Experiments Results and Plans of CLIO and Underground Understanding

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MG13 @ Stockholm Sweden July 2012
CLIO Introduction including
  • KAGRA Tunnel Design and Construction
  • Vacuum Duct Setting Simulation

Underground Lessen from LISM to CLIO

Thermal Noise Reduction

Digital System preparation for KAGRA

NQD (HOD) demo using CLIO for Lock Acquisition

Some plans

Summary
• 220km away from Tokyo
• 1000m underground from the top of the mountain. (Near Super Kamiokande)
• 360m altitude
• In the Hard rock of Hida gneiss (5 [km/sec] sound speed)
KAGRA between Two Faults

- 1 mm/year slip or creep for 3 million years.
- It made crank shape of Takahara river near LCGT.

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“GW” Atotsu Tunnel (Corner station access tunnel) excavation started in July/22/2012

- 50m>/week speed. Total 100m excavation.
Mozumi Tunnel (Y arm End access tunnel) excavation started in May/22/2012.

- 50m+/week speed. Total 240m excavation.
Arm Duct Tube Setting simulation

- Arm duct (φ = 80cm) and expected tunnel housing was simulated in a MIRAPRO factory.
Deep underground (>200m) -> noise shielding effects surface noises (temperature, seismic noise, rain falls, underwater variation, cosmic rays, newtonian noise, etc.)

Hard basement rock (gneiss : Sound velocity~ 5000m/s) good for precise measurements with low background. -> detection of small signals from deep interior of earth for geophysics.

But... recently, seasonal change due to water in the ground and snow on the surface can be trend noise (very low frequency).

It is important know them ahead of KAGRA operation for keeping lock as long as possible and to understand what will happen in seismic motion.
Effort to Know Kamioka Underground using Strain Meters (horizontal motion)

Linear strain meter

Shear meter (Strain $\sim 10^{-12}$)

Fabry Perot strain meter (Strain $\sim 10^{-9}$)
Effort to Know Kamioka Underground using Super-conductive Gravimeter (Vertical motion)

- Liquid He cooled inside.
- Liquid He is recycled by PT type Refrigerator

- A ball is levitated by Meissner effect.
- The position change of the ball is detected by a capacitive sensor.
Earthquakes (M = 5 ~ 7) took place ~ 300km away from Kamioka.

Sumatra-Andaman earthquakes (M = 9) took place 5600 km away.
Effect of Water & Snow

- Superconductive Gravimeter Data -

Gravity change including SG Trend.

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1.5km Laser Strain-meter

- set along KAGRA -

in each arm
Seismic noise below 1Hz. Dominated by ocean wave condition.

Seismic Noise Level Comparison

By Rana
Kamioka Seismic Noise
- fine day and stormy day -

Strain Meter Data
(< 20Hz)

070215 : Stormy day
070213 : fine day

10 times enhancement of micro seismic noise due to ocean waves can be observed.
Acceleration variation in one day

Mark Becker et al., NIKHEF (Netherland) data in May 28th after GWADW2010
Seismic Noise around Kamioka Area

- $f < 1\text{Hz}$
  Outside(\text{Moz,Ato}) = \text{CLIO}$
- $1\text{Hz} < f < 10\text{Hz}$
  Outside(\text{Moz,Ato}) > \text{CLIO}$
- $f > 10\text{Hz}$
  Outside(\text{Moz,Ato}) = \text{Tokyo}$

This shows that natural events such as atmospheric and ocean events dominate the seismic noise above $\sim 10\text{Hz}$, while human activity dominates it below $\sim 10\text{Hz}$. 
Alignment Noise of one CLIO mirror

MMT2 Pitch Motion
(20070627-Sunny)

MMT2 Pitch motion
PD Noise

Frequency [Hz]

10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}

10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
CLIO for thermal noise reduction Test bench

Per- EM- Cryostat  Per- 100m Arm

Inline- EM- Cryostat

Per- Arm PickOff

BS

Telescope 1

MC

Inline- 100m Arm

Inline- NM- Cryostat

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CLIO Features

- 100m base-line, Critical coupling FP cavities (finesse ~ 3140),
- Locked-FP style for the control easiness.
  (one arm : used for Laser Freq. Stb. The other arm : mass locking)
- About Cryogenic R&Ds, Technical combination of products of
  - CLIK(2000-02) for first cryogenic interferometer development
  - LISM(1999-2002) for the first? Underground IFO characterization
  - Ultra low vibration PT
    refrigerator developments
    at KEK(2004-2006)

- Demonstrate an improvement of sensitivity by reduction of the mirror and suspension thermal noise using mirror cooling technique.
Displacement in November 2008
– Almost thermal noise limited at 300K condition–

CLIO Displacement Noise Improvement from April/2008 to December/2008

CLIO displacement touched the predicted thermal noise levels.

- Sapphire mirror thermoelastic noise (80Hz~250Hz) Green Line
- Suspension thermal noise (20Hz-80Hz) Blue Line
Noise Budget

CLIO noise budget at 300K

Displacement noise [m/Hz $^{1/2}$]

Frequency [Hz]
CLIO Mirror Suspension

Heat Linking: Pure AL wires (φ0.5mm diameter (5N RRR2400))

① Magnet Base – Inner Shield: one 10cm
② CryoBase – Inner Shield: one 31.5cm
③ CryoBase – UpperMass: one 11.5cm
Suspension thermal noise reduction

- Suspension wires are pure aluminum, not sapphire fibers.

- "Suspension thermal noise" was decreased, as the aluminum wires were cooled as, 
  (251K → 225K → 91K) 
  (Green, Black, Red)
Mirror Thermo-elastic Noise Reduction

- Only two input mirrors were cooled, accounting for smaller spot size on these mirrors.

- According to noise budget verification, main noise contributions are ...
  - Shot noise
  - Suspension thermal noise
  - Mirror thermo-elastic noise

- Sapphire mirror thermo-elastic noise reduction seems to contribute the displacement noise improvement around 200Hz.
CLIOにおける低温化の成果
- サファイア鏡のThermoelastic Noiseの低減 -

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LIGO Digital Control System Introduction
– MOU with LIGO Group–

● Training and Basic system preparation for KAGRA

● Developed systems at CLIO using digital system
  – Auto initial alignment system for MC using picomotor
  – Auto Lock acquisition system
  – Calibration system
  – Local damping system
  – The same sensitivity as analog with white/dewhite filters

● Very near future
  – Auto beam centering system (sensitivity depends on beam centering strongly at CLIO)
  – Long term monitors for laser power, seismic motion, temperature etc.
  – Auto noise budget system
LIGO Digital Control System Introduction
- Digital Control system -

ADC/DAC In
Expansion Chassis

Anti Imaging filters
Anti Alias filters
Real time PC

DAC adapter
ADC adapter
Binary output adapter
ADC/DAC In
Expansion Chassis

Differential Driver
For BO

To NIM modules
PCI Connection

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Client system

- AutoLock -> Measure -> Improve process by using script.
LIGO Digital Control System Introduction
- AD/DA noise check with CLIO sensitivity -

![CLIO sensitivity graph](image)

- ADC noise
- DAC noise
- Digital best (2010/08/19)
- 20K Analog best (2010/03/20)

Displacement noise (m/Hz)

Frequency (Hz)

*T0=08/09/2010 01:16:38  *Avg=17/Bin=4L  *BW=0.187493

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Lock Acquisition Demo using NQD
- for the simplest FP lock acquisition -

• Lock Acquisition Techniques are required for the long baseline FP cavity that has ~ msec storage time
  – Green Locking (LIGO and KAGRA default plan)
  – Offset Locking
  – Trigger Locking
  – Etc.

• We proposed another technique, named NQD, and HOD as a last rescue. (Ref: App. Opt. 49, 5217-5225 (2010))
  – NQD : Near Q-phase Demodulation in PDH method
  – HOD : Sum of Odd harmonic demodulation signal in PDH
  – To Obtain wider linear range and beat-less signal by setting RF(AF) modulation frequency near the resonance width area (not far from it as normal selection).
Normal PDH I-Phase signal assuming a FP cavity with RF sideband near resonance. (assuming 30nm/sec mirror speed for 1550 finesse of 3km arm FP)

Just set demodulation phase not in-phase but “near Q”. Then, signal linear range can be extended according to modulation frequency setting.

X-axis : normalized by Resonance width, Y-axis : Arbitrary but comparable
Lock Acquisition Demo using NQD

- What is NQD and HOD -

- Take 1\textsuperscript{st}, 3\textsuperscript{rd}, 5\textsuperscript{th} In-phase demodulation signal and add them at proper ratio.

- Some merits and demerits of NQD and HOD
  - Beating becomes small
  - Zero of error signal at resonance position.
  - Linear range can be extended over modulation frequency.
  - Noisy signal

\[ S_{1T} + \frac{J_1(m)}{J_3(m)} S_{3T} \]
\[ S_{1T} + 2 \frac{J_1(m)}{J_3(m)} S_{3T} + \frac{J_1(m)}{J_5(m)} S_{5T} \]
We verified NQD signal can be realized by using small rigid FP.
Lock Acquisition Demo using NQD

- Demonstration by CLIO Mode Cleaner (9.5m finesse:??)-

● Swing MC End Mirror and obtain a hard beet signal of normal PDH.

● Try MC locking using Laser Thermal, Laser PZT and outer EOM feedback paths with ~300kHz UGF.

● Preliminarily, Normal PDH almost filed to lock. On the other hand NQD method showed high lock acquire rate and kept lock as long as the PZT feedback voltage did not over the dynamic range.

● Mass locking is to do.
CLIO Silicon Mirror Test Plan
- for the 3rd Generation GWD-

• **Good Aspects**
  – Less absorption for 1.5um wavelength (<1ppm/cm).
  – High thermal conductivity at cryogenic temperature. (comparable with sapphire)
  – Low mechanical loss at cryogenic temperature
  – No birefringence.
  – Has critical temperature.

• **Required R&Ds**
  – Polish and low loss coating on silicon substrate.
  – Verification of less absorption and mechanical loss.
  – High power and stable laser for 1.5 um wavelength.
  – Etc.

• **Install Silicon mirrors in CLIO for these R&Ds**
CLIO Silicon Mirror Test Plan
- Two silicon mirror polishing results (normal quality) -

**R = 151.55 m**

- Waviness < λ/20 (Φ80mm)
- Micro rough. < 3A (Φ0.3mm)

**R = 151.67m m**

- Waviness < λ/20 (Φ80mm)
- Micro rough. < 2.7A (Φ0.3mm)

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The CLIO has finally demonstrated the sapphire mirrors thermo-elastic noise and Al wires’ suspension thermal noise reduction at around $10^{-19} \text{[m/rHz]}$ displacement lever around 100Hz.

KAGRA underground understanding continues.

KAGRA tunnel excavation finally started. Completion around April 2014 is desired.

Digital system has been also prepared using CLIO with the support of LIGO group.

NQD demonstration for lock acquisition shows positive results.

Silicon mirrors were prepared for basic verification.