**INTERFEROMETRIC SEISMIC IMAGING OF ASTEROID 99942 APOPHIS.**
P. Sava[1], E. Asphaug[2], [1]Center for Wave Phenomena, Colorado School of Mines, Golden, CO 80401, psava@mines.edu, [2]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, asphaug@arizona.edu.

**Introduction:** Accurately imaging the interior structures of small planetary bodies, e.g., asteroid 99942 Apophis, is essential for understanding their origin and evolution, their basic compositional properties, as well as for planetary defense if their trajectories bring them dangerously close to Earth. Interior structure is not immediately visible but can be characterized using radar data for dielectric properties, and seismic data for mechanical properties. Combined, these measurements can constrain the key geophysical properties, seismic waves penetrating deeper into rocky materials, and radar allowing global imaging of a cold icy nucleus. Both approaches rely on the existence of a system that emits energy (source), combined with another system (receiver) that records the wave return after its interaction with the body interior. The specific source/receiver configuration determines the cost, risk, and effectiveness of the investigation.

**Seismic receivers:** A key difference is that radar can be done by remote sensing, with source and receiver mounted on the spacecraft (or on Earth, i.e., Arecibo). Conventional seismic investigations require that receivers be deployed and anchored to the surface of an asteroid to capture and record its mechanical behavior. To achieve solid mechanical coupling to the asteroid while providing the necessary processing and communications, landers would be costly and complex.

We advocate monitoring with laser Doppler vibrometers (LDV) as remote sensing seismometers. [1] LDVs are well established instruments that can detect ground motion at arbitrary locations on the asteroid, by measuring Doppler shifts of laser beams reflected off the surface. [2] They are advantageous over conventional seismometers in several ways. They sense ground motion remotely, thus avoiding landing and anchoring. They share the spacecraft power, computing, and comms (no sub-spacecraft necessary). They provide dense global seismic acquisition by pointing and tracking on a boulder or other surface.

**Rendezvous or flyby?** In a rendezvous mission, remote sensing seismology would use high resolution wavefield imaging and other techniques to give a clear picture of an asteroid's interior. Combined with gravity, radar, thermal, and other data and analysis of camera images and composition, the asteroid would become known, for purposes of further scientific exploration and mining, utilization, and hazard mitigation.

A fast flyby mission can be done at much lower cost, and arrive much sooner at an asteroid, comet, or interstellar interloper. Although the time spent within the encounter distance is only about a second, LDV is the only hope of attaining seismology in a flyby.

**Seismic sources:** 3D interior imaging is based on the analysis of seismic data acquired for many source-receiver pairs, on the principle of computer tomography [3]. This requires an active source of energy. In terrestrial seismic imaging, such sources consist of explosions, impactors or vibrators shaking the ground using pre-determined chirps. Such sources are difficult to deploy to a small body with low surface gravity. They require high mass and energy to operate for long durations and are not easily relocatable over time.

For active source seismology of a small body, the only currently known active sources are impactors and explosions. These relatively straightforward devices have their own drawbacks, e.g., could cause hazards to the deploying spacecraft by dislocating surface materials. They also would be finite in number and thus capable of assembling only several source-receiver pairs, insufficient for high resolution 3D imaging.

**Seismic interferometry:** An alternative to active-source seismic imaging exploits the principles of seismic interferometry. [4] A powerful feature of this method is that it can retrieve the seismic response (Green's functions) between two points in a medium through cross-correlation of the noise recorded at these points, i.e., using signals caused by noise sources in the medium. This property holds in arbitrary 3D media, provided that random and uncorrelated noise sources surround the two points in-between which the Green's functions are evaluated. The method has many alternative formulations, e.g., by replacing cross-correlation with deconvolution, and has been applied in many science fields, including seismology. [5]

Seismic interferometry is ideally suited for imaging asteroid interiors for several reasons:

- Asteroids exhibit natural seismicity [6], possibly due to differential heating, or micro-meteorite impacts; asteroid 99942 Apophis would feel tidal effects at the time of its closest encounter with Earth.
- Natural seismic sources that may exist are likely widespread and could safely be assumed to be random and uncorrelated. Such source diversity is a feature for seismic interferometry, rather than a drawback as it would be the case for conventional seismology.
- Seismic waves generated at random locations could bounce multiple times from its surface, thus further increasing the diversity (origin time, propagation direction, etc.) of waves in its interior.

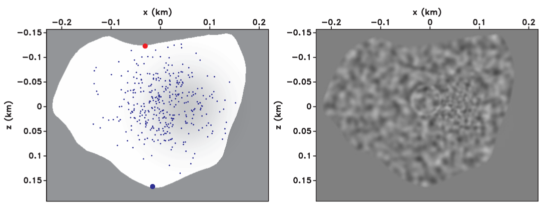


**Figure 1:** Model of asteroid 99942 Apophis indicating the positions of simulated random seismic sources (left) and the corresponding random wavefield (right).

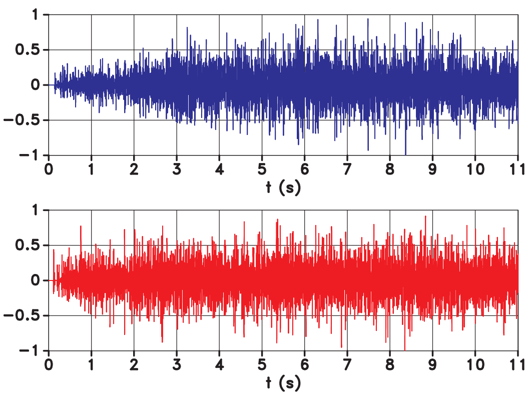


**Figure 2:** Seismic noise observed remotely by mobile LDVs at two locations (red and blue in Figure 1).

Figure 1 illustrates this idea with a model reflecting the current best estimate of the shape of Apophis [7]. The small blue dots reflect randomly distributed seismic sources in its interior. In the simulation, we generate waves of random frequencies at random times, and with random amplitudes. After superposition and repeated bounces off the exterior asteroid surface, the wavefield is essentially random and does not reflect any identifiable seismic phase.

Using two mobile LDVs sensing motion remotely from opposite sides of the asteroid (red and blue dots in Figure 1), we would recover noise seismograms as shown in Figure 2. These recordings are done from LDVs that move at slow speed (10cm/s) comparable with the relative motion of spacecraft like OsirisREX [8]. Thus, the acquisition points where the LDV laser beam hit the surface also translate during acquisition.

Following the logic of seismic interferometry [9], the cross-correlation between the noise recordings in Figure 2 yields the time series in Figure 3 (top) depicting multiple seismic phases, of which the strongest correlates in time and phase with what one would obtain by direct modeling between, Figure 3 (bottom).

**Seismic tomography**: The seismic pulses recovered using seismic interferometry already contain important information, of which the propagation time is the most readily available. However, more advanced processing is possible on data thus recovered without an active seismic source, i.e., we could use these seismograms to construct so-called sensitivity kernels (bandlimited rays). These kernels describe the model sensitivity to data perturbations and form the basis for seismic tomography [9]. Figure 4 shows the sensitivity kernels connecting the observation points (Figure 1) starting from seismic data modeled or recovered using seismic interferometry from noise observations recorded using remote sensing seismometers (Figure 3).

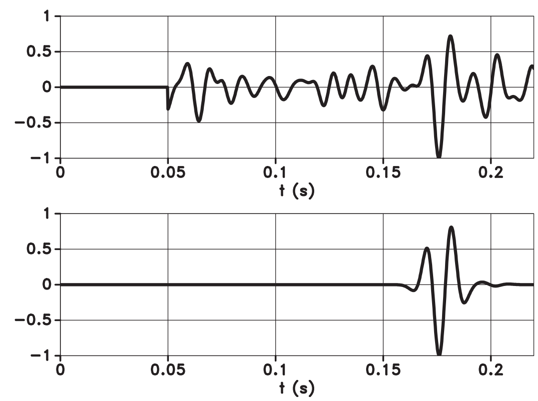


**Figure 3:** Seismic data reconstructed from seismic noise (top) relative to seismic data modeled directly (bottom).

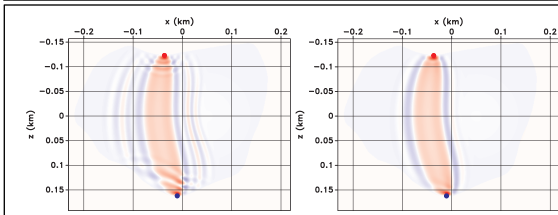


**Figure 4:** Sensitivity kernels constructed from reconstructed (left) and modeled (right) seismic data.

**Conclusions**: The interior structure of asteroids can be imaged using data acquired remotely using LDVs that function as remote sensing seismometers. In the case of natural sources, seismic imaging could provide the foundation for data recovery using seismic interferometry. This technique relies on the presence of many (large and small) random sources that do not need to be known. The diversity of sources leads to randomness of seismic waves that is enhanced by (potentially) multiple bounces off the exterior surface of the asteroid. These data acquired in motion at many locations over the asteroid body open the possibility for unprecedented high resolution interior imaging using state-of-the-art seismic tomography techniques.

**References:** [1] Sava P. & Asphaug E. (2019) *Adv. Space Res. 64,* 527-544. [2] Donges A. & Noll R. (2015) *Springer*. [3] Nolet, G. (2008), *Cambridge*. [4] Wapenaar, K. et al., (2008), *SEG Reprints Series*. [5] Snieder, R. & Larose, E., (2013), *Ann. Rev. Earth Planet Sci*. [6] Lauretta, D. et al., (2019), *Science*. [7] Brozovic, M. et al., (2018), *Icarus*. [8] Lauretta, D. et al., (2019), *Nature*. [9] Tromp, J. et al., (2010), *Geoph. J. Int*.