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
Contents

1. Source localization

2. Detector development
Gravitational wave

First detection! done!

→ New astronomy!
From where?

Gravitational wave

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

Time delay

Localization

Delay \( \Delta t \)
From where?

1) Only a few detectors  
   → × Continuous observation

2) Only 2~3 detectors  
   → Blind spots
From where?

1) Only a few detectors
   \implies \times \textbf{Continuous observation}

2) Only 2~3 detectors
   \implies \textbf{Blind spots}
For EM and $\nu$ follow-up observation:

Source localization: more precise is better.
We have different sensitivities.. OK?

Ex.) SNR > 5 → detection

(Expected situation)
We have different sensitivities.. OK?

Ex.) SNR > 5 → detection

1) Triple (or more) coincidence → Rare

2) Localization → Not Precise

(Expected situation)
We have different sensitivities.. OK?

Ex.) SNR > 5 → detection

1) Triple (or more) coincidence → Rare
2) Localization → Not Precise

We have to establish a method for EM follow-up!

(Expected situation)
Hierarchical network search

1) High/Low sensitivity $\rightarrow$ higher/lower SNR threshold

2) high sensitivity detector $\rightarrow$ low sensitivity detector

This signal!
During this period!

This signal should be the counterpart.

GW localization

EM follow-up observation
Calculation setup / Assumption

1. GW-EM pipeline for GWs from CBC

- GW detectors
- MBTA
- BAYESTAR
- EM telescopes

Signaling
Event info: SNR, arrival time, etc.
Sky map probability

2. Two LIGOs (70 Mpc), Virgo (20 Mpc)
   - High sensitivity × 2 / Low sensitivity × 1
Calculation setup / Main flow 1

MBTA → Existing measured data → BAYESTAR → Artificial data → Localization performance

248 Injection data

Arrival timing, SNR, Phase.

(Random) or (true + δ)
Calculation setup / Main flow 2

Localization performance

1) **Accuracy**
   - Searched area (deg²)

2) **Precision**
   - 90% confidence area (deg²)

Histograms from 248 events.

*median values*
Expected performance, HLV

(SNR threshold for H, L = 5.)

By including low sensitivity detectors, errors on sky maps can be reduced by a factor of $\sim 0.7$. 
How about 4 detectors, HLVK?

(High: 70 Mpc)

(High: 70 Mpc)

(Low: 20 Mpc)

(Low: 20 Mpc)
Expected performance, HLVK (SNR threshold for H, L = 5.)

准确性 → 不如预期提高。

精度 → 提高！

4th detector contributes to EM follow-up!

More improvement → Necessary to improve sensitivity.
Summary 1

A localization with hierarchical network is demonstrated. (From sky maps → first time.)

In network by 3 GW detectors (70 Mpc × 2 and 20 Mpc),
  - Accuracy: 137 deg$^2$ → 93 deg$^2$
  - Precision: 840 deg$^2$ → 600 deg$^2$
→ Low sensitivity detector can contribute!

In network by 4 GW detectors (70 Mpc × 2 and 20 Mpc × 2),
  - Accuracy: 137 deg$^2$ → 87 deg$^2$
  - Precision: 840 deg$^2$ → 500 deg$^2$
→ 4th detector contributes! → useful for EM follow-up!
Source localization → detector development

We want ..

Necessary to improve sensitivity!

In particular, KAGRA.

Detector noise $[1/\sqrt{\text{Hz}}]$ vs. Frequency $[\text{Hz}]$
Gravitational wave detector

1) Michelson-based interferometer
2) Optical cavities
3) km-arm
4) Suspended core optics

Ex. KAGRA

Mirror (dummy)
Detector noise

- Quantum noise
- Thermal noise
  ...
- Seismic noise

Mirror vibration
→ Necessary to suppress

So many noise sources...

In case of KAGRA

Detector noise [1/\sqrt{Hz}]

Frequency [Hz]

Seismic noise
Seismic noise

Seismic noise (Tokyo)

Seismic noise (KAGRA site)

Target sensitivity

Displacement [m./Hz]

Frequency [Hz]

10^{-8}
Seismic attenuation

Mirror displacement $x$ [m/√Hz]

Frequency [Hz]

Ground
Single
Double
Triple

KAGRA suspension

Requirement

Ex. KAGRA
Mirror (dummy)
Resonance damping & drift compensation

→ Active control

Starting interferometer operation

Servo

Actuator

Displacement sensor

Stable interferometer operation
KAGRA project

KAGRA
1) Japanese detector
2) now being developed
3) underground

iKAGRA
1) test run in 2016
2) Simple interferometer

KAGRA interferometer

Light source

IMC

PR2

PR3

ETMY

BS

ETMX

3 km

3 km
KAGRA suspension development

iKAGRA-PR3 work:
1) Assembly
2) Performance test
3) Upgrading for KAGRA

iKAGRA-PR3 suspension:
Alignment mirror of iKAGRA for initial alignment for stable operation.
iKAGRA-PR3 suspension / Assembly
iKAGRA-PR3 suspension / Sensors and actuators

For vertical

Displacement sensor and coil-magnet actuator 1

Displacement sensor and coil-magnet actuator 2

Angular sensor

Light source

Photo Detector

Mirror

iKAGRA-PR3 SAS

Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii

28 / 37
Performance test / Measurement vs. simulation

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

Test 2: Residual vibration estimation

1/e decay time
Performance test 1

1) Control OFF → Necessary to feedback measurement.
2) Control ON → Consistent.
Performance test 2

Simulation

Seismic motion

Uncertainty ~1 order

Suspension point shift?

Lower seismic motion?

→ Uncertainty ≲ 1 order
→ For designing, calculate using high seismic noise.

Seismic motion at KAGRA site

Measurements

Simulation

Uncertainty ~1 order

Simulation

Measurement

Simulation (Control OFF)
Simulation (Control ON)
Measurement (Control OFF)
Measurement (Control ON)
Upgrading for KAGRA

iKAGRA-PR3 SAS \rightarrow \text{Type-Bp SAS}

In order to meet KAGRA requirement.

Design active control systems.

iKAGRA-PR3 SAS

Type-Bp SAS
Designing active control system

Calm-down phase

Observation phase
Designing active control system 1

Calm-down phase:
Suppress large disturbance

1/e decay time

Not disturb operation
→ No problem.

Requirement

(if all sensors available)
Designing active control system 2

**Observation phase:**
Suppress RMS (Root Mean Square) & control noise

![Graph showing frequency response comparison between control OFF and ON phases.](image)

- **Requirement**
- **Control OFF**
- **Control ON**

**Magnitude [rad/\sqrt{Hz}] or RMS [rad]**

**Frequency [Hz]**: 10^-1 to 10^1

**Seismic noise**

**Requirement**

**Control OFF**

**Control ON**

Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii
Summary 2

1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
2) Its performance were tested.
   \[\rightarrow \text{Simulation gives reasonable prediction.}\]
3) Active control system for a KAGRA-SAS is designed.
   \[\rightarrow \text{Next: implement into actual suspensions.}\]
Summary

1. Source localization
   A localization with hierarchical network is demonstrated.
   → Low sensitivity detector can contribute.
   → 4th detector contributes. → useful for EM follow-up.

2. Detector development
   1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
   2) Its performance were tested.
      → Simulation gives reasonable prediction.
   3) Active control system for a KAGRA-SAS is designed.
      → Next: implement into KAGRA suspensions.
Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii
Seismic noise of Kamioka (on 2016.5.10)

Seismic noise was measured on 2016.5.10.

PR3 measurement was conducted 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 $\sim 5e3$. 

**Measured**

1/e decay time without controls

- Type-Bpp (measured)
- Type-B1proto (measured)

- $Q = 5000$
- $Q = 2$

**Model**

1/e decay time without controls

- Type-Bpp (model)
- Type-B1proto (model)

- $Q = 1e6$
- $Q = 1$
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

Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii

41 / 37
Designing active control system / Type-Bp SAS

1. Calm-down phase

2. Lock-acquisition phase

3. Observation phase

- DC+Damp
- DC
- Damp
- Optical sensors
- Displacement sensor (LVDT)
- Displacement sensor (OSEM)

- DC+Damp
- DC
- Damp
- Optical sensors
- Displacement sensor (LVDT)
- Displacement sensor (OSEM)

- DC + Damp
- Optical sensors
- Displacement sensor (LVDT)
- Displacement sensor (OSEM)

Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii
TypeBpp SAS
Eigen mode List : 24 modes
TypeBp SAS
Eigen mode List : 36 modes
<table>
<thead>
<tr>
<th>#21</th>
<th>#22</th>
<th>#23</th>
<th>#24</th>
<th>#25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.261Hz</td>
<td>1.261Hz</td>
<td>1.351Hz</td>
<td>1.352Hz</td>
<td>1.369Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#26</th>
<th>#27</th>
<th>#28</th>
<th>#29</th>
<th>#30</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.906Hz</td>
<td>11.611Hz</td>
<td>15.924Hz</td>
<td>48.97Hz</td>
<td>64.629Hz</td>
</tr>
</tbody>
</table>

Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii
<table>
<thead>
<tr>
<th>#31</th>
<th>#32</th>
<th>#33</th>
<th>#34</th>
<th>#35</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.843Hz</td>
<td>78.843Hz</td>
<td>97.094Hz</td>
<td>98.66Hz</td>
<td>100.617Hz</td>
</tr>
</tbody>
</table>

- **Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii**
* Start to generate skymaps with 4 detector (V1, K1 threshold = 3.5)
Calculation setup / 3 detector network by HLV

2. Transform HL into HLV coincidences.

1) Generating V1 triggers

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

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

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

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

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)
Expected localization performance / by HLV

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

HL+Vrandom

<table>
<thead>
<tr>
<th>SNR (H)</th>
<th>SNR (L)</th>
<th>SNR(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.8</td>
<td>11.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

HL+Vinjection

<table>
<thead>
<tr>
<th>SNR (H)</th>
<th>SNR (L)</th>
<th>SNR(V)</th>
</tr>
</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.
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.
Calculation setup / 4 detector network by HLVK

2. Transform HL into HLVK coincidences.

1) Generating V1 triggers

V1 trigger based on random parameters: \( V_r, K_r \)

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

V1 trigger based on injection parameters: \( V_i, K_i \)

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

2) Mixing V1 triggers

Case 1: worst case
HL+\( V_r \), HL+\( K_r \), HL+\( V_r+K_r \) or HL
(Based on FAP)

Case 2: best case
HL+\( V_i \), HL+\( K_i \), HL+\( V_i+K_i \) or HL
(Based on SNRth)

Case 3: Realistic case
HL+\( V_r \), HL+\( K_r \), HL+\( V_r+K_r \), HL+\( V_i \), HL+\( K_i \), HL+\( KVi+K_i \), HL+\( Vr+K_i \), HL+\( ViKr \), or HL
(Based on FAP and SNRth)
Expected localization performance / by HLVK

HL + Vi + Ki

HL + Vr + Kr

HL + Vi + K

HL + Vr + K

Master’s thesis defense on 3rd February, 2017, Yoshinori Fujii
Expected localization performance / by HLVK

**HL + Vi + Ki**

[Diagram 1]

**HL + Vr + Kr**

[Diagram 2]

**HL + Vr + Ki**

[Diagram 3]

**HL + Vi + Kr**

[Diagram 4]