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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 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.

Although SAR images are considered to be independent of weather conditions, this is only partially true at higher frequencies, e.g. X-band. In fact, observations can present signature corresponding to high intensity precipitating clouds, i.e. rain cells. Further, ScanSAR images may be characterized by the presence of processing artifacts, called scalloping, that corrupt image interpretation.

In this paper we review these key facts that are at the basis of an effective use of X-band SAR images for marine applications.

1 Introduction

In marine and maritime applications is of paramount relevance the revisit time. In order to improve the revisit time, one can deploy a SAR virtual or real 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 SARs and therefore on the actual SAR data that a user can exploit for his/her marine applications.

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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 min.

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.

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 (Alpers et al., 2004). Therefore, techniques able to analyze hydrometeors effects in X-band SAR images have been developed (Alpers et al., 2004; Dnaklmayer et al., 2009; Marzano et al., 2012; Weinman et al., 2009; Baldini et al., 2011; Schulz-Stellenfleth et al., 2004; Schiavulli et al., 2012a).

Within such a framework, in order to improve revisit time, Scanning SAR (ScanSAR) is the most tailored SAR acquisition mode. In CSK the ScanSAR acquisition mode provides data with a resolution of 100 m for Multi-look and 30 m for single look with a swath of 200 km × 200 km. In TSX the ScanSAR acquisition mode gathers data with a resolution up to 18.5 m and a scene size of 100 km (width) × 150 km (length).

Unfortunately, ScanSAR images are affected by an intrinsic processing artifact, scalloping. Scalloping is a periodic artifact that appears as thin bars in SAR images. A set of de-scalloping procedures have been developed and they can be sorted into two categories: processing and post-processing techniques (Shimada, 2009; Bamler, 1995;

Hawkins et al., 2002; Bamler et al., 1996; Monti-Guarnieri et al., 2001; Wollstadt et al., 2012; Romeiser et al., 2010; Schiavulli et al., 2012b).

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

2 Rain cells

One of the most important problem affecting microwave for spaceborne radars 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 (Dnaklmayer 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 (Dnaklmayer 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 (Dnaklmayer 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 (Dnaklmayer 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 (Dnaklmayer et al., 2009) while hydrometeors severely affects signal propagation at X-band.

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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) (Alpers et al., 2004). The rain effects can produce two effects in SAR images: dark patches due to attenuation and bright areas due to partial backscattering (Alpers et al., 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. Alpers et al. (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 Dalkmayer 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 (Dalkmayer 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.

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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 et al. (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 climate models. However, several limitations are present in retrieval of meaningful precipitation intensity since hydrometeors are in relative motion and can produce image distortion (Dalkmayer 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

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to verify such property is accomplished by implementing the test of image homogeneity (Schulz-Stellenfleth et al., 2004; Schiavulli et al., 2012a).

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. (2012a) 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.

3 Scalloping

ScanSAR is widely used for marine and meteorological applications, due to its peculiarities to gather data with a huge swath and therefore minimizing the revisit time. ScanSAR systems share the azimuth integration time between several subswaths and transmit only a short bunch of pulses in each beam position. The energy that a scatterer contributes to the received echo ensemble depends on the relative scatterer position following the azimuth antenna pattern. Hence, the focused image of a single burst shows a modulation that leads to periodic artifacts in final images called scalloping. Scalloping is generally evident by azimuth aligned bars but in some case these artifacts can be slightly differently oriented (Romeiser et al., 2010). Scalloping represents a non-trivial problem in SAR image interpretation, since they can cause severe misunderstandings in marine features extraction.

Several de-scalloping techniques, that can be classified in processing (Shimada, 2009; Bamler, 1995; Hawkins et al., 2002; Bamler et al., 1996; Monti-Guarnieri et al., 2001; Wollstadt et al., 2012) and post-processing (Romeiser et al., 2010; Schiavulli et al., 2012b) procedures, have been developed in order to mitigate this problem.

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In the first case one adjusts the SAR raw data processing while in the second case one has access only to processed SAR images and therefore only a sub-optimal de-scalloping can be accomplished.

Shimada (2009) proposed a method starting from the idea that the scalloping is caused by a mismatch of the real azimuth antenna pattern (AAP) and the model AAP and it can be suppressed if the noise floor level or the saturation rate of the SAR data is not too high and if the Doppler frequency can be accurately estimated. The proposed correction is based on the normalization of the Signal-to-Noise-Ratio (SNR) radar signal by the AAP shift with time. In Bamler (1995) a technique based on a set of antenna pattern correction functions for burst mode processing has been developed. These functions should satisfy the following conditions: image signal energy becomes constant over azimuth, noise energy becomes constant over azimuth and the ENL is maximized over azimuth. By allowing a variation in the signal image level in the derivation of the constant SNR weighting functions, the sensitivity of residual scalloping to Doppler centroid frequency estimation error is reduced. In Hawkins et al. (2002) a model for quantitative prediction of the scalloping, is presented. Such a model is based on the combined effects of poor Doppler estimation, placement of the burst sequence in the azimuth beam pattern for the target area and the details involved in performing azimuth compression of the data. In Bamler et al. (1996) high precision SAR algorithms for data processing are presented. In this paper the scalloping effects are compensated by the spectral weighting of the processor transfer function. Monti-Guarnieri et al. (2001) proposed a different focusing technique for low resolution SAR based on an optimized set of short kernels to reconstruct source reflectivity in the minimum mean square error (MMSE) sense. The proposed procedure converge to classical focusing when the burst extent is large. In Wollstadt et al. (2012) an investigation on scalloping correction in the Terrain Observation by Progressive Scan (TOPS) imaging mode for SAR systems with electonically steered phased array antenna is presented. A theoretical simulation based on general cardinal sine (sinc) antenna model as well as on the TSX antenna

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model is presented. Real TSX data acquired over the rainforest are used for testing scalloping simulation and correction. Morevoer, a calibration approach is introduced.

Although the scalloping problem is theoretically understood and several techniques to correct scalloping formation in SAR processor exist, it is still possible to get scalloped ScanSAR images from practically all satellites. Therefore, procedures able to mitigate the scalloping effect in processed ScanSAR images are needed.

In Romeiser et al. (2010) an efficient post-processing de-scalloping technique is proposed and tested over ScanSAR data. This procedure works partly in time and partly in Fourier domain and requires few iterations. The technique processes ScanSAR images working on subimages overlapped each other and mitigates the scalloping effect in both time and Fourier domain.

Schiavulli et al. (2012b) proposed an innovative and efficient technique to mitigate scalloping artifacts over CSK MGD ScanSAR images.

The algorithm is based on Wavelet Transform (WT) Multi Resolution Analysis (MRA) that operates as a directional filter working in wavelet domain able to mitigate periodic patterns due to scalloping allowing a good information extraction from imprints generates by sea surface atmosphere interaction.

Of course, any post processing de-scalloping technique is intrinsically suboptimal since a trade-off between SAR image spectra preservation and scalloping mitigation is needed. This compromise is obviously connected to the application the ScanSAR data will serve for.

4 Conclusions

In this paper a review of the most severe problems to be dealt with before any X-band SAR marine applications have been reviewed. In particular it has been focused on the rain cells that at some latitudes and especially in rainy seasons can heavily reduce the nominal revisit time. This is of great operational impact and at the moment is the major problem. On the processing side it is important that high quality ScanSAR processing

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is made and it is desirable that de-scalloping is native within the processing chain so that users get the best images. This is a problem in the actual CSK processing chain that is expected to be solved in the near future.

On a long-term view it is desirable that the new SAR technologies that greatly enhance the revisit time without hampering polarimetric or spatial resolutions performances are operated.

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