ORBITAL SEISMOLOGY BY LASER DOPPLER VIBROMETRY. 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@lpl.arizona.edu.

Introduction: The interior structure of small planetary bodies holds clues about their origin and evolution, from which we can derive an understanding of the solar system formation. Structure can be evaluated indirectly from surface observations, e.g. that asteroid Itokawa is a rubble pile [1] or that comet 67P/Churyumov-Gerasimenko (67P/C-G) is a primordial agglomeration of cometesimals [2]. These inferences can shape ideas about how the solar system is formed, e.g. quiescently or violently, and how small bodies such as near-Earth asteroids respond to collisions. Imaging the interior structure of small bodies is also driven by practical considerations, i.e. to deflect hazardous NEOs.

High resolution geophysical imaging of small bodies can use either radar waves for dielectric properties, or seismic waves for elastic properties. Radar investigation is efficiently done from orbiters, but conventional seismic investigation requires landed instruments (seismometers, geophones) mechanically coupled to the body. However, radar waves cannot always penetrate deep in the interior of a small body, unlike seismic waves. It is thus necessary to develop low-cost missions to investigate seismologically the internal structure without landed operations.

Good understanding of the interior structure of a small planetary body requires observations from multiple directions, as in medical tomography. 3D seismic imaging is well-developed in terrestrial environments and takes advantage of two main opportunities: instruments are coupled to the ground, and seismometers form dense networks (antennas). Neither condition can be satisfied with conventional instruments on a small planetary body. Various mission concepts emplace seismometers on the surface. Anchoring a seismology package to a small body requires robust technology that does not yet exist. The complexity of a landed package raises the cost of a mission and increases its risk. Strong seismic waves may even dislodge the payload from the surface. These challenges led to complex methods for embedding seismic payloads on a small body, with large thermal, power, mechanical and communications issues.

Vibrometry: Our proposed method [3] removes the need for instrument surface deployment by employing Laser Doppler Vibrometers (LDV). LDV send a laser beam to a moving target (e.g. the ground surface) and observe the Doppler frequency shift of the reflected laser beam caused by motion of the ground. LDVs used as seismometers have many technical advantages over conventional landed seismometers: (1) take measurements from orbit, thus avoiding expensive landers; (2) do not use mechanical ground coupling, thus avoiding anchors; (3) have simple electronic design, without fragile mechanical components; (4) are mobile and can measure ground motion at distributed locations; (5) utilize stable orbital platforms that are decoupled from ground noise. These benefits simplify the design and execution of a remote seismology mission, while providing data with wide spatial coverage capable to image in detail the 3D internal structure of small bodies.

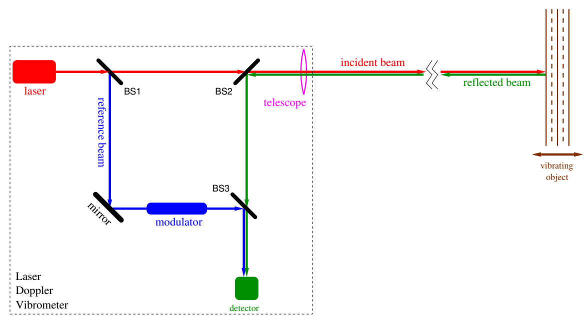

Figure 1: Key components of a laser Doppler vibrometer system: laser (red), modulator (blue), detector (green), telescope (magenta), beam splitters and mirrors (black).

Laser Doppler vibrometers use the Doppler principle [4] and do not rely on mechanical components whose performance might degrade over time, and consist of components already used in space missions (Figure 1). A laser beam of known wavelength is split into reference and incident beams. The incident beam is focused using a telescope on a distant vibrating surface of a small body. The reflected beam (green), has a different frequency as a result of the Doppler effect caused by ground motion. The frequency shift is proportional with the velocity of the ground in the direction of the laser beam. The reference and reflected laser beams are combined to form a composite signal with frequency modulated by the mismatch between their frequencies.

Acquisition: Many seismic acquisition configurations are possible, using the orbital LDV mobility. Acquisition of vector ground motion is possible with multiple (e.g. three) coordinated LDVs investigating the same point on the surface at different times.

We assume small bodies spinning around an axis that defines their polar direction (Figure 2). Acquisition can be done from spacecraft moving slowly in polar orbits, in a similar concept of data acquisition as a global radar investigation [5]. In a reference frame relative to the small body, the spacecraft follow helical trajectories, thus allowing LDVs to sample multiple locations around the body over time. The density of spacecraft vantage points depends on the acquisition duration and rotation period of the body. For orbiter periods that do not match the small body period, the trajectories do not repeat, and sampling density progressively increases.

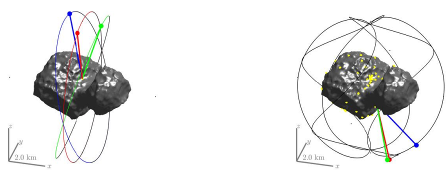

Figure 2: (left) Orbital acquisition of ground velocity using three coordinated spacecraft in (tilted) polar orbits. (right) Configuration of the LDV system in small-body coordinates; the yellow dots show all ground points sampled previously.

Imaging: Two special features facilitate seismology on a small body: (1) We can assume that the exterior shape of the studied object is known with high accuracy. Such information can be obtained from photogrammetry [6]. (2) Seismic waves are confined to the small body interior reverberate for a long time, possibly tens of minutes [7], and traverse the object in many different directions, while reflecting on the known exterior boundary. Known strong reflectors, i.e. the shape boundary, provide rear-view mirrors that can constrain physical properties in the body interior [8,9]. Highly irregular objects benefit imaging, since multiple reflections on its boundary traverse the body on many and progressively diverse paths, similarly to how multiple views generate high-resolution medical images.

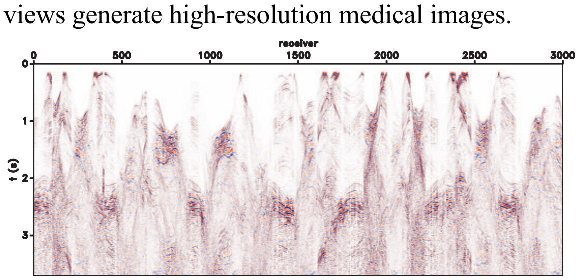

Figure 3: Seismic wavefields observed at the surface of the small body. Data from a subset of the LDV observation points are shown, for clarity. Data from many other acquisition points are available for imaging, but not shown in this figure.

Wavefield imaging produces a representation of physical properties and can be separated in two main categories: (1) Tomography, a technique designed to infer volumetric properties, e.g. the seismic velocity, at every location in the small body interior. (2) Migration, a technique designed to infer interface properties, e.g. the regions of high contrast between different physical properties. These techniques work in tandem, i.e. information providing by one improves the accuracy of the other. We use reverse time migration [10,11,12] which is a state-of-the-art imaging method that exploits known principles of time-reversal [13]. Figures 3 and 4 illustrate the imaging potential provided by dense seismic acquisition using LDVs: data simulating repeated activation of internal faults and acquired at the surface of a small body modeled after comet 67P/C-G (Figure 3) are imaged at high resolution using time reversal (Figure 4).

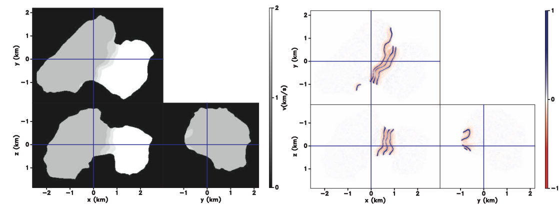

Figure 4: (left) Velocity model based on the shape of comet 67P/C-G. (right) Seismic image obtained by high resolution time-reversed imaging. Imaging uses LDV data acquired at all points sampled using the strategy depicted in Figure 2.

Conclusions: Laser Doppler vibrometers can effectively record (vector) ground motion of a small body surface. They are advantageous over conventional seismometer acquisition because they: (1) measure ground motion from orbit; (2) do not require landing and anchoring; (3) do not use mechanical components; (4) are mobile and can relocate around the body; (5) operate from stable and robust orbital platforms. Seismology from a remote sensing platform enables a new class of geophysics missions that avoid the complexity and mass of landed payloads on small bodies and can facilitate detailed 3D seismic imaging of their internal structure. Dense global seismic acquisition enables imaging by high resolution wavefield migration and tomography.

Acknowledgment: This work was supported by the NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program (NNH16ZDA001N).

References: [1] Fujiwara A. et al (2006), *Science 312, 1330-1334.* [2] Massironi M. et al (2015), *Nature 526, 402-405.* [3] Sava P. & Asphaug E. (2019) *Adv. Space Res., in review*. [4] Donges A. & Noll R. (2015) *Springer*. [5] Safaeinili A. et al. (2002) *Meteor. & Planet. Sci., 37*, 1953-1963. [6] Preusker F. et al (2015), *Astron. & Astroph., 583, A33.* [7] Walker J. et al., *Adv. Space Res. v. 37.* [8] Sava P. & Asphaug E. (2018) *Adv. Space Res. v. 61, 2198-2213.* [9] Sava P. & Asphaug E. (2018) *Adv. Space Res. v. 62 1146-1164.* [10] Baysal E. et al (1983), *Geophysics, 48, 1514-1524.* [11] Lailly P. (1983), *Proc. Conf. Inv. Scat. 206-220.* [12] McMechan G. (1983), *Geoph. Prosp. 31, 413-420.* [13] Fink M. (2002), *Springer.*