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!
For starting astronomy, 

→ Source localization.

for follow-up observation.
From where?

Gravitational wave

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

Time delay

Localization

Delay \( \Delta t \)

SNR

Time
For localization, we want..

→ Several detectors!

Continuous observation

All sky coverage

Precise localization!
Different sensitivities.. OK?

Ex.) SNR > 5 $\rightarrow$ detection

(At the beginning)
Different sensitivities.. OK?

Ex.) SNR > 5 \rightarrow detection

1) Triple (or more) coincidence
   \rightarrow Rare

2) Double coincidence
   \rightarrow Not precise localization

(At the beginning)
Hierarchical network search

**If**

1. A trigger is detected by *high sensitivity* detectors with *high SNR threshold*

2. Analyze *low sensitivity* detectors with *low SNR threshold* using *small time window*.
Assumption in calculation

1. GW-EM pipeline for GWs from CBC

GW detectors → MBTA → BAYESTAR → EM telescopes

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

2. Two LIGOs (70 Mpc), Virgo (20 Mpc)

High sensitivity × 2 / Low sensitivity × 1
Calculation main flow 1

MBTA → Existing measured data (H)

MBTA → Artificial data (V)

Time of arrival, SNR, Phase.

BAYESTAR → Sky map probability

248 Injection data

My calculation

(Random event) or (True event + fluctuation)
Calculation 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.)

Accuray

Precision

HL: 137 deg²

HL: 840 deg²
→ By including low sensitivity detector, errors on sky maps will be reduced by a factor of \( \sim 0.7 \) than HL.
How about 4 detectors, HLVK?

(High: 70 Mpc)  (Low: 20 Mpc)
LIGO Hanford (H)   Virgo (V)
LIGO Livingston (L)
(KAGRA (K)  (Low: 20 Mpc)
(Assumed situation)
Expected performance, HLVK

(SNR threshold for H, L = 5.)

HL: 137 deg$^2$

93 deg$^2$

HL: 840 deg$^2$

600 deg$^2$
Expected performance, HLVK

(SNR threshold for H, L = 5.)

Accuracy → Not so improved..
Precision → improved!

4th detector contributes to improvement!
Summary 1
A localization with a hierarchical network is demonstrated.

In network by 3 GW detectors (70 Mpc × 2 and 20Mpc),
Accuracy
Precision are reduced by a factor of ~ 0.7 than HL.
→ **Low sensitivity detector can contribute!**

In network by 4 GW detectors (70 Mpc × 2 and 20Mpc × 2),
Accuracy: HLV ~ HLVK
Precision: reduced by a factor of ~ 0.8 than HLV.
→ **4th detector can contributes!**
→ **useful for follow-up observation!**
Source localization $\rightarrow$ detector development

We want ..

Necessary to improve sensitivity!

$\star$: True position

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

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

Ex. KAGRA

3 m

Mirror (dummy)
Detector noise

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

→ Necessary to suppress

So many noise sources...

In case of KAGRA

Detector noise [1/√Hz]

Seismic noise

Frequency [Hz]
Seismic noise
Seismic noise

- Seismic noise (Tokyo)
- Seismic noise (KAGRA site)
- Target sensitivity

Graph showing displacement versus frequency with a target sensitivity of $10^{-8}$.
Seismic attenuation

Mirror displacement $x$ [m/$\sqrt{\text{Hz}}$]

Frequency [Hz]

Ground
Single
Double
Triple

Mirror

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Seismic attenuation

Mirror displacement $x$ [m/$\sqrt{\text{Hz}}$]

-5 $\quad$ -10 $\quad$ -15 $\quad$ -20 $\quad$ -25 $\quad$ -30 $\quad$ 0.1 $\quad$ 1 $\quad$ 10

Ground  Black  
Single  Red  
Double  Green  
Triple  Blue  
5-stage  Pink

KAGRA suspension

Requirement

Ex. KAGRA

Mirror (dummy)

3 m

Ground  Single  Double  Triple  5-stage

Mirror displacement $x$ [m/$\sqrt{\text{Hz}}$]
Resonance damping

Starting interferometer operation
Resonance damping

→ Active control

Starting interferometer operation

Stable interferometer operation
KAGRA project

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

KAGRA interferometer
KAGRA project

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

iKAGRA
1) test run in 2016
2) Simple interferometer

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iKAGRA suspension development

Development work:
1) Assembly
2) Measurement
3) Upgrade for final phase

iKAGRA suspension:
Alignment mirror of iKAGRA for initial alignment for stable operation.
Assembly

Mirror protection

2015.10
Assembly

Mirror protection

Mirror (bloody expensive)
Assembly

2015.10

Mirror protection

Mirror (bloody expensive)
Assembly

2015.10

Mirror protection

Mirror (bloody expensive)

2016.2
Sensors and actuators

Displacement sensor and coil-magnet actuator 1

Angular sensor

Displacement sensor and coil-magnet actuator 2

iKAGRA suspension

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1. Frequency response

For each Component:

- **Frequency [Hz]**: 10, 1, 10, 1, 10, 1
- **Phase [deg]**: 0, 90, 180, 90, 180
- **Amplitude**: Simulation: $\propto f^{-2}$

![Diagram of frequency response](image)
1. Frequency response

For each Components:

1) Measurement ➔ Consistent with Simulation

2) Components ➔ Pendulum
2. Decay time

For damping resonances

1/e decay time

DC

Damp
2. Decay time **without** damping

Measured

![Graph showing decay time vs. resonant frequency](image)

Control OFF

- **$\frac{1}{e}$ decay time**

- **Measured**

- **Fitted**
2. Decay time with damping

Measured

Control OFF  Control ON

Decay time [sec]

Resonant frequency

1/e decay time

Resonances → damped
2. Decay time with damping

Measured

Simulated

Simulation \rightarrow consistent with measurement
Measurement:

1. Frequency response
   - Suspension $\rightarrow$ Pendulum
   - Resonances $\rightarrow$ Damped
   - Measurement $\rightarrow$ Consistent with simulation

2. Damping time
   - $1/e$ decay time
Upgrade: iKAGRA $\rightarrow$ final KAGRA

In order to meet final requirements:

**Initial phase**

**Final phase**

$\rightarrow$ Design active control systems.

Initial phase

Final phase

Add one more stage

Design active control systems.
Steps for observation

Free swinging

Calm-down phase

All stages → Damping

Interferometer Lock

Observation phase

Upper stage → Damping

Lower stage → Alignment
Calm-down phase: 
Suppress large disturbance

Requirement: 1min

1/e decay time

Control OFF

Decay time [sec] vs. Frequency [Hz]
Calm-down phase: 
**Suppress** large disturbance

![Graph showing frequency vs. decay time with control OFF and ON]

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

Requirement: 1 min

1/e decay time

Frequency [Hz]

Decay time [sec]

- Control OFF
- Control ON
Observation phase: Suppress RMS (Root Mean Square) & control noise

Requirement: 2urad

![Graph showing frequency versus magnitude or RMS][1]
Observation phase: Suppress RMS (Root Mean Square) & control noise

Requirement: $2 \mu$rad

Magnitude [rad/Hz] or RMS [rad]

Frequency [Hz]

Requirement: $10^{-15}$ m/√Hz at 10 Hz

Magnitude [m/√Hz]

Frequency [Hz]
Summary 2

1) An iKAGRA suspension was assembled for iKAGRA operation.
2) Its performance were tested.
   → Measurement: consistent with simulation.
3) Active control system for a suspension is designed.
   → Clam-down phase: resonances → damped.
   → Observation phase: RMS & control noise → suppressed.
Summary

1. Source localization

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

2. Detector development

1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
2) Its performance were tested.
   - Simulation was consistent with measurement.
3) Active control system for type-Bp suspension is designed.
   - Clam-down phase: resonances damped.
   - Observation phase: RMS & control noise suppressed.
Summary

1. Source localization

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

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1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
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   → Simulation was consistent with measurement.
3) Active control system for type-Bp suspension is designed.
   → Clam-down phase: resonances → damped.
   → Observation phase: RMS & control noise → suppressed.
Seismic noise of Kamioka (on 2016.5.10)

Seismic noise was measured on 2016.5.10.

PR3 measurement was conducted on 2016.5.24.
Performance test 1

1) Control OFF → Necessary to feedback measurement.

Measured

Simulated
Angular fluctuation of the mirror

Measured angular fluctuation of the mirror (Yaw):

- **Requirement:** 0.3 urad

RMS values:
- **Control OFF:** 0.63 urad
- **Control ON:** 0.040 urad

Measured angular fluctuation of the mirror (Pitch):

- **Requirement:** 0.3 urad

RMS values:
- **Control OFF:** 0.4 urad
- **Control ON:** 0.1 urad
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
Designing active control system / Type-Bp SAS

1. Calm-down phase

2. Lock-acquisition phase

3. Observation phase

Optical sensors

Displacement sensor (OSEM)

Displacement sensor (LVDT)

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

DC+Damp

DC

Damp

WFS
Designing active control system 1

Calm-down phase:
Suppress large disturbance

1/e decay time

Not disturb operation → No problem.

(if all sensors available)
Simulation model: Based on rigid-body

Wire → rigid-body

Wires → rigid-body
1. Frequency response

For each Component:

Band width: 0.02 Hz

Window: Hanning

Overlap: 50 %

Average: 5
TypeBpp SAS
Eigen mode List : 24 modes
### TypeBp SAS

Eigen mode List: 36 modes

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<th>#3</th>
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<tr>
<td>#11</td>
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<td>#20</td>
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<td>#32</td>
<td>#33</td>
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<td>97.094Hz</td>
<td>98.66Hz</td>
<td>100.617Hz</td>
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<td>126.38Hz</td>
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<td><img src="image6" alt="Diagram" /></td>
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</table>
Calculation setup: False Alarm Probability (FAP)

\[ \text{FAP} = 1 - \exp(-R \times T) \]

- \( R \): cumulative rate of background triggers per template, above a given threshold, per template,
- \( T \): analyzing time for the V1 (less sensitive detector)

SNR distribution (per template) → Cumulative SNR distribution (per template) → False Alarm Probability (per template)

Should be generated from noise

Should be generated from signal

[Graphs showing SNR distribution, cumulative trigger rate, and false alarm probability]
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)

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

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

- \( SNR \) = metadata + Gauss(0,1)
- \( Timing \) = metadata + Gauss(0,0.66 ms* \( \frac{6}{SNR} \))
- \( Phase \) = measured + Gauss(0,0.25 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)
Mixing triggers: \( \text{HL} \rightarrow \text{HL} \) or HLV

Considered 3 patterns:

Case 1: \( \text{HL} \rightarrow \text{HL} \) or \( \text{HL} + \) random \( V \)

\[
\text{If } p > \text{FAP}, \quad \text{otherwise}
\]

Noise-based trigger, or HL

Case 2: \( \text{HL} \rightarrow \text{HL} \), or \( \text{HL} + V \) based on injection

\[
\text{If } \text{V1 SNR} < \text{threshold}, \quad \text{otherwise}
\]

Signal-based trigger, or HL

Case 3: \( \text{HL} \rightarrow \text{HL} \), or \( \text{HL} + \) random \( V \), or \( \text{HL} + V \) based on injection

\[
\text{If } p > \text{FAP} \text{ and V1 SNR} < \text{threshold}, \quad \text{If } p < \text{FAP} \text{, If } p > \text{FAP} \text{ and V1 SNR} > \text{threshold}
\]

1. Noise-based trigger, or
2. Signal-based trigger, or
3. HL
Update the sky localization performance in the case 3:
Summary of sky localization performance

Number of triggers in the case 1 var.

Number of triggers in the case 2

Number of triggers in the case 3

\[ HL_{Vi} = HL + V_{injection} \]
\[ HL_{Vr} = HL + V_{random} \]

HL
Optimization of Virgo threshold:

SNR threshold for $H, L = 5$. 

*Case 1 (worst)*  
*Case 2 (Best)*  
*Case 3 (Realistic)*
* Start to generate skymaps with 4 detector (V1, K1 threshold = 3.5)
Expected localization performance / by HLV

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

HL+Vrandom

- Typical sky maps in this method
  → sometimes fail to predict the location within 90% confidence area.

<table>
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HL+Vinjection

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Expected localization performance / by HLV

- 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.
2. Transform HL into HLVK coincidences.

### 1) Generating V1 triggers

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

- **SNR** = random following measurement
- **Timing** = \( t_H1 \) or \( t_L1 \)
  + random \([-35ms:35ms]\)
- **Phase** = random \([0:2\pi]\)

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

- **SNR** = metadata + Gauss(0,1)
- **Timing** = metadata
  + Gauss(0,0.66 ms* \( \frac{6}{SNR} \))
- **Phase** = measured + Gauss(0,0.25 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+\( K Vi+K_i \), HL+\( V r+K_i \), HL+\( V iKr \), or HL
  (Based on FAP and SNRth)
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**

![HLVK map](image1.png)  
![HL map](image2.png)

**HL + Vr + Kr**

![HLVK map](image3.png)  
![HL map](image4.png)

**HL + Vr + Ki**

![HLVK map](image5.png)  
![HL map](image6.png)

**HL + Vi + Kr**

![HLVK map](image7.png)  
![HL map](image8.png)