**Introduction:** Future missions to the Moon, Mars, and asteroids require a detailed picture of the subsurface to evaluate landing site safety and identify features of interest (e.g. void spaces that could serve as shelter). Radar and seismic techniques have been employed to this end, but often without the necessary level of detail. Here, we quantify physical properties of the regolith through simultaneous ground penetrating radar (GPR) and seismic reflection analysis, and take advantage of the opposite effects of density contrasts on the respective wave speeds. To start, we benchmark our methodology using a single void model (Fig. 1), and will proceed to incorporate more complicated subsurface structures. We propagate numerically simulated electromagnetic and seismic waves through the model, compute common midpoint (CMP) stacks, and migrate both records. Our goal is to use these simulations to spearhead a joint GPR and seismic analysis of regolith containing small-scale and large-scale heterogeneous scatterers; this will help us to validate methods to both characterize subsurface structures and determine optimal acquisition geometries for their detection.

Both methods add space on the array edges to prevent boundary interactions. The GPR simulation outputs are imported into the *REFLEXW* software, where we organize the individual shots into a CMP gather, manually construct a 2D velocity profile using semblance analysis, stack the velocity profile, and perform a 2D Kirchhoff migration (Fig. 2b). We mirror this process for seismics using a mix of the *CREWES MATLAB Software Library* and our own code (Fig. 2d). The migrated images capture the depth and first-level structure of the void space; for the seismic migration image, multiple reflections of the P-wave and S-wave from the void ceiling result in some contamination. With this baseline simulation test on hand, we will apply our methods to image subsurface structures in data from terrestrial analogs and planetary bodies.

![Figure 1](image1.png)

**Figure 1.** Model setup for a 25-m radius hemisphere lava tube void space, ceiling 25 m below surface.

**GPR and Seismic Joint Inversion Methods:** We respectively create our GPR and seismic model spaces using *gprMax* (a Finite-Difference-Time-Domain modeling software) and *gmsh* (an open-source meshing software). Our simulations entail 25 sources modeled through *gprMax* and 13 sources through *SPECFEM2D*, a full waveform imaging spectral element solver that computes the seismic wavefield; GPR and seismic wavefields for the source directly above the void are shown in Fig. 2a and Fig. 2c. The GPR simulations assume receivers spaced every 2.5-m and move the source antenna 5-m forward from its previous position. The seismic simulations incorporate receivers spaced every 0.5m and the 100-Hz at-surface moment tensor source is moved 5-m between shots.

![Figure 2](image2.png)

**Figure 2.** a) GPR wavefield and c) seismic wavefield with source located at the surface above the void. b) GPR migration and d) seismic reflection migration assuming a constant P-wave velocity of 3km/s.

**Future Work:** The next test is to apply our codes to subsurface structures with multiple void spaces, randomly generated stochastic scattering media, and in-situ field data. GEODES’ joint inversion project will determine cost- and time-effective methods of locating subsurface void spaces and assessing regolith porosity in new geophysics missions to the surfaces of the Moon, Mars, and asteroids.

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