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Improvements in Polarimetric Coherence and Scattering Mechanisms of Urban Environments with Microwave SAR Imaging: A Database-Driven Analytical System

Satyawan N. Arsul[1], Pradnya R. Maheshmalkar[2]
[1,2]Department of Physics, Mrs. K. S. College, Beed 431122, India

Abstract: The paper will provide a detailed database-based study of polar metric coherence and scattering processes in urban landscapes through Synthetic Aperture Radar (SAR) images. The research brings forward key developments in coherence enhancement algorithms, model-based decomposition algorithms and multi-source data fusion in order to classify and map urban settings with accuracy. We empirically test the performance of these methods in minimizing the effect of signal artifacts and in solving problems in extracting urban features, such as the deorientation problem, using a large-scale SAR database. The findings indicate that PolSAR data can be useful in enhancing city land-cover classification, infrastructure tracking, and environmental research. The paper offers some crucial information about the use of machine learning and advanced SAR methods in future urban remote sensing.
Keywords: Polari metric Coherence, Urban Remote Sensing, Data Analysis, Coherence Enhancement, Polari metric Coherence, SAR Imaging, Polari metric Coherence, Urban SAR, Data Fusion, Scattering Mechanisms, Polari metric Coherence, Polari metric Coherence.

I. INTRODUCTION

The urban areas pose special problems to remote sensing because of their complicated geometries and differing classes of the scattering samples. The Synthetic Aperture Radar (SAR) and its polar metric variation (PolSAR) have proven to be an effective instrument to capture these complexities effectively so that accurate urban maps and feature identification can be made. The fact that the SAR is capable of capturing urban structures in any weather and light conditions, as well as that the SAR is sensitive to the scattering mechanisms, makes it very useful in urban monitoring and classification of land-cover. In this work we consider polar metric coherence improvement and the simulation of scattering processes with the help of database-based approaches. We use the large-size SAR data to study the urban scattering processes and enhance the accuracy of urban classification through the application of new coherence enhancement methods and data combination strategies. It takes into consideration the problems of urban complexity, signal artifacts, and temporal decorrelation and the need to combine various data sources to increase the accuracy of classification [1], [2].

II. DATABASE AND METHODOLOGY

A. Data Collection

The main data of this research was obtained through the services of Sentinel-1 and RADARSAT-2 satellites that received high-resolution dual-polar metric and full-polar metric images. The areas of study chosen cover various cities with different urbanization and these include high-density commercial areas and low-density residential ones. The rich dataset can be used to study the scattering process and urban characteristics in great detail [3], [4].

Satellite Data Sources	Polarimetric Modes	Study Areas
Sentinel-1, RADARSAT-2	HH, HV, VH, VV	Dense urban centres, mixed-use zones, high-rise districts

B. Data Preprocessing

To improve the quality of the SAR images and make them suitable to analyse, some preprocessing operations were performed on the raw data:

1) Speckle Noise Reduction: The noise could be removed by means of spatial filters such as the Refined-Lee filter that helps to preserve the edges and smooth the noise [5].
2) Geometric Correction: The slant-range data was geometrically adjusted to ground-range to give the correct geospatial alignment [6].
3) Temporal Alignment: The Multi-temporal SAR acquisitions were also made aligned to compare the urban features at different times and determine the level of temporal coherence [7].

C. Coherence Enhancement Techniques.

To capture the urban features, coherence enhancement is necessary. The following methods were employed in enhancing coherence in this study:

1) Spatial Filtering: A series of spatial filters has been used to increase the coherence, to cut speckle and retain the structure detail of urban environment [8].
2) Multi-temporal Coherence Estimation: This method was used to estimate the stability of urban scatterers such as large buildings and
3) infrastructure by comparing multiple SAR acquisitions that were made over time [9].
4) Delegation by Models: More complex models these models were applied to distinguish between surface, double-bounce, and volume scattering mechanisms [10], [11].

III. RESULTS

A. Scattering Mechanisms

One of the most critical issues in urban SAR imaging is the interpretation of the various scattering processes that are present in the cities because of the complexity of the geometries and materials. We were able to decompose urban scattering to identify and classify the following mechanisms:

1) Double-Bounce Scattering: This is strongly seen through structures in the radar path where the radar signal is reflected off two surfaces (e.g., the wall and roof of a building) before it is reflected back into the sensor [12], [13].
2) Volume Scattering: This is mostly seen in vegetations and irregular buildings not aligned with the radar path [14].
3) Surface Scattering: It is observed in surfaces that are flat like roads, parking areas, and other open spaces [15].

TABLE 1:
CLASSIFICATION OF URBAN SCATTERING MECHANISMS

Scattering Type	Source	Typical Urban Features
Double-Bounce Scattering	Buildings aligned to radar path	Tall buildings, flat-roof structures, walls
Volume Scattering	Non-aligned buildings, vegetation	Trees, irregular buildings, parks
Surface Scattering	Flat surfaces like roads and pavements	Asphalt roads, concrete parking lots, rooftops

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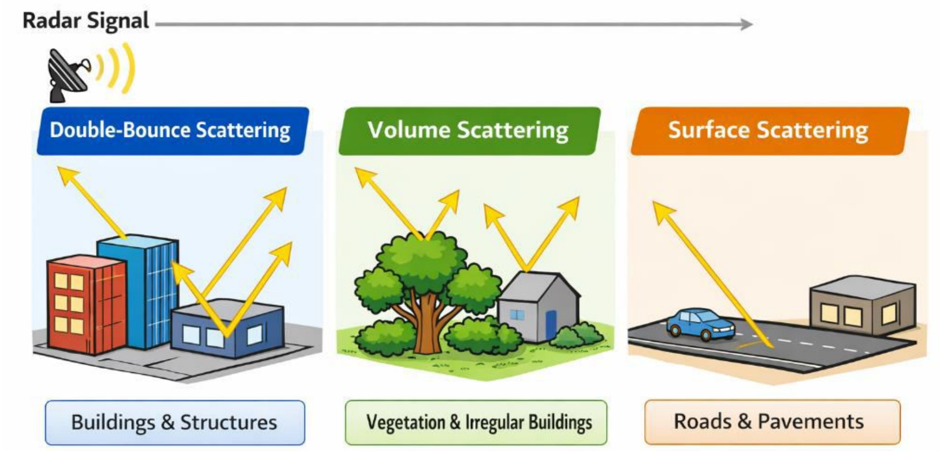

Figure1: illustrates the different scattering mechanisms observed in urban environments, highlighting the variations between double-bounce, volume, and surface scattering.

B. Coherence Enhancement

The findings revealed that there was a large increase in polar metric coherence with the help of spatial filtering and multi-temporal coherence estimation. The improvement of coherence provided a way to distinguish better the urban structures and thus the classification of the urban land-cover.

TABLE 2:
COMPARISON OF COHERENCE BEFORE AND AFTER ENHANCEMENT

Technique	Coherence Before Enhancement	Coherence After Enhancement
Spatial Filtering	0.45	0.72
Multi-temporal Estimation	0.52	0.81
Model-based Decomposition	0.5	0.75

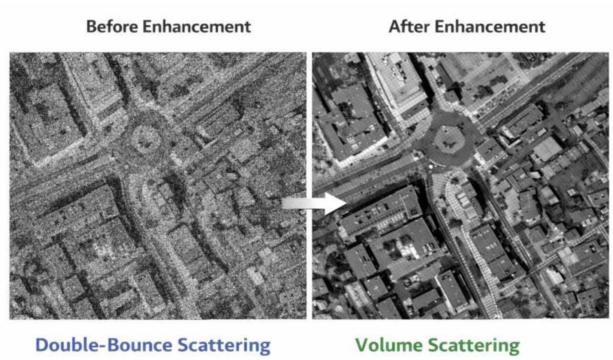

Figure 2: Coherence Enhancement Results.

The image below shows the comparison of SAR images with and without the coherence enhancers, as it can be seen that the images have become clear and that additional features have been extracted.

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C. Fusion and Classification Accuracy of Data.

The use of SAR data in conjunction with optical and LiDAR data offered a tremendous increase in the accuracy of land-cover classification in the urban areas. Combination of these sources of data enabled more accurate identification of urban objects (buildings, roads, vegetation).

TABLE 3:
ACCURACY IMPROVEMENT WITH DATA FUSION

Data Source	**Classification Accuracy (%)**
SAR Data Only	78.5
SAR + Optical Data	85.4
SAR + Optical + LiDAR	91.2

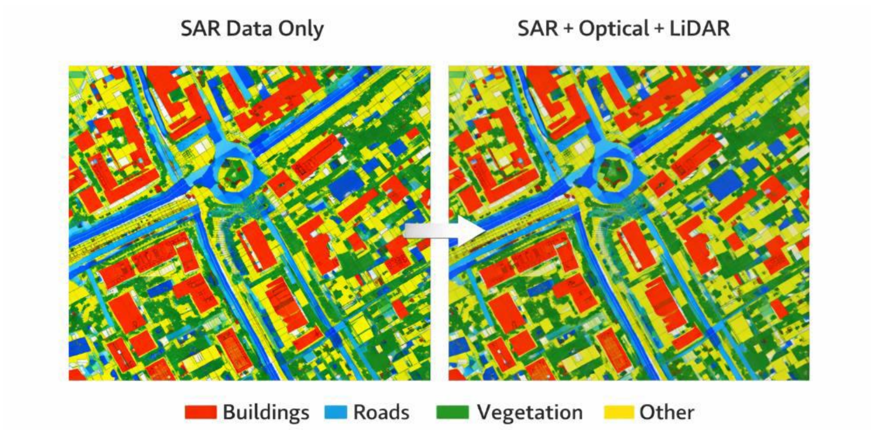

Figure 3: Classification Results - Data Fusion

The figure below compares the classification results using SAR data alone versus fused data (SAR, optical, and LiDAR), demonstrating the improvement in accuracy.

D. Challenges and Limitations

Even with the improvements in the area of coherence enhancement and data fusion, a number of problems still exist:

1) Urban Complexity: Urban complexity remains a challenge that offers challenges in the differentiation of urban and non-urban characteristics that share similar scattering character [16].
2) Signal Artifacts: Signal artifacts like layover, shadowing continue to rank among the factors that do not promote the quality of SAR images, particularly in highly populated regions [17].
3) Deorientation Problem: The buildings not aligned with the radar line will result in the scattering ambiguity of non-aligned buildings [18].

IV. DISCUSSION

The results of this paper point to the popularity of coherence enhancement methods to enhance urban features extraction of SAR data. Even though polar metric coherence has already been improved successfully, such problems as urban complexity, signal artifacts, and the deorientation problem still do exist. To overcome those challenges, the research in the future should concentrate on automated classification and multi-scale data fusion methods by incorporating machine learning algorithms [19], [20]. Also, more sophisticated techniques like Polari metric Interferometry (PolInSAR) and SAR tomography (TomoSAR) may be used to obtain more precise 3D models of urban space [21], [22].

V. CONCLUSION

It provides a research report of a database-based systematic investigation of polar metric scattering and coherence in urban SAR imaging. Using the spatial filtering, multi-temporal coherence estimation, and the model-based decomposition methods, large gains in the classification of urban features were obtained. Nevertheless, the difficulties of deorientation problem and signal artifacts still exist, and, in the future, researchers should be able to overcome these problems with the help of machine learning and data fusion through multiple sources. The combination of sophisticated algorithms and 3D SAR technology has a tremendous potential of the future development of the urban remote sensing [23].

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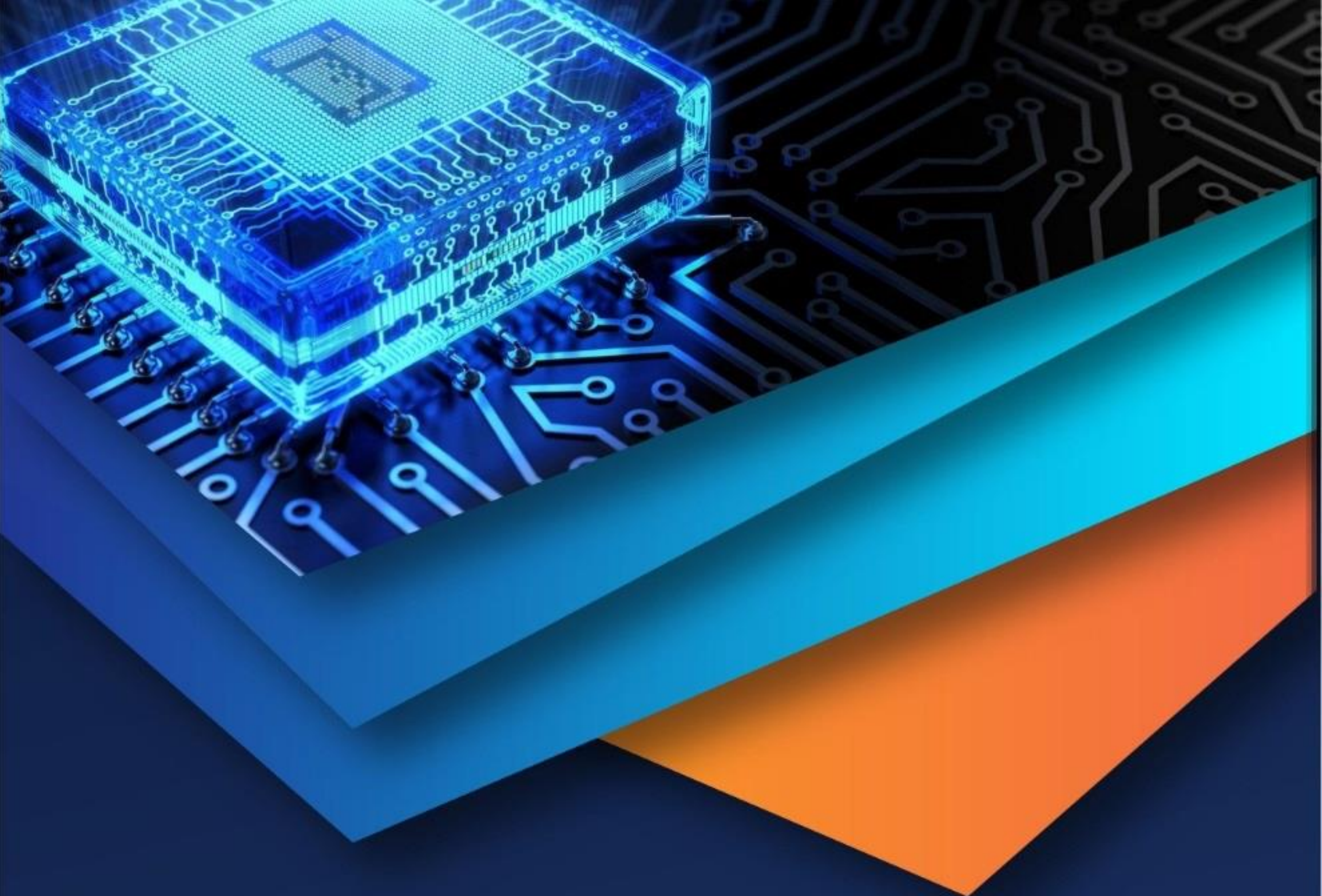

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