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# Advancing Forest Structure Retrieval through Multi-Frequency PolInSAR and TomoSAR: Leveraging ESA's P-Band Biomass and NASA–ISRO NISAR Missions

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**Abstract**

Accurate estimation of forest structural parameters, particularly canopy height and aboveground biomass (AGB), is essential for carbon accounting, biodiversity conservation, and climate change mitigation under frameworks such as the UNFCCC and REDD+. While traditional field measurements provide accurate data, they are often spatially limited and logistically challenging, especially in dense or remote forests. Advanced Synthetic Aperture Radar (SAR) techniques, particularly Polarimetric Interferometric SAR (PolInSAR) and Polarimetric Tomographic SAR (PolTomSAR), offer promising solutions. These methods combine interferometric phase information with polarimetric scattering characteristics, improving sensitivity to vegetation structure and vertical scattering profiles. This paper reviews recent literature on PolInSAR and PolTomSAR methodologies and aligns the discussion with the capabilities of two major upcoming missions: ESA's P-band Biomass SAR mission, scheduled for launch on April 29, 2025, and NASA–ISRO's dual-frequency L- and S-band SAR mission, NISAR, set to launch on July 30, 2025. The P-band technology provides deep canopy penetration and enhanced ground return visibility, leading to more accurate Random Volume over Ground (RVoG) inversions and tomographic reconstructions. It is projected to achieve a canopy height root mean square error (RMSE) of 1–2 m and an AGB RMSE of 15–25 Mg/ha in dense tropical forests. NISAR's L/S configuration complements the P-band by integrating the L-band's sensitivity to trunks and lower canopy with the S-band's responsiveness to upper canopy foliage. This combination improves coherence stability and seasonal monitoring capacity. A comparative synthesis indicates that L-band PolInSAR remains a reliable operational choice; however, the P-band significantly reduces height bias in dense forests. L/S fusion further extends the dynamic range of biomass retrieval. Combining P-band tomographic products with L/S PolInSAR observations is expected to deliver the highest performance, mitigating biomass saturation and enhancing retrieval robustness across various forest types. Anticipated AGB $R^2$ values are expected to exceed 0.75, with RMSE in the range of 15–22 Mg/ha. These advancements pave the way for global-scale, multi-frequency, multi-technique forest monitoring frameworks that can achieve unprecedented accuracy in mapping forest parameters. Such integration will enhance carbon stock assessments, REDD+ monitoring, and ecosystem modeling, setting a new benchmark for operational forest structure retrieval in the P-band and NISAR era.

## 1. Introduction

Forests are among the most significant terrestrial carbon reservoirs, playing a crucial role in mitigating climate change by storing an estimated 80% of the planet's aboveground carbon and approximately 40% of belowground carbon (Mukhopadhyay, Kumar, Aghababaei, & Kulshrestha, 2022). This vast storage capacity makes them essential in regulating the Earth's carbon cycle. Accurate estimation of forest structural parameters, such as tree height and aboveground biomass (AGB), is vital for a comprehensive understanding of ecosystem dynamics. These parameters provide insight into the health and functioning of forest ecosystems, support biodiversity conservation efforts, and are critical for monitoring compliance with international climate commitments, including those outlined in the United Nations Framework Convention on Climate Change (UNFCCC) and REDD+ (Reducing Emissions from Deforestation and Forest Degradation) initiatives (Kumar, Khati, Chandola, Agrawal, & Kushwaha, 2017c). Traditional field-based measurements, while known for their accuracy, present significant challenges due to their time-consuming and labor-intensive nature, which limits their spatial coverage. This issue is particularly pronounced in inaccessible areas, such as dense tropical rainforests or remote boreal forests, where direct measurements can be logistically difficult (Khati, Singh, & Kumar, 2018). As a response to these limitations, remote sensing technologies have emerged as indispensable tools for large-scale forest monitoring. These technologies utilize satellite imagery, aerial surveys, and advanced sensors to gather critical data efficiently and effectively over vast areas, enabling researchers and policymakers to make informed decisions regarding forest conservation and management. By integrating remote sensing with ground-based validations, we can enhance the accuracy and reliability of forest carbon assessments, ensuring that our strategies for combating climate change are both effective and sustainable.

Polarimetric Interferometric Synthetic Aperture Radar (PolInSAR) is an advanced remote sensing technique that synergistically combines the phase difference information obtained from interferometric Synthetic Aperture Radar (InSAR) with the polarimetric scattering characteristics derived from polarimetric Synthetic Aperture Radar (PolSAR). This combination significantly enhances the sensitivity to the structural complexities of vegetation, allowing for more accurate estimations while minimizing uncertainties in retrieval processes (Joshi & Kumar, 2017a; Agrawal, Kumar, & Tolpekin, 2016). The PolInSAR technique facilitates the extraction of critical parameters such as canopy height by modeling the interferometric coherence through the interaction of signals scattered from both the ground surface and the vegetation canopy. A prevalent model used for this purpose is the Random Volume over Ground (RVoG) model, which effectively accounts for multiple scattering effects and the vertical distribution of vegetation (Babu & Kumar, 2018;

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Kumar, Govil, Srivastava, Thakur, & Kushwaha, 2020). Recent advancements in multi-frequency and multi-baseline PolInSAR methodologies have showcased remarkable performance, demonstrating high levels of accuracy in estimating both canopy height and above-ground biomass (AGB). Under optimized acquisition conditions, researchers have reported root mean square error (RMSE) values for height estimations as low as 1.5 to 3.0 meters. Additionally, coefficients of determination ($R^2$) for biomass estimations have been found to exceed 0.80, highlighting the robustness of these techniques in accurately quantifying vegetation metrics (Khati et al., 2015; Singh, Kumar, & Kushwaha, 2014). These advancements not only improve the precision of ecological assessments but also contribute significantly to better understanding of vegetation dynamics, which is vital for addressing challenges related to climate change, biodiversity conservation, and sustainable land management.

Polarimetric Tomographic Synthetic Aperture Radar (PolTomSAR) significantly enhances the capabilities of Polarimetric Interferometric Synthetic Aperture Radar (PolInSAR) by utilizing multiple interferometric baselines to meticulously reconstruct the three-dimensional vertical distribution of scattering power (Kumar, Joshi, & Govil, 2017a; Joshi & Kumar, 2017b). This advanced technique facilitates a nuanced separation of contributions from different structural components of a forest, such as the canopy, trunks, and ground layers, thereby greatly improving our understanding and characterization of the vertical architecture of forests (Asopa & Kumar, 2020). TomoSAR has demonstrated remarkable potential in addressing saturation effects encountered in biomass retrieval, particularly in the context of dense tropical forests, where L-band and P-band observations allow for deeper penetration into the complex canopy layers (Kumar, Garg, Kushwaha, & Pandey, 2017b). The innovative combination of polarimetric data with tomographic analysis enabled by PolTomSAR allows for sophisticated height-dependent backscatter assessments. This capability is essential for accurately stratifying biomass and determining species composition, which are critical for effective forest management and ecological studies (Joshi, Kumar, Agrawal, & Dinh, 2016).

The integration of Polarimetric Interferometric Synthetic Aperture Radar (PolInSAR) and Polarimetric Tomographic Synthetic Aperture Radar (PolTomSAR) techniques effectively addresses the limitations inherent in traditional single-parameter Synthetic Aperture Radar (SAR) methods. By leveraging multi-dimensional information, these techniques enable more reliable and accurate retrievals in complex forest environments, where variations in tree structure and density can pose significant challenges. This review synthesizes recent advancements and research findings utilizing PolInSAR and PolTomSAR for forest height and biomass estimation. It focuses on three key areas: (i) innovative data acquisition strategies that optimize the collection of polarimetric signals, alongside sophisticated inversion algorithms that enhance the accuracy of parametric estimates, (ii) advanced tomographic approaches aimed at generating detailed vertical profiles of forest structures, thereby allowing for a comprehensive understanding of canopy architecture, and (iii) an analysis of reported retrieval accuracies and uncertainties, highlighting the precision of these techniques in various forest ecosystems. The study draws on an extensive array of recent peer-reviewed literature and conference proceedings, including significant contributions from Mukhopadhyay et al. (2022), Khati et al. (2018), and Kumar et al. (2020). This compilation provides a consolidated perspective on the current state-of-the-art methodologies in the field and outlines future directions for operational large-scale monitoring of forest ecosystems, underscoring the potential for these advanced SAR techniques to enhance environmental management and conservation efforts.

## 2. PolInSAR Data Acquisition Techniques and Algorithms

Polarimetric Interferometric Synthetic Aperture Radar (PolInSAR) leverages the combined strengths of Synthetic Aperture Radar (SAR) polarimetry and interferometry to achieve enhanced precision in retrieving forest structural parameters, such as canopy height, biomass, and forest density. The process of data acquisition for PolInSAR involves obtaining two or more complex SAR images of the same geographical area from slightly displaced vantage points, while utilizing multiple polarimetric channels. This dual approach allows for comprehensive analyses of both the interferometric phase, which provides information on topography and surface deformation, and polarimetric scattering, which reveals details about the material properties and structural characteristics of vegetation (Joshi & Kumar, 2017a; Agrawal, Kumar, & Tolpekin, 2016).

Data acquisition can be conducted in single-pass mode, as exemplified by missions such as TanDEM-X and the Shuttle Radar Topography Mission (SRTM). In this mode, two antennas collect data concurrently, thereby eliminating the risk of temporal decorrelation—a key advantage for high-density, rapidly changing environments such as tropical forests. This simultaneous acquisition fosters high-quality coherence measurements, which are critical for accurately capturing intricate forest structures (Khati, Kumar, Agrawal, & Singh, 2015). Conversely, in repeat-pass systems, including RADARSAT-2, ALOS PALSAR, and TerraSAR-X, images are gathered at various time intervals. These systems are inherently more vulnerable to decorrelation due to factors such as vegetation canopy density, seasonal growth patterns, and fluctuations in environmental conditions. Although these challenges can complicate data interpretation, several strategies can mitigate their impact. These include reducing the temporal baselines between acquisitions, optimizing polarimetric coherence through careful selection of imaging geometry, and acquiring data under consistent weather conditions, which collectively enhance the reliability of the results (Singh, Kumar, & Kushwaha, 2014; Joshi, Kumar, & Agrawal, 2016). In summary, PolInSAR is a powerful tool that, through its innovative methodologies, contributes significantly to our understanding of forest ecosystems and aids in effective natural resource management.

The selection of radar frequency is pivotal in influencing both the penetration depth and the sensitivity to the intricate structure of the canopy. X-band systems, characterized by a wavelength of approximately 3 cm, are predominantly attuned to detecting features in the upper canopy as well as the finer branches, making them ideal for capturing the nuances of the overstory. In contrast, C-band systems, with their greater capacity for penetration, effectively navigate through medium-density canopies, facilitating a more comprehensive assessment of canopy structure. L-band systems, boasting wavelengths around 23 cm, are particularly adept at delving deeper into dense foliage, thereby providing more accurate estimations of canopy height and aboveground biomass in both tropical and temperate forests (Khati, Singh, & Kumar, 2018; Kumar, Govil, Srivastava, Thakur, & Kushwaha, 2020).

While P-band is less frequently deployed, it offers unparalleled penetration depth, making it exceptionally well-suited for biomass estimation in high-biomass ecosystems. This capability is set to be further explored in forthcoming missions, such as the European Space Agency's BIOMASS initiative. In practical applications, L-band single-pass PolInSAR acquisitions have demonstrated remarkable height retrieval accuracies, yielding root mean square error (RMSE) values ranging from approximately 1.8 to 3.5 meters in tropical forests. Conversely, C-band repeat-pass systems typically produce RMSE values between 3 and 6 meters, largely due to increased decorrelation effects that can arise over time (Khati et al., 2015; Singh et al., 2014). Notably, X-band single-pass systems, exemplified by TerraSAR-X/TanDEM-X, have highlighted their efficiency by achieving high correlations, with $R^2$ values around 0.85, when validated against LiDAR-derived height measurements in structurally uniform forest stands (Joshi & Kumar, 2017a).

The processing workflow for PolInSAR (Polarimetric Interferometric Synthetic Aperture Radar) typically commences with a critical step of radiometric calibration. This procedure is essential to mitigate the various sensor and environmental effects that can distort data accuracy. Following this calibration, precise co-registration of the multi-polarization images is carried out to ensure accurate alignment and comparison of the data collected. To further enhance the analysis, polarimetric optimization techniques are employed, one of which is the well-known Cloude–Papathanassiou coherence optimization method. This technique adeptly identifies the interferometric channels that yield the greatest separation between volume scattering and ground returns, maximizing the utility of the collected data. Subsequent to this optimization, coherence estimation is performed within optimized or canonical polarization bases, as highlighted in the studies by Kumar et al. (2017c).

The extraction of forest height from the coherence data is often achieved using the Random Volume over Ground (RVoG) model. This conceptual framework views forest canopies as a randomly distributed volume of scatterers positioned above a coherent ground return, allowing for an insightful interpretation of the data. Various model inversion techniques are utilized, with the Three-Stage Inversion (TSI) method standing out due to its ability to simultaneously estimate canopy height and extinction coefficients. Additionally, coherence amplitude inversion is particularly beneficial for scenarios with noisy phase measurements, while multi-baseline RVoG inversion significantly enhances stability and accuracy, especially in heterogeneous forest environments, as demonstrated by Babu & Kumar (2018) and Kumar et al. (2020).

For aboveground biomass estimation, the integration of PolInSAR-derived height measurements with field-based allometric equations, airborne LiDAR calibration data, and robust statistical regression models is essential for enhancing accuracy and reliability. Traditional linear and multiple linear regression techniques have been widely applied in biomass estimation (Singh et al., 2014; Mukhopadhyay, Kumar, Aghababaei, & Kulshrestha, 2022), providing a foundational approach to quantifying biomass based on tree height and diameter measurements. However, advanced machine learning techniques, such as Random Forest and Support Vector Regression, have demonstrated superior performance in accurately estimating biomass in heterogeneous tropical forest environments. These methods have been shown to achieve $R^2$ improvements of 0.05 to 0.10 and reductions in root mean square error (RMSE) of up to 20% compared to traditional regression models (Mukhopadhyay et al., 2022), highlighting their potential for enhanced predictive power. Furthermore, the application of multi-frequency approaches, particularly those that combine L-band and C-band PolInSAR data, has proven effective in mitigating biomass saturation effects, especially in high-biomass zones where estimates exceed 200 Mg/ha (Khati et al., 2018; Kumar et al., 2017c). These multi-frequency methods help capture the various backscatter responses from vegetation structures, providing a more nuanced view of biomass distribution.

Ultimately, the accuracy of PolInSAR-based forest parameter retrieval hinges on several critical factors, including the careful consideration of sensor configuration, baseline geometry, and wavelength selection, as well as the adopted model inversion strategy. The emerging approach of multi-frequency, multi-baseline acquisitions is establishing itself as a robust solution for large-scale, operational forest monitoring, allowing for a comprehensive understanding of forest dynamics and facilitating better management practices. This holistic approach enables researchers and practitioners to derive reliable biomass estimates that are vital for carbon budgeting, ecological assessments, and sustainable forestry initiatives.

## 3. SAR Tomography for Forest Parameters Retrieval

Synthetic Aperture Radar Tomography (SAR TomoSAR) represents a cutting-edge extension of SAR interferometry, designed to facilitate the three-dimensional reconstruction of the scattering structure within a target volume, such as forest canopies. This is achieved by utilizing multiple interferometric acquisitions that feature varying perpendicular baselines, allowing for a nuanced analysis of the scattering contributions from different layers within the forest. In forestry applications, the primary objective is to delineate vertical scattering profiles, which enables the disaggregation of returns from distinct components such as the canopy, trunk, understory, and ground. This level of detail is crucial for accurately estimating forest height and improves the retrieval of aboveground biomass (AGB), ultimately contributing to more effective forest management and monitoring strategies (Kumar, Joshi, & Govil, 2017; Joshi & Kumar, 2017b). The data acquisition strategy employed in TomoSAR significantly contrasts with that of standard Polarimetric Interferometric SAR (PolInSAR), as it necessitates a series of multiple baselines rather than relying on just one or two. This multi-baseline approach adequately samples the vertical spatial frequency domain, referred to as Kz-space, providing the necessary information to reconstruct the vertical distribution of backscatter through a sophisticated inversion process (Kumar et al., 2017b).

Variability in data acquisition can be achieved through multi-pass acquisitions from repeat-orbit SAR missions, including notable platforms like TerraSAR-X, TanDEM-X, and COSMO-SkyMed. These missions are particularly advantageous for their ability to select baseline configurations strategically and apply polarization control, which further enhances the data quality (Asopa & Kumar, 2020). On the other hand, single-pass multi-baseline TomoSAR remains constrained to specialized airborne or experimental configurations due to inherent hardware limitations. However, advancements such as bistatic single-pass systems—exemplified by the operation of TanDEM-X in a pursuit monostatic mode—can partially satisfy the baseline requirements by implementing optimized baseline scheduling (Kumar et al., 2017a). Such innovations expand the capabilities


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of SAR TomoSAR and open new avenues for high-resolution ecological monitoring and assessment.

Acquisition parameters play a critical role in the quality of the vertical resolution achievable through TomoSAR. The vertical resolution, Δz, is inversely proportional to the total spread of perpendicular baselines, ΔB⊥, and directly related to the radar wavelength λ and range R according to $\Delta z \approx \lambda R / (2\Delta B_\perp)$. This means that longer wavelengths, larger baseline spreads, and shorter ranges improve the vertical resolution (Kumar, Garg, Kushwaha, & Pandey, 2017). In forestry studies, L-band TomoSAR provides an effective compromise between canopy penetration and resolution, allowing discrimination of scattering layers with vertical separations of approximately 5–10 m in spaceborne acquisitions, and as fine as 2–3 m in airborne campaigns with large baseline diversity (Joshi et al., 2016). X-band TomoSAR offers finer nominal vertical resolution due to its shorter wavelength, but the limited penetration restricts its ability to retrieve lower canopy and ground-level scattering in dense tropical forests, often underestimating true forest height (Kumar & Joshi, 2016). The number of baselines also affects reconstruction fidelity: while three baselines are theoretically sufficient for resolving three main scattering components, practical scenarios with volumetric decorrelation, speckle noise, and baseline-dependent SNR degradation demand five or more well-distributed baselines for robust profile retrieval (Babu & Kumar, 2018).

The TomoSAR processing workflow begins with radiometric calibration and precise co-registration of all multi-baseline datasets, ensuring sub-pixel alignment across images to preserve phase fidelity (Kumar et al., 2017b). The next step involves determining the baseline geometry and calculating the Kz-spectrum, which quantifies the sampling density in the vertical frequency domain. Sparse or irregular Kz-sampling leads to sidelobe artifacts in the reconstructed profiles, which can be mitigated using adaptive spectral windowing or regularization techniques (Asopa & Kumar, 2020). Tomographic inversion is the core algorithmic stage, and multiple approaches are available depending on the desired resolution and noise robustness. The conventional Fourier beamforming method reconstructs vertical profiles through inverse Fourier transforms of the measured complex coherences, providing a straightforward implementation but suffering from high sidelobe levels in sparse acquisitions. Adaptive beamforming techniques such as Capon filtering improve resolution and sidelobe suppression by adaptively weighting the data based on noise statistics, while subspace-based methods such as MUSIC exploit eigen-decomposition of the covariance matrix to achieve super-resolution capability and are particularly effective in separating closely spaced scattering layers (Kumar et al., 2017a; Joshi & Kumar, 2017b).

The retrieved vertical backscatter power profiles enable the identification of scattering layer boundaries, from which forest height can be estimated as the elevation of the highest significant backscatter peak above ground level (Kumar et al., 2017c). This approach mitigates the biases observed in PolInSAR-derived heights in cases of strong volume decorrelation or low ground return visibility. Moreover, TomoSAR provides detailed structural parameters such as canopy depth, understorey contribution, and vertical attenuation rates, which can be directly linked to forest biomass models or used to improve allometric regression equations (Kumar et al., 2020). Studies using airborne L-band TomoSAR over tropical and boreal forests have reported height retrieval accuracies with RMSE values between 1.5 and 3 m and correlations ($R^2$) exceeding 0.9 when validated against LiDAR datasets (Asopa & Kumar, 2020). Spaceborne X-band TomoSAR, although more affected by canopy opacity, has achieved RMSE values around 2–4 m in moderately dense forests and remains valuable for structural change detection due to its finer spatial resolution (Kumar & Joshi, 2016).

| Study (ref) | Technique | Platform | Forest type / site | Key outcomes |
|---|---|---|---|---|
| Kumar, Joshi & Govil (2017) | TomoSAR | Spaceborne (multi-pass) | Tropical & deciduous | Capon algorithm improved resolution; multi-frequency mitigated saturation. |
| Joshi & Kumar (2017) | TomoSAR | Spaceborne (single-pass) | Plantation / mixed | High resolution; shallow penetration in dense canopy. |
| Babu & Kumar (2018) | PolTomSAR (RVoG inversion) | Airborne UAVSAR | Dense tropical | Multi-baseline reduced bias across canopy classes. |
| Asopa & Kumar (2020) | TomoSAR | Airborne UAVSAR | Tropical Gabon | Dense baselines gave highest vertical resolution; LiDAR fusion boosted AGB accuracy. |
| Mukhopadhyay et al. (2022) | PolSAR + PolInSAR (ML) | Spaceborne (RADARSAT-2) | Tropical deciduous | Random forest fusion improved AGB prediction vs. conventional regression. |
| Agrawal, Kumar & Tolpekin (2019) | PolInSAR | Spaceborne (RADARSAT-2) | Tropical | Polarimetric decomposition improved scattering-based biomass models. |
| Khati et al. (2018) | PolInSAR | Spaceborne | Tropical Indian forests | Multi-frequency evaluation; L-band best for canopy penetration. |
| Kumar et al. (2020) | PolInSAR inversion | Spaceborne (multi-frequency) | Mixed tropical | Multi-frequency approach reduced uncertainties in forest height retrieval. |

In aboveground biomass estimation, TomoSAR-derived structural metrics outperform single-height estimators by capturing biomass variations in tall and structurally complex forests where saturation effects limit the performance of backscatter- or height-only models (Mukhopadhyay, Kumar, Aghababaei, & Kulshrestha, 2022). Combining TomoSAR profiles with PolInSAR coherence information further enhances retrieval accuracy, as demonstrated in multi-sensor fusion approaches achieving biomass estimation $R^2$ values of 0.85–0.92 and RMSE reductions of 15–25% compared to single-technique approaches (Kumar et al., 2018). Consequently, SAR tomography stands as a critical methodology for next-generation forest monitoring frameworks, particularly in synergy with missions such as NISAR and BIOMASS, where multi-frequency, multi-baseline acquisitions will provide unprecedented volumetric forest information at global scales.

## 4. Discussion

The literature on PolInSAR and PolTomSAR clearly indicates that the accuracy of retrieving forest height and aboveground biomass (AGB) is fundamentally influenced by several factors: (i) radar wavelength and polarimetric information, (ii) the geometry of the interferometric/tomographic baseline (referred to as Kz coverage), (iii) the inversion algorithm and decomposition techniques employed, and (iv) the availability of independent calibration and validation data, such as TLS, LiDAR, or field plots (Singh, Kumar, & Kushwaha, 2014; Agrawal, Kumar, & Tolpekin, 2016; Kumar et al., 2017). Studies utilizing multi-frequency data or tomographic stacks have consistently demonstrated improved performance. This is because multi-frequency signals can penetrate different depths of the canopy, while tomography effectively resolves vertical scattering distributions (Khati et al., 2018; Kumar, Joshi, & Govil, 2017; Babu & Kumar, 2018). The advent of high-quality P-band and NISAR L/S observations now provides practitioners with the necessary sensor capabilities to tackle two of the most significant challenges: penetrating to near-ground scatterers within very dense tropical forests and achieving robust retrieval of multi-layer canopy structures across a wide range of canopy heights.

P-band, which has a very long wavelength of approximately 70 cm, significantly enhances the likelihood of receiving a coherent ground component in tall, dense canopies. In such environments, C- and X-bands experience strong attenuation, and even L-band often struggles with ground visibility. Existing literature indicates that height inversion accuracy improves when the ground return meaningfully contributes to the complex interferometric signal. Both RVoG and coherence-based inversions rely on a discernible ground coherence term (Cloude & Papathanassiou; see applied reviews by Kumar et al., 2017; Singh et al., 2014). Thus, after processing P-band stacks, we can anticipate that PolInSAR RVoG inversions will be more stable and less susceptible to the “ground invisibility” bias, which typically leads to systematic underestimations of canopy height in dense tropical stands (Khati et al., 2018; Agrawal et al., 2019). In practice, P-band tomographic stacks will facilitate clearer differentiation between canopy volume and ground responses when used in combination with polarimetric decomposition methods (such as Freeman-Durden and Yamaguchi extensions) that are adapted for P-band scattering physics (Agrawal et al., 2016).

Given the improvements seen with L-band PolTomSAR and multi-frequency fusion in the referenced studies (Asopa & Kumar, 2020; Babu & Kumar, 2018), it is reasonable to project that P-band tomography will reduce height root mean square errors (RMSEs) below the current results from L-band observations. In optimally designed tomographic experiments, we can expect the RMSE for canopy height to approach approximately 1–2 m, with a significantly stronger correlation ($R^2$ > 0.85) against LiDAR/TLS measurements for many tropical sites. This projection is based on the principles of deeper penetration and the existing tomographic literature, and it will depend on factors such as signal-to-noise ratio (SNR), baseline diversity, and calibration quality (Kumar et al., 2017; Joshi & Kumar, 2017).

NISAR utilizes both L- and S-band signals to enhance data collection through their complementary characteristics, effective revisit intervals, and stable coherence. The L-band channel is particularly adept at penetrating the canopy and providing volumetric sensitivity, which many PolInSAR, RVoG, and TomoSAR methods effectively leverage (Khati et al., 2018; Kumar et al., 2020). In contrast, the S-band contributes sensitivity to finer branches, foliage, and moisture levels closer to the top of the canopy. By combining L- and S-band data, we can better distinguish between vertical scattering layers: the L-band focuses on deeper trunks and lower canopy scattering, while the S-band captures clearer signals from the upper canopy and foliage.Research indicates that multi-frequency approaches can reduce biomass saturation and enhance the range of data retrieval (Khati et al., 2018; Kumar et al., 2020). Furthermore, NISAR’s frequent revisit schedule and uniform global acquisition strategy will help mitigate the temporal decorrelation effects that have previously hindered many repeat-pass PolInSAR analyses (Singh et al., 2014). This improvement will make coherence-based inversions (CAI, TSI) more robust across different seasons and variations in vegetation. When NISAR’s L/S PolInSAR products are integrated with P-band tomographic layers, we can expect a synergy that will improve height retrieval by 20–30% compared to single-band PolInSAR baselines. This enhancement will also significantly extend the effective aboveground biomass (AGB) retrieval range before saturation occurs (Kumar et al., 2017; Mukhopadhyay et al., 2022).

PolTomSAR (Tomography + Polarimetry) offers significant advantages for building multi-layer biomass models. Tomographic reconstruction techniques, such as Fourier beamforming, Capon adaptive beamforming, and subspace methods like MUSIC, generate vertical backscatter power profiles. These profiles can be analyzed to extract important metrics, including the canopy top, canopy base, and vertical scattering distribution (Kumar et al., 2017; Joshi & Kumar, 2017). Capon and subspace methods are particularly effective in reducing sidelobe artifacts and enhancing effective vertical resolution, which is crucial for obtaining meaningful layer metrics used in biomass models (Kumar et al., 2017; Asopa & Kumar, 2020). Research indicates that incorporating these vertical metrics into PolInSAR coherence and polarimetric decomposition inputs significantly improves above-ground biomass (AGB) regressions. Airborne L-band tomographic studies, when combined with terrestrial laser scanning (TLS), often report biomass $R^2$ values in the 0.8–0.9 range, with root mean square error (RMSE) values that are substantially lower than those derived from height-only models (Asopa & Kumar, 2020; Babu & Kumar, 2018). Looking ahead to the P-band Biomass and L/S-band NISAR era, we can anticipate that tomographic layers obtained from P-band data will provide detailed structural descriptors of deep canopies, such as lower-canopy scattering power and trunk-layer signals. This information can be integrated with L/S polarimetric coherence,


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Table:2 Expected Performance of P-band, L-band, and L/S Fusion for Forest Height and AGB Retrieval

| SAR Configuration | Key Physical Advantages | Expected Canopy Height RMSE | Expected Height $R^2$ | Expected AGB RMSE | Expected AGB $R^2$ | Notes / Source Basis |
|---|---|---|---|---|---|---|
| L-band PolInSAR (e.g., ALOS-2, NISAR L) | Good penetration; sensitive to woody biomass; widely validated | 2.0–3.5 m | 0.70–0.85 | 25–35 Mg/ha | 0.55–0.70 | Khati et al., 2018; Kumar et al., 2020; Singh et al., 2014 |
| P-band PolInSAR / PolTomSAR (ESA mission) | Deep penetration; higher ground visibility; reduced canopy opacity; strong trunk scattering | 1.0–2.0 m | 0.85–0.90+ | 15–25 Mg/ha | 0.75–0.90 | Projection based on Babu & Kumar, 2018; Asopa & Kumar, 2020; Kumar et al., 2017 |
| Dual-frequency L/S PolInSAR (NISAR) | L: canopy penetration; S: foliage/upper canopy sensitivity; coherence stability; seasonal monitoring | 1.8–2.5 m | 0.75–0.88 | 20–28 Mg/ha | 0.65–0.80 | Khati et al., 2018; Kumar et al., 2020 |
| P-band Tomography + L/S PolInSAR Fusion | Full vertical profile from P-band; complementary L/S frequency scattering; improved biomass saturation limits | 1.0–2.0 m | 0.85–0.90+ | 15–22 Mg/ha | 0.75–0.90+ | Projection based on Agrawal et al., 2019; Mukhopadhyay et al., 2022 |

backscatter, and decomposition metrics to develop multi-layer biomass estimators that outperform previously developed models, particularly for high AGB scenarios (exceeding 200–300 Mg/ha) (Agrawal et al., 2019; Mukhopadhyay et al., 2022).

Projected quantitative performance and caveats. Drawing on performance ranges reported in the citations (e.g., PolTomSAR airborne RMSEs ≈1.5–3 m; spaceborne L-band PolInSAR RMSEs ≈2–3.5 m; PolInSAR biomass $R^2$ ≈0.4–0.7, with machine-learning fusion improving $R^2$ to ~0.65 and reducing RMSE around 24–33 Mg/ha), and recognizing P-band's deeper penetration, the combined P-band + NISAR L/S data stack is expected to deliver the following plausible improvements in well-configured experiments: canopy height RMSE could fall into the ~1.0–2.0 m range across many dense tropical sites, and biomass models that fuse tomographic P-band metrics with L/S polarimetric and coherence features could push AGB model $R^2$ into the 0.75–0.90 range with RMSEs approaching 15–25 Mg/ha in calibrated regions. These projections echo the incremental gains reported when moving from C-band PolInSAR → L-band PolInSAR → airborne L-band TomoSAR in the literature (Singh et al., 2014; Khati et al., 2018; Asopa & Kumar, 2020). However, these gains are conditional: baseline geometry (Kz coverage), acquisition SNR, radiometric and phase calibration (especially important for long-wavelength P-band), and reliable ground truth remain limiting factors (Kumar et al., 2017; Agrawal et al., 2016). P-band data will also introduce different scattering regimes (e.g., greater trunk scattering, possible increased depolarization), implying RVoG and EWCM/IWCM parameterizations should be re-tuned for P-band extinction and scattering amplitude characteristics rather than simply reused from L-band parameter sets (Agrawal et al., 2016; Agrawal, Kumar, & Tolpekin, 2019).

Processing implications and algorithmic recommendations. After data acquisition, the standard polarimetric and interferometric preprocessing chain (radiometric calibration, speckle filtering, sub-pixel coregistration, polarimetric orientation angle compensation, coherency/covariance matrix estimation) remains mandatory (Agrawal et al., 2016; Joshi et al., 2016). For P-band, extra attention to radiometric calibration and ionospheric effects (if present) is necessary because of the long wavelength. In inversion and tomographic stages, the literature supports the following: when Kz sampling is dense (airborne or well-planned spaceborne stacks), Fourier beamforming is a fast baseline method, but Capon or MUSIC should be preferred for operational retrieval because of better sidelobe suppression and superior separation of closely spaced scattering layers (Kumar et al., 2017; Joshi & Kumar, 2017). Multi-baseline RVoG inversion (Babu & Kumar, 2018) provides robustness across heterogeneous height classes; coupling such inversions with polarimetric decomposition from PolInSAR yields a physically anchored set of predictors for biomass models (Agrawal et al., 2016; Agrawal et al., 2019).

Validation, machine learning and fusion. The literature shows that machine-learning regressors (Random Forest, SVR) consistently outperform simple linear models for AGB when supplied with a diverse set of radar observables, including tomographic profile metrics (Mukhopadhyay et al., 2022; Kumar et al., 2017). Thus, practical utilisation of P-band + NISAR data should include extensive feature engineering (canopy top height, canopy depth, integrated backscatter at discrete height slices, layer-wise polarization ratios, coherence magnitudes, decomposition volume/double bounce/surface terms) and validation against a representative TLS/LiDAR + plot network. Fusion architectures that include physics-informed limits (e.g., RVoG constraints on ground/volume ratios) plus machine learning to capture residual nonlinearities have been shown to deliver the best performance (Mukhopadhyay et al., 2022; Agrawal et al., 2019). Practically, one should anticipate that transferability of ML models will improve when input features include P-band tomographic descriptors because these descriptors reduce ambiguity due to canopy opacity and saturation.

Operational and scientific challenges. Despite the promise, several practical challenges remain. Long-wavelength P-band SAR requires stringent electromagnetic and radiometric calibration and may present increased susceptibility to ionospheric distortions and increased radio regulatory constraints; these technical issues must be managed to realize the full potential of ground-sensitive returns. Temporal decorrelation remains a challenge for repeat-pass tomographic strategies in highly dynamic tropical regions, although NISAR's revisit cadence and careful acquisition planning can mitigate this to a degree. Baseline planning for tomographic stacks remains expensive and operationally complex at global scales; effective Kz sampling strategies must balance revisit, coverage, and coherence requirements. Lastly, large-scale generation of P-band tomographic products will demand substantial processing resources and robust, well-documented workflows that combine polarimetric, interferometric and tomographic steps—ideally implemented in scalable cloud or HPC environments to support continental or global mapping efforts (Kumar et al., 2017; Joshi et al., 2016).

Synthesis and outlook. In summary, the literature indicates that the combined use of newly available P-band tomographic stacks and NISAR L/S dual-frequency PolInSAR data constitutes a major step change for forest structural mapping and biomass estimation. P-band's deeper penetration should reduce ground invisibility bias and enable more accurate RVoG and tomographic inversions in dense tropical forests, while NISAR L/S will supply complementary frequency sensitivity, high revisit coherence stability, and wide coverage. By coupling PolInSAR coherence and polarimetric decomposition with P-band tomographic vertical profiles and by applying multi-baseline RVoG inversions and robust beamforming (Capon/MUSIC) plus machine-learning fusion models trained against TLS/LiDAR, operational height retrieval RMSEs near 1–2 m and AGB RMSE reductions into the 15–25 Mg/ha regime (with $R^2$ often exceeding 0.75 in well-calibrated regions) appear feasible. Achieving these gains will require careful attention to calibration, baseline design, fusion algorithm development, and representative ground validation. The convergence of P-band and NISAR L/S data thus opens the pathway to more accurate, less saturated, and spatially transferable forest parameter products at regional to global scales—delivering the structural information necessary for improved carbon accounting and forest management (Singh et al., 2014; Khati et al., 2018; Mukhopadhyay et al., 2022; Kumar et al., 2017).

Table 2 summarises the expected performance of different SAR frequency configurations—L-band PolInSAR, P-band PolInSAR/PolTomSAR, dual-frequency L/S-band PolInSAR, and combined P-band tomography with L/S-band fusion—in estimating forest canopy height and aboveground biomass (AGB). These projections are grounded in results from the cited literature for operational and experimental systems, while also incorporating physics-based expectations for upcoming missions such as ESA's P-band SAR and NASA–ISRO's NISAR. L-band PolInSAR, as implemented with spaceborne sensors such as ALOS-2 and expected from NISAR's L-band channel, has been widely validated for forest height and biomass estimation. Its intermediate wavelength allows for moderate canopy penetration while retaining sensitivity to woody components. Literature results, such as those reported by Khati et al. (2018), Kumar et al. (2020), and Singh et al. (2014), show canopy height retrievals with RMSE values between 2.0 and 3.5 m and coefficients of determination ($R^2$) between 0.70 and 0.85. For AGB, typical RMSE ranges from 25 to 35 Mg/ha, with $R^2$ between 0.55 and 0.70. These values reflect the strength of L-band for general applications, though they are susceptible to saturation effects in high-biomass forests.

P-band PolInSAR and PolTomSAR, as will be provided by ESA's recently launched mission, is projected to deliver superior performance due to its longer wavelength, which penetrates deep into the canopy and enhances ground return visibility. This capability improves the separation between ground and volume scattering components, resulting in more accurate height inversion using RVoG models and sharper vertical profiles from tomography. Based on studies such as Babu and Kumar (2018), Asopa and Kumar (2020), and Kumar et al. (2017), expected canopy height RMSE is between 1.0 and 2.0 m with $R^2$ exceeding 0.85, while AGB RMSE can be as low as 15 to 25 Mg/ha with $R^2$ reaching 0.90 in well-calibrated conditions. The dual-frequency L/S-band PolInSAR mode of NISAR combines the deeper penetration of L-band with the higher sensitivity of S-band to upper canopy foliage and smaller woody elements. This combination can improve coherence stability across seasons and enhance sensitivity to canopy structural changes. Projected performance, based on Khati et al. (2018) and Kumar et al. (2020), suggests canopy height RMSE between 1.8 and 2.5 m and $R^2$ from 0.75 to 0.88, while AGB estimation could achieve RMSE between 20 and 28 Mg/ha with $R^2$ between 0.65 and 0.80. This configuration is particularly advantageous for monitoring dynamic changes rather than mapping absolute maxima of biomass.

Finally, integrating P-band tomography with L/S-band PolInSAR provides a complementary approach that leverages the full vertical profile resolution of P-band with the multi-frequency scattering sensitivity of L/S. This synergy can significantly alleviate biomass saturation and improve retrieval accuracy across diverse forest types. Expected canopy height performance mirrors P-band alone (1.0–2.0 m RMSE, $R^2 >$ 0.85), but AGB accuracy benefits from the fusion, with RMSE between 15 and 22 Mg/ha and $R^2$ consistently above 0.75. As indicated by Agrawal et al. (2019) and Mukhopadhyay et al. (2022), this multi-frequency, multi-technique integration is a promising direction for operational biomass mapping under the upcoming missions. In summary, the table illustrates that while L-band remains a robust and well-validated choice for many forest parameter retrieval applications, P-band provides a step-change improvement in penetration and structural discrimination, and L/S fusion offers valuable multi-layer sensitivity. The combination of P-band tomography and L/S PolInSAR represents the highest potential for reducing uncertainty in both height and biomass estimates, especially for dense tropical and subtropical forests where saturation limits have previously constrained SAR-based approaches.

## 5. Conclusion

This study synthesised key advances in the utilisation of Polarimetric SAR Interferometry (PolInSAR) and Polarimetric SAR Tomography (PolTomSAR) for the retrieval of forest canopy height and aboveground biomass (AGB), drawing on well-established literature and aligning the discussion with the forthcoming capabilities of ESA's P-band SAR mission (launched 29 April 2025) and NASA–ISRO's NISAR mission (launching 30 July 2025). The reviewed works demonstrate that PolInSAR at L-band has already proven to be a robust operational tool for height estimation and biomass mapping, achieving RMSE values of 2–3.5 m for height and 25–35 Mg/ha for biomass in a variety of forest conditions. However, limitations due to biomass saturation in high-density forests and reduced sensitivity to sub-canopy structure remain evident. The P-band SAR capability, with its enhanced canopy penetration and improved separation of ground and volume scattering, offers the potential to significantly reduce retrieval uncertainty, particularly when combined with multi-baseline RVoG inversion and tomographic reconstruction. Expected accuracies from P-band processing, supported by findings in Babu and


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Kumar (2018), Asopa and Kumar (2020), and related works, suggest canopy height retrievals with RMSE as low as 1–2 m and biomass estimations with RMSE of 15–25 Mg/ha, with $R^2$ often exceeding 0.85–0.90. Tomographic techniques at P-band further enable detailed vertical profiling of vegetation, opening new possibilities for structural ecology studies and biomass stratification.

The dual-frequency L/S-band PolInSAR capability of NISAR will complement P-band datasets by providing multi-layer sensitivity to both woody and foliage components, improving coherence stability across seasons, and aiding in monitoring dynamic forest changes. When integrated, P-band tomographic products and L/S-band PolInSAR features form a multi-frequency, multi-technique framework that is uniquely suited for mitigating saturation effects, enhancing retrieval precision, and delivering consistent products across diverse forest types and biomass ranges. Looking ahead, the synergistic use of P-band tomography with NISAR's L/S-band PolInSAR is poised to deliver unprecedented accuracy and spatial detail in forest height and biomass mapping. Such integrated datasets will be pivotal for carbon stock assessments, REDD+ monitoring, ecosystem modelling, and policy-relevant reporting under climate change mitigation frameworks. Operational workflows will need to incorporate advanced calibration, ionospheric correction, adaptive multi-baseline inversion, and robust machine learning modelling to fully exploit these datasets. With the near-simultaneous availability of these two flagship missions, the global remote sensing community has a unique opportunity to establish a new benchmark in forest biophysical parameter retrieval, addressing long-standing limitations and enabling more precise and actionable forest monitoring on a global scale.

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