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Imaging the Earth's small structures: AI-driven, Bayesian inference of microstructure descriptors from finite-frequency waves

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More often than not, important geologic processes occur at micro-scales, e.g., fluid flow, mineral-phase changes, chemically-induced alteration, rock-frame compaction, or even mechanical ruptures/instabilities leading to large earthquakes. However, reliably imaging material properties at such scales from remote long-wavelength information contained in either seismic or EM fields has long been a challenge to the geophysical, engineering and material science communities. In this talk, we present a general framework for the estimation of sub-wavelength material properties from long-scale waves, building on recent advances on statistical microstructure descriptors (SMDs) within the field of material science.

In geoscience, traditional approaches to describing material microheterogeneity rely on either analytical inclusion-based models, or in sample-based digital rocks: each of these having their pros and cons. Here, we instead rely on SMDs, namely two-point correlation and polytope functions, to describe microheterogeneous geo-materials in a manner that is capable of generalizing complex geometrical information hidden in microstructures, while also retaining realism and sample fidelity. Using SMDs, we rely on wave-equation-based Strong Contrast Expansions (SCEs) to predict frequency/scale-dependent effective wave properties for acoustic, elastic and EM waves. We briefly discuss how SMD-described microstructures affect long-wave properties – and in particular how they not only predict frequency-dependent attenuation due to sub-wavelength scattering, but that attenuation is particularly sensitive to microstructure when compared to effective wavespeeds.

When it comes to the estimation of microstructure properties from wave observations, the problem becomes substantially more difficult because realistic microscale parameters could in principle have far too many degrees of freedom than what is observable from finite-frequency wave data. As such, it is key that any method that aims at realistically retrieving microstructure information from long-scale wave data accounts for uncertainty, while also handling the highly nonlinear nature of microstructure-dependent effective wave properties. To that end, we combine our SMD and SCE approaches for effective wave properties with the supervised machine-learning

method of Random Forests to construct a Bayesian approach to infer microstructure properties from effective wave parameters as observables. This method yields full posterior distributions for microstructure parameters (e.g., property contrast, volume fraction, and geometry information) from frequency-dependent observations of wave velocities and attenuation. We present several examples of inference scenarios, showing, for example, that i) attenuation is key to microstructure imaging, and ii) microgeometry information can only be reliably retrieved if contrast and volume fraction are relatively well known a priori. We illustrate of inference approach with several examples of analytical and real microstructures, including data from a laboratory compaction experiment controlled by microscale CT imaging.