Online monitoring of alignment noises in TAMA300

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Abstract. We report on online monitoring of alignment noises in TAMA300 detector of Japan. The continuous monitoring of noise contributions is necessary for the veto analysis. To detect gravitational wave signals, fake events should be removed by veto analysis. We investigated a procedure for evaluating various noise contributions continuously. The procedure has been applied to several noise sources such as laser intensity and auxiliary length control. An investigation of alignment noises is the focus of this paper.

1. Introduction
Since 1999, the Japanese laser interferometric gravitational-wave (GW) detector TAMA300 has performed observations nine times. Total 3086 hours of data have been accumulated in these observations. The detector sensitivity and its stability have been also improved gradually during the observation periods [2]. The evaluation of the noise contributions has been performed since the beginning of TAMA construction in order to reduce noise level. It is useful to hunt the noise sources.

To detect the gravitational wave signals [3], one must remove noises which might be misidentified as GW signals [4, 5]. Our study focuses on evaluating various noises quantitatively and on noise mechanisms which contaminate the GW channel. Continuous monitoring of the noise contributions is necessary for veto analyses, because the detector condition will change occasionally during long-time observation. The veto analysis with continuous noise monitoring will remove burst like noises, and reduce non-stationary noise contributions, from the inspiral search and various GW searches.

To realize such an online monitoring system, the study has been carried with the following procedure:
(i) Possible noise paths were considered, then each transfer function (TF) was calculated,
(ii) Measurements of the transfer function were made by injecting artificial signal at the noise sources,
(iii) The dominant noise mechanism was identified among the possibilities,
(iv) Possible time variation of the noise coupling coefficient and how to monitor it were considered

The investigation of noise contamination mechanisms is described in Section 2. In Section 3 and 4, the details of the noise coupling coefficients and the online monitor are described.
2. Alignment noise

The above noise investigation procedure has been applied to several noise sources such as laser intensity and auxiliary length controls. As an example, an investigation of alignment noises is reported in this paper.

TAMA is a power-recycled Fabry-Perot Michelson interferometer which consists of many mirrors. The alignment noises originate from rotational motion of the mirrors. If a laser beam passes through the center of mirror gyration, there is no influence on GW channel in principle. Otherwise, the rotational motions are converted to the displacement noise along the beam axis. In this paper, such a noise contamination of the GW channels is called alignment noise. Noise coupling coefficients are determined by displacements between beam axis and the mirror center. Hereafter the displacement is called off-centering.

In the frequency band of TAMA observation, such rotational motions are caused by alignment sensor noises. The rotational motions are well suppressed by a wave-front sensing and servo systems which have a unity gain frequency of 10 Hz. Measurements of the transfer functions and noise spectra revealed that the rotational motions contaminate GW channel via path illustrated in Fig. 1.

\[ L_{\text{align}} = \epsilon_a \cdot \alpha, \] 
\[ \alpha \sim \frac{A_a}{WF_a} V_a \quad (f \gg 10\text{Hz}), \]

therefore, 
\[ L_{\text{align}} = \epsilon_a \cdot \frac{A_a}{WF_a} V_a . \]

Here \( \alpha \) is a rotational motion of the mirror. \( \epsilon_a \) is a coupling coefficient of the alignment noise.
WF, A, H, D and F are transfer functions of whitening filters, coil actuator, an interferometer, photo detector and servo filter, respectively.

The coupling coefficient can be obtained by measurement of transfer function \( TF \) from \( V_a \) to \( V_0 \) by injecting artificial signal of \( V_{\text{inj}} \) to the alignment control servo.

\[
TF \equiv \frac{V_0}{V_a} = \frac{G A WF_{fb}}{1 + G A \cdot WF_{a}} \cdot \epsilon_a
\]  
(4)

\[
\epsilon_a = \frac{1 + G A \cdot WF_{a}}{G A WF_{fb}} \cdot \frac{V_0}{V_a}
\]  
(5)

\[
G \equiv H \cdot D \cdot F \cdot A
\]  
(6)

Here \( G \) is open-loop gain of the \( L_- \) control servo. We measured the transfer function of \( A, A_a, WF_{fb} \) and \( WF_{a} \) beforehand. These are assumed to be stable. The open-loop gain of \( G \) is being monitored by online calibration system [1]. By monitoring the ratio of \( V_0 \) to \( V_a \), we can obtain the coupling coefficient continuously.

3. Coupling coefficient

The relationships between the coupling coefficient and off-centering were investigated. As described above, the coupling coefficient \( \epsilon_a \) corresponds to the amount of off-centering exactly. It has a dimension of length. To reduce the noise contributions, each mirror is controlled by the following methods. The gyration centers of the front mirror are adjusted against the beam axis. Four coil actuators are installed for each mirror to control cavity length and two rotational motions. The coupling coefficients are minimized by adjusting the actuator gain balance. For end mirrors, beam orientations are controlled by steering mirrors.

The relationships between the coupling coefficient and actuator gain balance are shown in Fig. 2. The left and right panels show that of pitch and yaw motion, respectively.

![Figure 2](image)

**Figure 2.** The relationships between the coupling coefficient and off-centering were investigated for a front mirror. Front mirror centers are adjusted by the actuator gain balance. The left and right panels show the relationship for a front mirror pitch and yaw motion, respectively.

After the adjustment of the actuator gain balance, we can reduce the off-centering to 0.1mm or less. Due to the beam jitter, we can not adjust the centering more finely than this. Similar centering accuracies are also realized for the end mirrors with beam orientation control.
4. Monitoring of noise spectra
The spectrum of the alignment noise is useful for monitoring various detector conditions, and
for veto analysis. To obtain the total amount of the alignment noise, eight degrees of freedom
are taken into account. In our detector, four mirrors, which are components of two Fabry-Perot
cavities, have the most important role in producing the GW signal. Moreover, each mirror has
two important rotational degrees of freedom, pitch and yaw. Because these degrees of freedom
are assumed to be independent, their noises are added in quadrature Figure 3 shows noise
spectrum of $L_-$ and the total alignment noise with solid and dashed line, respectively.

To monitor the coupling coefficients, a calibration signal at a fixed frequency is injected into
the alignment servo loop. Because there are eight degrees of freedom, eight calibration peaks
are needed to monitor each loop simultaneously. To minimize the number of calibration peaks,
each coupling coefficient is evaluated every 210 sec with a calibration signal. The calibration
frequency is chosen to be 78.125Hz, because alignment noise is dominant in the frequency region
below 100Hz as shown in Fig. 3. The Nyquist frequency of our analog-to-digital converter limits
an observation band to 156.25Hz. In the frequency region above 200Hz, other noise sources
contaminate to the GW channel.

5. Summary
We investigated a procedure for evaluating various noise contributions continuously. This
procedure has been applied to several noise sources such as laser intensity and auxiliary length
control. An investigation of alignment noises is the focus of this paper.

Online monitoring of the alignment noises is useful for the veto analysis. To detect
gravitational wave signals, fake events must be removed. Fake events can be identified by
this noise monitor. The following results were obtained in this study:
• Noise contamination mechanisms can be investigated by transfer function measurements. It is a useful tool for noise hunting.

• Monitoring of the coupling coefficient is also useful to check detector conditions and to minimize noise contributions. Using this monitor, more stable sensitivity for gravitational signals will be available.

Online veto analysis using a similar technique is also under investigation.

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