TOBA: a Low-frequency Gravitational-Wave Antenna

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Background and Motivation
Torsion-Bar Antenna

TOBA: **Torsion-Bar Antenna**

Two bars suspended as torsion pendulum

Detect differential rotation by GW

GW Science at Low Frequency

• Low-Freq. ($\sim$0.1Hz) GW antennae will provide original sciences:
  * Mass and orbital parameters of binaries,
  * Intermediate-Mass Black Hole binaries,
  * Stochastic background GW.

↓

• Good sciences by ground-based antennae: $h < 10^{-19} \text{ Hz}^{-1/2}$.
• Fruitful sciences by space-borne antennae: $h < 10^{-23} \text{ Hz}^{-1/2}$.
Observable Range

30\(M_\odot\) BBH Merger: 200 Gpc (\(z>10\)) range.

SNR=8, Optimal Direction/Polarization

GWADW2016 (May 24th, 2016, Elba Island, Italy)
• Low-freq. observation has significance much more than the ‘detectable range’.
• With low-freq. GW telescopes, longer observation time is expected; in $30\,\text{M}_\odot$ BBH merger case, the signal is at 0.1Hz in 15 days before merger.
- Improved parameter estimation accuracy with larger cycle number ($\sim 10^5$):
  * Localization, Merger time $\rightarrow$ Alerts for GW-EM.
  * Mass, Distance, Spin $\rightarrow$ Origin and nature of BBH.
Low-Freq. (~0.1Hz) GW antennae will provide original sciences:
* Mass and orbital parameters of binaries,
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Good sciences by ground-based antennae: \( h < 10^{-19} \text{ Hz}^{-1/2} \).
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Fundamental Noise Level of 10-m TOBA

Practical parameters \( \bar{\mathcal{h}} \simeq 3 \times 10^{-19} \) [Hz\(^{-1/2}\)]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar length</td>
<td>10m</td>
</tr>
<tr>
<td>Mass</td>
<td>7600kg</td>
</tr>
<tr>
<td>Laser source</td>
<td>1064nm, 10W</td>
</tr>
<tr>
<td>Cavity length</td>
<td>1cm</td>
</tr>
<tr>
<td>Finesse</td>
<td>100</td>
</tr>
<tr>
<td>Bar Q-value</td>
<td>( 10^5 )</td>
</tr>
<tr>
<td>Temperature</td>
<td>4K</td>
</tr>
<tr>
<td>Support Loss</td>
<td>( 10^{-10} )</td>
</tr>
<tr>
<td>Laser Freq. noise</td>
<td>&lt; 10Hz/Hz(^{1/2})</td>
</tr>
<tr>
<td>Freq. Noise CMRR</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Intensity noise</td>
<td>&lt; ( 10^{-7}/\text{Hz}^{1/2} )</td>
</tr>
<tr>
<td>Bar residual RMS motion</td>
<td>&lt; ( 10^{-12} ) m</td>
</tr>
</tbody>
</table>
Observable Range

Inspiral range for BH-BH binaries

$\rightarrow 10 \text{ Gpc} \left( \sim 10^5 M_\odot, \text{ SNR} = 5 \right)$

PRL105, 161101 (2010)
Prototype Developments

• Phase-I (2005-2010, Ishidoshiro, Ando, …)
  * Principle test and 0.1Hz GW observation
  * 20cm mass, Room temp, Poor seismic isolation
  * Two setups: Tokyo and Kyoto.

• Phase-II (2011-2015, Shoda, Okada, …)
  * Improved isolation design (Suspension + AVIT)
  * Principle test of multiple output configuration
  * Part of Cryogenics.

• Space-borne TOBA (2005-2011, Kokuyama, …)
  * Principle test and low-freq. GW observation.
  * Free floating, 5cm mass, Room temp.
What We learned so far ...

- **Phase-I TOBA:**
  - Seismic coupling coupling from disp.
  - External magnetic fluctuation coupling

- **Phase-II TOBA:**
  - Seismic coupling coupling from disp.
  - Readout sensor noise

K. Ishidoshiro+, PRL (2011)
A. Shoda, PhD thesis (2014)
Phase-III TOBA
Possible Next Step

Strain sensitivity of $10^{-15}\,\text{Hz}^{-1/2}$ at 0.1Hz.

\[ \downarrow \]

Multiple scientific outcomes expected:
* Observation of GWs,
* Direct measurement of Gravity-gradient noises $\rightarrow$ Test bench for cancellation.
* Earthquake early alert.
* Tiny force measurements for Quantum noise, Space missions, Fund. physics, ...
Conceptual Design of Phase-III TOBA

- Test Mass:
  
  Cupper (?), **Length 30cm, Mass 7.6kg, Temp. 4K.**

- Suspension:
  
  Silicon, Resonant Freq. \( \sim 2 \) mHz, Temp. 4K, Q-value \( > 3 \times 10^7 \)

- Optical Readout:
  
  \( \theta < 1 \times 10^{-15} \) rad/Hz\(^{1/2} \)
  
  Laser power \( > 0.1 \)W

- Seismic isolation:
  
  Active isolation
  
  + Passive suspension (3 stages)

\begin{center}
\begin{tabular}{|c|c|c|}
  \hline
  & Rotation [rad/Hz\(^{1/2}\)] & Displacement [m/Hz\(^{1/2}\)] \\
  \hline
  Active Isolation & \(< 3 \times 10^{-7}\) & \(1 \times 10^{-8}\) \\
  Damping Mass & \(6.3 \times 10^{-9}\) & \(1 \times 10^{-8}\) \\
  Upper mass & \(2.5 \times 10^{-12}\) & \(1 \times 10^{-8}\) \\
  Test mass & \(1 \times 10^{-15}\) & \(< 1 \times 10^{-11}\) \\
  \hline
\end{tabular}
\end{center}
Sensitivity of 30cm Cryogenic TOBA

Sensitivity vs. Frequency

- Rot. Seismic
- Suspension Thermal
- Rad. Press. Noise
- Bar Thermal
- Shot Noise
- Disp. Seismic

Length 0.3m, Radius 0.03m, Mass 7.6001kg, alpha 0.99626
Laser 9.2W, Finesse 1, Mass temp 4k
Phase-III TOBA Configuration

Active seismic-isolation stage:
- Geophone + Hexapod

Passive isolation:
- Triple suspension with damping

The setup is housed in a 
- cryostat vacuum tank.

Monolithic optical bench for readout:
- Power-recycled Michelson IFO

Monolithic test-mass bar, controlled using coil-coil actuator

Figure: Tomofumi SHIMODA
Current Phase-III TOBA Setup

The setup is housed in a cryostat vacuum tank.

Optical bench for readout: Michelson IFO
Not suspended.

Active seismic-isolation stage:
Geophone + Hexapod
Basement fixed to ground
Passive isolation:
single suspension

Test-mass bar, controlled using coil-magnet actuator
Cryostat and Cryo-cooler

- Cryostat vacuum tank
- Cryocooler: 2-stage pulse-tube cryocooler
- Valve unit
- Heat links
- 80k shield
- 4k anchor
Cryostat and Cryo-cooler

Figure: A. Shoda
Inside the Cryostat

Figure: A. Shoda

GWADW2016 (May 24th, 2016, Elba Island, Italy)
Technical Challenges

- Suspension thermal noise:
  \[ Q\text{-value} > 3 \times 10^7, \text{Temp. 4K} \, . \]

- Seismic noise:
  Rotational DoF, Coupling from displacement.

- Magnetic noise coupling:
  Torque by external magnetic fluctuations.

- Optical readout:
  \[ \delta x < 1 \times 10^{-16} \, \text{m/Hz}^{1/2} \]
  at 0.1Hz band.

- Cryogenic compatibilities.
• Tomofumi SHIMODA has made systematic survey of the seismic coupling noises, mitigation ideas, and quantitative estimation on the requirements.

Please take a look at his poster presentation.
Displacement-to-Rotation Coupling

One example: Displacement seismic noise coupling to rotation caused by the mismatch between the suspension point and CoM of the test mass.

- Required Accuracy: \( \Delta x < 10 \text{nm} \) (Adjustment of 100mg mass position sub-mm accuracy)
- Possible to be adjusted by intentional small tilt of the mass.
Naoki Aritomi is developing a new-type of actuator, so as to abandon permanent magnet from the test mass. → **Inductive actuator with coils.**

Please take a look at his poster presentation.
Magnetic Noise Coupling

• Operation of small TOBA with coil-coil actuator.
• Evaluation of external magnetic coupling.

Figure: Naoki ARITOMI
Monolithic Optical Bench

- Monolithic test mass and optical bench. Power-recycled Michelson IFO in this case.
  - Silica test mass, 20cm length, $\lambda/10$ polished.
  - Silica optical bench, optics will be glued.

Figure: Naoki ARITOMI
Previous Result

- S.Sato’s Mach-Zehnder IFO experiment
  → Monolithic optical bench is promising to realize shot-noise-limited sensitivity at low-frequency below 1Hz.

S.Sato (2013)
Monolithic Optical Bench

- Fused Silica components have been delivered.
  - Test mass: Polished and Mirror-coated.
  - Optical bench: Polished and shaped for sus.

Fused Silica Test Mass
(Not unpacked yet)

Fused Silica Optical Bench
Summary
Schedule (prediction)

- **Tests at room temp. (~2016.12)**
  - Investigation and experimental tests on seismic noise coupling noise.
  - Tests of Coil-Coil actuator
  - Operation and noise evaluation with monolithic optical bench.

- **Cryogenic operation (~2018.12)**
  - Tuning of active isolation stage.
  - High-quality wire for suspension.
  - Cryogenic operation to reach sensitivity
    \[ h < 1 \times 10^{-15} \text{ Hz}^{-1/2} \]
Summary

• In U-Tokyo, we are in a design phase of the next TOBA experiments
  * Sensitivity of $h \sim 10^{-15} \text{ Hz}^{-1/2}$ is a good target.
    - Best GW antenna in this band.
    - Scalable up to the 10-m TOBA.
    - Open several possibilities in application.
  * 30-cm scale cryogenic torsion pendulum.

Any suggestion in this workshop are welcome!