Final Draft of bKAGRA Phase 1 Paper

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on be half of the Paper Writing Team:
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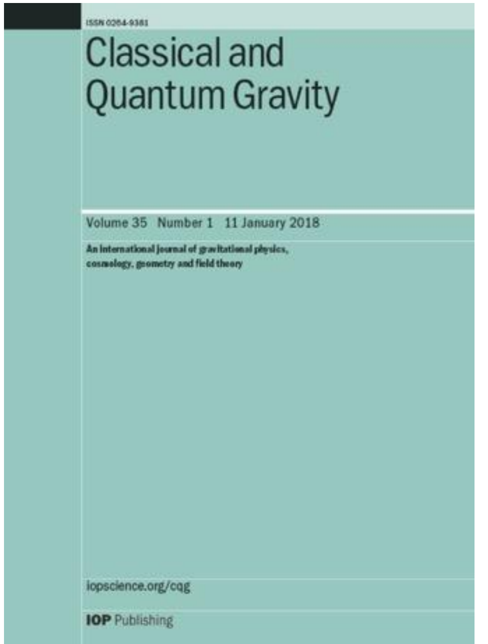
Status

- Draft finalized by the Paper Writing Team, with a lot of help from many people
  Available at JGW-P1809289
- November 19: Presented at KSC telecon, circulated to kagra mailing list for comments
- November 30: Deadline for comments
- To be submitted to CPC after this F2F
- To be submitted to CQG after approval from CPC and referees

Practical Overview

- Title:
  First cryogenic test operation of underground km-scale gravitational-wave observatory KAGRA
- Author:
  Author List 2016 + 2017
  + Y. Obuchi, S. Saitou, N. Sato, F. Uraguchi
- Target Journal:
  Classical and Quantum Gravity



Main Message

- Successful operation of 3-km cryogenic interferometer for the first time
- Show that cryogenic cooling is compatible with 3-km interferometer alignment and control
- Things already demonstrated in iKAGRA
  - Underground operation
  - 3-km alignment of vacuum tubes
  - 3-km link between real-time machines
  - Data transfer to Osaka, Kashiwa, etc.
- First things in bKAGRA Phase 1
  - Cryogenic ETMY
  - Real Type-A, Type-B suspensions
  - Initial alignment through cryogenic ducts and baffles
  - Measured beam positions in vacuum tanks

Sections

1. Introduction
2. Interferometer configuration of KAGRA
3. bKAGRA Phase 1 operation
   3.1 Initial alignment and installation accuracy
   3.2 Cryogenic cooling of the sapphire mirror
   3.3 Characterization of suspensions
   3.4 Interferometer control and calibration
   3.5 Data transfer
   3.6 Interferometer sensitivity and stability
4. Conclusions and outlook

1. Introduction

- Detections of GWs (upto GWTC-1)
- Introduction to aLIGO and AdV
- Necessity of KAGRA for more precise parameter estimation, sky localization, and polarization tests
- Introduction to KAGRA
- What we have done in iKAGRA and purpose of bKAGRA Phase 1

Table 1. Summary of the phases of KAGRA. Type-C suspension is a double pendulum and Type-A suspension is a full eight-stage pendulum (see Section 2 for details).

	iKAGRA	bKAGRA Phase 1	bKAGRA
Operation year	Mar-Apr 2016	Apr-May 2018	2019- (planned)
Interferometer configuration	3-km Michelson	3-km Michelson	3-km RSE
Test mass substrate	Fused silica	Sapphire	Sapphire
Test mass temperature	room temp.	18 K/room temp.	22 K
Test mass suspension	Type-C	Type-A	Type-A

2. Interferometer Configuration

- Interferometer, mirror, suspension, and cryopayload configuration in full bKAGRA
- Latest estimated sensitivity of bKAGRA
- Quite in detail to show the latest design so that this paper will be cited as a reference for KAGRA from now on

  (Many parameters and cryopayload configurations are updated from [Somiya CQG 2012](#) and [Aso PRD 2013](#))

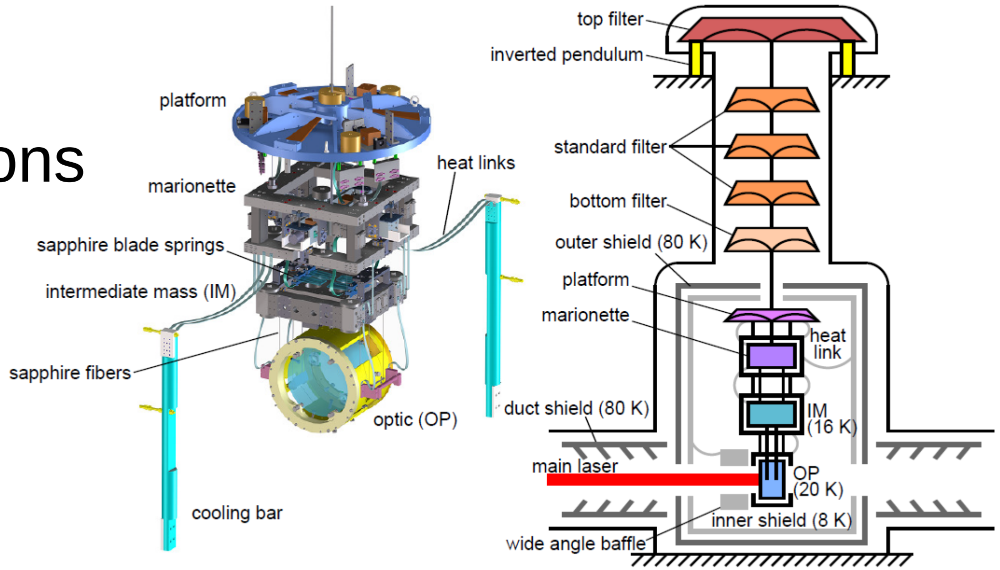
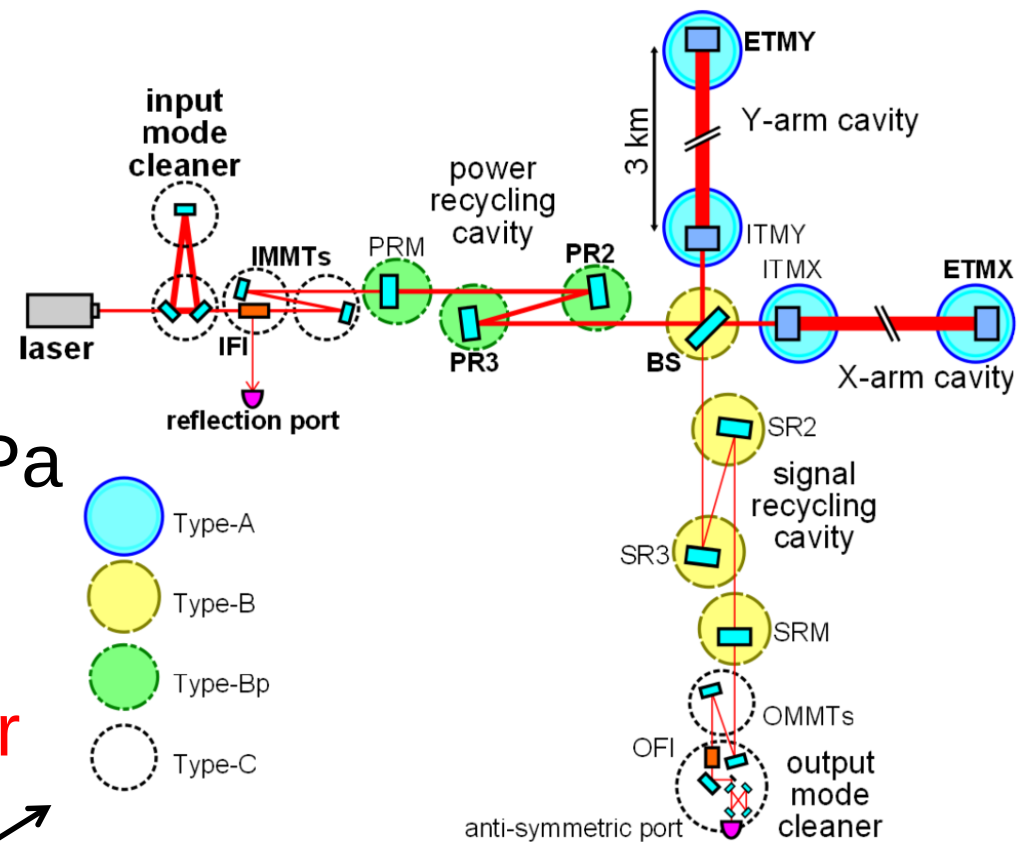


Figure 3. The CAD drawing of the cryogenic payload (left) and the schematic of the cryogenic suspension system of sapphire test masses (right).

3. bKAGRA Phase 1 Operation

- Differences between full bKAGRA and Phase 1
  - ITMs and SRs not installed
  - PRM misaligned
  - signal extraction from REFL at f1
  - 50 mW at BS
  - 10^{-5} to 10^{-4} Pa instead of 10^{-7} Pa
  - ETMX without heat links
  - pilot ETMY mirror



Optics used in Phase 1 operation are labeled in bold

Figure 1. Schematic of the bKAGRA interferometer. All the mirrors shown are suspended inside the vacuum tanks with four types of vibration isolation systems. IMMT (OMMT): input (output) mode-matching telescope, IFI (OFI): input (output) Faraday isolator. Optics used in the Phase 1 operation are labeled in bold.

3.1 Initial alignment

- Tools to aid initial alignment procedure
  - Prototype baffle PDs
  - Tcam

    successfully monitored the cryogenic mirror
- Installation accuracy measurement
  - within 1 cm from designed positions
  - IMC length measurement show IMC length was different from the designed by 1.3 cm
  - Reasonable result
  - Enough accuracy to form a full interferometer (within mirror position and alignment tuning range)

3.2 Cryogenic cooling

- ETMY cooled down to below 20 K within a month
- Finally IM reached 16 K and TM reached 18 K
- Almost as expected
- O(100) urad drift during cool down, but can be recovered using actuators (actuators have enough range)

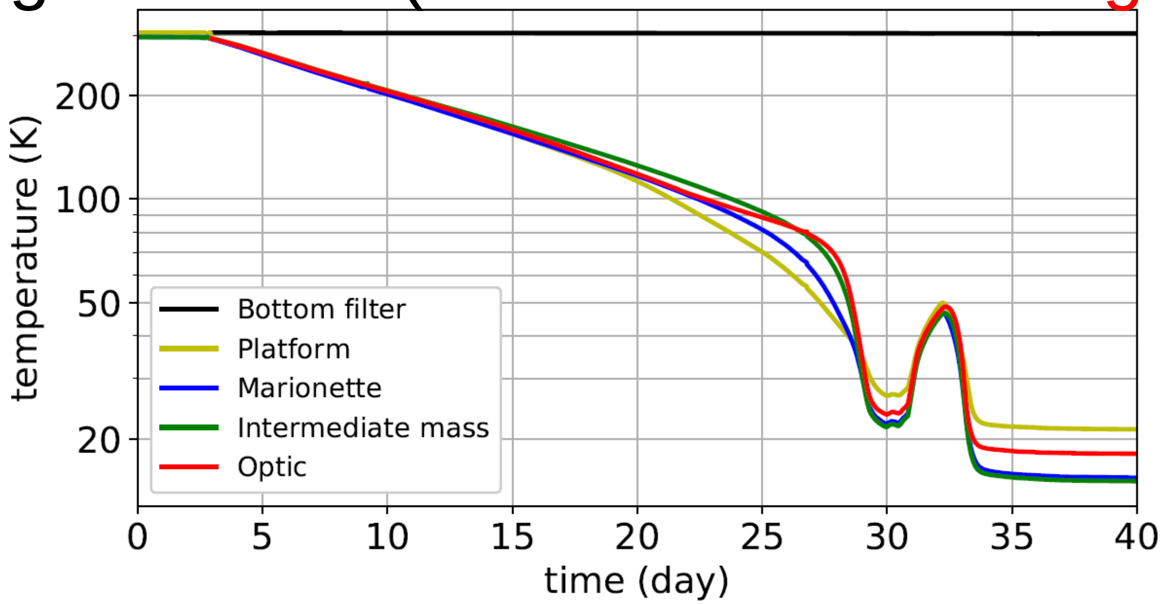
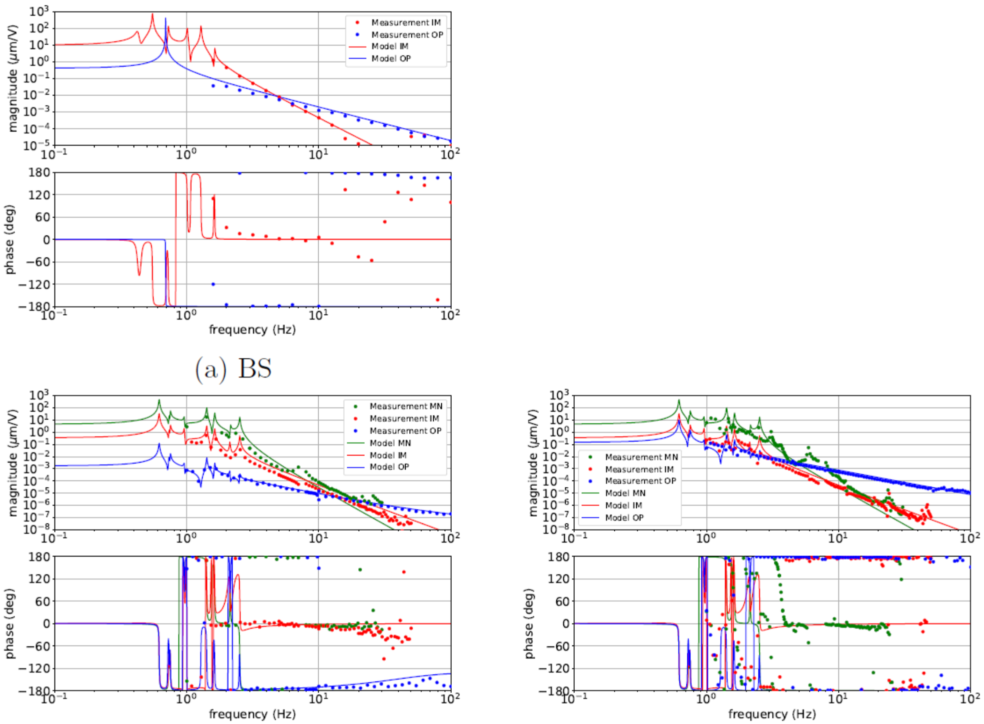


Figure 5. Cooling curve of ETMY. The bump starting from around 30th day is due to the restart of cryocoolers.

3.3 Characterization of suspensions

- Measured actuator transfer functions
- BS and ETMX matched with the model within a factor of two
- ETMY had spurious couplings
  - maybe from touching
  - touching was successfully solved for ETMX
- ETMY (18K) > ETMX by 30%



(a) BS

(b) ETMX

(c) ETMY

Figure 6. Actuator transfer functions of BS (top left), ETMX (bottom left) and ETMY (bottom right). The measurement results and expected curves from suspension models described in Ref. [12] are plotted for marionette (MN), intermediate mass (IM) and optic (OP) stages. The transfer functions are in the unit of the optic displacement per voltage applied to the coil drivers.

3.4 IFO control and calibration

- Used BS IM and TM for the feedback (crossover at 0.4 Hz)
- Digital system ADC/DAC details and time delay measurements
- Optical gain calibration by Michelson free swing
- UGF drift estimated from calibration line at 91 Hz
- Online calibration with <1 sec latency

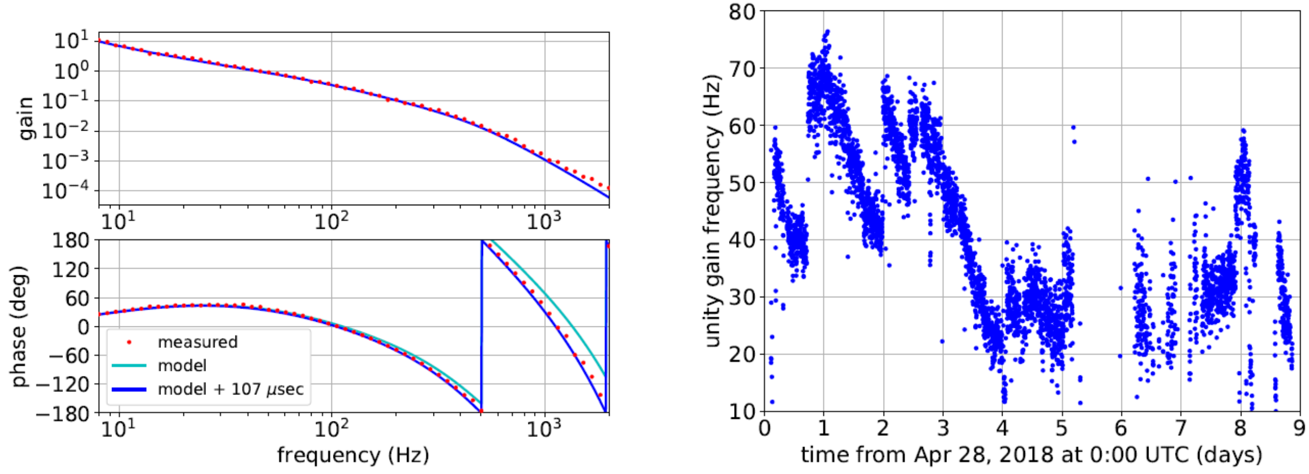


Figure 8. The openloop transfer function of the Michelson interferometer control (left) and estimated unity gain frequency over time (right).

3.5 Data transfer

- Overview of data transfer system
- Result of the test
  - Speed from detector to analysis building
    ~200 MB/s (meets requirement)
  - Latency from detector to OCU
    ~3 seconds

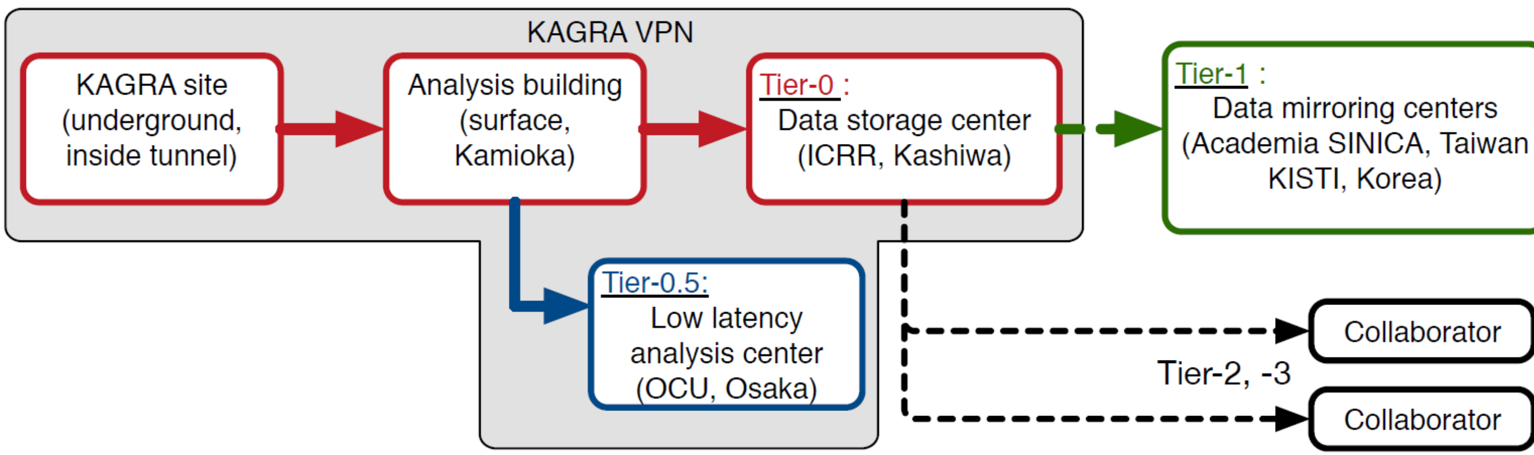


Figure 9. Overview of the KAGRA data transfer system. Tier-0 (original) and Tier-0.5 (low latency) are formed as isolated local network using VPN (Virtual Private Network).

3.6 IFO sensitivity and stability

- Sensitivity limited by angular controls noise and photo diode dark noise
- Better than iKAGRA because acoustic noise coupling was lower (not evacuated in iKAGRA)

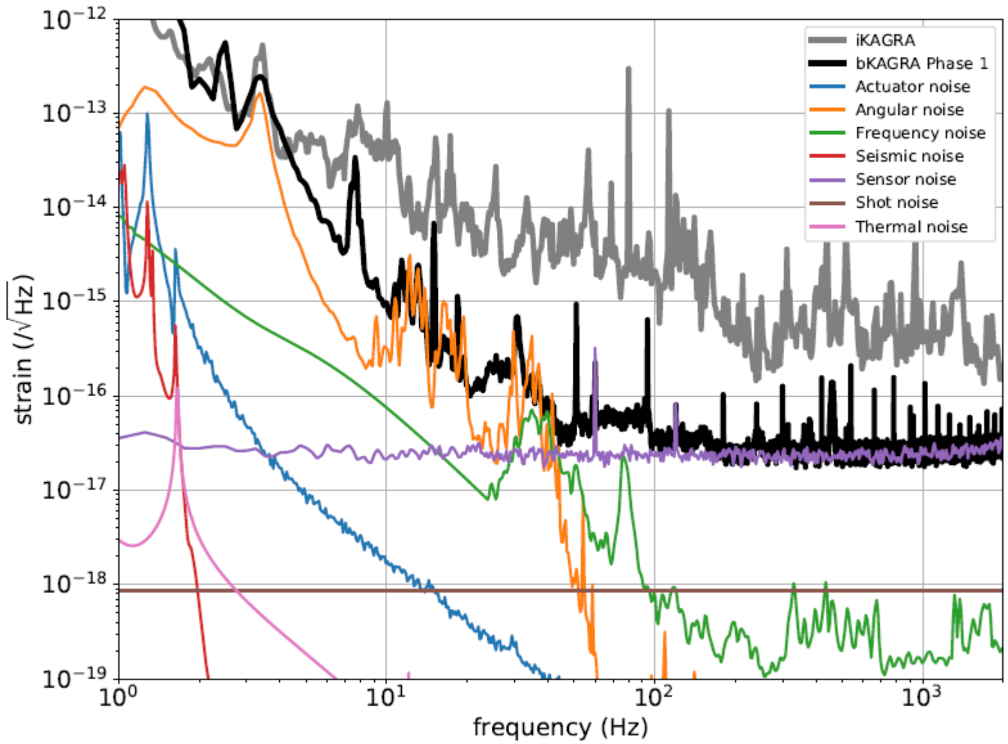


Figure 10. The strain sensitivity of KAGRA during Phase 1 operation, compared with various strain equivalent noises. Actuator noise is the sum of the displacement noise

3.6 IFO sensitivity and stability

- BNS range about 17 pc
- Duty factor: 69 % (88.6% for first half)
  - due to stormy weather and earthquakes
  - effect was higher because of ETMY touching
- Automatic lock using Guardian
  - lock often took less than 10 min
  - longest lock 11.1 hours

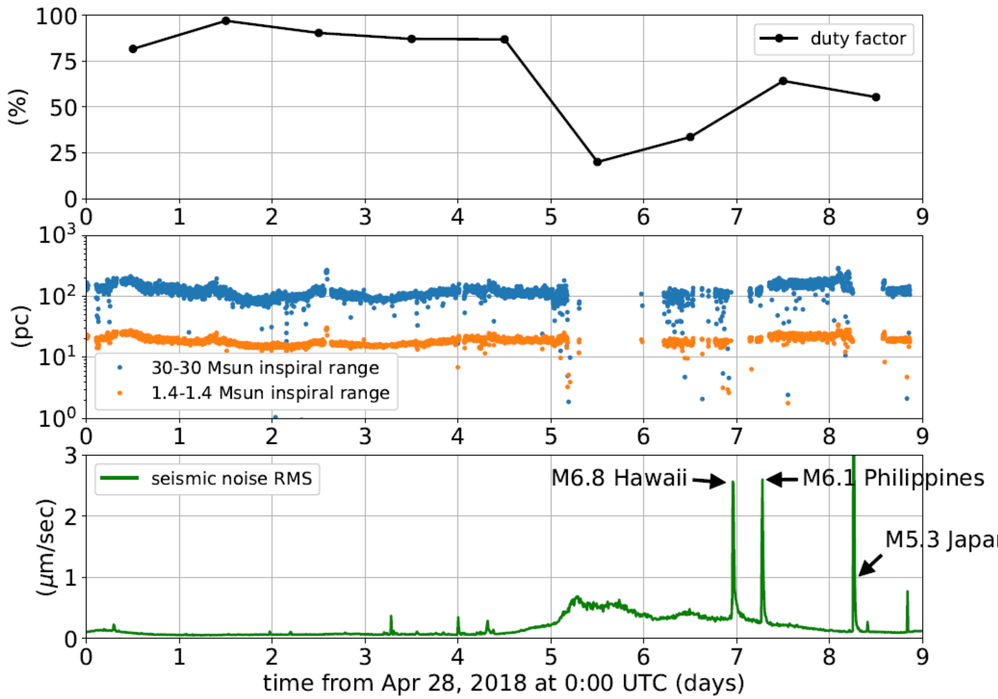


Figure 11. Daily duty factor (top), inspiral range (middle), and seismic-noise level (bottom) during Phase 1 operation. The root-mean-square (RMS) of the ground velocity measured with a seismometer is shown.

4. Conclusions and outlook

- Sapphire mirror suspended by a full system was cooled down to below 20 K within 35 days
- Alignment drift and mirror actuation was measured, and confirmed cryogenic cooling is compatible with interferometer alignment and control
- Installation accuracy was enough to form a full interferometer
- There were ETMY touching issues but successfully solved

- Expect to finish installations by March 2019, first observing run in late 2019

Details Not Discussed

- Details of several things are not written in this Phase 1 paper so that people can write their papers
  - Sapphire mirror
  - Tcam
  - Type-A and Type-B characterization
  - Type-Bp characterization
    ⟶ Shoda-san's paper
  - Cryopayload

Summary

- bKAGRA Phase 1 paper draft was finalized
  Available at [JGW-P1809289]
- To be submitted to CPC after this F2F
- Thank you very much for comments
- We welcome further comments by CPC deadline, as always

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