PERFORMANCE EVALUATION OF POLARIMETRIC SAR INTERFEROMETRY (POLINSAR) IN URBAN SCENARIOS: ANALYSIS OF SIMULATED IMAGES AND CROSS-CORRELATION WITH REAL DATA

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ABSTRACT

This paper performs a preliminary study about the potentialities of 3D dispersion maps on developing building characterization. Polarimetric Interferometric SAR images obtained from the SAR simulator GRECOSAR are used to evaluate if buildings can be differentiated by means of a particular 3D distribution of scattering centers accounting the Pauli mechanisms. If true, patterns with accurate geometrical information can be defined, which can benefit a large range of applications, such as subsidence or land thematic maps. To do this, two main activities have been carried out, namely: 1) to develop a scattering study by synthesizing fine scattering maps of building models with GRECOSAR and 2) to apply the resulting geometry-scattering relations in subsidence and classification studies. Classification performance is studied by generating building patterns and processing them with a recently proposed methodology that is appearing to be efficient for ships. Along the paper, data obtained from GRECOSAR is used, which, when possible, will be cross-correlated with real TerraSAR-X and RADARSAT-2 images.

I. INTRODUCTION

Urban scenarios account complex Electromagnetic (EM) interactions due to the high density of small scale details and the lack of symmetry. Up to now, the information within SAR images has not been able to properly deal with such properties and this has limited the applications that have been derived. Historically, most of focus has been placed on subsidence studies where the exploitation of large temporal series allows to balance some limitations of a single image [1].

But the situation is changing with the new orbital SAR sensors (TerraSAR-X, Cosmo-Skymed or Radarsat-2) as provide improved performance in terms of resolution and polarimetry. Now, advanced urban applications are defined, which focus on building characterization for improved classification and subsidence. Some attempts have been made trying: 1) to characterize scatterers with POLInSAR descriptors [2]; 2) to discriminate buildings via simple scattering approximations [3]; 3) to develop cluster-based classifier of urban images [4] or 4) to improve subsidence with geometrical analysis [5].

For a proper performance, all these activities need from an accurate urban scattering study that fixes the connections between specific geometries and particular dispersion behaviors for the largest range of scenarios possible. Evaluating the weight of small scale details and investigating the influence of the environment and time dimension in the overall scattering should not be diminished. Recent attempts have been made with the SAR simulator GRECOSAR [6]. Simulated polarimetric scattering maps with very fine resolution have been synthesized for different urban models inspired in real buildings. The analysis for diverse observation conditions has shown that the dispersion of buildings is configured by a particular 3D distribution of independent scattering centers with limited dispersion stability along the radar aspect angle [7]. Up to certain extend, it can be assumed that some geometries could be classified if certain conditions are met and the same aspect angle is used along different acquisitions.

In this framework, the current paper first investigates the potentialities of POLInSAR technologies for basing building classification. Support for improved subsidence will be also provided in spite of defining advanced criteria for selecting guide scatterers. The paper is structured in three main parts, namely: 1) presentation of the main results of the scattering study to highlight the critical points regarding geometry-scattering relations, 2) evaluation of the results in real data and 3) application of the scattering conclusions in subsidence and classification. To do this, building patterns summarizing the distribution of scatterers better describing the processed geometries are defined. Simulated images derived from GRECOSAR are used along the paper, which, when possible, will be compared with TerraSAR-X and RADARSAT-2 images to assess how the simulation results apply to real cases.

Section II provides a brief explanation of GRECOSAR and validates scenario realism. Section III summarizes the main conclusions of urban scattering by analyzing scattering maps and simulated SAR images. Cross-correlation with real data is performed in Section IV. Section V evaluates the application of scattering results to subsidence and classification.

II. SIMULATION ENVIRONMENT: GRECOSAR

A. Tool description

GRECOSAR is a numerical tool able to reproduce with notable realism the SAR signatures of complex targets in simple PC configurations [6] [8]. It can deal with Polarimetric SAR (POLSAR), POLInSAR and Polarimetric Inverse SAR (POLISAR) imaging geometries for any operating band, mode (strip, scan or spot) and system resolution within configurable scenarios. The kernel of the simulator is the UPC’s GRaphical Electromagnetic COmputing (GRECO®) solver.
that estimates, for each single frequency, the RCS of 3D targets via high-frequency methods. Any type of complex target can be processed if modeled with parametric surfaces via CAD tools\(^1\). Exhaustive tests with simple and complex targets have validated the code and scenario realism [8].

Details regarding EM calculations put on scene that high flexibility, reduced processing time and efficient usage of available resources is achieved. This is due to the adopted graphic-based approach for which a bitmap resident in the RAM memory is generated from the input model. By using a particular illumination point of view fixed by the user-defined Line of Sight (LOS) direction, GRECOSAR renders the model with the PC graphic card and isolates the visible entities from the back-facing ones. Over these entities, EM methods are applied making RCS prediction faster and independent of the input geometry. The main EM methods used are:

- Physical Optics (PO) for perfectly conducting surfaces.
- Method of Equivalent Currents (MEC) with Ufimtsev’s Physical Theory of Diffraction (PTD) coefficients or Mitzner’s Incremental Length Diffraction Coefficients (ILDC) for perfectly conducting edges.
- Multiple reflection analysis by a Geometrical Optics (GO) + PO ray-tracing algorithm. Bi-static GO is used for all reflections except the last one, for which PO is used. In curved surfaces, GO divergence factors are approximate.

These methods allow to analyze targets of electrical size as large as \(2^n\lambda/16\), with a maximum phase error of \(\lambda/8\), where \(n\) is the number of bits in which the distance to the observer is discretized. For a proper EM performance, input models have to be tessellated with a meshing procedure that discretizes parametric surfaces into small planar facets. This product is the input to the simulator, which is used by the PC’s graphic card to generate the GRECO\(^2\) bitmap. Therefore, two main parameters control EM simulation accuracy (and the demanded PC resources): the length of each facet defining the input model and the pixel size of GRECO\(^2\) bitmap.

B. Realism evaluation

One main advantage of the simulator is its scenario flexibility. Besides the typical parameters related with the acquisition process and later data processing (orbit, antenna pointing, chirp signal or radar aspect angle), some environmental parameters can be also managed. Most of them are focused to marine scenarios (configurable and dynamic surrounding sea, bearing, speed and target dynamics) where more efforts in simulator development have been initially putted on. Regarding urban scenarios, buildings can account dielectric information.

Considerations related with a proper scenario realism concern the degree of detail, roughness and perfect geometries.

- The degree of detail should consider all small scale geometries possible without increasing in excess the computational load. If not, the resulting model will be coarse and box-like shaped with a reduced number of scatterers. Most of them are canonic with high RCS and a restrictive angular behavior. As such, models are not useful because they do not reproduce the conditions of real scenes. In this work, the degree of detail is fixed by comparing scattering maps retrieved for diverse versions of building models with increased refinement. When the differences are not significant, refinement is stopped.
- Another topic lies on avoiding modeling perfect geometries as, otherwise, strongly-polarized mechanisms with high RCS can mask others. In addition, diffraction phenomenon in 2D corners is not properly simulated. To overcome these drawbacks, discretizing efforts should focus on: 1) avoiding perfect square angles among the different planes conforming a trihedral and 2) avoiding perfect flat planes for making the angular behavior less restrictive and diffraction to appear. To solve the previous problems, a surface roughness has been adopted as a type of surface rugosity. It is simulated by adding a random variable with particular distribution to the coordinates of the points delimiting each facet of a model. In the current work, an uniform distribution with zero mean and a variance of \(\sigma_r\) has been selected. Note that the purpose of surface roughness is to break with perfect geometries and not to realistically simulate the roughness of some structures. Under such conditions, the distribution selected is not fairly significant.

III. URBAN SCATTERING STUDY

A. Models and Scenario configuration

Two target models have been used in the ongoing work (Fig. 1). They are qualitative versions of the two urban structures identified in the photo of Fig. 2. There, an area of a neighborhood test site is shown where subsidence measurements have taken place with an UPC’s GB-SAR sensor [10] \(^2\). Model dimensions and details have been deduced by inspecting the photo with no support of blueprints. Material information is defined by the complex dielectric permittivity sampled at a specific range of frequencies. Due to GRECO\(^2\) restrictions, EM absorption at each facet can not be performed and, thus, information about the transmitted EM field is not available. At maximum, dielectric material can be modeled as a fine layer (of user’s fixed width) located over the default perfect conductor so that reflection coefficients becomes modified and, hence, the value of RCS. Regarding discretizing parameters, the roughness for model 1 takes \(\sigma_r = 0.05\) m and, for model 2, \(\sigma_r = 0.2\) m. In both models, facet length is not larger than 3 mm and bitmap pixel size than 1 cm.

Scattering maps have been obtained with the Inverse SAR (ISAR) imaging geometry depicted in Fig. 3. It is based on the circular spotlight mode where the sensor is in circular motion around a static target for a constant incidence \(\phi\), target orientation \(\beta\) (relative to \(r_T\)) and angular aperture \(\Delta\Omega\). The resulting images are projected over the incidence plane as

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\(^1\)The CAD package GiD\(^\circ\) of the International Center of Numerical Methods for Engineering [9] has been adopted here.

\(^2\)Test site is located in Sallent, a city 50 km North from Barcelona (Spain), with important mining-induced subsidence phenomena.
observed by a viewer located at the perpendicular axis [11]. With the suitable values of $\Delta \Omega$ and signal bandwidth, image resolutions can be fined up to the centimetric order.

The resulting polarimetric scattering maps have been processed with the Pauli theorem. Intensity images are color-coded according to the weight of each Pauli mechanism in each image pixel. The code follows red for 1st Pauli mechanism (sphere, trihedral, . . .), green for 2nd Pauli mechanism (dihedral) and blue for 3rd Pauli mechanism (dihedral 45° or anti-symmetric). The result is a colored scattering map that gives the chance to analyze the scattering behavior of buildings from a point view quite difficult to obtain in real data.

B. Scattering maps

First of all, urban scattering analysis have been carried out by processing the two models in the following sets: 1) orientation set obtained at C band for $\beta = \{170, 180, 190, 200\}^\circ$ and $\phi = 60^\circ$; 2) incidence set obtained at C band for $\beta = 190^\circ$ and $\phi = \{40, 60, 75\}^\circ$; 3) frequency set obtained at C and X band for $\beta = \{190, 200\}^\circ$ and $\phi = 60^\circ$ and 4) temporal set obtained at C band for $\beta = \{190, 200\}^\circ$.

Fig. 1. Models 1 and 2 related with the buildings identified in the Sallent test site according to Fig. 2. The color code shows the adopted materials.

Fig. 2. Photo of the neighborhood test site located in Sallent (50 km North from Barcelona, Spain) where GB-SAR subsidence measurements have taken place. Black numbers isolate the structures modeled in Fig. 1.

Fig. 3. Inverse SAR imaging geometry of GRECOSAR. Sensors are in circular motion over the incidence plane $\Phi_{ISAR}$, defined by the longitudinal (LOS) ($\hat{r}_l$) and transversal (perpendicular) ($\hat{r}_t$) direction.
due to the large number of spots within a resolution cell.

- Variations of the polarimetric scattering behavior seems less critical along the relative target orientation than incidence. Certainly, a distribution of guide scatterers that play the role of a pattern can be only isolated from the analysis of images obtained at the same incidence.
- Few variations along frequency are observed and certain polarimetric stability along the electrical length can be fixed. The main cause may lay on the physical dimensions of main scatterers, which are large in terms of $\lambda$.
- Each scattering center is independent of each other and, hence, the influence of multi-scatter interaction is less important than initially seems to be. This means that for fine enough resolutions (lower than a meter) time dimension could not be so critical. Only local variations would be observed, which would not cause important changes

Fig. 4. RGB Pauli simulated scattering maps of the orientation set obtained at C band and $\phi_{ISAR} = 60^\circ$. Building model 1 and 2 are presented for $\beta_{ISAR} = 190^\circ$ (a), (c) and $200^\circ$ (b), (d). The point of view is backwards with near-range at the top of the image. Dark lines help in a proper overlapping.

Fig. 5. SAR imaging geometry of GRECOSAR. An ideal linear track is assumed for a squint $\alpha$ and incidence $\phi_{SAR}$ angle. For $\alpha = 0$ and $\phi_{SAR} = \phi_{ISAR} = \phi$, $\hat{r}_r$||$\hat{r}_t$ and $\hat{r}_g$||$\hat{r}_l$. 
Fig. 6. RGB Pauli simulated SAR images obtained at X band for $\phi_{\text{SAR}} = 60^\circ$ and $\beta_{\text{SAR}} = 190^\circ$. The related simulated scattering maps have been attached for comparison, jointly with the associated real GB-SAR image. There, the response related to the modeled building have been isolated from the whole image of Fig. 3. The white rectangle delimitates approximately the image bounds of the simulated SAR image whereas the white circles isolate key spots that allow to identify the processed building and to establish relations with the scattering maps. All three images follow the same convention with the point of view backwards being near-range at the top of the image.

C. Simulated SAR images

In order to evaluate how the dispersion behavior observed in the scattering maps apply in SAR images (with lower resolution), some additional simulations have been made. The previous sets (orientation, incidence, frequency and temporal) have been processed at X band for the imaging geometry of Fig. 5 with a resolution of 1.5 m in range and 2.5 m in azimuth. Fig. 6 shows some samples analyzed with the Pauli theorem, which are complemented with scattering maps and real images for similar aspect angles. Real images are clips of a POLSAR GB-SAR dataset acquired for the GB-SAR subsidence test site of Fig. 2 [10]. They isolate the dispersion measured for the two buildings modeled in Fig. 1.

In general, it can be stated that the reflectivity of SAR images is similar to that present in the scattering maps and GB-SAR data. Some common dispersion characteristics appear, as the mechanisms related with frame and joints points (model 1), and those linked with 3D corners and wall-street interactions (model 2). As happens in the scattering maps, some of these scatterers (specially 3D corners) are good candidates to be guide points in subsidence and classification. Note also the layover effect observed in both dataset for a trihedral-like mechanism in building 2. As shown in Fig. 6(b), this scatter corresponds to a 3D corner over the roof that appears focused close to the wall-street mechanism in near-range. As observed later with real data, this phenomenon is very adverse.

IV. REAL DATA ANALYSIS

This section evaluates up to which extend the urban dispersion derived in simulated images apply to the real world. Efforts will be devoted to analyze, under a qualitative point of view, TerraSAR-X images obtained from a trial dataset and RADARSAT-2 images obtained with a SOAR application.
Fig. 7. Portion of a TerraSAR-X image of the city of Tokyo acquired with spotlight mode at 2007-11-29. Image resolution is 1.79 in ground-range and 1.49 in azimuth with an imaged area of 0.6 km². “Building M” label means modern building (high buildings with symmetric facades with 3D corners) whereas “Building T” traditional ones (short buildings with no evident 3D corners on the structure, except punctual appearance over the roof).

A. TerraSAR-X

The TerraSAR-X dataset used in this work corresponds to the city of Tokyo. The imaged area (∼ 560 km²) is of particular interest as old and traditional buildings are surrounded by modern and high skyscrapers. The considered image has been acquired at 2007-11-29 in spotlight mode providing a resolution of 1.79 m in ground-range and 1.49 m in azimuth. Only the magnitude of the HH channel is available limiting polarimetric analysis.

An image snapshot is presented in Fig. 7. There, skyscrapers and traditional buildings are within the same area, jointly with public parks and streets. On the one hand, traditional buildings present marked mechanisms at the base of the facade due to the wall-street interaction. Some 3D corners, mainly at the roof, can be located, but they are not by far the dominant mechanisms in the overall target scattering. On the other hand, modern skyscrapers are characterized by a regular grid of intense scattering centers along the facade. They are induced by the 3D corners on window frame or the external metallic structure shelling the facade.

According to the results presented in Section III, the retrieved scattering information is very similar of what retrieved within the simulated scenario. There, wall-street interactions behave as dihedrals and 3D corners as trihedrals. With current real images, the lack of polarimetric information avoids to completely validate this point, but significance differences are not expected. Also important is layover effects that make image post-processing and interpretation more difficult. With high skyscrapers, this is extremely adverse.

B. RADARSAT-2

Another example is provided in the RADARSAT-2 data shown in Fig. 8. There, a clip (∼ 30 km²) of an image sensing the city of Barcelona in quad-pol mode is presented after processed with the Pauli theorem (color convention follows previously used). The area presents details of the historical neighborhood with part of the harbor. In general, resolution is worse than in the previous case and less details can be
isolated. This is the price to pay in order to have polarimetric information and validate part of the geometrical key issues identified via scattering maps.

First of all, note that dihedral-like linear features induced by 2D wall-street interactions are not dominant (except for some particular streets and harbor areas). The fact that the slant-range direction is not perpendicular to most of geometries and building distribution in Barcelona follows a regular grid are the main reasons. In general, buildings and man-made structure can be differentiated from streets and public parks where a clear polarimetric behavior trend is not observed.

Some strongly-polarized trihedral-like mechanisms can be isolated at the upper-left side of the clip image (see wider red dots in regular grid building distribution). They appear focused at the roof of buildings and may correspond to the 3D corners of the terraces present. They seem similar to those retrieved for building model 2, but without more ancillary information conclusive asseveration can not be made.

V. APPLICATION OF URBAN SCATTERING STUDY

This section evaluates the benefits that the geometry-scattering relations fixed with scattering maps can provide to classification and subsidence. For the former, patterns are defined and processed with the Vessel Classification Algorithm (VCA) [14] [15]. There, particular combination of Permanent Polarimetric Scatterers (PePS) are used to characterize geometries, which cross-correlation with measurements provides the decision rule. Despite VCA has been initially conceived to work with ships, it can deal with any complex target.

A. Building Classification

1) Pattern generation: Building patterns have been generated for each model by selecting the distribution of PePS (guide scatterers) that, first, better describes the macro-scale characteristics of targets and, second, is more robust against variations on the observation conditions (aspect angle and time dimension). So, PePS are defined as those scatterers presenting a RCS 10 dB higher than the surrounding scatterers and stable polarimetric behavior within a solid angle of at least $\pi/3$ steradian [15]. In other words, they are such scatterers that induce local maxima in SAR images with the same dominant Pauli mechanism along the marked solid angle.

PePS are formulated via a simple formulae based on quantitative parameters (feature set), which can be easily measured with real SAR data. PePS definition needs from a reference positioning system different to the SAR azimuth/slant-range one. So, coordinate system transformations are required for which $\beta$ should be estimated from image features. The Radon transform is useful for such purpose. The PePS selection procedure detailed in [15] has been applied to the scattering maps. Two patterns result, which are valid for a set of observation conditions: 1) $180 < \beta < 220$, 2) $50 < \phi < 65$ and 3) $5.3$ (C band) $< f_s < 9.65$ (X band). Out of these ranges, the patterns do not allow to properly identify target structure.

2) Algorithm description: VCA algorithm consists basically on estimating, from POLInSAR data, possible feature sets according to the related formulae [15]. The resulting vectors are then correlated with the reference ones and a similarity value is provided. The geometry which reference set provides the highest similarity is used to describe the observed target. To do this, all the local maxima present in all the polarimetric channels $m$ are isolated and combined in all the possible ways with all the available patterns. For a pattern $p$ with $M$ PePS, $P = m \cdot (m!)/((M-m)!)$ correlations are performed with a similarity value for each one [15]. The highest value is used to associate the similarity of pattern $p$ with the measured target. From all the patterns, the one having the largest similarity is selected to identify the observed target. All this process is repeated for different dynamic ranges and, after pondering, a final decision is made.

3) Results analysis: To evaluate the performance of VCA with building models, a set of POLInSAR datasets have been generated. Master and slave acquisitions have been made with the imaging geometry of Fig. 5 assuming an across-track interferometric configuration with a orthogonal baseline of 30 m. System parameters have been tuned close to TerraSAR-X sensor with an effective range and azimuth resolution of 1.5 m and 2.5 m. The same observation conditions than those used for synthesizing the scattering maps have been adopted.

VCA correlation result is reported in Table I for the indicated cases. The similarity parameter $0 < S < 1$ is the result of pondering the differences between the values the parameters of the feature set take in the image and a pattern. The values of $S$ show that positive classification are achieved in particular situations, despite the trend seems to indicate that classification fails. Two main reason come to mind, namely:

1) Lack of symmetry. VCA has been conceived to deal with ships where target symmetry is evident and helps to reduce the dependency of the scattering behavior with respect to the radar aspect angle.

2) Dihedral PePS. Patterns have dihedral PePS due to 2D corner interaction. Such mechanisms are more sensitive

<table>
<thead>
<tr>
<th>Model Processed</th>
<th>$\beta[^\circ]$</th>
<th>$\phi[^\circ]$</th>
<th>$S^1$</th>
<th>$S^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1</td>
<td>190</td>
<td>60</td>
<td>17.3</td>
<td>67.8</td>
</tr>
<tr>
<td>Building 1</td>
<td>200</td>
<td>60</td>
<td>66.4</td>
<td>0</td>
</tr>
<tr>
<td>Building 1</td>
<td>210</td>
<td>60</td>
<td>0</td>
<td>61</td>
</tr>
<tr>
<td>Building 2</td>
<td>190</td>
<td>60</td>
<td>26.8</td>
<td>0</td>
</tr>
<tr>
<td>Building 2</td>
<td>200</td>
<td>60</td>
<td>40.4</td>
<td>76.8</td>
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<tr>
<td>Building 2</td>
<td>210</td>
<td>60</td>
<td>72.5</td>
<td>11.5</td>
</tr>
</tbody>
</table>
to changes on the radar aspect angle causing significant variations on RCS. This affects VCA performance. Additional tests performed by erasing dihedral PePS from patterns show that no significant improvement is achieved. Only for targets with strongly-polarized trihedral-like mechanisms, reasonable results are found.

B. Subsidence

Subsidence applications may benefit from the scattering maps presented in Section III in two main points, namely: 1) definition of the characteristics of the guide scatterers with a more robust and stable dispersion behavior along time and aspect angle; and 2) fixing the zones where main scattering centers are normally located (street, facade, roof, balconies, ...) in spite of a morphological analysis.

Actually, the combination of polarimetry plus morphological analysis is proposed for defining new selection criteria of quality pixels within a POLInSAR framework. The idea is to use simulated scattering maps for defining characterization patterns with a set of PePS and, then, use the pattern to locate similar structures within the data and apply the dispersion information. The result may be more efficient selection criteria where not all the pixels are scanned for finding those with more quality, but only those within the zones marked by the pattern. In addition, they can be more robust for preventing selecting pixels that seem to be stable according to a limited set of data, but they are subjected to sudden changes due to human activity (garage doors or marquee). But to properly evaluate the potentialities and benefits of simulated-made buildings patterns in subsidence, it is necessary to develop measurement campaigns in real scenarios. Some preliminary attempts have been made with the UPC’s GB-SAR sensor leading to encouraging results.

VI. CONCLUSIONS

In this paper, the potentialities of POLInSAR technology on helping developing new building classification and subsidence approaches have been evaluated. For such purpose, a scattering study has been generated in order to accurately fix how specific urban geometries backscatter to SAR sensors under specific observation conditions. The results show that 3D corners, normally located on window frames, and 2D corners, normally due to facade-street interaction, are the main scattering centers sensed. The former presents an angular behavior less restrictive, which would be proper for deriving guide scatterers (PePS) within the framework of a characterization pattern.

After the analysis of a lot of scattering maps synthesized with GRECOSAR, two patterns have been derived for two building models. They are valid under specific observation conditions accounting relative orientation, incidence and operating frequency. Their classification performance has been evaluated with VCA, an algorithms able to provide robust classification capability for ships via POLInSAR analysis. The results show that building patterns defined with PePS and processed with VCA do not lead to robust urban classification as so much fails are observed. Two main reasons come to mind, namely: 1) the lack of symmetry and 2) the presence of dihedral mechanisms induced by 2D corners. It is worth noting that none of them applies to ships as they are symmetric and the 2D corners with higher RCS are induced by mast-surface interaction with almost no radar aspect angle dependence. Regarding subsidence, simulation-made patterns present great potentialities for improving current performance with more accurate selection criteria and more physical sense for data analysis. Future works should further investigate this field and how POLInSAR can help on developing urban applications.

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