External review for digital system

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Digital system subgroup member

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1. Design for bLCGT

1-1. Definition of Subsystem

Digital system (DGS) subgroup provides functions which digitalize analog sensing signals extracted from an interferometer and subsystems, produce signals in computers for control, monitor and data acquisitions, and re-produce analog signals to actuate the interferometer.

This subsystem has following items.

I. Development of real-time (RT) control computer
   (a) Signal input/output as ADC/DAC modules
   (b) Binary switch as BO modules
   (c) Real-time software for monitor/diagnosis
   (d) Real-time communication network interface
II. Development of client workstations (RT system monitor) for monitor/diagnosis
III. Network design and development for following data transfer
   (a) Real time control
   (b) Timing
   (c) Data acquisition (DAQ)
   (d) General network
IV. Producing frame data for data storage

Note that we ask each subgroup to develop application software like compiling an interferometer control model, development of analysis software using frame data and so on. Of course, we offer typical model for application software and instructions/lectures for how to use the digital system.

1-2. Requirements

This subsystem provides a platform to control the km scale large interferometer. Global requirements for this subsystem should come from Detector Configuration (DET) subgroup or Main Interferometer (MIF) subgroup and other related subgroups. Items of the global requirements will be something like that;

I. Observation band width
II. Dynamic range
III. Number of input channels
IV. Number of output channels

Since global requirements has not been shown for our digital system subgroup, we assume appropriate minimum global requirements here.

Observation band width = 5kHz
Dynamic range = 120dB
Number of channels = 2000
Number of output channels - 500

Required dynamic range is determined by the amplitude and noise of error signals during GW observation, or by how much dynamic range the lock acquisition needs. Reason of this 120dB is explained in Appendix A.

To satisfy this requirement, we define our internal requirements in Table 1. We selected 16bit ADC/DAC for the required dynamic range. From this table, the dynamic range of ADC will be >15V/3uV=134dB and the dynamic range of ADC will be >10Vpp/3uV=130dB at least.

Item	**Requirements**	**Comment**
Sampling rate	>16384Hz	65536Hz at ADC, then decimated to 16384Hz
ADC bit resolution	>=16bit	
Dynamic range of input	>+/-15V	Differential input
Dynamic range of output	>+/-10V	Differential output
ADC noise	<3uV/rHz	Effectively reduced by whitening filter
DAC noise	<3uV/rHz	Effectively reduced by dewhitening filter

time delay	<100usec	For >200Hz UGF
Input channel numbers	>2048ch	(16kHz:>128ch, 2kzHz:>512ch, 64Hz>1024ch)
Output channel numbers	>512ch	For mirrors, seismic attenuators, PZTs etc.
Stored channel numbers	16kHz:>64ch, 2kzHz:>512ch, 64Hz>1024ch, 16Hz>10000ch	~300TB/year

Table 1. Requirements for digital subsystem

1-3. Interface

1-3-1. Interface for signals

Our main interface to other subgroups is for signal input/output and switch. These interface are defined as follows;

Signal input

- ADC 32ch/card, differential (64ch for single input)
- Sampling rate: 16kHz sampling
- Maximum input range: +/-20V
- Noise: 4uV/rHz
- Input filter: Anti alias filter
- Connector: D-sub 9pin (for differential 4ch)

Signal output

- DAC 16ch/card (32ch for single output)
- Maximum output range: +/-10V
- Noise: 3uV/rHz
- Output filter: Anti imaging filter
- Connector: D-sub 9pin (for differential 4ch)

Switch

- Binary output (BO) 32ch/card
- Output voltage: 0 or +5V
- Connector: D-sub 9pin (for differential 4ch)

(Ex. Variable gain amp for 16 steps/1 D-sub connector)

1-3-2. Frame data

Digital system subgroup is responsible for data acquisition and data formatting. All LCGT data will be formatted as the same as world standard GW data (like LIGO, VIRGO) through Frame Builder (FB). The FB is a part of digital system and the produced data will be stored through DAQ network into raw data archive by 100TB class RAID data storage located at the front room. This raw archive is a temporary data storage which can be used for commissioning or pre-data analysis etc. at the site. Term of this temporary storage should be at least for longer than 1 month. All the data over 100TB will be sent to another huge data storage located in Kamioka-building or Kashiwa GW computer center (to be determined). These stored data is handed over to data analysis subgroup.

1-4. Preliminary Design

1-4-1. Hardware

Real-time Core (RTC) software runs on computers with the following minimum configuration:

1) Dual x86 processors, with four CPU cores each.
2) Processor clock speed of 3GHz.
3) Eight (8) Gigabyte of memory.
4) Two Gigabit Ethernet interfaces.
5) One, or more, real-time network interfaces
    a. Reflected Memory (RFM)
    b. PCI Express (PCIe) network interface
6) A PCIe interface to the PCIe expansion chassis with a maximum of 14 PCIe cards installed.

1-4-2. Software

The software is divided into the following functional groups;

I. Real-time Core (RTC) Software:
    (a) Real-time Sequencer (RTS): That software which performs the functions of

scheduling and I/O interfaces for all real-time applications.

   (b) DAQ: That software which performs the function of real-time data acquisition and data formatting.

II. Real-time Common Library: A standard real-time code library for use in all real-time user applications.

III. Real-time Support Software: The software necessary to communicate between the RTC and operational support and DAQ software via Ethernet connections. This includes:

   (a) EPICS interface software
   (b) Arbitrary wave form generator (AWG) / Test point manager (TPM)
   (c) DAQ Network Interface

IV. Real-time System Monitor: Software to run on a designated real-time computer designed to monitor the overall status of all real-time systems and networks.

1-4-3. Related analog circuits

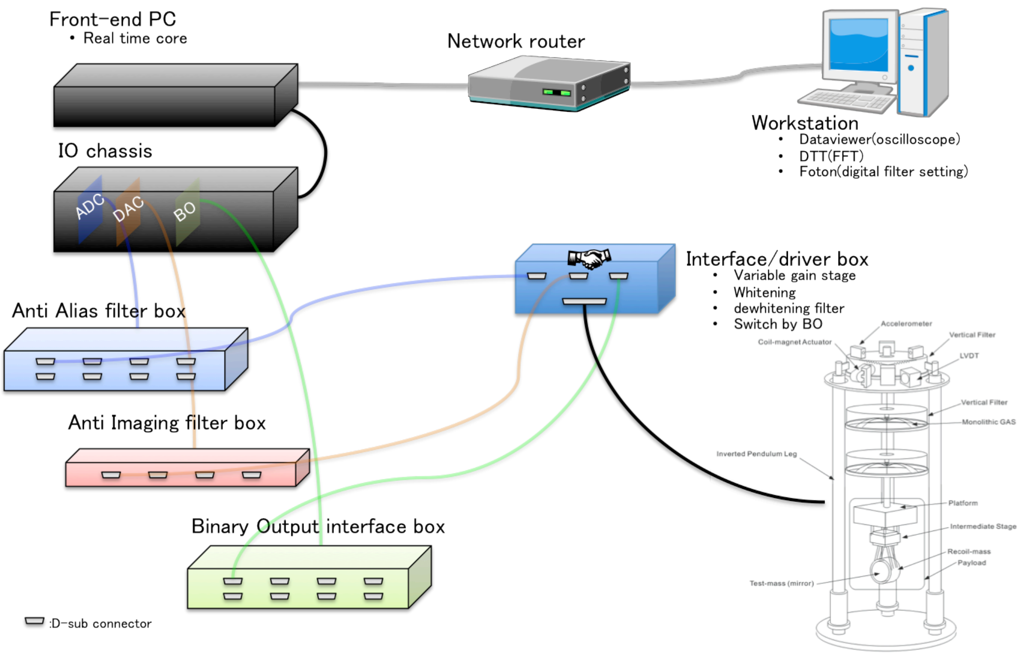

Figure 1. Typical connection between digital system and subsystems

Generally an anti alias filter (AA) is required for ADC input, and an anti imaging (AI) filter is required for DAC output. Typical signal stream will be like this;

I. Analog signal -> satellite box (including variable gain amplifier (VGA), whitening filter (WF)) -> long metal cable (~10m) -> driver box ->
II. AA filter -> ADC-> Computer -> DAC -> AI filter ->
III. Driver box -> long metal cable -> satellite box (including dewhitening filter (DWF)) -> actuation signal

and the connection between digital system and subsystems is shown as Fig. 1. Digital system subgroup is responsible for II, i.e. analog AA filter and AI filter are provided from digital system subgroup, and other driver box and satellite box etc. should be manufactured by each subgroup.

AA and AI filter have the same frequency response that has a steep low-pass filter at the half of raw sampling frequency. In this system the low-pass frequency will be 32768Hz.

Typical whitening/dewhitening filter has zero-pole/pole-zero for 15Hz and 150Hz. The frequency should be adjusted for each subsystem. VGA should be also implemented upstream whitening filter with gain step controlled by binary output signal. For example, 4bit (of 32bit of one BO module) can have 16 steps, so one BO card can control 4 VGA in this case.

1-4-4. Rack design and location

All PCs, circuits, network equipment are mounted into 19 inch rack. Total 12-20 racks for digital system will be located inside LCGT (Fig. 2). Racks are categorized as following;

I. Front room (blue): length (1), WFS (1), auxiliary (1), network (1)
II. Laser room (red): Laser (1)
III. Center room (orange): Input optics(1-2), suspensions(1-3)
IV. Main suspensions (green): ITMX (1-2), ITMY (1-2), ETMX (1-2), ETMY (1-2)

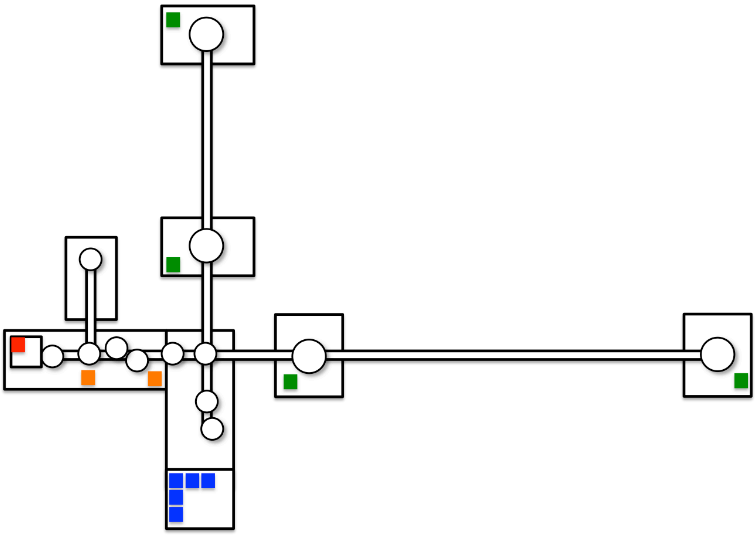

Figure 2. Location of racks for digital system.

1-4-5. Network design

We recognize that the importance and difficulties of complicated network system with many RTS computers. The most important thing is how to connect RTS computers with enough fast transfer rates for real-time control, data stream. We list up what kinds of network are needed for LCGT and the schematic is shown in Fig. 3.

I. Real time control network: connection during RT PCs for control
  (a) Reflective memory network
    Hub: GE Fanuc 5595
    Cable: single mode fiber, <10km
  (b) PCIe network (Dolphin network)
    Hub: Dolphin DXS410
    Cable: metal or fiber, x10 faster than GE, <100m
II. DAQ network: data collection from all RT PCs to raw data storage, NDS
  Router: NETGEAR 7224/7352, Fujitsu XG2600 or similar, through OpenMX (10GBbps using open Mirynet protocol)
  Cable: metal (CAT6 or 7) for PC-router, fiber for router-router
III. Timing network: timing distribution of absolute time for all RT PSs and 1PPS signal for ADC/DAC

GPS, frequency distributer, Master/Fanout/Slave aLIGO timing system,

IV. General network: PXE network boot for RT PCs, client workstations for control/monitor/diagnosis in control room, security and authentication, NAT, NTP, NFS, ilog, wiki etc.

Router: NETGEAR 7224/7248 or similar

Cable: metal (CAT5e or 6) for PC-router, fiber for router-router

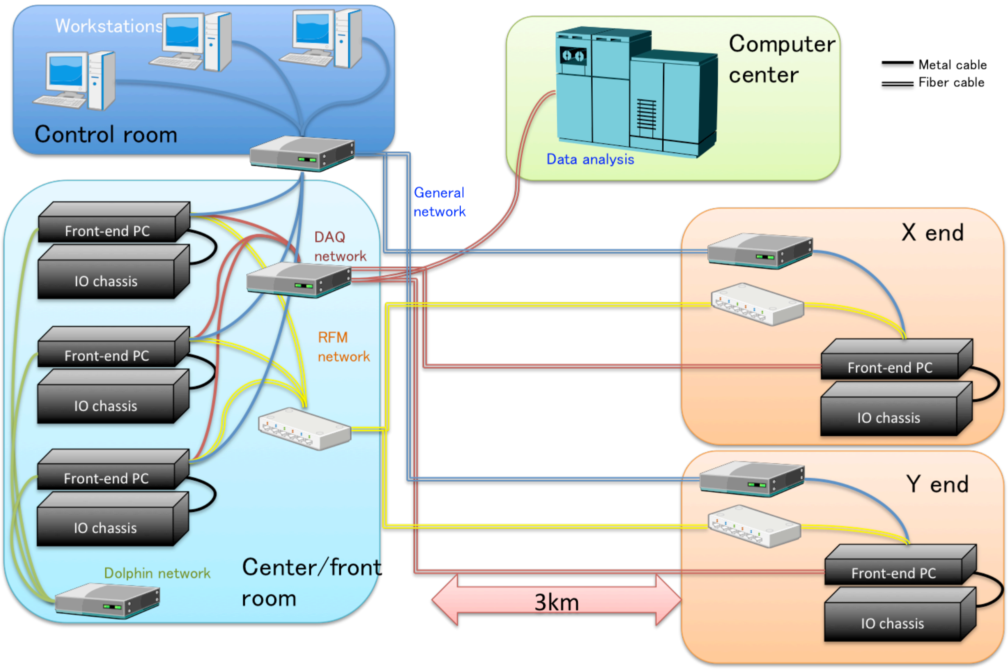

Figure 3. Conceptual figure of whole network for LCGT

1-5. Schedule

Before LCGT funded

~FY2010: Development of prototype system at/using CLIO

After LCGT funded

FY2011: Delivering standalone system to subgroups

Circuits design

Small Test bench of networks for digital systems
FY2012: Test operation system as whole network at Kamioka building
FY2013~: Installation of full digital system into mine

1-6. Prototype Test Plan

Basic prototype test for digital system has been performed in Japan using CLIO 100m prototype interferometer. We succeeded in locking the mass lock loop of CLIO and showed the performance that the noise of ADC and DAC is at least 10times bellower than best sensitivity of CLIO using low temperature mirrors (shown Fig. 4). We also performed some application technic using the digital system like producing normalized error signal, auto alignment, auto lock procedure and so on. During these experiences, we learned how to obtain required equipment in Japan with a reasonable price and reasonable term. We are thinking that essentially there is no problem to use aLIGO type digital system in Japan.

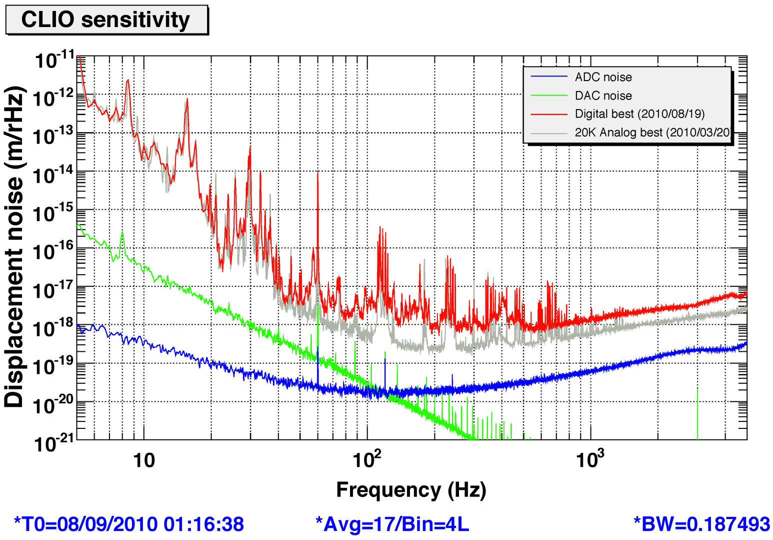

Figure 4. Calibrated CLIO displacement noise using digital system

The main prototype test will be performed in FY 2011 by other subgroups with delivered digital systems. Total 5sets of standalone digital system will be provided from digital system subgroup to other subgroups that need the digital system for development of the subsystem. Following items will be offered to subgroups;

1) Real time PC as front-end
2) Client workstation PC with software setup
3) Expansion chassis
4) Timing slave board
5) ADC, DAC, Binary Output
6) Anti Alias/Anti imaging

This prototype test may provide a good chance for subgroups to be familiar with the digital system before commissioning LCGT. It is very important to be accustomed the digital system, so that we hope that new application technics will be invented from other subgroups. At the beginning we will offer typical model file and some lectures or instructions to understand the digital systems.

1-7. First Article Test Plan

We plan to have a test operation system (TOS) with computer and networking for whole LCGT. This will be placed in the new Kamioka building in FY2012. This system is independent from actual signal input/output, which means that the TOS does not have analog circuits like AA/AI filters or interface board to analog signals. This system consists of following equipment;

1) ~5 real-time PCs with I/O chassis
2) ~2 client workstations
3) GPS antenna
4) Timing network with Master /slave timing board
5) DAQ network
6) RFM network
7) PCIe network
8) Fiber connected network routers
9) Several network PCs* (1 file server, 1 ntp server, 2 nds servers, 2-3 DAQ servers)

10) ~3 Security, authentication PCs.

*Note that multiple nds and DAQ are for redundancy.

1-8. Installation/Adjustment Procedure

Whole test operation system (TOS) will be moved into mine and placed in proper location. Network racks and some of RST racks are placed into the front room, and most of RTS racks are moved to the place where each subsystem is located. Network equipment are connected through the fibers for 3km arms.

Additionally standalone systems that have been used for development of each subsystem will be merged into whole network. One of the advantages of this installation is what the same model as development used in standalone system can be used. The number of standalone system is limited and additional RTS will be installed into whole system, but duplication of the control model from standalone system to new additional RTSs is quite easy and it can extremely reduce the installation/adjustment time for all sybsystems.

Actual installation will be done when the iLCGT starts with some limited channel numbers, but essentially there is no difference on whole digital system between iLCGT and bLCGT.

1-9. Risk Management

Here is a list of risks of this subsystem.

- Cyber security
  - Probably we need professional level network security system
- Implementation of timing signal into each RT PC
  - We will obtain aLIGO timing system via Columbia University.
- Management of huge number of channels
  - Japanese GW group has no experience to treat such channel numbers for order of 1000. Digital system itself is a solution but still the number of channels is huge.
- Management of mass production of circuits
  - This is also related to the number of channels. For many channels, selection of

cable, connector and matching interface to all subsystem are very important.

- Finding problems from many channels when a trouble happened
  - Sometimes for large computer system, all of the system can be stopped by only one small trouble. It is very important to have enough redundancy and to develop a self-diagnostic system.

Since LCGT decided to use aLIGO type digital system, we were relieved a lot of work, for example, selection of ADC/DAC modules, development of real time code, loop test for control using combined PC, IO, circuits etc. First of all, we have to thank LIGO CDS group for offering us such a useful device.

On the other hands, everything can be a black box if we do not understand carefully inside the device and it can be difficult to hunt troubles in the future for LCGT construction. Fortunately we have been developed prototype digital system for CLIO in these 2-3years with LIOG CDS group and we have experienced a lot to construct several RT PCs from scratch. These experiences will be a great help during LCGT commissioning for ourselves.

However it is the fact that we do not have enough experience for constructing whole network. Technically we knew that the 3km data transfer for real time control which we were concerned about was fixed in LIGO already and we knew that what kind of network equipment we need to make whole network work properly with enough data transfer speed.

Essentially we do not think we have serious trouble for development of whole digital system for LCGT. Needless to say, this digital subsystem is related almost all subsystems and the trouble of this system can be a serious delay for LCGT. We continuously should perform reliable operation test and preparation for smooth installation and commissioning of LCGT.

2. Design for iLCGT

2-1. Definition of Subsystem

The same as bLCGT.

2-2. Requirements

The same as bLCGT.

2-3. Interface

The same as bLCGT.

2-4. Final Design

Essentially there is no difference of digital subsystem between iLIGO and bLIGO except for channel numbers. At the beginning of iLCGT, the number of channels is very limited, and it will be increased with development and commissioning of iLCGT and bLCGT.

2-5. Schedule

The whole schedule including for iLCGT is shown in bLCGT schedule.

2-6. First Article Test Plan

The same as bLCGT first article test plan.

2-7. Installation/Adjustment Procedure

Essentially everything will be installed when iLCGT starts. Installation procedure is explained in the bLCGT.

2-8. Risk Management

The same as bLCGT risk management.

Appendix A. Design Match to Requirements

A-1. bLCGT

We estimate the requirement of dynamic range by lock acquisition and error signal during observation.

1) During lock acquisition, the arm cavity moves ~1um. Finesse of the arm cavity is designed as ~1500, so the full width half maximum (FWHM) is ~1e-9m. When the cavity is locked the motion of cavity should be ~1/1000 of FWHM, so the motion is roughly 1e-12m. Dynamic range should be > 1e-6m/1e-12m=120dB.

2) Error signal amplitude during observation can be estimated by expected seismic motion and suppression factor by expected control gain. Typically maximum seismic motion is ~1e-5m/rHz and this low frequency motion is suppressed by a control loop. Suppression factor can be estimated by expected unity gain frequency (UGF) = 200Hz and gain slope of f^-4 between 1Hz and 100Hz, so the suppression factor roughly estimated as 1e8. On the other hand, target sensitivity expected displacement noise will be 1e-21m/rHz, so the raw dynamic range will be 1e16=320dB, and required dynamic range with the suppression will be 1e8=160dB. Additionally we can use whitening filters which typically consists of 2nd or 4th order of 15Hz-150Hz zero-pole fileter, so effectively the whitening filter reduce the required dynamic range by 80dB with 2nd order filter at least. So the assumption of 120dB dynamic range is enough. Note that the power line at 60Hz practically can be a big peak and may limit this dynamic range.

A-2. iLCGT