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Evaluation of the global magnetic noise for the stochastic gravitational wave background search

Tatsuki Washimi,[a,*] **Isamu Fukunaga,**[b] **Yousuke Itoh,**[b] **Nobuyuki Kanda,**[b] **Atsushi Nishizawa,**[c] **Jun'ichi Yokoyama**[c,d] **and Takaaki Yokozawa**[e]

[a] *Gravitational Wave Science Project (GWSP) Kamioka Branch, National Astronomical Observatory of Japan (NAOJ),*
Kamioka-cho, Hida City, Gifu 506-1205, Japan

[b] *Department of Physics, Graduate School of Science, Osaka Metropolitan University,*
Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan

[c] *Research Center for the Early Universe (RESCEU), The University of Tokyo,*
Bunkyo-ku, Tokyo 113-0033, Japan

[d] *Department of Physics, The University of Tokyo,*
Bunkyo-ku, Tokyo 113-0033, Japan

[e] *Institute for Cosmic Ray Research (ICRR) KAGRA Observatory, The University of Tokyo,*
Kamioka-cho, Hida City, Gifu 506-1205, Japan

E-mail: tatsuki.washimi@nao.ac.jp

The stochastic gravitational wave background (SGWB) is a weak and persistent background of gravitational waves (GW) that originated from the early universe and can provide us valuable insights into the origins and evolution of the universe. To detect the SWGB, the cross-correlations between the multiple GW detectors are calculated and local noises are canceled, but global coherent noises such as Schumann resonance are remains and affect the observation. Schumann resonance is a natural phenomenon in which the Earth's electromagnetic field resonates at extremely low frequencies (ELF), around 8 Hz, 14 Hz, 20 Hz, *etc.*This frequency is close to the wavelength of the Earth's circumference and is produced by the interaction of lightning discharges in the ionosphere and the Earth's surface. To evaluate the characteristics of Schumann resonance, we are monitoring the magnetic field at the KAGRA site, both on the surface and the underground. In this study, we introduced a setup for the Schumann resonance observation at the KAGRA site and evaluated the time variation of the spectrum. Its impact on the SGWB search based on our data is also estimated by the Fisher matrix formalism.

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*Speaker

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1. Introduction

A gravitational wave (GW) is a wave of space-time distortion predicted by the general theory of relativity. The first direct detection of a GW was achieved by LIGO in the US (Hanford and Livingston) in 2015 [1], and more than 90 events of compact binary coalescence (CBC) have been observed [2] by LIGO and Virgo in Italy [3]. KAGRA [4, 5] is a GW detector located underground in Kamioka, Japan. Its construction was started in 2012, and the international joint observation run with other observatories was performed in 2020 [6, 7]. Stochastic GW background (SGWB) is a random superposition of GWs from many black holes, inflation of the universe, *etc.*, and it is quite a tiny and long-term signal. It has not been detected directly yet, but recently, pulsar timing array experiments such that EPTA+InPTA [8], NANOGrav [9], and PPTA [10] reported the suggestions of an indirect SGWB signal at the frequency of nano-Hz. To detect the SGWB by the ground-based interferometric GW detectors (LIGO, Virgo, KAGRA, and further planned detectors), the cross-correlations between the multiple GW detectors are calculated and local noises are canceled, but global coherent noises are remains and affect the observation.

Schumann resonance [12, 13] is a natural phenomenon in which the Earth's electromagnetic field resonates at extremely low frequencies (ELF), around 8 Hz, 14 Hz, 20 Hz, *etc.*, produced by the interaction of lightning discharges in the ionosphere and the Earth's surface. It has been pointed out that the Schumann resonances produce the correlated noise through the instrumental magnetic couplings and affect the searches for an SGWB [14, 15, 18]. Its impact on parameter estimation of an SGWB is studied in Mayers *et al.* [16] for the 3-detectors (HLV) case by the Bayesian inference and in Himemoto *et al.* [20] for the 4-detectors case including KAGRA by the Fisher matrix formalism. These studies were based on the magnetic field and its correlations measured at LIGO and Virgo [22] without considering their time variance. At the KAGRA site, short-time measurements (a few hours – 2 weeks) of the Schumann resonance were performed several times [5, 21, 22], but continuous observations had not been.

In this study, we introduced a setup for the Schumann resonance observation at the KAGRA site and evaluated the time variation of the spectrum. Its impact on the SGWB search based on our data is also estimated by the Fisher matrix formalism.

2. Observation and modeling of the global magnetic field

Continuous observation of the global magnetic field at the entrance of the KAGRA tunnel was started at the end of August 2022. The magnetometers are Metronix MFS-06e [23] 1-axial induction coils and operated with a Metronix ADU-08e [24] synchronized by a GPS clock. The observation period, sampling rate, and direction of the two horizontal magnetometers are summarized in Table 1. In this paper, the data of "axis 2" in the second period is used for the following analysis.

Figure 1 (blue) shows one example of the power spectral density (PSD) of the magnetic field for 1 hour from 2022-12-07 20:00 UTC. The peaks of the Schumann resonance from the first to the fourth mode are clearly seen. To evaluate the characters of the spectrum, a combination of the

Table 1: Observation

Period		Sampling rate	Direction from North	
start	end		axis 1	axis 2
2022-08-26	2022-10-24	64 Hz	230°	110°
2022-10-24	2022-12-13	128 Hz	200°	110°
2023-05-04	continuing	256 Hz	200°	110°

Lorentzian functions

$$M(f) = \sum_{\ell} M_{\ell}(f) + M_{\rm BG}(f), \tag{1}$$

$$M_{\ell}(f) = A_{\ell} \frac{(f_{\ell}/2Q_{\ell})^2}{(f - f_{\ell})^2 + (f_{\ell}/2Q_{\ell})^2} \tag{2}$$

is introduced referring to the literature in the atmospheric physics field [25–28]. Here, $M_{\ell}(f)$ is the PSDs, A_{ℓ} is the peak value, f_{ℓ} is the resonant frequency, and Q_{ℓ} is the quality factor for the ℓ–th mode, $M_{\rm BG}(f)$ represents a background component including some local noises (not the Schumann resonance) and it is settled to be a constant in this paper. A result of the χ^2–fitting for the measured PSD with this function is shown in Fig. 1 (orange).

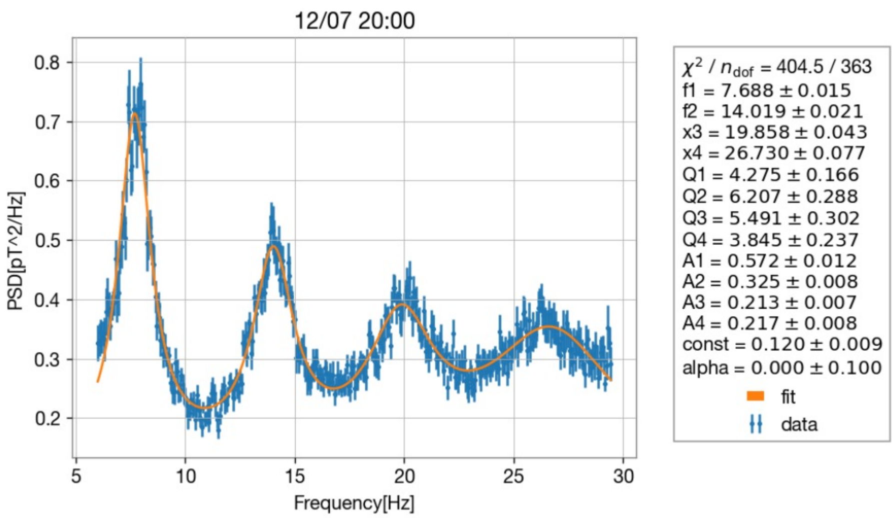

Figure 1: Example of the power spectral density (PSD) of the magnetic field (axis 2) for 1 hour from 2022-12-07 UTC. Blue: observed data (median±5%), Orange: fitting result.

The same procedures are performed for each hour in the observation data from October 24 to December 13. Figure 2 (top) shows the obtained Schumann resonance parameters $\{f_{\ell}, Q_{\ell}, A_{\ell}\}$ for every 1 hour, averaged over the date because they have approximately 1-day period [26]. The PSDs of the Schumann resonance using each parameter are shown in Fig. 2 (bottom). The green dotted line is the PSD calculated using the mean values of each parameter.

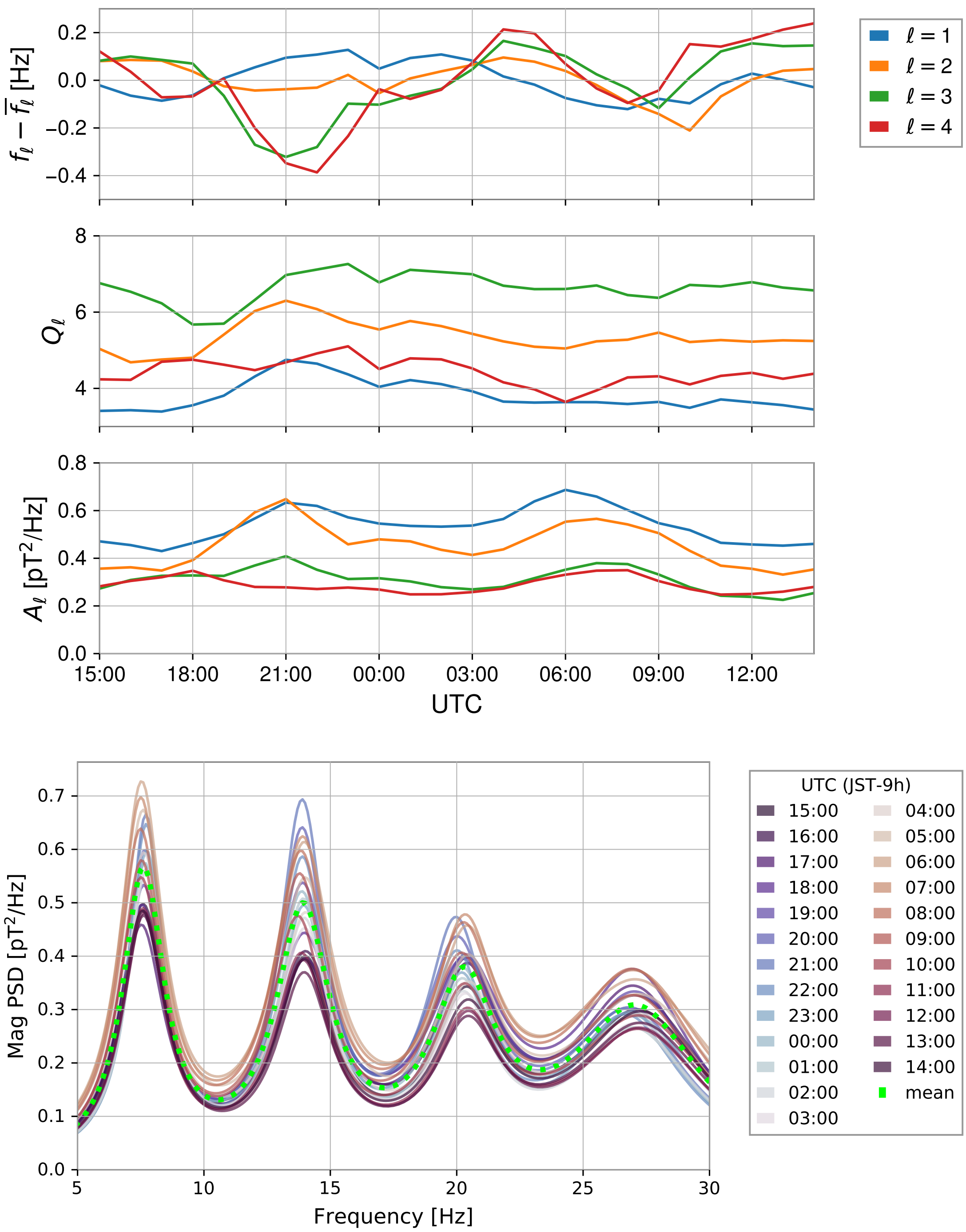

Figure 2: Top: Time variance of the obtained Schumann resonance parameters for every 1-hour, averaged over the date. Bottom: Power spectral densities (PSDs) of the Schumann resonance for every 1-hour using each parameter.

3. Fisher analysis for a stochastic gravitational-wave search

To check the impact of the time variance of the Schumann resonance spectrum on an SGWB search, the Fisher analysis is performed based on the Himemoto *et. al.* [20] assuming the four GW detectors (LIGO Hanford, LIGO Livingston, Virgo, KAGRA) with their design sensitivities. A cross-spectrum density (CSD) of the SGWB signal between i–th and j–th GW detectors $U_{ij}^{\rm GW}$ is given by

$$U_{ij}^{\rm GW}(f;\Omega_0,n_{\rm GW}) = \frac{3H_0^2}{10\pi^2}\frac{\Omega_{\rm GW}(f)}{f^3}\gamma_{ij}(f), \tag{3}$$

$$\Omega_{\rm GW}(f) = \Omega_0\cdot\left(\frac{f}{25{\rm Hz}}\right)^{n_{\rm GW}}, \tag{4}$$

where f is the frequency, H_0 is the present Hubble parameter, and $\gamma_{ij}(f)$ is the overlap reduction function of the SGWB signal [29]. The GW parameters are set to be $\Omega_0 = 3\times10^{-9}$ and $n_{\rm GW} = 2/3$ in this study. A CSD of the global correlated magnetic noise $U_{ij}^{\rm GW}$ is given by

$$U_{ij}^{\rm Mag}(f;\kappa_i,\kappa_j,\beta_i,\beta_j,\psi_i,\psi_j) = r_i(f)\cdot r_j(f)\cdot\sum_{\ell=1}^{4}M_l(f)\cdot\gamma_{ij,\ell}^{\rm Mag}(\psi_i,\psi_j), \tag{5}$$

$$r_i(f) = \left(\frac{\kappa_i}{10^{23}\ {\rm pT}}\right)\left(\frac{f}{10\ {\rm Hz}}\right)^{-\beta_i}, \tag{6}$$

where $r_i(f)$ is the coupling function from a magnetic field to a strain signal on the GW detector, $\gamma_{ij,\ell}^{\rm Mag}(\psi_i,\psi_j)$ is the overlap reduction function for the ℓ–th mode of the Schumann resonance [18]. The magnetic coupling parameters $\{\kappa_i,\beta_i,\psi_i\}$ are set to be the values in the TABLE I in Ref. [20].

The Fisher matrix considering the global correlated magnetic noise [20] is given by

$$F_{ab} = 2T_{\rm obs}\sum_{(i,j)}\int_{f_{min}}^{f_{max}}\frac{\partial_a U_{ij}\partial_b U_{ij}}{S_i S_j}df, \tag{7}$$

$$U_{ij}(f;\theta_a) = U_{ij}^{\rm GW}(f;\Omega_0,n_{\rm GW}) + U_{ij}^{\rm Mag}(f;\kappa_i,\kappa_j,\beta_i,\beta_j,\psi_i,\psi_j), \tag{8}$$

where $T_{\rm obs}$ is the observation time (set to be 1 year in this work) and S_i is the sensitivity of the i–th GW detector. The statistical error of the parameter θ_a is given by $\sigma_a = \sqrt{[F^{-1}]_{aa}}$. In this study, the parameter set is $\{\theta_a\} = \{\Omega_0, n_{\rm GW},\kappa_i,\beta_i,\psi_i\}$. The magnetic field is assumed to be observed by magnetometers independently and the Schumann resonance parameters $\{f_\ell, Q_\ell, A_\ell\}$ are not included in the Fisher matrix. Moreover, the systematic biases $\Delta\theta_a$ in the best-fit parameters from the true values caused by missing the presence of a global magnetic field are given by

$$\Delta\theta_a = \sum_b[\mathcal{F}^{-1}]_{ab}\ s_b, \tag{9}$$

$$\mathcal{F}_{ab} = 2T_{\rm obs}\sum_{(i,j)}\int_{f_{min}}^{f_{max}}\frac{\partial_a U_{ij}^{\rm GW}\partial_b U_{ij}^{\rm GW} - U_{ij}^{\rm Mag}\partial_a\partial_b U_{ij}^{\rm GW}}{S_i S_j}df, \tag{10}$$

$$s_b = 2T_{\rm obs}\sum_{(i,j)}\int_{f_{min}}^{f_{max}}\frac{U_{ij}^{\rm Mag}\partial_b U_{ij}^{\rm GW}}{S_i S_j}df \tag{11}$$

The blue graphs in Fig. 3 are the results of the Fisher analysis based on the stationary magnetic field using the Schumann resonance parameters fixed at each time or the mean values (shown in Fig. 2). To consider the day-modulation of the magnetic field, the observation time $T_{\rm obs}$ is divided into 24 segments, and the Fisher analysis is performed for each hour. Finally, a summation for them is taken;

$$F_{ab} = \sum_{n=0}^{23} \frac{1}{24} F_{ab}(t_n), \quad \mathcal{F}_{ab} = \sum_{n=0}^{23} \frac{1}{24} \mathcal{F}_{ab}(t_n), \quad s_b = \sum_{n=0}^{23} \frac{1}{24} s_b(t_n). \tag{12}$$

The orange graphs in Fig. 3 are the results for the time variation case. The errors for the GW parameters are smaller and the biases are almost the same compared with the results for the stationary magnetic field case fixed at the mean value of the Schumann resonance parameters.

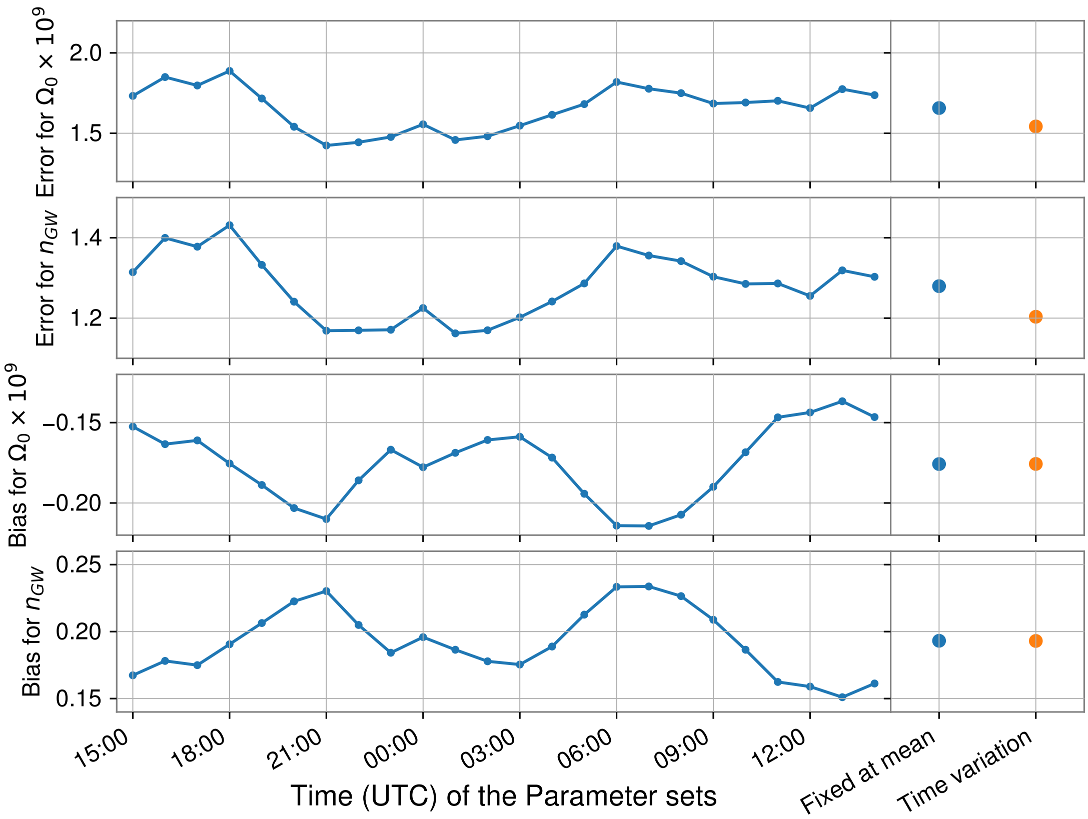

Figure 3: Error-Bias

4. Summary and prospects

In this study, we started the continuous observation of the magnetic field at the entrance of the KAGRA tunnel and characterized the time variance of the Schumann resonance. The effect of the global magnetic noise on an SGWB search is evaluated by the Fisher analysis based on the observed magnetic field, and we found that the errors for the GW parameters are smaller and the biases are almost the same compared with the results for the stationary magnetic field case fixed at the mean value of the Schumann resonance parameters.

As further prospects, longer-term observational data will be applied. Investigation for the directional information of the magnetic field vector is also essential and the overlap reduction function of the magnetic noise will be replaced from the theoretical model to the observational data, considering its time variance. The magnetic coupling to the GW channel should be measured for KAGRA via injection test and applied for the Fisher analysis.

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