Sea wave numerical simulations with COSMO-SkyMed© SAR data

Guido Benassai†, Maurizio Migliaccio‡, Antonio Montuori∞

† Dept. of Applied Sciences, University of Naples Parthenope, Centro Direzionale Is. C4, 80143 Naples, IT
gbenassai@iol.it
guido.benassai@uniparthenope.it

‡ Dept. of Technology, University of Naples Parthenope, Centro Direzionale Is. C4, 80143 Naples, IT
maurizio.migliaccio@uniparthenope.it


ABSTRACT


In this paper, X-band COSMO-SkyMed© Synthetic Aperture Radar (SAR) data are first experimented as wind field forcing of coastal wind-wave oceanographic modeling for sea-wave numerical simulation. Experiments consist of numerical wave simulations of the SWAN model accomplished with respect to some relevant wave storms recorded in the test area during the winter season of 2010. The wind forcing is provided by X-band COSMO-SkyMed© SAR-based wind field estimations which are properly blended with both buoys wave data and ECMWF model winds to retrieve meaningful wave parameters (e.g. significant wave height, wave directions and periods) as physical descriptors of storm events. Experimental results accomplished with X-band COSMO-SkyMed© SAR-based wind field forcing are successfully compared with the ones gathered by using both buoys wave field data and ECMWF model winds, only. The results obtained with the use of blended COSMO-SkyMed©-ECMWV data are satisfactory in terms of sea storm reconstruction, so this source of data can be used also for coastal management purposes.

ADDITIONAL INDEX WORDS: SWAN model, numerical simulations, X-band COSMO-SkyMed SAR data.

INTRODUCTION

In this paper, X-band COSMO-SkyMed© Synthetic Aperture Radar (SAR) data are first experimented as wind field forcing of coastal wind-wave oceanographic modeling for sea-wave numerical simulation. Experiments consist of numerical wave simulations of the SWAN model accomplished with respect to some relevant wave storms recorded in the test area during the winter season of 2010. The wind forcing is provided by X-band COSMO-SkyMed© SAR-based wind field estimations which are properly blended with both buoys wave data and ECMWF model winds to retrieve meaningful wave parameters (e.g. significant wave height, wave directions and periods) as physical descriptors of storm events.

The sea wave numerical simulations are properly accomplished in this coastal environment by means of wind field forcing provided by X-band COSMO-SkyMed© SAR-based wind field retrievals. The SAR data set consists of 60 X-band VV-polarized Level 1B Detected Ground Multi-look (DGM) ScanSAR Huge Region mode COSMO-SkyMed© SAR measurements collected in the Southern Tyrrhenian Coastal area on 2010. Sea wave numerical simulations are accomplished through the SWAN model with respect to some relevant wave storms recorded in the considered test area during the winter season of 2010. A blended wind field product is provided as wind forcing of the SWAN model, which consists of X-band COSMO-SkyMed© SAR-based wind field (i.e. wind speed and direction) retrievals and either buoys wave field or ECMWF model data. Within such a framework, the SAR-based wind speed estimation is accomplished by means of the Azimuth cut-off procedure (Chapron et al., 1995; Kerbaol, 1998; Korsbakken et al., 1998; Migliaccio et al., 2012; Montuori et al., 2012), while the SAR-based wind direction retrieval is accomplished by using the Multi-Resolution Analysis of Discrete Wavelet Transform (MRA-DWT) (Du et al., 2002).

The output of SWAN model numerical simulations allows providing relevant wave parameters (e.g. significant wave height, wave directions and periods), which are used as physical descriptors of storm events.

The experimental results gathered with X-band COSMO-SkyMed© SAR-based wind field forcing are compared with the ones provided by using both buoys wave field data and ECMWF model winds, only. The comparison is accomplished to analyze the capabilities of blended wind field products composed by X-band COSMO-SkyMed© SAR wind field estimations and model data in terms of sea wave numerical simulations, in order to be further used for coastal management purposes.

The innovative features of the project are the following:
1. With respect to the SAR-based wind field estimation procedures, the proposed approach was the SAR Wind Algorithm (SWA) based on the Azimuth cut-off procedure (Korsbakken et al., 1998; Bruning et al., 1990; Kerbaol et al., 1998). This approach, based on the filtering operated by SAR system in the azimuth channel, allows estimating the wind speed over the sea by

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means of the Azimuth cut-off procedure. It is able to provide accurate wind speed estimation at sea without requiring both the a priori wind direction information and the calibration accuracy that characterize GMF-based methods. The proposed approach has been implemented and tested only for ERS C-band SAR data, therefore it was both scientifically and operationally interesting to first extend and then properly calibrate the Azimuth cut-off procedure over X-band SAR data, taking benefits of COSMO-SkyMed® SAR measurements.

2. With respect to the surface wave modeling, a multiple-connected modeling system specifically conceived for wave forecast was used in the considered coastal area, based on the Wave Watch III (WWIII) model, the well-known third generation wave model developed at NOAA/NCEP (Tolman, 1991, 2009), which is operational since January 2005 at the DSA unit of the University “Parthenope” (Benassai, 2006; Benassai & Ascione, 2006). Outputs from the model include significant wave height on gridded fields, with the associated wave directions and periods, and spectral information about wave energy at different wavelengths. The model was coupled with PSU/NCAR mesoscale model (M5S/WRS), which gives wind forcing at 1-h intervals, and was implemented using a nested grid configuration covering the Mediterranean Sea until the Southern Thyrrenian Sea, in order to produce numerical simulations of relevant wave storms. Since a coastal application was needed, the SWAN model was run, which is based on the WWIII taking also into account the shoaling and refraction terms in the coastal zone (Holthuisen et al., 1993).

The paper is organized as follows: the data pre-processing and the methodology at the basis of 1) X-band SAR-based wind field retrieval, 2) SWAN model is briefly described in the following section. Experimental results relevant to the X-band SAR-based wind field retrieval and sea wave numerical simulations are presented and discussed in the subsequent session. Conclusions are finally drawn in last section.

METHODS

Pre-processing X-band SAR wind field retrieval

Since the SAR-based wind field estimation is strongly affected by SAR data quality, a pre-processing analysis has been accomplished, which aims at improving the image quality of X-band VV-polarized Level 1B DGM ScanSAR huge Region mode COSMO SkyMed® SAR measurements. In fact, on one side, X-band SAR data may be severely affected by tropospheric and atmospheric phenomena (e.g. rain cells, cloud coverage, oceanic fronts, convective cells, etc.) that, especially at higher frequencies, can drastically hamper both the SAR imagery interpretability and therefore the retrieval of some meaningful geophysical parameters, such the sea surface wind field (Lee et al., 1995). On the other side, the peculiar burst acquisition mode of ScanSAR SAR measurements is characterized by the presence of the scalloping pattern, i.e. periodic processing anomalies along with the azimuth direction that, appearing as bars in SAR imagery, strongly affects the accuracy of SAR-based wind field estimation (Schiavulli et al., 2011, 2012).

With this respect, an automatic two-steps pre-processing procedure, first developed in (Schiavulli et al., 2011), has been here adopted to effectively account for both the above-mentioned phenomena and therefore improve the quality of SAR images. The first step aims at removing the scalloping pattern in X-band ScanSAR COSMO-SkyMed® SAR data by means of a filtering technique based on the Discrete Wavelet Transform Multi Resolution Analysis (DWT-MRA) (Mallat, 1989; Schiavulli et al., 2011, 2012). The proposed approach naturally describes the directional features of an image at different spatial scales and therefore it is able to both highlight and then remove the scalloping pattern, which is related to the SAR image spectrum. As demonstrated in (Schiavulli et al., 2011, 2012) for the specific COSMO-SkyMed® SAR data product, it was not possible for the users to reprocess the SAR raw data and therefore only a sub-optimal de-scalloping post-processing procedure had to be taken into account. The second step of the pre-processing procedure allows detecting and then removing all the atmospheric phenomena in X-band SAR data by means of a homogeneity test based on the variance to mean square ratio (VMSR) of SAR image power spectral density (Schultz-Stellenfleth et al., 2004; Schiavulli et al., 2011). The proposed approach is able to univocally discriminate among sea, i.e. homogeneous, and non-homogeneous parts of SAR images, such as ships, coastline and atmospheric fronts.

Following the pre-processing analysis, the SAR-based wind field retrieval is accomplished by means of a two-step procedure, which allows estimating the sea surface wind speed and wind direction, independently.

Wind field retrieval

The SAR-based wind speed estimation is accomplished by means of a SAR wind speed algorithm based on the Azimuth cut-off procedure (Chapron et al., 1995; Kerbaol, 1998; Korsbakken et al., 1998; Migliaccio et al., 2012; Montuori et al., 2012), which allows consistently retrieving the surface wind speed without requiring both a priori wind direction information and the calibration accuracy of SAR normalized radar cross section (NRCS) measurements of the observed scene. The physical rationale at the basis of the proposed approach lies on the well-known azimuthal Doppler mis-registration due to the orbital motion of sea surface waves, which affects the sea surface SAR imaging, based on both sensor’s parameters (e.g. platform altitude, velocity, etc.) and sea state conditions (Chapron et al., 1995; Kerbaol, 1998; Korsbakken et al., 1998). It limits the shortest detectable wavelength in the azimuth direction $\lambda_a$, which has been demonstrated to be a key parameter that, accounting for sea waves orbital motions within SAR integration time, can be considered a robust indicator of the sea surface wind speed (Chapron et al., 1995; Kerbaol, 1998; Korsbakken et al., 1998). Based on this rationale, a SAR wind speed algorithm based on the Azimuth cut-off procedure has been developed and tested for C-band SAR measurements only (Chapron et al., 1995; Kerbaol, 1998; Korsbakken et al., 1998), where $\lambda_a$ is retrieved from the noise-free SAR auto-correlation function (ACF) and physically related to the sea surface wind speed according to the following linear semi-empirical model:

$$U_{10} = a(\lambda_a - \Lambda),$$

where $U_{10}$ (m/s) is the wind speed at 10m above the sea surface, $\Lambda$ (m) is the SAR nominal azimuth resolution and $a$ (1/s) is an empirical parameter. Following this theoretical background, the physical rationale at the basis of the Azimuth cut-off procedure has been successfully extended and tested to the X-band VV-polarized Level 1B DGM ScanSAR huge Region mode COSMO-SkyMed® SAR measurements (Migliaccio et al., 2012; Montuori et al., 2012).

The SAR-based wind direction estimation is accomplished by means of a SAR wind direction retrieval procedure based on the WT-MRA (Du et al., 2002; Schiavulli et al., 2011). The physical rationale of this technique accounts for sea-air interaction processes and is focused on the theory that sea surface wind direction retrieval lies on the measurements of texture features in SAR images over the sea. The proposed approach aims at
retrieving the orientations of atmospheric boundary layer (ABL) rolls, which are often present in SAR images and appear as sea surface streaks at kilometer scales.

**SWAN model**

In this sub-section, the theoretical background and the methodology at the basis of the SWAN wave model used in this paper is briefly described.

The SWAN model is a third-generation numerical wave model, which allows computing random, short-crested waves in coastal regions with shallow water and ambient currents (Holthuijen et al., 1993; Booij et al., 1999; Benassai, 2006, Benassai et al., 2006). It describes the temporal and spatial variation of the wind-induced surface elevation, the white-capping effects and the friction with the sea bottom layer (Holthuijen et al., 1993; Booij et al., 1999; Benassai, 2006, Benassai & Ascione, 2006). In SWAN the waves are described with the two-dimensional wave action density spectrum $N$ and periods ($\sigma$, $\theta$), even when non-linear phenomena dominate (e.g., in the surf zone). The action density spectrum $N$ is considered rather than the energy density spectrum $E(\sigma, \theta)$, since in presence of currents only the action density is conserved (Whitham, 1974). The evolution of the spectrum is described by the spectral action balance equation (Hasselman et al., 1973):

$$\frac{d}{dt} N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial \sigma} c_\sigma N + \frac{\partial}{\partial \theta} c_\theta N = S \sigma$$

(2)

where $S$ is the effect of the difference between the inner and the outer energy for the spectrum $F$ and $\sigma$ is the intrinsic frequency. The first term on the left-hand side of Eq. (2) represents the timely-change rate of the local action density spectrum. The second and third term on the left-hand side of Eq. (2) represents the propagation of the action density spectrum in the Cartesian coordinates space, with propagation velocities $c_y$ and $c_x$. The fourth term on the left-hand side of Eq. (2) represents the shifting of the relative frequency in the action density spectrum due to variations in depths and currents, with a propagation velocity $c_\sigma$. The fifth term on the left-hand side of Eq. (2) represents both the depth- and the current-induced refraction of the local action density spectrum, with propagation velocity $c_\theta$. The term at the right-hand side of the action balance Eq. (2) is the source term of the energy density, representing the effects of generation, dissipation, and non-linear wave-wave interactions.

The SWAN model is operational at Dipartimento di Scienze Applicate (DSA) of the University of Naples Parthenope since January 2005 and is adopted for simulating both waves generation and propagation in the Gulf of Naples. The model is typically forced by using the wind field forcing at 1-hour intervals provided through the Advanced Research Weather Research and Forecast (WRF-ARW) wind field data, i.e. the next-generation mesoscale numerical weather model predictions that are designed to serve both operational forecasting and atmospheric research needs (Holthuizen et al., 1993; Booij et al., 1999; Benassai, 2006; Benassai & Ascione, 2006). The model is implemented on nested grids, with an implicit numerical propagation scheme, which implies that the computations are more economic in shallow water (Holthuizen et al., 1993; Booij et al., 1999; Benassai, 2006; Benassai et al., 2006). Outputs from the SWAN model include significant wave height ($H_s$) on gridded fields, with the associated wave directions ($D_w$) and periods ($T_p$), and the wave energy spectral information at different wavelengths.

**EXPERIMENTAL RESULTS**

In this section, some meaningful experimental results are presented and discussed, which are relevant to the application of the SWAN model in a coastal environment, with forcing provided by COSMO-SkyMed® SAR-derived wind field estimations. Before proceeding to the description of the experimental results relevant to the sea wave numerical simulations, a preliminary analysis about the effectiveness of X-band COSMO-SkyMed® SAR-derived wind field estimation is provided, which aims at both validating the X-band SAR-based wind field product and therefore evaluating its consistency as wind field forcing for the wind-wave oceanographic modeling. Fig. 1 reports the coastal domain considered, in the Southern Thyrrenian Sea.

**SAR wind field retrieval**

In this sub-section some meaningful results are described, which are relevant to the X-band COSMO-SkyMed® SAR-derived wind field (i.e. wind speed and wind direction) estimation based on the wind field retrieval approach described in Methods section. The ground truth, which is used as reference wind field for both comparison and validation purposes, is provided by timely and spatially co-located ASCAT scatterometer wind fields (freely available at [http://podaac.jpl.nasa.gov](http://podaac.jpl.nasa.gov)), with a spatial gridding resolution of 12.5km×12.5km. In the particular case where the ASCAT scatterometer ground truth is not available for the X-band COSMO-SkyMed® SAR acquisition, the reference ground truth is then provided by European Centre for Medium Weather Forecast (ECMWF) model data (available at: [http://www.ecmwf.int/](http://www.ecmwf.int/)), with a spatial resolution of 0.2° (20km×20km). Since the reference ground truth wind field (both the ASCAT scatterometer and the ECMWF model ones) is not always both timely co-located with respect to the SAR image acquisition, a linear interpolation in time is accomplished between the ground truth reference wind field data acquired before and after the SAR acquisition time, thus providing the timely co-located reference wind field. Moreover, since the reference ground truth is available at the given resolution gridding scale of both 12.5km×12.5km and 20km×20km for the ASCAT scatterometer and the ECMWF model wind field, respectively, a bi-linear spatially interpolation of the timely co-located wind field is accomplished inside of the spatial domain of SAR image at the specific SAR sub-image gridding scale (N×M) used for wind field retrieval purposes.
Some results are summarized in the scatter plots of Figs. 2, where the 12.5km×12.5km SAR-based wind speed and wind direction retrievals are consistently compared with respect to the 12.5km×12.5km ASCAT scatterometer reference wind speed and wind direction, respectively, for the whole processed COSMO-SkyMed® SAR data set. Experimental results demonstrate the consistency of X-band COSMO-SkyMed® SAR-derived wind field estimations with respect to the ASCAT scatterometer reference ground truth. In detail, the COSMO-SkyMed® SAR-ASCAT wind speed inter-comparison (see Fig. 2(a)) provides a mean error ($\mu$) value of $-0.73$ m/s, a standard deviation ($\sigma$) value of $2.07$ m/s and an RMSE value of $2.19$ m/s. On the other side, the COSMO-SkyMed® SAR-ASCAT wind direction inter-comparison (see Fig. 2(b)) provides a mean error ($\mu$) value of $1.71^\circ$, a standard deviation ($\sigma$) value of $18.88^\circ$ and an RMSE value of $18.95^\circ$. These results effectively demonstrate the consistency of X-band COSMO-SkyMed® SAR-derived wind field retrievals with respect to the ASCAT scatterometer ground truth.

Such results demonstrate the effectiveness of both the X-band Azimuth cut-off model function and the WT-MRA technique presented in pre-processing analysis to get consistent wind speed and wind direction estimation, respectively, even through X-band SAR data. Furthermore, experimental results show the full benefits of X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed® SAR data as alternative source of wind field estimation.

### Sea wave numerical simulations

In this subsection, sea wave numerical simulations of SWAN model are described with respect to some relevant wave storms recorded in the considered test area during the winter season of 2010 (see Table 1). A first meaningful set of results relevant to the application of SWAN model is shown in Fig. 3 with respect to the wave storm of 8-10 November 2010 (see Table 1). In this case, neither the maximum wave heights nor the time evolution of the storm are properly simulated with the wind field forcing provided by ECMWF model winds. In fact, the maximum values of $H_s$, which are obtained by using both ECMWF model winds and buoys wave field data only, are 5.5m and 4.0m, respectively, which are both shifted 15 hours earlier.

### Table 1. Wave storms of the winter season 2010, properly used for sea-wave numerical simulations. Significant wave height, peak period and wave direction at the storm peak are reported.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Date</th>
<th>$H_s$ (m)</th>
<th>$T_p$ (s)</th>
<th>$D_w$ ($^\circ$N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Nov. 8-10th 2010</td>
<td>4.23</td>
<td>9.5</td>
<td>218</td>
</tr>
<tr>
<td>#2</td>
<td>Dec. 17-18th 2010</td>
<td>5.01</td>
<td>9.5</td>
<td>231</td>
</tr>
<tr>
<td>#3</td>
<td>Dec. 23-25th 2010</td>
<td>4.29</td>
<td>10.0</td>
<td>255</td>
</tr>
</tbody>
</table>

However, these higher maximum wave heights may be overestimated because on the poor amount of data inside the spatial domain reported in fig. 1.

![Figure 2](image.png)

Figure 2. 2-D probability density scatter plot relevant to the comparison between the 12.5km×12.5km X-band COSMO-SkyMed® SAR-derived wind field estimation and the 12.5km×12.5km ASCAT scatterometer reference ground truth, for the whole processed COSMO-SkyMed® SAR data set. (a) Wind speed inter-comparison (b) Wind direction inter-comparison.

![Figure 3](image.png)

Figure 3. Simulated and measured $H_s$ for the winter storm of 9-10 November 2010. Comparison among buoys (continuous), ECMWF (dotted), COSMO-SkyMed® SAR (dashed and dotted), and blended ECMWF and COSMO-SkyMed® SAR-derived wind fields (dotted).
The use of a blended wind field product provided by COSMO-SkyMed® SAR-derived wind field estimations and ECMWF model winds gives more accurate results, with an underestimation of 0.5m in $H_s$ (3.5m instead of 4.0m), a more accurate resemblance of the storm and a lower temporal shift, as confirmed by inspection of Fig. 3.

A second meaningful set of results relevant to the application of SWAN model is shown in Fig. 4 with respect to the wave storm of 17-18 December 2010 (see Table 1). The sea wave numerical simulation accomplished by using the blended COSMO-SkyMed®-ECMWF wind field products shows that the COSMO-SkyMed® SAR-derived wind field estimations are able to catch the changing storm characteristics, although the peaks of the wave storm are quite underestimated. In fact, the blended wind field product provided by COSMO-SkyMed® SAR-derived wind field estimations and ECMWF model winds retrieves the peak value of $H_s$, which numbers 3.5m, instead of 5.0m. This result is less accurate than the one obtained by using a wind field forcing provided by ECMWF model winds only, mainly because of the lower time resolution of the wind data and in spite of the higher spatial resolution. In fact, the wave storm event presents a quite fast time evolution, which cannot be interpreted by using wind field data with a temporal interval of 12-24 hours. Compared to both buoys wave field observations and ECMWF model winds, very effective results are obtained with the blended wind field products provided by COSMO-SkyMed® SAR-derived wind field estimations and ECMWF model winds. More generally, numerical simulations demonstrate that the SWAN model allows providing significant and accurate sea wave estimations even by using blended wind field product composed by both model and remotely sensed wind field data.

A third meaningful set of results relevant to the application of the SWAN model is shown in Fig. 5 with respect to the wave storm of 23-25 December 2010 (see Table 1). Numerical simulations agree with previous experimental results. In particular, the blended wind field product provided by COSMO-SkyMed® SAR-derived wind field estimations and ECMWF model winds allows improving the retrieval of the SWAN-based wind-wave interaction parameters especially in the first part of the wave storm, where numerical simulations accomplished with ECMWF model winds tends to provide an $H_s$ value overestimation.

Moreover, the storm severity underestimation provided by using a blended wind field product composed by both model and remotely sensed wind field data is confined in a mean difference of about 1.0m (20% of its maximum value).

So, with regard to the storm reconstruction, experimental results demonstrate that sea wave numerical simulations accomplished with blended COSMO-SkyMed®-ECMWF wind field forcing closely follow the true significant wave height of the wave storms. This important result can be used for further research relevant to the use of COSMO-SkyMed® SAR data as alternative integrated source of sea surface wind field information. Furthermore, experimental results effectively demonstrate that a blended wind product including both ECMWF model data and COSMO-SkyMed® SAR-derived wind field estimations can provide valuable improvements of wind-wave interaction modeling.

**DISCUSSION**

In the previous section we demonstrated the effectiveness of X-band COSMO-SkyMed® SAR-derived wind field for providing consistent wind field forcing for the wind-wave oceanographic modeling. The sea wave numerical simulations and their validation with buoy wave data demonstrated the effectiveness of this database for coastal applications and management. With respect to the results of the numerical simulations, the main differences were experienced among the three considered wave storms:

a) Numerical simulations carried out with ECMWF model winds properly describe the sea storms at the peak with regard to the significant wave heights $H_s$. The only exception is represented by the first wave storm (see Fig. 4 and Table 1), where the peak value of $H_s$ is overestimated of about 38%. With regard to the wave storm duration, the first two storms are properly described (see Figs. 4 and 5, respectively, and Table 1), while the third one exhibits an overestimation of 9% (see Fig. 5 and Table 1).

b) Numerical simulations carried out with a blended wind field product provided by ECMWF model winds and COSMO-SkyMed® SAR-derived wind field estimations better follow the significant wave heights at the peak for the first wave storm (see Fig. 4 and Table 1), while for the other two wave storms there is an underestimation of the peak significant wave height of 32% and 15%, respectively (see Figs. 5 and 6, respectively, and Table 1).
Taking into account the wave storm duration, the results agree with the buoy wave field data for both the first and third wave storms (see Figs. 4 and 6, respectively, and Table 1) and give an underestimation of 37% for second wave storm (see Fig. 5 and Table 1).

CONCLUSIONS
In this paper, X-band COSMO-SkyMed® SAR data are first successfully experimented as wind field forcing of wave oceanographic modeling for sea-wave numerical simulation in a coastal environment. The SAR data set consists of 60 X-band VV-polarized Level 1B DGM ScanSAR Huge Region COSMO-SkyMed® SAR measurements, collected in the test area during the winter season of 2010. The wind-wave oceanographic modeling is based on the third-generation SWAN model, run with the different data.

With respect to the storm reconstruction, experimental results demonstrate that the wave sea numerical simulations accomplished with blended COSMO-SkyMed®-ECMWF wind field forcing closely follow the true significant wave height of the first wave storm (see Table 1). In fact, a slight Hs underestimation of 9% is provided against the Hs overestimation of 38% provided by considering wave sea numerical simulations accomplished with ECMWF model wind forcing only. However, for the other two wave storms (i.e. the second and the third ones in Table 1), experimental results provide an Hs underestimation of 32% and 15%, respectively.

Experimental results firstly show how X-band COSMO-SkyMed® SAR-derived wind field estimations can be effectively used to force the SWAN coastal wave model for oceanographic applications. Meaningful tests are successfully accomplished in the Southern Tyrrhenian Sea basin, where some significant wave storms have been both recorded and analyzed. This is of both scientific and operational relevance.

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LITERATURE CITED