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# Remote seismic exploration of small planetary bodies

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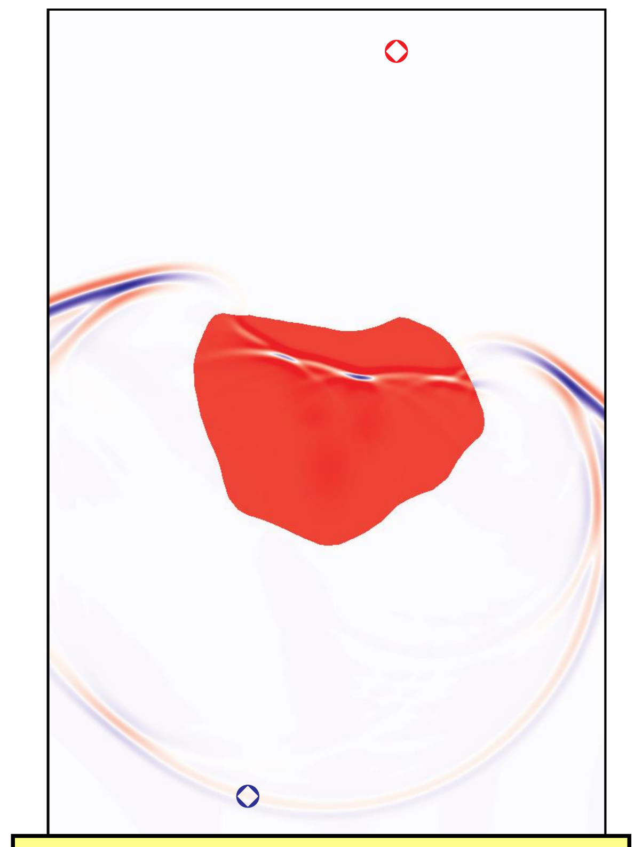
## ① Remote sensing seismology (RSS)

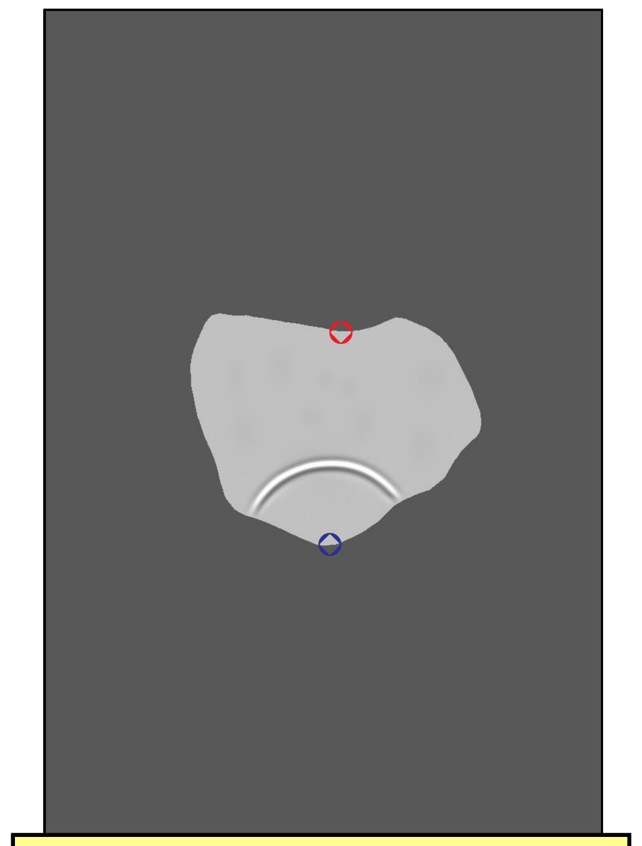
Small planetary bodies (i.e., moons, asteroids, comets) are critical in understanding solar system evolution, developing planetary defense strategies, and supporting human exploration. Landed exploration mission designs are extremely limited due to microgravity conditions and the threat of debris. Remote observations are key to probing the subsurface of small bodies.

**Remote radar**



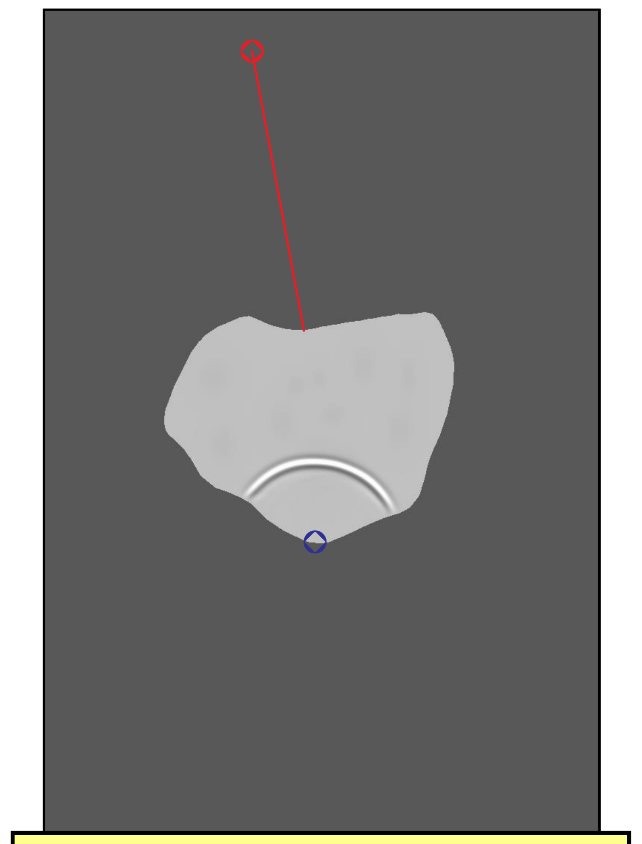
Bistatic radar mission concept around Asteroid Apophis.

**Landed seismic**



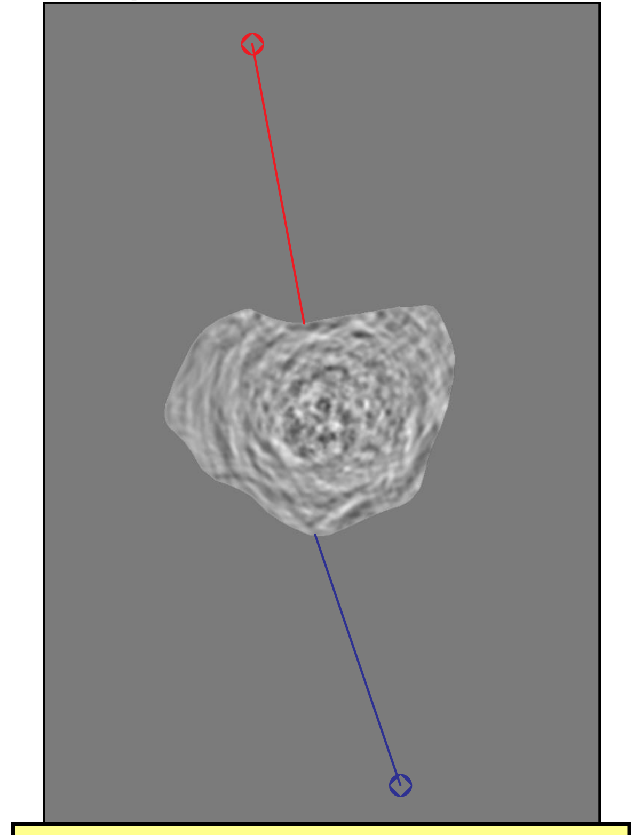
Conventional seismic with landed sources & receivers.

**Semi-remote seismic**



1 LDV design using an active source to create seismic activity.

**Fully remote seismic**



2+ LDV mission design using ambient seismicity.

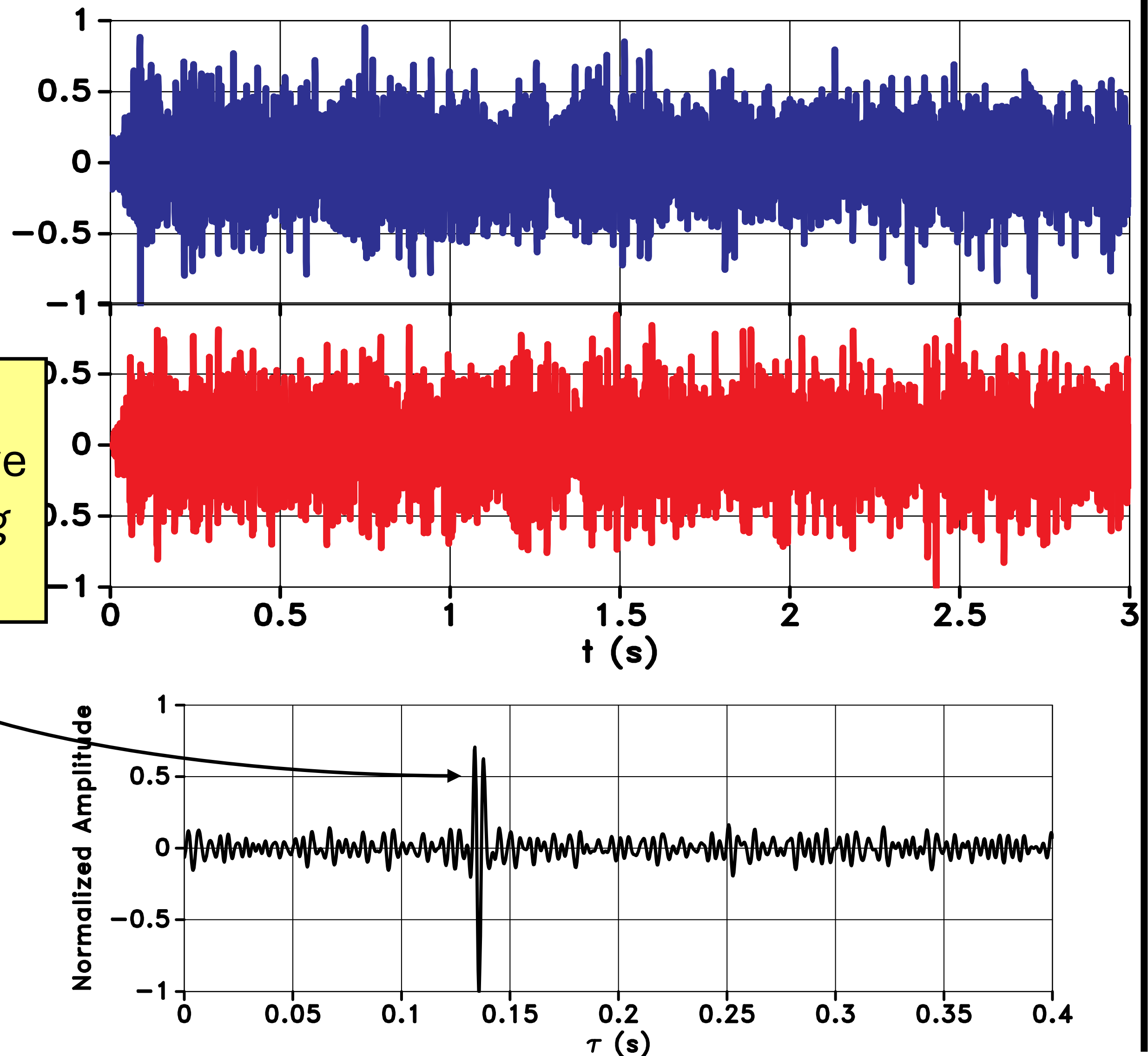
The two most promising methods of subsurface exploration are radar & seismic. Attenuation through radar scattering can severely limit penetration depths, while seismic waves penetrate deep into the interior. Normal seismic surveys assume landed geophones but this is challenging (microgravity, anchoring, receiver uplift, debris fields, limited illumination). **Here, we propose a fully remote method of seismic investigation that enables wavefield imaging of small body interiors without the need for active sources.**

## ② Remote Sensing Seismology (RSS) by laser Doppler vibrometry (LDV)

LDVs measure frequency shift in a reflected laser. **The shift of the reflected beam is proportional to the velocity of surface motion, thus recording the seismic wavefield** [1].

## ③ Ambient noise seismic interferometry (SI)

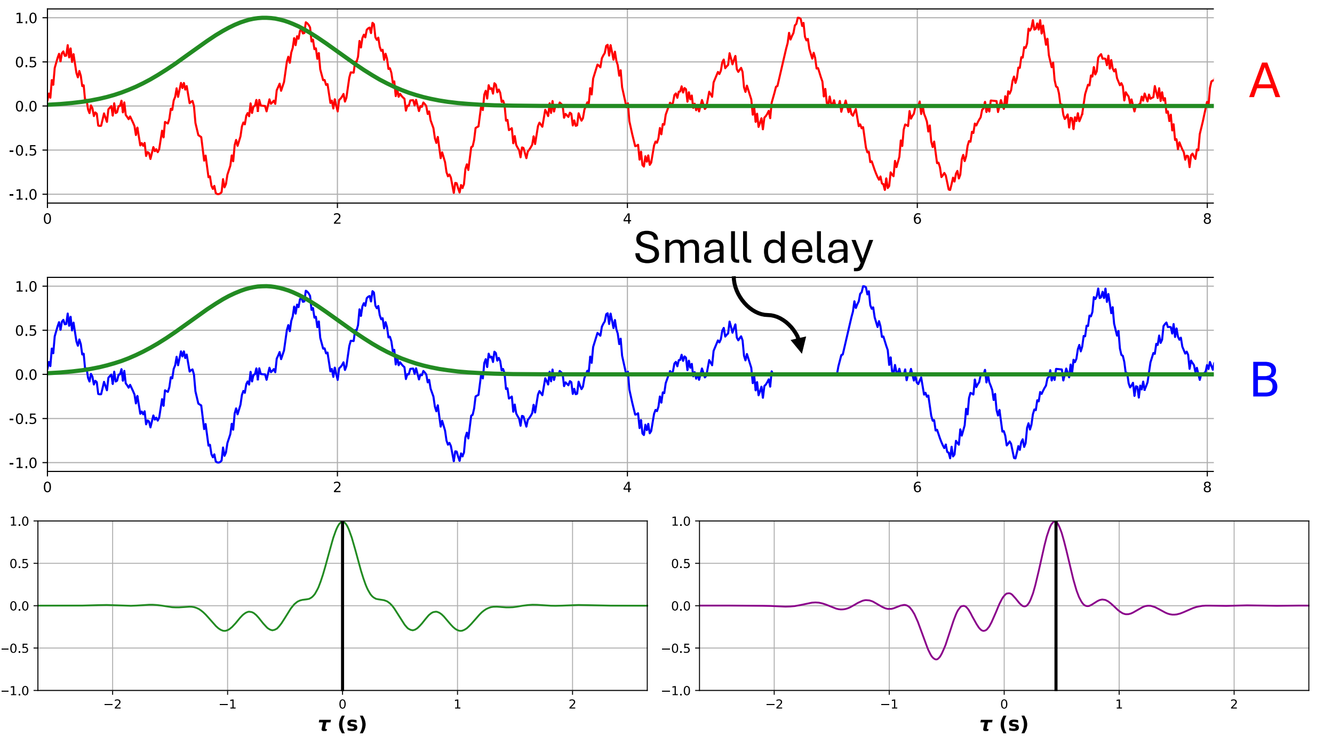
Seismic interferometry uses natural seismicity to estimate the travel time between the "virtual" source and receiver locations, thereby enabling travel time tomography [**2**].



Ambient seismic noise recorded by two receivers (**top** & **middle**). By cross-correlating these observations, we *recover the* *travel time* (**bottom**) *for the wave travelling directly between the receivers.*

## References

[1] Scruby, C.B. and Drain, L.E. (1990). *Laser Ultrasonics: Techniques and Applications*. Bristol: Adam Hilger. [2] K. Wapenaar, et al. (2010). Tutorial on seismic interferometry: Part 1-Basic principles and applications. *Geophysics,* 75, 195-209. [3] Hale, D. (2006). An efficient method for computing local cross-correlations of multi-dimensional signals. *Technical Report Center for Wave Phenomena*, Colorado School of Mines. [4] Brozović, M., et al. (2018). Goldstone and Arecibo radar observations of (99942) Apophis in 2012–2013. *Icarus*, 300, 115-128.



Local correlation highlights *changing travel times*. Here, identical signals (A & B) have a small delay. **Green** is lag before shifting and **purple** is lag after.

## ④ *Local* cross-correlation

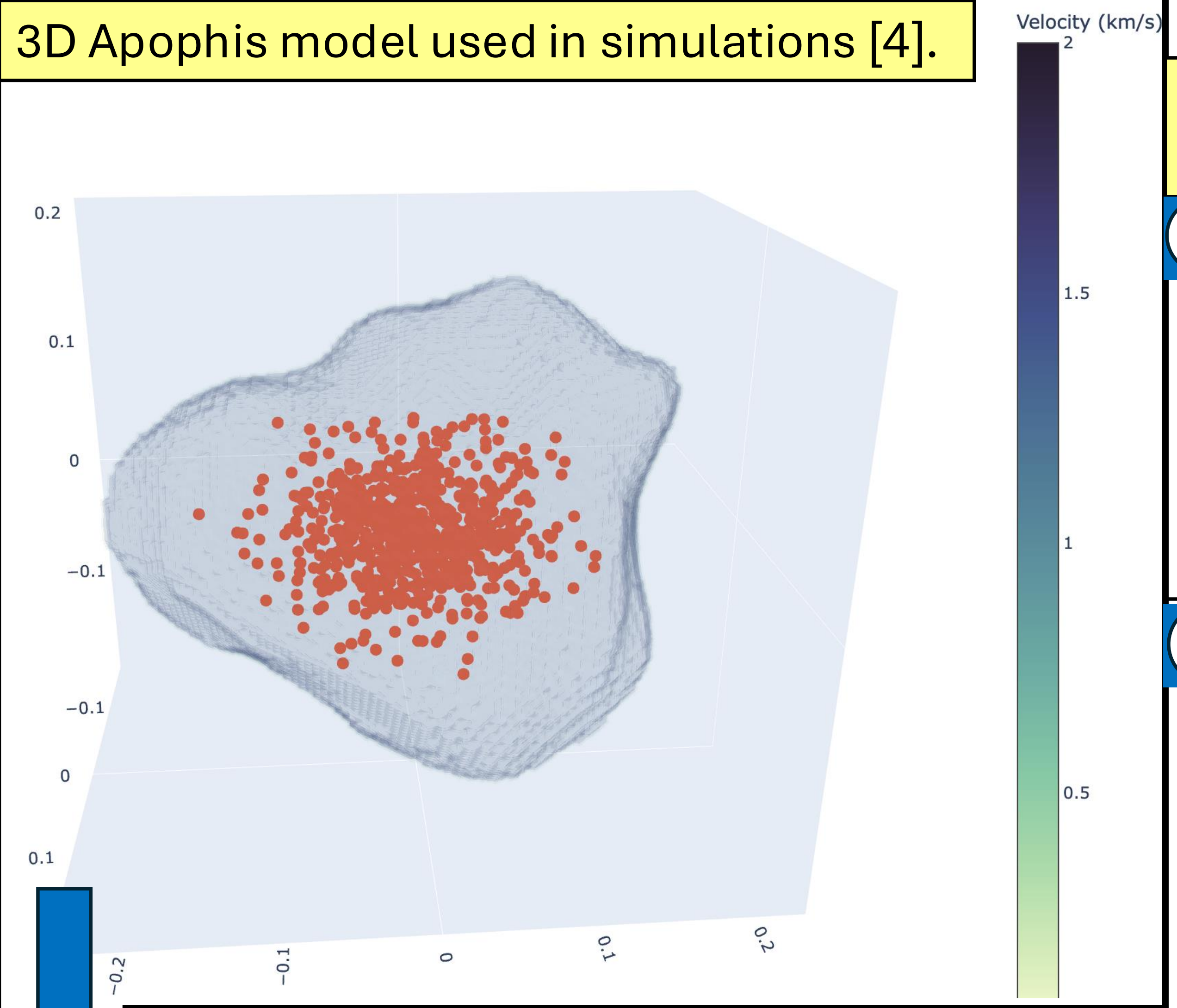
Because receivers orbit, we use *local* cross-correlations [3] to observe how the time lag *changes as a function of time.*

$$c(\tau) = \int_0^{\gamma}\int_0^{t} S(t)u_A(t-{}^{\tau}/_{2})u_B(t+{}^{\tau}/_{2})g(\gamma-t;\tau)\,dt\,d\gamma$$

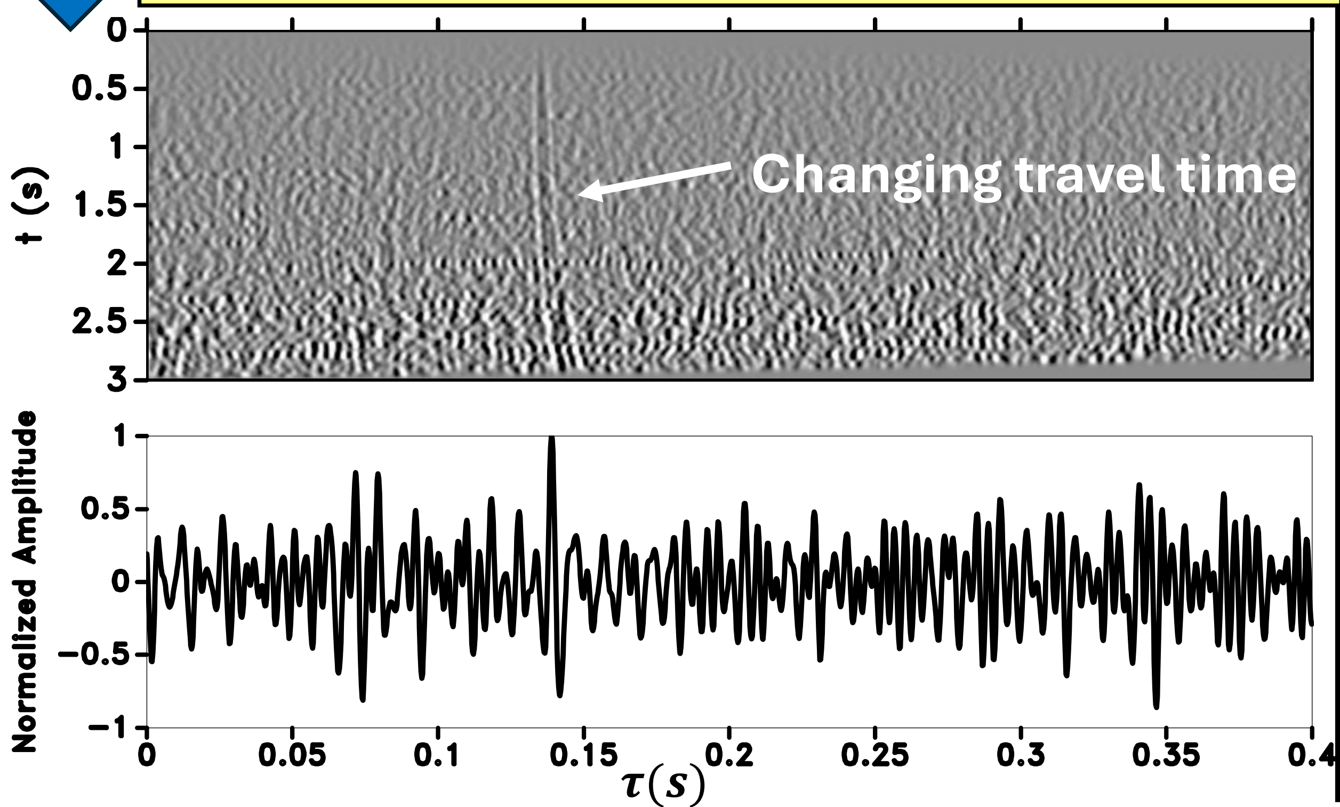
## ⑤ Seismic modeling

Fully remote seismic modeling. Velocity anomalies are distributed throughout the body. 721 random sources (**orange dots**) are spread throughout.

3D Apophis model used in simulations [4].



Local correlation highlighting the constantly changing travel times as receivers orbit Apophis (top). Regular correlation (bottom) fails to separate changing time lags.



**(1)** $f(\boldsymbol{m}) = \frac{1}{2}||\boldsymbol{d}_{obs} - \boldsymbol{d}_{pre}(\boldsymbol{m})||^2$ Travel time tomography

**(2)** $i(\boldsymbol{x}) = \sum_{e,t} u_s u_r$ Reverse time migration

$u_s = u_s(\boldsymbol{x},t) \longrightarrow$ source wavefield

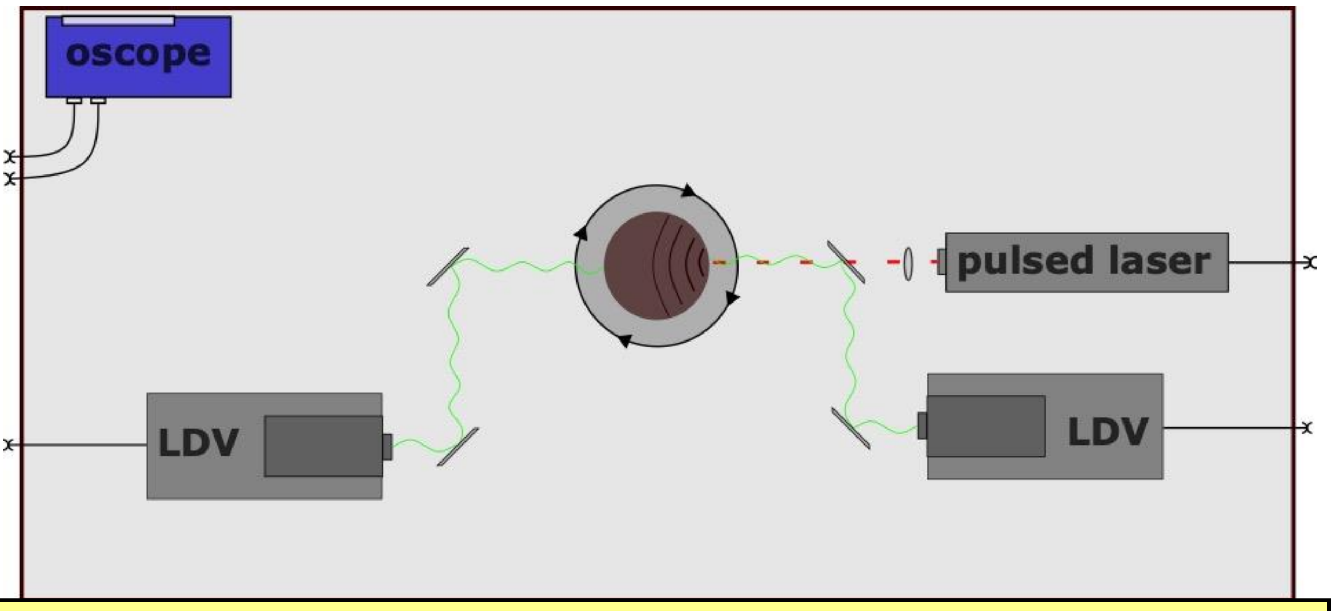
$u_r = u_r(\boldsymbol{x},t) \longrightarrow$ receiver wavefield

## ⑥ Imaging the subsurface

RSS will solve an inverse problem to infer the subsurface velocity structure. We can also implement reverse time migration to image reflectors.

## ⑦ Laboratory demo

A high energy pulsed laser excites wavefields. 2+ LDVs record the arrival. A rotating source mimics orbital motion of the receivers according to the reciprocity theorem.

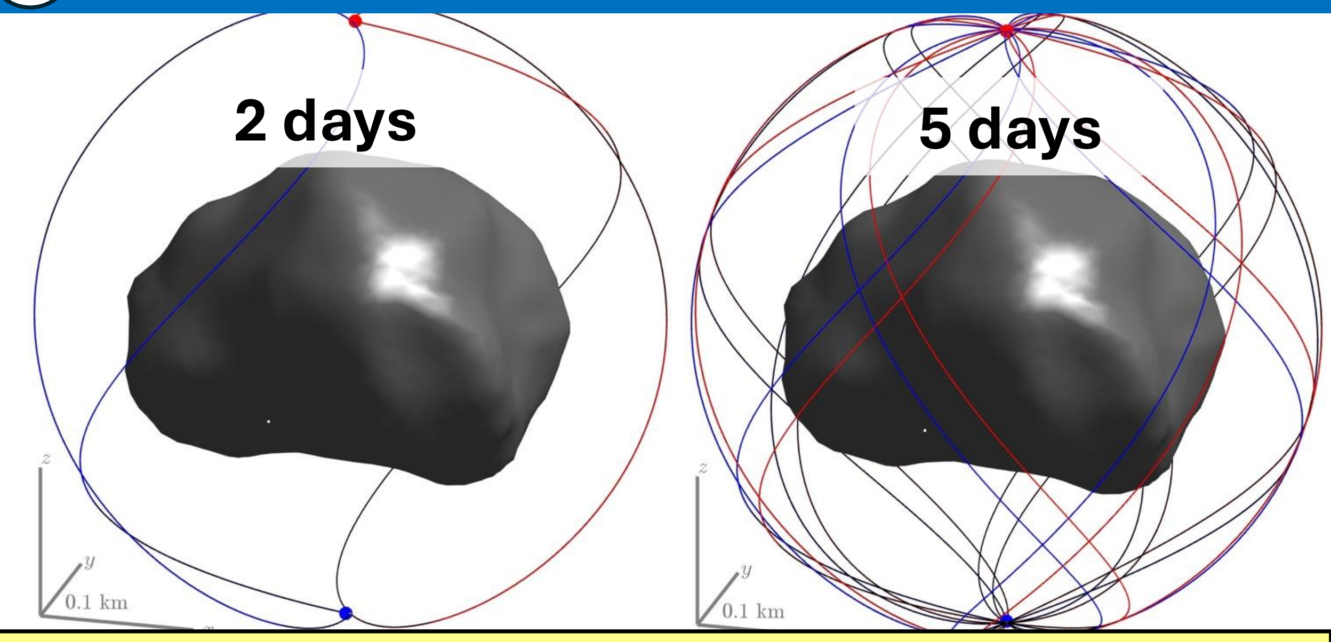


Benchtop demo of RSS. A laser creates seismicity. Twin Polytec IVS-500s record the wavefield.

## ⑧ Future work

This approach provides an opportunity for complimentary experiments. With a single LDV, we can perform normal mode analysis. This ensures redundancy if a spacecraft fails & also provides a second independent measure of subsurface properties.

## ⑨ Example orbit coverage of 99942 Apophis



Possible orbit for dense coverage that illuminates different parts of the subsurface, improving seismic imaging resolution and certainty.