REMOTE SEISMIC IMAGING OF ASTEROID 99942 APOPHIS. N. Dorogy[1], P. Sava[2], [1]Center for Wave Phenomena, Colorado School of Mines, Golden, CO 80401, ndorogy@mines.edu, [2]Center for Wave Phenomena, Colorado School of Mines, Golden, CO 80401, psava@mines.edu.

Introduction: A comprehensive understanding of small planetary bodies, such as asteroid 99942 Apophis, is paramount in discerning the evolution of the solar system, ensuring planetary defense, and supporting human exploration. Information about the subsurface can provide evidence about planetary formation and thus validate theories for early solar system coalescence and subsequent evolution. Knowledge of the interior structure and mechanical composition is also needed to deflect the trajectory of dangerous near-Earth objects. For detailed, high-resolution interior imaging, the two most promising geophysical sensing techniques are radar and seismic. Ground penetrating radar combines well with spectral imagery of the surface but struggles to penetrate through rocky or conductive materials. Seismic waves however excel in probing rocky and icy interior structures. Thus, a dedicated seismic exploration instrument can constrain key geophysical properties that might otherwise be unattainable.

Seismic investigation: Traditionally, the most significant complication of seismic exploration is the need for receivers to be anchored onto the surface to record seismicity. Anchoring onto microgravity bodies is both complex and risky, while the necessary processing, communications, and attitude control introduce further challenges for mission planning. Instead of landing instrumentation, we propose the use of laser Doppler vibrometers (LDV) to act as remote sensing seismometers [1]. LDVs are a well-established technology used in a variety of commercial applications across a broad range of industries [2]. By measuring the Doppler shift of a laser beam reflected from the surface of an object, we record the displacement of the ground, which is equivalent to the measurements taken by conventional geophones. Aside from the main benefit of measuring seismic activity remotely, LDV technology holds several key advantages over conventional seismometers. The required instrumentation would be capable of sharing preexisting spacecraft power, computing, and communications subsystems so that no additional spacecraft hardware would be necessary. Moreover, this approach would provide dense spatial resolution of the target body by continuously observing the surface over many orbits. If sufficient seismic sources were present, we could then produce a 3D tomographic image of the asteroid interior.

Seismic sources: Tomographic inversion requires many source-receiver pairs to reliably reconstruct an interior image of the target [3]. In terrestrial seismic imaging, active sources (explosives, impactors, or vibrators) are used as controlled sources with predetermined behaviors. However, such sources are difficult and dangerous to deploy to a small body with low surface gravity. The only currently plausible active sources, kinetic impactors and explosive charges, are straight forward to use but would produce ejecta material that could strike the orbiting spacecraft and thus increase mission risk. Moreover, active sources would introduce additional mass requirements and would be finite in number thus limiting the source-receiver pairings needed for high resolution imaging.

Seismic interferometry: An alternative to active-source seismic imaging is seismic interferometry. This method can be used to extract the seismic response between *two or more* receivers using many uncontrolled sources randomly distributed around the studied body, avoiding the need to determine the exact source waveform and location. Terrestrial seismic interferometry is a well-studied technique with numerous theoretical and practical demonstrations [4]. The underlying principle makes use of the fact that random seismic noise can be cross-correlated to obtain signals resembling active source wavefields propagating between two or more receivers [5]. This property holds in arbitrary 3D media if random and uncorrelated noise sources encircle the receivers used for interferometry. In addition, the source distribution requirement would not change even for mobile receivers (e.g., LDV's on an orbiting spacecraft). If we assume that random sources were distributed uniformly throughout the target, there would be sufficient coverage to fully illuminate the subsurface between the receivers. Figure 1 (left) displays the idealized source distribution requirement for two stationary receivers. The red and blue lines indicate the position of two receivers at different times (the vertical axis), while the green dots represent random (noise) sources. We observe that for stationary receivers, the source distribution requirement remains unchanged

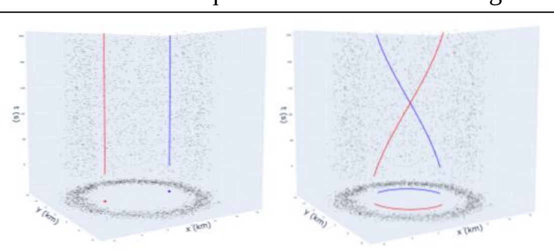

Figure 1: Idealized source distribution required for seismic interferometry between two stationary receivers (left) and two mobile receivers (right).

through time. Figure 1 (right) also shows two receivers denoted by red and blue lines that are now in circular motion (e.g., LDVs sampling the seismic wavefields at different locations at the asteroid surface). We note that the source distribution requirement does not change because the uniform illumination requirement covers all azimuths. Under these conditions, conventional geophysical tomography can be performed to determine the 3D internal structure of the object using remote seismic sensing.

Seismic interferometry is ideally suited for imaging asteroid interiors. Recent investigation suggests that noisy activity is abundant on small bodies possibly due to thermal gradients, micro-meteorite impacts, and tidal forces [6]. Asteroid 99942 Apophis might also experience strong tidal variations during its transit by Earth [7]. Such natural sources would likely be distributed uniformly across the body, and we could assume these sources to be random and uncorrelated. This source diversity is an important benefit for seismic interferometry, rather than a drawback as commonly viewed by conventional seismology. Moreover, seismic waves generated at random locations could experience multiple reflections within the asteroid, thus improving the diversity in origin time, propagation direction, source waveform, and wave path coverage.

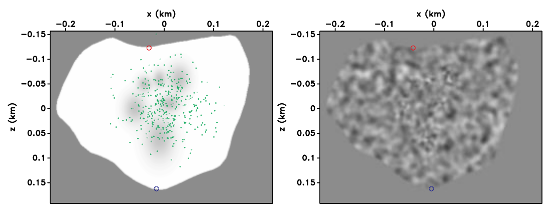

Figure 2: Model of asteroid 99942 Apophis with simulated receivers and random seismic sources (left) and the corresponding random wavefield (right).

Figure 2 illustrates the concept of remote seismic imaging with a model of asteroid 99942 Apophis [7]. Small blue dots represent randomly distributed seismic sources inside the asteroid. In our simulation, waves of random frequencies are generated at random times, and with random amplitudes. After superposition and repeated bounces off the surface of the asteroid, the wavefield becomes incoherent. Localized density contrasts within the asteroid mimic the effect of several large boulders. We also introduce uniform exponential attenuation to simulate damping in a poorly consolidated micro-gravity body.

By deploying two mobile LDVs recording surface motion remotely from opposite sides of the asteroid (red and blue dots in Figure 2), we can recover the noise seismograms as shown in Figure 3. The LDVs in this experiment move in opposite directions at slow speed (10 cm/s) realistic for the relative motion of spacecrafts around a rotating body [8].

In seismic interferometry [9], the cross-correlation between the noise recordings in Figure 3 yields the time series in Figure 4 (top) depicting a complex waveform in which the strongest response correlates in time and phase with the direct arrival modeled between the two receivers as shown in Figure 4 (bottom).

Conclusions: The interior structure of asteroids can be reconstructed using data recorded by LDVs that function as remote sensing seismometers. If natural sources are present in the asteroid, the acquired data could be sufficient to fully image the subsurface using seismic interferometry. This technique is dependent on the presence of numerous random sources that need not be known. This diversity of sources would lead to a distribution of seismic waves enhanced by multiple reflections off the surface of the asteroid. The data acquired at many locations over the asteroid body open the possibility for unprecedented, high resolution interior imaging using seismic tomography techniques.

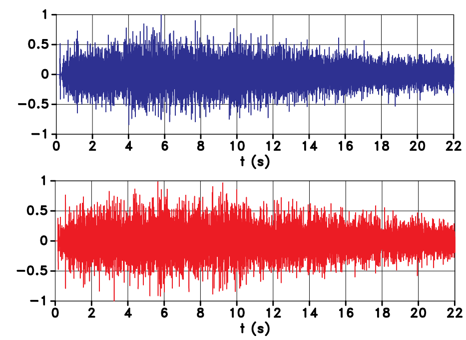

Figure 3: Seismic noise recorded remotely by the mobile LDVs at two locations (red and blue in Figure 1).

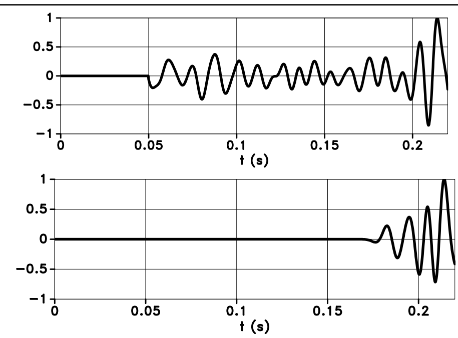

Figure 4: Seismic data reconstructed from seismic noise (top) relative to seismic data modeled directly (bottom).

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