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Multiscale analysis of full-scale phased array antennas for thermo-elastic behavior prediction using high-order modeling

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ABSTRACT

Over the past decade, extensive research has focused on developing large-scale antenna systems for advanced space applications, targeting structures up to 100 meters for space-based solar power generation. Despite their promising potential, several technological issues persist, primarily related to structural integrity and electromagnetic efficiency. As an intermediate step toward this ambitious objective, this study explores the structural performance of a Geostationary Precipitation Radar (GPR) satellite antenna, approximately 30 meters in size [1]. A primary structural concern involves thermal deformation induced by mismatches in coefficients of thermal expansion among composite material layers. The antenna structure examined in this research consists of three distinct layers: copper foil, dielectric material, and carbon fiber-reinforced polymer (CFRP). Achieving precise flatness and stability under extreme operational temperature fluctuations is critical to maintaining optimal electromagnetic performance.

To efficiently evaluate thermal deformation, this research introduces a computationally effective multiscale methodology, combining micromechanical homogenization with detailed localization analyses of stress and strain distributions at material interfaces. Employing a multiscale framework significantly reduces computational complexity while preserving accuracy in deformation and stress predictions. At the microscale, structural analysis leverages the Mechanics of Structure Genome (MSG) methodology, distinctly separating global responses from local phenomena. MSG employs the Variational Asymptotic Method (VAM) to determine effective thermoelastic properties based solely on material properties and geometry, eliminating explicit external loading conditions and significantly enhancing computational efficiency. Furthermore, the structural response of the antenna is captured through high-order finite elements formulated within the Carrera Unified Formulation (CUF). This model accurately represents the antenna's Representative

Volume Element (RVE) geometry using Legendre polynomial expansions across the cross-section [2]. Thus, the approach achieves accuracy comparable to traditional solid finite element models but with substantially reduced computational effort.
The proposed multiscale modeling approach represents a robust and efficient framework for structural assessment of large-scale planar antennas, demonstrating significant potential for future satellite antenna designs.

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