Real Time Control for

KAGRA
3km Cryogenic Gravitational
Wave Detector in Japan

October 7, 2013 ICALEPCS at San Francisco, U.S.A

Osamu Miyakawa (ICRR, UTokyo)
and
KAGRA collaboration
Einstein’s Theory: *information carried by gravitational radiation at the speed of light*

Gravitational waves!

- Coalescing compact binaries (neutron stars, black holes)
- Non-axi-symmetric supernova collapse
- Non-axi-symmetric pulsar (rotating, beaming neutron star)
Detection of gravitational wave using laser interferometer

GWs move mirrors differentially. We measure the distance between mirrors using fringe of light.

**Expected length change by GW:**

$\sim 1 \times 10^{-19} \text{m}$
Location of KAGRA

- Underground Kamioka mine, Gifu prefecture.
- ~250km away from Tokyo.
- ~40km away from Japan sea.
- This area is being used as cosmic ray observatories.
KAGRA tunnel entrance (New Atotsu)

春(Spring)
KAGRA tunnel entrance (New Atotsu)

冬(Winter)
~80% of tunnel Done

Center room
Low temperature operation at KAGRA to reduce thermal distortion
Development of optical configurations

Michelson interferometer (MI)  
Keep dark condition at detection port to reduce shot noise

Fabry-Perot MI (FPMI)  
Longer light path using Fabry-Perot cavities

Power recycling (PRFPMI)  
Higher laser power by a power recycling mirror at laser port

Dual recycling (DRFPMI)  
Enhance the GW signals by a signal recycling mirror at the dark port

TAMA, LIGO, VIRGO  
KAGRA, aLIGO, aVIRGO
Development of optical configurations

**Michelson interferometer (MI)**
- Keep dark condition at detection port to reduce shot noise

**Fabry-Perot MI (FPMI)**
- Longer light path using Fabry-Perot cavities
- CLIO

**Power recycling (PRFPMI)**
- Higher laser power by a power recycling mirror at laser port

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**KAGRA, aLIGO, aVIRGO**
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TAMA, LIGO, VIRGO

CLIO

KAGRA, aLIGO, aVIRGO
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TAMA, LIGO, VIRGO

KAGRA, aLIGO, aVIRGO

JGW-G1301851
Development of optical configurations

Michelson interferometer (MI)        Fabry-Perot MI (FPMI)

Power recycling (PRFPMI)        Dual recycling (DRFPMI)

Keep dark condition at detection port to reduce shot noise
Longer light path using Fabry-Perot cavities
Enhance the GW signals by a signal recycling mirror at the dark port

To keep interferometer being operated, we need Very Low Noise Control all the time

Higher laser power by a power recycling mirror at laser port

Position: ~10DOFs
Angle: ~20DOFs
Others: ~100DOFs

TAMA, LIGO, VIRGO
KAGRA, aLIGO, aVIRGO

KAGRA, aLIGO, aVIRGO
KAGRA control network design
KAGRA control network design

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KAGRA control network design

Real-time PCs

Center room

3km

3km Y arm cavity

3km X arm cavity

Laser
KAGRA control network design

Real-time PCs

Center room

3km

3km Y arm cavity

3km X arm Cavity

X end
KAGRA control network design

Real-time PCs

Center room

3km

3km X arm Cavity

Laser

Y end

X end
KAGRA control network design
KAGRA control network design

- Center room
- Real-time PCs
- Long RFM network
- 3km X arm cavity
- 3km Y arm cavity
- Laser
- Circuit
- 3km

Diagram showing the network design for KAGRA with connections between the center room, real-time PCs, and arms.
KAGRA control network design

- Center room
- Real-time PCs
- Long RFM network
- RT control signal: very low latency
- X end
- Y end
- 3km
- 3km X arm cavity
- 3km Y arm cavity
KAGRA control network design

RT control signal: very low latency

3km X arm Cavity

3km Y arm cavity

Long RFM network

Circuit

Real-time PCs

Center room

X end

Y end

3km
KAGRA control network design

- Real-time PCs
- Metal cable
- Fiber cable

RT control signal: very low latency

3km

Circuit

3km X arm Cavity

3km Y arm cavity

Laser

X end

Y end

Center room

Short RFM network

Long RFM network

Real-time PCs

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KAGRA control network design

- **Metal cable**
- **Fiber cable**

**Circuit**

- **RT control signal: very low latency**

Real-time PCs

3km

Center room

3km X arm Cavity

**Laser**

3km Y arm cavity

X end

Y end

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KAGRA control network design

Center room
Real-time PCs

3km

Metal cable
Fiber cable

Long RFM network
Short RFM network
DAQ network

RT control signal: very low latency

3km X arm cavity
3km Y arm cavity

X end
Y end

Circuit

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KAGRA control network design

- **Metal cable**
- **Fiber cable**

- **3km Y arm cavity**
- **3km X arm Cavity**

- **Long RFM network**
- **Short RFM network**

- **Real-time PCs**

- **Center room**

- **Circuit**

- **DAQ network**

- **GW data:** huge amount, low latency

- **RT control signal:** very low latency

- **RT control signal:** very low latency

- **3km**
KAGRA control network design

**Front room**
- Severs

**Center room**
- Real-time PCs
- DAQ network
- Long RFM network
- Short RFM network
- RT control signal: very low latency
- GW data: huge amount, low latency

**Circuit**
- RT control signal: very low latency

**Networks**
- Metal cable
- Fiber cable

**Locations**
- Front room
- Center room
- X end
- Y end
- 3km X arm cavity
- 3km Y arm cavity

**Distances**
- 3km
KAGRA control network design

Outside

Mine

Front room

Severs

Circuit

Real-time PCs

Center room

DAQ network

Short RFM network

Long RFM network

RT control signal: very low latency

GW data: huge amount, low latency

3km Y arm cavity

3km X arm Cavity

Metal cable
Fiber cable

3km

Y end

X end
KAGRA control network design

Outside

Mine

Front room

Severs

Circuit

General network

DAQ network

Long RFM network

Short RFM network

Real-time PCs

Center room

X end

3km

Y end

Metal cable

Fiber cable

RT control signal: very low latency

GW data: huge amount, low latency

RT control signal: very low latency

3km X arm cavity

3km Y arm cavity

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KAGRA control network design

- **Front room**: Real-time PCs
- **Severs**: KAGRA control network design
- **Outside**
- **Mine**
- **Center room**: General network, DAQ network, Long RFM network, Short RFM network, Real-time PCs
- **X end**: 3km X arm cavity
- **Y end**: 3km Y arm cavity
- **Circuit**: RT control signal: very low latency, GW data: huge amount, low latency
- **TCP/IP**: EPICS, NFS, network boot
- **Metal cable**: Fiber cable
- **3km**: Y end - X end

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KAGRA control network design

Outside

Mine

Front room

Severs

Circuit

DAQ network

General network

TCP/IP: EPICS, NFS, network boot

GW data: huge amount, low latency

RT control signal: very low latency

Long RFM network

Short RFM network

Real-time PCs

Center room

3 km

X end

Y end

Metal cable

Fiber cable

3 km X arm cavity

3 km Y arm cavity

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KAGRA control network design

Client workstations

Remote Control room

Front room

Severs

Outside

Mine

- Metal cable
- Fiber cable

X end

3km Y arm cavity

Y end

3km X arm cavity

Circuit

DAQ network

Long RFM network

Short RFM network

General network

TCP/IP: EPICS, NFS, network boot

GW data: huge amount, low latency

RT control signal: very low latency

RT control signal: very low latency

3km

Center room

Real-time PCs

Real-time PCs

Severs

Front room

Client workstations

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KAGRA control network design

Outside

Mine

Client workstations

Remote Control room

Front room

Severs

Circuit

General network

TCP/IP: EPICS, NFS, network boot

DAQ network

GW data: huge amount, low latency

RT control signal: very low latency

Real-time PCs

Center room

3km

3km Y arm cavity

Metal cable

Fiber cable

X end

Y end

3km X arm Cavity

Short RFM network

RT control signal: very low latency

Long RFM network

TCP/IP: EPICS, NFS, network boot

GW data: huge amount, low latency

RT control signal: very low latency

TCP/IP: EPICS, NFS, network boot

GW data: huge amount, low latency

RT control signal: very low latency
KAGRA control network design

- **Computer center**
  - Data storage

- **Remote Control room**
  - Client workstations

- **Front room**
  - Severs

- **Center room**
  - Real-time PCs
  - DAQ network
  - TCP/IP: EPICS, NFS, network boot
  - GW data: huge amount, low latency
  - RT control signal: very low latency

- **Outside**
  - Metal cable
  - Fiber cable

- **Mine**
  - 3km Y arm cavity
  - 3km X arm cavity

- **Networks**
  - Short RFM network
  - Long RFM network
  - Circuit
  - General network

- **RT control signal:** very low latency
- **GW data:** huge amount, low latency
- **TCP/IP:** EPICS, NFS, network boot
KAGRA control network design

Outside

Mines

Client workstations

Remote Control room

Severs

Front room

Computer center

Data storage

Real-time PCs

Center room

DAQ network

General network

TCP/IP: EPICS, NFS, network boot

GW data: huge amount, low latency

RT control signal: very low latency

RT control signal: very low latency

Outside

3km Y arm cavity

3km X arm Cavity

Metal cable

Fiber cable

Circuit

3km

Y end

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KAGRA control network design

Client workstations
Remote Control room
Severs
GPS antenna
Timing master

Outside

Computer center
Data storage
Front room

Mine
Severs

Center room

Real-time PCs

DAQ network
RT control signal: very low latency
GW data: huge amount, low latency
TCP/IP: EPICS, NFS, network boot

3km Y arm cavity
3km X arm cavity

Metal cable
Fiber cable

Circuit

40
KAGRA control network design

Client workstations

Remote Control room

Computer center

Data storage

Severs

Front room

GPS antenna

Timing master

Outside

Mine

3km Y arm cavity

3km X arm cavity

Metal cable

Fiber cable

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Rack layout for initial setup

Network for Kamioka building

Network for front-room in mine

DAQ servers, storages

Real-time PC test for Center area

Real-time PC test for End area

DAQ servers, storages

Data storage: NEXAN E18

Real-time PC test

Timing R1GC-3: LUGO-09000301

L2 switch: G8S/224v2 (rear)

L2 switch: G8S/224v2

Reflective Memory: ACC5555

KVM switch

Anti Alias chassis: D1100621

Anti Image chassis: D1100650

Data storage: NEXAN E18

KVM switch

Reflective Memory: ACC5555

Will be expanded when going to mine

Color Key

Installed

Mounted but not being used

Ready for installation

Waiting for mount

Title

Rack Layout for Large Network System

Date: 2012/05/11

Sheet 1 of 2

Drawn by Osamu Miyakawa

Document number: JGW-D1201569

Rev. 0 2012/05/11

KAGRA
Rack layout for initial setup

Network for Kamioka building

Network for front-room in mine

DAQ servers, storages

Real-time PC test for Center area

Real-time PC test for End area

Will be expanded when going to mine

Note: Status as of 17 July 2013
Location: Kamioka branch

Color Key
- Green: Installed
- Blue: Mounted but not being used
- Yellow: Ready for installation
- Red: Waiting for mount

Title: Rack Layout for Large Network System

Date: 2012/07/14
Sheet 1 of 2

Document number: JGW-D1301569

Drawn by: Osamu Miyakawa
Rack layout for initial setup

Real time PC test for Center area
Real time PC test for End area

Will be expanded when going to mine
Real time model on Matlab, Simulink
Actual control signals (filter bank, matrix, trigger, linearization etc.) will be generated automatically when building real time modules.

// Start of subsystem LSC **************************************************

// FILTER MODULE
lsc_pox = filterModuleD(dsp_ptr, dspCoeff, LSC_POX, dWord[0][0], 0);

// FILTER MODULE
lsc_poxfb = filterModuleD(dsp_ptr, dspCoeff, LSC_POXFB, dWord[0][1], 0);

for(ii=0; ii<1; ii++)
{
    lsc_nxmtrx[1][ii] = pLocalEpics->ctr.LSC_NXMTRX[ii][0] * lsc_trx + pLocalEpics->ctr.LSC_NXMTRX[ii][1] * lsc_poxdc;
}

// Relational Operator
lsc_operator = ((pLocalEpics->ctr.LSC_XTHRESH) <= (lsc_trx));

// DIVIDE
if(lsc_nxmtrx[1][0] != 0.0)
{
    lsc_divide = lsc_pox / lsc_nxmtrx[1][0];
}
else{
    lsc_divide = 0.0;
}
Actual control signals (filter bank, matrix, trigger, linearization etc.) will be generated automatically when building real time modules.

```c
// Start of subsystem LSC
// FILTER MODULE
lsc_pox = filterModuleD(dsp_ptr,dspCoeff,LSC_POX,dWord[0][0],0);

// FILTER MODULE
lsc_poxfb = filterModuleD(dsp_ptr,dspCoeff,LSC_POXFB,dWord[0][1],0);

for(ii=0; ii<1; ii++)
{
    lsc_nxmtrx[1][ii] = pLocalEpics->ctr.LSC_NXMTRX[ii][0] * lsc_trx + pLocalEpics->ctr.LSC_NXMTRX[ii][1] * lsc_poxdc;
}

// Relational Operator
lsc_operator = ((pLocalEpics->ctr.LSC_XTHRESH) <= (lsc_trx));

// DIVIDE
if(lsc_nxmtrx[1][0] != 0.0)
{
    lsc_divide = lsc_pox / lsc_nxmtrx[1][0];
}
else{
    lsc_divide = 0.0;
}
```

Running as kernel modules of Linux.
MEMD screen -- GUI for EPICS --
MEMD screen -- GUI for EPICS --
MEMD screen -- GUI for EPICS --

Sensor
- Feedback filter
- Offset control
- Input Matrix
- Global control
- Output Matrix
- Actuator

Sensor Inputs
- Whitening
- Offset control

Output Matrix
- ETH F0

Actuator
- Set Inputs
- DEVIATE
- Gain

Input Matrix
- Whitening
- Offset control

Feedback filter
- Bamp
- TH ON
- TH OFF

Offset control
- Pivot

Global control
- TH ON
- TH OFF

Actuator
- DEVIATE
- Gain

Load Coefficients
- Modified IIR file
Local control for Pre-Isolator

Pre-Isolator

Real Time PC
ADC/DAC
Anti Alias
Anti Image

Control ON

Time series

Signal

T₀=01/02/2012 09:44:22

0 10 20 30 40 50 60
Time (s)

Avδ=1

MEDM
Dataviewer (oscilloscope)
Client WS

Diagnosis on Mac through wireless LAN

DTT (FFT)
DAQ items

- ~30 RT front-end PC
- ~30 Fiber connected PCIE extension chassis
- ~60 ADC (x32ch) : total ~2000ch
- ~40 DAC (x16ch): total ~500ch
- ~80 DO (x32ch): total ~2000ch

Diagrams and images of various components and configurations.
Network design for controls and DAQ

RFM RT control signal: very low latency
DAQ GW data: huge amount, low latency
Timing: Synchronization for all RT PC and ADC/DAC
TCP/IP: EPICS, NFS, network boot

GW buildings at Kamioka

Data Storage
iKAGRA: 250TB
bKAGRA: 1PB/year
The project started in 2010.
Due to the March 11 earthquake (2011), budget implementation was delayed and the whole schedule shifted 1 year behind. KAGRA will be in 2 stages: iKAGRA and bKAGRA.

### Schedule

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**initial KAGRA**
- Room-temp. FPMI
- Low laser power (10W)
- Simple seismic isolation
- 10kg silica TM

**baseline KAGRA**
- Cryogenic RSE
- High laser power (180W)
- Low frequency seismic isolation
- 23kg sapphire TM