A discussion on the use of X-band SAR images in marine applications

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Abstract

The Synthetic Aperture Radar (SAR) is able to generate images of the sea surface that can be exploited to extract geophysical information of environmental interest. In order to enhance the operational use of these data in the marine applications the revisit time is to be improved. This goal can be achieved by using SAR virtual or real satellite constellations and/or exploiting new antenna technologies that allow huge swath and fine resolution. Within this framework, the presence of the Italian and German X-band SAR constellations is of special interest while the new SAR technologies are not nowadays operated.

In this paper we review the most relevant marine applications with special attention to X – band and related SAR image quality. Special care is also paid to high intensity precipitating clouds, i.e. rain cells, since they represent a weather condition that hampers use of X – band SAR image for marine applications.

1 Introduction

In marine applications is of paramount relevance the revisit time. In order to improve the revisit time, one can deploy a SAR virtual or real satellite constellations and/or design special modes that enhance the revisit time. In this latter case one can refer to some SAR operating mode that are nowadays already used or exploit new SAR antennas technologies that are under study and in few cases are matter of first experimentations, e.g. (Villano et al., 2012).

In this paper we make reference to the present state-of-art of satellite SARs and therefore on the actual SAR data that a user can exploit for his/her marine applications.

Therefore, it is appropriate to exploit the actual and virtual X-band SAR constellations, i.e. COnstellation of small Satellites for the Mediterranean basin Observation (Cosmo-SkyMed, CSK) and TerraSAR-X (TSX).

CSK is an earth observation satellite system funded by Italian Ministry of Research and Ministry of Defense and conducted by the Italian Space Agency (ASI), intended for both military and civilian use. CSK constellation is composed by four full operational satellites equipped with a SAR operating at X-band. The four satellites are planned for a sun-synchronous polar orbit, phased at 90° and at an altitude of 619 Km with an orbit of 97 minutes.

TSX is a German earth observation satellite funded by a joint partnership between the German Aerospace Center (DLR) and EADS Astrium. In addition with TanDEM-X (TerrSAR-X add-on for Digital Elevation Measurements), TSX gives rise to an X-band working frequency constellation. The two satellites fly in a sun-synchronous polar orbit with typical distances between 250 and 500 m at an altitude of 514 Km.

The most relevant scientific and operational marine applications, that can benefit of denser X – band virtual or real constellations, are summarized in this paper. They are: oil slick detection, man-made metallic targets detection, wind vector estimation, coastal wave monitoring and sea current analysis. In this review we pay special attention to recent X – band studies and to the impact of SAR image quality. In this paper, an up-to-date review of marine applications and SAR image quality is made.

Unfortunately, X – band is not immune to atmospheric hydrometeors. In particular, high intensity precipitating phenomena may significantly impair X – band SAR images or part of it (Jackson and Apel, 2004). Therefore, techniques able to analyze hydrometeors effects in X – band SAR images have been developed (Jackson and Apel, 2004) (Danklmayer et al., 2009) (Marzano and Weinman, 2012) (Weinman et al., 2009) (Baldini et al., 2011) (Schulz-Stellenfleth et al., 2004) (Schiavulli et al., 2011). For its scientific and operational relevance at X – band, this severe weather condition is also reviewed in this paper.

In this paper we review all these key facts in order to facilitate marine users in exploiting X – band SAR data.

2 Marine Applications

In this section, we briefly review the main satellite SAR marine applications with some emphasis on X – band SARs that are at core of this paper. A general review on this matter can be found for example in (Kerbaol and Collard, 2005) and (Jackson and Apel, 2004). The most relevant scientific and operational SAR marine applications are meant to be (Kerbaol and Collard, 2005): oil slicks monitoring, detection of man-made metallic targets, high resolution wind fields, coastal wave fields and sea surface currents.

Marine oil slicks arise from natural and anthropogenic phenomena. In both cases, the SARs sensor is the key sensor to monitor them. With respect to marine oil pollution the main concern regards either accident or illegal oil discharge, which are typically connected to discharge of heavy oil. The first attempt to accomplish such a task was made by single polarization, typically VV, SAR images. In very simple terms, the physical model predicts that the standard sea surface two scale model, that at small scales is governed by the Bragg scattering, does not apply over sea oil slicks. Hence, sea oil slicks appear as low scattering areas, i.e. dark patches, in SAR images. However, the problem is in real life much more complicated due to the presence of other phenomena that generate similar dark area over SAR images. Discrimination between dark areas due to oil slicks or these other phenomena is not at all straightforward. In (Gambardella et al., 2010), it has been shown theoretically and experimentally that this problem cannot be solved by SAR information only. With this respect, a brand new scientific and operational contribute has come from the availability of polarimetric SAR measurements and appropriate models (Solberg, 2012). A relevant and recent X – band polarimetric SAR papers on this topic is (Velotto et al., 2011).

SAR observation of man-made metallic targets at sea is of paramount importance for several marine working activities, such as shipping, fishing, oil fields, etc. In single polarimetric SAR images man-made metallic targets at sea, such as ships and oil rigs, can be detected since these targets generate a strong and coherent backscattering, i.e. bright spots over SAR images (Kerbaol and Collard, 2005). A modern approach exploits the geophysical nature of the speckle to detect such bright spots in full resolution SAR images (Migliaccio et al., 2007) (Gambardella et al., 2008). New advancement in this marine application has been also achieved exploiting polarimetric SAR data and models (Nunziata et al., 2012). Relevant and recent X – band SAR papers on this topic have been published (Migliaccio et al., 2012a) (Nunziata and Migliaccio, 2013) (Velotto et al., 2013a).

Wind vector over the sea is fundamental to predict and understand meteorological and climatic processes. Classical remote sensing technique to retrieve wind field is based on scatterometer measurements (Kerbaol and Collard, 2005) (Migliaccio and Reppucci, 2006). Although the SAR was not designed to accomplish such a task, due to the high quality of new SAR sensors, especially in terms of radiometric accuracy, several successful attempts have been developed. Two main SAR wind speed retrieval procedures over VV or HH single polarimetric data have been conceived. The first procedure is the so called scatterometer one, which is based on the retrieval of a non - linear Geophysical Model Function (GMF). In this case, an *a priori* information on wind direction and high quality calibration Normalized Radar Cross Section (NRCS) are requested. A different approach has been proposed in (Kerbaol et al., 1998) and does not call for *a priori* knowledge of wind direction and high quality calibration NRCS. Wind direction can be retrieved by detecting some features in SAR images (Jackson and Apel, 2004) (Horstmann et al., 2002). Recent and relevant X – band SAR papers on this topics are (Ren et al., 2012) (Migliaccio et al., 2012b) (Montuori et al., 2012).

Coastal wave fields monitoring can only be made by SAR (Kerbaol and Collard, 2005) (Jackson and Apel, 2004). The spectral non – linear inversion model is critically dependent on first guess wave spectra. However, interesting scientific and operational results have been reported in (Kerbaol and Collard, 2005). A recent study on the use of X – band SAR data is described in (Li et al., 2010).

SAR retrieval of ocean currents is one of the most complex marine application. In fact, the relevant features appear in SAR images through the hydrodynamic modulation of the sea surface roughness, which results into intensity variation of SAR images. But other environmental parameters affect sea surface roughness (Kerbaol and Collard, 2005). Although scientific techniques have been proposed, the retrieval of current field from SAR intensity images is meant not mature enough to be suitable to generate operational products (Kerbaol and Collard, 2005). Different and interesting techniques based on the along – track interferometry (ATI) and Doppler Centroid (DC) measurements have been proposed (Kerbaol and Collard, 2005). Recent studies relevant to X – band satellite SAR are reported in (Romeiser et al., 2007).

3 SAR data quality

SAR data quality is one of the key elements to retrieve reliable marine added value products. In this section, we briefly review the SAR data quality indicators with special regards to marine applications (Jackson and Apel, 2004) (Vespe et al., 2012).

SAR data quality is a multi facet property that is given by several indicators. Of course, according to the specific marine added value procedure a sub – set of such SAR data quality indicators is more relevant than others.

The SAR data quality indicators can be classified into global and local. The global indicators are (Vespe et al., 2012): radiometric sensitivity, radiometric resolution, radiometric error accuracy and stability, spatial resolution and geolocation accuracy. The local indicators are (Vespe et al., 2012): peak to side lobe ratio (PSLR) and integrated side lobe ratio (ISLR), interference artifacts, saturated data, missing data.

The radiometric sensitivity is the value of backscattering coefficient that would give a signal level equal to receiver noise level (Vespe et al., 2012). This parameter is relevant in low backscattered areas and therefore of special relevance in low wind and oil slicks areas. In polarimetric SAR data, this parameter must be carefully analyzed when polarimetric oil slicks approach are considered especially for the HV channel.

The radiometric resolution is a measure of the ability of a SAR system to distinguish areas characterized by different NRCS. It depends on the Equivalent Number of Looks (ENL). Although more and more SAR marine applications rely on Single Look Complex (SLC) data, there are still some procedures that only work with multi–look SAR data. When high radiometric resolution is advisable one should not hamper the intrinsic radiometric resolution by an inappropriate multi – look (Vespe et al., 2012). With this respect, the use of ScanSAR images and SpotLight can be critical. Whenever use of ScanSAR data is of interest, one can apply some algorithms to improve the radiometric resolution (Moreira, 1991). Recently, for German X – band SAR satellite mission, i.e. TSX, a technique based on the use of a higher transmitted bandwidth has been implemented to enhance the radiometric resolution (Mittermayer et al., 2012). In CSK, the improvement of radiometric resolution is performed by means of the reduction of the intrinsic multiplicative – like speckle noise (Italian Space Agency, 2007). This characteristic is of particular relevance for wind vector estimation.

The radiometric error is a measure of the relative radiometric calibration performance (Vespe et al, 2012). The radiometric accuracy (absolute calibration) and stability (over time) are relevant (Vespe et al, 2012). For ScanSAR images, other two important quality aspects are residual scalloping and radiometric mismatch. In particular, scalloping is an intrinsic processing artifact that affects ScanSAR images and appears as thin bars particularly visible over the sea. Although several techniques have been developed to mitigate scalloping effect in SAR processor (Shimada, 2009) (Bamler, 1995) (Hawkins et al., 2002) (Bamler and Eineder, 1996) (Monti-Guarnieri and Guccione, 2001) (Wollstadt et al., 2012), one can still get SAR images affected by this problem. Therefore, post processing techniques able to mitigate scalloping have been developed. In particular, for X – band SAR images two procedures have been developed (Romeiser et al., 2013) (Schiavulli et al., 2013). Of course, these post processing procedures are intrinsically suboptimal and appropriately tailored for specific applications. For example (Romeiser et al., 2013) has been tested for wind wave application and (Schiavulli et al., 2013) for wind vector estimation.

The spatial resolution accounts for both azimuth and range resolution. Azimuth resolution is constant over a whole SAR image except for ScanSAR acquisition mode, where different subswaths in the same image may have different resolution (Vespe et al. 2012). However, in order to estimate the poorest performance for quality analysis the near range resolution measurement is considered. Recently, techniques to improve X – band SAR images spatial resolution have been presented (Mittermayer et al., 2012) (Italian Space Agency, 2007). This indicator is of particular relevance in SAR observation of small and weak man-made target at sea.

The geolocation accuracy is a quality parameter that can be neglected on open sea application. However, near the coast, geolocation errors may occur particularly in near – real – time applications. Recent works successfully dealt with this problem in X – band SAR images (Breit et al., 2012) (Italian Space Agency, 2007).

Let us now move to consider the local quality indicators.

The PSLR is the ratio between the returned signal of the main lobe and that of the first side lobe of the point target. The ISLR is the ratio between the returned energy of the main lobe and that integrated over several lobes on both sides of the main one over the noise level (Vespe et al., 2012). High values of PSLR or ISLR mean that the energy from a point target is spread out along and/or cross track, which can severely affect geophysical inversion model

(Vespe et al., 2012). These two indicators are of interest especially when strong man-made targets are present over the marine scene. As matter of fact, SAR observation of such targets generates a strong cross-like signal which may hide other targets and generate ambiguities. Ambiguities are ghost images of strong targets and they occur both in range and in azimuth direction (Vespe et al., 2012). Ambiguities can become prominent when the contrast between the scatterer and the background is high, e.g. ship and sea surface. It has been widely shown that ambiguities primarily occur for HH SAR images over the sea in low wind conditions or for near coast zones (Vespe et al., 2012). Recently, techniques to avoid presence of ambiguities in X – band SAR images have been developed and successfully tested over TSX data (Mittermayer et al., 2012) (Velotto et al., 2013b).

Ground Radio Frequency (RF) emissions in SAR bandwidth may cause false alarm or mask targets. Although the International Telecommunication Unit (ITU) regulates the frequency allocation in order to avoid/mitigate such interferences, this is a well known problem especially even for SAR working at L and P band.

Saturated SAR data are caused by the limited dynamic range of the analog-to-digital converter (Vespe et al., 2012). Techniques able to provide solution to this problem have been developed in the last years (Shimada, 1999).

A limited amount of missing raw SAR data may result in a reduced geometric resolution while a larger amount may result in missing data in the processed product. Usually, missing data are expressed as a block of pixels with zero value and automatic tools to detect it has been developed (Vespe et al., 2012). Of course, these latter three indicators affect all marine applications independently of the specific algorithm.

4 Rain Cells

One of the most important problem affecting X – band satellite SARs is the attenuation through the atmosphere. The atmosphere can be divided into two major layers, i.e. ionosphere and troposphere. Through this two atmospheric layers the microwaves can be affected by delays, attenuation, noise, scintillation and depolarization which are caused by the atmospheric phenomena, such as gases, precipitation, clouds, fogs or free electrons in the ionosphere (Danklmayer et al., 2009).

The ionosphere is a part of the upper atmosphere, from about 85 Km to 600 Km altitude, comprising portions of the mesosphere, termosphere and exosphere, distinguished because it is ionized by solar radiation. It has practical importance because, among other functions, it influences radio propagation to distant places on the Earth (Danklmayer et al., 2009). Ionosphere can affect microwaves with scintillation, Faraday Rotation (FR), refraction, diffraction, absorption, noise emission, etc… and these effects result intensified for lower microwave frequencies (Danklmayer et al., 2009). A serious ionospheric effect is the FR which is proportional to the inverse of the squared working frequency, hence at X – band results to be below of 0.5° and can be neglected for most applications (Danklmayer et al., 2009).

The troposphere is the lowest part of the atmosphere, ranging from the Earth surface to approximately 12 Km. It causes attenuation of crossing signal due to hydrometeors, atmospheric gases, fog and clouds. Attenuation due to fog and non precipitating clouds is usually negligible for carrier frequencies up to 10 GHz (Danklmayer et al., 2009) while hydrometeors severely affects signal propagation at X – band.

Radar signature of rain, in SAR images acquired over the sea, are caused by radar backscattering from the sea surface and by scattering and attenuation of the microwaves by rain drops in the atmosphere (volume scattering and attenuation) (Jackson and Apel, 2004). The rain effects can produce two effects in SAR images: dark patches due to attenuation and bright areas due to partial backscattering (Jackson and Apel, 2004). The strength of these effects is driven by rain rate, raindrop size, shape, density, orientation and temperature. Furthermore, wave polarization can strongly influence this interaction. Several studies have been conducted in order to analyze the effect of rain cells in SAR imagery. Jackson and Apel (2004) showed that the modification of the sea surface roughness by impinging rain drops on the sea surface depends strongly on the wavelength of the water waves. The net effect of impinging rain drops on the sea surface is a decrease in amplitude of water waves with wavelength above 10 cm and an increase in amplitude of water waves with wavelengths below 5 cm. The critical wavelength at which impinging rain drops cause an increase of the wave amplitude rather than a decrease is not well defined. The effect of rain drops is particularly visible at X – band where the Bragg waves are generally enhanced. Within this context, SAR images provided by the constellations operating at X – band, i.e. CSK and TSX, have been widely investigated in order to monitor and analyze precipitations, since they provide data with lower revisit time. In (Danklmayer et al., 2009) TSX data are used to show the effect of strong attenuating precipitation volumes and a comparison between weather-radar and SAR data acquired nearly simultaneously. Furthermore, statistical aspects of precipitation and attenuation are highlighted accounting for several parameters, such as signal frequency, polarization, climate zone, latitude and elevation angle, have been accounted for. It is possible to calculate attenuation for a given annual probability or the rain rate for a given climatic zone and annual probability (Danklmayer et al., 2009).

In (Weinman et al., 2009) the precipitating events have been observed by using a dual frequency technique over an inhomogeneous sea surface. Precipitation distribution is retrieved by X – band normalized cross section (NRCS) that is strongly modified in the proximity of rain fall.

Following this rationale, some studies investigated the potentialities of polarimetric sensor such as CSK and TSX to infer informations about rain. In fact, due to the anisotropy of many hydrometeors, and the look angles typically used by SAR, propagation and backscattering are expected to depend on polarization and therefore different polarimetric signatures can be detected by polarimetric SAR sensors. In (Baldini et al., 2011), precipitations effects, such as attenuation, signal extinction degradation of spatial resolution, over HH and VV CSK polarimetric images are explored. In (Marzano and Weinman, 2012) the studies are focused on the extraction of the 3-D distribution of liquid and ice hydrometeors by using a high resolution mesoscale atmospheric model, based on the characterization of polarimetric SAR signatures due to precipitation and dependence on frequency band, on the correlation analysis between hydrometeor columnar content and SAR polarimetric response, on the quantification of the relative contribution of volumetric and surface backscattering and on the analysis of the effects of incidence angle and ground inhomogeneity.

Hence, SAR-based observations may be considered as an added value product for meteorological models. However, several limitations are present in retrieval of meaningful precipitation intensity since hydrometeors are in relative motion and can produce image distortion (Danklmayer et al., 2009).

Of course this precipitating atmosphere phenomena impair the use of X – band SAR imagesfor marine applications. Therefore if one is interested to marine applications, it is important to identify and remove these areas before any further marine added value processing.

Hence, to deal with the presence of rainfall in SAR images, some applications detect and flag area affected by the presence of these phenomena in order to discriminate area where features produced by atmosphere sea surface interaction, useful to extract environmental information, are present. These techniques start from the assumption that the presence of atmospheric fronts calls for anomalies in the sea SAR image spectra. Therefore, a further investigation on SAR images, to adequately verify if the ocean spectral characteristics are no longer homogeneous, is needed. A useful method to verify such property is accomplished by implementing the test of image homogeneity (Schulz-Stellenfleth et al., 2004) (Schiavulli et al., 2011).

This method is able to detect all the inhomogeneities on SAR images such as rain cells, ships, coastlines by means of a technique based on data spectral analysis. The mentioned technique is strictly linked to a threshold that depends on the Equivalent Number of Looks (ENL) of the data. In (Schulz-Stellenfleth et al., 2004) the tests are accomplished over C-band single look complex data, while in (Schiavulli et al., 2011) for the first time X – band multi – look Ground Detected (MGD) CSK data are successfully processed. This procedure is able to univocally discriminate between sea, i.e. homogeneous, and non-homogeneous parts of SAR images.

5 Conclusions

In this paper an up-to-dated review of X – band SAR marine applications has been provided. Critical analysis of the different CSK and TSX operating modes, e.g. polarimetric, ScanSAR, etc…, in terms of marine added value products and image quality has been presented. Further, the criticality of rain cells at X – band that are quite frequent at medium-low latitudes in rainy seasons, hampering the nominal revisit time, has been also reviewed.

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