INTERFEROMETRIC SEISMIC IMAGING OF ASTEROID 99942 APOPHIS. P. Sava¹, E. Asphaug²,
¹Center for Wave Phenomena, Colorado School of Mines, Golden, CO 80401, psava@mines.edu, ²Lunar 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.
Seismic interferometry is a technique that allows the reconstruction of seismic data from noise observations recorded using mobile LDVs as remote sensing seismometers. Through the combination of noise recordings from multiple LDVs, it is possible to recover seismic data that would otherwise be lost due to noise. The cross-correlation between the noise recordings 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 the observation points (Figure 1) starting from seismic data modeled or recovered using seismic interferometry from noise observations recorded using mobile LDVs (Figure 3).

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 imaging using state-of-the-art seismic tomography techniques.