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Almar, R

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## On the use of the Radon transform to estimate longshore currents from video imagery

Rafael Almar<sup>1,\*</sup>, Stanislas Larnier<sup>2</sup>, Bruno Castelle<sup>3</sup>, Timothy Scott<sup>4</sup>, France  
Floc'h<sup>5</sup>

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### Abstract

A direct estimation of longshore currents using in-situ instruments is difficult and costly, and often limited to punctual measurements over short durations. Video remote sensing systems offers an alternative when drifting features, like foam induced by breaking waves or other streaks, are visible. In this paper we describe a method based on the application of the Radon transform on longshore spatio-temporal images. The sinogram from the Radon transform is used to find the angle of the drifting, further converted into current. Our approach is first tested using synthetic fields created using anisotropic Gaussian random currents and waves. Comparison is also made with in-situ currents from the Grand Popo 2014 experiment in Benin (Gulf of Guinea, West Africa). Results show an overall good agreement ( $O(30\%)$ ) in the swash, surf and inner shelf zones while the method offers best skills in the surf zone (17%) where the drifting foam induced by wave breaking is evident. The width of the Radon peak is found to be a good proxy of accuracy. This remote sensing method allows a long term monitoring of the longshore current and its cross-shore structure, which brings new perspectives in quantifying sediment drift variability.

*Keywords:* Nearshore, Video imagery, anisotropic Gaussian random fields,

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\*Corresponding author

*Email address:* [rafael.almar@ird.fr](mailto:rafael.almar@ird.fr) (Rafael Almar)

<sup>1</sup>IRD-LEGOS (CNRS/Univ. Toulouse/IRD/CNES), Toulouse, France

<sup>2</sup>CNRS-LAAS, Toulouse, France

<sup>3</sup>EPOC (CNRS/Univ. Bordeaux), Bordeaux, France

<sup>4</sup>University of Plymouth, UK

<sup>5</sup>LDO-IUEM, Brest, France

## 1. Introduction

Longshore current has attracted a major attention in the nearshore science for decades, generally within the scope of estimating longshore sediment transport (Komar, 1998). It is generated by oblique breaking waves, is rather vertically uniform and can reach values up to meter per second (Komar & Inman, 1970; Lippmann, 1970). Observations have shown that longshore current peaks at the location of the maximum of breaking and can present a multi-modal structure in case of barred beach (Schoonees & Theron, 1993; Putrevu & Svendsen, 1995; Haller & Svendsen, 2002; Feddersen, 2014). Tidal modulation of wave breaking and subsequent longshore current can be large, in particular at low tide terrace and barred beaches (Thornton & Guza, 1986; Feddersen, 2003), and intense current ( $> 0.5$  m/s) have shown to present a substantial variability at low frequency scales (minutes), likely explained by shear instabilities (Allen et al., 1996; Oltman-Shay et al., 1989). At longer term, seasonal to inter-annual fluctuations are likely to be induced by wave conditions modulation due to climatic modes (Splinter et al., 2012; Almar et al., 2015). Suited documentation on its multi-scale spatio-temporal evolution has long been hampered by difficulties in measuring such fluctuating structures by conventional in-situ instrument arrays, while the application of recent shore-based remote sensing methods has a large potential.

Radars and video imagery have proved to be very efficient tools in monitoring the nearshore and in particular the surface current (Holman & Haller, 2013), for a reasonable running cost and over typical areas of kilometers and footprint of meters. Radar-based Doppler effect of backscattered signal from rough surface (Haller & Svendsen, 2014) is probably the most direct way in estimating surface currents. Video systems have been developed for over twenty years (Holman & Haller, 2013). From their incomparable low cost ( $< 1000$  eur) and intuitive use, video stations are rapidly growing over world coasts, including developing coun-

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9 29 tries, offering the exciting potential of an unequaled documentation of coastal  
10 30 zones from local to regional scale (Mole et al., 2013). Video methods were ap-  
11 31 plied originally to estimate submerged and intertidal bathymetry (Lippmann  
12 32 & Holman, 1990; Stockdon & Holman, 2000) and time-varying location of the  
13 33 shoreline (Plant & Holman, 1997). Following the improvement of sensors resolu-  
14 34 tion, an increasing number of methods have been developed recently to quantify  
15 35 wave’s characteristics (Lippmann & Holman, 1991; De Vries et al., 2011; Stock-  
16 36 don & Holman, 2000; Almar et al., 2012) but only a few were dedicated to  
17 37 surface currents (Holman & Haller, 2013), though its key importance.

18 38 In this paper, we are interested in estimating the longshore current from  
19 39 video, in a similar way to (Chickadel et al., 2003). This contrasts with the two-  
20 40 dimensional approach based on a Particle Image Velocimetry (PIV) method  
21 41 (Holland et al., 2001; Puloe et al., 2003) generally applied in laboratory experi-  
22 42 ments (Cox & Anderson, 2001; Kimmoun & Branger, 2007) because it requires  
23 43 high temporal and spatial resolutions. Our choice of a one-dimensional ap-  
24 44 proach rises from the availability of video spatio-temporal images (also called  
25 45 Hovmoller diagram or timestack) widely used to conserve high frequency infor-  
26 46 mation of cross-shore and longshore waves and current components, avoiding  
27 47 saving the whole high frequency video, which is particularly pertinent for long  
28 48 term monitoring. The second interest is because spatio-temporal format is per-  
29 49 fectly suited for angle separation methods based on the Radon transform (RT,  
30 50 (Radon, 1917)). The RT has recently been successfully applied to ocean waves,  
31 51 in particular for the detection of ship wave (Copeland et al., 1995) and more  
32 52 recently to nearshore wave dynamics (Yoo et al., 2011; Almar et al., 2014a)  
33 53 and swash (Yoo et al., 2009) but no attempt was conducted to estimate the  
34 54 longshore current, despite the high potential of use.

35 55 In the next section our method is tested over synthetic data and field observa-  
36 56 tion from Grand Popo, Benin (Gulf of Guinea, West Africa). The Bight of Benin  
37 57 is subject to increasing erosion due to anthropic perturbation of the strong long-  
38 58 shore sediment transport (approximately  $500.000 \text{ m}^3/\text{yr}$ , (Almar et al., 2015))  
39 59 exacerbated by the rapid development of deep water harbors in the main cities



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60 from Accra to Lagos. Observing and quantifying this longshore drift is crucial  
10 here to improve coastal zone management. The RT algorithm is described in  
11 the first section and the synthetic and field datasets used in this paper are pre-  
12 sented in the second section. In third section, the method’s skills are tested  
13 against these synthetic and field data, an application is provided to illustrate  
14 the potential of the method and finally some concluding remarks are given.  
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20 **2. Radon transform and algorithm**

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22 *2.1. Radon transform*

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24 The Radon transform (Ramm & Katsevich, 1996; Mallat, 2008; Feeman,  
25 2010)  $R(\rho, \theta)$  over a bi-dimensional field  $\mu(x, y)$  can be defined as:  
26

$$27 \quad R(\rho, \theta) = \iint \mu(x, y) \delta(x \cos(\theta) + y \sin(\theta) - \rho) dx dy \quad (1)$$

28  
29 where  $\delta$  is the Dirac delta function,  $\theta$  and  $\rho$  are respectively the angle and  
30 distance from origin of the integration line defined as  $\rho = x \cos(\theta) + y \sin(\theta)$ .  
31 The origin is the center of the two-dimension field. The Radon transform  $R(\rho, \theta)$   
32 is defined for all possible values of  $\theta$  from  $[0 \text{ to } 180^\circ]$  and  $\rho$  from 0 to the diagonal  
33 length.  
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39 [Figure 1 about here.]

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41 The Figure 1 shows the application of the RT to a disk and inclined lines.  
42 The projection of a disk in Figure 1.a has a constant density at all angles while  
43 the projection of the lines in Figure 1.d has two peaks, indicating their angles  
44  $\theta$ .  
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48 [Figure 2 about here.]

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51 *2.2. Orientation detection algorithm*

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53 Figure 2 illustrates the application of the RT to a realistic video longshore  
54 timestack (120×120 pixels, with spatial and temporal resolution of  $dx = 0.25$   
55 m/pix and  $dt = 0.5$  s/pix respectively. Figure 2.a shows the raw image where  
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85 both wave crests and drifting foam can be seen. A high-pass radius filter (run-  
86 ning average) is applied in the polar space to isolate highly-textured small-scale  
87 foam streaks and remove signal longer than a threshold (here  $\rho < 20$  points)  
88 associated to water background intensity value, remaining foam and long wave  
89 crests. Figure 2.b shows the resulting image used to determine the orientation  
90 of the current. Figure 2.c shows the RT of the image in Figure 2.a where prop-  
91 agating features are clearly visible as local maxima. RT resolution increases for  
92 oblique angles around  $45^\circ$ ; it is recommended that the user adapt either spatial  
93 or temporal resolution in order not to squeeze signal at  $0^\circ$  or  $90^\circ$  (horizontal  
94 or vertical lines). The maximum of variability in the polar domain provides  
95 the dominant propagation angle  $\theta$  (see previous section), which can be further  
96 converted into current velocity  $V = \tan(\theta)dx/dt$ , where  $dx$  and  $dt$  are spatial  
97 and temporal resolution, respectively.  $V$  stands for the dominant velocity of the  
98 features over the image. Noteworthy, a localized RT or local maxima detection  
99 can be applied to retrieve the velocity  $V(x, t)$  of individual features.

### 100 3. Data

#### 101 3.1. Synthetic cases

102 In order to perform a first validation of a current orientation detection algo-  
103 rithm, it is possible to simulate synthetic longshore timestacks (Chickadel et al.,  
104 2003). The approach proposed in this article is based on anisotropic Gaussian  
105 random fields.

106 The Matlab code titled "Generation of Random, Autocorrelated, Periodic  
107 Fields" by Cirpka, O.A., available online on <http://m2matlabdb.ma.tum.de> was  
108 used to create anisotropic Gaussian random fields. The method utilizes the  
109 fact that the Fourier transform of the covariance function is the power spectral  
110 density function of all realizations. Random autocorrelated fields are generated  
111 by creating random phase spectra meeting the conditions of real numbers in  
112 the physical domain. The realizations are then given by back-transformation of  
113 the power- and phase-spectrum into the physical domain. Since the method is

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9 based on the discrete Fourier transformation, the generated fields are periodic  
10 rather than stationary.  
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12 The synthetic cases generated for this paper have  $100 \times 100$  pixels size,  
13 Gaussian laws of mean 0 and variance 10. Figures 6.a-c present one synthetic  
14 case created with our approach. Figure 6.a shows a first anisotropic Gaussian  
15 random field representing the foam pattern. The anisotropy can be compared to  
16 an ellipse with a major and minor axes, which are described here by correlation  
17 lengths of the signal in  $x$  and  $y$ , and an orientation  $\theta$ . If the ratio of correlation  
18 lengths decreases, the ellipse is more elongated and the anisotropy increases.  
19 The correlation lengths in Figure 6.a are 20 and 2 pixels in  $x$  and  $y$ , respectively.  
20 The orientation is  $\theta = 55^\circ$ . A second anisotropic Gaussian random field is shown  
21 in Figure 6.b representing the incoming waves with correlation lengths in  $x$  and  
22  $y$  of 50 and 2 pixels, respectively. The orientation of the wave field is  $\theta = 0^\circ$ .  
23 In Figure 6.c, they are combined to obtain a realistic test case.  
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26 Based on this initial wave-current field, Figures 6.d-f illustrate the influence  
27 of the correlation length ratio on the anisotropic Gaussian current fields. The  
28 correlation length ratio are 0.05, 0.15 and 0.25. Foam anisotropy decreases when  
29 correlation length increases, making streaks angle less evident.  
30

31 To take into account for different levels of drifting streaks signature with  
32 waves and lighting conditions, an intensity threshold is applied. In Figures  
33 6.f-h, the level of kept information are described by the percentage of pixels  
34 not changed, 30%, 50% and 70%, respectively. The lower the percentage of  
35 kept information is, the weaker are the foam streaks and more difficult their  
36 detection.  
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### 39 3.2. Field observations

40 The Bight of Benin(Figure 3) is a sandy open wave-dominated microtidal  
41 environment exposed to long period swells (ECMWF Erainterim reanalyse 1979-  
42 2013 annual deep water wave averages:  $H_s=1.36$  m,  $T_p=9.4$  s, Dir= $S - SW$ ,  
43 see Dee (2011)) generated at high latitudes in the South Atlantic. The beach  
44 (Figures 2 and 3) presents an longshore-uniform low tide terrace and a steep  
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9 144 upper shoreface. An eastward littoral drift of 0.8 to 1.5  $m^3/yr$  has been reported  
10 145 in the literature (Anthony & Blivi, 1999; Blivi et al., 2014), driven by year-round  
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12 146 oblique long swells (Almar et al., 2015).

13  
14 147 A field experiment was conducted at Grand Popo beach (6.2°N, 1.7°E, Fig-  
15 148 ure 3) from 10 to 18 March 2014 (Almar et al., 2014b). Inner shelf waves and  
16 149 currents were measured using an Acoustic Doppler Current Profiler (ADCP)  
17 150 moored in 10-m depth. Every day, various drifters releases were conducted in  
18 151 the surfzone around mid-tide to determine longshore current variability (Castelle  
19 152 et al., 2014). An Acoustic Doppler Velocimeter (ADV) was deployed in the  
20 153 swash zone during daylight hours. Hourly wind observations are provided by  
21 154 Cotonou airport, 80-km distant from Grand Popo and 500 m from the shore  
22 155 (i.e. sea breeze is observed). Figure 8 shows that during the experiment, tide  
23 156 varied from neap to spring tidal ranges, from 0.3 m to 1.2 m, respectively).  
24 157 Waves were energetic and relatively long ( $1.2\text{ m} < H_s < 1.6\text{ m}$  and  $T_p = 10\text{-}12$   
25 158 s), with initial higher waves (up to 1.8 m), coming from south-west, generating  
26 159 consistent eastward longshore currents. Surf zone longshore current varied from  
27 160 0.4 m/s to 0.8 m/s, inner shelf current from 0.05 to 0.3 m/s, and swash current  
28 161 from 0 to 0.5 m/s.

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31 162 A long-term video camera VIVOTEK IP7361, 1600x1200 pixels (Figure 3.c)  
32 163 was deployed in February 2013 (Almar et al., 2014b) on a 15 m-high semaphore  
33 164 belonging to the navy of the Republic of Benin, 80-m distant from the shore  
34 165 (i.e. which is the approximate beach width). During the experiment, full 2-Hz  
35 166 videos were stored. Rectification of images from pixels into real world coor-  
36 167 dinates was accomplished by direct linear transformation using GPS ground  
37 168 control points (Holland et al., 2013) after a correction of the lens radial dis-  
38 169 tortion (Heikkila & Silven, 1997) (Figure 3.d). Although varying somewhat  
39 170 throughout the field of view, the pixel footprint was less than 0.1 and 0.05 m in  
40 171 the region of interest (surf-swash zones of the instrumented zone) for cross-shore  
41 172 and longshore direction, respectively (Figure 4). In the video data, the location  
42 173 of swash and surf zones were estimated from 10-min averaged cross-shore pixel  
43 174 intensity timestacks; the location of the surf being estimated as the maximum  
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175 of breaking-induced intensity and the swash as the transition between the beach  
176 and surf (see illustration in Figure 5). Inner shelf video point is chosen constant,  
177 close to the location of the ADCP. For the use of the RT, 100-m long longshore  
178 spatio-temporal images (Figure 4) are reinterpolated on a regular grid of 0.25 m  
179 and separated into subwindows of 5 m (see sensitivity analyze of the RT on res-  
180 olution and windows size in Section 4.2), for resulting sub-images of 20 pixels  
181 in space and 120 pixels in time and a regular spatial grid of 5 m both in the  
182 cross-shore and longshore directions.

183 [Figure 3 about here.]

184 [Figure 4 about here.]

185 [Figure 5 about here.]

186 [Figure 6 about here.]

187 **4. Results and discussion**

188 *4.1. Tests on synthetic data*

189 A numerical study is performed to determine the sensitivity of the method's  
190 skill on the drifting streaks anisotropy, intensity and orientation (i.e. velocity).  
191 Numerous synthetic realistic timestacks are generated to cover a wide range of  
192 conditions. Figure 7 presents the results of the sensitivity analysis. Figure 7.a  
193 shows that method's skills increase with anisotropy (and decrease with correla-  
194 tion length ratio) of the Gaussian random current fields. Figure 7.b shows that  
195 the threshold value on the current field has not a substantial influence, which  
196 indicates that the method is able to detect weak drifting streaks, as encountered  
197 offshore of the surf zone. Results in Figure 7.c show that the orientation affects  
198 the estimation, with a better accuracy at oblique angles close to 45°.

199 [Figure 7 about here.]

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200 *4.2. Comparison with in-situ measurements*

201        Figures 8 and 9 show that video and in-situ currents are in good agreement,  
202 with a RMS error of 0.07 m/s (35%,  $R^2 = 0.65$ , significant at the 95% level).  
203 RMS errors are 0.06 m/s (17%), 0.09 m/s (44%) and 0.07 m/s (29%) for the  
204 surf, swash and inner shelf zones, respectively. The RT method offers better  
205 skills in the surf zone because of clear drifting foam (Figure 4) but is able to  
206 estimate the current at more challenging zones where optical signature is weaker:  
207 oscillating drift in the swash and turbidity streaks at the inner shelf. These  
208 results show the ability of the RT-based method in estimating the whole cross-  
209 shore profile of longshore surface current with a better spatial and temporal  
210 resolution than any in situ deployment, though accuracy is lower (O(30%)).  
211 Figure 10.a shows that the error is linked to the width of the RT peak width  
212 in the polar space (correlation coefficient of 0.42, significant at 95% level), the  
213 uncertainty increasing with the peak width. This can be used as a proxy to  
214 discard estimates with large uncertainties encountered for afternoon sea breeze  
215 or sun glint. Figure 10.b shows that the choice of the spatial dimension has  
216 only a minor influence. In the contrary, the method accuracy increases with  
217 resolution. The resolution might explain part of the errors in the inner shelf,  
218 where the pixel footprint worsen to 1-2 m/pixel (Figure 4). Finally, even if  
219 the main source of discrepancy can be attributed to the video method itself  
220 and geometrical characteristics, in-situ data can cause some spreading in our  
221 results, though it is difficult to quantify. Some studies reported accuracy of 0.01  
222 to 0.5 m/s (MacMahan et al., 2009) for instant drifter velocities, which is largely  
223 reduced by our hourly averaging. The longshore current is considered vertically  
224 uniform. However, some discrepancies may arise between video estimate at  
225 the surface and in-situ measurements in the water column: 35-cm and 1-m  
226 average from the surface for the ADCP and the drifters, respectively, and a few  
227 centimeters above the bed for the swash ADV.

228        To illustrate the potential of our method, Figure 11 shows its application  
229 to the cross-shore structure of the longshore current. Video-derived profile in  
230 Figure 11.a shows a good agreement with in-situ measurements, peaking in the

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231 surf zone and extending to the inner shelf. Swash, surf and inner shelf currents  
232 have different behavior. A multiple linear regression with the main forcing  
233 (longshore wave energy flux, tide and wind) was conducted over the experiment  
234 duration (hourly averaged, when video estimates are available). The relative  
235 contribution of each forcing was computed as the ratio of individual variability  
236 (variance) over the total reconstructed variance by the multiple liner regression.  
237 Figure 8 shows that the swash is dominantly influenced by tidal modulation  
238 (40%) of wave action rather than by offshore wave height (30%), certainly due  
239 to tidal modulation of surf zone saturation; surf zone is as expected largely  
240 dominated by wave action (65%) and wind dominates (20%) at the inner shelf.  
241 The decrease of the total reconstructed signal with the distance to the shore  
242 (from 90 % in the surf to 25 % on the shelf) denotes the difficulties in retrieving  
243 the surface current with decreasing pixel resolution and less drifting features,  
244 but also suggests a complex transitional zone behavior, influenced by both inner  
245 shelf and nearshore processes. This difference of forcing for the three zones has  
246 considerable implications in terms of longshore sediment drift. The possibility  
247 of using the RT to estimate longshore current clearly provides new perspectives  
248 in quantifying the longshore sediment drift and its variability.

249 [Figure 8 about here.]

250 [Figure 9 about here.]

251 [Figure 10 about here.]

252 [Figure 11 about here.]

253 **5. Conclusions**

254 Our understanding of the nearshore longshore current has been hampered  
255 for long by the lack of adapted tool. This article presents a new approach to  
256 estimate longshore currents from video spatio-temporal fields using the Radon  
257 transform, recently applied to waves (Almar et al., 2014a). It is an alternative

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258 to other approaches in one (Chickadel et al., 2003) and two dimensions (Holland  
259 et al., 2001). The Radon transform is tested and validated on synthetic and field  
260 data collected during the Grand Popo 2014 (Benin, West Africa) experiment.  
261 A sensitivity analyze using synthetic data shows that method’s skills improve  
262 with streaks anisotropy and for oblique orientation close to  $45^\circ$  but stays fairly  
263 insensitive to the level of streaks signature. Comparison with field data shows  
264 a good agreement ( $O(30\%)$ ) in the swash, surf and inner shelf zones with RMS  
265 errors of 0.06 m/s (17%), 0.09 m/s (44%) and 0.07 m/s (29%), respectively.  
266 Error worsen when resolution decreases and Radon transform polar density peak  
267 enlarges. A first application of this method shows that during the experiment,  
268 swash, surf and inner shelf longshore currents were controlled preferentially  
269 by tide, waves and wind, respectively. This clearly illustrates the potential of  
270 such remote method in quantifying the longshore current, in particular when  
271 considering its spatio-temporal variability and the need to cover longer scales.

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276 Benin at Grand Popo for their logistic support during the field experiment and  
277 for allowing the installation of the permanent video system on the semaphore.

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392 **List of Figures**

393 1 Radon transform (RT) practical use. RT of a disk and inclined  
394 lines in upper and lower panels respectively, and from left to  
395 right: original fields, RT in polar space, and resulting integrated  
396 angular density. . . . . 18  
397 2 Illustration on the separation of waves from drifting features in  
398 longshore spatio-temporal images using the RT. a) mixed wave-  
399 current intensity timestack, b) wave-filtered current timestack  
400 and c) Polar space visualization of timestack in b). Grand Popo  
401 spatio-temporal longshore image from video,  $dx = 0.25m/pix$ ,  
402  $dt = 0.5s$ . Dashed line at  $\theta = 106^\circ$  shows the variance maximum,  
403 or dominant velocity ( $V = 0.14m/s$ ). . . . . 19  
404 3 Grand Popo beach (6.2°N, 1.7°E), in the Bight of Benin, Gulf of  
405 Guinea West Africa (a-b). c) Permanent video camera, on a 15-  
406 m high semaphore and d) rectified 15-min averaged image from  
407 video system. . . . . 20  
408 4 Instant video image with superimposed black iso-contours of pixel  
409 footprint (m/pix) in the longshore direction and in white loca-  
410 tion of 100-m long longshore spatio-temporal transects, b) in the  
411 swash, c) surf and d) inner shelf zones. Drifting features at these  
412 3 zones are clearly visible. . . . . 21  
413 5 Cross-shore timestack derived from time-averaged images. Time-  
414 varying swash and surfzone locations used in the RT method are  
415 superimposed. Inner shelf location is taken constant. . . . . 22  
416 6 Examples of synthetic test cases, a-c): from left to right, anisotropic  
417 random Gaussian currents and wave fields and a combination of  
418 both. Random Gaussian current field with in d-f) from left to  
419 right, correlation ratio of 0.05, 0.15 and 0.25, and in g-i) from  
420 left to right, thresholds on kept pixels of 30%, 50% and 70%. . . 23  
421 7 Sensitivity analyze on RT skills in retrieving current velocity from  
422 synthetic Gaussian random current fields. RMSE error as a func-  
423 tion of a) Correlation length ratio (isotropy), b) threshold on kept  
424 information (in percent of pixels not changed) and c) orientation  
425 (or velocity). . . . . 24  
426 8 Forcing and longshore current during Grand Popo 2014 experi-  
427 ment. a) Waves ( $H_s$ ,  $T$ ,  $Dir$ ) and b) tide measured by ADCP, c)  
428 observed wind at Cotonou airport d) Comparison of co-localized  
429 video (continuous line) and in-situ current measurements in the  
430 surf zone (red), swash (black) and inner shelf (blue), from drifters,  
431 ADV and ADCP, respectively. . . . . 25  
432 9 Video-derived versus in-situ current, in the surf zone (red), swash  
433 (black) and inner shelf (blue), from drifters, ADCP and ADV,  
434 respectively. . . . . 26

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435 10 RT-method error as a function of a) RT-transform peakness (width  
436 of the peak in polar space) and b) resolution (0.1 m/pixel (triangles), 0.2 m/pixel (circles) and 0.4 m/pixel (squares)) and spatial  
437 dimension (pixels). In a) are shown estimates for the inner shelf  
438 (blue), surf- (red) and swash-zones (black). . . . . 27  
439  
440 11 a) Cross-shore profile of longshore current derived from the RT  
441 (continuous line), ADV in the swash (square), drifters in the surf  
442 (circle) and ADCP (diamond), averaged when both video and  
443 in-situ measurements were available. b) Percentage of variance  
444 of RT-derived current timeseries at each location retrieved from  
445 waves and tide (ADCP) and wind (80-km distant Cotonou airport  
446 - 500 m from coastline). . . . . 28

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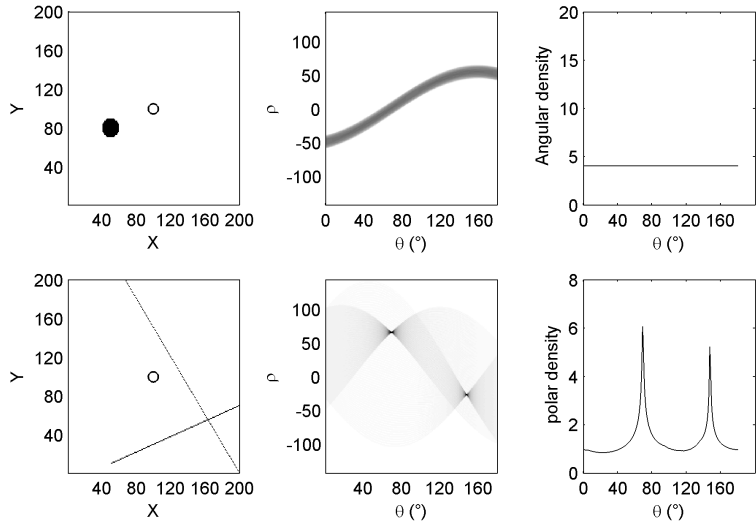


Figure 1: Radon transform (RT) practical use. RT of a disk and inclined lines in upper and lower panels respectively, and from left to right: original fields, RT in polar space, and resulting integrated angular density.

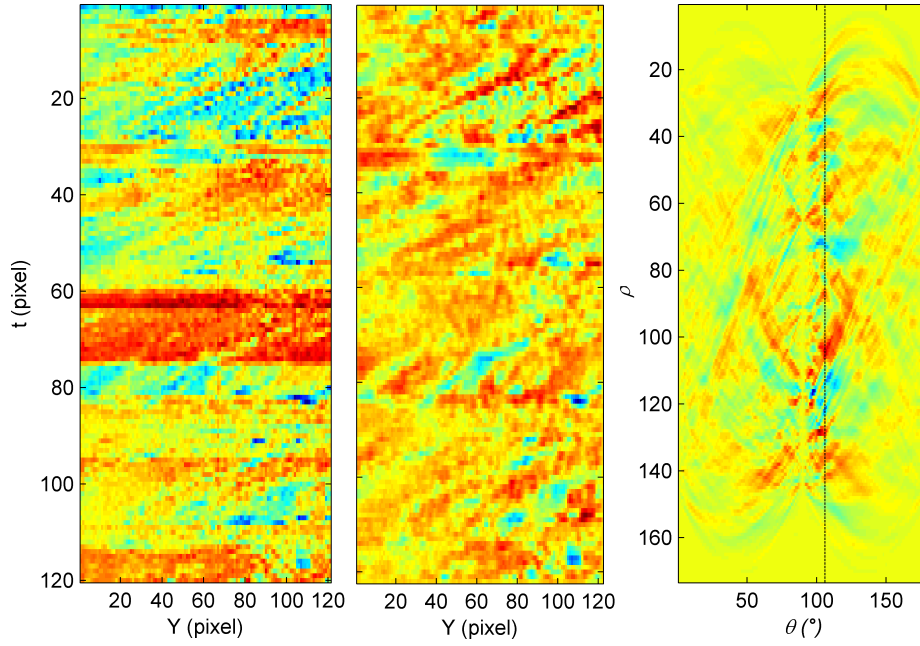


Figure 2: Illustration on the separation of waves from drifting features in longshore spatio-temporal images using the RT. a) mixed wave-current intensity timestack, b) wave-filtered current timestack and c) Polar space visualization of timestack in b). Grand Popo spatio-temporal longshore image from video,  $dx = 0.25m/pix$ ,  $dt = 0.5s$ . Dashed line at  $\theta = 106^\circ$  shows the variance maximum, or dominant velocity ( $V = 0.14m/s$ ).



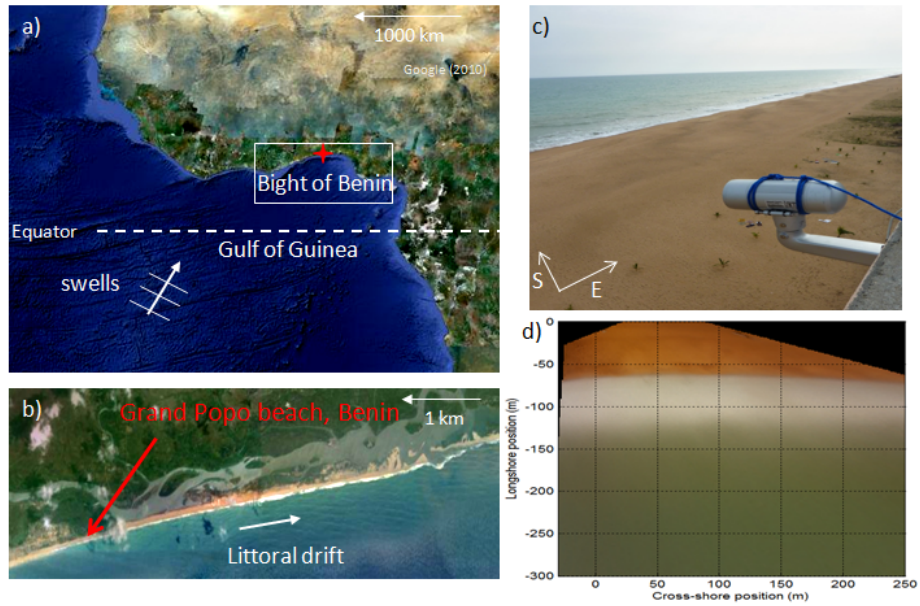


Figure 3: Grand Popo beach ( $6.2^{\circ}\text{N}$ ,  $1.7^{\circ}\text{E}$ ), in the Bight of Benin, Gulf of Guinea West Africa (a-b). c) Permanent video camera, on a 15-m high semaphore and d) rectified 15-min averaged image from video system.

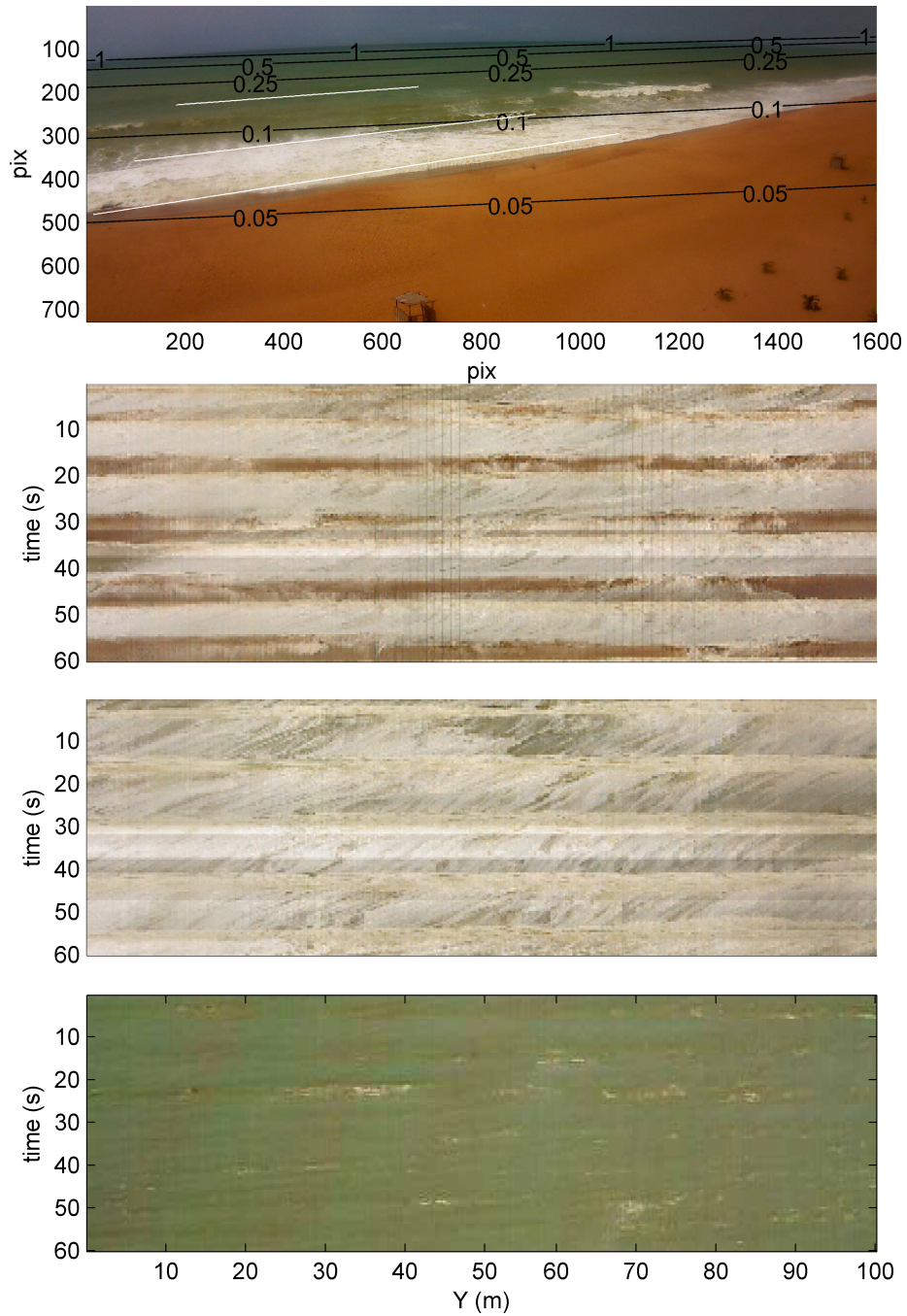


Figure 4: Instant video image with superimposed black iso-contours of pixel footprint (m/pix) in the longshore direction and in white location of 100-m long longshore spatio-temporal transects, b) in the swash, c) surf and d) inner shelf zones. Drifting features at these 3 zones are clearly visible.

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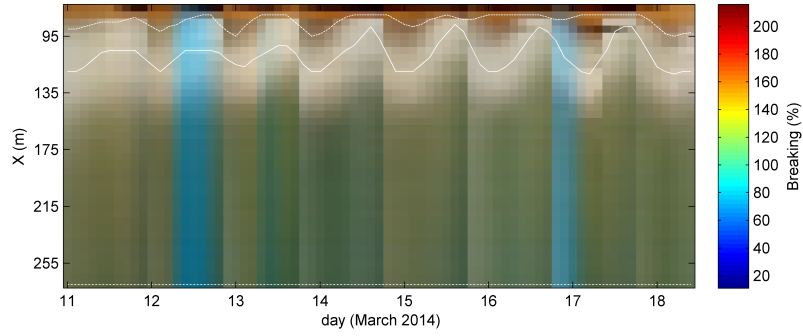


Figure 5: Cross-shore timestack derived from time-averaged images. Time-varying swash and surfzone locations used in the RT method are superimposed. Inner shelf location is taken constant.

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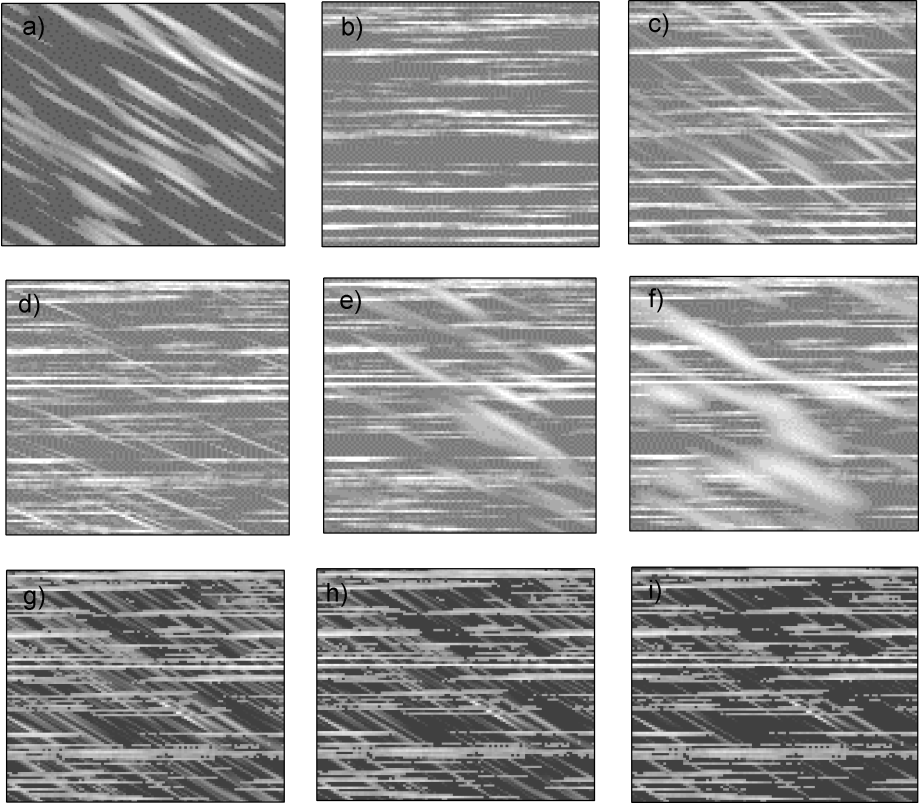


Figure 6: Examples of synthetic test cases, a-c): from left to right, anisotropic random Gaussian currents and wave fields and a combination of both. Random Gaussian current field with in d-f) from left to right, correlation ratio of 0.05, 0.15 and 0.25, and in g-i) from left to right, thresholds on kept pixels of 30%, 50% and 70%.

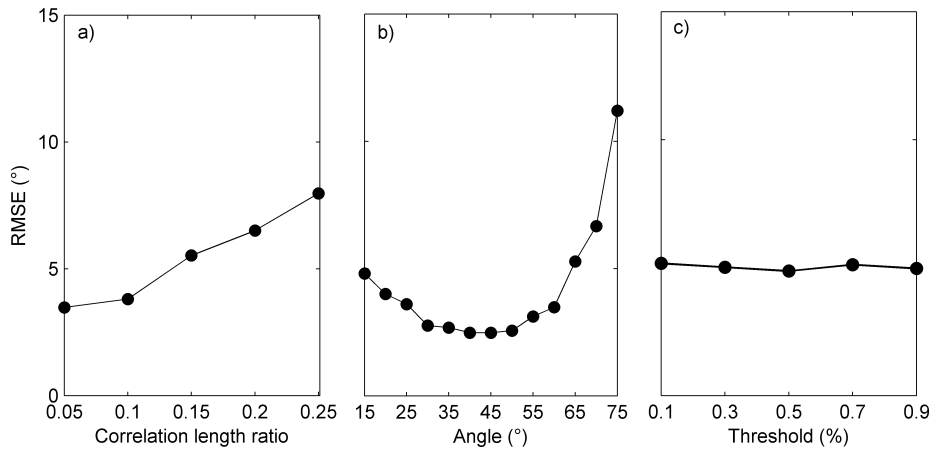


Figure 7: Sensitivity analyze on RT skills in retrieving current velocity from synthetic Gaussian random current fields. RMSE error as a function of a) Correlation length ratio (isotropy), b) threshold on kept information (in percent of pixels not changed) and c) orientation (or velocity).

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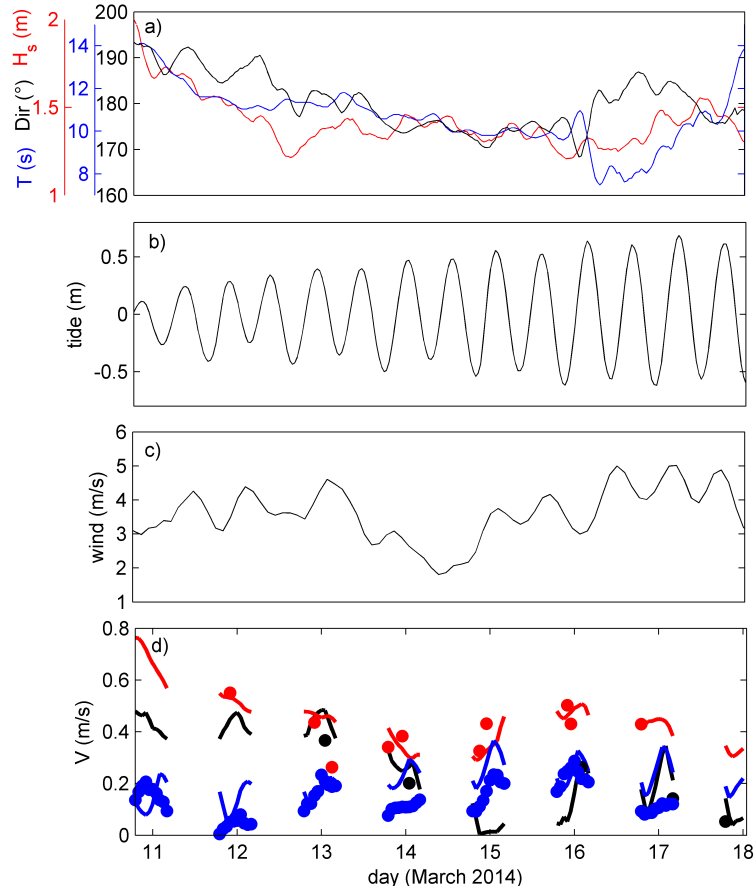


Figure 8: Forcing and longshore current during Grand Popo 2014 experiment. a) Waves ( $H_s$ ,  $T$ ,  $Dir$ ) and b) tide measured by ADCP, c) observed wind at Cotonou airport d) Comparison of co-localized video (continuous line) and in-situ current measurements in the surf zone (red), swash (black) and inner shelf (blue), from drifters, ADV and ADCP, respectively.

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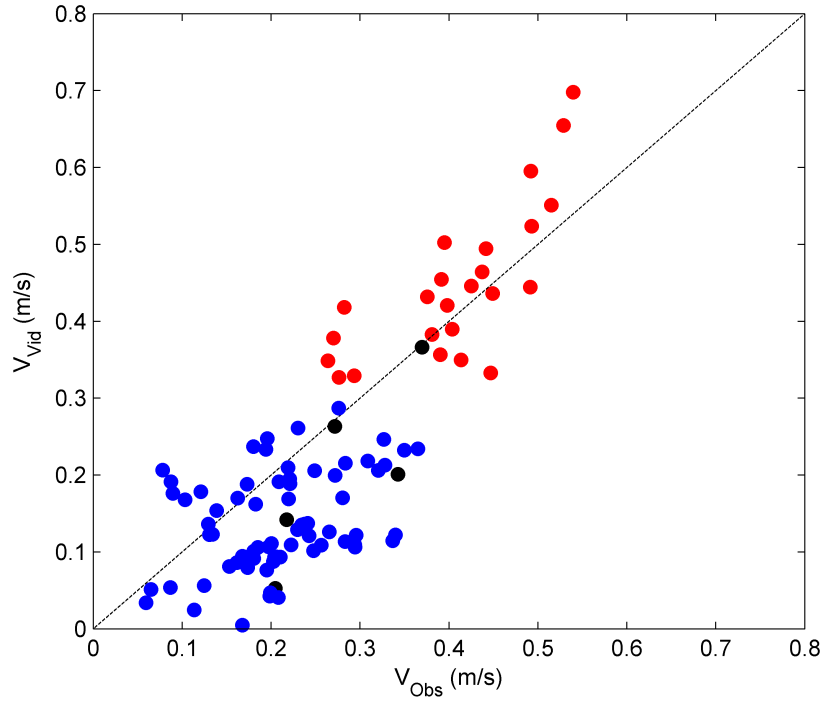


Figure 9: Video-derived versus in-situ current, in the surf zone (red), swash (black) and inner shelf (blue), from drifters, ADCP and ADV, respectively.

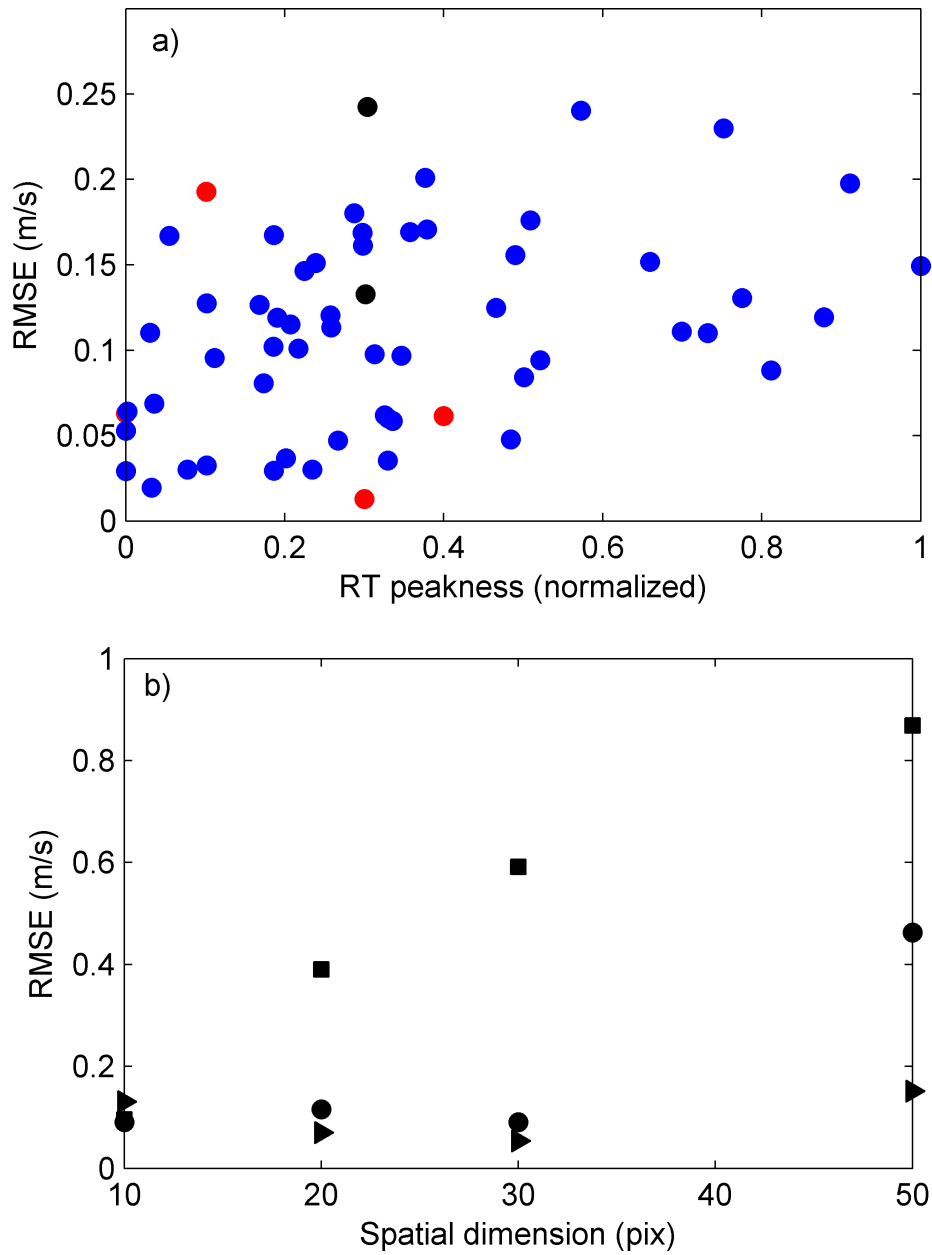


Figure 10: RT-method error as a function of a) RT-transform peakness (width of the peak in polar space) and b) resolution (0.1 m/pixel (triangles), 0.2 m/pixel (circles) and 0.4 m/pixel (squares)) and spatial dimension (pixels). In a) are shown estimates for the inner shelf (blue), surf- (red) and swash-zones (black).



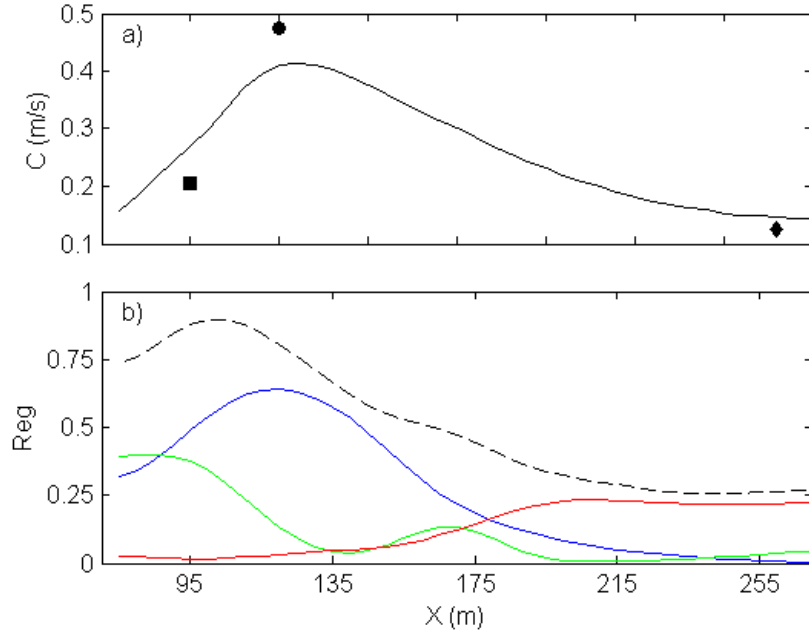


Figure 11: a) Cross-shore profile of longshore current derived from the RT (continuous line), ADV in the swash (square), drifters in the surf (circle) and ADCP (diamond), averaged when both video and in-situ measurements were available. b) Percentage of variance of RT-derived current timeseries at each location retrieved from waves and tide (ADCP) and wind (80-km distant Cotonou airport - 500 m from coastline).