Recent Progress of TAMA300

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on behalf of the TAMA collaboration
TAMA300 interferometer

- **Laser interferometer GW detector**
  - Arm length: 300m
  - Location: National Astronomical Observatory of Japan (Mitaka, Tokyo)

- **purposes**
  - Development of the detector capable to catch GW events in nearby galaxies
  - Establishment of interferometer technologies for LCGT
## Progress of TAMA300

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995-1997</td>
<td>Facility/Vacuum System Construction</td>
</tr>
<tr>
<td><strong>Recombined Interferometer</strong></td>
<td></td>
</tr>
<tr>
<td>1999-2001</td>
<td>6 times of observation runs (Total 1370 hours)</td>
</tr>
<tr>
<td><strong>Recycled Interferometer</strong></td>
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<tr>
<td>2001</td>
<td>Implement of power recycling</td>
</tr>
<tr>
<td>2003-2004</td>
<td>3 times of observation runs (Total 1740 hours)</td>
</tr>
<tr>
<td><strong>Seismic Attenuation System (SAS)</strong></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Start installation of SAS</td>
</tr>
<tr>
<td>2007</td>
<td>Full interferometer lock with SAS</td>
</tr>
</tbody>
</table>
Current focus

- Establishment of detector operation with SAS

Replacement of the vibration isolation system

- pneumatic
- active isolator
- + stack
- + double pendulum

To realize the improvement

- Optimization of SAS control
- Optimization of interferometer control
- Application of digital control system

=> Enables the complex servo system
=> High level automatization of the operation
Interferometer configuration

300m Fabry-Perot Cavity

Optical Levers

Wave Front Sensors

Length sensors

10-W inj.-locked Nd:YAG laser

10-m Mode Cleaner

SAS for test masses
**Seismic Attenuation System**

- **Structure of SAS**
  - Multiple pendulum suspended from IP

**Diagram:***
- **IP top**
- **MGAS filter** (Monolithic Geometric Anti-Spring)
- **platform**
- **inverted pendulum (IP)**
- **double pendulum with recoil mass**
Seismic Attenuation System

- **Vibration Isolation**
  Passive isolation with soft springs + active damping

**Tortional**
- Tortion Pendulum: f~40mHz
- Inverted Pendulum: f~500mHz

**Horizontal**
- Inverted Pendulum: f~30mHz
- Multiple Pendulum: f~650mHz

**Vertical**
- MGAS Filter: f~500mHz
- MiniGAS Filter: f~1.5Hz
Seismic Attenuation System

Active Control of SAS

Local control stabilize the mirror motion
=> to enable lock of the interferometer

Local control
IP Position
Sensor: LVDT
Bandwidth: ~60mHz

IP Inertial damping
Sensor: Accelerometer
Bandwidth: 60m~2Hz

Tortion damping
Sensor: Photo Sensor
Bandwidth: 40mHz

Test mass servo
Sensor: Optical Lever
Bandwidth: ~2Hz

Global control
IP Position
Bandwidth: ~10mHz

Platform
Bandwidth: ~10mHz

Test mass (angular)
Bandwidth: <3Hz

Test mass (Length)
Bandwidth: <1kHz
Inertial damping of IP

- Diagonalization of Sensors / Actuators
  Decompose Actuator -> Sensor response
  into mechanical eigenmodes of IP

  => servo design becomes simpler
  allows the different strategy for each modes
Inertial damping of IP

- **Two loop configuration**

  LVDT loop (position sensing loop) \( f < 60 \text{mHz} \)
  - drift control of the IP position

  Accelerometer loop (inertial sensing loop) \( 60 \text{mHz} < f < 2 \text{Hz} \)
  - stabilization of IP in terms of the inertial frame
  - damping of the pendulum reactions at around 1Hz
Test mass control

- Optical lever servo

Rather complicated servo loops have been realized in virtue of digital control

![Graph showing openloop gain and phase versus frequency with distinct peaks and notches for Yaw and Pitch, along with a note about Unity Gain Frequency ~3Hz.](image-url)
**Performance of SAS**

- **Test mass angular motion**
  Mirror angular motion: sub-μrad\textsubscript{RMS}

  => Sufficiently stable for interferometer operation

  (with previous suspension system: 1.0 μrad\textsubscript{RMS})

### Pitch
- Free Run: 1.4 μrad\textsubscript{RMS}
- Controlled: 0.23 μrad\textsubscript{RMS}

### Yaw
- Free Run: 12 μrad\textsubscript{RMS}
- Controlled: 0.16 μrad\textsubscript{RMS}
Performance of SAS

- Legth Fluctuation of 300-m arm

Comparison with the previous suspension system
=> improvement above 0.1Hz was confirmed

![Graph showing displacement noise vs frequency with comparisons between old and new suspension systems.](image-url)
**Interferometer configuration**

- **300m Fabry-Perot Cavity**
- **10-W inj.-locked Nd:YAG laser**
- **10-m Mode Cleaner**
- **Optical Levers**
- **Wave Front Sensors**
- **Length sensors**
- **SAS for test masses**

**Recycled Fabry-Perot Michelson interferometer**
Interferometer Operation

- Recycling operation with SAS was achieved in July

Control configuration

Test mass length control:
- Analog based servo

- DSP based digital filter
  - only for lock acquisition
  - switched to analog based system after the lock

Test mass alignment control:
- LabView based digital control

  Optical lever control      for fast control
  Wave Front Sensing        for drift control
Digital mass lock filter

- DSP based digital filter (TI TMS32C6713 225MHz)

  Sampling freq: 200kHz
  Control BW: ~800Hz

Realized comparable bandwidth to analog filters
Digital mass lock filter

- Some simple operations to the error signal
  - Trigger at the resonance
    Eliminates glitches by sidebands/ higher order modes
  - Normalizeaton of the error signal by cavity transmitted light
    Expands linear range (about x3)
  - Adaptive change of the digital filter coefficient
    Low frequency gain boost at the lock

=> In combination with SAS, lock of RFPMI was realized even with 3 times weaker actuator
**Pre-emphasis / De-emphasis**

- One of the demerits of the digital system about 100-1000 times larger noise than analog circuits

- Pre-emphasis/De-emphasis filter

![Image of filter diagram]

**Signal level is enhanced while the range at low frequency is preserved**

- **pre-emphasis**: effect of ADC noise is reduced
- **de-emphasis**: effect of DAC noise is reduced
Pre-emphasis / De-emphasis

Analog

Optical Lever

PE: Z 3Hz-P 300Hz

ADC

Digital

Anti-PE: P 3Hz-Z 300Hz

Gain Fader

Servo Filter
Target UGF 2-3Hz

Anti-DE: Z 3Hz-P 300Hz

DAC

Analog

DE: P 3Hz-Z 300Hz

LabView (fs=1kHz)

DSP (fs=200kHz)

Wave Front Sensor

PE: Z 3Hz-P 300Hz

Servo Filter
Target UGF 800Hz

Pound Driver Hall Signal

Matrix Circuit

Coil Driver
Sensitivity

- Tuning of the system still underway
  So far, improvement below 150Hz was confirmed

TAMA300 Displacement Sensitivity
(2007/08/31)

Best with SAS

Previous best
Tuning of the system still underway
So far, improvement below 150Hz was confirmed

TAMA300 Displacement Sensitivity (2007/08/31)

Dark port light power is still attenuated
Alignment control noise (DA noise)
Plan

• How to achieve further improvement
  For alignment noise
    Additional DA noise reduction is in progress
    Activation of fast WFS servo (~x100 better sensing noise)

  For high frequency
    more power at the dark port

  For further investigation
    noise budgetting => needs more stability

  For further improvement of SAS
    performance of SAS is limited by the accelerometers
    => accelerometer study
Summary

- **Current status**
  - SAS is now functioning
  - Shaking down of the detector system Underway. Still a lot of things to do.
  - Improvement was partially confirmed Between 0.1 to 150Hz
  - Gradually getting familiar with digital systems

- **Plan**
  - Improved binary range
    -> participation to AstroWatch campaign
Optical Lever System

- Diode Laser
  optical table attached on the window frange

- Position Sensitive Detector  
  Aperture size: 12mm x 12mm
Locked FP Sensitivity

(2007/08/29)

Displacement noise [m/Hz]

Frequency [Hz]

2006/08/30 1 SAS arm test
2006/09/16 1 SAS arm test
2007/03/15 1st 4 SAS test (OL)
2007/03/16 4 SAS test (WFS)
2007/03/20 A2L tuning
2007/08/15 New TM servo
2007/08/17 A2L tuning
2007/08/28 Coil DE
2007/08/29 OL PE
2003/11/04 RFPMI best
TAMA300 Displacement Sensitivity

Frequency [Hz]

Displacement noise [m/Hz$^2$]

- $\text{dL- (2003/11/04)}$
- $\text{dL- (2007/08/07)}$
- $\text{dL- (2007/08/22)}$
- $\text{dL- (2007/08/29)}$
- $\text{dL- (2007/08/30)}$
- $\text{dL- (2007/08/31)}$
Interferometer Automatization by LabView

Digital Servo / Supervising
Interferometer Automatization by LabView

Dynamic changing of servo parameters

<table>
<thead>
<tr>
<th>Filter Bank Pitch</th>
<th>Filter Bank Yaw</th>
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<tbody>
<tr>
<td><strong>NM1</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Fc p</td>
<td></td>
</tr>
<tr>
<td>Q p</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
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<tr>
<td>0.979</td>
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<tr>
<td>0.4565</td>
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<tr>
<td>2.466</td>
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<td>0.26</td>
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<td>19.4</td>
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<td>28.2</td>
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<td>37.7</td>
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<tr>
<td>25</td>
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<tr>
<td>0.01</td>
<td></td>
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<tr>
<td></td>
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</tr>
<tr>
<td><strong>Fc z</strong></td>
<td><strong>Fc p</strong></td>
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<tr>
<td>2.915</td>
<td>0.4565</td>
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<tr>
<td>2.343</td>
<td>0.26</td>
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<td>0.01</td>
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<tr>
<td><strong>Q z</strong></td>
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<td>38.37</td>
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<tr>
<td><strong>Gain</strong></td>
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</table>

*NM1* represents the filter bank for pitch and yaw. Each row corresponds to a different filter set, with columns indicating the parameters (Fc, Q, Gain) for both pitch and yaw. The *Submit* and *Close* buttons are used to apply changes and close the interface, respectively.
Digital Filter ~ gain up issue

- Low frequency gain boost at the lock
  - lock acquisition with large gain margin
  - => low freq gain boost for larger control gain after the lock

- Sudden gain up can cause unlock
  - Sudden increase of suppression
Digital Filter ~ gain up issue

Adaptive change of digital filter coefficient

Initial State                       Final State

\[ H(z) = 1 \quad \text{Final State} \quad H(z) = 1 + b_1 z^{-1} + b_2 z^{-2} \]

\[ H(z) = 1 + a_1 z^{-1} + a_2 z^{-2} \]

2nd order zero

2nd order pole

\[ H(z) = 1 + b_1 z^{-1} + b_2 z^{-2} \]

\[ H(z) = 1 + [a_1 \alpha + b_1 (1-\alpha)] z^{-1} + [a_2 \alpha + b_2 (1-\alpha)] z^{-2} \]

\( \alpha = 0 \): initial state

\( \alpha = 1 \): final state
Digital Filter ~ gain up issue

- What happens in between?
  => modest change of pole freq and Q

- Suppression ratio
  = inverse of DC gain
  = \([\left(\frac{f_{\text{pole}}}{f_{\text{zero}}}\right)^2]^{-1}\]

  linear change of \(\alpha\)
  => linear change of suppression
  This is ideal!

  low computation cost
  => useful for fast digital control