Combining High-Resolution Local Models with the SCEC CVMs
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Overview: Accurate models of seismic velocities form a core SCEC data deliverable, with the Community Velocity Models (CVMs) forming a cornerstone of the SCEC modelling framework. However, despite increasingly better performance of the SCEC CVMs in validation exercises, the two current generation models (CVMS-4.26 and CVM-H) still mis-predict important engineering seismology measurements crucial to accurate assessment of seismic hazard within Southern California. An example is given in Figure 1, in which the pseudo-spectral accelerations of the Mw 7.1 July 5 2019 Ridgecrest Earthquake, as recorded at on the Community Seismic Network (CSN) array, are compared with 3D finite difference simulations through the CVMs using the Graves & Pitarka framework (Pitarka et al. 2020). Within the 4-9 s period band that is particularly important for basin resonance coupling with high-rise buildings in downtown Los Angeles, the intensities and spatial distributions of relative amplification are poorly predicted. This suggests that further refinement of the basin structure utilizing local updates to the CVMs is required.

Figure 1: Relative amplification of pseudo-spectral accelerations from the Mw 7.1 July 5 2019 Ridgecrest Earthquake as recorded on the Community Seismic Network (CSN), and as simulated using the Graves & Pitarka rupture generator and a 3D finite difference waveform solver for both the CVM-H and CVM-S 4.26 models.

With this motivation in mind, the overarching goal of this project is to develop methodology for principled inclusion of geological structures within the SCEC CVM framework via local tomographic updates. We investigated the use of the level set method to implicitly define the boundaries between geological regions, and also proposed a new derivative-free approximate-Bayesian inverse problem framework for rapidly iterating between different model...
parametrizations and data sets without having to create the requisite machinery for obtaining derivatives via the adjoint method or similar.

**Data:** We utilized the novel MEMS accelerometer dataset of the CSN to perform structural inversion of the North-Eastern Los Angeles Basin. The CSN provides high-resolution spatial coverage of this important part of the basin, which includes downtown Los Angeles, by siting inexpensive accelerometers within the campuses of the Los Angeles Unified School District. This allows for permanent deployment of dense instrumentation within an urban setting. The primary scientific goal of the CSN is high-resolution strong-ground-motion reporting from local earthquakes, and as such the selected instrumentation has been designed with both a high clipping amplitude and a high noise floor. Consequently, the CSN array cannot employ ambient-noise cross-correlation based techniques, as the combination of instrument noise and local low-power anthropogenic noise (which are incoherent across the array) overwhelms coherent noise sources. As such, we utilize surface waves from the Mw 6.4 and Mw 7.1 Ridgecrest earthquakes recorded on the CSN as data, as they were cleanly recorded on the array. Specifically, the strongest arriving phase from both earthquakes is the Love wave packet, and so we used both phase velocities derived from eikonal tomography and relative amplifications of Love waves as the dataset for inversion. Spatial binning of residuals relative to the mean of the two earthquakes allows for estimation of the error associated with the measurements.

**Level Set Based Basin Parametrization:** In this work, we aim to update the velocity model of the Los Angeles basin; however, the geometry of the basin is not known *a priori*. Therefore, we parametrize the unknown surface of the update as a component of the inverse problem using the level set method as described in Muir & Tsai 2020. By appropriately penalizing the deviation of this surface away from a reference basin surface estimated from the statistical properties of the CVM-S 4.26 model, as well as its roughness, we can parsimoniously weight the contributions of the reference model and the observed data. Within the basin region to be updated, we use a hierarchical Gaussian Process (GP) framework to parametrize the velocity perturbations relative to CVM-S 4.26. The GP parametrization uses allows for physically meaningful hyperparameters (such as the characteristic length-scales of velocity perturbations & their amplitudes) to be incorporated in the model update covariance matrix – these hyperparameters are also solved for in a hierarchical fashion to minimize the operator bias introduced by setting up the inverse problem.

**Figure 2:** Schematic of the model parametrization used in this study. The model consists of two components – the boundary of the inversion domain, which is parametrized using the level set method, and the update to the CVM background model itself, which is parametrized using a hierarchical Gaussian Process (GP).
Inverse Problem Solver: In order to solve the hierarchical inverse problem, we have extended the derivative-free approximate-Bayesian Ensemble Kalman Sampler (EKS, Garbuno-Inigo et al. 2020) to handle hierarchical models. The EKS designs a particle based Kalman filter with a stationary particle distribution that acts as a Gaussian approximation to the true posterior probability distribution of the inverse problem. By making use of the empirical covariance of the particle swarm, the method avoids taking derivatives of the posterior in respect to the model parameters – allowing rapid development iteration between different model parametrizations and data sets. Our extension of the EKS makes use of a Cholesky decomposition-based coordinate transformation of the GP updates to decouple the updates to the hyperparameters (which require derivative calculations) from the velocity updates themselves, which can then be fully derivative-free. The EKS sampler is especially well suited to heterogeneous cluster computing as the particles only communicate after the forward model prediction.

Results of Inversion: After our local update is made, we see a variance reduction of \(\sim 50\%\) relative to the forward prediction using CVM-S 4.26 alone. The principle result of the inversion is a deepening of the Los Angeles Basin along towards the Northeast relative to CVM-S. This is shown in profile A-A’ of Figure 3, which highlights the velocity reduction along the steep wall of the basin which is coincident with the inferred trace of the Upper Elysian Park fault.

Figure 3: Results of local tomographic update utilizing the level set method. The subfigures along the right column are, from top to bottom, the reference CVM-S 4.26 profile, the inversion result with inferred boundary of local update shown by a black dotted line, the difference in the two models, and the estimated uncertainty in the inversion. Due to the approximate nature of the EKS algorithm, the inversion uncertainty is best regarded as a relative estimate.
The secondary major feature is the shallowing of the low velocity zone in the hills that mark the junction between the San Fernando and San Gabriel basins, seen at the A’ end of the profile in Figure 3. Within the basin, this deepening increases the amplification of Love waves in the 4-9 s period band, with consequently increased danger of basin resonance coupling to these waves for tall buildings with the requisite fundamental period.

References: