PROCEEDINGS OF SCIENCE

Calibration of the gravitational wave telescope KAGRA

Dan Chen[a,*] **on behalf of the KAGRA collaboration**

[a] *Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan.*

E-mail: dan.chen@nao.ac.jp

KAGRA is a Laser interferometer based gravitational wave telescope in Japan, joining the international gravitational wave observation run, O4 with other telescopes LIGO and Virgo. In previous gravitational wave observation runs, O1, O2, and O3, 90 observation events have been reported, and many more are expected to be observed in this O4 period. With the beginning of the gravitational wave astronomy, the calibration of the observed gravitational wave signal is becoming more important than ever before. The main calibration system used in KAGRA, LIGO, and Virgo is Photon calibration system (Pcal) which injects reference signals into a telescope by radiation pressure of a Laser. Based on the preparation and operation of KAGRA Pcals in O3, we made a upgrade plan for O4, which includes 3 main improvements: better Pcal laser beam alignment system, lower noise performance, and lower uncertainty. Improvement work was carried out between the end of O3 and the start of O4 following this plan, with the following results. First, precise remote alignment was made possible in the critical Pcal laser path region. Second, Pcal noise sources were identified and improved by about 50 dB, reducing the Pcal noise below the design sensitivity of KAGRA. Third, the calibration procedure of the Pcal was reviewed, and studies on temperature dependence and laser incidence state dependence were carried out to reduce the uncertainty on Pcal, which is directly related to the uncertainty of the telescope signal. The details of KAGRA Pcal, and these improvements between O3 and O4 are reported here.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

[*]Speaker

1. Calibration of a gravitational wave telescope KAGRA

On 14th Sep. 2015, the Advanced Laser Interferometer Gravitational Wave Observatory (LIGO [1]) accomplished the first direct detection of gravitational waves (GWs), and the event was marked as the beginning of gravitational wave astronomy[2]. Since then, there were three observing runs, and we are currently in the midst of the fourth international joint observing run, called as O4, from May 2023. A total of 90 GW events were reported by the observation run 3 (O3), which includes the first multi-messenger event kicked by a GW detection, GW170817[3]. As the number of observations continues to increase, the importance of observational accuracy has become as important as the detectability of GWs. In the field of multi-messenger astronomy, which incorporates follow-up observations using optical telescopes, precise localization estimation of GW sources has become crucial.

Increasing the number of operating telescopes not only makes higher frequency detection, but also improves source localisation estimation. KAGRA is a Laser interferometer type GW telescope built in Japan [4], which started operating in 2019 and is participating in O4. Although its sensitivity is still not as high as LIGO or Virogo [5], it has an observation direction that can cover areas difficult to observe by other telescopes, and it continues to be upgraded to be part of the GW observation network.

In KAGRA telescope, many real-time control loop are used to maintain the telescope in a highly sensitive state. In particular, the differential arm (DARM) control loop (Figure 1) which contains the GW signal is the most important calibration target.

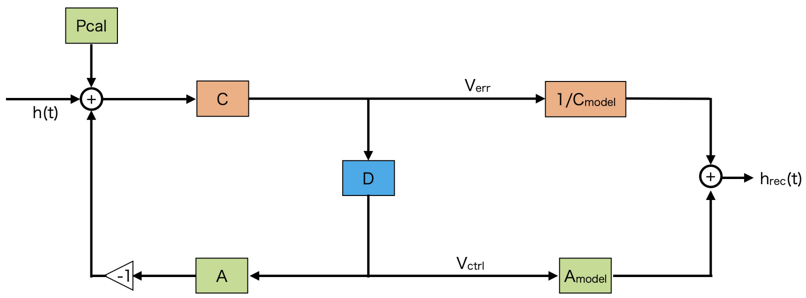


Figure 1: DARM loop, and the h(t) reconstruction.

The DARM control loop is a negative feedback system, which is composed of sensor C or the interferometer, digital filter D, and actuators A which are coil magnet actuators on an end mirror or end test mass (ETM) of the interferometer. To reconstruct the injected signal which can contain GW signal, $h(t)$ in Figure 1, we use the output signal from C (error signal V_{err}), and signal into A (control signal V_{ctrl}), and the model of C and A (C_{model} and A_{model}). The reconstructed signal $h_{\mathrm{rec}}(t)$ is the main output data of the telescope, which is called strain data. In the KAGRA telescope, Photon calibration systems (Pcals) are used as the primary calibrator as well as other telescopes [6]. Pcal is a calibrated actuator, which can inject signals into the interferometer to measure the response or transfer function of C and A to make the models. We have upgraded the Pcals after O3GK (a joint observation in 2020 by KAGRA and GEO 600[7], a GW observatory in Germany.).

2. Photon calibration system

2.1 Photon calibration system: Pcal

Photon calibration system, Pcal is a system that injects laser beams on an ETM to make a displacement with the radiation pressure. In KAGRA, independent Pcal was installed for each of the two ETMs (ETMX and ETMY), called Pcal-X and Pcal-Y, which have the same concept design. The Pcal-X is used as the main calibration system and the Pcal-Y is a backup system. The following mainly describes Pcal-X, but the improvements described below were applied to both. Figure 2 shows the concept of a Pcal, which consists of a transmitter(Tx) module, which generates the Pcal laser beams and controls the power, and an Rx module, which receives the laser beams reflected by the ETM. Two Pcal laser beams generated by a Continuous Wave Ytterbium Fiber Laser source provided by KEOPSYS by Lumibird are injected to a non-centered suitable point on the ETM to avoid exciting the internal resonant mode. The model number of the laser source is CYFL-TERA-20-LP-1047-AM1-RG0-OM1-T305-C1 for Pcal-X, and CYFL-TERA-20-LP-1047-AM1-RG0-OM1-B306-C31 for Pcal-Y. Each beam passes through an AOM (Acousto-Optic Modulator, ISOMET 532C-4), and is extracted by a beam sampler (SA-014-1-Y-A provided by HOLO/OR) into a PD (Photo Detector) named OFS PD and Tx PD with the power of $0.4 \pm 0.07\%$ of the injection power[8][9] (Figure 2). The output of the OFS PD is input into a control filter and into the AOM as an actuator for laser power to configure a laser power stabilisation system, which is necessary to provide reference signals without significant noise injection. Furthermore, the control system has an input port, where the laser power is controlled by following the voltage signal input here. For this reason, this control system is called the OFS (Optical Follower Servo) system. The two beams are injected into vacuume chamber through an optical window, and aligned by some mirrors in A chamber toward the ETM, and reflected by it into Rx module, then received by the Rx PD. To accurately and precisely measure the laser power emitted from the Tx module and received by the Rx module, integrating sphere type laser power meters are used for the Tx PDs and Rx PD. Due to the conditions of the installation site the Pcal system was installed in an area called A chamber area, 34.9 m far from the ETM, which makes the beam alignment to be difficult.

The displacement generated by the Pcal is presented by the following equation[6]:

$$x(f) = -\frac{2P(f)\cos\theta}{cM(2\pi f)^2}\left[1 + (\vec{a}\cdot\vec{b})\frac{M}{I}\right], \tag{1}$$

where $x(f)$ is the displacement in frequency domain, P is the total Pcal laser power injected on the surface of the ETM, θ is the incident angle, c is the light speed, M is the mass of the mirror, $\vec{a}$ and $\vec{b}$ are the position vector of the sum of the Pcal beams, and the main interferometer IR beam, respectively, I is the mirror's moment of inertia. We assumed the mirror response as a free mass.

Interferometer calibration is performed in the frequency domain, so sinusoidal waves are injected into the interferometer from Pcal. For this purpose, the Pcal laser power is held at a certain DC value and sinusoidal waves are added on it. The sinusoidal waves are always input as reference signals when the telescope is in observation.

The signal from Pcal is used as a reference for the interferometer calibration, so the uncertainty of the Pcal itself directly affects the uncertainty of the telescope. From the equation 1, we can estimate the extent to which the uncertainty in the measurement of each parameter value affects

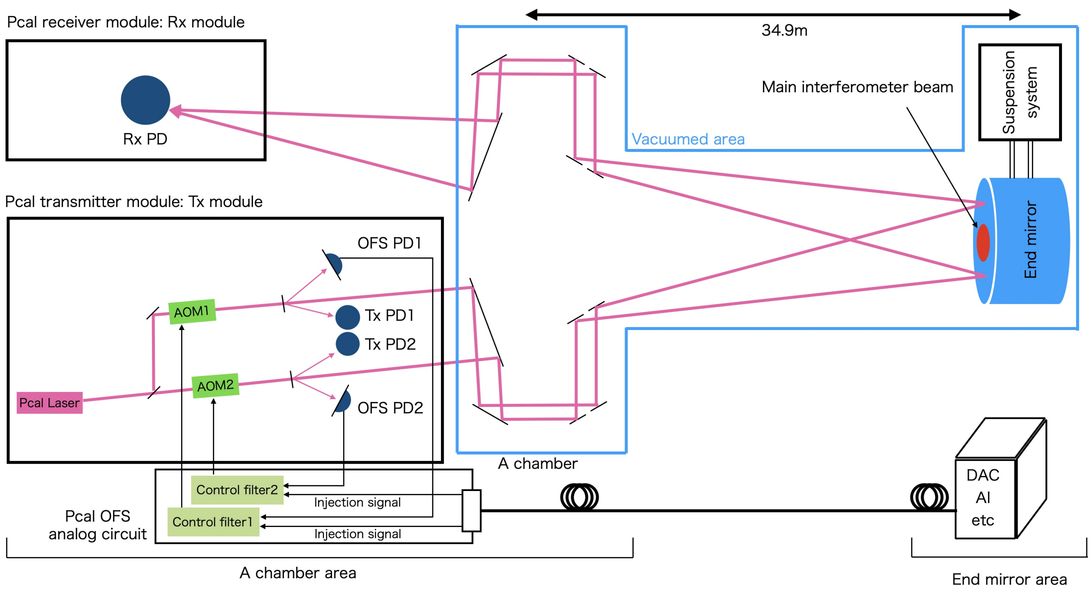


Figure 2: KAGRA Pcal

the uncertainty of the Pcal. The measurement uncertainty of laser power used Rx PD and TxPDs is the most particularly dominant. This is the reason why we need accurate and precise absolute calibration of the integrating spheres.

2.2 Integrating sphere calibration

For the calibration of the integrating spheres, the LIGO group calibrates a standard integrating sphere GSK(Gold Standard of KAGRA) for KAGRA based on the absolutely calibrated integrating sphere GSL(Gold Standard of LIGO) by National Institute of Standards and Technology, NIST[6][10]. This GSK is maintaind at University of Toyama and acts as the standard in KAGRA. In order to calibrate integrating spheres in KAGRA site such as Rx PD, another integrating sphere named WSK(Working Standard of KAGRA) is used to carry the calibration factor from GSK at University of Toyama to the KAGRA site. This work is carried out about once a month to monitor long-term changes in the calibration factor of each integrating sphere in KAGRA. When calibrating the WSK with the GSK, we essentially adopt the method described in [6], injecting a laser separated by a beam splitter to the GSK and the WSK and measuring the output ratio of the two integrating spheres [12]. Figure 3 illustrates the integrating spheres calibration procedure. A global network for the calibration of GW telescopes is planned that includes not only NIST but also The Physikalisch-Technische Bundesanstalt, PTB as a standard orbit to have better reliability[10].

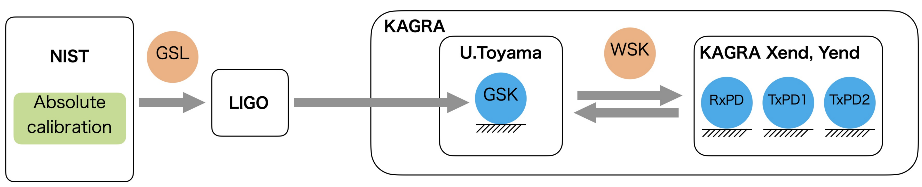


Figure 3: Integrating spheres calibration procedure.

2.3 Issues, and points of enhancements found by O3GK

By O3GK we have enabled Pcal installation, and basic operation[11]. During the installation and operation, the following issues and points for improvement were found.

A. Difficulty of the beam alignment and beam position adjustment on ETM

B. Noise on main interferometer caused by Pcal

C. Calibration uncertainty improvements

A: the first issue is related to the Pcal beam alignment work efficiency. As indicated above, we need to perform a 70 m round trip laser beam alignment. This 70 m part is a vacuum pipe and it is difficult to enter and check the beam position, therefore a delicate alignment from the A chamber area is required. In O3GK, we did not have an effective alignment system for this 70 m part. In particular, after vacuuming, the Pcal beam positions still needed to be fine-tuned, but there was no mechanism that could do this efficiently.

B: the second point is about the noise on the interferometer caused by Pcal. After O3GK, the noise of Pcal-X was checked and found to be greater than expected, which was above the KAGRA design sensitivity and had possibility to limit the sensitivity in O4. During the observation run, Pcal continues to input reference sin signals to the interferometer, but is assumed to be sufficiently quiet at other frequencies.

C: the last point is an improvement point to have better uncertainty on Pcal, which can improve the uncertainty of the telescope. The uncertainty of Pcal in O3GK was estimated to be 3% [11], which was larger than that of LIGO's one, which was 0.75%[6]. This indicates the possibility to improve the uncertainty.

These three points were our Pcal upgrade target points towards O4.

3. Upgrades for the observation run 4 (O4)

3.1 Installation of remote-contrable mirrors

For the issue A, Piezo actuators were installed on the mirror mount holding a mirror for the Pcal laser beam in A chamber to be able to remote-control the alignment at the point just before the long vacuum pipe. The actuators are 8301-UHV or 8302-UHV, which are vacuum compatible Piezo Linear Actuators (Picomotors) provided by Newport, and whose travel ranges are 12.7 mm and 25.4 mm. Figure 4 shows the mirrors with the Picomotor-installed mount, which have a white marking tape temporarily. Because the purpose of the picomotors are to fine-tune the beam positions on the ETM on the order of a few mm to a few cm, considering that the mirrors are 3-inch mirrors and the distance to the ETM is 34.9 m, the travel ranges are sufficient. This remote alignment system not only made the initial alignment more efficient, but also compensated for alignment changes caused by vacuuming.

3.2 Pcal noise hunting and countermeasure

During the investigation of the Pcal noise, a large unexpected sinusoidal signals was found in the signal to the Pcal system, which was finally identified as the origin of the noise. The Pcal OFS

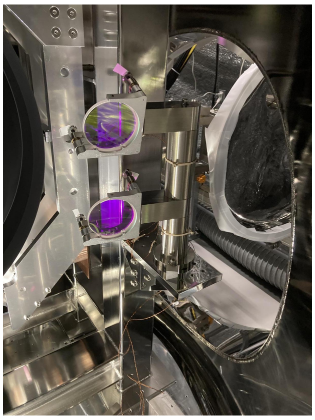


Figure 4: Picomotor-installed mirrors in A chamber. These mirrors are aligning the Pcal beams to ETM, which is 34.9 m away through a vacuum pipe. The remote control system with the Picomotors is useful for fine alignment adjustment.

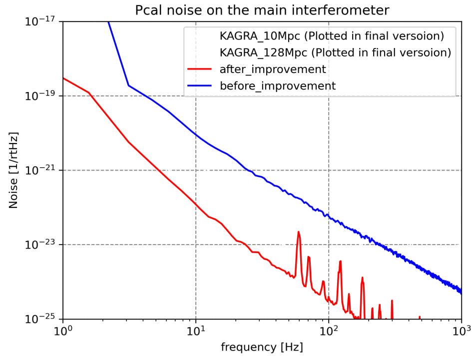


Figure 5: Estimated noise on the main interferometer caused by Pcal. The noise was improved by nearly 50dB, which is enough low compared with the final target sensitivity of KAGRA.

system is assembled with analogue circuitry, but ports such as those for reference signals and for setting the DC value of the laser power are supplied with signals from the KAGRA digital system through DAC (Digital-Analog converter) and AI (Anti-Imaging) filters (Figure 2). The unexpected signals were about 5 Vpp around 500 kHz, and observed at the input ports of the Pcal OFS analog circuit, which means they may cause unexpected effects on the OFS system. Our investigation revealed that OP amps (AD8622 provided by Analog Devices) with output impedance 100 Ω in the final stage of the AI circuit make the unexpected signals because it could not provide enough current required by the parasitic capacitance of the long cable, which is over 35 m long and runs between the OFS circuit at A chamber area and a DAC system at the end mirror area. We therefore added a buffer circuit just after the AI circuit, consisting of AD8672 provided by Analog Devices and 500 Ω output impedance, so that it would not make the oscillation.

The noise on the interferometer caused by the Pcal is shown on Figure 5. With the laser power stabilised condition by the OFS control loop, the RIN (Relative Intensity Noise) was obtained by measuring the laser power fluctuation with the TxPD1 and TxPD2, and then using Equation 1 and the following parameters, the mirror displacement noise produced by this Pcal laser was calculated and divided by the baseline length 3000 m to give the strain equivalent noise. The used parameters are $\theta = 0.755$ deg, $M = 22.945$ kg, and $c = 2.99792458 \times 10^8$ m/s. And, $(\vec{a} \cdot \vec{b})M/I$ was ignored because the value is sufficiently small relative to 1 when the beam positions are adjusted well. In addition, as the value of the DC laser power depends on the sensitivity of the interferometer, a value of 1 W each path was assumed, which is similar to the value used or planed to used in O3GK (3.2 W) and O4 (1 W). During the noise measurement, no reference signal was injected. This result shows that the sensitivity of the interferometer could be limited by the Pcal before this improvement, but after it the noise is sufficiently low. Note that if the interferometer sensitivity is good as design, even with a lower laser power, the Pcal reference signal can be observed with enough SNR in the interferometer, which means that the noise caused by the Pcal laser can be lower.

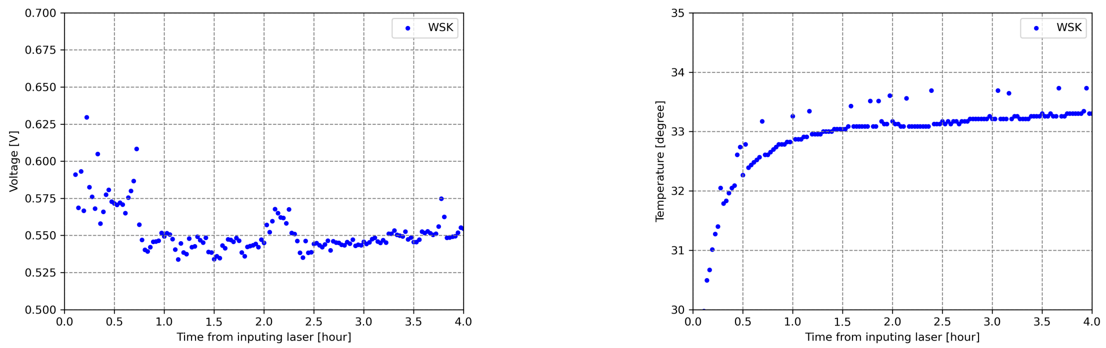
3.3 Uncertainty improvement with an updated integrating sphere calibration procedure

A close investigation of the integrating sphere calibration data in O3GK showed that the variability of data in the long term monitor was greater than expected. We have focused on the two points listed below to identify the causes of the variation and implement countermeasures. The overall results of the data acquired and countermeasures taken for O4 will become clear in the future, but the investigations and countermeasures for these two points are described in this section.

a. Temperature dependence of integrating spheres

b. Injection conditions of the beam into an integrating sphere

For point a, we monitored the time evolution of WSK output in our laboratory by injecting a laser into it[12]. A silicon diode thermometer (DT-670-CU-HT-1.4H) was attached to the sensor part of WSK and monitored the temperature at the same time. The results are shown on Figure 6, which implies the temperature change stabilises 30 minutes or one hour after laser incidence and the output of WSK has correlation with the temperature, which may make about 10% changes. In our integrating sphere calibration, we always compare 2 integrating spheres, so if the time variation is similar at the 2 integrating spheres, this temperature dependence effect would be smaller. Based on these results, we decided to give a warming-up time of one hour after laser incidence in our integrating sphere calibration procudure.



(a) Output from WSK. **(b)** Temperature changes.

Figure 6: Time changes of WSK output and changes in temperature.

Regarding point b, integrating sphere laser power sensors are generally supposed that the output is independent of the angle and polarization of the incident laser, and the position of the incident laser as long as it is well inside the edge of the incident port. However, our research shows that these factors also need to be taken into account for the few percent or lesser than one percent uncertainty we are targeting for O4 and beyond. As described in [13] in details, the effect of the incident angle becomes significant from around 10 degrees, with an effect of about 8 % in the worst case measured. Even at an incident angle between +5 degree and -5 degree, the effect of about 0.1 % is possible. The incidence position dependence has also been investigated by LIGO calibration group and suggests a few tenths of a percent impact[14]. For O4, in order to reduce the influence from the effects, a mark or positioning mechanism was applied on the Tx/Rx module and the calibration measurement setup for the WSK so that the incident angles are 0 degrees and the beam positions are at the center of the port at each calibration measurement.

4. Conclusion

As the number of observed gravitational wave (GW) events increases, the calibration of GW telescopes becomes increasingly important. KAGRA has been calibrated using a photon calibration system (Pcal), similar to ones of LIGO and Virgo, and we had been upgrading the system for O4 started in May 2023 from the end of O3GK.

The three main upgrades, an improved laser beam alignment system; reduced laser power noise; and tasks fro improving calibration uncertainty of the Pcal itself; were completed before O4. In particular, the laser noise suppression has been improved by nearly 50 dB, and as a result, the noise is sufficiently low compared to the final target sensitivity of KAGRA. The Pcal overall uncertainty, including the effect of the improvements above, will be obtained after the ongoing O4 and analysis, which is anticipated to be better than 3 % at O3GK.

Pcal is a calibration method that has been used for many years in GW telescopes, but has the potential to aim for even lower uncertainty. Since improving the calibration accuracy, precision, and reliability of the telescope is our past and future challenge, we will further improve the Pcal as well as develop other new methods.

References

[1] https://www.ligo.caltech.edu/

[2] B.P.Abbott et al., 2016 *PRL*, 119.161101

[3] B.P.Abbott et al., 2017 *ApJL*, 848 L12

[4] https://gwcenter.icrr.u-tokyo.ac.jp/en/

[5] https://www.virgo-gw.eu/

[6] S.Karki et al., 2016 *Rev Sci Instrum*, 87, 114503

[7] https://www.geo600.org/

[8] https://www.holoor.co.il/

[9] Bin-Hua Hsieh, 2018 *Master thesis of U.Tokyo*

[10] Sudarshan Karki et al., 2022 *Galaxies*, 10, 42

[11] T.Akutsu et al., 2021 *PETP*, 05A102

[12] Koki Ito, 2021 *Master thesis of U.Toyama*

[13] Shingo Fujii on behalf of the KAGRA collaboration, 2023 *ICRC*

[14] Matthew Spidell et al, 2021 *Metrologia* 58 055011

Full Authors List: KAGRA Collaboration

H. Abe[1], T. Akutsu[2,3], M. Ando[4,5], M. Aoumi[6], A. Araya[7], N. Aritomi[8], Y. Aso[2,9], S. Bae[10], R. Bajpai[2], K. Cannon[5], Z. Cao[11], R.-J. Chang[12], A. H.-Y. Chen[13], D. Chen[14], H. Chen[15], Y. Chen[15], A. Chiba[16], R. Chiba[17], C. Chou[18], M. Eisenmann[2], S. Fujii[17], I. Fukunaga[19], D. Haba[1], S. Haino[20], W.-B. Han[21], H. Hayakawa[6], K. Hayama[22], Y. Himemoto[23], N. Hirata[2], C. Hirose[24], S. Hoshino[24], H.-F. Hsieh[25], C. Hsiung[26], S.-C. Hsu[27,25], D. C. Y. Hui[28], K. Inayoshi[29], Y. Itoh[19,30], M. Iwaya[17], H.-B. Jin[31,32], K. Jung[33], T. Kajita[34], M. Kamiizumi[6], N. Kanda[30,19], J. Kato[16], T. Kato[17], S. Kim[28], N. Kimura[6], T. Kiyota[19], K. Kohri[35], K. Kokeyama[36], K. Komori[5,4], A. K. H. Kong[25], N. Koyama[24], J. Kume[5], S. Kuroyanagi[38,37], S. Kuwahara[5], K. Kwak[33], S. Lai[18], H. W. Lee[39], R. Lee[15], S. Lee[40], M. Leonardi[41,2], K. L. Li[12], L. C.-C. Lin[12], C-Y. Lin[42], E. T. Lin[25], G. C. Liu[26], L.-T. Ma[25], K. Maeda[16], M. Matsuyama[19], M. Meyer-Conde[19], Y. Michimura[43,5], N. Mio[44], O. Miyakawa[6], S. Miyamoto[17], S. Miyoki[6], S. Morisaki[17], Y. Moriwaki[16], M. Murakoshi[45], K. Nakamura[2], H. Nakano[46], T. Narikawa[17], L. Nguyen Quynh[47], Y. Nishino[2,48], A. Nishizawa[5], K. Obayashi[45], J. J. Oh[49], K. Oh[28], M. Ohashi[6], M. Ohkawa[24], K. Oohara[50,51], Y. Oshima[4], S. Oshino[6], M. A. Page[2], K.-C. Pan[15,25], J. Park[40], F. E. Peña Arellano[6], S. Saha[25], K. Sakai[52], T. Sako[16], R. Sato[24], S. Sato[16], Y. Sato[16], T. Sawada[6], Y. Sekiguchi[53], L. Shao[29], Y. Shikano[54,55], K. Shimode[6], H. Shinkai[56], J. Shiota[45], K. Somiya[1], T. Suzuki[24], T. Suzuki[1], H. Tagoshi[17], H. Takahashi[57], R. Takahashi[2], A. Takamori[7], K. Takatani[19], H. Takeda[58], M. Takeda[19], M. Tamaki[17], K. Tanaka[59], S. J. Tanaka[45], T. Tanaka[58], A. Taruya[60], T. Tomaru[2], K. Tomita[19], T. Tomura[6], A. Toriyama[45], A. A. Trani[5], S. Tsuchida[61], N. Uchikata[17], T. Uchiyama[6], T. Uehara[62], K. Ueno[5], T. Ushiba[6], M. H. P. M. van Putten[63], H. Wang[4], T. Washimi[2], C. Wu[15], H. Wu[15], K. Yamamoto[16], M. Yamamoto[16], T. Yamamoto[6], T. S. Yamamoto[37], S. Yamamura[17], R. Yamazaki[45], L.-C. Yang[18], Y. Yang[18], S.-W. Yeh[15], J. Yokoyama[5,4], T. Yokozawa[6], H. Yuzurihara[6], Y. Zhao[17,2], Z.-H. Zhu[11,64]

[1]Graduate School of Science, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan. [2]Gravitational Wave Science Project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan. [3]Advanced Technology Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan. [4]Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. [5]Research Center for the Early Universe (RESCEU), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. [6]Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan. [7]Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan. [8]LIGO Hanford Observatory, Richland, WA 99352, USA. [9]The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan. [10]Korea Institute of Science and Technology Information (KISTI), 245 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea. [11]Department of Astronomy, Beijing Normal University, Xinjiekouwai Street 19, Haidian District, Beijing 100875, China. [12]Department of Physics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan. [13]Institute of Physics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan. [14]Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan. [15]Department of Physics, National Tsing Hua University, No. 101 Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan. [16]Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan. [17]Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan. [18]Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan. [19]Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan. [20]Institute of Physics, Academia Sinica, 128 Sec. 2, Academia Rd., Nankang, Taipei 11529, Taiwan. [21]Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China. [22]Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan. [23]College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan. [24]Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan. [25]Institute of Astronomy, National Tsing Hua University, No. 101 Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan. [26]Department of Physics, Tamkang University, No. 151, Yingzhuan Rd., Danshui Dist., New Taipei City 25137, Taiwan. [27]Department of Physics, University of Washington, 3910 15th Ave NE, Seattle, WA 98195, USA. [28]Department of Astronomy and Space Science, Chungnam National University, 9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea. [29]Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, China. [30]Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan. [31]National Astronomical Observatories, Chinese Academic of Sciences, 20A Datun Road, Chaoyang District, Beijing, China. [32]School of Astronomy and Space Science, University of Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, China. [33]Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea. [34]Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan. [35]Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan. [36]School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK. [37]Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan. [38]Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain. [39]Department of Computer Simulation, Inje University, 197 Inje-ro, Gimhae, Gyeongsangnam-do 50834, Republic of Korea. [40]Technology Center for Astronomy and Space Science, Korea Astronomy and Space Science Institute (KASI), 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea. [41]Department of Physics, University of Trento, via Sommarive 14, Povo, 38123 TN, Italy. [42]National Center for High-performance computing, National Applied Research Laboratories, No. 7, R&D 6th Rd., Hsinchu Science Park, Hsinchu City 30076, Taiwan. [43]LIGO Laboratory , California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA. [44]Institute for Photon Science and Technology, The University of Tokyo,

2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan. [45]Department of Physical Sciences, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara City, Kanagawa 252-5258, Japan. [46]Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan. [47]Department of Physics and Astronomy, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA. [48]Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. [49]National Institute for Mathematical Sciences, 70 Yuseong-daero, 1689 Beon-gil, Yuseong-gu, Daejeon 34047, Republic of Korea. [50]Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan. [51]Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan. [52]Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikatakai, Nagaoka City, Niigata 940-8532, Japan. [53]Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan. [54]Graduate School of Science and Technology, Gunma University, 4-2 Aramaki, Maebashi, Gunma 371-8510, Japan. [55]Institute for Quantum Studies, Chapman University, 1 University Dr., Orange, CA 92866, USA. [56]Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan. [57]Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya, Tokyo 158-0082, Japan. [58]Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan. [59]Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan. [60]Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan. [61]National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan. [62]Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan. [63]Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea. [64]School of Physics and Technology, Wuhan University, Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, China.