Torsion-Bar Antenna for Low-Frequency Gravity Gradient Observation

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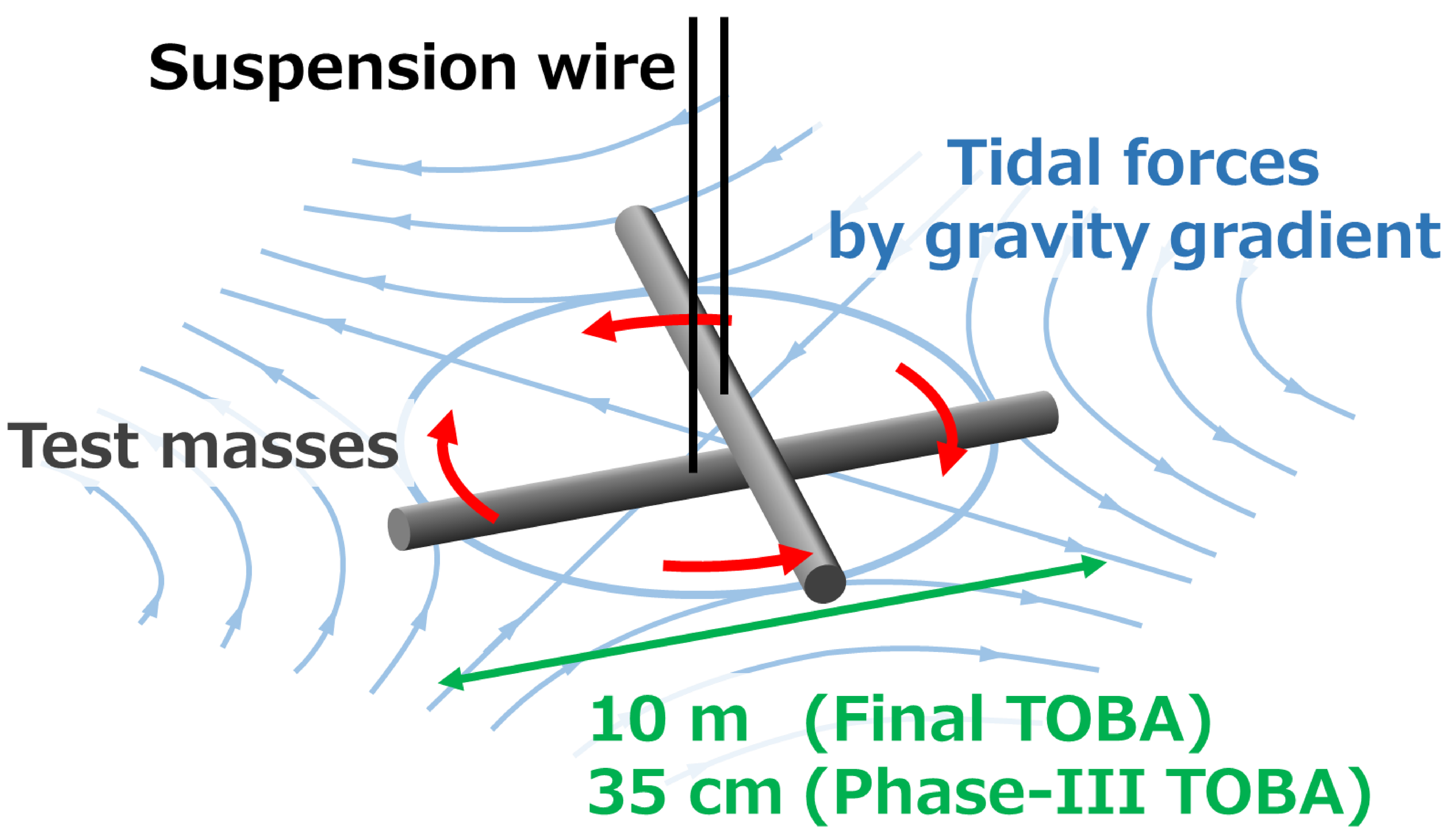
Abstract

Torsion-Bar Antenna (TOBA) is a low-frequency gravity gradient detector using torsion pendulums. Gravity gradient fluctuation is measured as the differential rotation of two horizontally suspended bars. The resonant frequency of torsional motion is low (~1 mHz) therefore TOBA has good design sensitivity, specifically 10^{-19} /√Hz between 0.1−10 Hz. TOBA can be used for earthquake early warning and gravitational-wave observation. A prototype detector Phase-III TOBA with a 35 cm-scale pendulum at cryogenic temperature is under development to demonstrate noise reduction. The target sensitivity is set to 10^{-15} /√Hz. We finished designing readout optics for Phase-III TOBA and mechanical parts fabrication is underway.

1. Principle of TOBA

TOBA: Torsion-Bar Antenna [1]

- Ground-based gravity gradient detector
- Composed of two test masses suspended horizontally
- Aim to detect the differential torsional rotation of test masses
- The resonant frequency of torsional motion is low (~1 mHz)
  → Good sensitivity in 0.1−10 Hz even on the ground

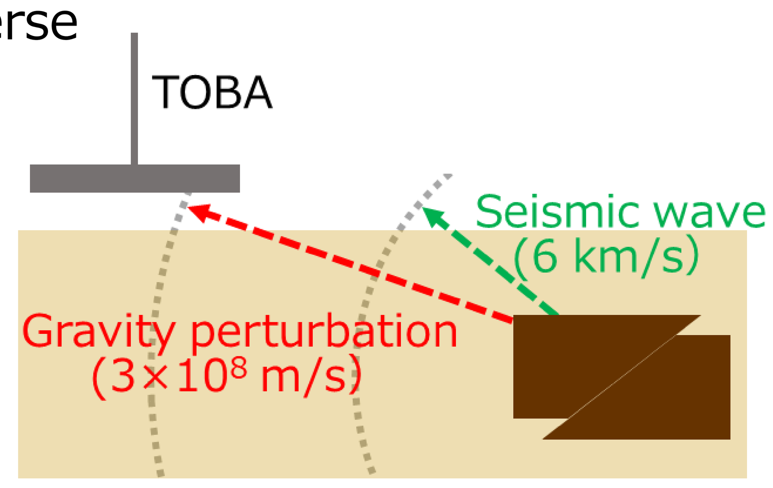


[1] M. Ando et al., Phys. Rev. Lett. 105, 161101(2010)

2. Science of TOBA

For astrophysics

- Gravitational waves
  from intermediate-mass black hole binary mergers
  → Formation process of super-massive black holes
  - Within ~1 Mpc (Phase-III TOBA) [1]
  - Within ~10 Gpc (Final TOBA)
- Gravitational wave stochastic background
  → Direct exploration of the early universe
  - Ω_{GW} ~10^{-7} (Final TOBA)



For geophysics

- Earthquake early warning
  → Contribution to a safer society
  - Within 10 sec for M7 earthquakes far from 100 km (Phase-III) [2]
- Newtonian noise: the fluctuations of the gravitational field
  by seismic and atmospheric perturbations
  → Contribution to noise reduction
  for third-generation gravitational wave detectors
  - First direct detection (Final) [3]

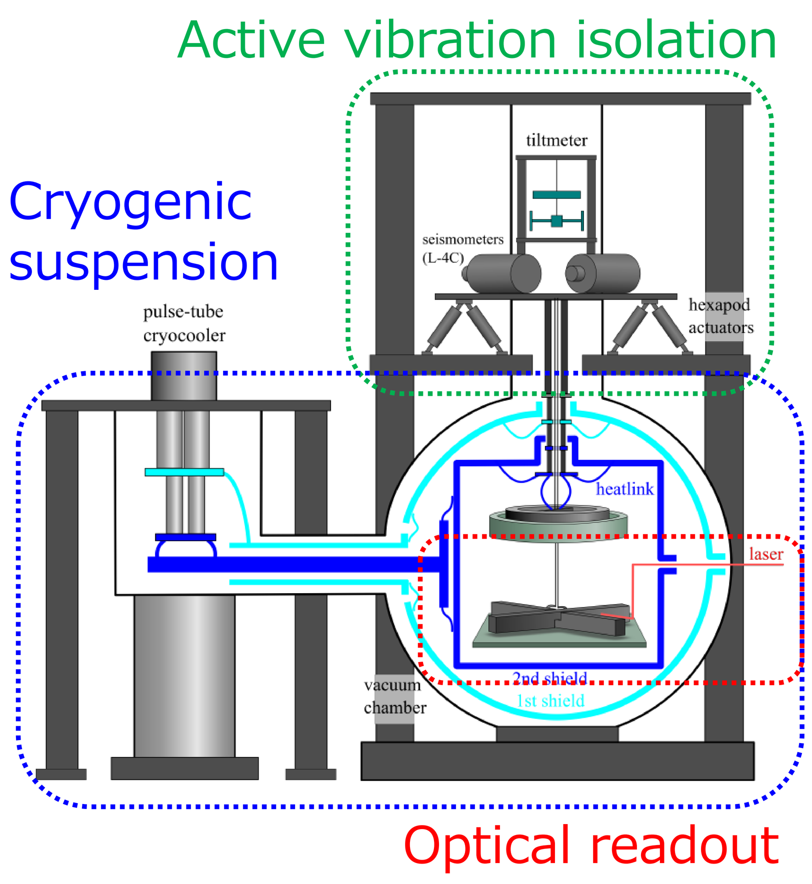
[2] T. Shimoda, Ph.D. thesis, University of Tokyo (2019)
[3] J. Harms et al., Phys. Rev. D 88, 122003 (2013)

3. Phase-III TOBA

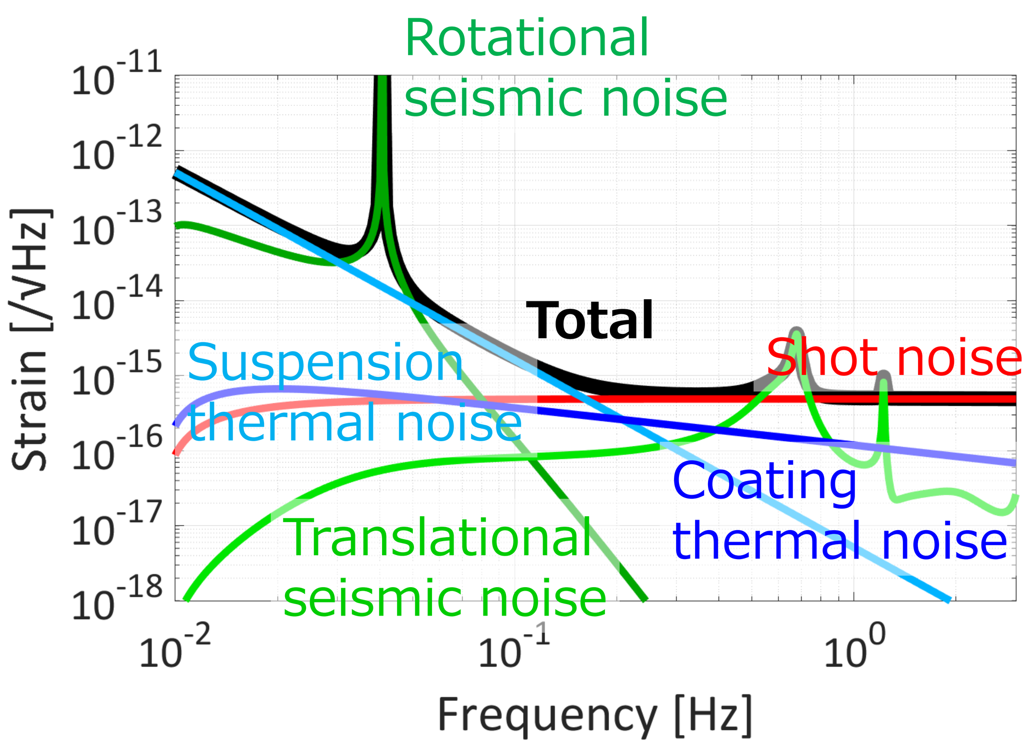
Development plan [4]

Phase-I (2009)	Phase-II (2015)	Phase-III (Now)	Final (Future)
Principle test		Technical demonstration	Observation
10^{-8} /√Hz (Established) 20 cm bars Room temp.		10^{-15} /√Hz (Target) 35 cm bars Cryo. temp. (4 K)	10^{-19} /√Hz (Target) 10 m bars Cryo. temp. (4 K)

Configuration [2]



Design sensitivity

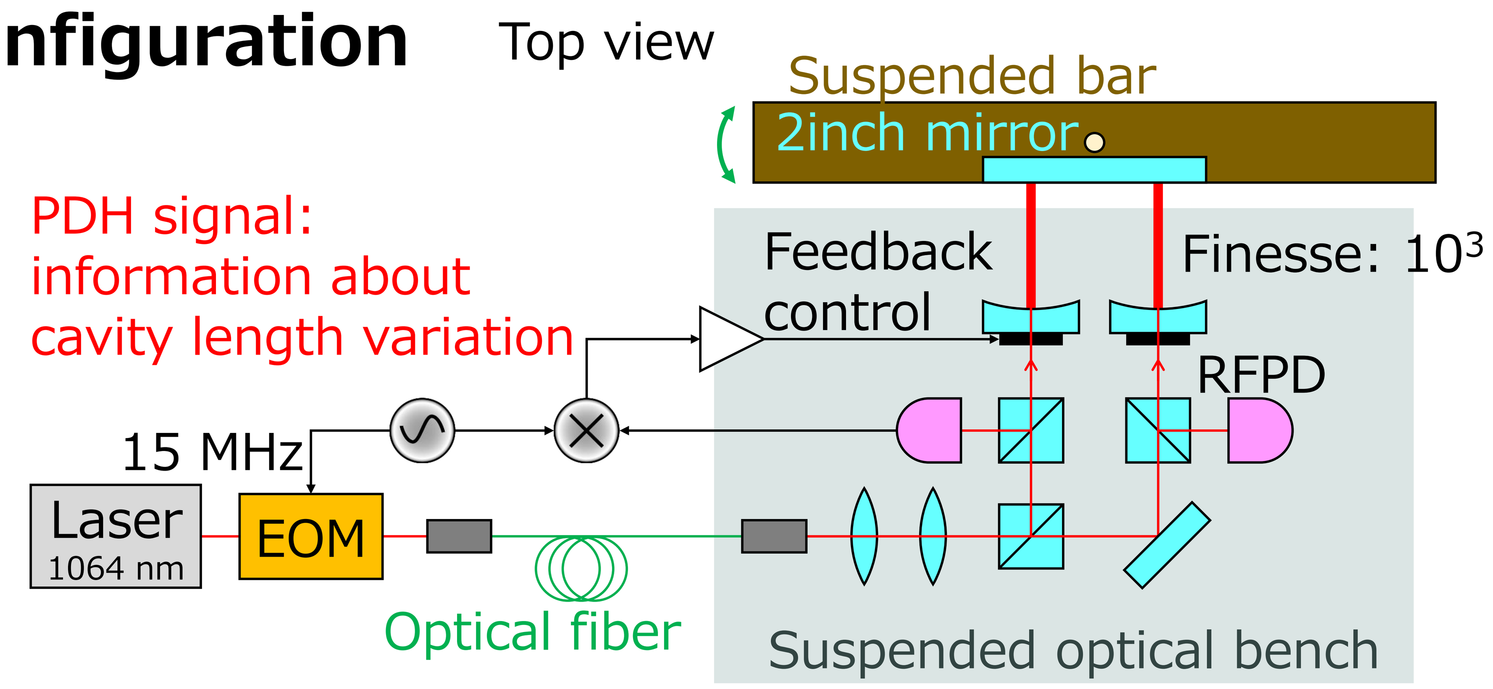


- Test masses were successfully cooled down to 6 K [2]
  → Next step: fabrication of torsion pendulums and readout optics
  to achieve the design sensitivity

[4] T. Shimoda et al., International Journal of Modern Physics D 29, 1940003 (2020)

4. Design of readout optics

Configuration



- Requirement: 5×10^{-16} rad/√Hz (limited by quantum shot noise)
- Read out the rotation from the subtraction of two PDH signals
- Use a 2-inch mirror as an end mirror to reduce translational coupling
- Inject laser beam with an optical fiber to reduce beam jitter noise

5. Summary & Future plans

- TOBA can detect gravity gradient fluctuation caused by gravitational waves, earthquakes, and Newtonian noise between 0.1−10 Hz
- We finished designing readout optics for Phase-III TOBA
- We plan to build a setup after mechanical parts fabrication

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