

Bayesian Learning Framework for High-Fidelity Far-Field Prediction in ISAR Imaging

Incheol (Aiden) Jung, Kenneth Jao, Shen Lin, and Zhen Peng

University of Illinois at Urbana Champaign, Urbana, IL 61801, USA (zvpeng@illinois.edu)

Inverse synthetic aperture radar (ISAR) imaging has diverse applications ranging from geographical surveying to astronomical observation and military surveillance. The quality of ISAR images depends on the accuracy and resolution of complex far-field scattering data. Generating such data computationally requires numerous evaluations over wide angular and frequency ranges, which is both time-consuming and computationally expensive, especially for complex and electrically large structures.

This paper addresses these challenges by framing the data generation process as a Bayesian uncertainty quantification problem within a Gaussian Process (GP) framework. Compared to existing GP methods, our approach incorporates two key innovations: **(1) Local Fourier NonStationary Matérn (LF-NSM) kernel:** The proposed GP kernel captures both (small-scale) localized scattering variations and (large-scale) quasi-periodic behaviors across angular and frequency domains. It improves predictive accuracy by accounting for angular- and spectral-dependent correlations. **(2) Variance-Minimizing Adaptive Sampling (VMAS):** It represents an active learning strategy that dynamically enriches the sampling process by targeting regions of high uncertainty. It achieves controllable accuracy with fewer data samples, leading to substantial savings in both computational effort and data acquisition time.

We demonstrate the performance of the proposed work using an Open-Duct PRIME airplane model (A. Maicke et al., “A Benchmark Airplane Model with Ducts”, AP-S/URSI, pp. 657-658, 2022). The desired far-field data spans an angular range of $\phi \in [0, \pi/2]$ radians with 0.5° increments and a frequency range of $f \in [9.5, 10.5]$ GHz with 10 MHz increments. A total number of $361 \times 101 = 36461$ data points are required to generate a high-quality ISAR image.

Table 1 summarizes the root mean square errors (RMSEs) for different combinations of kernel designs and sampling strategies. Each method is limited to 1,440 samples. Standard Matérn kernels with Latin Hypercube Sampling (LHS) exhibit RMSE values exceeding 2%. Incorporating VMAS reduces the RMSE by about 25% - 40%. Moreover, replacing the standard Matérn kernel with our proposed LF-NSM kernel dramatically improves the accuracy, achieving RMSE under 1%. Finally, combining LF-NSM with VMAS achieves RMSE below 0.05%, representing roughly a 100-fold improvement in accuracy over the baseline method. These results highlight the potential of our proposed LF-NSM kernel and VMAS method in producing high-resolution far-field data for ISAR imaging.

Table 1: Open-Duct Final RMSEs for Various Schemes.

Model	Kernel	Sampler	$\mathbf{E}_{VV}^{\text{sca}}$	$\mathbf{E}_{VV}^{\text{sca}}$	$\mathbf{E}_{VV}^{\text{sca}}$	$\mathbf{E}_{VV}^{\text{sca}}$
A	Matérn	LHS	2.626%	2.531%	2.339%	2.268%
B	Matérn	VMAS	2.200%	1.766%	1.664%	1.519%
C	LF-NSM	LHS	1.681%	0.249	0.271%	0.069%
D	LF-NSM	VMAS	0.033%	0.021%	0.031%	0.031%