Vibrations and rotations of asteroids: internal structure imaging with 6 degrees of freedom instruments

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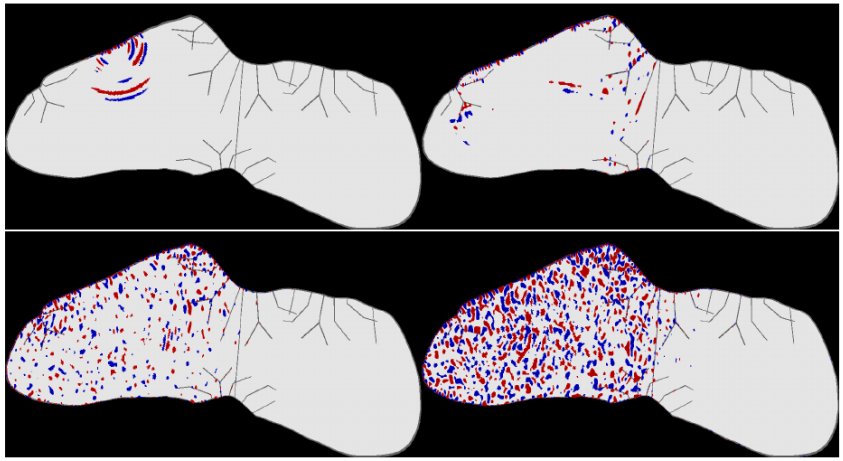
Why monitoring asteroid vibrations ?

1. **Seismology is the main tool to image the internal structure of the planets.**
2. **For asteroids :**
   - **The signals are expected mainly above 5 Hz**
   - **The natural seismic sources are either rare (impacts) or weak (thermal cracks)**
   - **The wave propagation and attenuation in porous media in low gravity is not fully understood (Discrete and continuous mechanics models are curently competing without representative data sets)**
3. **But seismic waves can infer :**
   - **Mechanical properties**
   - **Heterogeneity levels**
4. **Need seismological measurements !!!**

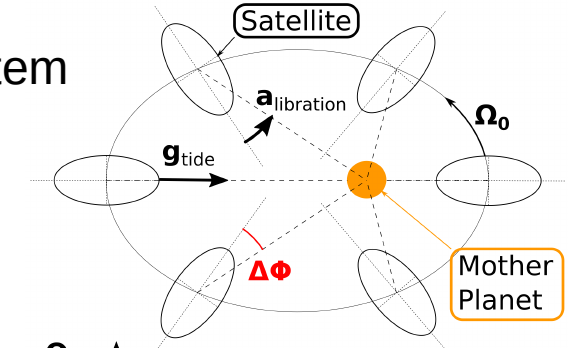
Seismic wave simulations for Eros
(Martin et al., 2008)

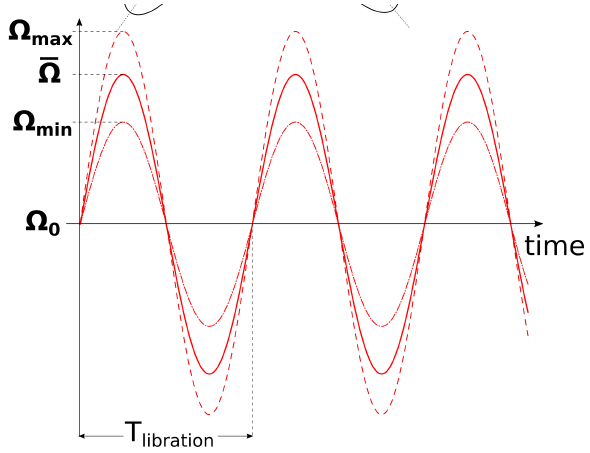


Why monitoring asteroid rotations ?

1. **Monitoring of global rotation dynamics is widely used to obtain global scale parameters (MoI, precessions and nutations...) for planets. It allows to infer their internal structure.**
2. **For asteroids :**
   - **Rotations variations are slow processes except for flybys, binary systems and impact related variations**
   - **Frequency range is on the order of asteroid rotation period (~10^{-5} Hz)**
3. **But rotation monitoring can infer :**
   - **Global scale internal structure**
   - **Global scale elastic parameters**
4. **Need asteroid rotation measurements independent of spacecraft dynamics (estimates from asteroid imaging)**

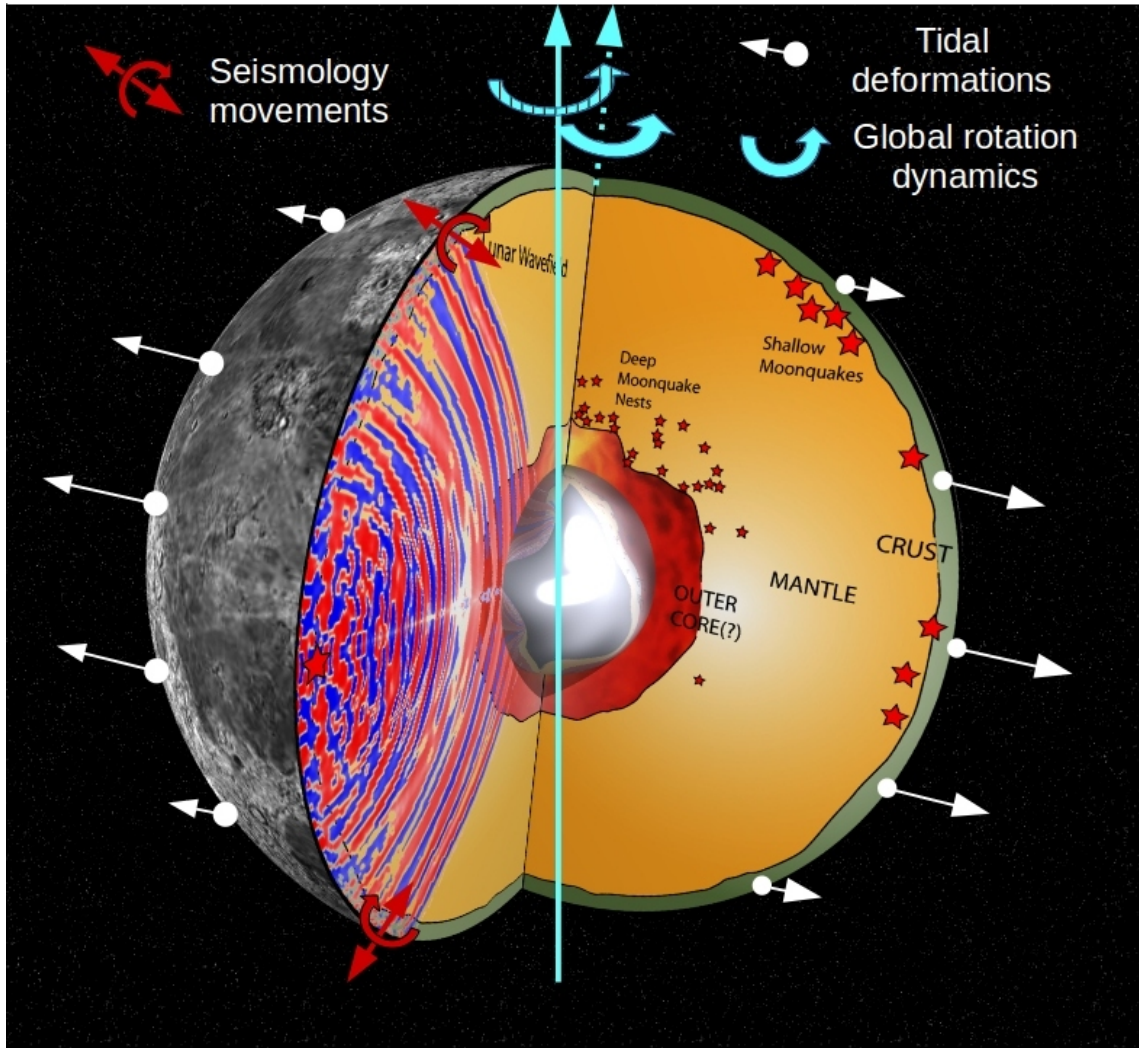
Forced librations in a binary system
Bernauer et al., 2020





We can measure these vibrations and rotations with a 6 DoF instrument on the asteroid surface?

1. **A 6 Degrees of Freedom instrument is measuring ground accelerations and rotations with translation and rotation sensors (high performance IMU)**



Adapted from a figure by Michael Thorne

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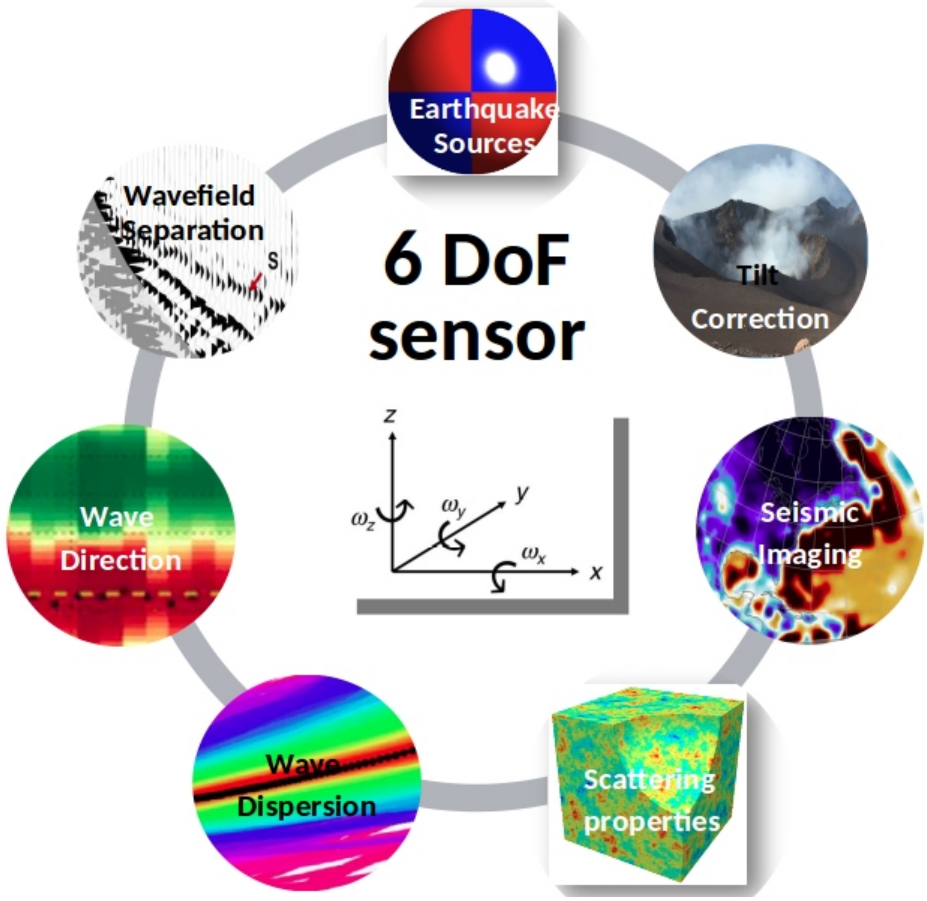
2. **Adding rotation measurements of seismic waves convert the instrument in a small network (rotations = spatial gradients of translation)**



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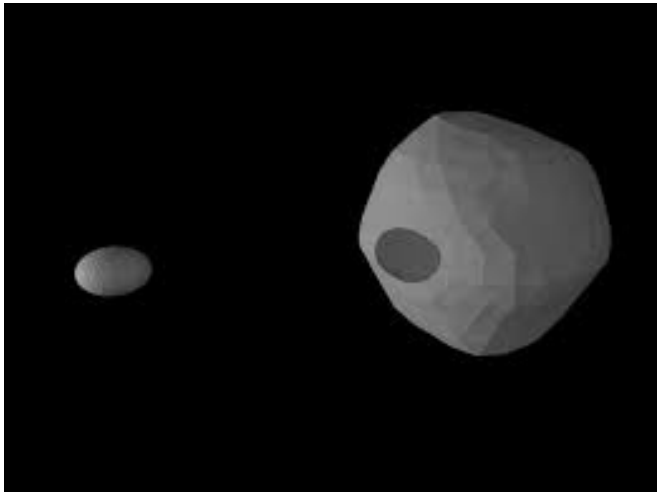
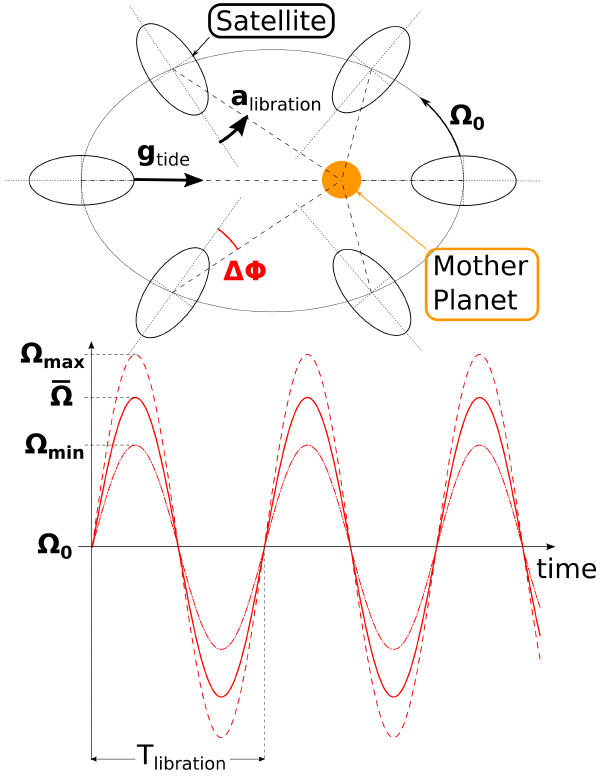
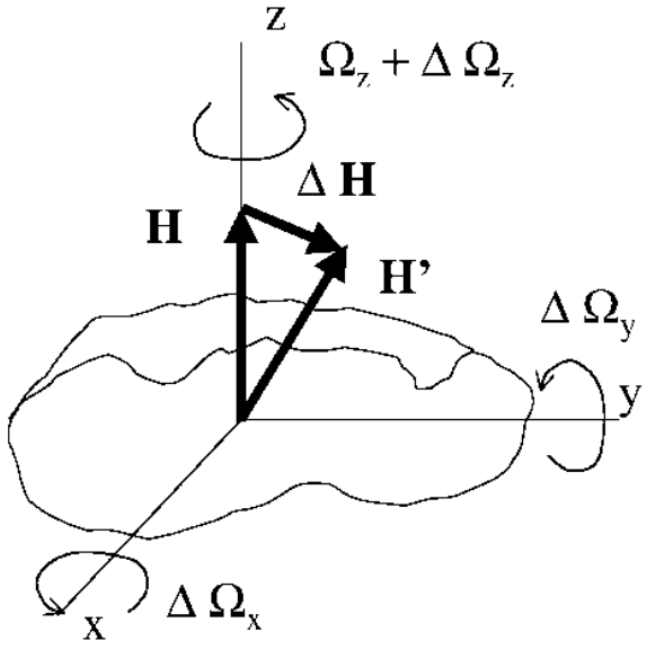
Rotational dynamics
(forced librations, tides...)
in binary systems



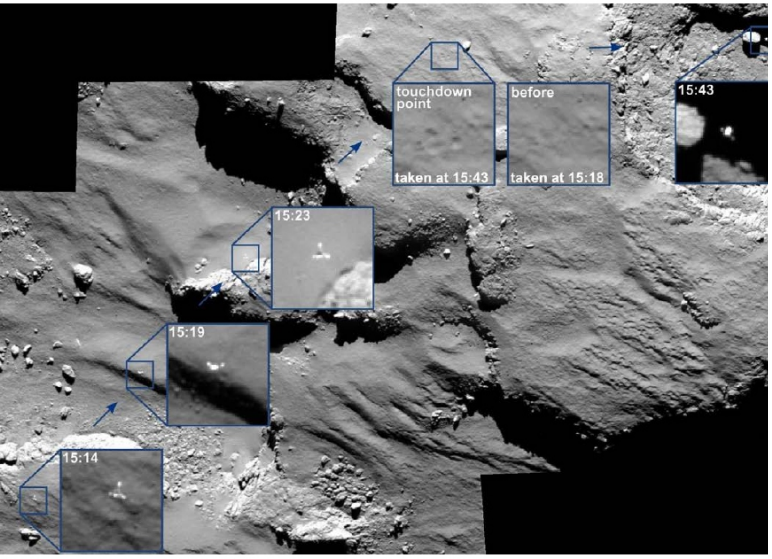




Toutatis case
(Scheeres et al., 2000)

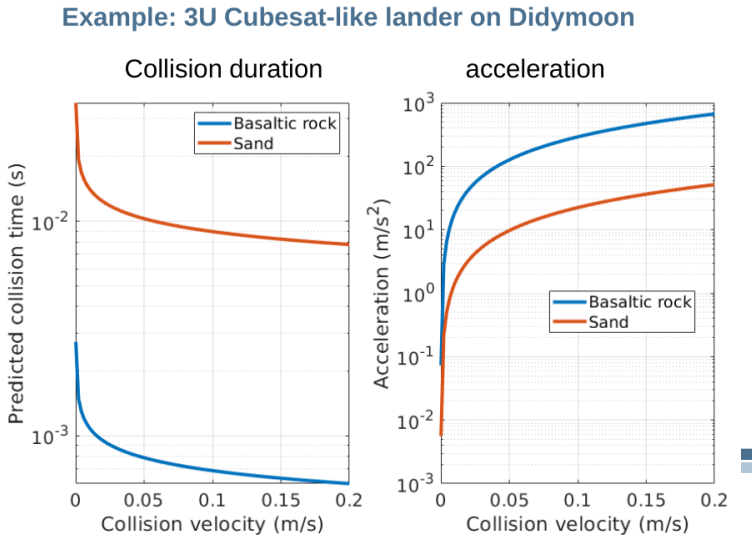
We can measure these vibrations and rotations with a 6 DoF instrument on the asteroid surface?

1. **A 6 Degrees of Freedom instrument is measuring ground accelerations and rotations with translation and rotation sensors (high performance IMU)**
2. **Adding rotation measurements of seismic waves convert the instrument in a small network (rotations = spatial gradients of translation)**
3. **But we expect also to measure global rotation dynamics by using fiber optics gyroscopes, because sagnac effect provides an absolute rotation measurement**
4. **Another science objective for asteroids is measurements of lander/surface interactions (rebounds) to constrain the sub-surface**

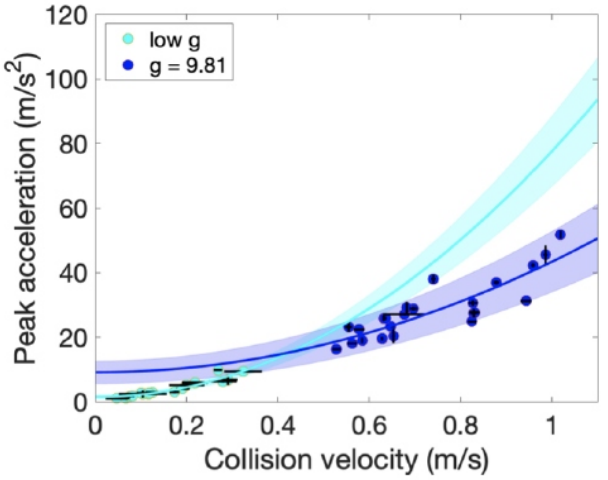


Rebounds of Philea lander (credits ESA)

Worse case
Bernauer et al., 2020

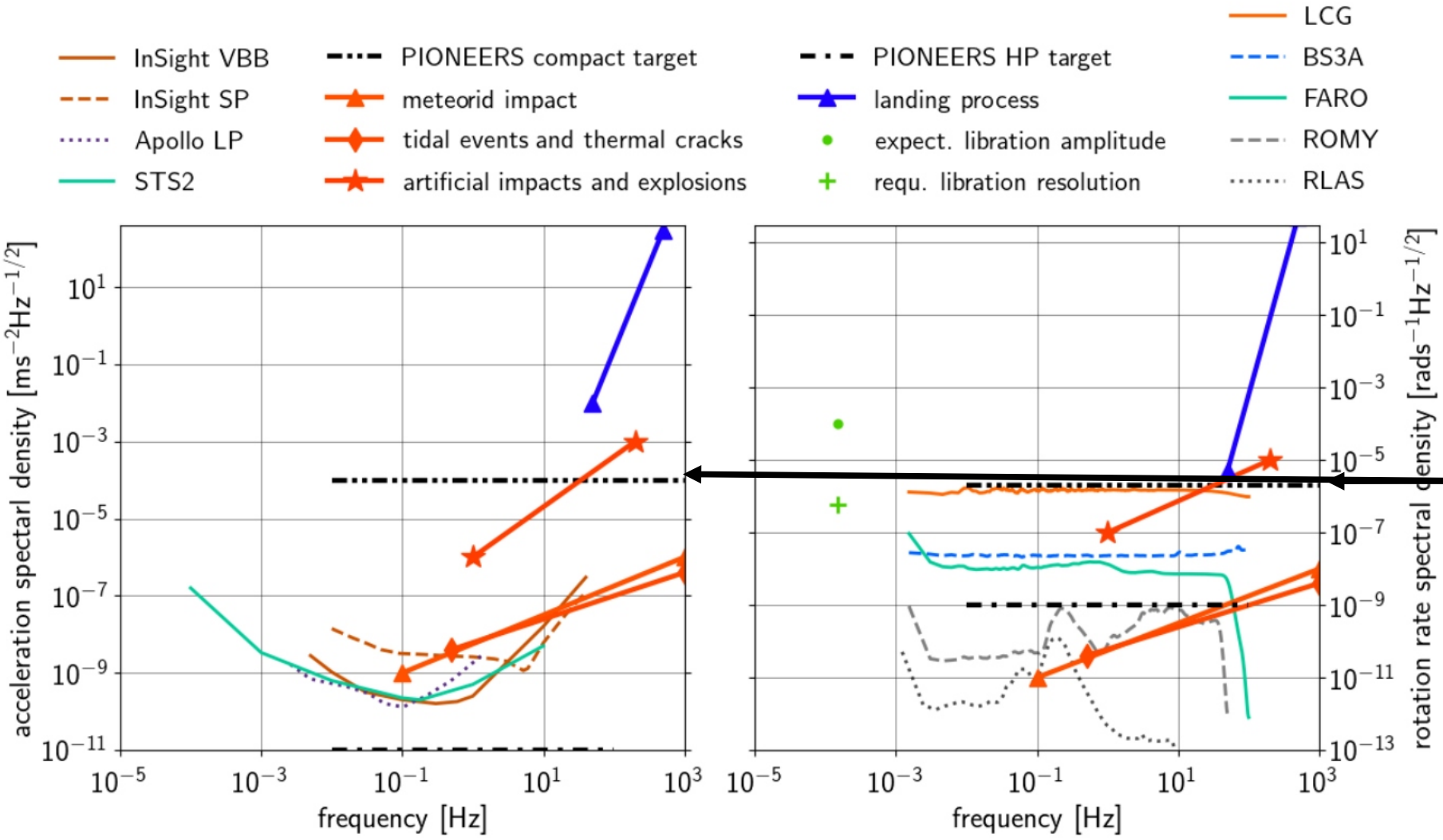


Expect lower accelerations
From experiments results
Murdoch et al., 2021



Science case of a 6 DoF instrument (DiMorphos)

1. **Expect to measure lander rebounds, asteroid forced librations and active seismic experiments**

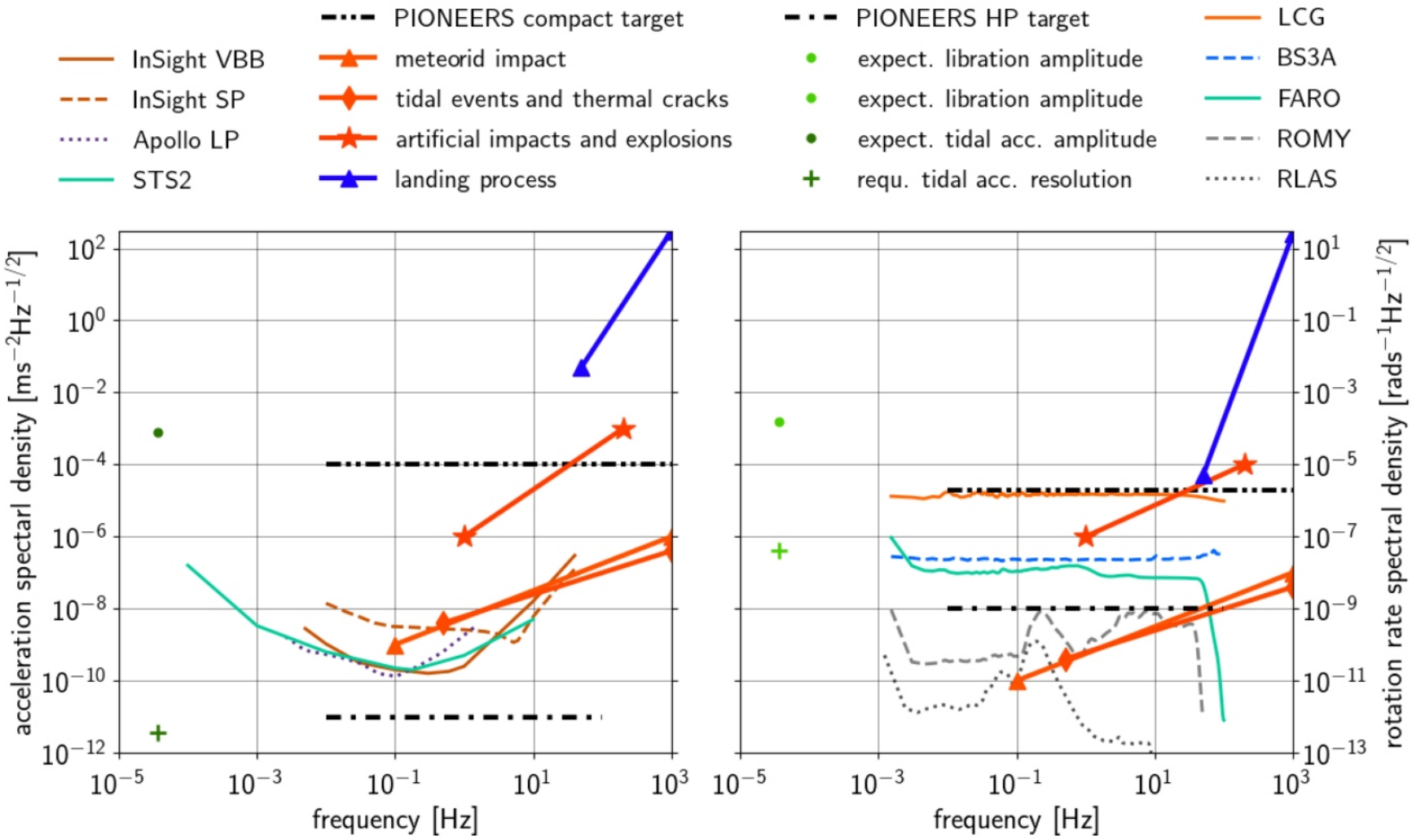


Expected noise Levels for PIONEERS Compact Model

Bernauer et al., 2020

Science case of a 6 DoF instrument (Phobos)

1. **Expect to measure lander rebounds, asteroid forced librations and active seismic experiments**



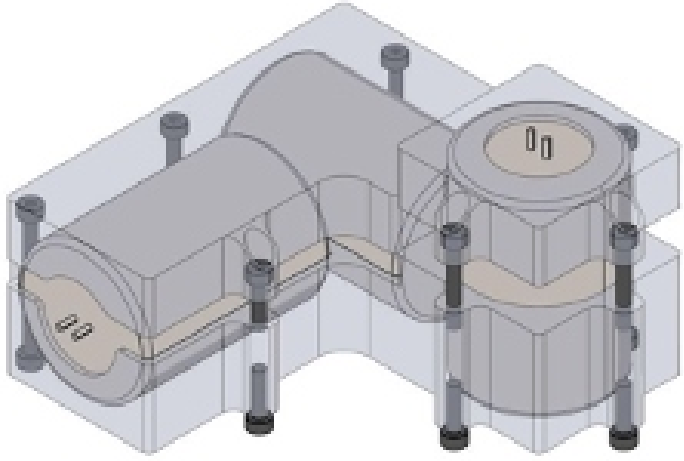
Bernauer et al., 2020

Science case of a 6 DoF instrument on Asteroids

1. **Need to cover a very large frequency range :**
   - **From global rotation variations around 10^{-5} Hz**
   - **To high frequency accelerations, induced by lander rebounds or artificial impacts, up to ~200 Hz**
2. **Expect to measure lander rebounds, asteroid forced librations and active seismic experiments**
3. **Natural seismic sources (impacts, thermal cracks …) produce signals >3 orders of magnitude smaller than our expected noise floor for both translations and rotations**

   => to be investigated by geophones (see N. Murdoch talk in this session)

Preliminary design of the ISAE-SUPAERO geophone instrument



On-going technical developments

PIONEERS project (https://h2020-pioneers.eu/) is developing 2 instruments with European Commission funding

- A High performance planetary instrument (next Generation after SEIS/InSight) up to prototype level

- A compact model for small bodies up to Flight model (MEMs Accelerometers + small Fiber optic gyros) by re-using and space qualifying technologies of iXblue company

MEMS Acc.
iXal-A5

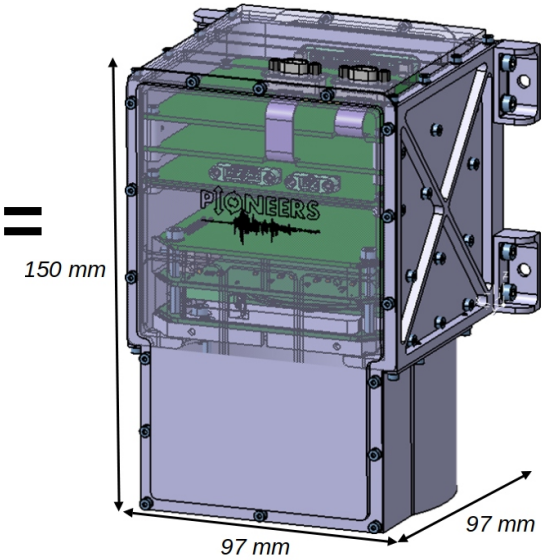
+

Fiber Optics Gyros
Technology from
Astrix range

+

On-board processing
Power management
Mechanical design
Data storage
Autonomy

=



Status of on-going technical developments

PIONEERS compact model is at CDR level for sensor sub-systems and PDR level for the whole instrument :

- Performances of F.O.G. and Accelerometer sensors and reading electronics have been demonstrated on Engineering models

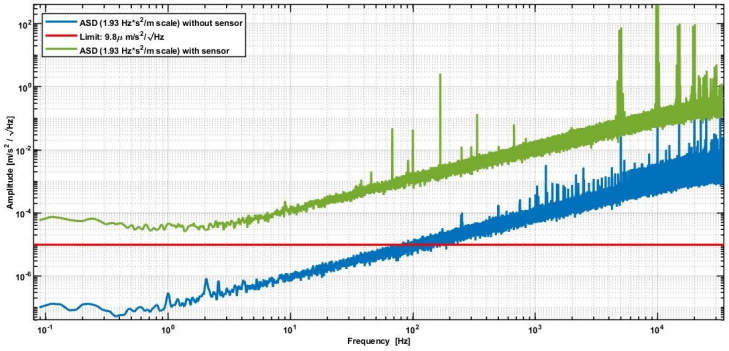
- Space qualification of these sensors and related sub-systems is on-going

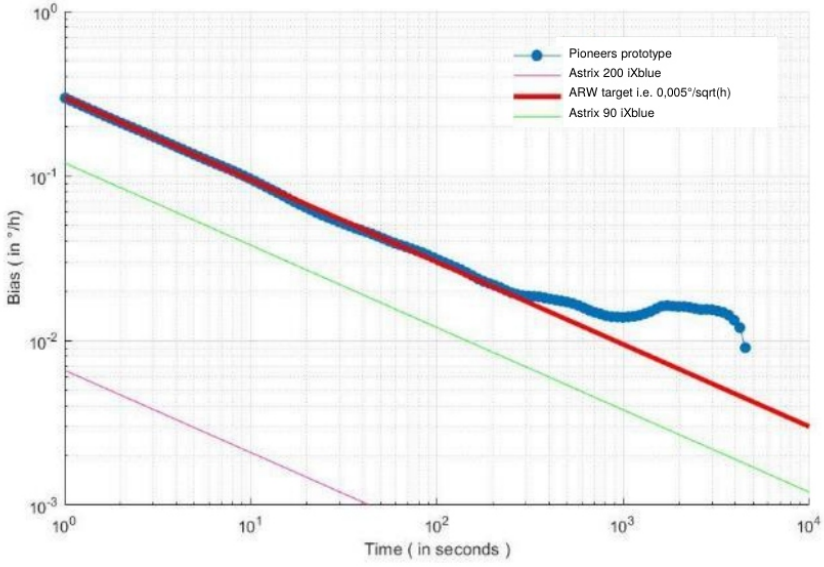
- Mechanical and thermal designs of the instrument have been validated by analysis

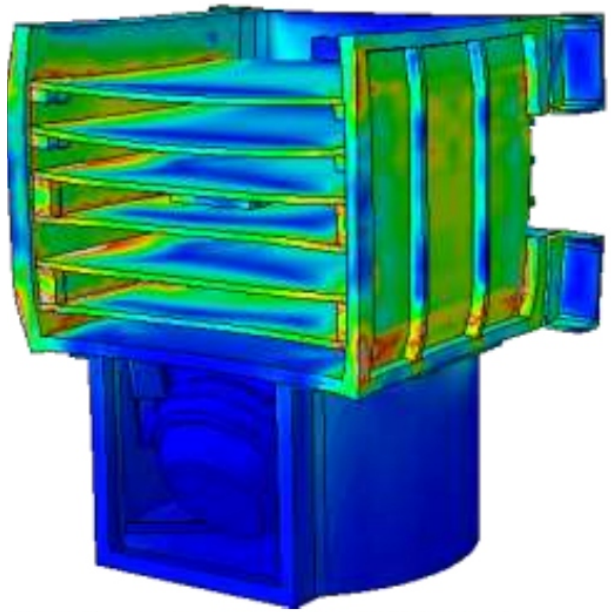
- Flight model at TRL 5-6 available in 2023 (delays induced by Covid)

"First light" very preliminary assessment of sensor noise on Breadboards

FOG Allan variance at requirement
ACC PSD close to requirement







Internal thermal stresses

Programmatic prospects

PIONEERS compact model is an ideal instrument for one of these cases:

- landers on asteroids (rebounds monitoring and navigation)

- missions planning active seismology experiments (large artificial impacts, large explosions…)

- asteroid binary systems (including Phobos) and asteroid planetary flyby events (for which large rotation variations and induced seismicity are expected)

In addition :

- The high quality IMU will improve the navigation of the landing component during landing and surface operation phases

- The instrument will provide a measurement of asteroid rotation independent from the ones obtained by imaging

Science case has been demonstrated for DidyMoon and Phobos (Bernauer et al., 2020). Other asteroid cases and asteroid planetary flyby events are under analysis.

Acknowledgements

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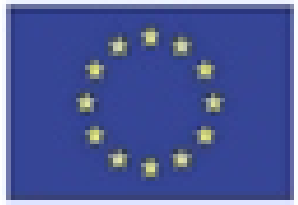

Backup slide : PIONEERS compact model system budget Current best estimate

Performances:

Rotation rate:
Range: +/- 50 rad/s
Bias: < 5 µrad/s (1 °/hour)
Noise: < 5 µrad/s/sqrt(Hz) over 1-200 Hz
BW max.: DC-800 Hz

Acceleration:
Range: +/-30 g
Bias: < 1 mm/s²
Noise: < 100 µm/s²/sqrt(Hz) over 1-200 Hz
BW max.: DC-800 Hz

Functions:

- Data reduction (filtering & decimation)
- Data storage (1 GB)
- Event detection
- Attitude integration & restitution

System budgets:

Power: < 15 W
Mass: < 1.5 kg
Size: 97x97x150 mm
Temperature: -40/+85 °C (storage),
-30/+45°C (highest performance operating range)
Radiations: 10 krad(Si)

Development plan:

- **Breadboard of sensors acquisition electronics** (TRL 3) mid 2021
Functional and performance tests
COTS parts
- **Instrument EM (TRL 4/5)**: early 2022
Fit-form instrument with most functionalities and full performances
COTS parts with higher grade equivalent available
Environment sustainability analyses
- **Instrument QM (TRL 5/6):** late 2023
Instrument with all functionalities and full performances in relevant environment
SP/EM, MIL, AUT grade parts, as far as possible