Design of Coupled Wave Front Sensor for TOtorsion-Bar Antenna

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Abstract

TOtorsion-Bar Antenna (TOBA) is a ground-based gravitational wave (GW) detector using torsion pendulums. The resonant frequency of torsional motion is ~1 mHz, therefore TOBA has good design sensitivity of $10^{-10}$ /Hz in 0.1 – 10 Hz. TOBA can detect intermediate mass black hole binary mergers, etc. A prototype detector Phase-III TOBA with a 35 cm-scale pendulum is under development to demonstrate noise reduction. The target sensitivity is set to $10^{-15}$ /Hz at 0.1 Hz. To achieve our target sensitivity, we need to measure the pendulum rotation precisely. We propose a coupled wave front sensor (WFS) as an angular sensor for Phase-III TOBA. In our method, an auxiliary cavity is used to enhance the first-order TEM modes in the main cavity. Here we show the principle and experimental design of a coupled WFS.

1. Introduction of TOBA

TOBA [1]
- Low frequency GW detector
  - Target: $10^{-15}$ /Hz in 0.1 - 10 Hz
- Use torsion pendulums
  - Low resonant frequency (~ 1 mHz)
- Ground-based configuration
- Scientific targets: intermediate mass black hole binary mergers,
  Newtonian noise, etc.

Development plan [2]

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Principle test</td>
<td>Technical demonstration</td>
<td>GW observation</td>
<td>-</td>
</tr>
<tr>
<td>$10^{-9}$ /Hz at 0.1 Hz (Established)</td>
<td>$10^{-15}$ /Hz at 0.1 Hz (Target)</td>
<td>$10^{-19}$ /Hz at 0.1 Hz (Target)</td>
<td>-</td>
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</tbody>
</table>

Developing items for Phase-III TOBA

- 35 cm Si torsion pendulums
- Active vibration isolation
- Cooling system
- High-Q suspension wire
- Coupled WFS: a highly sensitive angular sensor to measure the rotation of bars (GW signal)

2. Proposal of Coupled WFS

**Conventional WFS**

HG$_{00}$ ➞ Resonance
HG$_{10}$ ➞ Off resonance

= Angular signal

**Coupled WFS**: improved WFS for Phase-III TOBA

HG$_{00}$ ➞ Resonance
HG$_{10}$ ➞ Resonance

= Angular signal

→ HG$_{00}$ mode signal can be amplified by finesse of main cavity

**Comparison of angular sensors**

<table>
<thead>
<tr>
<th></th>
<th>Michelson interferometer</th>
<th>Conventional WFS</th>
<th>Coupled WFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot noise</td>
<td>✔</td>
<td>✘</td>
<td>✔</td>
</tr>
<tr>
<td>(Phase-III TOBA requirement: $5 \times 10^{-18}$ rad/s)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Frequency noise</td>
<td>✘</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Cross-coupling</td>
<td>✘</td>
<td>✔</td>
<td>✔</td>
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</tbody>
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3. Experimental Setup of Coupled WFS

**Design of optical cavities**

- Fold main cavity to extract signal inside main cavity
- Suspend front mirror by pendulum to look like TOBA’s bar
- Build cavities inside vacuum chamber to achieve good sensitivity

**Robustness to cavity loss**

- Detune from resonance
- Some/no solutions exist

**Cavity locking scheme**

- Lock the length of main and auxiliary cavities with PDH technique
- Use two different modulation frequencies

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Line width of carrier</th>
<th>Modulation frequency of sidebands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>13 MHz</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Auxiliary</td>
<td>1.3 MHz</td>
<td>4 MHz</td>
</tr>
</tbody>
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4. Summary & Future Plans

- A prototype GW detector Phase-III TOBA is under development
- We propose a coupled WFS as an angular sensor for Phase-III TOBA
  - HG$_{00}$ and HG$_{10}$ can be resonant simultaneously
  - We design the experimental setup
- We are planning the experimental demonstration to confirm angular signal amplification and locking scheme