Current status of the TAMA300 gravitational-wave detector

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Abstract. TAMA300, an interferometric gravitational-wave detector with a 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 24 hours stably and continuously with a strain noise level of $2 \times 10^{-21}\,/\sqrt{\mathrm{Hz}}$. We carried out nine observation runs, and obtained over 2700 hours of data so far. These data are being analyzed to look for gravitational wave signals. In this article, we review the design of the TAMA300 interferometer and the observation results, and briefly review the data-analysis activities. In addition, recent efforts to improve the detector are also reported.

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1. Overview of TAMA300

TAMA is a Japanese project to construct and operate an interferometric gravitational-wave detector at the Mitaka campus of National Astronomical Observatory in Tokyo [1, 2, 3]. The interferometer, called TAMA300, is a Michelson interferometer with 300-m Fabry-Perot arm cavities, and with power recycling to enhance the effective laser power (Fig. 1). The power recycling gain is 4.5 in the current configuration. An LD-pumped Nd:YAG laser with an output power of 10 W is used as the light source (developed by Sony Corp.) [4]. The mode cleaner of TAMA300 is an independently suspended triangular ring cavity with a length of 9.75 m [5, 6].

The mirrors of the main interferometer are made of fused silica (Suprasil-P10, produced by Shin-Etsu Quartz Products Co., Ltd.). Each mirror has a diameter of 100 mm, and a thickness of 60 mm. The surface figure error is around $\lambda/40$, which satisfies the requirement of $\lambda/20$. The surface was super-polish so that the micro-roughness would be less than 10^{-10} $\mathrm{m_{rms}}$ [7, 8]. The polished surface was coated by an IBS (ion-beam sputtering) machine at JAE (Japan Aviation Electronics Industry Ltd.). The estimated loss of the mirror is 30 ppm from measurements with smaller sample mirrors [9, 10].

The mirrors of the main interferometer are isolated from seismic motion with double pendulums, three-stage stacks, and active isolation systems. An optical breadboard is

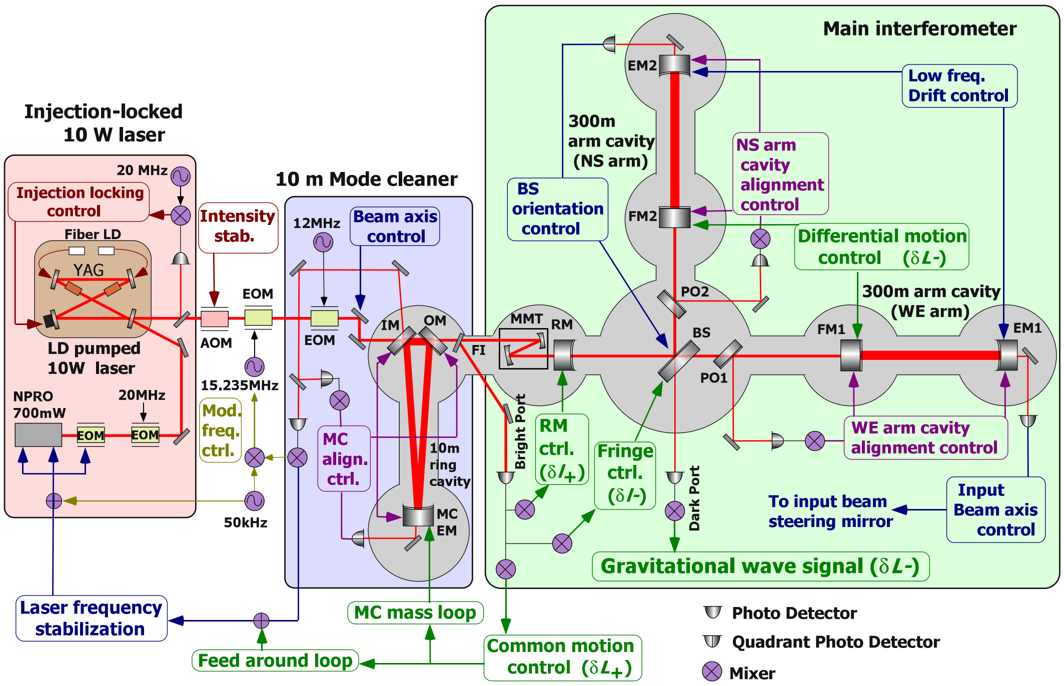

Figure 1. Optical and control design of the TAMA300 interferometer. TAMA300 is a Fabry-Perot-Michelson interferometer with a baseline length of 300 m and with power recycling. The laser source is an LD-pumped Nd:YAG laser with an output power of 10 W. A triangular ring cavity is inserted between the 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.

supported by three legs of the stack [11]; each stack comprises three layers of rubber (Chloroprene) and disk blocks of stainless steel. Each rubber block is sealed in bellows so as to avoid outgassing. The suspension system placed on the breadboard is a double pendulum [12]; the mirror is suspended by two loops of tungsten wire from an upper mass, which is also suspended by four wires. The motion of the upper mass is damped by an eddy current with permanent magnets surrounding it. A bottom plate of the isolation system (a stack and suspension system) is supported by four active isolation units. Each unit, called $\alpha 2$ (Tokkyo-kiki Corp.), is comprised of a pneumatic spring, feedback control, and feedforward control. The seismic noise level of the mirror is quieter in the daytime with the $\alpha 2$ system than at midnight without $\alpha 2$. As a result, the detector is operated stably even in the daytime.

The interferometer is housed in a vacuum system comprising eight chambers connected with vacuum ducts having a diameter of 400 mm [13]. The inner surface of the vacuum system was polished by ECB (Electro-Chemical Buffing) so as to reduce the outgassing rate. With this surface processing, a vacuum pressure of less than 1×10^{-6} Pa was achieved without baking [14, 15]. The system is evacuated by rotary pumps and 8 turbo-molecular pumps, and kept in a vacuum with 16 ion pumps during operation of the

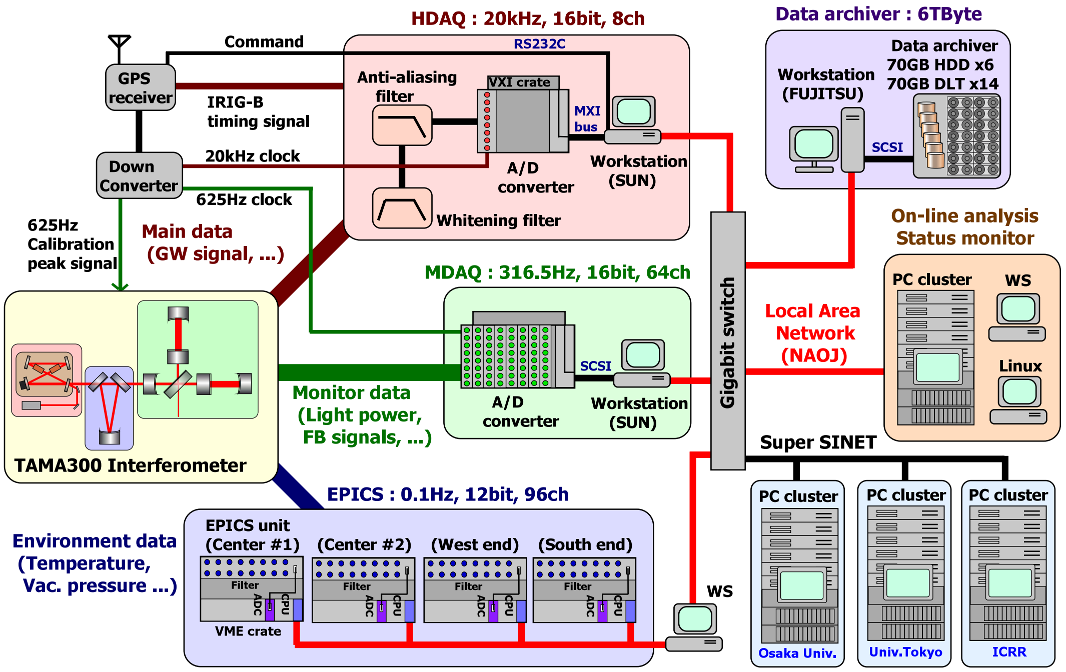

Figure 2. Data-acquisition system of TAMA300. Detector signals are recorded with HDAQ (20 kHz, 8 channel), MDAQ (316.5 Hz, 64 channel), and LDAQ (0.1 Hz, 96 channel). The acquired data are sent to a data archiver, and recorded to DLT tapes. Stored data are distributed by a high-speed optical network connection.

interferometer. With this vacuum system, we have confirmed that the residual gas does not affect the detector sensitivity with direct measurements [16].

The control system is designed to realize high sensitivity and stability at the same time [3, 17]. 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$1 minutes) stability and high sensitivity, and a beam-axis drift control system for long-term ($\sim$ a few hours) stable operation (Fig. 1). A frontal modulation scheme [18] is used for length control; 15.235 MHz phase modulation is used for signal extraction. The alignment control signals are extracted by a wave-front-sensing scheme [19], and fed back to each mirror. 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 lower frequency part for detector diagnoses (Fig. 2). The main output signals of the interferometer are recorded with high-frequency A/D converters (20 k samples/sec, 16 bit, called HDAQ), after passing through whitening filters and 5 kHz anti-aliasing low-pass filters [20]. Seven channel signals are recorded with a timing signal locked to UTC within

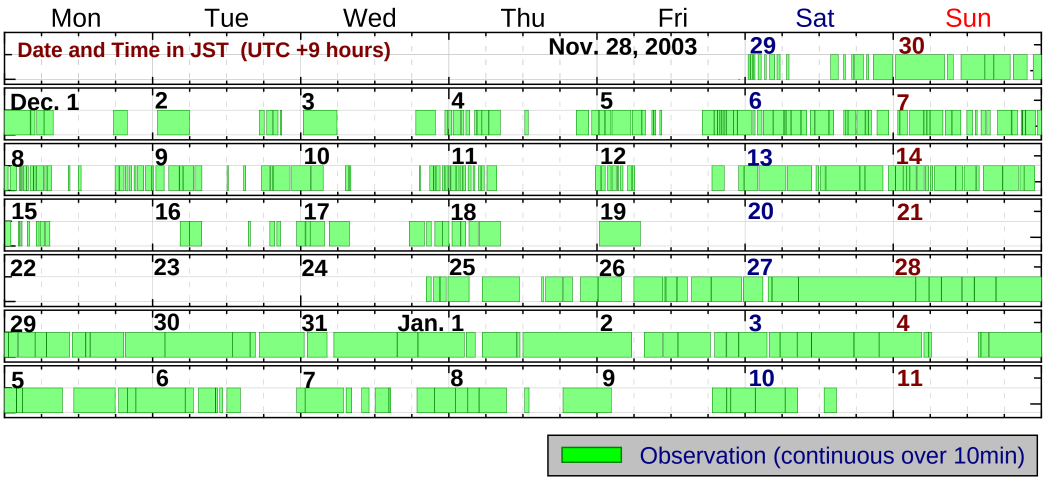

Figure 3. Operation status of the TAMA300 gravitational-wave detector during the ninth data-taking run (DT9) performed from November 28 in 2003 to January 10 in 2004. We operated the detector in the observation mode only at night and weekends in the first half; we spent most of the day time for tuning and characterization of the detector system. On the other hand, we operated the detector in full time with a high-duty cycle in the second half.

an error of 110 nsec. Along with the high-frequency system, interferometer monitoring signals (light power on photo detectors, control signals, and so on) are collected with a 64-channel medium-frequency (316.5 Hz, called MDAQ) data-acquisition system. In addition, environmental monitoring data (vacuum pressure, temperature, and seismic motion) are recorded with a low-frequency data-acquisition system, a 96-channel EPICS (Experimental Physics and Industry Control System) system. During operation, the mirrors of the detector are shaken by a 625 Hz sinusoidal signal, which enables us to calibrate the detector sensitivity continuously [21, 22, 23, 24].

Most of the acquired data with these systems are sent to a data archiver by local-area networks, and recorded to DLT tapes. The collected data are also sent to data-analysis computers at collaborating institutes by dedicated Giga-bit optical network connections.

2. Observation runs with TAMA300

2.1. Data-taking runs

In TAMA, nine observation runs have been carried out so far since the first observation run in 1999, and over 2700 hours of data have been collected [25, 26, 27]. Among them, we obtained a large amount of data in the sixth, eighth, and ninth data-taking runs (DT6, DT8, and DT9, respectively, Table 1). We obtained over 1000 hours of data in each of DT6 and DT8, operating the detector stably and with a good duty cycle. While the interferometer was operated without the power-recycling mirror in DT6, DT8 was carried out with the power-recycling mirror. The detector noise level was improved in DT8 thanks to the increased power by the power recycling and various improvements. However, the duty cycle was slightly degraded from that of DT6 because of environmental disturbances and the complexity of the detector configuration. In DT9, most of the day time was spent to adjust and to characterize the detector during the first half term. On the other hand, we obtained data of uniform quality with a high duty cycle in the second half; the duty cycle was 96% in this quiet term of DT9 (Fig. 3).

In the second half of DT9, the detector was operated without shift members on site. The TAMA300 control system was supervised by a master-control computer, which organized switching and gain adjustment of the control circuits. When the lock condition of the interferometer was lost, the master-control computer recovered its operational condition, following a given lock-acquisition sequences. In addition the master control system monitored the detector condition, and adjusted the alignment of the interferometer automatically, if necessary. When the good operational condition could not be recovered, the master control computer called an expert person in charge. The detector could be monitored and operated in remote control by way of a control web site. This system reduced the load of the shift members during the observation, and enabled stable and high-duty-cycle operation of the detector.

Typical noise spectra in these observation runs are shown in Fig. 4. The noise level has been gradually improved by detector investigations between these runs. The floor level is $2 \times 10^{-21}\,\mathrm{Hz}^{-1/2}$ in DT9 at around 1 kHz. Each spectrum has several line peaks caused by an injected sinusoidal signal for calibration at 625 Hz, violin-mode fluctuations of the mirror suspension at around 520 Hz and its harmonics, and lines of power-supply at 50 Hz and its harmonics. The noise level is limited by several noise sources: seismic motion (DC - 30 Hz), alignment-control noise (30 Hz - 300 Hz), electronics noises and Michelson phase-detection noise (300 Hz - 1 kHz), and the shot noise and photo-detector noise (1 kHz -). The detectable range estimated from the DT9 typical noise level is 73 kpc for $1.4\,M_\odot$ neutron-star inspiral events (with signal-to-noise-ratio threshold of 10, for the events at optimal direction from the detector). Thus, the detector has a sensitivity to cover most of events within our galaxy.

Table 1. Summary of long data-taking runs by TAMA300. The noise level, the total observation data amount (T_{obs}), the longest continuous operation (T_{LCO}), and the duty cycle throughout the data-taking run are described.

Term			Noise level $[\mathrm{Hz}^{-1/2}]$	T_{obs} [hours]	T_{LCO} [hours]	Duty cycle
DT6	Aug.-Sept. 2001	(50 days)	5×10^{-21}	1038	22.0	87%
DT8	Feb.-April 2003	(2 months)	3×10^{-21}	1157	20.5	81%
DT9	Nov. 2003 - Jan. 2004	(6 weeks)	2×10^{-21}	558	27.0	54%

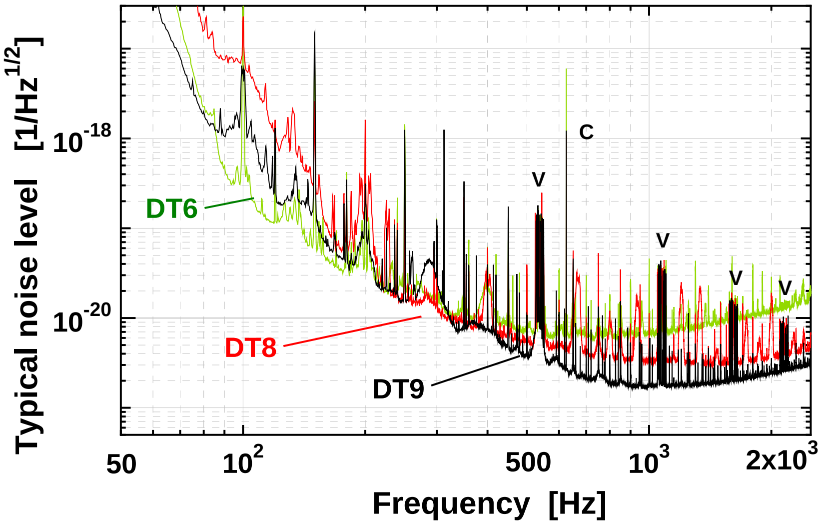

Figure 4. Typical noise spectra of the TAMA300 detector during data-taking runs. The noise level has gradually been improved by detector investigations between these runs. The floor level is 2×10^{-21} [$\mathrm{Hz}^{-1/2}$] in DT9 at around 1 kHz. Each spectrum has several line peaks caused by an injected signal for calibration (625 Hz, shown as 'C'), violin-mode fluctuations of the mirror suspension (around 520 Hz and its harmonics, shown as 'V'), and lines of power-supply (50 Hz and its harmonics).

Figure 5 shows the stability of the noise level during data-taking runs; floor noise levels are plotted, as a function of the time from the beginning of each data-taking run. This figure shows that there were drifts in the noise level during two months of observations. In addition, there were diurnal changes in the noise levels in DT6, DT8, and the first half of DT9. On the other hand, we obtained good and uniform quality data in the second half of DT9; the noise level was less than that of the previous runs, and had much lower diurnal change and drifts. This is because the seismic activities were very quiet (this term covered the Christmas and new-year holidays) and an automatic adjustment system was working pretty well.

2.2. Data Analysis activities

The data collected by TAMA300 are being used to search for GW signals with several kinds of waveforms. Though we have not yet obtained any clear evidence of a GW signal, we developed data-analysis schemes and set upper limits on GW signals.

For chirp GW signals from binary inspirals, we developed a data-analysis scheme using matched filtering for extracting event candidates, and a χ^2-test for rejecting fake events [28, 29]. With a Monte-Carlo simulation using the TAMA DT8 data, we found that the TAMA 300 detector has a high detection efficiency of 60% for Galactic events. As a result of the data analysis, we set an upper limit of 29 events/year on the event rate in our Galaxy with a confidence level of 90%, using the DT8 data [30]. The TAMA data

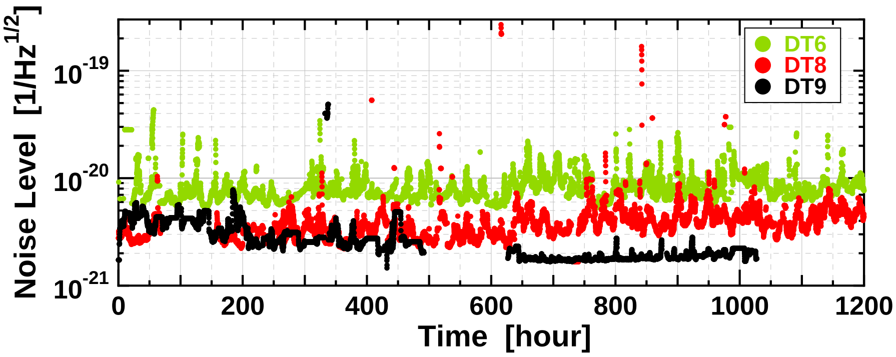

Figure 5. Stability of the noise level. Floor noise levels are plotted as a function of the time from the beginning of each data-taking run. There are diurnal changes in the noise levels in DT6, DT8, and the first half of DT9. On the other hand, the noise level is very stable in the second half of DT9.

are also used for coincidence analysis with LIGO data [31]. A subset (10%) of the full coincident data set from LIGO-S2 and TAMA-DT8 has been analyzed to date, and the analysis pipelines are being tuned.

As for burst GW signals, several analysis schemes, called burst filters, have been developed [32, 33, 34]. In addition, fake reduction schemes are being developed using a time-scale selection of event candidates and using auxiliary monitor signals of the interferometer obtained during data-taking runs. Using the data of DT9, we set an upper limit of 5×10^3 events/sec on the event rate of GW signals from stellar-core collapse in our Galaxy with a confidence level of 90% [35, 36]. The TAMA data are also used for burst-wave coincidence analysis with LIGO data. Preliminary results have been obtained and reported for LIGO-S2 and TAMA-DT8 data [37, 38].

On a ringdown GW signals, which are radiated from quasi-normal-mode oscillation of new-born or excited blackholes, an analysis scheme based on a matched filtering has been developed [39, 40, 41]. In the analysis, two methods to reject fake events in the time domain are used: an event selection with goodness of fit to a theoretically predicted exponential decay, and that with evaluation of the asymmetry of a filter output around the event trigger. As a result, the number of fakes were reduced by an order with a false-dismissal probability of 5% [40].

We are also analyzing the TAMA data for continuous GW signals from rotating neutron stars (pulsars) [42, 43]. In a continuous-wave analysis, we use an analysis scheme based on a matched filtering with a correction of pulsar spin down, a Doppler effect caused by the relative motion between the pulsar and the Earth, and so on. As a result of a analysis using the TAMA DT9 data, we set a preliminary upper limit of 4×10^{-23} for the strain amplitude of GW from a reported pulsar in the 1987A remnant [43].

Besides the GW search, we are analyzing the collected data for detector characterization: real-time monitoring of the contributions of various noise sources to the detector output [44], detector diagnosis [45], and investigations of veto schemes for reduction of fake events [28, 35, 40, 46, 47].

3. Recent activities for detector improvements

3.1. Noise hunting efforts

Though the sensitivity of the TAMA300 detector is sufficiently good to observe galactic events, such as neutron-star mergers, there still is a discrepancy between it and the ultimate one calculated from the design parameters of the detector, because of unidentified noise sources. In order to identify the noise sources that limit the detector sensitivity and reduce them, we investigated the interferometer behavior by simplifying it to a power-recycled Michelson interferometer configuration without arm cavities for about one year. We mainly worked on noises originating in scattered light from the optical components, such as window plates of the vacuum tank, lenses used to focus the beam on photo detectors, and photo-detector surfaces [48, 49]. As a result, the noise level of the power-recycled Michelson interferometer has been improved by a factor of 10 at around 300 Hz. After that, we have been recovering the full configuration of a Fabry-Perot-Michelson interferometer with power recycling.

3.2. Upgrade of seismic isolation system

We are planning to upgrade the seismic isolation system to a better-performance one in order to improve the detector stability and sensitivity at low frequency ($\sim$100 Hz). The new isolation system, called TAMA-SAS (Seismic Attenuation System), is comprised of a low-frequency ($\sim$30 mHz) inverted pendulum for horizontal attenuation, two-stage MGAS (Monolithic Geometric Anti-Spring) filters with a resonant frequency of about 300 mHz for vertical isolation, and double suspension with eddy-current damping [50, 51, 52, 53]. TAMA-SAS has been developed and tested using a prototype interferometer with a 3-m Fabry-Perot cavity. In this experiment, the obtained isolation ratio was as good as we had expected: a better isolation ratio than that of the current TAMA isolation system by a factor of 10^3 around 4 Hz [54]. Currently, we are assembling four TAMA-SASs for four main mirrors of the Fabry-Perot arm cavities. The first one will be installed to TAMA in a few months, and TAMA will be operated with them by the end of the year 2005.

4. Summary and future works

The TAMA300 gravitational-wave detector has been developed and operated with sufficient sensitivity to detect gravitational-wave events within our galaxy and sufficient stability for observations. We have carried out nine observation runs and obtained over 2700 hours of data to date. In particular, the interferometer was operated for over 24 hours stably and continuously with a typical strain noise level of $2 \times 10^{-21}\,/\sqrt{\mathrm{Hz}}$ in the best case of the ninth data-taking run (DT9). The collected data are being analyzed to search chirp, burst, ringdown and continuous gravitational waves.

In order to increase the detection probability for GW events farther away from our galaxy, we are improving the TAMA300 detector to have better sensitivity and stability with noise-hunting efforts and with a replacement of the seismic isolation system.

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