Stable Operation of a 300-m Laser Interferometer with Sufficient Sensitivity to Detect Gravitational-Wave Events within Our Galaxy

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TAMA300, an interferometric gravitational-wave detector with 300-m baseline length, has been developed and operated with sufficient sensitivity to detect gravitational-wave events within our galaxy and sufficient stability for observations; the interferometer was operated for over 10 hours stably and continuously. With a strain-equivalent noise level of $h \sim 5 \times 10^{-21}/\sqrt{\mathrm{Hz}}$, a signal-to-noise ratio of 30 is expected for gravitational waves generated by a coalescence of $1.4 M_\odot$-$1.4 M_\odot$ binary neutron stars at 10 kpc distance. We evaluated the stability of the detector sensitivity with a 2-week data-taking run, collecting 160 hours of data to be analyzed in the search for gravitational waves.

Introduction.—The direct observation of gravitational waves (GW) is expected to reveal new aspects of the universe [1]. Since GWs are emitted by the coherent bulk motion of matter, and are hardly absorbed or scattered, they carry different information from that of electromagnetic waves. However, no GW has yet been detected directly because of its weakness. In order to create a new field of GW astronomy, several groups around the world are devel-oping laser interferometric GW detectors. Compared with resonant-type GW detectors [2], interferometric detectors have an advantage in that they can observe the waveform of a GW, which would contain astronomical information.

Interferometric GW detectors are based on a Michelson interferometer. The quadrupole nature of a GW causes differential changes in the arm lengths of the Michelson interferometer, which are detected as changes in the

interference fringe. Interferometric detectors have been investigated with many table-top [3] and prototype [4] experiments to evaluate the principle of GW detection and their potential sensitivity to GWs. With the knowledge obtained from these experimental interferometers, several GW detectors with baseline lengths of 300 m to 4 km are under construction: LIGO [5] in the U.S., VIRGO [6] and GEO [7] in Europe, and TAMA [8] in Japan. In these detectors, both high sensitivity and high stability are required because the GW signals are expected to be extremely small and rare.

TAMA is a Japanese project to construct and operate an interferometric GW detector with a 300-m baseline length at the Mitaka campus of the National Astronomical Observatory in Tokyo (35°40′N, 139°32′E). In this article, we report on an important achievement in interferometric detectors: the TAMA detector was operated with sufficient sensitivity and stability to observe GW events at the center of our galaxy. The interferometer was operated stably and continuously over several hours in typical cases, and over 10 hours in the best cases. The noise-equivalent sensitivity was $h \sim 5 \times 10^{-21}/\sqrt{Hz}$ at the floor level (700 Hz to 1.5 kHz). With this stability of the sensitivity, TAMA has the ability to detect GW events throughout much of our galaxy: chirp signals from the coalescence of binary neutron stars or binary MACHO black holes [9], and burst signals from supernova explosions.

Detector configuration.— In the interferometer, called TAMA300, the arms of the Michelson interferometer are replaced by 300 m Fabry-Perot arm cavities to enhance the sensitivity to GWs (Fig. 1). The arm cavities have a finesse of around 500, and a cutoff frequency of about 500 Hz; the light is stored in the cavities for about 0.3 msec. Since a high-power and stable laser is required as a light source, we use an LD-pumped Nd:YAG laser with an output power of 10 W [10]. In addition, a mode cleaner is inserted between the laser source and the main interferometer to reject higher-mode beams and to stabilize the laser frequency. The mode cleaner of TAMA300 is an independently suspended triangular ring cavity with a length of 9.75 m [11]. Electro-optic modulators (EOM) for phase modulation (for mode cleaner and the main interferometer control) are placed in front of the mode cleaner. Thus, the wave-front distortion by the EOM is rejected by the mode cleaner before entering into the main interferometer.

The mirrors of the main interferometer are made of fused silica. Each mirror has a diameter of 100 mm, and a thickness of 60 mm. The mirrors are coated by an IBS (ion-beam sputtering) machine to realize low-optical-loss surfaces [12].

The mirrors of the main interferometer and the mode cleaner are isolated from seismic motion by over 165 dB (at 150 Hz) with three-stage stacks [13] and double-pendulum suspension systems [14]. The suspension points are fixed to motorized stages, which are used for an initial adjustment of the mirror orientations. The fine position and orientation of each mirror is controlled with coil-magnet actuators; small permanent magnets are attached to the mirror.

The interferometer is housed in a vacuum system comprising eight chambers connected with beam tubes with a diameter of 400 mm. With surface processing, called ECB
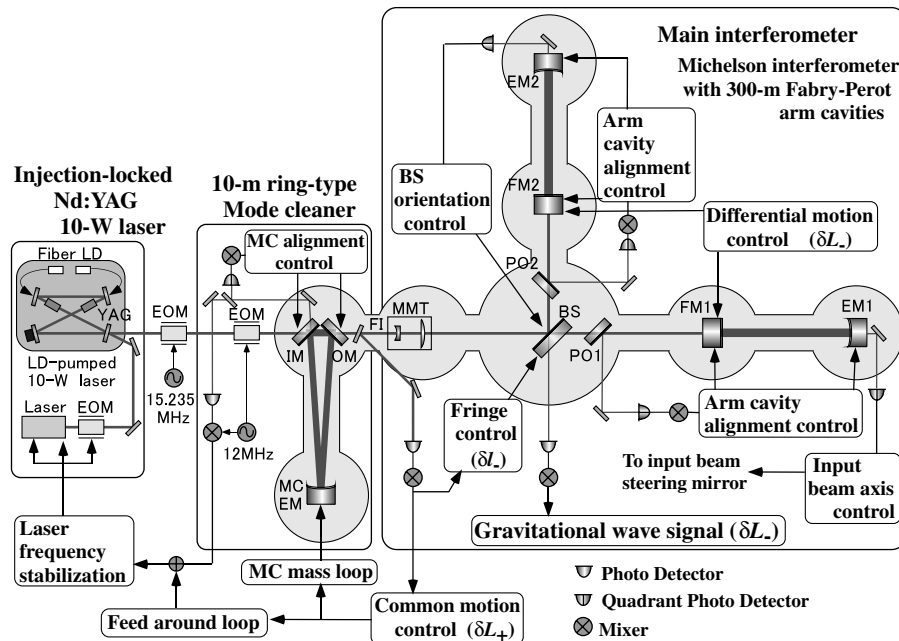

FIG. 1. Optical and control design of the TAMA300 interferometer. TAMA300 is a Fabry-Perot-Michelson interferometer with a baseline length of 300 m. A triangular ring cavity is inserted between the main interferometer and the laser source as a mode cleaner. The control system is designed to realize high sensitivity and stability of the detector at the same time.

(electrochemical buffing), a vacuum pressure of less than 10^{-6} Pa is achieved without baking [15].

The control system is designed to realize high sensitivity and stability at the same time. It consists of three parts: a length control system to keep the interferometer at its operational point, an alignment control system to realize short-term ($\sim$1 min) stability and high sensitivity, and a beam-axis drift control system for long-term ($\sim$a few hours) stable operation. A frontal modulation scheme [16] is used for the length control; 15.235 MHz phase modulation is used for signal extraction. The differential motion signal of the arm cavities (δL_-) is fed back to the front mirrors with a bandwidth of 1 kHz. The common motion signal (δL_+) is fed back to the mode cleaner and the laser source to stabilize the laser frequency. The motion in the Michelson interferometer part (δl_-) is fed back to the beam splitter.

An alignment control system is necessary for stable and sensitive operation because angular fluctuations (about several μrad) of the suspended mirrors excited by seismic motion make the interferometer unstable. The control signals are extracted by a wave-front-sensing scheme [17], and fed back to each mirror; the angular motions are suppressed by over 40 dB to 10^{-8} rad in root mean square.

Low-frequency drift control of the laser beam axis plays an important role in maintaining long-term operation. The beam axes are controlled with 300 m optical levers; the beam positions of the light transmitted through the arm cavities are monitored with quadrant photo detectors, and are fed back to the input steering mirror and the beam splitter of the main interferometer.

The data-acquisition system comprises a high-frequency part for the main signals and a low-frequency part for detector diagnosis. The main output signals of the interferometer are recorded with high-frequency analog-to-digital converters (2×10^4 samples/sec, 16 bit) after passing through whitening filters and 5 kHz antialiasing low-pass filters. Seven channel signals are recorded together with a timing signal, which provides a GPS-derived coordinated universal time (UTC) within an accuracy of 1 μsec. Along with the high-frequency system, 88 channels of monitoring signals are collected with a low-frequency data-acquisition system for interferometer diagnosis.

Detector noise level.—Figure 2 shows the typical noise level of TAMA300 (black curve). The displacement noise level of the interferometer is 1.5×10^{-18} m/$\sqrt{\text{Hz}}$, which corresponds to 5×10^{-21}/$\sqrt{\text{Hz}}$ in strain. Almost all of the noise sources which limit the interferometer noise level have been identified. The gray curve in Fig. 2 represents the total contribution of the identified noise sources: seismic motion (10–30 Hz), alignment-control noise (30−300 Hz), Michelson phase-detection noise (300 Hz−3 kHz), and the laser frequency noise (3–10 kHz). The seismic noise and the laser frequency noise are estimated to satisfy the design requirements in the observation band (around 300 Hz).
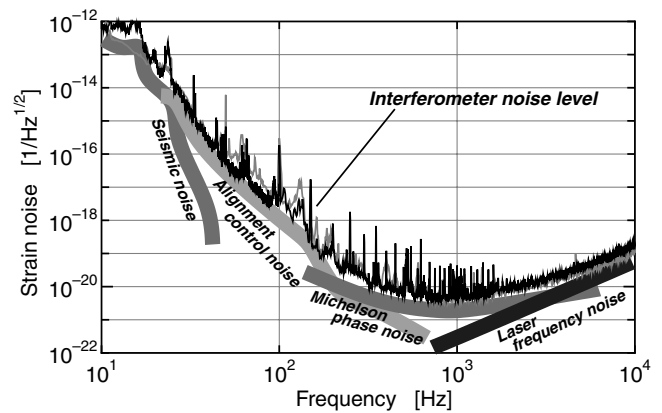

FIG. 2. Noise level of the TAMA300 interferometer (black curve) and the total contribution of identified noise sources (gray curve). The floor level is 5×10^{-21}/$\sqrt{\text{Hz}}$ in strain. The thick curves represent the contribution of the noise sources.

Though the alignment control system is indispensable for the stable operation of the interferometer, this system can introduce excess noise to the interferometer [18]. The noise in the alignment control error signal causes displacement noise by coupling with miscentering of the beam on a mirror, and efficiency asymmetries of the coil-magnet actuators on a mirror. In order to reduce this noise, the actuator balances are adjusted so that the rotational center is at the beam spot on a mirror. In addition, the beam position on each mirror is controlled to be still by the beam-axis control system.

The noise floor level is limited by the phase-detection noise of the Michelson part of the interferometer. Phase changes in the light caused by GW are amplified in the arm cavities, and detected by the Michelson interferometer. In order to realize the designed detector sensitivity, the noise level of the Michelson part of the interferometer should be limited only by the shot noise in the observation band. However, in TAMA, as well as by the shot noise, it is currently limited by the scattered light noise caused by the antireflection coating of the mode-matching telescope (MMT in Fig. 1) between the main interferometer and the mode cleaner. To realize the designed detector sensitivity which is purely limited by the shot noise, the scattering noise should be removed.

Stability of operation.—With the total system described above, we performed a 2-week observation run from 21 August to 3 September 2000. Figure 3 shows the operational state during the observation; the gray and black boxes represent the time when the interferometer was operated and when the data were taken, respectively. The time is shown both in UTC and in Japan standard time (JST). The interferometer was operated for over 160 h, 94.8% of the total data-taking-run time. (Periods of continuous lock shorter than 10 min are not included.) We operated the interferometer mainly during the night for the efficient collection of high-quality data. During the
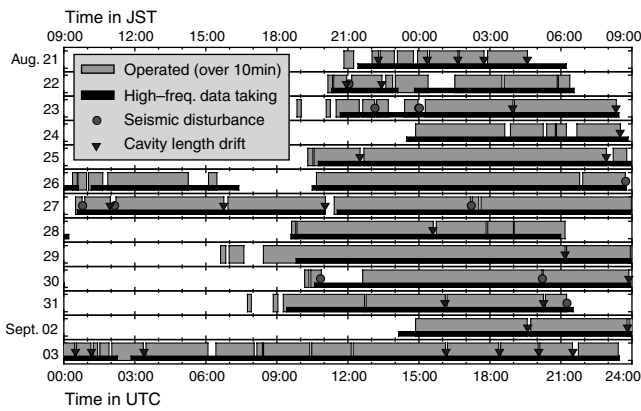
FIG. 3.   Operation status of the TAMA interferometer during a data-taking run performed from 21 August to 3 September in the year 2000. The interferometer was operated stably for over 160 h, 94.8% of the total data-taking-run time.

observation, the noise level was degraded slightly from the Fig. 2 level, because of electronic noises by many cables connected to the interferometer for data taking. The longest continuous locking time was over 12 h (several hours in typical cases); the main cause of loss of lock of the interferometer was large seismic disturbances, including earthquakes (closed circles), and rather large drifts of δL_+ (triangle marks). From a coincidence analysis of signals from seismometers placed at the center and end rooms, we found that the interferometer was knocked out of lock by accelerations of 12 mgal (1–10 Hz frequency range). The interferometer was also knocked out of lock by large drift of δL_+; a drift of over 120 μm could cause saturation in the feedback loop. The other causes of loss of lock are thought to be local seismic disturbances caused by human activities, spikes due to instability of the laser source, and so on.

The interferometer noise level was stable thanks to the alignment and drift control systems; the drift of the noise level averaged for 1 min was kept within a few dB, typically. During the 2-week data-taking run, the noise floor-level drift was kept within 3 dB for about 90% of the total operation time. In addition, in typical cases, the noise level was easily recovered without any manual adjustment after the unlock and relock of the interferometer with these automatic control systems. The noise level of the interferometer was calibrated continuously using a sinusoidal calibration signal at 625 Hz; from the amplitude and phase of this peak signal, we estimated the optical gain and cutoff frequency of the cavity. The Gaussianity of the noise level was evaluated every 30 sec. We observed about 10 non-Gaussian (confidence level of 99%) events per hour in this observation run. The non-Gaussian noise will be partly removed by veto analysis using other channels, such as seismic motion, laser intensity noise, contrast fluctuation, and a δL_+ signal.

In order to check the GW-detection ability of TAMA, we calculated the expected SNR for GW from inspiraling

binaries with the interferometer noise spectrum and calculated chirp signals (Fig. 4) [19]. Here, we assumed optimally polarized GWs from an optimal direction for the detector. TAMA would detect GW events at the Galactic center with sufficient SNR; the SNR is about 30 in the case of chirp signals from a coalescence of $1.4M_\odot$-$1.4M_\odot$ binary neutron stars at 10 kpc distance. With the burst signals from supernova explosions, TAMA would detect GWs with a strain amplitude of $h_{rms} \sim 1 \times 10^{-18}$ (which corresponds to a mass energy of $\sim 0.01M_\odot$, again at the distance to the Galactic center) with a SNR of about 10 at the frequency band from 700 Hz to 1 kHz. However, as well as a veto analysis with the other recorded channels, a coincidence analysis with other GW detectors or other astronomical channels will be required for the detection to reject non-Gaussian noise background.

Conclusion.—The TAMA300 interferometer has been operated stably for over 10 h without loss of lock, with a noise-equivalent sensitivity of $h \sim 5 \times 10^{-21}/\sqrt{Hz}$ at the floor level. With this sensitivity and stability, TAMA has the ability to detect GW events within our galaxy, though such events are expected to be very rare. In order to increase the detection probability for GW events farther away from our galaxy, we are improving the detector sensitivity and stability further. Almost all of the noise sources which limit the detector sensitivity have been identified. The noise level will be improved with new alignment control filters and a reflective mode-matching telescope. The stability of the operation will be improved further with installation of an active isolation system and replacement of a suspension system by one with effective damping.

The achieved performance of the TAMA detector is a significant milestone in the quest for direct detection of GW, and for the establishment of GW astronomy with interferometric detectors.
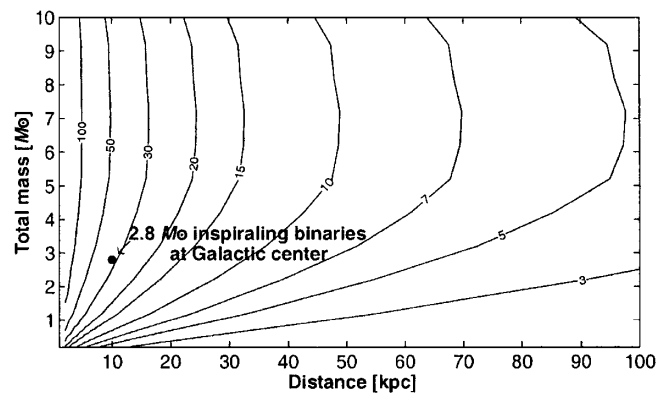
FIG. 4.   Contour plot of expected SNR for GW from inspiraling compact binaries with equal mass. Optimally polarized GWs from an optimal direction for the detector are assumed. TAMA has the sensitivity to detect $1.4M_\odot$-$1.4M_\odot$ binary coalescence at Galactic center with SNR of 30.

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