NUMERICAL SIMULATIONS OF SEISMIC WAVE PROPAGATION WITHIN ASTEROIDS. E. Bell[1], N. Schmerr[1], J. Plescia[2]; [1]University of Maryland, Department of Geology, 8000 Regents Dr., College Park, MD 20742-4211 ebell1@umd.edu, nschmerr@umd.edu; [2]The Johns Hopkins University, Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel MD 20723-6099 jeffrey.plescia@jhuapl.edu

Introduction: Numerical methods are routinely used for examining theoretical seismic wave propagation through a range of scales on the Earth [1]. This includes their use in determining both shallow subsurface structures, as well as examining the deep interior layers of the planet. Our interest lies in using similar methods to determine appropriate capabilities of hardware for the exploration and seismic probing of the interior of an asteroid similar to analysis performed by Walker, et. al. [2][3]. Asteroids are of particular interest since by nature they are remnents of the original material from the period of planetary accretion of the Solar System. In order to best determine the geologic history of an asteroid, it is important to not only analyze the surface, but also the interior, thus the need for seismic exploration [3].

Approach: We undertake a numerical analysis to provide insight into the minimum number of instruments required for a seismic network on an asteroid. Additionally, the results will provide constraints on the required seismic source sizes and locations in relation to the receiving stations. Source size and location is of importance for several reasons. For one, seismic sensing on an asteroid will require an active source, as the likelyhood of internal seismicity will be unknown. Additionally, in order to minimize the number of receiving stations (possibly to a single location), the location and size of the source will need to be well known in order to properly analyze the results. This is in contrast to a passive seismic array on Earth that is used to determine a seismic event's position and magnitude. These analyses provide an understanding of the geophysics for application to a future mission conducting seismologic studies on asteroids of various consistencies, ranging from a solid body to a rubble pile.

We demonstrate the seismic detectability of various source energies using a one-dimensional model of a layered spherical asteroid using the seismic wave propagaton code GEMINI [4]. This code constructs the Green's Function for the elastodynamic equation of a spherically symmetric model in the frequency domain. The displacement field is expanded into vector spherical harmonics and solved for using an inhomogeneous system of ordinary first-order differential equations. Our version of the code is modified to provide the displacement response of spherical objects at frequencies up to 250-300 Hz. The models consist of a regolith layer overlying solid rock and where warranted, a metal core (**Fig. 1**). Internal structure is constrained by asteroid mass and moment of inertia (where available). All models use low attenuation consistent with the Moon [5], although their one-dimensional geometry cannot fully account for the expected scattering that will occur within the megaregolith of the asteroid [6].

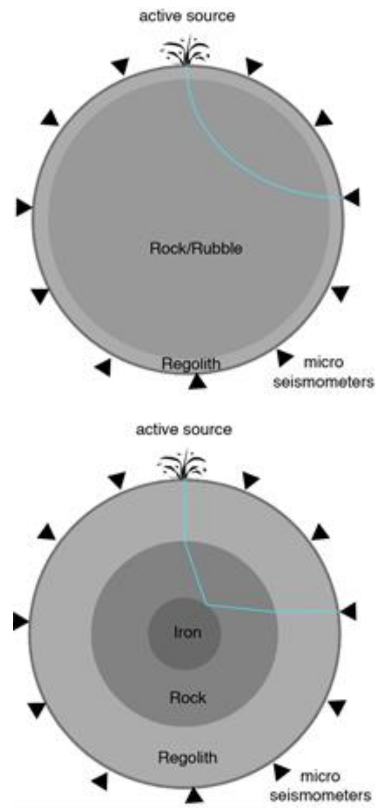

Figure 1. Simplified internal models of range of asteroid compositions used in this study. Seismic energy generated by an active source traverses interior and is recorded by seismometers on the asteroid surface. (upper panel) Homogeneous interior covered by thin layer of regolith. (lower panel) Differentiated model.

We used GEMINI to investigate wave propagation for a 250 m radius layered spherical asteroid (**Fig. 2**). Our results show that a seismic event propagating at frequencies below 1 Hz will create normal modes of the asteroid, which will permit data acquisition via a single receiving station if desired. The required amplitude is expected to be small, on the range of a few microns/second. It is expected that these results will show a requirement for a frequency range that will drive the need for seismic receivers with a response range similar to that found in standard terrestrial geophones. For

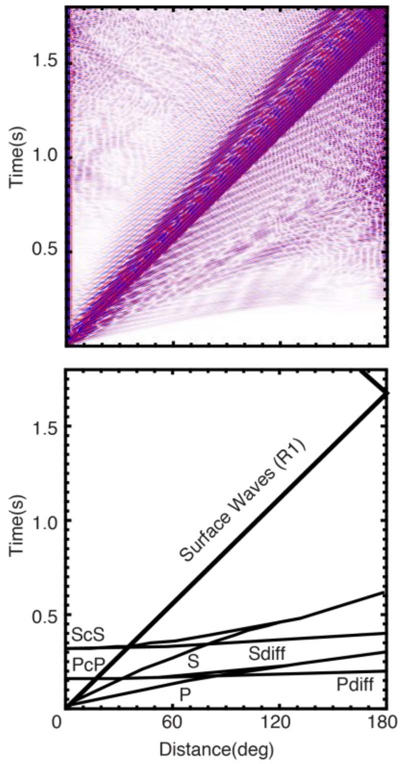

Figure 2. GEMINI computed seismc wavefield inside a 1-D asteroid. (upper panel) Positive amplitudes are red, negative blue. (lower panel) Expected travel times for various seismic phases.

this analysis, a seismic efficiency for the source equivalent to loose soil (1e-5) was used. As for a seismic source, a range of initial options have been examined that assume an impactor of sizes ranging from 0.1 kg to 100 kg, with impact velocities of 2 m/s to 5000 m/s which result in equivalent magnitudes of -7 to +1. For reference, with these parameters, a hammer blow to a metal plate would result in magnitude of -6, or with a higher seismic efficiency of 1e-2, a magnitude -2 seismic event (**Fig. 3**).

Areas of uncertainty in the current analytic analysis include the attenuation of the asteroid, as well as the background noise. It is expected that the attenuation will not be a concern, as highly attenuating mediums on Earth still provide for sensing of a hammer blow at distances of greater than 100 m. The natural background noise of the asteroid though is unknown.

As a follow-on to this one-dimensional analysis, more complex meshes of three-dimensional asteroid models will be created [7]. These will initially be spherical in shape for use as a benchmark against the outputs of the initial one-dimensional codes. Once verifying consistency, between the one-dimensional and three-dimensional models, more complex morphological features, such as fissures, irregular morphologies, and variable regolithic thicknesses will be added to the models to increasingly more realistically approximate actual candidate asteroids.The work will be performed with a finite difference mesh using a spectral-element method (SEM) [8]. Our work will draw from previous finite difference strategies developed by Martin, et. al. for seismic wave propagation in an asteroid [7], as well as numerical methods developed by Nissan-Meyer [9].

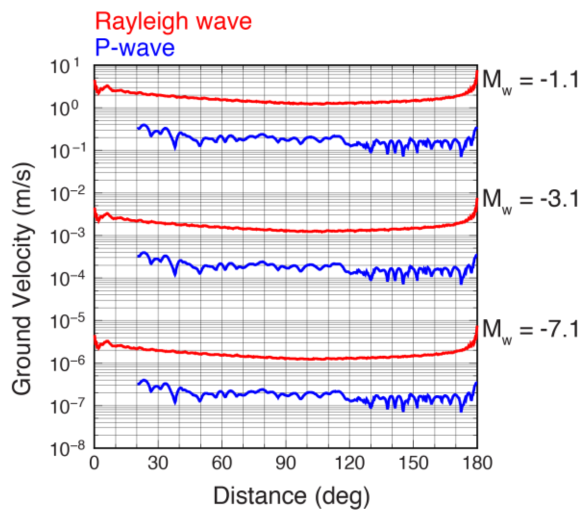

Figure 3. Detectablity of different source magnitudes for a 250 meter diameter asteroid. The absolute amplitude of the Rayleigh wave and P-wave are shown for various source magnitudes.

Conclusion: In conclusion, our initial one-dimensional model shows that it is feasible for a single seismic receiver to be used to detect the seismic waves from an impact source ranging in size from 0.1 kg to 100 kg onto a 250 m radius asteroid. The data collected at this single source can then be used to analyze the interior structure of an asteroid. Additional three-dimensional models will be used to further refine constraints for potential exploration of an asteroid.

References:

[1] Igel, H. *et al.* (2000) *Physics of the Earth and Planetary Interiors* 119, 3. [2] Huang, H. *et al.* (2013) *Applied Physics Letters* 102, Artn 19351210.1063/1.4806983. [3] Walker, J. *et al.* (2006) *Advances in Space Research* 37, pp. 142-152. [4] Friederich, W. *et al.* (1995) *Geophysical Journal International* 122, 537 Doi 10.1111/J.1365-246x.1995.Tb07012.X. [5] Nakamura, Y. *et al.* (1982) *Journal of Geophysical Research* 87, 4855. [6] Dainty, A. M. *et al.* (1974) *Transactions-American Geophysical Union* 55, 362. [7] Martin, R. *et al.* in *Book* (2008) Palma, J. L. *et al.*, Eds. vol. 5336 pp. 350-363. [8] Komatitsch, D. *et al.* (1999) *Geophysical Journal International* 139, 806. [9] Nissen-Meyer, T. *et al.* (2014) *Solid Earth* 5, 425 10.5194/se-5-425-2014.