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HIGH-RESOLUTION IMAGING THROUGH SYNTHETIC APERTURE RADAR: CHALLENGES AND OPPORTUNITIES

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Abstract: This thesis provides an overview of my research contributions in the field of Synthetic Aperture Radar (SAR). The primary focus of my research has been on the development of signal processing methods applied to both single-channel and multichannel wideband SAR systems. SAR systems have the capability to produce images comparable to optical photographs, with satellite-borne systems often achieving finer resolutions than their optical counterparts. Notably, SAR has been utilized for imaging celestial bodies such as the moon, Venus, and Saturn's satellites, obtaining high-resolution images. Additionally, SAR finds applications in detecting changes in ice sheets and monitoring deforestation. This thesis specifically examines SAR systems capable of high relative resolution imaging, utilizing data from the VHF system CARABAS-II and the UHF system LORA, both characterized by high relative bandwidth. Two key areas of focus in this thesis involve the detection and estimation of parameters associated with moving targets in SAR. This structure allows for a comprehensive exploration of target detection and recognition models, their workflows, and their respective advantages and disadvantages. It also provides a foundation for researchers to understand the potential future directions and considerations for developing hybrid models in this field.

Keywords: Synthetic Aperture Radar (SAR), High-Resolution Imaging, Radar Signal Processing, Synthetic Aperture Radar Applications, Radar System Design.

I. INTRODUCTION

Synthetic Aperture Radar (SAR) serves as an imaging radar typically installed on an unstable platform. As an active radar system, SAR exhibits the capability to function effectively under diverse weather conditions. This adaptability has resulted in its extensive use in domains like disaster risk assessment, identification of natural oil slicks, and applications in civil and military defense. Numerous Earth observation enterprises are launching satellites integrated with SAR sensors. An example is the initiative of the Finnish company ICEYE, planning to deploy around eighteen or more SAR sensors in the foreseeable future. Furthermore, emerging entities like Capella Space and other small satellite startups are developing their own SAR missions. The increasing number of SAR-equipped satellites contributes to the generation of substantial data volumes, presenting significant challenges in terms of data archiving, processing, and analysis. The accessibility of SAR data is not guaranteed to be straightforward merely because it is available, given the inherent complexity associated with it.

Consequently, researchers have explored diverse approaches to process SAR images, aiming to extract meaningful information. Despite these efforts, numerous challenges persist in the processing pipeline.

The synthetic aperture radar (SAR) data collected during the wet season, characterized by humid and wet canopies, displayed limited sensitivity to in situ biomass. The biomass estimates exhibited a significant correlation with the season of SAR data acquisition, underscoring the crucial role of selecting the appropriate season for enhancing satellite-based biomass estimates. This study anticipates that the findings will make a valuable contribution to monitoring both the quantity and quality of forest biomass not only in Vietnam but also in other tropical countries. [1-3].

Synthetic Aperture Radar (SAR) systems play a crucial role in the continuous monitoring of Earth's climate and serve as essential sensors for high-resolution mapping of celestial bodies. This thesis comprises an introductory section on SAR, covering fundamental SAR processing algorithms alongside other techniques applied in the presented research The fundamental principle of SAR involves collecting radar echoes from an imaginary stationary ground scene as the SAR system traverses along a linear flight track, referred to as the synthetic aperture. The resolution in the final SAR image is determined solely by the integration angle, signal bandwidth, and center frequency. This characteristic renders the resolution independent of the distance from the scene. In essence, a satellite capturing an image from a considerable distance can achieve the same resolution as an aircraft imaging the same area from a much shorter distance. This stands in contrast to optical sensors constrained by resolution within the viewing angle. [4-7]

The operational use of synthetic aperture radar interferometry (SAR) for monitoring surface deformation and reconstructing topographic profiles is often hindered by temporal and geometrical decorrelation, along with potential inaccuracies due to atmospheric disturbances. The authors introduce a comprehensive method to identify and utilize stable natural reflectors or permanent scatterers (PSs) based on extensive temporal series of interferometric SAR images. In cases where the dimension of the PS is smaller than the resolution cell, ensuring good coherence even with larger baselines than the decorrelation threshold, all available images from the ESA ERS dataset can be effectively leveraged. This approach enables achieving submeter accuracy in digital elevation model (DEM) generation and detecting millimetric terrain motion, as atmospheric phase screen (APS) contributions can be estimated and corrected. The study includes examples demonstrating small motion measurements, DEM refinement, and APS estimation and removal, focusing on a sliding area in Ancona, Italy. [8-12]

Numerous algorithms capable of deriving a Synthetic Aperture Radar (SAR) image have been introduced based on the pulse-compressed data. Noteworthy among these are the Range Migration and Global Back projection algorithms, which demonstrate robust performance even in cases involving large integration angles. The fundamental functionalities of these algorithms have been outlined earlier.

In this manuscript, we present an overview of diverse strategies employed in radar polarimetry for target decomposition theory. We categorize three primary theorems: those derived from the Mueller matrix and Stokes vector, those utilizing eigenvector analysis of the covariance or coherency matrix, and those applying coherent decomposition of the scattering matrix. We bring together these varied approaches by employing transformation theory and conducting an eigenvector analysis. Additionally, we demonstrate how specific variations of these decompositions are applicable in the significant scenario of backscatter from terrain with general symmetries.

SAR techniques utilize the motion of the radar in orbit to simulate a virtual antenna that spans 10 kilometers, extending from the actual 10-meter antenna in the direction of the flight. During its trajectory, the radar sweeps the antenna's footprint across the ground while continuously transmitting pulses—brief signal bursts separated by time—and capturing the echoes of the reflected pulses. The distinctive advantage of synthetic aperture radar

(SAR) is its ability to penetrate through darkness, clouds, and rain, enabling the identification of changes in habitat, water and moisture levels, impacts of natural or human-induced disturbances, and modifications in the Earth's surface subsequent to events such as earthquakes or sinkhole openings. [16-20]

In contrast to optical technology, SAR stands out due to its ability to "see" through various environmental conditions. Unlike typical optical satellites that rely on visible light, SAR operates independently of weather conditions. It provides exceptionally high-resolution images, making it a superior choice for surveillance purposes. SAR-equipped satellites excel in their imaging quality and possess the ability to penetrate clouds, haze, and darkness. This unique feature enables the analysis of ground changes irrespective of weather conditions or the time of day. Therefore, opting for SAR-equipped satellite analytics is crucial for utilities seeking enhanced disaster management capabilities.[21]

Utilized for generating highly detailed 2D and 3D images or reconstructing objects, such as landscapes. II) Applied for mapping land cover and land use in regions persistently shrouded by clouds, like rainforests. III) Enables the detection of surface displacements over time through a series of images, with applications in mining, oil and gas extraction, construction, and excavation. IV) Capable of identifying land disturbances, whether caused by natural disasters or human activities, and detecting pathways or troop movements by capturing subtle changes in vegetation visible in the imagery. V) Facilitates swift assessment of natural disasters due to the ability to rapidly revisit areas and provides a broad observation swath. VI) Possesses unique attributes advantageous for forest monitoring, flood monitoring, and water quality applications. VII) Operates independently of sunlight conditions. VIII) Allows for polarimetric observations, such as HH, VV, HV, VH. IX) Provides coherency information.

EMISAR stands as a fully polarimetric, dual-frequency (L- and C-band), high-resolution synthetic aperture radar (SAR) system crafted for remote-sensing applications, boasting a 2x2 meter resolution. This SAR operates at elevated altitudes aboard a Gulfstream G-3 jet aircraft. The system, exhibiting low sidelobes and minimal cross-polar contamination, has undergone meticulous calibration. Leveraging digital technology, the radar is both flexible and highly stable, offering variable resolution, swath width, and imaging geometry. Thermal control mechanisms and multiple calibration loops are integrated to ensure system stability and absolute calibration. The calibration process incorporates accurately measured antenna gains and radiation patterns. [22-24]

II. HISTORY

Target detection and position determination have been fundamental objectives for radar systems since their inception. In earlier times, monopulse radar played a role in assisting with target position determination. The history of synthetic-aperture radar traces back to 1951 when mathematician Carl A. Wiley invented the technology, and its subsequent development occurred over the following decade. Initially designed for military applications, this technology has found diverse use, extending into the field of planetary science. Synthetic Aperture Radar (SAR) represents a remote sensing technology utilizing radar to generate high-resolution images of the Earth's surface. Its history dates back several decades and has seen significant advancements over time. Here's an overview of the history of SAR technology: 1) Early Development (1950s1960s): The concept of SAR was developed during the 1950s and 1960s, primarily for military reconnaissance purposes. Early SAR systems were used in airborne and spaceborne platforms, but their imaging capabilities were limited by technological constraints. 2) Debut in Space (1970s): The first operational SAR satellite was the Seasat mission, launched by NASA in 1978. Seasat was a pioneering satellite designed to observe Earth's oceans and featured a SAR sensor. Although it operated for only a few months, it demonstrated the potential of SAR for various applications. 3) Military and Scientific Use (1980s-1990s): During the 1980s and 1990s, SAR technology found applications in military reconnaissance and scientific research. Various countries developed SAR-based reconnaissance and surveillance systems. In the scientific realm, SAR was used for geological mapping, environmental monitoring, and disaster assessment. 4) Commercialization (1990s): The 1990s saw the commercialization of SAR technology. Companies like European Space Agency (ESA), Airbus, and Radarsat began launching SAR satellites for commercial use. These systems provided data for applications such as agriculture, forestry, and environmental monitoring. 5) Advancements in Spaceborne SAR (2000s-2010s): The 2000s and 2010s witnessed significant advancements in spaceborne SAR technology. Satellites like TerraSAR-X, Cosmo-SkyMed, and Radarsat-2 offered high-resolution, all-weather imaging capabilities, making SAR a valuable tool for a wide range of applications, including disaster response, agriculture, and maritime surveillance. 6) Advancements in Airborne SAR: Alongside spaceborne SAR systems, there were developments in airborne SAR technology. Airborne SAR systems are used for mapping, environmental assessment, and surveillance. They provide flexibility and higher spatial resolution for specific applications. 7) Polarimetric SAR and Interferometry: Advances in SAR technology have also led to the development of polarimetric SAR (PolSAR) and interferometric SAR (InSAR). PolSAR offers the ability to capture additional information about the properties of the imaged targets, while InSAR enables the measurement of ground deformation, which is particularly useful for monitoring earthquakes and land subsidence. 8) Constellations and Miniaturization: In recent years, there has been a trend towards SAR satellite constellations and miniaturization. Smaller satellites equipped with SAR sensors, such as those in the CubeSat format, are providing cost-effective and frequent imaging opportunities. 9) Integration with Artificial Intelligence: The integration of SAR data with artificial intelligence (AI) and machine learning has opened up new possibilities for automated image analysis, feature detection, and classification. 10) Seasat and Early SAR Satellites (1970s): In 1978, NASA launched the Seasat mission, which was the first operational SAR satellite. Seasat's synthetic aperture radar sensor demonstrated the potential of SAR for Earth observation. Despite its short operational life, it provided valuable data for various applications.

In recent years, the Frequency Modulated Continuous Wave (FMCW) technology has increasingly played a significant role in the development of compact, lightweight, and cost-effective Synthetic Aperture Radar (SAR) systems designed for installation on small, low-altitude platforms such as airplanes, helicopters, and drones. Accurate focusing of FMCW SAR images requires precise knowledge of certain system parameters, including the frequency sweep rate of the radar signal transmitted. However, instances may arise where the radar provider's measurement of the frequency sweep rate is not highly accurate, leading to the use of an incorrect parameter value during the SAR data focusing process. This discrepancy can result in significant geometric distortion effects in the focused FMCW SAR images. To address these challenges, this study introduces a procedure to estimate the actual frequency sweep rate employed by the FMCW radar. This crucial information can then be effectively utilized to achieve accurate focusing of the SAR data acquired by the radar system in question. Specifically, we propose an algorithm that leverages the focused SAR images affected by geometric distortion induced by the imprecise knowledge of the radar parameter. Additionally, the algorithm utilizes precise, in-situ measurements of the positions of a limited number of Corner Reflectors (CRs) strategically deployed across the observed scene. The efficacy of the proposed algorithm has been validated through testing on actual data acquired by an airborne X-band FMCW SAR system.SAR technology continues to evolve and find applications in a wide range of fields, including agriculture, forestry, environmental monitoring, disaster management, and defence. Its all-weather, day-and-night imaging capabilities make it a valuable tool for a variety of remote sensing applications. [26-30]

III. BLOCK DIAGRAM

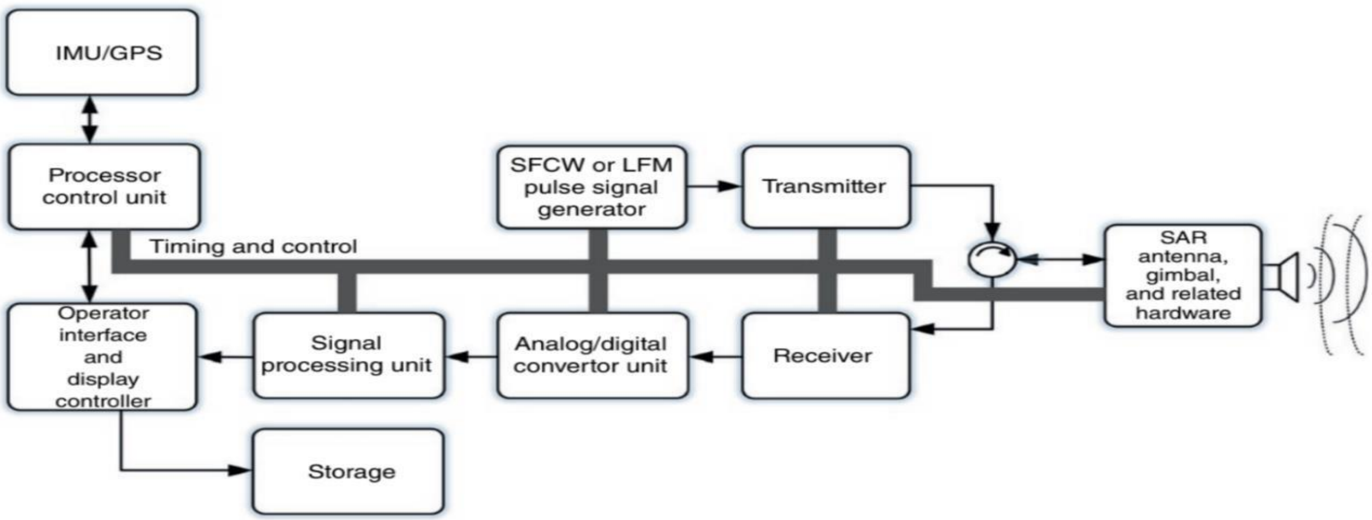


Fig. 1 Block Diagram of Synthetic Aperture Radar

Most Synthetic Aperture Radar (SAR) systems operate in either a single or dual-antenna configuration, with closely situated antennas for both transmitting and receiving the SAR signal, typically functioning in the monostatic mode. The SAR antenna, gimbal, and antenna beamformer collaborate to shape and direct the primary beam toward the designated terrain or target of interest. Subsequent to the scattering of the transmitted SAR signal from the scene, the SAR antenna captures the returning signal, which is then conveyed to the receiver.[31]

The received signal is subsequently sampled and digitized by the analog-to-digital converter. Following this, the unfocused SAR image is generated through processing by the signal processing unit. At this juncture, the generated Synthetic Aperture Radar (SAR) image remains unprocessed or raw, containing errors attributed to synthetic aperture instabilities caused by platform motion and other factors such as range migration and range walk. The fundamental assumption in SAR theory is that the platform follows a uniform motion along a straight line or a constant-speed circular path. Deviations from this uniform motion, such as yawing, rolling, or pitching, introduce errors or shifts in the phase of the received signal, which holds critical information about scatterer locations in the scene.

To address these instabilities, most SAR systems incorporate motion sensors like Inertial Measurement Units (IMU) and Global Positioning System (GPS) sensors, which record the flight's mission history. The raw SAR image can be visualized on the operator's screen on certain SAR consoles within the platform. Additionally, both the raw image and the motion data from IMU/GPS sensors can be stored for future processing or transmitted to a remote station for in-depth signal and image analysis. Post-processing of the raw SAR data is then undertaken to rectify these errors, resulting in the construction of the final focused SAR image. [32-34]

IV. FUTURE SCOPE AND ITS APPLICATIONS

Synthetic Aperture Radar (SAR) is a versatile remote sensing technology that has a wide range of applications. Here are some of the key applications of synthetic aperture radar. 1) Earth Observation and Environmental Monitoring: Land Cover and Land Use Mapping: SAR is used to monitor and map changes in land cover, such as urban expansion, deforestation, and agricultural changes. 2) Deforestation Detection: It can detect illegal logging and changes in forest cover. 3) Flood Monitoring: SAR can quickly identify flood extent and changes in water bodies. 4) Maritime Applications: a) Ship Detection: SAR can be used for maritime surveillance to detect and track ships. b) Oil Spill Detection: It's valuable in detecting and monitoring oil spills at sea. 5) Agriculture: a) Crop Monitoring: SAR can monitor crop growth, soil moisture, and identify areas affected by pests or disease.

b) Soil Moisture Measurement: It can estimate soil moisture levels, aiding in irrigation management. 6) Geology and Mining: a) Mineral Exploration: SAR can detect mineral deposits by analyzing surface and subsurface characteristics. b) Ground Deformation Analysis: It's used to monitor ground movements in mining areas or near fault lines. 7) Infrastructure Monitoring: a) Bridges and Buildings Inspection: SAR can be used to monitor the structural integrity of infrastructure. b) Pipeline Monitoring: It's valuable for identifying leaks or ground subsidence around pipelines. 8) Defence and Security: Surveillance: SAR is used for border surveillance, battlefield awareness, and tracking of moving objects. 9) Urban Change Detection: It can be used to monitor changes in urban areas for security and intelligence purposes. 10) Archaeology: Archaeological Site Detection: SAR can reveal buried archaeological structures and features. 11) GlacioloThe efficacy of the proposed algorithm has been validated through testing on actual data acquired by an airborne X-band FMCW SAR system.gy and Polar Studies: Ice Sheet Monitoring: SAR is used to monitor changes in ice sheets, glaciers, and polar regions. 12) Search and Rescue: SAR imagery can assist in locating missing persons in remote areas, especially in adverse weather conditions. 13) Forestry and Woodland Management: SAR is used for forest inventory, tree height measurement, and monitoring of forest health. 14) Weather Forecasting: SAR data, when combined with other meteorological data, can improve weather forecasting, especially in areas with limited weather station coverage. 15) Navigation and Cartography: SAR data is used for updating maps and improving navigation systems, especially in areas with dynamic topography. 16) Oil and Gas Industry: SAR is used for monitoring offshore oil and gas infrastructure and detecting oil spills. 17) Environmental Conservation: SAR data can be used to monitor wildlife habitats and track the movement of animals, aiding in conservation efforts. SAR technology continues to evolve, with new applications emerging as the technology becomes more accessible and cost-effective. It plays a crucial role in various scientific, commercial, and government activities due to its ability to provide detailed information about the Earth's surface, often in conditions where optical imagery may be limited or unavailable. [35-37]

V. METHODOLOGY

To assess the efficacy of this method on Synthetic Aperture Radar (SAR) images, it was employed on two co-registered PHARUS images of The Hague (Dekker 2003a). PHARUS, developed by TNO, is an airborne polarimetric C-band SAR. In Figure 2(a), a false-color composite of both images is presented, where altered land cover is represented in red or cyan, while unchanged land cover appears as various shades of grey. The classification of both images was conducted using an object-based approach as outlined by Benz et al. (2004), resulting in three classes: buildings, trees, and smooth surfaces. Smooth surfaces include features such as roads, bare soils, low vegetation like grass, and water. [38]

As the SAR platform progresses along a theoretical straight flight path, it emits and receives pulses. For a specific target of interest, the distinction between pulses is influenced by signal attenuation due to path loss, antenna pattern, and changes in the distance to the target. The image formation on SAR can be accelerated by using the convolution theorem. Thus, the range or the Azimuth compressed data can be written as follows:

$$I(t) = \int_{-\infty}^{\infty} s(t).h(t-\tau)d\tau = s(t) * h(t) \quad (eq.1)$$

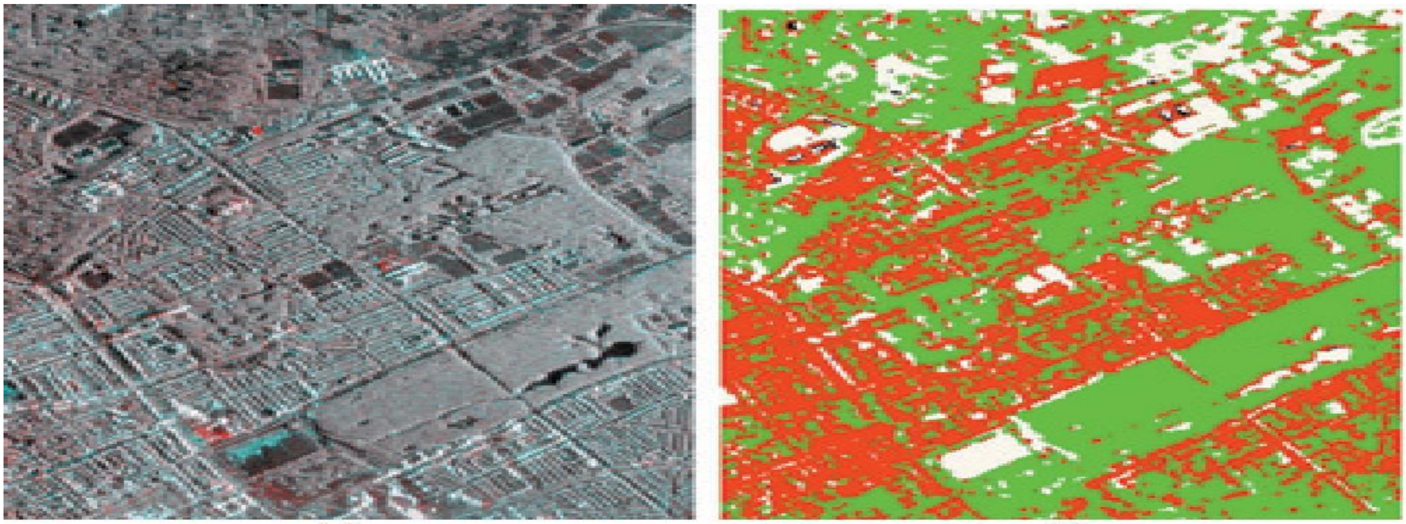
The symbol s(t) represents the chirp pulse in the azimuth Synthetic Aperture Radar (SAR) signal, while h(t) denotes the impulse response of the matched filter. [39]

The Fourier Theory can be speed up by FT concept:

$$I(t) = F^{-1}\{F\,\{s\,(t\,)\}\,.\,\{h(t\,)\}\} \qquad (eq.2)$$

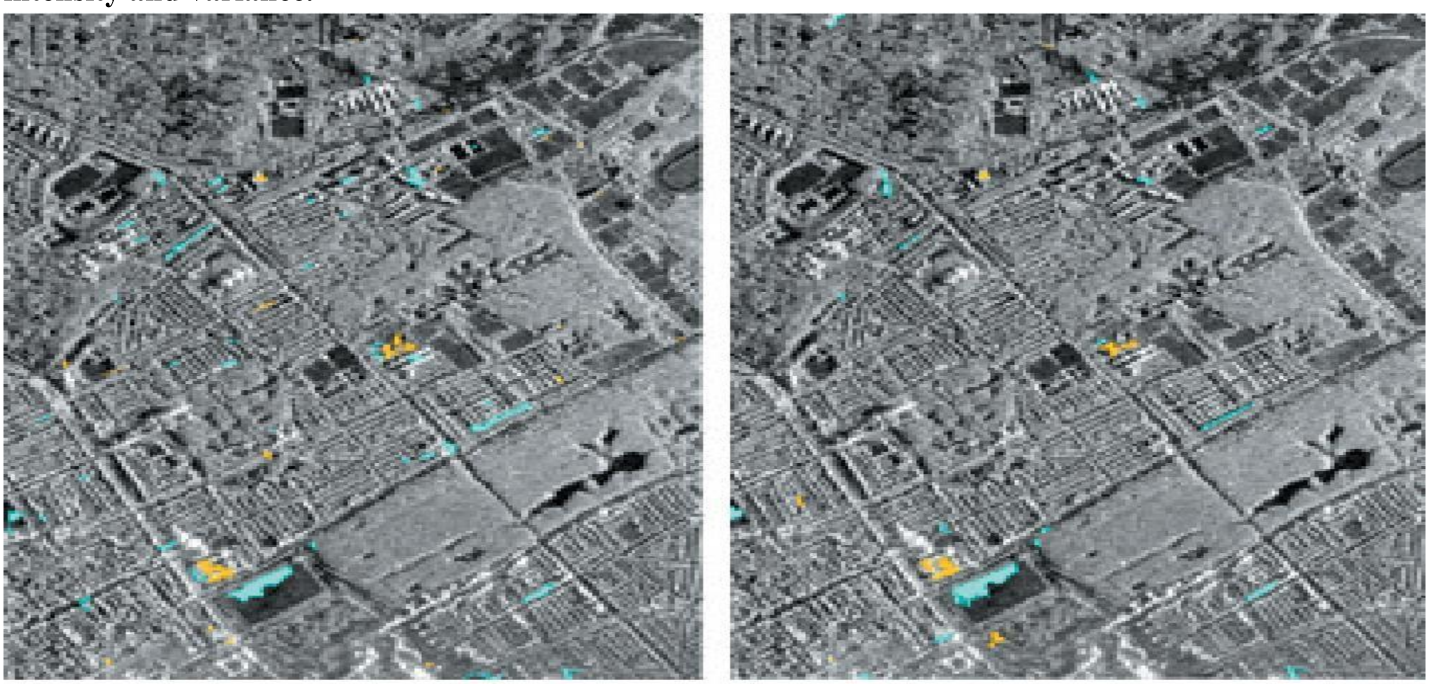
The classification was based on texture measures, including mean intensity, variance, weighted-rank fill ratio, and semivariogram. Figure 2(b) displays the classification results for the PHARUS image captured on January 27,

1998. A comparison of both classified images revealed numerous false alarms, indicating changes that do not actually exist



(a) (b)

Figure 2(a) displays a false-colour composite of two PHARUS Synthetic Aperture Radar (SAR) images, while (b) illustrates the classification results of the PHARUS image utilizing measures such as mean intensity and variance.



(a) (b)

Figure 3 depicts the outcomes of pre-classification change detection. Panel (a) showcases the results of multichannel segmentation, and in panel (b), new objects are represented in orange, while disappeared objects are shown in blue.

Its utility extends to the identification of distributed changes. Figure 3(a) illustrates the process of change detection through adaptive filtering. The application of this method to the PHARUS SAR images of The Hague is depicted in Figure 1(a). The threshold for this application was set at ± 9dB. Figure 4 displays the outcomes of the method when applied to two Radarsat-1 images. [40]

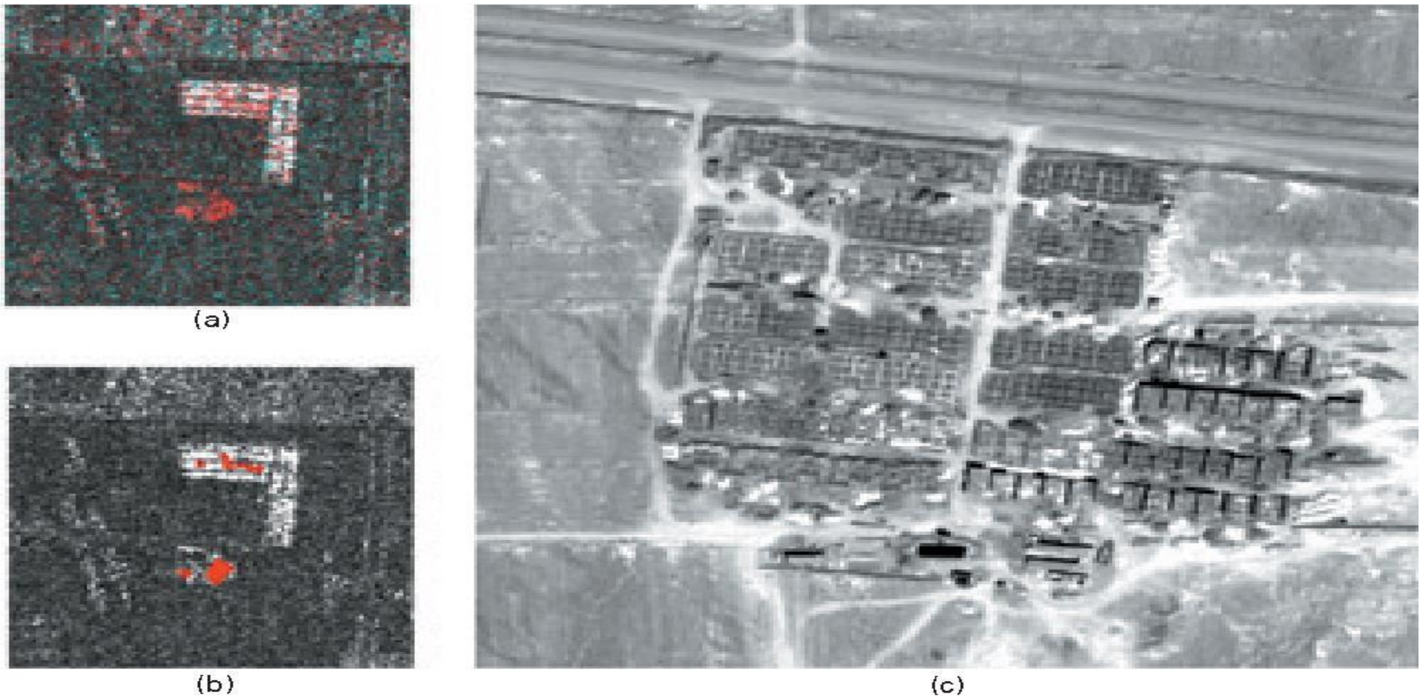


Figure 4 illustrates the outcomes of change detection through adaptive filtering applied to two Radarsat-1 images.

Panel (a) presents the color composite, (b) showcases the identified changes, and (c) displays the corresponding Quickbird image.

The inspiration behind traditional radar systems lies in the echolocation techniques employed by bats and dolphins. Incorporating cognitive elements into classical radar systems enhances their overall tracking performance. Cognitive radar operates based on the perception-action cycle, drawing inspiration from the functioning of the visual brain. Nested Cognitive Radar (NCR) introduces three additional components—memory, attention, and intelligence setting it apart from Basic Cognitive Radar (BCR). For nonlinear tracking at the receiver, the Cubature Kalman Filter (CKF) proves to be a fitting choice. [41-46]

VI. CONCLUSION

In summary, Synthetic Aperture Radar (SAR) imaging, leveraging radar technology, stands out as a versatile and dependable tool applicable across diverse fields. It excels in acquiring high-quality data under varied environmental conditions, playing pivotal roles in earth observation, agriculture, forestry, defense, and disaster management. SAR technology continues to advance, adapting to ongoing technological progress. Synthetic Aperture Radar (SAR) imaging is a powerful technology that has a wide range of applications in remote sensing, earth observation, defense, and more. Here is a summary of the key points and conclusions regarding SAR imaging using radar technology:

1) SAR technology offers the capability to generate high-resolution images of the Earth's surface, establishing itself as a valuable tool with diverse applications such as agriculture, forestry, geology, and urban planning. 2) All-Weather Capability: A notable benefit of SAR technology is its capacity to function effectively in diverse weather conditions. It is not hindered by cloud cover, rain, or darkness, which is especially important for Earth observation and defense applications. 3) Day and Night Operation: SAR can capture imagery day and night, thanks to its active sensor technology, which means it can monitor and gather data 24/7.

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