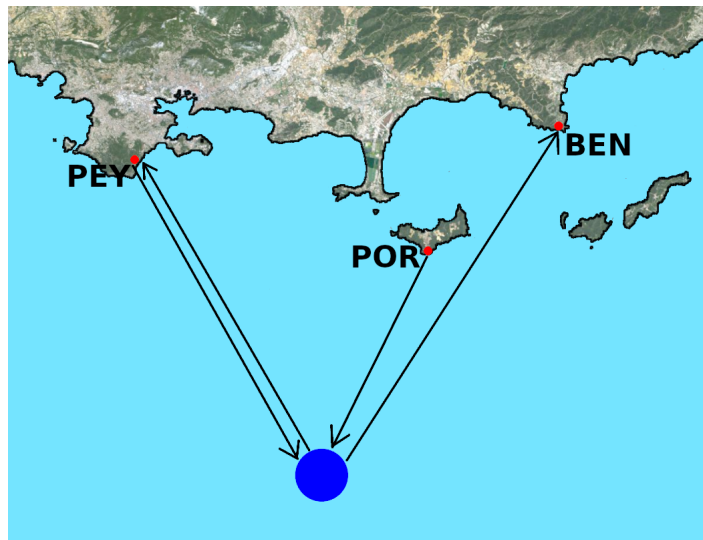
41 The aforementioned chain of processing is common to monostatic and bistatic configuration with
42 some adaptation in the geometrical formulas (see e.g. Lipa et al. (2009)). For a bistatic pair of
43 (TX, RX) the iso-range radar cells follow ellipses with focal points at the transmitter and receiver
44 locations (as opposed to circles around the transmitter in the monostatic case). The resonant Bragg
45 frequency f_B in the Doppler spectrum depends on the bistatic angle φ (with $f_B^2 = g \cos \varphi / (\pi \lambda)$)
46 hence on the sea surface patch, while it is constant in the monostatic case (with $f_B^2 = g / (\pi \lambda)$).
47 Any observed Doppler shift Δf with respect to this local Bragg frequency is proportional to the
48 projected component U_n of the surface current vector \mathbf{U} onto the normal direction to the ellipse,
49 which is referred to as the elliptical velocity ($U_n = \lambda \Delta f / (2 \cos \varphi)$). In the monostatic case, this
50 frequency shift is proportional to the radial component U_r of the surface current vector along the
51 radar look direction, ($U_r = \lambda \Delta f / 2$).

52 The most critical and system-dependent operation in processing HFR data for producing current
53 maps is the azimuthal discrimination of the backscattered antenna signal. For linear or quasi-linear
54 extended arrays of antennas, this is usually done with a Beam Forming (BF) technique which
55 allows steering the bearing angle by numerically adjusting the relative phase shifts of the antenna
56 signals (e.g. Gurgel et al. (1999b)). This makes it possible to continuously sweep the angular sector
57 covered by the radar. However, the resulting azimuthal accuracy depends on the array extension
58 and deteriorates as the steering angle deviates from the central direction. Compact antenna systems
59 rely on high-resolution methods such as Direction Finding (DF) techniques with the weak point
60 being that this requires longer integration time, produces lacunary maps, and is more prone to
61 errors. These two techniques will be analyzed and compared in the following sections in context of
62 the HFR network in Toulon. This last system has been operated for one decade in bistatic mode and
63 is running in multistatic mode as of January 2019 (Grosdidier et al. (2014); Guérin et al. (2019);
64 Dumas et al. (2020)). While developing specific software for the azimuthal processing of these
65 data in such a nonstandard configuration we made use of a novel opportunity offered by the bistatic
66 mode, namely a possible instantaneous calibration of the receiving antenna with the direct signal of
67 the remote transmitter. The idea of using opportunistic external sources for calibration is not new
68 (see e.g. Solomon et al. (1999); Fernandez et al. (2003); Kohut and Glenn (2003); Washburn et al.
69 (2017); Emery et al. (2014)) but this technique avoids running dedicated campaigns that require
70 the deployment of ships, aerial drones, or other external sources.

71 This simple and automatic technique is referred to as a “self-calibration” method since it does
72 not require any specific action from the operator (besides an additional line of code in the software)
73 and can be performed in real-time for every time series. As seen later, an hourly update of the array
74 calibration is necessary as the required phase corrections follow a diurnal cycle and a seasonal
75 evolution. Another original aspect of the historical network was the limited extension and irregular
76 form of the initial antenna arrays (8 antennas from 2012 to 2018) which led its first operators to
77 develop high-resolution DF methods (Barbin et al. (2009); Barbin (2011)). The antenna arrays were
78 extended to 12-antenna linear arrays in 2019 and 2020 but the idea of using DF for non-compact
79 arrays was maintained and improved. In 2019 an improved DF technique was devised, based on
80 testing multiple subarrays, a method that was termed “antenna grouping”. The self-calibration and
81 antenna grouping techniques are currently running on-site for the processing of near real-time HFR

82 data in Toulon (<http://hfradar.univ-tln.fr/>) and have been used for the reprocessing of historical data
83 (2012-2018). This HFR network will be briefly presented in Section 2 and the following sections
84 will introduce the self-calibration method (Section 3), the antenna grouping method (Section 4),
85 and the noise mitigation techniques (Section 5). When used together, these methods allow for a
86 significant improvement of surface current mapping in terms of accuracy, coverage, and robustness
87 to hardware failure. An assessment of the accuracy of these novel techniques and comparison with
88 classical BF is performed in the light of a drifter campaign (Section 6).

89 2. The HFR in Toulon



90 FIG. 1. The three HFR sites in the region of Toulon: 1) Fort Peyras (TX/RX, “PEY”); 2) Cap Bénat (RX,
91 “BEN”); 3) Porquerolles Island (TX, “POR”).

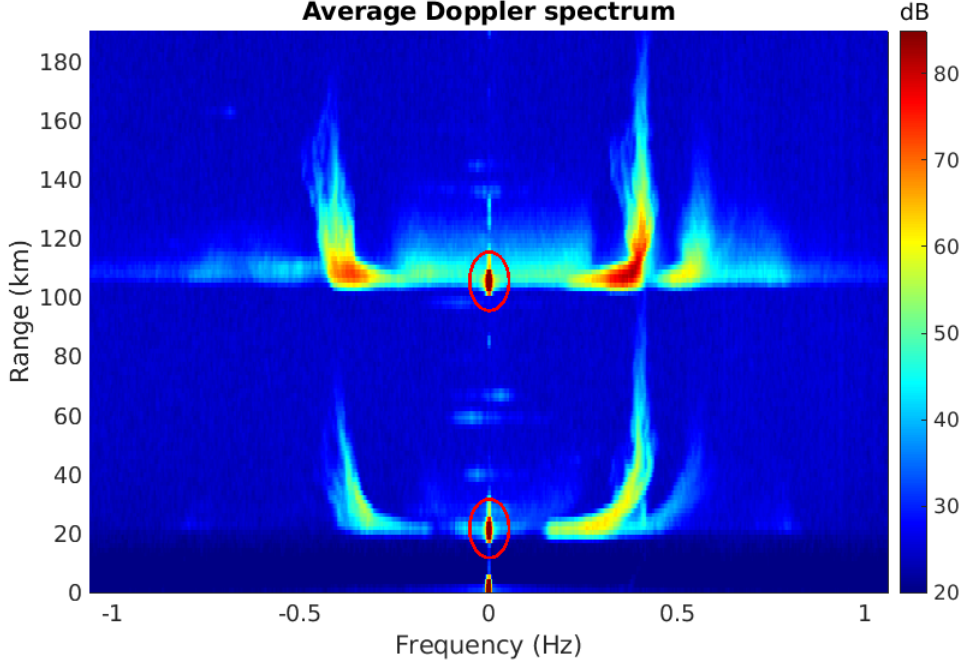
92 The HFR network in Toulon is manufactured by WERA Helzel Messtechnik. It is composed of
93 2 transmitters and 2 receivers located on three distant sites (Figure 1). A standalone transmitter is
94 located on Porquerolles Island, 27 km South-East of Toulon; its single, non-directional, emitting
95 antenna illuminates a wide sea area to the South. The first receiver is located at Cap Bénat, 35
96 km East of Toulon, with a regular linear array of 12 receiving active antennas (70 deg from North,
97 anticlockwise) with 0.45λ spacing. The second transmitter and receiver are located at Fort Peyras
98 about 8 km South West of Toulon. The receiving array is composed of a linear array of 12 passive
99 antennas along the North-South direction with a 0.45λ spacing as well. Note that the present

100 combination of 2 TX and 2 RX leads to 3 bistatic pairs and 1 monostatic pair which can be used
 101 for the surface current vector reconstruction. One can refer to (Gurgel et al. 1999a) for a detailed
 102 account of the processing of the radar signal and to (Guérin et al. 2019) for its adaptation to the
 103 multistatic mode. Range gating is obtained by the standard frequency-modulated continuous wave
 104 (FMCW) HFR technology. The two transmitters POR and PEY send continuous chirp ramps of
 105 duration 0.26 seconds within a frequency band of 100 kHz around the same central frequency
 106 $f = 16.150$ MHz, allowing for a 1.5 km range resolution. In FMCW HF radar technology, the
 107 range gating is obtained by Fourier Transforming the radar signal on the fast time and binning the
 108 received signal in frequency shifts (Gurgel and Schlick 2009). A complex Doppler spectrum is
 109 calculated for every single range cell and antenna by Fourier Transform of the recorded voltage
 110 time series at the slow time, that is at the chirp rate. Its squared modulus is referred to as the
 111 omnidirectional Power Spectral Density (PSD). In order for the receivers to discriminate the signal
 112 scattered from the two different sources, the two emitting central frequencies are offset by a multiple
 113 of a frequency bin in such a way that the first half of the range cells is allocated to one transmitter
 114 and the other half to the second transmitter. Figure 2 shows typical range-Doppler maps obtained
 115 by processing the range-resolved temporal signal received on a single antenna in Cap Bénat and
 116 Fort Peyras, respectively. The first “floor” corresponds to the bistatic sea echo from the Fort Peyras
 117 transmitter while the second floor is the bistatic return from the Porquerolles transmitter. Note the
 118 typical features of the bistatic Range-Doppler spectrum, that is U-shaped Bragg lines and an offset
 119 in the range corresponding to half the straight distance between transmitter and receiver.

123 3. Self-calibration of antenna arrays

124 a. Beam-Forming and its issues

125 For extended antenna arrays, BF is the traditional method to discriminate the radar signal in
 126 azimuth. Consider the canonical problem of a periodic linear array of N identical antennas with
 127 spacing d , illuminated by a plane wave with wavenumber $K = 2\pi/\lambda$ incoming from a direction θ_s
 128 measured from the normal to the array. In the absence of noise and assuming a perfectly coherent
 129 monochromatic incident wave, the complex time series recorded on the I&Q channels of each
 130 antenna is proportional to $e^{i2\pi ft} S_n$, where f is the radar frequency and S_n is a complex antenna
 131 gain depending only on the source direction θ_s . For simplicity, the antennas are assumed to have



120 FIG. 2. Bistatic Range-Doppler spectra on the Bénat receiver with 2 simultaneous transmitters. The upper
 121 floor corresponds to the Porquerolles transmitter and the lower floor to the Peyras transmitter. The direct signal
 122 from the transmitter to the receiver is a strong echo at the zero-Doppler cell (red circles)

132 the same unit gain in amplitude and to differ only by a phase shift. Once normalized by the first
 133 antenna, the complex signal S_n on the n th antenna depends only on its position in the array and the
 134 direction of the source:

$$S_n = e^{-i(n-1)Kd \sin \theta_s} \quad (1)$$

135 The so-called Array Factor (Balanis (2016)):

$$AF(\theta) = \sum_{n=1}^N e^{i(n-1)Kd(\sin \theta - \sin \theta_s)} \quad (2)$$

136 gives the remote electric far-field amplitude that would be produced by an array of identical
 137 radiators S_n by the principle of reciprocity. It is maximal in the direction of the source $\theta = \theta_s$ with
 138 a main lobe of width $\lambda/(Nd)$. An array factor can also be defined for irregular arrangements. This
 139 is important as the site topography often prevents the installation of the complete array along a
 140 straight line. Denoting \mathbf{d}_n the relative vector position of the n th antenna with respect to the first

141 one, the array factor for an incoming source in direction θ_s can be written as:

$$AF(\theta) = \sum_{n=1}^N e^{+iK(\mathbf{u}(\theta) - \mathbf{u}(\theta_s)) \cdot \mathbf{d}_n} \quad (3)$$

142 where $\mathbf{u}(\theta)$ is the outgoing unit vector in direction θ . For later use note that the array factor can
 143 be expressed as a scalar product between the so-called steering vectors in direction of the source
 144 (θ_s) and in direction of observation (θ):

$$AF(\theta) = \mathbf{a}(\theta) \cdot \mathbf{a}(\theta_s)^*, \quad (4)$$

145 where the steering vector is defined as:

$$\mathbf{a}(\theta) = \left(1, e^{iK\mathbf{u}(\theta) \cdot \mathbf{d}_1}, \dots, e^{iK\mathbf{u}(\theta) \cdot \mathbf{d}_N} \right) \quad (5)$$

146 BF consists in re-radiating the received complex multidimensional signal $\mathbf{S} = (S_1, \dots, S_N)$ at infinity
 147 while continuously steering the angle θ in the array factor to unveil all incoming sources. This is
 148 done for each chirp number and range index so that in the end the following complex time series
 149 is obtained as a function of range (R), bearing (θ) and time (t):

$$X(R, \theta, t) = \mathbf{a}(\theta) \cdot \mathbf{S}^*(R, t) \quad (6)$$

150 A directional PSD can be obtained with the square modulus of the Fourier Transform of this matrix
 151 along the time axis leading to the so-called directional Range-Doppler spectra. The angular spread
 152 of the AF determines the accuracy and the quality of the azimuthal discrimination and therefore the
 153 resolution of the Bragg lines in the directional Doppler spectra. In particular, secondary lobes can
 154 be an important source of error if insufficiently rejected since they may “capture” strong sources
 155 (through their Bragg lines) away from the focusing direction. Secondary lobes can be efficiently
 156 rejected by using a tapering window but the azimuthal resolution remains bound to the array extent.
 157 In addition, the perturbations of the electromagnetic environment as well as the misalignment of
 158 the antennas induce phase shifts with respect to the theoretical values which depend only on the
 159 array geometry. This results in a deformation of the array factor with possible mispointing and

160 enhancement of secondary lobes. The phase perturbation can induce a mispointing of a few degrees
 161 and a strong enhancement of secondary lobes. This will cause a systematic error in the direction
 162 of arrival of any source.

163 *b. Self-calibration with one single source*

164 The classical technique for HFR antenna calibration is based on using a transponder on a boat trip
 165 surrounding the emission site and measuring the complex response of each antenna, the so-called
 166 antenna manifold. This operation is in general time and money-consuming, requires dedicated
 167 manpower, and can only be performed once in a while. However, one can take advantage of the
 168 bistatic configuration to calibrate the antennas using the direct signal of the remote transmitter. The
 169 direct signal refers to the EM wave train which propagates in a straight line from the transmitter
 170 to the receiver without being scattered by sea surface patches on the travel path. It corresponds to
 171 the minimal bistatic distance, which is the distance between the transmitting and receiving sites. It
 172 is also concentrated on the zero-Doppler cell because this source is not Doppler-shifted by waves.
 173 The direct signal is therefore a strong echo concentrated on a particular cell in the range-Doppler
 174 map. It can be seen in Figure 2 as the red spots inside the red circles. The complex direct signal D_n
 175 recorded on the n th antenna can thus be extracted from the zero-Doppler cell at the minimal range
 176 after range and Doppler processing of the I and Q signals. Now, from the receiving array point of
 177 view, the direct signal is that from an incoming plane wave in direction θ_s of the transmitter. It
 178 should therefore produce the expected relative phase shifts $-K\mathbf{u}(\theta_s) \cdot \mathbf{d}_n$ ($= -(n-1)Kd \sin \theta_s$ for
 179 a linear periodic array). In terms of complex gain, this means:

$$D_n = e^{-iK(\mathbf{u}(\theta_s) \cdot \mathbf{d}_n)} D_1 = e^{i\phi_n} D_1 \quad (7)$$

180 The idea of self-calibration is to compare the theoretical geometrical phase shift between antennas
 181 to the actual phase shift measured from the direct signal. The difference between the expected
 182 and actual phase shift is a phase perturbation that should be compensated for when processing
 183 the antenna signals in azimuth. This idea has been already proposed to calibrate antenna arrays
 184 from ships equipped with transponders (Fernandez et al. 2003) but is more challenging to make
 185 automatic in this context. Using the signal from a remote transmitter at a fixed and known location
 186 allows for a complete automatization of the procedure.

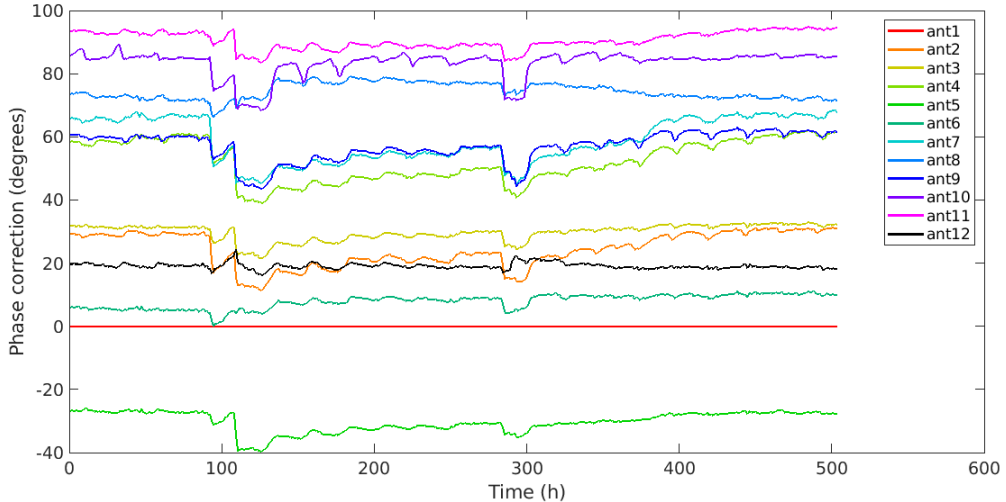
187 The self-calibration procedure, therefore, runs as follows:

- 188 1. For each chirp and each antenna, extract the complex direct signal \tilde{D}_n on each antenna by
189 retaining the zero-Doppler/minimal range cell from the range-resolved I & Q signal and
190 calculate its phase $\tilde{\phi}_n = \arg(\tilde{D}_n/\tilde{D}_1)$ relative to the first antenna in the array.
- 191 2. Calculate the phase difference $\delta\phi_n = \tilde{\phi}_n - \phi_n$ with respect to a theoretical array illuminated by
192 a plane wave in direction of the transmitter (θ_s).
- 193 3. Before extracting the directional signal $X(R, \theta, t)$ as in (6), correct the complex antenna gain
194 by this phase difference:

$$\tilde{S}_n(R, t) = S_n(R, t)e^{i\delta\phi_n} \quad (8)$$

195 By doing this it is assumed that the phase corrections $\delta\phi_n$ do not depend on the bearing θ . This
196 important property is not granted *a priori* and the only certitude is that these phase corrections are
197 appropriate in the direction θ_s of the transmitter. We, therefore, need the additional assumption
198 that the required phase corrections $\delta\phi_n$ do not vary (at least, not appreciably) with the bearing.
199 This is the main weakness of the method as compared to classical boat calibration, where all
200 bearings can in principle be tested. Nevertheless, the calibration error resulting from a constant
201 phase correction can be evaluated whenever a second remote transmitter is available since the direct
202 signal in this last direction can also be extracted and compared with the predicted and corrected
203 phase shifts using the first transmitter. This was done with the Bénat receiver using the Peyras and
204 Porquerolles transmitters, which are separated by about 50 degrees in bearing. We found an RMS
205 phase error of 20 degrees as compared to 32 degrees without any correction. As will be seen in
206 the next subsection, this can be further improved by using multiple source calibration. Again, the
207 main advantage of self-calibration over dedicated in situ campaigns is that it can be automatically
208 updated at each radar observation cycle (in our case, one hour) and can therefore follow the natural
209 evolution of the array response in time. The hourly variations of the Bénat receiver calibration
210 phases were investigated over 3 weeks (November 4-24, 2020, corresponding to the drifters period
211 in Section 6) with the Porquerolles emitter (Figure 3). As seen, the phase corrections can vary
212 by about ± 10 degrees from a mean over timescales of a few hours or longer. A diurnal cycle is
213 visible in the variations as well as some abrupt changes (at hour 100 and 300). We hypothesize
214 that this is caused by changes in humidity and temperature that would affect the cables and antenna

215 impedances as well as the antenna grounding to earth. It shows in any case that the instantaneous
 216 picture provided by a one-time ship or drone campaign is only approximate when used over a longer
 217 period. Even though the phase variations remains small, they appear to be strongly correlated from
 218 one antenna to another. Hence, neglecting these corrections could induce an overall mispointing
 219 of the array of the same order of magnitude (that is, ± 10 degree) while steering the observation
 220 angle.

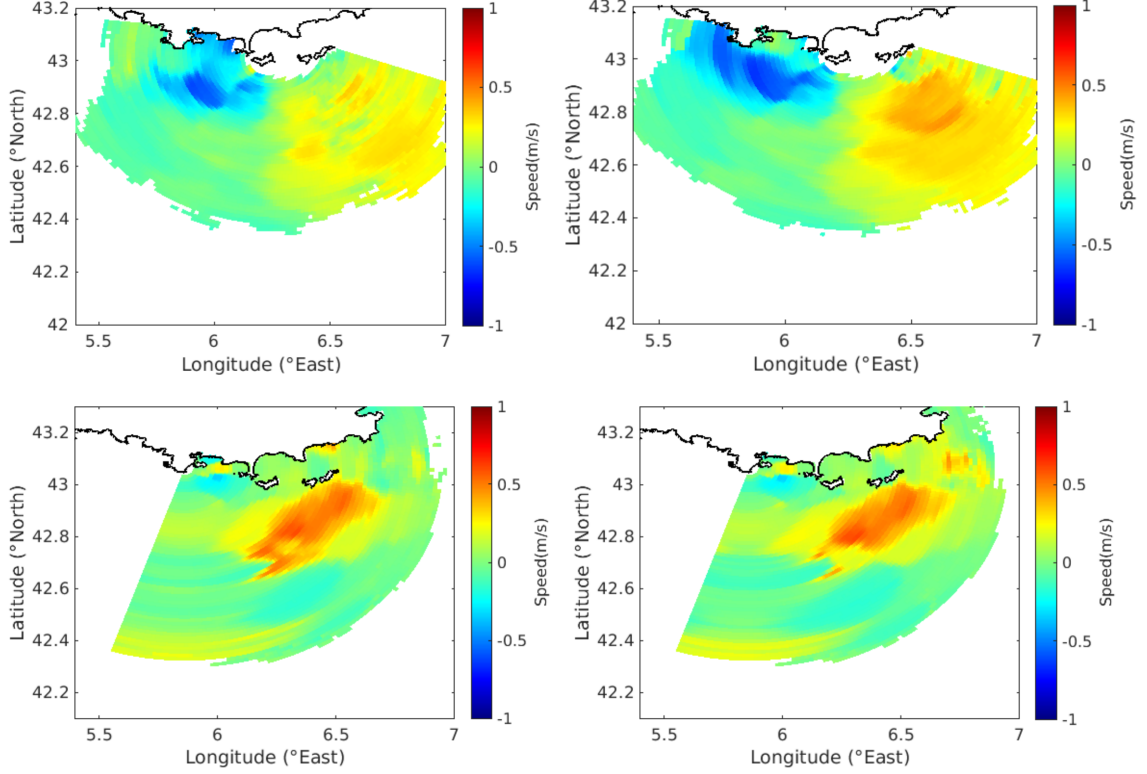


221 FIG. 3. Hourly variations of the self-calibration phases obtained with the Porquerolles emitter on the Bénat
 222 receive array. Antenna 1 is the reference.

223 Figure 4 shows two examples of elliptical/radial velocity maps obtained by processing one hour
 224 of data from each receiver. The azimuthal processing has been performed using the BF technique
 225 without (left panel) and with (right panel) self-calibration of the complex antenna gains. As
 226 seen, this makes important changes in the radial current map. The uncalibrated version shows
 227 disconnected and noisy radial current patterns which do not correspond to the main picture of a
 228 dipole structure expected for a dominant westwards flowing current vein. The calibrated map is
 229 more consistent in this respect.

235 *c. Self-calibration with multiple sources*

236 Whenever several far sources are available, the strong hypothesis of constant phase corrections
 237 $\delta\phi_n$ can be relaxed and a dependence on the bearing can be introduced. This is the case for the



230 FIG. 4. Top panels: elliptical velocity maps obtained on October 13, 2019, 17.00 UTC from one-hour
 231 observation with the Porquerolles transmitter and Cap Bénat receiver. The azimuthal processing of HFR data has
 232 been performed using the BF method without (top left panel) and with (top right panel) self-calibration. Bottom
 233 panels: radial velocity map obtained on November 11, 2020, 03.00 UTC from one-hour observation with the
 234 Peyras transmitter and receiver, without (bottom left panel) or with (bottom right) self-calibration.

238 multistatic HFR network in Toulon where the two distant emitters (POR and PEY) can be used
 239 on the receiver site (BEN). Consider the general situation of M available far sources in directions
 240 $\theta_1 \leq \dots \leq \theta_M$. The one-source calibration can be generalized by defining the relative phase $\tilde{\phi}_{m,n}$ of
 241 the complex direct signal produced by the m th source on the n th antenna:

$$\tilde{\phi}_{m,n} = \arg \left(\frac{\tilde{D}_{m,n}}{\tilde{D}_{m,1}} \right) \quad (9)$$

242 leading to a phase correction:

$$\delta\phi_{m,n} = \tilde{\phi}_{m,n} - \phi_{m,n} \quad (10)$$

243 A bearing-dependent phase correction $\delta\phi_n(\theta)$ can be obtained by the utilization of the above
 244 coefficients in the vicinity of each source direction. To avoid the discontinuity of the phase
 245 corrections and to ensure their consistency the prescribed phase corrections (in fact, their sinus
 246 and cosinus to avoid phase ambiguity) are interpolated in every angular sector defined by two
 247 successive source bearings θ_m and θ_{m+1} . For bearings that are beyond the extreme sources ($\theta \leq \theta_1$
 248 and $\theta \geq \theta_M$) a constant phase correction given by the closest source (θ_1 or θ_M) is assumed.

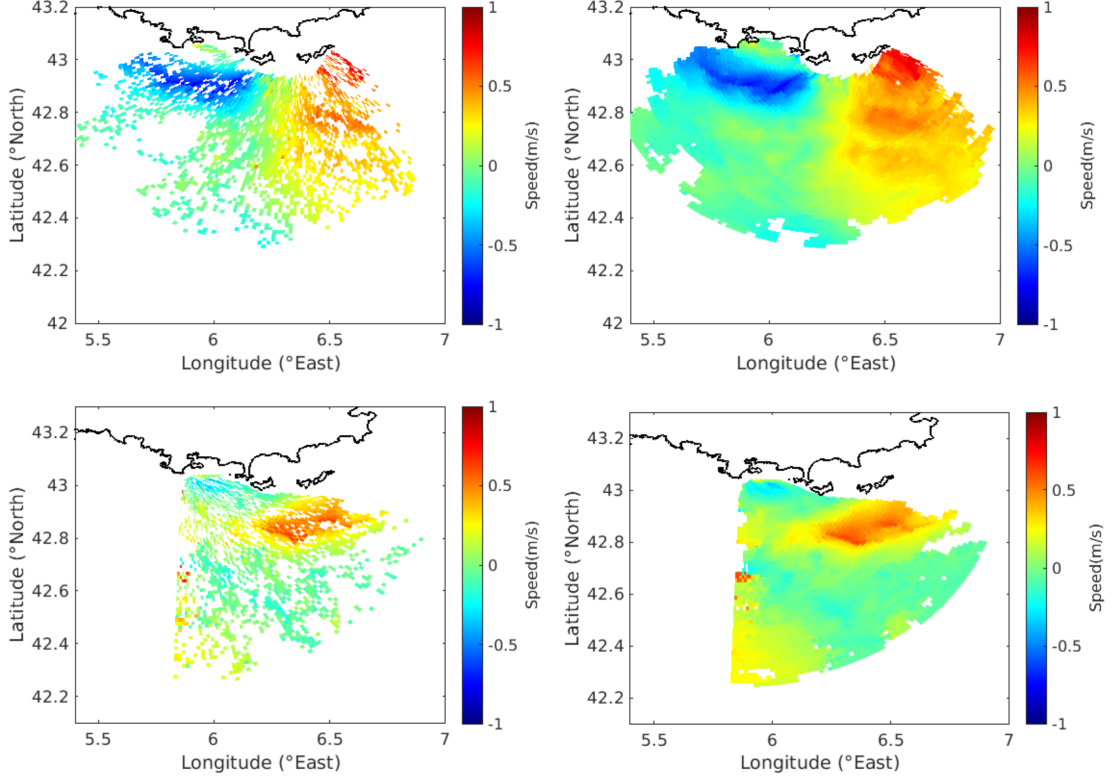
249 4. Antenna grouping

250 a. Direction Finding and its issues

257 The DF technique is a high-resolution method for determining the directions of arrival (DOA)
 258 of unknown sources (also referred to as “emitters” in the literature) in the far field. It is based on
 259 the MUSIC (MULTiple SIGNAL Classification) algorithm (Bienvenu and Kopp 1983; Schmidt 1986;
 260 Krim and Viberg 1996) applied to each complex Doppler ray measured on every single antenna.
 261 It allows finding at most $N - 1$ DOA by combining N antennas. In the context of surface current
 262 mapping, the DOA are the bearings associated with each given value of the radial or elliptical
 263 velocity, corresponding to a given Doppler shift. The MUSIC algorithm assumes that the signal
 264 originating from the different sources is a discrete, stationary random process (of dimension N)
 265 and is perturbed by an additive white random noise vector. The covariance matrix Σ of the complex
 266 antenna signals is a $N \times N$ matrix with elements

$$\Sigma_{ij} = \text{Cov}\left(Y_i, Y_j^*\right) \quad (11)$$

267 where Y_i is the complex Doppler ray (at a given frequency shift) from the i th antenna. To evaluate
 268 this quantity, the coherent time series recorded on each antenna channel is split into overlapping
 269 intervals and an estimation of the complex Doppler spectrum is obtained for each time interval.
 270 This provides for each pair (i, j) of antennas and each Doppler ray a certain number of (quite)
 271 independent samples from which the ensemble average in (11) can be evaluated. The optimal
 272 number of samples results from a trade-off between the convergence of the matrix cross-products
 273 to their statistical mean and the Doppler frequency resolution which decreases with the sample
 274 size.



251 FIG. 5. Elliptical velocity obtained on October 13, 2019, 17.00 UTC from one-hour observation with the
 252 Porquerolles transmitter and Cap Bénat receiver. The azimuthal processing of HFR data has been performed
 253 using DF azimuthal processing with one single array of 12 antennas (top left panel) and antenna grouping with
 254 all subarrays of 8 to 12 antennas (top right panel) and with stacking from 1 to 6 sources with each subarray. The
 255 self-calibration of antenna phases has been applied in both cases. Same case with Peyras on November 11, 2020,
 256 03.00 UTC at the bottom.

275 Next, a Singular Value Decomposition (SVD) of the covariance is sought, $\Sigma = U\Lambda U^*$ where $\Lambda =$
 276 $\text{Diag}(\lambda_1, \dots, \lambda_N)$ is the diagonal matrix of singular values ($\lambda_1 \geq \dots \geq \lambda_N \geq 0$) and $U = (U_1, \dots, U_N)$
 277 is the matrix of eigenvectors U_j . In the absence of noise, the M positive singular values $\lambda_1 \geq \dots \geq$
 278 $\lambda_M > 0$ identify the number and strength of the different sources and the associated eigenvectors
 279 U_1, \dots, U_M their direction. Precisely, the eigenvectors coincide with the normalized steering vector
 280 in the direction θ_j of the source, $U_j = \mathbf{a}(\theta_j) / \|\mathbf{a}(\theta_j)\|$. The remaining $N - M$ eigenvalues $\lambda_{M+1} =$
 281 $\dots = \lambda_N = 0$ and associated eigenvectors $U_{M+1} \dots U_N$ define the null subspace. In the presence of
 282 noise, these last eigenvalues are nonzero but are supposed to be lower than the signal eigenvalues

283 $(\lambda_N \leq \dots \leq \lambda_{M+1} \ll \lambda_M)$; the corresponding subspace is called the noise subspace. The idea of
 284 the MUSIC algorithm is to identify the direction of arrival by minimizing the projection of the
 285 steering vector onto the noise subspace, which amounts to maximizing its inverse:

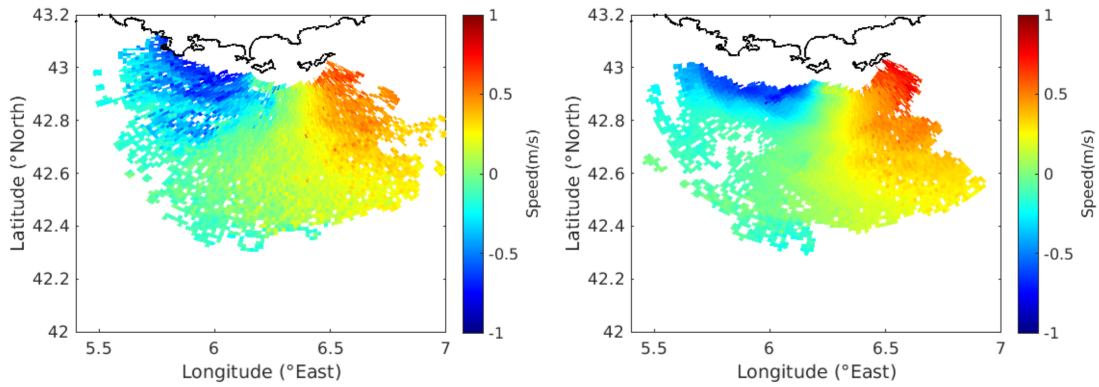
$$Q(\theta) = \frac{\|\mathbf{a}(\theta)\|^2}{\|\sum_{m=M+1}^N [\mathbf{a}(\theta) \cdot \mathbf{U}_m^*] \mathbf{U}_m\|^2} \quad (12)$$

286 This quantity is referred to as the MUSIC DOA function; its first M maxima above some threshold
 287 identify the sources. As it is well-known, the main advantage of the DF method with respect
 288 to the BF method is its better ability to detect sharp spatial variations of surface current and the
 289 better robustness of its estimates to decreasing Signal-to-Noise Ratio (SNR) and increasing bearing
 290 angles (Laws et al. (2000)). However, there is no plain definition of azimuthal resolution in that
 291 case and statistical quantification based on the uncertainty of the DOA must be devised to replace
 292 this concept (Emery and Washburn (2019)), wherein the size of the antenna array implicitly plays
 293 an important role.

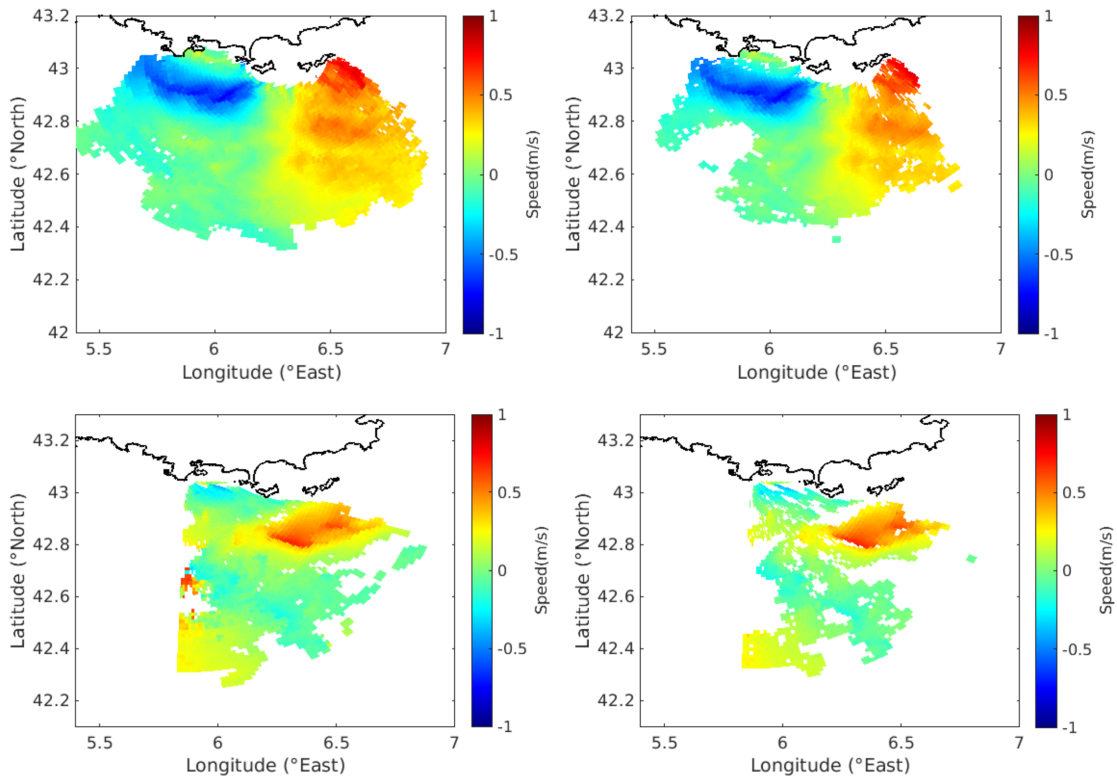
294 The left panel in Figure 5 shows an example of elliptical velocities obtained with the Porquerolles
 295 - Cap Bénat pair on the same dates. The range-resolved time series have been processed with DF
 296 using the full array (12 antennas) assuming 3 sources and using the same radial grid as for BF
 297 processing ($1.5 \text{ km} \times 1 \text{ degree}$). As expected, the DF processing leads to current maps with
 298 sharper contrasts and a gappy structure while BF smoothes out the small current patterns. For such
 299 high-resolution maps with small angular steps, many bearings are either not identified or do not
 300 pass the MUSIC thresholds, leaving blank areas. Increasing the filling ratio can in general only be
 301 realized at the expense of accuracy and a trade-off between these two requirements must be found
 302 with the setting of the DF parameters. As seen in the next section, antenna grouping is a way to
 303 optimize the filling ratios without reducing the thresholds.

304 *b. Antenna grouping*

310 Except for rare exceptions (Wang and Gill 2016; Kirincich et al. 2019), high-resolution techniques
 311 are employed with compact systems having a small number of antennas (typically 3, as for the
 312 SeaSonde CODAR) while the BF techniques are used with extended arrays of at least 8 antennas.
 313 Using DF processing with large antenna arrays open new possibilities which are not permitted by
 314 compact systems. A major improvement to prevent the lacunarity of radial or elliptical surface



305 FIG. 6. Same case as Figure 5 with DF azimuthal processing using 10 admissible subarrays of 3 antennas with
 306 (left panel) and without (right panel) self-calibration



307 FIG. 7. Same case as Figure 5 with DF azimuthal processing using antenna grouping with all subarrays of 4
 308 to 12 antennas whenever 1 antenna (number 7, top left panel) or 3 antennas (number 3, 7 and 8, top right panel)
 309 in the array are out of service. Same case with Peyras at the bottom.

315 current maps is to extend the DF processing to all possible combinations of subarrays made of
316 consecutive antennas, a method that will be referred to as “antenna grouping”. Instead of restricting
317 the covariance analysis to a single maximal set of antennas, it can be applied as many times as there
318 are admissible subarrays of arbitrary size. The idea of using subarrays in DF is not completely new
319 as it is a well-known method (see the review in (Krim and Viberg 1996)) to improve the estimation
320 of the covariance matrix at the cost of a reduction of the signal subspace dimension. However,
321 one can take advantage of subarrays differently, as they can be used to obtain many independent
322 estimations of elliptical velocities and can be allowed an arbitrary size, from a minimal N_{min} to a
323 maximal size N corresponding to the length of the full array. It is simple combinatorics to see that
324 there are $(N - N_{min} + 1)(N - N_{min} + 2)/2$ such subarrays. The idea is to perform a weighted mean
325 of elliptical velocities obtained with the different subsets of antennas, by averaging all the elliptical
326 velocities falling into each bin of bearing. As there are many subarrays, this increases considerably
327 the probability of visiting a given radar cell (that is, one range and one bearing) with the DF
328 algorithm. In fact, most bearings will be visited several times while looping over the subarrays,
329 with possibly different values of the elliptical velocity (that is, possibly distinct Doppler rays). This
330 improves the filling of the map and also provides more reliable and accurate estimates of elliptical
331 velocities with fewer outliers. A quality check is performed by rejecting the azimuthal bins inside
332 which the standard deviation of velocities is too large (> 20 cm/s in our case). Smaller groups of
333 antennas have in principle a coarser azimuthal resolution than larger groups. As a result, they are
334 less accurate to evaluate the surface elliptical velocity because they tend to smooth the latter. In
335 addition, they are limited to a small number of sources with the effect that they can miss some
336 specific features of the surface current pattern in case of complex meandering structures. However,
337 they are more robust to noise and have a better filling factor. On the other hand, larger groups
338 have an increased azimuthal resolution and accuracy and allow for a larger number of sources but
339 are more lacunary. These complementary strengths and weaknesses of small and large antenna
340 groups compensate each other when the outcome of all possible subarrays is averaged. A stronger
341 weight is attributed to the current estimated with large antenna groups which are sparser but more
342 accurate. At this stage of the discussion, only qualitative considerations will be given regarding
343 the various parameters involved in this improved DF processing; quantitative detailed information
344 will be found in Section d.

345 The right panel in Figure 5 shows the same map as the left panel, with a weighted mean of the
346 elliptical velocities obtained with a DF process applied to consecutive groups of 8 to 12 antennas
347 with source stacking (see subsection c) from 1 to 4, 5 or 6 sources depending of the size of the array
348 (85 combinations) with a preliminary complex antenna gain correction with the self-calibration
349 method. The radial grid resolution is unchanged, that is $1.5 \text{ km} \times 1 \text{ degree}$. A clear increase of the
350 spatial coverage is obtained with almost the same filling ratio as for BF while the surface current
351 patterns appear with finer details and enhanced contrast, a qualitative improvement that will be
352 confirmed quantitatively in Section 6. Note that antenna grouping technique can be applied to
353 monostatic as well as bistatic or multistatic systems.

354 The key point in using small antenna subarrays is a good preliminary phase calibration which
355 is a requisite for the success of antenna grouping. Whereas a missing or imperfect calibration of
356 complex antenna gains is less visible when performing DF on a long array, it can have a noticeable
357 impact on short arrays since it can produce a small rotation of the elliptical current maps. When
358 averaging the individual elliptical currents obtained with the different short arrays, this can blur
359 the final elliptical velocity map. This artifact can be mitigated with the self-calibration technique
360 which allows correcting the complex antenna gains first inferred from geometrical considerations.
361 To test the efficiency of self-calibration, surface current maps were produced with 10 groups of 3
362 antennas with and without self-calibration (Figure 6). On the left panel, the effect of individual
363 group rotation is visible in the dispersed blue area at the western end of the domain; after phase
364 correction, the current maps obtained with the different groups have a better overlap and show a
365 clearer pattern of the dipolar radial current.

366 Besides increased resolution and filling ratio, another interesting performance of the antenna
367 grouping method is its robustness to the failure of some antennas in the array. This is a very
368 valuable quality as it often occurs for various reasons that one or several antennas in the remote
369 receiving sites are out of service (because of e.g. corrosion, damaged individual receiver or
370 connector, vandalism, etc) and cannot be repaired at once. Contrarily to BF, the DF with antenna
371 grouping can still be efficient with an incomplete array, even though the resulting elliptical current
372 maps deteriorate little by little as an increasing number of antennas are missing. Figure 7 shows the
373 same radial current map as in Figure 5 obtained by applying the DF method with antenna grouping
374 to all subarrays of 4 to 12 antennas whenever a certain number of antennas are discarded.

375 *c. Source stacking*

376 In the subspace-based methods for DOA (e.g Krim and Viberg (1996)), the number of sources is
377 defined as the dimension of the signal subspace or, what amounts to the same, the number of non-
378 zero eigenvalues. The complementary subspace with null eigenvalues is referred to as the noise
379 subspace. However, in actual situations with real data, it is difficult to separate unambiguously the
380 zero and non-zero eigenvalues, as a continuum set of decreasing values is obtained after SVD of
381 the covariance matrix with no clear change in the order of magnitude of the latter. This makes the
382 automatic detection of the number of sources quite challenging, even though some theoretical or
383 empirical approaches have been proposed in the literature (e.g. Kirincich et al. (2019)). Given the
384 possibly large number of sources with phased arrays (here, from 1 to 11), there is no obvious choice
385 for the best compromise. Using a low number of sources allows to reduce the false detections in
386 MUSIC peaks and yields smoother, less noisy current maps; it loses, however, some fine structures
387 of the circulation pattern such as meandering, veins of current, or eddies. Increasing the number
388 of sources allows for a faithful rendering of the complex geometrical patterns but is more prone
389 to noise and spurious detection (e.g. Kirincich et al. (2019)). To operate a trade-off between
390 these two constraints, a principle similar to that of the antenna grouping can be employed. The
391 MUSIC algorithm can be applied several times with a varying number of sources and the resulting
392 radial surface currents can be averaged with a weight that depends on the number of sources. This
393 technique will be referred to as “source stacking” as it permits to increase the number of estimations
394 and the spatial coverage by accumulating the results obtained with different number of sources.
395 Source stacking is applied to every sub-array in the antenna grouping procedure. This improves
396 the mapping of complex geometrical current patterns while reducing noise and lacunarity.

397 *d. How should one set the DF parameters ?*

398 They are many required parameters to float to optimize the DF with antenna grouping and source
399 stacking and a quasi-infinite way to do this. We tried to devise an automatic and sufficiently
400 universal way to select them, which was validated in the light of the drifter comparisons (Section
401 6). If not optimal, this choice has the merit of being reproducible by other users of the oceanic
402 community. The setup of the different parameters is listed hereafter.

- 403 1. Setting the limits of the first-order Bragg region in the range-Doppler spectrum is the first
404 important step of the DF processing. The key point is to avoid misinterpreting second-order
405 Bragg lines as first-order peaks (see the detailed discussion in Section 4d and references
406 therein). Dynamical and automatic bounds have been chosen for the first-order region based
407 on the statistical distribution of radial currents. Starting with an absolute maximal value of
408 1 m/s for the radial current (a threshold that is adapted to the local situation) a preliminary
409 DF analysis is performed at each cycle of processing (that is, every hour) to estimate the
410 distribution of radial currents over the radar coverage. Outliers to the distribution, some of
411 which could be due to misinterpreted second-order Doppler spectra, are removed by restricting
412 the first-order limits to the 99% quantile of the Doppler frequency shifts. The improved DF
413 analysis is then performed with these refined first-order limits.
- 414 2. The size N_{sub} of subarrays (i.e. the number of consecutive antennas defining a subgroup)
415 should be as large as possible to preserve accuracy while keeping a sufficient number of
416 possible combinations. With a 12-antenna array, one can retain the sub-arrays of size ≥ 8 ,
417 leading to $5+4+3+2+1=15$ possible groups.
- 418 3. To preserve a good contrast of the local maxima of the MUSIC DOA function with respect to
419 secondary peaks, the dimension of the noise subspace should be left as large as possible while
420 preserving the existing sources. A minimal dimension of 3 is imposed for the noise subspace.
- 421 4. The number of sources should be sufficiently large to account for all physical sources but one
422 should not create fictitious sources by making this number too high. We found that increasing
423 the number of sources beyond 3 deteriorates the accuracy even if it allows filling the remaining
424 gaps in the current map.
- 425 5. The MUSIC thresholds should realize a trade-off between missing detection and false alarms.
426 Their magnitude depends on the size of the group and the dimension of the noise subspace.
427 To make an automatic adjustment of the threshold, the statistical distribution of values of
428 the MUSIC DOA function was evaluated by looping over all range-Doppler cells for a given
429 size of group and number of sources. The “big” factors corresponding to the actual MUSIC
430 maxima are identified by a percentile of the distribution multiplied by a scaling factor (which
431 generalizes the usual 2 standard deviation criterion for Gaussian distributions). We found

empirically that the threshold should be set to 1.8 times the 72th percentile of the MUSIC DOA function.

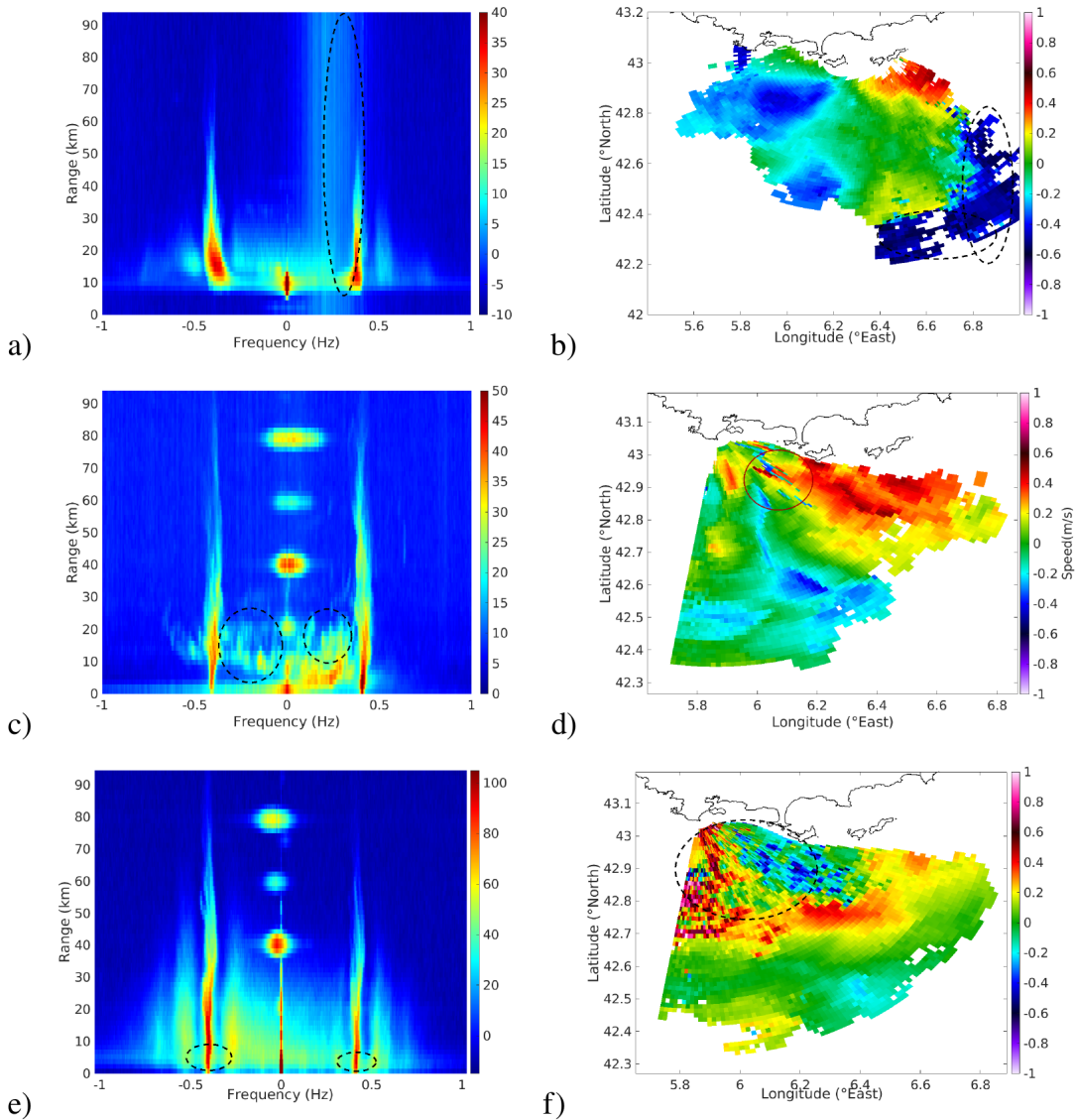
6. The weights $w_{N_{sub},M}$ of the subarrays should favor the largest arrays and the number of sources smaller than 4, with damping of higher sources more pronounced for the smallest arrays. The following empirical formula was found to work for 12 and 16 antenna arrays:

$$w_{N_{sub},M} = 1.3^{N_{sub}} \exp\left(-2 \frac{(M - N_{sub}/9)^4}{(2N_{sub} - 3)^2}\right) \quad (13)$$

5. Denoising

a. The different types of noise

The main limitation of surface current mapping is the presence of noise on the antenna signals, which deteriorates both the range and the accuracy of the estimation. While external sources of noise can in general not be removed, their impact can be mitigated by adequate signal processing techniques. There are 3 types of parasitic external noise, which must be handled with different techniques. The first source of external noise is the interference of external emitters in neighboring frequency bands. These are commonly referred to as Radio Frequency Interferences (RFI). Their characteristic signature is a vertical strip in the range-Doppler representation (Figure 8a) and the contamination of an entire azimuthal sector in the radial maps (8b). The second type of noise originates from the ship echoes (Gurgel and Schlick 2005). Whenever a vessel crosses a radar cell with a radial speed of the same order of magnitude as the surface current, it produces a bright spot around the corresponding location in the range-Doppler map. Figure 8c shows an example of a range-Doppler map with many presumable ship echoes between the 2 first-order Bragg rays. Figure 8d shows a typical artifact of a ship echo in the radial current map, here an intense outlier (red spot) in the central region. The third type of parasitic signal is the sea surface echo itself when taken at second-order. In the omnidirectional Doppler spectra, the first-order Bragg peaks are broadened by the variation of the radial currents over the radar coverage and can overlap the second-order components of the Doppler spectrum. Figure 8e shows an example of strong second-order echoes overlapping the first-order rays. This results in erroneous spots of various sizes and intensities on the radial map, here a cyan spot in the upper left region of the radial map (Figure 8f).



439 FIG. 8. Range-Doppler spectra (a, c and e) and associated radial maps (b, d and f) illustrating the 3 types of
 440 parasitic signals that deteriorate the surface current estimation. The effect of noise is highlighted with the black
 441 dashed ellipses. The vertical RFI strips seen on the range-Doppler spectrum from the Bénat receiver (a) produce
 442 an erroneous estimation of the elliptical velocity in the Eastern part of the map (b); ship echoes seen as cyan
 443 spots inside the Bragg region produce numerous artifacts on the Peyras radial map (d) ; second-order echoes in
 444 the vicinity of first-order Bragg rays (d) contaminate the shorter ranges of the Peyras radial map (f). The color
 445 scale is given in dB for the spectra and in m/s for the radial speeds.

465 Judging from the observed statistics at the Toulon HFR network, RFIs are the most frequent and
466 problematic noise (on average 2 hours at specific periods of the day) while ship pollution is sparser
467 in time and space even if it occurs every day. The perturbation induced by second-order echoes
468 is less frequent as it is bound to strong sea states and large currents. In this section, an ensemble
469 of simple methods is proposed for mitigating the aforementioned three types of noise. They are
470 mostly based on appropriate threshold criteria and therefore possibly close to the standard practice
471 of users and manufacturers. However, such techniques are rarely detailed in the literature and we
472 found it important to provide a full quantitative description that makes them reproducible.

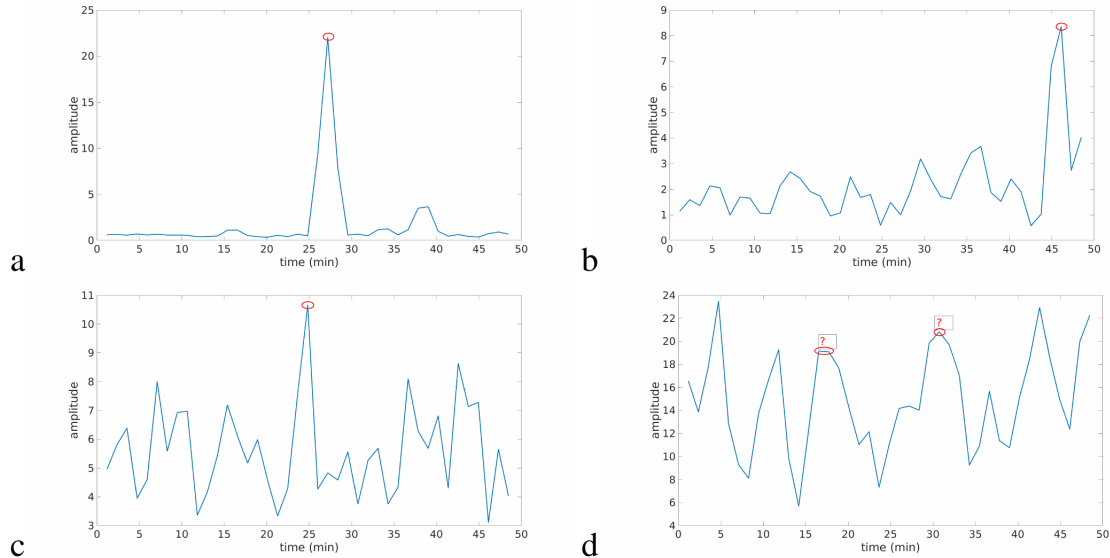
473 *b. RFI removal*

474 There exists a wealth of techniques in the radar literature for RFI removal in the context of
475 phased-array oceanographic radars. Many authors use orthogonal subspace methods to cancel the
476 noise interferences (e.g. (Zhou et al. 2005; Zhou and Wen 2012; Chen et al. 2018a)) or Complex
477 Empirical Mode Decomposition (e.g. (Chen et al. 2018b; Nazari et al. 2019)). These methods
478 have been shown efficient but are somewhat complex to apply and require some a priori assumption
479 on the mathematical description of the parasitic signal. Other techniques consist in combining the
480 radar signal with the sea echo removed with the original radar signal including the echoes; this is
481 routinely done with the WERA radar, where the FFT-based range gating process allows to store the
482 echo-free signal corresponding to negative range cell (the so-called “.RFI” files). This technique
483 is well performing and is implemented in commercial software (Gurgel et al. (2007); Gurgel and
484 Schlick (2009)) but requires an extra amount of storage and processing. Here a simple empirical
485 and versatile method is proposed, based on threshold criteria for the far-range Doppler spectrum.

486 The vast majority of RFI display a characteristic structure in the range-Doppler map, namely
487 they exhibit range-invariant vertical strips. They can thus be easily identified and removed by
488 checking the few farthest range cells for each Doppler bin. Let us denote $\hat{X}(f, d)$ the complex
489 Doppler spectrum at frequency f and range d and $R(f)$ the average power of the Doppler spectrum
490 at frequency f in the last few range cells (that is, those ranges that fall beyond the maximum
491 excursion of Bragg rays). A valid Doppler bin is qualified with a simple 3 dB SNR criterion, that
492 is requiring $|\hat{X}(f, d)|^2 > 2R(f)$, otherwise the corresponding spectral line is considered as either

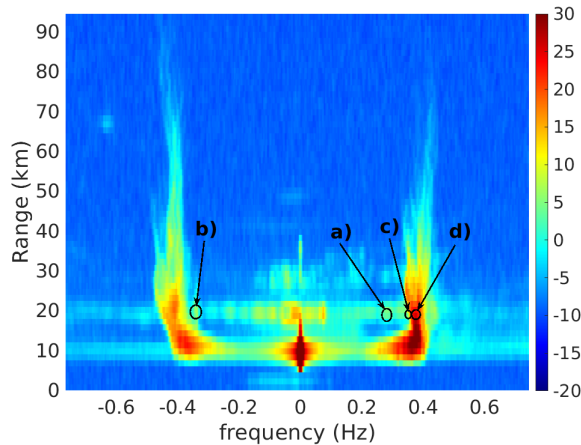
493 RFI or noise and is rejected. Figure 11a illustrates the RFI removal from the elliptical velocity
494 map in Figure 8a.

495 *c. Removal of ship echoes*



496 FIG. 9. Times series of the amplitude of Doppler spectrum at 4 distinct locations in the radar-Doppler map
497 indicated in Figure 10. a) A cell in the background noise with a presumable ship echo (circled in red); b) A cell
498 with a weak Bragg signal and a strong ship-like echo; c) A cell with a strong Bragg signal and a slightly stronger
499 ship-like echo; d) A cell with equally strong sea and ship echoes that cannot be discriminated.

502 The ship echoes are due to the strong backscattered signal from boats or floating objects. In the
503 range-Doppler maps they cause well-localized bright spots around one or several range-frequency
504 cells and this specific structure allows for their identification (Gurgel and Schlick (2005); Gurgel
505 et al. (2011)). The location of the ship echoes in the range-Doppler map varies in time as both
506 the position and radial speed of the ship change. In general, the integration time is much longer
507 that the travel time of a ship through a given radar cell. As the MUSIC DF procedure requires the
508 calculation of a large number of sub-spectra within the integration time (typically one hour), it will
509 be jeopardized by the few samples that have been contaminated by the ship echoes. The spoiled
510 samples can be easily identified through a strong amplitude peak in the time series of sub-spectra
511 at a given range-frequency cell. This is exemplified in Figure 9, where the sub-spectra have been



500 FIG. 10. An instantaneous Range-Doppler spectrum used in the time series of Figure 9. The 4 different test
 501 cells are labeled from a) to d).

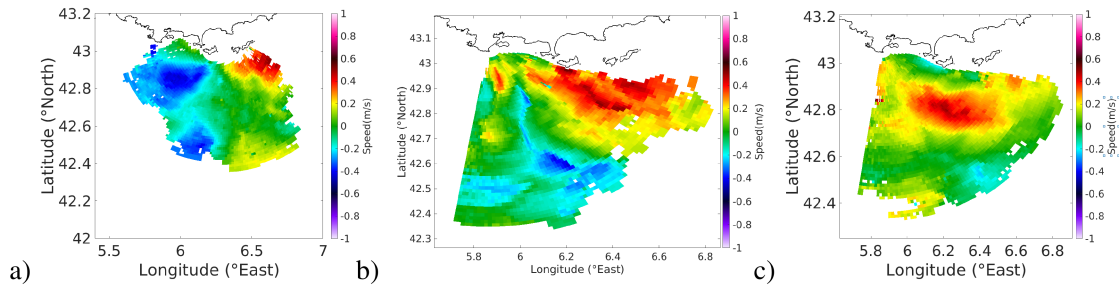
512 calculated by using 75% overlapping sliding time intervals of 6 min; they are removed before
 513 application of the DF processing. The effect of ship echoes removal is illustrated in Figure 11b.

514 There are, however, some critical but rare cases where ship echo removal is not possible. The
 515 method fails in the instances where the ship echo and the first-order Bragg peak have close locations
 516 and magnitude in the range-Doppler map, in which case they cannot be distinguished from one
 517 another. The different cases that can be encountered are illustrated in Figure 9, where very likely
 518 ship echoes have been identified (even though they could not be certified with AIS or other external
 519 information) with increasing level of criticality from a) to d), corresponding to different locations
 520 in the range-Doppler map as seen in Figure 10. The sub-figure a) shows the easiest situation of
 521 a ship crossing a range-Doppler cell in the background noise with unambiguous identification of
 522 the corresponding echo at the time stamp between 25 and 30 min. The second situation b) shows
 523 the case of a weak sea echo mixed with a strong ship echo at about 45 min which is still clearly
 524 identified. Situation c) is close to critical as the ship echo dominates the sea echo by a smaller
 525 amount and thus requires a more stringent test for elimination (that could possibly cause a false-
 526 positive). The sub-figure d) shows an instance of the critical case, where ship and Bragg echos
 527 cannot be separated. Hence, it is possible to eliminate most of the ship echoes, except for those
 528 corresponding to the critical situation d). When establishing a threshold for ship echo identification
 529 in the Doppler spectra, a trade-off must be found as usual between the probability of detection and

530 the probability of false alarm (in which case sea echos are eliminated). We chose and checked
531 empirically a threshold equal to twice the median value of the time series of spectral amplitude at
532 the range-Doppler cell.

533 *d. Removal of second-order sea echoes*

534 The second-order sea echoes are caused by the swell and wind waves. In general the first- and
535 second-order echoes are well separated by a minimum in the omnidirectional Doppler spectrum
536 and can thus be clearly identified. Classical limits for the first-order region rely on the position of
537 a “null” (that is, a minimum) in the Doppler spectrum (see e.g. Lipa and Barrick (1983); CODAR
538 (2002)). However, in the case of rough seas and/or strong currents, second-order peaks may overlap
539 the first-order Bragg region and can be misinterpreted in terms of surface currents. To overcome
540 this effect refined methods based on image segmentation techniques have been recently proposed
541 (Kirincich 2017) and shown to improve the detection of the first-order region with a small number
542 of parameters to tune. Here a simple alternative method is proposed for the elimination of spurious
543 second-order frequencies that does not require any image processing toolbox. It is based on the fact
544 that second-order peaks are usually much weaker than first-order peaks and can be removed using
545 an appropriate threshold criterion. To do this, the mean level of second-order rays is estimated
546 in each range cell d of the omnidirectional Doppler spectrum by averaging the latter in a narrow
547 frequency region at the border of the first-order Bragg frequency search domain (a typical interval
548 of width 0.05 Hz is used) leading to a reference value $B_2(d)$. In a similar way to RFI mitigation,
549 the spectral rays in the first-order Bragg region are compared with this reference value. For ratios
550 smaller than a given threshold (here 3 dB), they are interpreted as second-order and discarded
551 in the DF azimuthal processing. Figure 11c shows the result of second-order artifacts mitigation
552 on the radial current map from Figure 8f. As seen, some residual errors remain but most of the
553 second-order contributions have been eliminated. In setting the threshold, a trade-off must be found
554 between the complete removal of second-order and the loss of “true” first-order contributions.



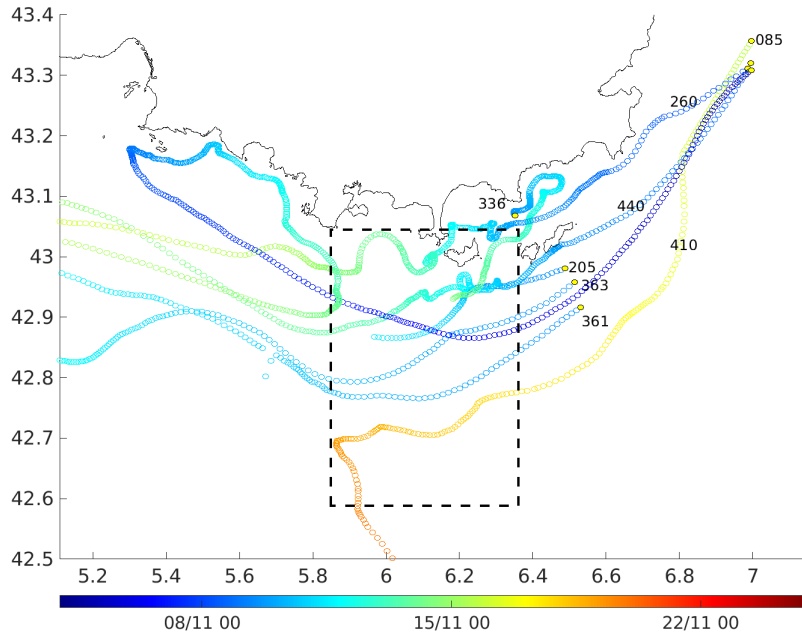
555 FIG. 11. Radial maps from Figure 8 after application of the 3 different techniques for mitigating the noise from
 556 a) RFI ; b) ship echoes; c) second-order echoes.

557 6. Performance assessment with drifters

558 a. The impact of self-calibration

559 The traditional method to assess the performances of HFR surface current measurement is to
 560 perform a comparison with in situ data such as ADCP and drifters (e.g. Graber et al. (1997); Essen
 561 et al. (2000); Ohlmann and et. al (2007); Parks et al. (2009); Kalampokis et al. (2016); Kirincich
 562 et al. (2019)). As it is well known, these comparisons are made difficult by the differences in the
 563 involved spatial and temporal scales (Rypina et al. (2014)), the measurement depth (Sentchev et al.
 564 (2017); Dumas et al. (2020)) and the Lagrangian or Eulerian viewpoints (Röhrs et al. (2015)).
 565 Nevertheless, the best comparisons achieve RMS differences for the hourly radial current of a few
 566 cm/s (e.g. Ohlmann and et. al (2007); Shay et al. (2007); Liu et al. (2014)) while most frequently
 567 the obtained RMS difference is of the order of 10-20 cm/s. Note that the difference between HFR
 568 and in situ data depends on many other factors such as the sea state (Wei et al. (2020)), the absolute
 569 magnitude of currents, or the radar cells that are selected for the comparison or the antenna pattern
 570 calibration (Kohut and Glenn 2003; Kalampokis et al. 2016). It follows that a fair comparison
 571 between any 2 different signal processing methods can only be performed using the same hardware
 572 and the same data. Here, the accuracy of radar-based surface currents will be evaluated, depending
 573 on whether they are obtained by BF or DF azimuthal processing, whether or not the self-calibration
 574 is applied, and whether or not antenna grouping and source stacking are employed.

578 In an earlier work (Dumas et al. (2020)), a first evaluation of the performances of the HFR
 579 network in Toulon was made using the newly developed processing methods (self-calibration and



575 FIG. 12. Drifter trajectories during the November 2020 campaign. 4 drifters were launched on November 9,
 576 off the Levant islands (drifters 205, 336, 361,363), 4 others came from Italy from an earlier launch (drifters 85,
 577 260, 410,440). The black dashed box shows the approximate radar coverage.

580 antenna grouping). At that time, the source stacking, multi-source calibration, and noise mitigation
 581 were not available and the methodological aspects of the DF processing were not discussed. The
 582 CARTHE drifters (Novelli et al. (2017)) were shown to be very relevant to assess the performances
 583 of HFR measurements in the near- and mid-range of the radar coverage, with only a few cm/s
 584 RMSD in comparison with the radar-derived radial velocities. They integrate the current over a
 585 depth of 65 cm which is close to the effective integration depth of the HFR at 16.15 MHz ($\lambda/8\pi =$
 586 74 cm). Here, another original campaign with the same kind of drifters is used to assess specifically
 587 the performances of the improved HFR data processing and its parametrization. The test area has
 588 been chosen wider and farther off the coast with some trajectories crossing the southern limit of
 589 the radar coverage. A launch of 4 drifters was realized on November 9, 2020, south of the Levant
 590 island in the easternmost region of the radar coverage, along a latitudinal section (43°N). This
 591 deployment strategy was dictated by the desire to target Northern Current and thus have trajectories
 592 traveling westward through the radar coverage. In addition, a cluster of 20 drifters was deployed

593 in the open sea area in front of Livorno (Italy) by our Italian colleagues from CNR one month
594 earlier (Berta et al. (2021)) and some of the drifters reached our area of interest. Combining
595 this opportunity experiment with our local experiment, a total of 8 drifters have crossed the radar
596 coverage in the period 9-12 November, some of them leaving and reentering the observation zone
597 such as the drifters 410 or 440, as shown in Figure 12.

598 The surface currents measured by the drifters were projected onto the local radial and elliptical
599 directions in order to be compared with the measurement of the corresponding surface current
600 component with the monostatic (Peyras) and bistatic (Bénat) HFR stations. To evaluate the perfor-
601 mances of the multiple source calibration, the elliptic velocity inferred from the bistatic receiver
602 in Bénat was calculated with either no external calibration, one single-source calibration (with
603 the Porquerolles or Peyras transmitter), or 2-source calibration (with the Porquerolles and Peyras
604 transmitters); similarly, the radial velocity inferred from the monostatic receiver in Peyras was
605 calculated with either no external calibration or one single-source calibration with the Porquerolles
606 transmitter. The antenna grouping and source stacking techniques were further employed to in-
607 crease the spatial coverage as described in Section b, with a choice of the DF parameters along the
608 guidelines of subsection d. The measurements along the 8 drifter trajectories and the correspond-
609 ing HFR estimations were stacked together and the global Root Mean Square Difference (RMSD)
610 between the in situ and HFR velocities was calculated along with the correlation coefficient. The
611 results are summarized in Table 1. The use of the self-calibration shows a clear improvement in
612 the accuracy, especially for the Peyras station where a reduction of about 2 cm/s is obtained for
613 the RMSD. Similarly, the use of the 2-source calibration yields slightly more accurate results than
614 with one single source.

620 *b. The impact of antenna grouping and source stacking*

621 The respective performances of antenna grouping and source stacking compared to the classical
622 MUSIC analysis were established with the bistatic Bénat receiver by calculating the RMSD of
623 drifters/HFR velocities as well as the resulting spatial coverage of surface currents. The latter
624 is defined as the percentage of successful surface current estimations on the range-azimuth grid,
625 which extends over 64 range bins (96 km) and 166 azimuthal bins (from 174 to 340 degrees
626 CCW from East). The DF estimation of surface velocities from the Bénat bistatic receiver with

	Peyras		Bénat	
	RMSD	Corr	RMSD	Corr
No calib.	9.5	0.89	10.1	0.90
POR	7.6	0.93	8.9	0.92
PEY	N/A	N/A	8.7	0.92
POR/PEY	N/A	N/A	8.2	0.93

615 TABLE 1. Statistical comparison between the HFR radial velocities measured from the Peyras and Bénat
616 stations and measured from the drifters. The azimuthal processing has been performed with DF using antenna
617 grouping and different modes of self-calibration: no calibration, calibration with the Porquerolles transmitter
618 (POR), the Peyras transmitter (PEY), or both (PEY/POR). The last two calibration modes are not applicable
619 (N/A) to the Peyras station. The Root Mean Square Difference (RMSD) is given in cm/s.

627 and without antenna grouping has been performed for a fixed number of sources ranging from 1
628 to 6 as well as with source stacking. Subarrays of size ≥ 8 have been considered and other DF
629 parameters have been set along the lines of subsection d. The results are summarized in Table
630 2. As seen, increasing the number of sources beyond 4 deteriorates the accuracy but does not
631 significantly increase the coverage. Adding antenna grouping increases the accuracy by about
632 10 – 20% and makes the coverage almost twice as large. Note that the poor performance of the
633 1-source estimation (12.1 cm/s RMSD) is mitigated by the antenna grouping technique (8.8 cm/s)
634 which can eliminate outliers in averaging the estimations of subarrays DF. The best performance
635 in all respects is achieved with combined source stacking and antenna grouping techniques.

640 *c. DF versus BF*

641 The reference of the drifter measurement allows for quantitative comparisons of the respective
642 performances of the BF and DF processing. As it is well known, both techniques have their
643 advantages and shortcomings (Laws et al. 2000). The BF yields a larger coverage with fewer
644 outliers but has a tendency to smooth the maps and diminish the contrast; it is therefore not adapted
645 to describe sharp fronts of currents. The DF can produce a higher level of detail but suffers from
646 lacunary estimation and frequent outliers. However, as these methods are in general designed for
647 different types of antenna arrays (compact arrays with DF and extended linear arrays with BF),
648 there are only a few benchmarks of the 2 techniques in the literature. To our best knowledge, this

# sources	grouping	RMSD (cm/s)	Corr	Coverage (%)
1	without	12.1	0.82	9.9
2	without	10.7	0.85	15.5
3	without	10.8	0.85	19.0
4	without	10.7	0.85	21.3
5	without	10.9	0.86	22.6
6	without	10.9	0.86	23.8
1	with	8.8	0.92	25.6
2	with	8.3	0.93	35.6
3	with	9.0	0.91	40.5
4	with	9.3	0.91	43.7
5	with	9.5	0.90	43.7
6	with	9.6	0.90	42.7
sources stacking	with	8.2	0.93	45.5

636 TABLE 2. Performances of HFR surface velocities estimation from the bistatic Bénat receiver when compared
637 to drifters velocities. The DF calculation is performed with a fixed number of sources without (upper half of the
638 table) and with (lower half of the table) antenna grouping. The last line shows the simultaneous performance of
639 source stacking (for 1 to 6) and antenna grouping.

649 has only been done in (Wang and Gill 2016), who performed such a comparison with an 8-antenna
650 array and concluded that the DF is slightly more accurate with a relative RMSD reduction of 0.8
651 cm/s. Here, this idea is pursued by comparing the radial and elliptical surface currents estimated
652 with either BF or DF azimuthal processing on the 12-antenna arrays and by taking advantage
653 of the antenna grouping method, which mitigates the main defaults of the latter (that is, strong
654 lacunarity and outliers). Note that our receive arrays illustrate both the monostatic (Peyras) and
655 bistatic (Bénat) configuration. To make a fair comparison, the same self-calibration has been
656 applied before processing and the same angular mask has been employed to ignore the regions
657 with poor SNR in the shadow of islands. The angular resolution of BF deteriorates by a factor
658 of 2 at a steering direction of 60 degrees away from the normal to the array. Therefore, an extra
659 calculation was made inside the ± 60 degrees receiving angle to evaluate the BF in appropriate
660 conditions. The results of the statistical comparison with drifter's are summarized in Table 3.
661 A significant improvement of the RMSD and the correlation coefficient is obtained with the DF

	Peyras		Bénat	
	RMSD	Corr	RMSD	Corr
DF	7.6	0.93	8.2	0.93
BF deg	9.9	0.86	15.8	0.72
DF $ \theta < 60$ deg	7.6	0.92	8.1	0.93
BF $ \theta < 60$ deg	9.2	0.86	11.2	0.85

668 TABLE 3. Respective statistical performances of the BF and DF azimuthal processing (with antenna grouping
669 and self-calibration) for the monostatic (Peyras) and bistatic (Bénat) receive stations when compared to the
670 drifters measurements. The Root Mean Square Difference (RMSD) is given in cm/s. The results are given for
671 the full radar coverage (with a land mask) and for a restricted angular opening $\theta < 60$ degrees.

662 method as compared to the BF method. Note that the amelioration is more pronounced with the
663 Bénat station than with the Peyras station. The reason is that the orientation of the antenna array
664 in Peyras is optimal to cover the NC in the Eastern direction, where most of the trajectories lie.
665 This is optimal for the resolution of the BF method, which is here employed at small incidence
666 angles. Nevertheless, the BF method is still outperformed by the DF method even in these optimal
667 conditions.

672 7. Conclusion

673 We have presented a series of techniques that improves the “voltage to current” processing chain
674 for phased-array oceanographic radars. They mostly address the azimuthal processing of sea
675 surface echoes for surface current mapping; at the same time, some simple and efficient empirical
676 solutions have been proposed to mitigate the impact of noise.

677 Range-resolved complex time series on each antenna are obtained by fast-time Fourier transform
678 of the radar signal within each chirp duration and a self-calibration is then operated on range-
679 resolved time series on the antenna array. A slow-time Fourier transform at the chirp rate is
680 applied to yield the omnidirectional Doppler spectra. These individual antenna spectra undergo a
681 denoising procedure before being combined in a DF analysis with the aforementioned improvements
682 (antenna grouping and source stacking). In the end, this leads to high-resolution surface current
683 maps. Quantitative comparisons with drifter measurements have shown the gain in accuracy that
684 can be obtained with this ensemble of techniques. A comparison has also been made with the

685 traditional BF method and has shown a global increase in accuracy and enhanced capabilities with
686 respect to this last method.

687 We hope that these novel processing techniques will be useful to other HFR oceanographic
688 networks. Preliminary results with the phased-array HFR systems in Normandy (Lopez et al.
689 2020) and in the Gulf of Trieste (Querin et al. 2021) have shown promising results. Another benefit
690 of the improved DF processing is that it no longer requires post-processing of surface current maps
691 that is usually done to fill the gaps and clean up the outliers. At this stage, the performances of
692 antenna grouping and optimal interpolation were not compared but we believe that this will be
693 beneficial in the case of big spatial gaps. Elucidating this point is left for future research.

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702 *Data availability statement.* Data are available on demand.

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