

# A Review on PolSAR for FOPEN Applications

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**Abstract:** PolSAR has become a significant focus of research due to its wide-ranging applications in structural monitoring, foliage penetration, and target detection. Despite its potential, work on FOPEN remains limited and often inconsistent, largely because forest environments differ considerably in structure and density. Integrating PolSAR with FOPEN techniques enhances the ability to detect obscured targets by exploiting polarization dependent scattering information that conventional radars cannot provide. This review outlines the limitations of traditional radar architectures, particularly their reduced capability for accurate image formation in complex environments, and highlights how SAR and PolSAR systems address these challenges through improved resolution, diverse polarization modes, and enhanced interpretability. A comprehensive examination and comparison of existing literature is presented, synthesizing current methods and insights relevant to PolSAR based FOPEN studies.

**Keywords:** Radar, SAR, PolSAR, Imaging, FOPEN.

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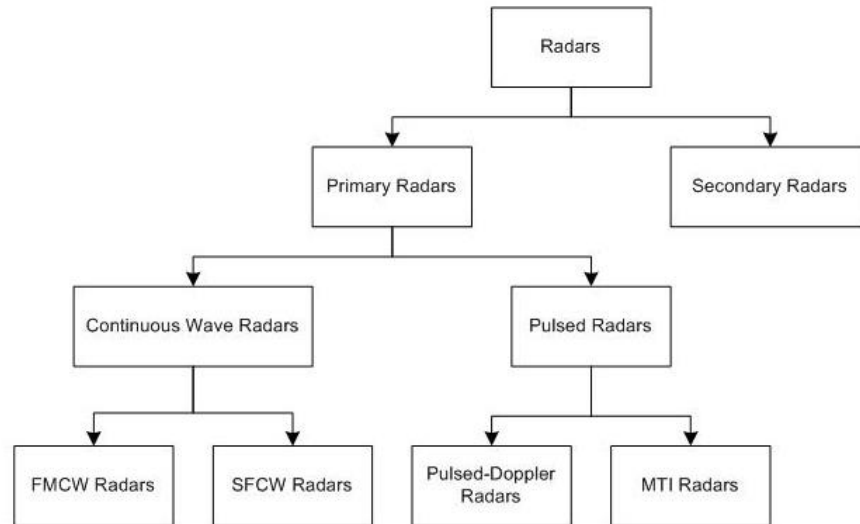
## I. INTRODUCTION TO RADAR SYSTEMS

RADAR, an acronym for Radio Detection and Ranging, is an electromagnetic sensing system that extracts target information such as range, velocity, angle, motion, and scattering characteristics by transmitting radio waves and receiving echoes from target. Radar systems are capable of operating in adverse weather, darkness and visually degraded environments, thus finding applications in numerous fields like surveillance, traffic control, weather and structural monitoring, subsurface imaging, and high-resolution remote sensing [2]. The amplitude and phase information in radar returns can be mapped into range and cross-range dimensions, enabling searching, tracking, Doppler processing, classification, and imaging. Radar receivers employ matched filtering, pulse compression, waveform design, and Doppler analysis to preserve signal-to-noise ratio (SNR) and minimize ambiguity [11,16].

On the basis of their transmitted waveforms, operating modes, and intended sensing functions, radar systems can be classified as follows: Continuous Wave (CW) radars that transmit a constant frequency signal and extract motion information through Doppler shifts [12-14]. Frequency Modulated Continuous Wave (FMCW) radars transmitting linearly swept chirps that encode both range and velocity in the beat frequency, and are widely used for short-range sensing applications [19-24]. Stepped Frequency CW (SFCW) radars that transmit a sequence of discrete tones, enabling fine range resolution and synthesizing large bandwidths in applications that require detailed profiling.

Pulsed radars determine range from the echo time delay. Its variants as shown in Fig. 1 are pulse-Doppler radar that uses Doppler analysis across pulses to estimate target velocity and determine range from echo time delay [26] and Moving Target Indication (MTI) radars that isolate moving objects from static clutter [37]. Other radars like Ultra-Wideband (UWB) radars transmit picosecond–nanosecond impulses with very large bandwidth, enabling high resolution sensing and through wall

or short-range detection [27-29]. Ground Penetrating Radar (GPR) systems similarly use broadband pulses for subsurface imaging in geophysics, archaeology, structural inspection, and environmental surveying [2-5]. Additional classes include Orthogonal Frequency Division Multiplexing (OFDM) based radars that employ multicarrier waveforms for spectral efficiency and flexible modulation [38], Multiple Input Multiple Output (MIMO) radars etc [39]. Emerging microwave-photonics radars use optical modulation, photodetection, and fiber optic distribution to generate ultra-wideband, high stability radar signals for multi-band operation and high-resolution sensing [40-44]. Advanced imaging radars such as Synthetic Aperture Radar (SAR) and Inverse SAR (ISAR) have been further discussed in the paper.



**Fig. 1 Classification of Radars**

Despite their historical success and broad applicability, conventional radar architectures exhibit limitations that restrict their imaging capability, resolution, target separability, and operational robustness. CW radars require additional processing or frequency-shifting techniques to determine motion direction and cannot measure target range despite their accurate Doppler measurement [12]. The resolution of FMCW radars is constrained by available bandwidth, their operation degrades at longer ranges, and they suffer from phase-nonlinearity and hardware distortion [19], while SFCW radars have slow acquisition times and degraded accuracy in dynamic environments. In pulse-Doppler radars short pulses require very high peak transmit power while long pulses demand complex pulse-compression techniques to mitigate poor resolution. The clutter suppression in MTI radars also requires significant resources. Radars like GPR and UWB also suffer from false detections [2], severe attenuation in wet or conductive media and have heavy computational requirements for tasks such as correlation processing, clutter averaging, and micro-motion analysis [27].

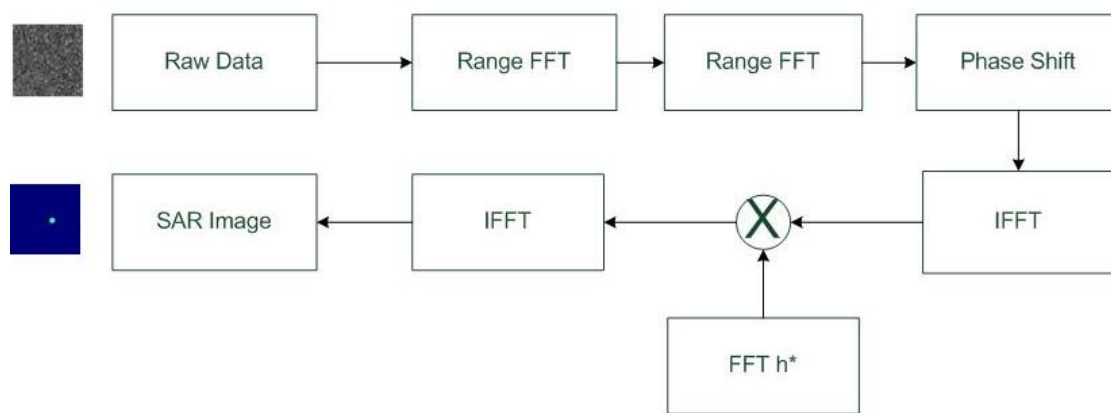
Structural limitations are also constant across all radar families. They include restricted spatial resolution; dependence on the physical antenna aperture for angular resolution; susceptibility to clutter and multipath; limited ability to discriminate closely spaced or low Radar Cross Section (RCS) targets; severe degradation in foliage or complex urban environments; and most importantly the inability to generate consistent, high-quality 2D or 3D imagery of extended areas. Even when enhanced with adaptive processing or photonic hardware, these systems fundamentally measure echoes from individual pulse transmissions and cannot synthesize the large effective apertures required for fine cross-range resolution [40].

These persistent limitations motivate the transition towards advanced systems like Synthetic Aperture Radar (SAR), which overcome physical aperture limits by synthesizing a very large antenna through platform motion. SAR provides high-resolution, coherent, two-dimensional imaging independent of instantaneous antenna size, using chirp or Linear Frequency Modulated (LFM) waveforms for fine downrange resolution and Doppler phase history for cross-range resolution [53]. SAR operates in all weather and at long ranges, enabling detailed imaging of low-RCS targets and complex terrain that traditional radar systems cannot resolve [59]. The second section of this paper talks about SAR in detail; whereas Polarimetric SAR (PolSAR), its types and applications are discussed in Section III followed by Section IV that talks about Imaging using PolSAR. The last section provides insights on how PolSAR can be effectively used for Forest Penetration (FOPEN) applications.

## II. INTRODUCTION TO SYNTHETIC APERTURE RADAR (SAR)

SAR is a coherent microwave imaging technique that forms high-resolution 2D images by synthesizing a large effective aperture through platform motion. Traditional radars such as pulse radar, CW radar, and FMCW radar etc achieve resolution directly through antenna size and transmitted bandwidth. As a result, azimuth resolution deteriorates with increasing range and is fundamentally limited by the physical antenna length [59]. SAR overcomes this by exploiting platform motion to synthesize a large virtual aperture. SAR further differs from classical LFM and OFDM radar implementations by incorporating chirp-based range compression, Doppler-based azimuth compression, and dedicated algorithms to correct range cell migration and fast platform motion induced Doppler [63, 74, 87].

SAR is capable of operating independent of daylight and weather and has flexible imaging modes like Strip-map, Squint strip-map, ScanSAR, and Spotlight [67, 74, 77], making it a versatile tool for remote sensing applications including environmental monitoring and target detection in cluttered areas [59]. These capabilities, however, rely on precise waveform design, motion compensation, and image-formation algorithms to manage effects such as range migration, Doppler variation, and speckle.



**Fig. 2 SAR image processing flow**

SAR processing as shown in Fig. 2 indicates both range compression and azimuth compression. The range resolution of radar depends on the pulse width, so to achieve high resolution the chirp is compressed through matched filtering, which is implemented using Fourier transformation. In the frequency domain, filtering becomes a simple multiplication. The focused range data is brought back to the time domain using the inverse Fourier transform. After applying a phase correction to remove range curvature caused by platform motion, azimuth compression is performed by taking the azimuth FFT, applying a Doppler matched filter, and then using an IFFT to focus the targets. Following this sequence, the blurred raw echoes are focused in both directions, producing the final high-resolution SAR image [133].

Waveform design plays a critical role: issues such as Inter Range Cell Interference (IRCI) arise from time domain sidelobes during pulse compression, degrading small target visibility and blurring range profiles [63,67,71]. OFDM waveforms with a sufficient cyclic prefix (CP) can eliminate IRCI by preventing inter symbol overlap, provided the CP length fully covers the illuminated range span [67]. Cyclic Prefix Orthogonal Time Frequency Space (CP-OTFS) waveforms offer IRCI-free compression and improved Doppler robustness, especially in Millimeter-wave (mmWave) SAR where intra pulse Doppler effects are severe [67].

Fine range resolution in SAR is achieved using large signal bandwidths and pulse compression, enabling the system to distinguish scatterers separated by small differences in slant range [74-77]. In Strip-map mode the synthesized aperture yields an azimuth (cross-range) resolution approximately equal to half the physical antenna length, independent of range [74,81]. In Spotlight mode, tighter beam steering further enhances azimuth resolution beyond that of Strip-map operation [67,77]. Accurate SAR focusing requires compensation for range cell migration, motion induced phase errors, and Doppler frequency migration. Early processors designed for airborne SAR were inadequate for spaceborne platforms experiencing large range migration, prompting development of correlation algorithms that separate range and azimuth components and apply efficient 1D corrections to prevent defocusing and range broadening [87].

Additional accuracy considerations arise in Interferometric SAR (InSAR), where elevation retrieval depends on coherence between image pairs. Imaging precision is affected by bandwidth, baseline length, geometric decorrelation, and system noise. Optimal baseline selection and appropriate baseline tilt are essential to maximize correlation and achieve meter-level height accuracy in global topographic mapping applications [81]. Repeat pass interferometry further reveals characteristic signatures of vegetation and surface change, as forested regions exhibit low correlation due to volume scattering and temporal decorrelation [84]

All studies collectively show that SAR can collect single or dual polarization data and the Stokes matrices can be derived from that data. However, it cannot recover HH–VV correlation, cross-polarized behaviour, or the full polarimetric structure required to analyse Bragg/non-Bragg transitions or complex scattering. SAR intensity imagery cannot distinguish scattering mechanisms accurately, lacks material discrimination, and is susceptible to speckle noise and ambiguity when applied to heterogeneous environments such as vegetation, urban structures, or mixed natural scenes. These limitations lead naturally to PolSAR, which extends SAR by transmitting and receiving multiple polarizations. PolSAR separates surface, double-bounce, and volume scattering; enhances classification of vegetation, buildings, soil, water, and man-made objects; suppresses clutter; and provides physically meaningful scattering information unobtainable through single polarization SAR. In doing so, PolSAR resolves many of the material, structural, and semantic ambiguities inherent to both conventional radar and standard SAR, providing a more complete and robust method for modern electromagnetic imaging.

### III. POLARIMETRIC SAR (POLSAR) TYPES AND APPLICATIONS

As opposed to conventional SAR, PolSAR measures the full scattering matrix, allowing the separation of dominant scattering mechanisms in forested regions and provides more information about natural and man-made targets. Unlike single polarization or even limited multi-polarization SAR, PolSAR captures both magnitude and phase of each polarization channel, enabling a deeper interpretation of target structure and improving classification performance [111, 125]. Multi-polarization data also resolves the limitations of single polarization SAR for surface and vegetation studies, where full scattering behaviour cannot be captured with a single channel [126].

PolSAR's ability to use multiple polarizations is especially valuable for surface feature delineation and forest vegetation studies. There can be four types of polarizations depending on what combinations are made using horizontal (H) and vertical (V) polarizations at the transmitting and receiving ends. These are Horizontal Transmit – Vertical Receive (HV), Horizontal Transmit - Horizontal Receive (HH), and similarly VV, VH. By comparing co-polarization (HH, VV) and cross-polarization (HV) strengths, PolSAR distinguishes urban surfaces (strong HH/VV, weak HV), forested areas (high HV), and soil-dominated regions (moderate HH/VV, lower HV) [126]. The polarization signature of different surfaces allows assessment of biomass, tree height, basal area, and general vegetation structure, though separation of volume, surface, and double-bounce contributions remains difficult [126].

Several methods address the challenge of separating scattering behaviours in both homogeneous and heterogeneous environments. Unsupervised classification using polarization properties can identify pixels dominated by odd bounce, even bounce, or diffuse scattering, although complexity increases over tree covered areas due to pixel mixing and higher incident angles [125]. Multichannel edge detection and de-speckling techniques improve interpretability of PolSAR images, especially under speckle noise. These include curvelet, shearlet, and eigen value-based methods, whitening filters, and hybrid thresholding approaches that distinguish weak and strong edges [114].

Dual-polarization PolSAR has also been explored for applications where full polarization data is unavailable. Methods exist to extend scattering power decomposition to dual-pol matrices by estimating missing components using symmetry and statistical assumptions, providing approximate surface, double bounce, and volume powers without losing interpretability [130]. Additional algorithms aim to differentiate forest from urban areas using delineation and separation factors to reduce misclassification [132].

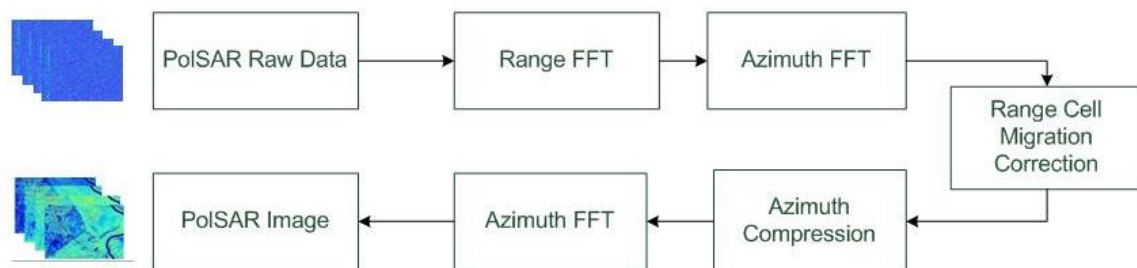
PolSAR has been widely adopted across domains such as agriculture (crop type mapping, soil moisture etc), forestry (forest structure monitoring), urban environments (area mapping, infrastructure change detection), and oceanic settings (oil-spill detection) because the additional polarization information enables discrimination of scattering mechanism rather than just the total backscatter [161-162]. Reviews highlight PolSAR's capability to provide enhanced land-cover classification and target feature extraction relative to single-polarization SAR because it captures scattering anisotropy, dielectric contrasts and structure orientation [159]; in agriculture the extra polarimetric channels boost information content for crop and residue mapping [160]. The versatile nature of PolSAR also makes it suitable for foliage-penetration scenarios.

Overall, PolSAR's multi-polarization capability, scattering mechanism interpretation, enhanced classification power, and sensitivity to structure make it highly effective across a wide range of applications, particularly where single-pol or conventional SAR fails to provide adequate target separability or clutter suppression. To support these applications, PolSAR imaging uses processing steps that preserve the full polarimetric information during image formation and interpretation. Techniques such as polarimetric focused range processing, decomposition-based representation of scattering behavior, and feature driven classification methods all contribute to generating clearer, more reliable images suited for detection and analysis.

#### IV. POLSAR IMAGING

PolSAR imaging exploits multi-polarization radar measurements to provide richer information about target structure, scattering behaviour, and land-cover characteristics of regions like forests. In practice, PolSAR imaging relies on the formation of polarization dependent channels and their subsequent processing to extract physical scattering mechanisms or to enable improved classification accuracy. In FMCW based PolSAR systems, signal processing methods such as the Range-Doppler Algorithm (RDA) with Range Cell Migration Compensation (RCMC) can be adapted for polarimetric data, enabling high-resolution imaging across multiple polarizations when triangular LFM waveforms are used. This type of processing has been validated on mobile, automotive PolSAR platforms where consistent speed acquisition allows accurate reconstruction of fully polarimetric FMCW imagery [134-135].

Beyond image formation, PolSAR imaging techniques also encompass target detection strategies. Small man-made targets are often difficult to separate from natural backgrounds. By incorporating reflection asymmetry and HV suppression, PolSAR imaging can be made more selective toward man-made structures, improving detection accuracy in cluttered scenes [136].



**Fig. 3 PolSAR image processing flow**

In vehicle borne PolSAR systems, the data collection is done while the vehicles move across the region, leading to many motion-induced effects. While processing, the raw echo data is first transformed using a Range FFT as shown in Fig. 3 so that the transmitted chirp can be matched-filtered in the frequency domain, producing sharper range responses. An Azimuth FFT is then applied to convert each range line into the Doppler domain, where effects such as range cell migration are corrected, ensuring that target energy is properly aligned. After that azimuth compression is performed by applying a Doppler-domain matched filter, an Azimuth IFFT brings the focused data back to the spatial domain. Through this sequence of frequency domain filtering and motion correction, the raw PolSAR data is focused into a high-resolution image where each point target appears clearly resolved [134].

Scattering mechanism-based imaging methods further enhance interpretability. Four-component decomposition techniques separate the covariance matrix into surface, cross, double-bounce and adaptive volume scattering components. Using an adaptive volume model reduces the common problem of volume overestimation in urban environments and underestimation in forested areas, resulting in more physically realistic PolSAR images [143]. These decompositions rely on the coherency matrix and its eigen structure, from which physically meaningful parameters like entropy (H), anisotropy (A) and alpha angle ( $\alpha$ ) are extracted. Entropy describes depolarization behaviour, anisotropy differentiates secondary mechanisms and alpha angle relates to dominant scattering mechanisms, making these parameters central to PolSAR imaging interpretation [146].

PolSAR imaging also supports classification-oriented representations, and it inherently requires speckle mitigation to preserve interpretability. Since speckle arises from coherent interference within each resolution cell, PolSAR systems apply

speckle reduction strategies such as the polarimetric Lee filter to smooth noise while preserving polarimetric correlations and edge structure [150]. In practice, these filtering steps are woven into the imaging chain so that polarimetric information remains stable for subsequent analysis. Similarly, machine learning approaches such as Random Forest (RF), K-Nearest Neighbour (KNN), Support Vector Machine (SVM), and semantic-segmentation networks like DeepLabv3+ have been applied directly to PolSAR imagery, leveraging polarimetric parameters and coherency matrix elements to generate accurate land use maps. Classical statistical approaches such as Wishart classification also remain relevant, performing maximum likelihood classification on the T matrix under a Wishart distribution model that accounts for speckle noise yielding competitive performance compared to SVMs, particularly in low frequency bands [146].

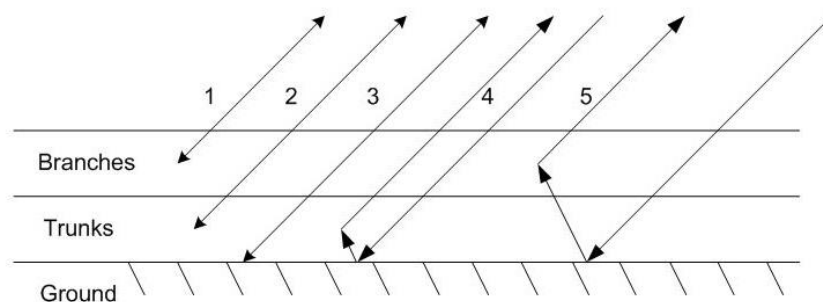
Emerging imaging methods explore modified antenna configurations such as radially polarized apertures for 3D polarimetric SAR reconstruction. Radial polarization inherently provides polarization diversity across the scan, enabling extraction of isotropic and anisotropic scattering components without requiring multiple orthogonal transmit or receive channels. This reduces hardware, scan time, and calibration burden while still enabling orientation independent imaging and improved clutter suppression using Convolutional Neural Network (CNN) aided filtering [147]. These developments extend PolSAR imaging toward more efficient and compact acquisition architectures.

Neural network assisted reconstruction methods have also been introduced for PolSAR imaging. Because PolSAR datasets are relatively small and heavily affected by speckle, CNN based reconstruction and enhancement models must address overfitting and noise sensitivity. Recent work highlights the need for speckle-robust architectures to produce cleaner and more consistent PolSAR images [149].

## V. POLSAR FOR FOPEN APPLICATIONS

In forested environments, FOPEN Radars can be used to send the signals through foliage like leaves, branches, canopies etc. FOPEN radars operate in lower frequency bands because longer wavelengths can penetrate the foliage canopy easily. However, these systems face challenges in isolating different scattering mechanisms. Multiple transmitter-receiver polarizations can be used to mitigate such effects. PolSAR is particularly valuable for FOPEN because it addresses the core limitations of low frequency SAR in dense vegetation environments. Low frequencies provide deeper penetration but suffer from lower resolution and increased image degradation from clutter, attenuation, and signal distortion [91-92, 118]. Multi-polarization data compensates for these weaknesses by improving signal-to-clutter ratio (SCR), reducing clutter speckle, and enhancing target recognition in foliage-obscured environments [92]. Polarimetric signatures can be used to differentiate between various scattering mechanisms and to get detailed information on different types of vegetation or terrain.

Understanding canopy propagation is another critical component of FOPEN. Measurements of attenuation through forest canopy highlight substantial variability due to the anisotropic and inhomogeneous nature of foliage, and precise measurement techniques such as trihedral based attenuation estimation help characterize the two-way loss encountered in FOPEN systems [98]. Additionally, studies on ground and canopy scattering show that coherent scattering models and interaction terms become more relevant at low frequencies, which aligns with FOPEN's reliance on long wavelengths to penetrate vegetation [106]. Structural modelling using 3D coherent frameworks further clarifies how scattering phase centres shift based on factors that influence target visibility beneath foliage [96].



**Fig. 4 Scattering Mechanisms**

Durden et al in their study [107] highlight that the classic three-scattering model presented by John Richards [92] does not

capture all phenomena in forest canopies, pointing out the need to consider additional mechanisms and more realistic models of canopy components. Thus, Fig. 4 shows a five component model where we include the following scattering mechanisms: (1) Backscatter from branches, (2) Backscatter from trunks, (3) Backscatter from ground, (4) Double-bounce scattering from trunks and ground and (5) double-bounce scattering from branches and ground [107]. The same can also be modelled into a mathematical equation of stokes matrices as,

$$M_{\text{total}} = M_b + T_b M_t T_b + T_b T_t M_{bg} T_t T_b + T_b T_t M_{tg} T_t T_b + T_b T_t M_g T_t T_b \quad (1)$$

Where  $M$  is the stokes matrix for backscattering,  $T$  is the stokes matrix for transmission through a layer and  $b$ ,  $t$  and  $g$  denote branches, trunks and ground respectively [107]. Polarization data allows us to perceive the same target from different positions. This data can be converted into scattering or Mueller matrices that are later used to compute the stokes matrix. The stokes parameters from the matrix give us valuable information like degree of polarization, ellipticity and orientation angles that are further useful in mapping the polarization signatures. These signatures tell us how the polarization information varies over time and other parameters.

PolSAR systems differentiate volume, surface, and double-bounce scattering mechanisms, which helps interpret forested and complex environments. Although advanced models often require detailed inputs such as tree geometry and ground roughness, the simplified decomposition by Freeman–Durden provides a practical way to use HH, VV, HV and VH channels to identify dominant scattering types [120]. Some studies focus on propagative and structural aspects of the canopy. Measurements of canopy attenuation show significant variation due to the inhomogeneous, anisotropic nature of forests; trihedral reflectors can be used to measure attenuation with high precision ( $\pm 0.3$  dB) [98]. Other work emphasizes the need for 3D structural representation such as the Coherent Scattering Model (COSMO) in which forest canopies are divided into cubes and mapped into SAR pixels based on time delay and phase. Such models highlight that the height of the scattering phase centre depends on attenuation, canopy height and gaps within the canopy [96].

Findings from multiple experiments highlight why PolSAR contributes significantly to FOPEN performance. Early foliage penetration studies demonstrated that radar systems at appropriate frequencies can penetrate vegetation, though clutter backscatter, foliage-induced attenuation, and image distortion limit target detection [91]. Later multi-frequency experiments extended this by simultaneously collecting backscatter, attenuation, phase, and amplitude fluctuations across multiple angles and polarizations to better characterize foliage effects. These studies confirm that foliage degrades imagery in three primary ways: (1) additional backscatter from the foliage itself, (2) two-way attenuation of transmitted and received signals, and (3) amplitude and phase fluctuations leading to distorted SAR focusing [118].

Comparisons across studies show that while single-polarization detection algorithms can be attractive due to robustness under unknown clutter conditions [111], fully polarimetric systems provide substantially richer information for FOPEN. Polarimetric matched filters and scattering-matrix exploitation enable more reliable target–clutter separation when full-pol data is available [111]. Whitening filters and multichannel processing further reduce speckle and enhance visibility of obscured targets [118]. Multi-polarization data also improves classification of obscured targets by overcoming inherent degradation seen in low-frequency, single-pol FOPEN images [92].

## VI. CONCLUSION

This review demonstrates that while traditional radar and conventional SAR provide valuable sensing capabilities, their limitations in resolution, mechanism interpretation, and clutter suppression make them insufficient for complex environments such as dense forests. PolSAR overcomes these constraints by capturing complete polarimetric information and thus enabling separation of surface, double-bounce, and volume scattering. It also helps in improving classification accuracy, and allowing meaningful physical interpretation of targets and environments. Across the literature, studies consistently show that FOPEN performance relies on the interplay between low frequency penetration and the interpretive power of polarization: foliage induces additional backscatter, two-way attenuation, and phase distortions, but multi-polarization data significantly mitigates these degradations by enhancing signal-to-clutter ratio, reducing speckle, and exposing scattering asymmetries that reveal obscured targets.

Collectively, the literature points toward a consistent conclusion that PolSAR enhances FOPEN capability by improving clutter suppression, increasing signal interpretability, enabling mechanism-level understanding of scattering, and providing structural insights into canopy propagation that single-pol SAR cannot offer. Gaps remain in modelling complexity, separation of scattering contributions under dense foliage, and distinguishing mechanisms that resemble one another, but the available evidence shows that PolSAR is better suited to the demands of FOPEN imaging.

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