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Comparative Study of Adaptive Filters, Boxcar, and Goldstein in Radar Interferometry Using Envisat Satellite Images over the Yazd-Ardakan Plain

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A B S T R A C T

Objective: This study aims to evaluate and identify the most effective speckle noise reduction filter for Synthetic Aperture Radar (SAR) images, specifically focusing on maintaining image clarity and preserving edge details.
Methods: SAR systems, which send microwave pulses to measure reflectors and distances, are prone to speckle noise due to the interference of reflected waves from heterogeneous surfaces. This noise negatively impacts image quality, complicating the extraction of accurate environmental data. The research utilized 1-Sentinel SAR images of the Yazd-Ardakan plain and applied various noise reduction filters to these images.
Results: The effectiveness of each filter was assessed based on its ability to reduce speckle noise while preserving critical features, particularly edges. Results indicated that the adaptive filter outperformed the other filters by maintaining sharp edges and reducing noise, making it the most suitable option for this type of image enhancement. The Goldstein filter, while effective in removing noise, compromised phase accuracy, and the Boxcar filter blurred edges.
Conclusion: This study concludes that the adaptive filter is the best option for SAR image enhancement in the study area, offering significant potential for more accurate environmental monitoring. Further research is recommended to explore the combination of different filters for improved results in complex environments.

1. Introduction

Microwave remote sensing systems, particularly radar-based systems, have revolutionized the way we observe and analyze the Earth's surface. These systems utilize electromagnetic waves in the microwave band, transmitting them as pulses, and measuring the time interval between these pulses to determine various surface characteristics, such as roughness, geometry, and moisture content. The radar's ability to send out signals in the microwave range (ranging from 1 mm to 1 meter in wavelength) enables it to penetrate through adverse weather conditions like dust and fog, which commonly affect optical sensors. This ability to function in any climate makes radar an invaluable tool for remote sensing applications (Salahshouri & Almodaresi, 2016). The radar system operates in the microwave spectrum, with both the transmitter and receiver in this range, allowing the generation of high-resolution images

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under all weather conditions, regardless of lighting (Panahi, 2017).

In recent years, innovative techniques based on radar interferometry have been developed. These methods rely on back-scatter points, which are reflected signals used to monitor changes in surface characteristics over time (Zarekamali et al., 2017). While radar remote sensing systems possess numerous advantages over optical imaging systems, such as the ability to operate in all weather conditions, they face challenges in image formation. These challenges arise from differences in how radar images are formed compared to optical images, which lead to radiometric limitations in active radar images. Specifically, the Synthetic Aperture Radar (SAR) system illuminates the surface with microwaves and records both the amplitude and phase of the back-scattered radiation, contributing to the complexities of interpreting radar data (Lillesand et al., 2008).

A significant challenge in SAR imaging is the presence of speckle noise. This noise is an inherent product of interference waves and the topography of the Earth's surface, negatively impacting the radiometric quality of SAR images. Speckle noise arises due to the continuous interference of reflected waves from multiple diffusers and is considered one of the primary factors contributing to errors in data interpretation and algorithmic results. This type of noise introduces variations that can hinder the extraction of accurate information from SAR images, often leading to misclassification or misinterpretation of features. As a result, it remains a critical issue in the remote sensing community (Domg & Milne, 2001; Oliver & Quegan, 2004; Saevarsson et al., 2004).

Speckle noise reduction is crucial for improving the quality of SAR images and ensuring more accurate analyses. However, the process of noise reduction itself can alter the image, necessitating the use of effective filtering techniques to minimize any potential destruction of data. Speckle noise is considered a multiplicative noise process, and it can degrade the quality of SAR images, thereby complicating the analysis, classification, and feature extraction tasks (Lee & Pottier, 2017). Generally, there are two main methods to address this issue: the first involves leveraging multiple phenomena, while the second relies on spatial filtering applied post-image creation. In this study, the second method, spatial filtering, has been employed to reduce speckle noise and improve image quality.

Before performing the primary analysis and feature extraction tasks on SAR images, it is common practice to apply a speckle noise reduction filter to mitigate the adverse effects of noise on image clarity (Ali et al., 2008). This pre-processing step is critical in ensuring that subsequent processes do not yield erroneous results. The persistence of speckle noise and its disruptive effects on image quality have been widely recognized, and many techniques have been proposed for its reduction. Several studies have evaluated the effectiveness of different filters, particularly in areas with dense vegetation or complex terrain. For example, Forouzanfar et al. (2010) examined the performance of various filters on JERS-1 SAR images from forested regions in northern Iran, selecting the most effective filter based on the specific characteristics of the study area. Other researchers have also contributed to this field by testing different filtering techniques, including those proposed by Maghsoudi (2011), Lopes et al. (1990), and Falahatibagherabadi and Amini (2010).

Objectives and Hypotheses:

The main objective of this study is to evaluate the performance of various speckle noise reduction filters in enhancing the quality of SAR images. Specifically, the study aims to:

- Identify the most effective speckle noise reduction filters for SAR images in diverse environmental settings, including urban and forested areas.
- Assess the impact of speckle noise reduction on the accuracy of feature extraction and classification algorithms applied to SAR images.
- Compare the effectiveness of multiple filters and determine their suitability for specific types of terrain and environmental conditions.

Based on these objectives, the study hypothesizes that:

- Speckle noise reduction filters will improve the quality of SAR images, leading to more accurate feature extraction and classification results.
- Different filtering techniques will vary in effectiveness depending on the specific environmental context and characteristics of the study area.
- Applying the optimal filter will reduce the impact of speckle noise significantly, making it possible to derive more reliable and accurate conclusions from SAR imagery.

By addressing these objectives and testing these hypotheses, this research aims to contribute valuable insights into the optimization of SAR image processing, which is crucial for remote sensing applications in various fields, including environmental monitoring, urban planning, and disaster management.

2. Material and Methods

2.1. Study area

The Yazd-Ardakan plain is one of the largest and most significant plains in Yazd province, Iran. It is located between longitudes 53°15′ to 54°50′ east and latitudes 31°15′ north. This expansive plain extends from the west and southwest, where it is bordered by the Shirukh mountains, and stretches eastward towards the mountainous villages. The plain encompasses several key cities, including Ardakan, Meybod, Ahazzar, Mehriz, and the provincial capital, Yazd. The total area of the Yazd-Ardakan plain is approximately 11,775 square kilometers, making it a significant geographic region for environmental and urban studies. The geographic location of this plain, characterized by its proximity to mountainous regions, contributes to a unique combination of environmental factors that influence the area's climate, vegetation, and land use. These features make the Yazd-Ardakan plain an ideal study area for examining the impact of climate and environmental parameters on various phenomena, including the assessment of hazards and risk management (Mirzadeh et al., 2021). Fig. 1 illustrates the geographical boundaries and cities of the Yazd-Ardakan plain.

Fig.1- Study area

2.2. Research Approach

This research adopts a descriptive-analytical approach to assess the quality and effectiveness of speckle noise reduction techniques in radar-based satellite images. The primary data sources for this study are radar images of the Yazd-Ardakan plain, obtained from the European Space Agency (ESA). These satellite radar images provide valuable insights into the environmental conditions of the study area, which are crucial for evaluating various speckle noise reduction methods.

2.3. Methodology

To process and analyze these images, the study employs the ENVI software platform, specifically utilizing the SARscape module. SARscape is a specialized tool within ENVI that is designed for the processing and analysis of Synthetic Aperture Radar (SAR) data. This module allows for advanced image processing tasks such as speckle noise reduction, image enhancement, and feature extraction. By leveraging the capabilities of SARscape, the research aims to evaluate the performance of different speckle noise reduction filters in improving the quality of SAR images.

2.3.1. Getting Radar Data

Successful data processing is highly dependent on the quality and suitability of the input data. Interferometric processing, in particular, requires complex radar imaging, where radar signals must not only carry the amplitude information but also include phase data, which is essential for SAR image processing.

In this study, the radar data used were obtained from the European Space Agency (ESA). To acquire the required images, the interface software Eloisa was utilized. This software is available through the ESA website and facilitates the ordering and retrieval of satellite radar images.

One of the key factors in selecting the appropriate data for the study is the time interval between the acquisition of the radar images and the correlation value between them. These factors are critical as they influence the accuracy and reliability of the interferometric analysis. The specifications of the data obtained for this study are presented in Table 1.

Table 1- Information about images received from the European Space Agency

Row	Image date	The name of the satellite	The name of the sensor	Data type
1	28/04/2008	ENVISAT	ASTER	ASA_IMS_IP
2	22/02/2010	ENVISAT	ASTER	ASA_IMS_IP

2.3.2. Data Entry and SLC Production Based on SARscape Format

A series of data transformations are necessary to import the radar data and produce Single Look Complex (SLC) images in the SARscape format. This process is carried out through the Standard Format command within the SARscape module. After importing the required radar data, the software proceeds to create the SLC images, which are essential for further analysis.

The SLC format contains important information such as power and phase, which are vital for subsequent interferometric processing and analysis. The phase data, in particular, plays a key role in evaluating the topography and surface displacement, while the power data helps in assessing the quality and intensity of the radar signal. By creating these SLC images, the study ensures that the radar data is in the appropriate format for accurate analysis and processing.

2.3.3. Determining the Two-Pass Interval

The first step in working with radar data is determining the relative positioning of the data points and evaluating whether the data is suitable for the formation of an interferogram. Interferometry requires two single-look images taken at two different times, and these images must be spaced at a standard distance to ensure valid results. In this section, the Slave and Master images are carefully selected, aiming for the shortest possible perpendicular baseline length.

Perpendicular Baseline: This term refers to the theoretical distance between two satellites used to capture the images, measured perpendicular to the line of sight. A smaller baseline is preferable as it improves the quality of the interferometric measurement by minimizing the phase noise and enhancing accuracy.

Height Ambiguity: Height ambiguity represents the maximum height difference that can be measured between two images based on the interferometric processing. This is linked to the $\lambda/2$ (half-wavelength) cycle fringe of the interferogram. The value of height ambiguity indicates the system's sensitivity to detecting subtle altitude differences, which is critical for precise topographic measurements.

Frequency of Doppler Centroid: This refers to the frequency difference between the central Doppler frequency of the two radar images. The Doppler centroid frequency helps in assessing the overall signal quality and determines the degree of shift between the images due to the relative motion of the satellite and the Earth's surface. A higher Doppler shift generally indicates better resolution in terms of detecting variations in the target's motion.

By considering these factors, the two-pass interval can be determined effectively, ensuring that the selected images meet the criteria for accurate interferometric analysis and that the measurements are reliable for further processing.

2.3.4. Interferogram Production

Interferometry of radar images can be generated when two radar images of the same region are captured at different times. Each pair of radar images is capable of producing an interference pattern, making it possible to create multiple interferograms from a series of images. Specifically, with n radar images of the same area, it is possible to create n (n-1)/2 interferograms (Maghsoodi & Mahdavi, 2016). Radar interferometry relies on measuring a characteristic of electromagnetic waves called phase. The transmitted wave follows a sinusoidal function, while the reflecting wave is shifted by$\pi/2$ resulting in a phase difference between the transmitted and reflected waves. The combination of these two waves controls the resultant wave. When these waves interact, they form an interferometric image, capturing the phase difference between the waves.

A key parameter in this process is coherence, which determines the accuracy of the interferograms produced. Coherence is a complex parameter whose amplitude indicates the quality of interference, based on the correlation of corresponding pixels between the two images. The phase value of coherence represents the phase difference between the two images and the interferometer phase (Hanssen, 2001). High coherence between the two images indicates a strong correlation and reliable results for further analysis.

The interferometric image reveals the movement of the Earth's surface, such as subsidence or uplift, relative to the radar sensor. The image consists of colored pixels, referred to as fringes, which represent variations in displacement. Each fringe, or color strip, corresponds to half the wavelength of displacement. If two points fall within the same color strip, it indicates that the same amount of movement has occurred at those locations (Fig. 2). In these images:

Yellow, red, and blue pixels indicate areas moving closer to the sensor.

Yellow, blue, and red pixels represent areas moving away from the radar.

This interferometric approach allows for the visualization and analysis of surface movements, such as land subsidence or uplift, within the studied area.

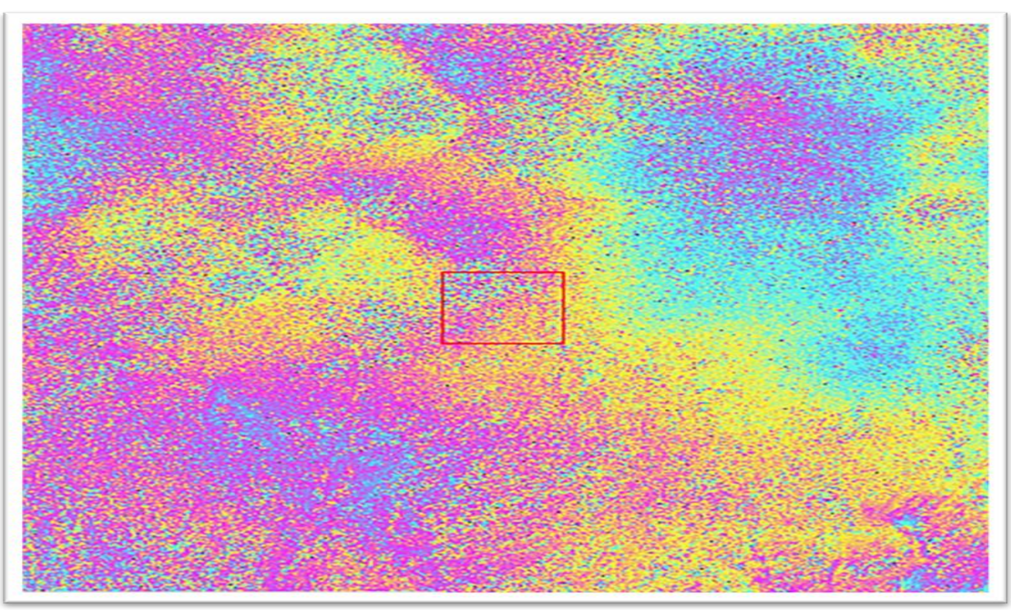


Fig.2- Interferogram containing noise

2.3.5. Filters and Their Function on Radar Images

Filters used in SAR (Synthetic Aperture Radar) images differ from those applied to other remote sensing images. These filters must be tailored to the specific characteristics of radar data and used strategically to address variations in different regions of the image. Below are three types of filters commonly employed in SAR image processing:

- Adaptive Filter

The adaptive filter uses the standard deviation of wave pixels within a kernel to calculate the value at the center of the filter. This filter does not alter the fundamental nature of the data and, since it affects the phase, it is particularly useful when there is movement on the Earth's surface. The adaptive filter sharpens the image, enhancing its details. Essentially, the filter adjusts the amount of smoothing applied to the image depending on its location within the image, making it more flexible and region-specific (Maghsoodi & Mahdavi, 2016: 72).

- Goldstein Filter

The Goldstein filter is applied when phase changes are not of primary concern. It manipulates all phases in the image and is particularly effective in creating clearer fringes. This filter is beneficial when the goal is to improve the visual quality of the interferogram by refining the phase information, even if it doesn't preserve all the fine details of the phase differences (Panahi, 2017).

- Boxcar Filter

The Boxcar filter is an intermediate filter, combining elements of both the adaptive and Goldstein filters. When applied to an image, it helps in removing sharp edges and high-frequency spatial details, resulting in a smoother overall appearance. This filter is often used to reduce noise and smooth the image without overly distorting the underlying features (Maghsoodi & Mahdavi, 2016: 72).

Each of these filters plays a distinct role in radar image processing, with their selection depending on the specific requirements of the analysis, such as preserving movement information, improving fringe quality, or reducing high-frequency noise.

3. Results

The filters mentioned above were applied to the radar images of the Yazd-Ardakan plain to evaluate their effectiveness in reducing speckle noise and preserving image quality. The study focused on identifying a filter that maintains the edges and textures of the image while providing a uniform appearance, free from excessive noise. The presence of edges or complications in the image indicates a significant change in the gray values due to noise reduction, which becomes apparent after filtering.

The Goldstein filter stood out as the most effective in this study, as it achieved the least amount of standard deviation and demonstrated an average value of 0.549557, which is closest to 1 compared to the other filters. This suggests that the Goldstein filter was the most effective in reducing noise while preserving the phase information in the radar images.

Table 2 presents the mean values and standard deviations of the filters applied to the images, showing the performance of each filter in terms of noise reduction and phase adjustment.

Table 2- Mean and standard division of applied filters

Row	Filter	Mean	Standard division
1	Afaptive	0 /442074	0/185478
2	Boxcar	0/471557	0/196395
3	Goldestein	0/549557	0/149797

Fig. 3 illustrates the mean values and standard deviations for the filters used, further highlighting the superior performance of the Goldstein filter in comparison to the others.

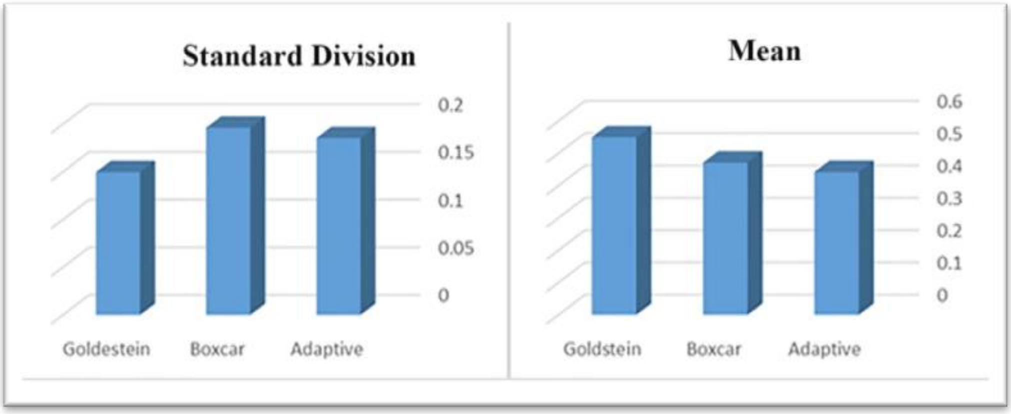


Fig.3- The standard deviation and mean graph

Fig. 4 displays the interframe images for each of the filters applied, offering a visual comparison of the effects of the noise reduction techniques on the radar images.

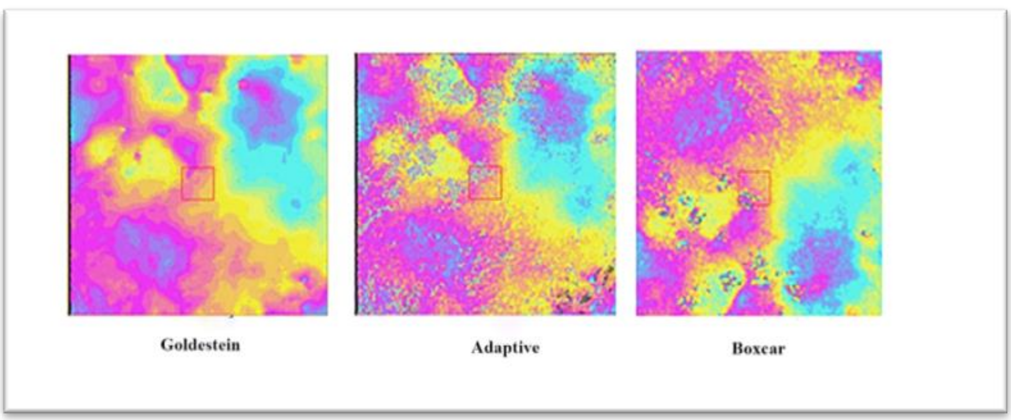
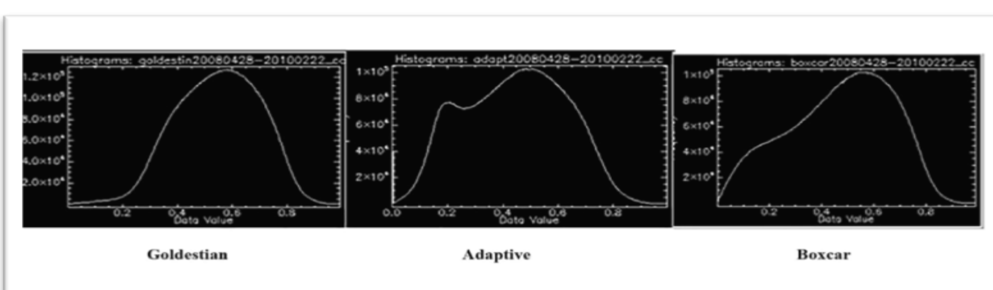


Fig.4- interferogram images for applied filters

Fig. 5 presents the histograms of the filters, providing additional insights into the statistical distribution of the image values before and after the noise reduction process.



ig.5- Histograms for applied filters

These findings suggest that the Goldstein filter offers the most effective balance between noise reduction and phase preservation, making it the best choice for enhancing radar images in the context of this study.

4. Discussion

This study aimed to evaluate and compare different speckle noise reduction filters applied to radar images of the Yazd-Ardakan plain, ultimately determining the most effective filter for improving the quality of Synthetic Aperture Radar (SAR) images. The filters tested in this study, including the Adaptive, Goldstein, and Boxcar filters, were analyzed based on their performance in reducing speckle noise while preserving important image features such as edges and phase information.

The findings of this study are in line with previous research, which has consistently demonstrated the importance of speckle noise reduction in SAR images to improve image quality and analysis accuracy. For example, Sedighi (2017) highlighted that adaptive filters, by focusing on interpolation-based error correction, are more effective than other filters in reducing speckle noise while maintaining the integrity of critical image details. This characteristic is particularly important because speckle noise, which is a multiplicative noise inherent to radar images, can significantly degrade the accuracy of results derived from SAR data. As noted by Domg and Milne (2001) and Oliver and Quegan (2004), speckle noise in SAR images can obscure subtle variations in surface characteristics, leading to errors in feature extraction and analysis. In this context, the application of adaptive filters, as demonstrated in this study, plays a crucial role in mitigating these issues.

The adaptive filter used in this study operates by calculating the filter weights at each pixel location based on the statistical properties (mean and variance) of the image area under the filter's window. This localized approach allows the filter to reduce speckle noise while preserving sharp contrasts and edges, which are often compromised by other types of filters. These results support the findings of Lee and Pottier (2017), who emphasized the adaptive filter’s ability to preserve image sharpness while reducing noise. Moreover, as Tso and Mather (2009) noted, the ability of adaptive filters to adjust contrast expansion for each pixel based on the surrounding pixel values allows for a more accurate representation of the underlying surface, which is essential for various remote sensing applications, including environmental monitoring.

On the other hand, the Goldstein filter, although effective at reducing noise and improving the quality of the fringes, was found to alter the phase information significantly, which could be a limitation for applications requiring precise phase measurements. However, as Panahi (2017) pointed out, Goldstein filters are particularly useful for applications where phase accuracy is not the primary concern, such as in the creation of clearer fringes and general noise reduction. In this study, the Goldstein filter provided a better visual representation of the image, but the loss of phase information may limit its effectiveness in detailed topographic or displacement analysis, as suggested by Hanssen (2001). Therefore, while the Goldstein filter may be beneficial for enhancing the overall image, it is not always the most appropriate choice for tasks that rely on phase coherence and accurate displacement measurements.

The Boxcar filter, in contrast, was less effective at preserving edges and sharp contrasts, as it smoothed out high-frequency spatial details. While this filter can be useful in applications where noise reduction is prioritized over edge preservation, it does not offer the same level of performance as the adaptive or Goldstein filters when the goal is to maintain sharp image features. As Maghsoodi and Mahdavi (2016) noted, Boxcar filters are often employed as intermediate solutions, but their inability to preserve fine details makes them less suitable for tasks that require a high level of image clarity and precision.

When comparing the performance of the filters used in this study to previous research, it is evident that adaptive filters offer the most balanced solution, successfully reducing speckle noise while preserving critical image features such as edges and contrasts. This is consistent with the findings of

Forouzanfar et al. (2010) and Maghsoudi (2011), who highlighted the advantages of adaptive filters in SAR image processing. In terms of practical applications, the results of this study suggest that adaptive filters are the most suitable choice for enhancing the quality of SAR images in the Yazd-Ardakan plain, where accurate feature extraction and environmental monitoring are essential.

This study contributes to the growing body of knowledge on SAR image processing by demonstrating the effectiveness of different speckle noise reduction filters. The adaptive filter, in particular, was found to be the most effective in preserving image quality while minimizing the effects of speckle noise, aligning with the findings of earlier studies. Future research could explore the combination of multiple filters or the development of new filtering techniques to further enhance SAR image quality, especially in challenging environments where noise reduction is critical for accurate analysis.

Overall, this study underscores the importance of selecting the appropriate noise reduction technique based on the specific requirements of the analysis and the characteristics of the SAR images being processed.

5. Conclusion

This study evaluated and compared the effectiveness of three speckle noise reduction filters—Adaptive, Goldstein, and Boxcar—in improving the quality of SAR images from the Yazd-Ardakan plain. The findings indicate that the adaptive filter outperforms the other filters by effectively reducing speckle noise while preserving key image features, such as edges and contrasts. This aligns with previous research, which highlights the adaptive filter's ability to maintain image sharpness and detail, essential for accurate environmental monitoring and analysis.

Although the Goldstein filter showed potential in improving the visual clarity of the image, it compromised phase accuracy, limiting its applicability for precise topographic analysis. The Boxcar filter, while effective for general noise reduction, failed to preserve important image details. Overall, the adaptive filter emerged as the most suitable option for enhancing SAR image quality in this study, offering significant potential for improving remote sensing applications in similar environments. Future research could explore further refinements or combinations of filters to optimize noise reduction and detail preservation in SAR imagery.

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