Orbital seismology by laser Doppler vibrometry

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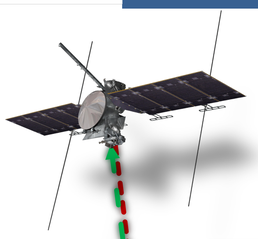

Orbital LDVs observe small body surface from distances of several km.

No component of the LDV system lands, thus reducing the complexity and increasing the robustness of the seismic acquisition system

The orbital platform is ideal for LDVs because it is **vibration-free** and projects the laser beam through **scatter-free** vacuum.

The sensing distance depends on the laser power, and the telescope size.

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. High resolution interior 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.

A 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.

Our method removes the need for instrument surface deployment by employing **Laser Doppler Vibrometers.** LDVs can effectively record ground motion of a small body surface and are advantageous over conventional seismometers 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 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 imaging developed in the context of terrestrial seismology**.** *Migration* identifies and positions the interior reflectors by time reversal. *Tomography* constrains the elastic properties in-between the interfaces. These techniques benefit from dense data acquired by the LDV system at the surface, and from knowledge of small body shape. In both cases, a complex body shape, such as a comet or asteroid, contributes to increased wave-path diversity in its interior, and leads to high (sub-wavelength) imaging resolution.

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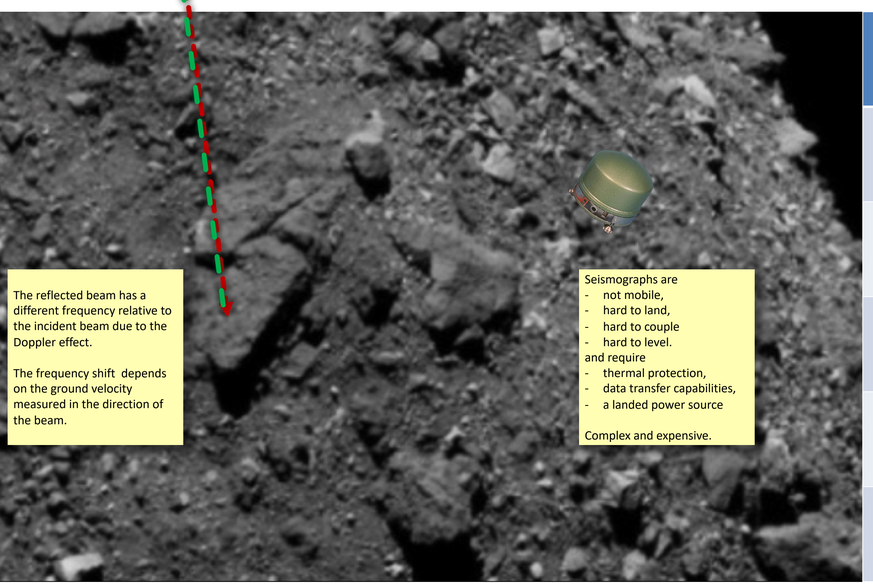


The reflected beam has a different frequency relative to the incident beam due to the Doppler effect.

The frequency shift depends on the ground velocity measured in the direction of the beam.

Seismographs are
- not mobile,
- hard to land,
- hard to couple
- hard to level.

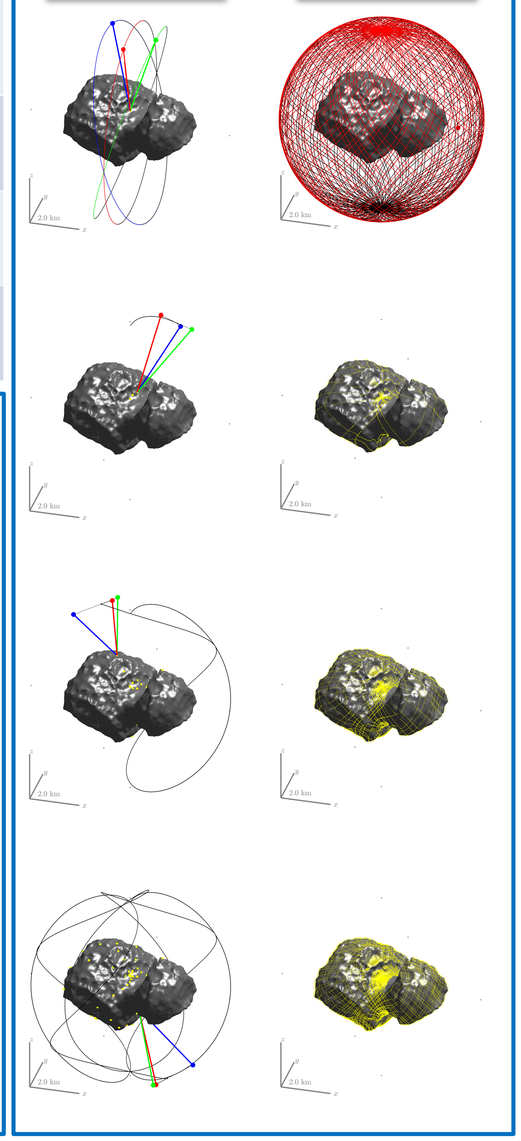
and require
- thermal protection,
- data transfer capabilities,
- a landed power source

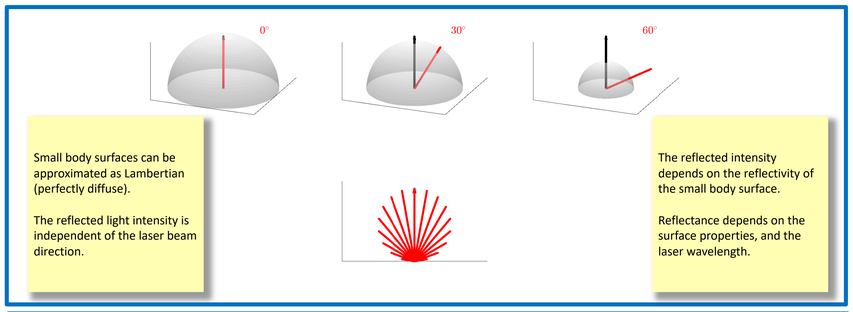
Complex and expensive.

	Seismograph	Laser Doppler Vibrometer
Landing	Difficult and requires expensive and complex operations; disrupts surface and orbiter.	Not needed.
Coupling	Difficult on rough surfaces; requires complex anchoring in micro-g environments; requires leveling.	Not needed.
Mobility	Not possible without complex, costly and risky near-surface maneuvers.	Full body coverage from orbiter.
Protection	Environment protection (thermal, radiation) increases complexity of landed instrument.	Provided by orbiter.
Power	Communications and operations increases the size and complexity of the lander.	Provided by orbiter.

Multiple spacecraft can observe the same spot on the ground from different directions. The 3 observations provide vector ground motion.

LDV orbiters follow helical trajectories relative to the body, thus providing view points that progressively cover the entire small body.



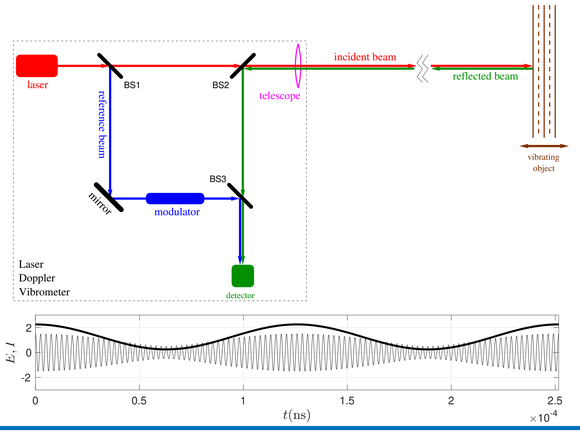


Small body surfaces can be approximated as Lambertian (perfectly diffuse).

The reflected light intensity is independent of the laser beam direction.

The reflected intensity depends on the reflectivity of the small body surface.

Reflectance depends on the surface properties, and the laser wavelength.



A laser beam is split into a reference and an incident beam, which is focused on a distant vibrating surface.

The reflected beam has a different frequency due to the Doppler effect.

The reference and reflected laser beams combine to form a composite signal with frequency modulated by the mismatch between their frequencies.

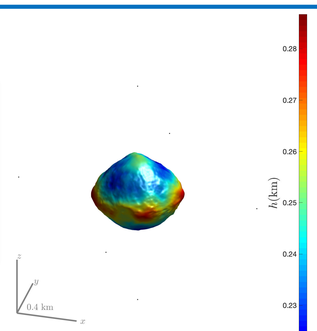
The modulated frequency is proportional with the ground velocity.

Bennu

Mean radius: 250m

Seismicity:
natural, unknown source

Altitude: ~1km

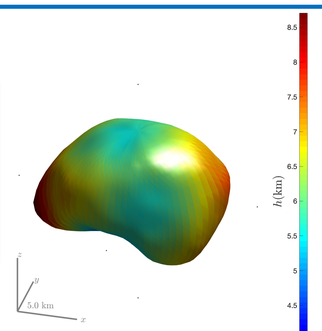


Deimos

Mean radius: 6km

Seismicity:
natural from Mars tides

Altitude: ~2km

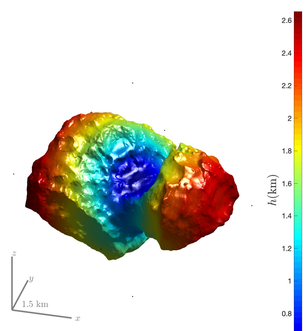


67P/CG

Mean radius: 2km

Seismicity:
natural from vents

Altitude: ~2km

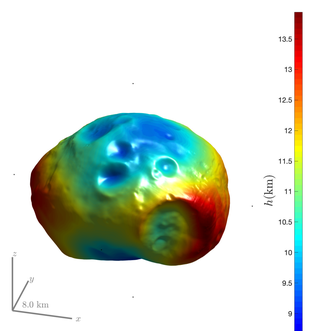


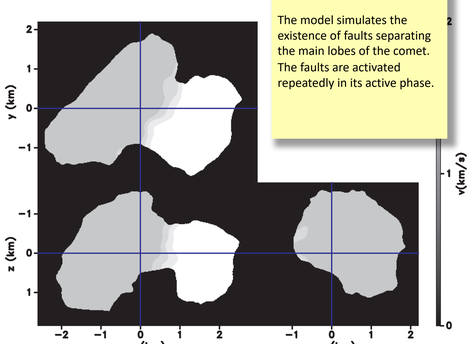
Phobos

Mean radius: 11km

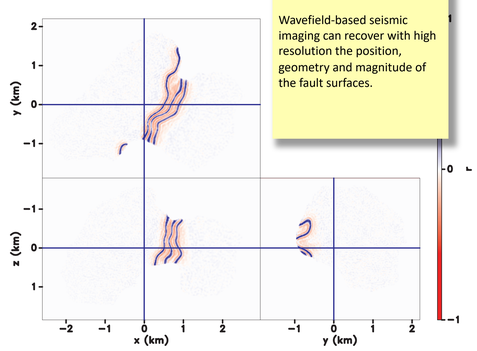
Seismicity:
natural from Mars tides

Altitude: ~5km

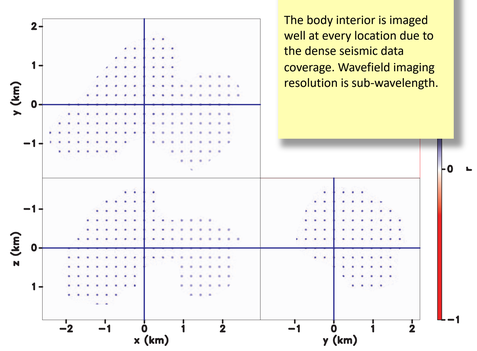




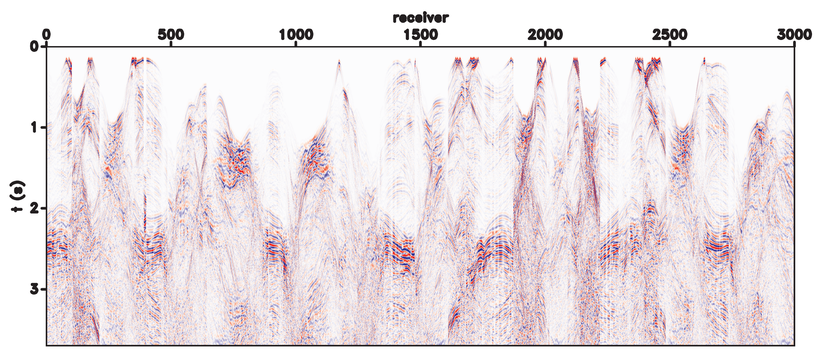
The model simulates the existence of faults separating the main lobes of the comet. The faults are activated repeatedly in its active phase.



Wavefield-based seismic imaging can recover with high resolution the position, geometry and magnitude of the fault surfaces.



The body interior is imaged well at every location due to the dense seismic data coverage. Wavefield imaging resolution is sub-wavelength.



Orbital LDV seismic acquisition generates dense data as a function of position around the small body.

The observed data are impossible to interpret without imaging, due to the complex body shape and interior parameters.