Development of a low frequency vibration isolation system for KAGRA, and study of the localization of coalescing binaries with a hierarchical network of gravitational wave detectors.

Master’s thesis defense
35-156218
Yoshinori Fujii
Abstract:
Development of a low frequency vibration isolation system for KAGRA

KAGRA → Japanese interferometric large-scale gravitational wave detector. → now being developed underground in the Kamioka mine.

core optics → suspended by the so-called seismic attenuation system (SAS). optic’s position → actively controlled using sensors and actuators.

Content : This work verified a simulation tool for the active control system by using a KAGRA-SAS.
Conclusion: It was confirmed the simulation tool worked for designing active control systems. By using the tool, active control systems for a KAGRA-SAS were designed.
Abstract:
Study of the localization of coalescing binaries with a hierarchical network of gravitational wave detectors.

In order to achieve source localization,
→ coincident observations by large-scale gravitational wave detectors
→ the sensitivities of those detectors can be different from each other.
→ Necessary to construct a method to effectively use the less sensitive detectors’ information.

Content : This work estimates performance of a hierarchical network search to deal with this situation.
Conclusion: This method can reduce the systematic error on a sky map probability by a factor of 0.7.
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Abstract

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2. Development of a low frequency vibration isolation system for KAGRA

3. Study of the localization of coalescing binaries with a hierarchical network of gravitational wave detectors

4. Summary
Introduction / Gravitational wave and its detection

Gravitational wave:
- It is a distortion of spacetime
- GW propagates at the speed of light
- Its typical amplitude $h$ on the earth
  \[ h \sim \frac{\Delta L}{L} \sim 10^{-21} \]

Observable gravitational wave sources:
- compact binary coalescence
- supernovae
- spinning of pulsars
- ..

First direct detection was achieved in 2015 from coalescing binary black hole system.
\[ \rightarrow \text{GW astronomy is starting.} \]
Introduction / Gravitational wave and its detection

Interferometric GW detectors:

1) Based on Michelson interferometer
   \(\rightarrow\) To measure distortion due to GWs.

2) km-arm Fabry-Perot cavities
   \(\rightarrow\) To expand optical pass length.
   \(\left(L \text{ largen} \rightarrow \Delta L \text{ largen}\right)\)

3) Suspended core optics
   \(\rightarrow\) To let them move as free particles.
   \(\rightarrow\) To isolate optics from external vibration.
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4. Summary
Vibration isolation system / Seismic noise

- Ground vibration changes the optical path length continuously and randomly.
  \[ \rightarrow \text{Seismic noise} \]

Necessary to attenuate the vibration on order of 8 ~ 10.
Vibration isolation system / Vibration attenuation

- Pendulum system attenuates vibration at high frequencies.
- Multi-pendulum system realizes stronger attenuation performance.
Vibration isolation system / damping system & drift compensation

- Suspended optics vibrate at low frequency **due to mechanical resonances, drifts.**
  → For stable interferometer operation, such vibration should be suppressed.

- **This low frequency vibration is suppressed by active control system using sensors and actuators.**
  → Servo system should be designed so that the sensor and actuator noises do not vibrate the optics so much.

  Ex. If sensor noise > actual displacement → control system causes optic vibration.
Vibration isolation system / Designing control system

- For designing the active control system
  → a simulation tool based on 3D rigid-body model.
  → This tool was tested only once so far.
  → This work tested the simulation tool
    by using a simple KAGRA-SAS.
Verification of simulation performance / iKAGRA-PR3 SAS

**iKAGRA:**
- test run in 2016
- Michelson configuration

**PR3 mirror:**
- steering mirror
  - (in iKAGRA)

**iKAGRA-PR3 SAS:**
- First KAGRA-SAS installed at KAGRA site
- 2 stage pendulum
- Controlled by digital system
Verification of simulation performance / Sensors and actuators

- Geometric Anti-Spring filter
- Intermediate mass
- Mirror

**iKAGRA-PR3 SAS**

**LVDT (Linear Variable Differential Transducer) and coil-magnet actuator**

For resonance mode damping of the mirror

**OpLev (Optical Lever)**

- Light source
- Quadrant Photo Detector

For alignment of the mirror

**OSEM (Optical Sensor and Electro-Magnetic actuator)**

For GAS-filter’s drift compensation control
Verification of simulation performance / Active control performance

Test 1: damping performance
→ 1/e decay time for each resonances

Test 2: Residual vibration estimation

Implemented control loops
Verification of simulation performance / Test 1: damping performance

Measured

Simulated

1) Without control → simulation has large uncertainties. → 
2) With controls → prediction is consistent with actual system.
Verification of simulation performance / Test 2: Residual vibration

- Measured seismic vibration at KAGRA site is implemented into the simulation.

- Measured by optical lever

- From ~ 0.2 Hz to ~1 Hz:
  1) Resonant frequency → well fitted.
  2) Simulation spectra → consistent with measurement.
  3) Q factor, without control → Simulation ≥ measurement
  4) Background spectra → simulation ≠ measurement → should be considered: seismic noise, hanging condition.
Verification of simulation performance / Test 2: Residual vibration

For further precise prediction:
- real-time seismic vibration, hanging condition, should be considered.

If a calculation
- with large Q factors and
- large seismic noise meets requirements on active control system, it should be met in actual system.

→ This simulation tool works for designing active control system.
Designing active control system / Type-Bp SAS

iKAGRA-PR3 SAS $\rightarrow$ upgraded into Type-Bp SAS
- In order to meet KAGRA requirement.
- three type-Bp SAS will be installed.

This work designed the active control systems by using the simulation tool.

iKAGRA-PR3 SAS

Type-Bp SAS
Designing active control system / Control phase

1. Calm-down phase
   - Suppress large disturbance

2. Lock-acquisition phase
   - Reduce RMS velocity
   - RMS angle (Root-Mean-Square)

3. Observation phase
   - Keep position with low noise control

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Designing active control system / Type-Bp SAS

1. Calm-down phase
   - DC+Damp
   - DC
   - Damp
   - Optical sensors
   - Displacement sensor (LVDT)
   - Displacement sensor (OSEM)

2. Lock-acquisition phase
   - DC+Damp
   - DC
   - Damp
   - Optical sensors
   - Displacement sensor (LVDT)
   - Displacement sensor (OSEM)

3. Observation phase
   - DC + Damp
   - DC
   - Damp
   - Optical sensors
   - Displacement sensor (LVDT)
   - Displacement sensor (OSEM)

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3. Observation phase

- Expected sensor noise couplings into mirror displacement fluctuation:

→ This control system was designed in order to meet requirements:

1) **Sensor noise coupling** < \(10^{-15} \text{ m/}\sqrt{\text{Hz}}\) in detection band (>10 Hz)

2) **Suppress RMS values**
Summary

1) A simulation tool for active control system is tested by using a KAGRA-SAS.
2) It is confirmed the simulation tool works for designing active control systems.
3) Active control system for a KAGRA-SAS is designed by using the tool.

Future work

1) Investigate mechanical responses of KAGRA-SAS
2) Implement the designed active control systems into assembled type-Bp SAS.
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Source localization by GW detectors

\[ \theta = \cos^{-1} \left( \frac{c \Delta t}{d} \right) \]

1) Array and coincident observation
2) Triangulation using time lags.
Network search by GW detectors with different sensitivities

1) For source localization $\rightarrow$ coincident search.

2) How does a network by GW detectors with different sensitivities look like?
Network search by GW detectors with different sensitivities

1) For source localization $\rightarrow$ coincident search.

2) How does a network by GW detectors with different sensitivities look like?

$\rightarrow$ Triple (or more) coincidence are rare.
$\rightarrow$ Hardly localized.

(If all the threshold are same.)

$\rightarrow$ Not suitable for rapid localization, EM follow-up observation.

But this situation should happen, in coming years.

(Ex. Current expected situation)
Network search by GW detectors with different sensitivities

1) For source localization $\rightarrow$ coincident search.

2) How does a network by GW detectors with different sensitivities look like?
   $\rightarrow$ Triple (or more) coincidence are rare.
   $\rightarrow$ Hardly localized.

Necessary to set lower SNR thresholds for low sensitivity detectors as long as not too many background triggers.

How about including less sensitive detectors,  
1. with low threshold,  
2. only when we analyze triggers from high sensitivity detectors’ coincidences?
Hierarchical network search

High sensitivity detectors

Low sensitivity detectors
(With low SNR thresholds)

This Template!

During this period!

This trigger should be the counterpart.

These are the recorded SNR, arrival timing, phase.

(Ex. Current expected situation)

Combine 3 (or more) detectors’ information

Sky map probability

EM follow-up observation

Send alarm to EM partners

Goal of this Part:
Estimate localization performance by this approach.
Calculation setup / 3 detector network by HLV

Assumption

1. Implementing a GW-EM pipeline for GWs from CBC
2. Two LIGOs (70 Mpc), Virgo (20 Mpc)

GW-EM pipeline for GWs from CBC

GW detectors → MBTA → BAYESTAR → EM telescopes

- GW data production
- Identification of candidate GW events
- Sky localization
- EM follow-up observations

SNR, arrival time, phase, mass, FAR, etc, par event

Compact Binary Coalescence

High sensitivity  Low sensitivity
Calculation setup / 3 detector network by HLV

Main flow
1. Prepare 248 sets of HL MBTA triggers from MDC.
2. Transform HL MBTA triggers to HL or HLV triggers (SNR, arrival timing, phase from each detector).
3. Generate sky maps with BAYESTAR.

---

1. Prepare 248 existing MBTA outputs from HL coincidences.
2. Transform HL into HLV coincidences.

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GW detectors → MBTA → BAYESTAR

GW data production → Identification of candidate GW events → Sky localization

Injection location

Localization performance

Maximum probability pixel
2. Transform HL into HLV coincidences.

1) Generating V1 triggers

V1 trigger based on random parameters: Vr (from noise)

\[ \text{SNR} = \text{random following measurement} \]
\[ \text{Timing} = t_{H1} \text{ or } t_{L1} + \text{random } [-35ms:35ms] \]
\[ \text{Phase} = \text{random } [0:2\pi] \]

V1 trigger based on injection parameters: Vi (from signal)

\[ \text{SNR} = \text{metadata} + \text{Gauss}(0,1) \]
\[ \text{Timing} = \text{metadata} + \text{Gauss}(0,0.66 \text{ ms}* \frac{6}{\text{SNR}}) \]
\[ \text{Phase} = \text{measured} + \text{Gauss}(0,0.25 \text{ rad}) \]

2) Mixing V1 triggers

Case 1: worst case
HL+Vr, or HL
(Based on FAP)

Case 2: best case
HL+Vi, or HL
(Based on SNRth)

Case 3: Realistic case
HL+Vr, or HL+Vi, or HL
(Based on FAP and SNRth)
Calculation setup / 3 detector network by HLV

Localization performance:
1) Searched area ($\text{deg}^2$)
   → Difference between injection position and prediction.
2) 90% confidence area ($\text{deg}^2$)
   → How spread/concentrated the map is.

Step 1: Plot sky map probability

Injection position

Step 2: Collect these values from 250 events

Step 3: Collect median values by changing $\text{SNR}^{th}$ for Virgo detector

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**Expected localization performance / by HLV**

In case 3:
1) Searched area (accuracy) is improved.
2) Prediction becomes more concentrated.

→ By using low sensitivity detectors, errors on sky maps can be reduced by a factor of 0.7.
Expected localization performance / by HLV

<table>
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<tr>
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<th>SNR (H)</th>
<th>SNR (L)</th>
<th>SNR(V)</th>
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<tr>
<td>HL+Vrandom</td>
<td>12.8</td>
<td>11.5</td>
<td>4.5</td>
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<tr>
<td>HL+Vinjection</td>
<td>16.5</td>
<td>17.1</td>
<td>3.9</td>
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</table>
Expected localization performance / by HLV

HL+Vrandom

HL+Vinjection

<table>
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<th>SNR (H)</th>
<th>SNR (L)</th>
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<th>SNR (L)</th>
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</thead>
<tbody>
<tr>
<td>16.5</td>
<td>17.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

- Typical sky maps in this method → sometimes fail to predict the location within 90% confidence area.
- In this hierarchical network search, HLV sky map → If there is no EM-counterpart in HLV map, HL map.
- It will be useful for GW-EM follow-up observation.
Summary

1) A fast localization with hierarchical network is demonstrated.
   → In network by 3 GW detectors (70 Mpc, 70Mpc, and 20Mpc),
   
   → By using this method, the systematic error on the sky map can be reduced, compared to HL double coincidence search.
   
   → the performance will be optimized when Virgo threshold is set at ~3.5.

2) It is confirmed this hierarchical network is useful for low sensitivity detectors.

Future work

1) Investigation of performance by two detectors with different sensitivities.
2) More theoretical prediction of optimal SNR threshold
Summary

Part 2:
- A simulation tool for active control system was verified by using iKAGRA-PR3 SAS.
- It is confirmed the simulation tool works for designing active control systems.
- Active control system for a KAGRA-SAS is designed by using the tool.

Part 3:
- Localization performance with a hierarchical network search is demonstrated
- It is confirmed this method can effectively use of low sensitivity detectors.

Thank you for your attention.
Back up
Seismic noise of Kamioka (on 2016.5.10)

In following calculation, seismic noise measured on 2016.5.10 is considered (blue one).

cf.) Following measurement was done on 2016.5.24.
Mechanical Q factor of free swinging: Type-B1proto vs. Type-Bpp

Highest mechanical Q (<20 Hz) in real life seems to be ~ 5e3.
TypeBpp SAS
Eigen mode List : 24 modes
<table>
<thead>
<tr>
<th>#</th>
<th>TypeBp SAS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eigen mode List : 36 modes</td>
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</table>

<table>
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<th>#1</th>
<th>0.1Hz</th>
<th>More</th>
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<td>#12</td>
<td>#13</td>
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<tr>
<td>-----</td>
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<td>0.659Hz</td>
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<td>0.849Hz</td>
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![Diagram #21](image1)

![Diagram #22](image2)

![Diagram #23](image3)

![Diagram #24](image4)

![Diagram #25](image5)

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<th>#28</th>
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<td>64.629Hz</td>
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![Diagram #26](image6)

![Diagram #27](image7)

![Diagram #28](image8)

![Diagram #29](image9)

![Diagram #30](image10)
Calculation setup: How to generate SNR, arrival timing, phase of the V1

Plot SNR distribution from ~ about 20 hours data
→ Choose typical curve ("quiet")
* Start to generate skymaps with 4 detector (V1, K1 threshold = 3.5)
For further accuracy improvement:

Measured uncertainties on arrival time vs. SNR.

Relation between timing error and SNR

Detected arrival timing has some uncertainties $\Delta t$ due to:
1) calibration uncertainty
2) discrepancies of templates.
and so on.

If SNR becomes large, $\Delta t$ becomes small.

Since, accuracy largely depends on $\Delta t$,
For further improvement of accuracy,
→ Necessary to reduce timing error
→ Necessary to improve sensitivity of GW detectors.
How about this hierarchical network by 4 detectors, HLVK?

Assumption

- Implementing a GW-EM pipeline for GWs from CBC
- Two high sensitivity detectors LIGOs (70 Mpc)
- Two low sensitivity detectors Virgo (20 Mpc), KAGRA (20 Mpc)
**Calculation setup / 4 detector network by HLVK**

2. Transform HL into \textit{HLVK} coincidences.

1) Generating V1 triggers

V1 trigger based on **random** parameters: \( Vr, Kr \)

\[
\textit{SNR} = \text{random following measurement} \\
\textit{Timing} = tH1 \text{ or } tL1 \\
+ \text{random } [-35\text{ms}:35\text{ms}] \\
\textit{Phase} = \text{random } [0:2\pi] \\
\]

V1 trigger based on **injection** parameters: \( Vi, Ki \)

\[
\textit{SNR} = \text{metadata + Gauss}(0,1) \\
\textit{Timing} = \text{metadata} \\
+ \text{Gauss}(0,0.66 \text{ms} \times \frac{6}{\text{SNR}}) \\
\textit{Phase} = \text{measured + Gauss}(0,0.25 \text{rad}) \\
\]

2) Mixing V1 triggers

**Case 1: worst case**

HL+Vr, HL+Kr, HL+Vr+Kr or HL

(Based on \textit{FAP})

**Case 2: best case**

HL+Vi, HL+Ki, HL+Vi+Ki or HL

(Based on \textit{SNR}th)

**Case 3: Realistic case**

HL+Vr, HL+Kr, HL+Vr+Kr, HL+Vi, HL+Ki, HL+KVi+Ki, HL+Vr+Ki, HL+ViKr, or HL

(Based on \textit{FAP} and \textit{SNR}th)
1) Accuracy (searched area) is so not improved since the timing error
2) In order to improve the accuracy of the map
   → Necessary to reduce timing error → Necessary to improve sensitivity of GW detectors.
3) Predicted area becomes more condensed.
   → By using low sensitivity detectors, systematic errors on sky maps can be reduced.
Expected localization performance / by HLVK

- HL + Vi + Ki
- HL + Vr + Kr
- HL + Vr + Ki
- HL + Vi + Kr
Expected localization performance / by HLVK

**HL + Vi + Ki**

**HL + Vr + Kr**

**HL + Vr + Ki**

**HL + Vi + Kr**

HLVK map

HL map