HFR OBSERVATIONS OF SURFACE CURRENTS IN TIDE DOMINATED REGIONS: IROISE SEA AND LA MANCHE

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Contribution
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OUTLINE

1. HF radar (WERA) survey in the Iroise sea.

2. Experimental settings and methodology
   a. Direction finding (MUSIC)
   b. Variational interpolation (2dVar)
   c. Stokes velocity estimation
   d. Filling gaps

3. Analysis of the interpolated fields
   a. Tidal dynamics
   b. Vorticity field
   c. Tidal and long-term residuals

4. Estimating tidal energy resources from HF radars

5. Summary
HFR observations in the Iroise sea

Two HF radars WERA operating for SHOM (Fr.Navy): northern site - Garchine, southern site - Brezellec

Operating frequency: 12 MHz

Long time series (from mid 2006 to date)

Time resolution: (1/3) h

Resolution: 10° in azimuth, 1.5 km along beam

Beam Forming (BF) algorithm provides 2d radial velocity maps

- surf. circulation derived from HFR
- num. model validation
- data assimilation in CM (coming …)
HFR data processing

- Direction finding (MUSIC) provides high resolution radial velocity maps.

**Beam Forming**
- 10° x 1.5 km

**Direction Finding**
- 2° x 1.5 km

- Variational interpolation (2dVar) - performs gap filling, smoothing,
  - provides velocity vector maps, $\text{curl } \mathbf{v}$, $\text{div } \mathbf{v}$ & error estimates.
Constrained interpolation of HFR data

Variational interpolation (2dVar) or constrained interpolation (Yaremchuk & Sentchev, CSR, 2009)

\[ J_d = \frac{1}{2} \sum_{k=1}^{K} \sigma^{-2} (v_k^*) [(v \cdot r_k) - v_k^*]^2 \]

\[ J_r = \frac{1}{2} \int_{\Omega} \left[ W^d(x, y)(\Delta \text{div} v)^2 + W^c(x, y)(\Delta \text{curl} v)^2 \right] d\Omega \]

Comparison showed that 2dVar is more flexible in reconstruction of the small-scale features of circulation (for diff noise level).

Provides more realistic interpolation within large gappy zones and when the discretization of the HFR data is comparable with the length scales of the reconstructed features.

Local & OMA interp.

(Muller et al., JMS, 2009)
Wave & wind induced currents

Contributions to total current, $U_R$, measured by the radar:
- Surface Ekman current, $U_E$
- Stokes current, $U_{SS}$ ($U_{10}$: wind speed)

*Ardhuin et al., JPO, 2008*

$$U_{SS}(f) = 1.25 \times 10^{-4} (5 - (2f)^{-1}) U_{10} \cdot \min(U_{10}, 14.5) + 0.025(H_S - 0.4)$$

High wind conditions ($U_{10} \sim 13\text{m/s}$)

Weak (<10-12 cm/s) but non-negligible contribution of wave induced current to total current velocity
EOF-based gap-filling technique

Caused by occasional malfunction (3-30h)
Acting on radial velocity before interpolation

Yaremchuk & Sentchev 2011

1. gap filling

Alvera-Azcarate et al. 2005

compute zeroth-approximation to C:

\[ C_{ij} = (\bar{v}_i - \bar{v}_j)(\bar{v}_j - \bar{v}_j); \quad \varphi_i \varphi_j = \frac{1}{N} \sum_{n=1}^{N} \varphi_{i}^{n} \varphi_{j}^{n} \]

expand \( u(x_k \in \Omega \setminus \Gamma^n) \) in \( K_a \) modes of C:

\[ \text{EOF decomposition} \quad \text{find } \alpha_i : \sum_{x_k \in \Omega \setminus \Gamma^n} \left[ u(x_k) - \sum_{i=1}^{K_a} \alpha_i^2 e_i(x_k) \right]^2 \to \min_{\alpha_i} \]

fill the gaps \( \Gamma^n \) using these expansions:

\[ \text{gap filling} \quad u^*(x_k \in \Gamma^n) = \sum_{i=1}^{K_a} \alpha_i^2 e_i(x_k \in \Gamma^n) \]

estimate the time-mean approximation error in \( u \):

\[ \varepsilon^2 = \frac{1}{N} \sum_{n=1}^{N} \sum_{x_k \in \omega} \left( u^*(x_k) - u(x_k) \right)^2 \]

compute new C using the filled data set

Highly efficient for small-scale gap-filling
Efficient for large-scale interpolation of gappy data (especially in tidal sea)
Tidal current field reconstruction by EOF/2dVar

Tidal ellipses obtained by 24-hour averaging of the interpolated velocity fields when only one radar was operating (CGN). Pattern a is obtained by 2dVar method, pattern b by the combined EOF/2dVar analysis. The reference pattern c is derived from averaging over two 12-hour periods preceding the period of malfunction of the WMX radar.
Results: Tidal currents

PCA-derived synthetic ellipses during primary spring tide (7-d averaged)

Rotary pw spectra & rotary coefficient

\[ r = \frac{(S_+ - S_-)}{(S_+ + S_-)} \]

- \( r < 0 \) for cw motion
- \( r > 0 \) for ccw motion
- \( r = 0 \) for unidirectional flow

(Emery, Thompson, 1997)

(Sentchev et al., ECSS 2009; Sentchev & Yaremchuk, CSR 2007)
Tidal current variability

Time/Space variations of the amplitude of tidal currents

1 to 4 m/s vel. variation

1.7 to 3.8 m/s

Spatial variability

Vel. magnitude > 1 m/s (majority of the domain)
Max velocity ranges from 0.7 to 4 m/s
Min velocity ranges from 0.2 to 1.7

Variability of cur. ellipses in two particular locations (the strongest current)

<table>
<thead>
<tr>
<th>Tidal constit.</th>
<th>M2</th>
<th>S2</th>
<th>N2</th>
<th>M4</th>
<th>MS4</th>
<th>2MN6</th>
<th>M6</th>
<th>2MS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Ushant</td>
<td>1.74</td>
<td>0.92</td>
<td>0.47</td>
<td>0.15</td>
<td>0.16</td>
<td>0.06</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>B: Fromveur</td>
<td>2.09</td>
<td>0.83</td>
<td>0.35</td>
<td>0.12</td>
<td>0.09</td>
<td>0.12</td>
<td>0.16</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Tidally generated eddies

Average vorticity field

- generation by bottom friction
- advection by tidal currents
- time-averaged vorticity of opposite sign appears on both sides of a cape or island

(Zimmerman, 1980; Robinson, 1983; Pingree et al., 1985)

Currents during one td cycle
Residual currents

**Features:**
- High velocity values (up to 0.5 m/s)
- Rotational field (permanent eddies)
- Control of the RC by bathymetry
- Off-shore and near-shore jets
- Pronounced fortnightly variability
Non-tidal residuals (late summer 2007)

Ushant thermal front

Temp. along the 48°N section on 14 Sep, 2007
(Le Boyer et al., CSR 2009)

SST on 14 Sep 2007 from MODIS

48.25°N

Observed wind

Time evolution of the RC along 48.25°N
(S-N velocity component)

RC : tidal currents removed
grey line – zero velocity contour

Long-term residuals :
Stokes, wind-induced vel. removed

14 Sep

Vel. scale (m/s)

Signature of the Ushant thermal front
is visible in the field of long-term residual velocities
Estimating Tidal Current Energy Resources from HFR

HFR measurements - efficient, reliable way for quantifying the Power Production Potential (PPP)

Useful for searching for the best location of tidal in stream energy conversion devices

Account for real conditions, wave-current coupling effect, non-linear dynamics, …

Complementary to modeling

Tool for improving model prediction of tidal stream energy resource at a given location

Siemens & Bluewater project for bay of Fundy

Siemens project for Wales coast

Curr. velocity at spring tide (model)
Mean (lines) and maximum (color) velocity magnitude from HFR velocity records in the Iroise sea.

Tidal current ellipses for mean tide & polarisation (+/- : red/bleu)

Variability of cur. direction

Current asymmetry
Tidal Current Asymmetry

Estimation: \( a = \frac{<V_{\text{flood}}>}{<V_{\text{ebb}}>} \)

The origin: compound tides & tidal residual

\[
U_1 \cos(\omega t) \cdot U_1 \cos(\omega t) = \frac{U_1^2}{2} \cos(2\omega t) + \frac{U_1^2}{2}
\]

Consistent with (Friedrich and Aubrey, 1990)

\[ \Delta \phi = 2 \phi_{M2} - \phi_{M4} \]
Power production

\[ P = \frac{1}{2} \rho \bar{u}^3 A c_p \]

\( \bar{u} \): depth avg vel \((0.8 \ U_{rad})\)

Frequency of occurrence (%) for particular velocity values
Site screening: Pas de Calais

VHF radar survey, ERMANO (Sentchev, 2007)

Velocity magnitude (max 2.5 m/s)

Freq of occurrence for V > 1 m/s

Current asymmetry: 1.5

Residual current velocity

Site screening: Pas de Calais

VHF radar survey, ERMANO (Sentchev, 2007)
Summary

1. HFR measurements are extremely useful for identification of areas with high Energy Potential (more precise, more reliable than model)

2. Based on time series analysis of HFR data, the power production becomes predictable. How to obtain more regular power production by combining devices in arrays: HFRs help for searching the best location, orientation, type of device, ...

3. Portable, easy to deploy HFR systems will be very helpful

Assessment of tidal dynamics in the Iroise sea

1. We have developed and applied a powerful technique (MUSIC & 2dVar) for processing, interpolating HFR measurements, filling gaps and smoothing HFR data. Contribution of wave-induced current is estimated

2. High quality current velocity maps were derived from the radar data and might be used for numerical model validation and data assimilation

Novel features:

a. Extremely strong (400%) variability of tidal currents in the vicinity of Ushant Island and strong eddy dynamics.

b. Coherent structures of vorticity generated by oscillating tidal currents around the Ushant Island.

c. The tidal RC fields evidence two principal jets (near-shore and off-shore) aligned with depth contours. High RC velocity is detected.

d. Ushant thermal front was visible in August 2007 in the field of long-term residual currents.
Radial Velocity Data

dynamical constraints (equations) & error covariances

outlier removal, gap-filling, error covariances

gapped vector data

weak dynamic & kinematic constraints

from, eg. OMA, 2dvar

assimilation

Optimal Model solution

forecast skill
OMA Open Boundary Modal Analysis

Kaplan & Lekien 2007

[parent method: NMA Lipphardt et al. 2000]

Principe: ajustement optimal des modes décrivant les structures possibles du courant aux mesures

\[ Q = \sum_{m=1}^{M} W_m^{(u)} \sum_{m=1}^{M} (\alpha_i u_i(\bar{x}_m) - u_{m}^{mes})^2 + \text{idem pour } V_i \]

M mesures, N modes

\[(u, v) = \sum_{j=1}^{\infty} \alpha_j^w \hat{k} \times \nabla \psi_j + \sum_{j=1}^{\infty} \alpha_j^p \nabla \varphi_j + \sum_{j=1}^{\infty} \alpha_j^b \nabla \varphi_j^b\]

modes : divergents (Neumann) a rotationnels (Dirichlet) frontière

Fernandez, Ferrer 2012

Pre-defined region where modes are computed and open (dashed line) and closed (continuous line) boundaries are defined.

Three sets of basic functions (truncated at an spatial resolution of 25 Km):

- Dirichlet (53) - vorticity
- Neumann (72) - divergence
- Boundaries (29) - normal flow through boundaries
**Period of analysis**

Mid-spring: 10 Apr – 5 May 2007

- Strong tidal forcing (range ~7m) and moderate winds

Late summer: 24 Aug – 19 Sep 2007

- Strong tidal forcing and more strong winds