KAGRA Data Analysis White Paper 2013

KAGRA Data Management Subsystem and Data Analysis Subsystem

January 10, 2014

Contents

1 Introduction

The purpose of the KAGRA data analysis white paper is to clarify the objectives and the tasks of the data analysis activities, to share these information among the group, and to increase the efficiency of our works. This documents will also be useful to check whether there are any missing items in the target and the tasks, to evaluate the manpower needed, and to judge whether rearrangement of the manpower is necessary or not.

In this document, Following items are written for each data analysis tasks.

- Science goal (or just goal of the task)
- Contents of the task
- Current situation
- Priority items for this year
- Mid-term plan toward iKAGRA in 2015, and bKAGRA in 2017.

This document is rewritten in every March, and describe the contents of the tasks for the next Fiscal Year of Japan (from April until March next year).

For the fiscal year 2013, following items are described in this whitepaper.

(1) Data handling

(2) CBC search

(3) Continuous wave search

(4) Radiometry

It is important for the chair person for each task item to share information with other tasks and cooperate with people in other tasks. It is also important to write research papers at the same time to proceed the tasks for KAGRA data analysis.

An existing reference document on the data analysis of KAGRA which was written before is LCGT Blueprint (in Japanese) [2]. The LSC-Virgo Whitepaper 2012-2013 is Ref. [8], and 2013-2014 version is Ref.[9].

2 Data Handling

Nobuyuki Kanda (Osaka City Univ.)

2.1 Grand Design of KAGRA data

The KAGRA data system consists of parts of acquisition, transfer, storage, distribution and exchange. Each parts have to design as working independently but be highly depend on themselves for the complete action of KAGRA data.

DGS (Digital System) subsystem of KAGRA is a front-end of control of the detector instruments and also is a digitization of any signal for computing. Here, we describe KAGRA data system after DGS system to final processing of data ; i.e. event searches.

2.1.1 KAGRA VPN

KAGRA main data stream from the interferometer site to the Tier-0 (primary full data archive) is closed by VPN (Virtual Private Network). Low latency search part is also included the VPN.

Kamioka detector site (inside the mine) DGS subsystem inside the mine will derive the data in frame format (frame-writer).

Once the data file generated by DGS frame-writer, the file will be sent to primary storage server immediately. (See Fig.2 in following sub-section.) Data files will be transferred to the data server in surface building, via optical fiber for data transfer exclusive use.

Rate of raw data derived from DGS subsystem is about 20MB/s ($\sim$ 630 TB/year).

Kamioka detector site (surface building) In surface building at Kamioka 'Analysis building', temporary storage system, transfer system to Kashiwa and some calculation nodes will be installed by the end of fiscal year 2013. The temporary storage system is not only a safety spool of network transfer but also quick access storage for on-site studies. Some pre-process of data that including calibration or off-line detector characterization will be processed by calculation nodes. Raw data and these processed data will be sent to Kashiwa main storage.

In addition, the storage and calculation computers architecture is extendable to PB-class storage / much more calculation nodes.

Kashiwa main storage Kashiwa main storage will store all KAGRA data-sets : raw, full-processed and simulation data. Its capacity must be larger than 5PB for 5years observation and must have a enough performance of file management for $10^7 - 10^8$ files.

Low Latency Searches Processed data and main signal data will be sent at Osaka City university /Osaka university immediately for 'low latency search'.

2.1.2 ICRR common computing facility

We will use ICRR's common computing facility. However, since the facility is not KAGRA usage only, we connect KAGRA main data storage to ICRR common computer.

2.1.3 Data distribution

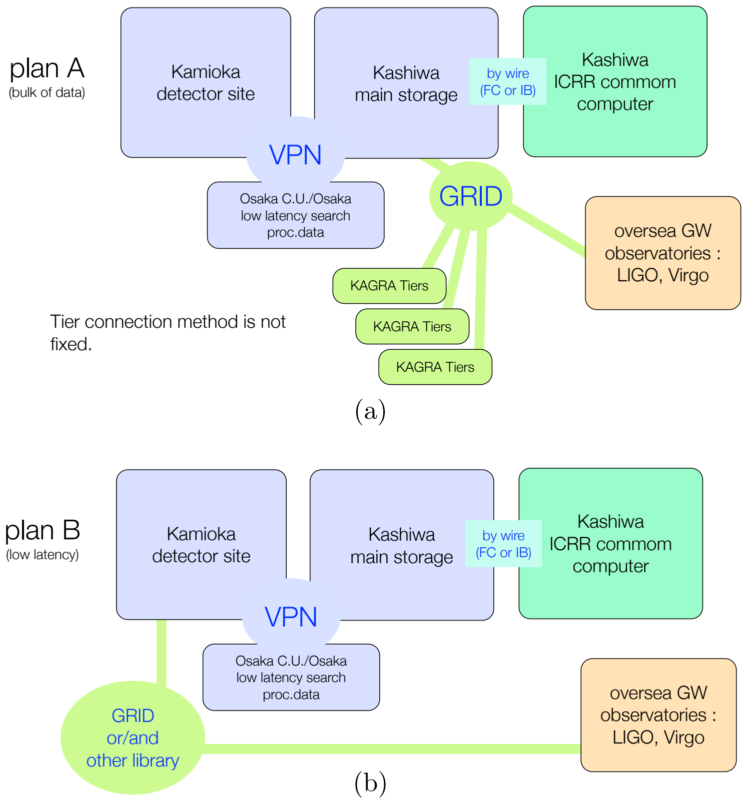
How to distribute the KAGRA data is important problem for all the collaborators. Moreover, the data exchange between other GW observatories is also design carefully to make smooth data exchange possible in technically.

GRID is one of the solution of data distribution for many collaborators and external observatories. However, GRID requires much administration costs.

Distribution in KAGRA collaboration

GRID or other connection tools between LIGO/Virgo

Figures 1 (a) (b) shows variation of KAGRA data ground design according to GRID/data distribution options. 'GRID' appears in the figures, but it is tentative plan.



(a)

(b)

Figure 1: Schematic Drawing of KAGRA data design

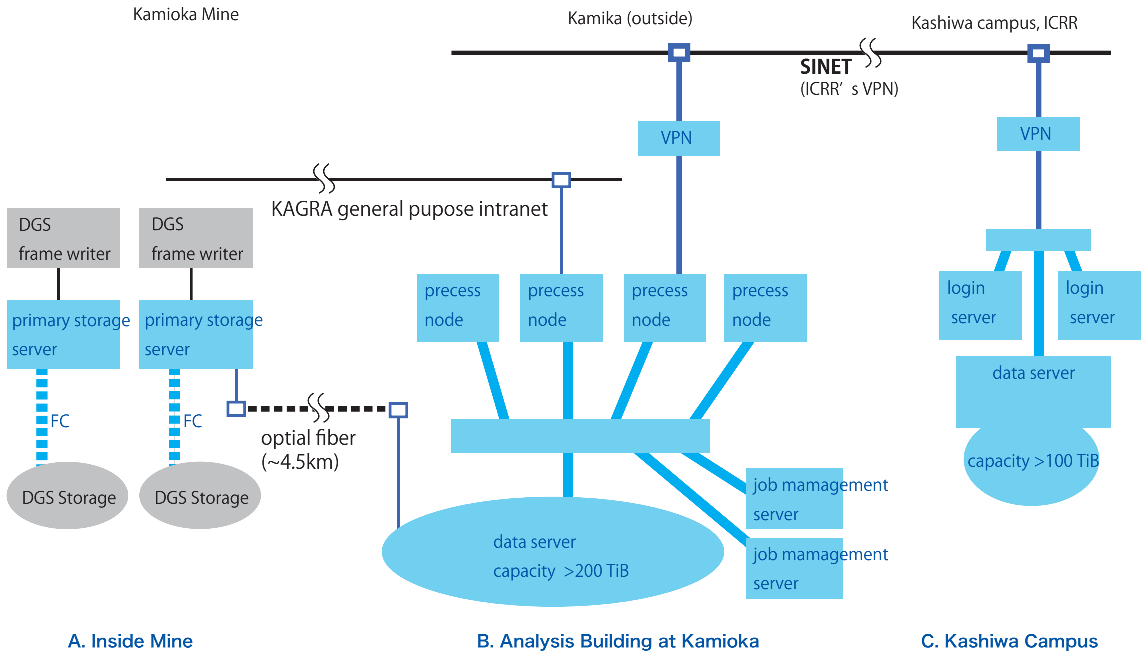


Figure 2: iKAGRA data transfer-storage system

2.1.4 iKAGRA data transfer-storage system

Schematic figure of the 'iKAGRA data transfer-storage system' is shown in Figure 2.

2.2 Data Flow and Tier

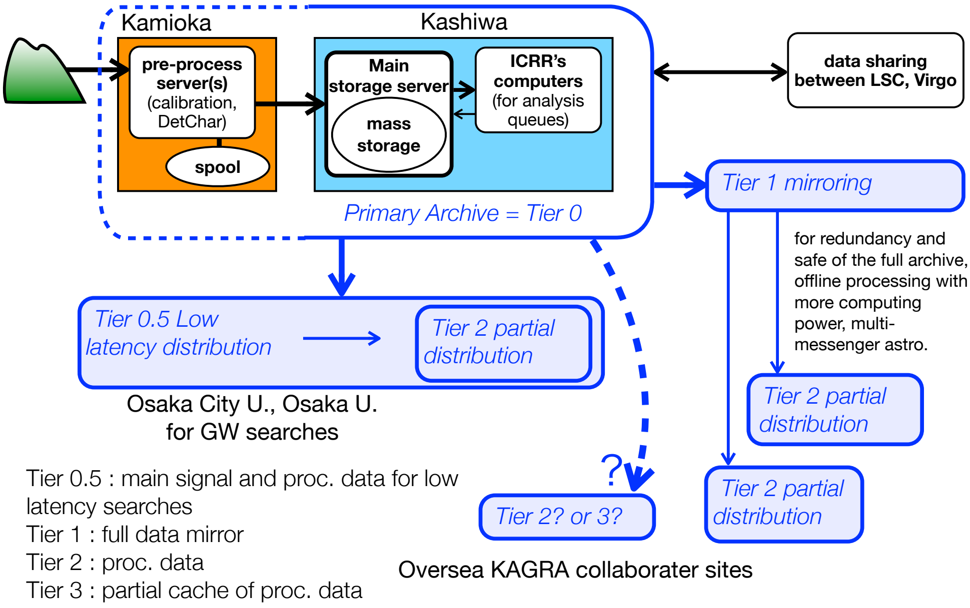


Figure 3: default

2.3 Data files

2.3.1 Format

KAGRA data will be stored in the 'Frame' format files. The 'Frame' format is common data format in current gravitational wave observations : i.e. LIGO, Virgo. We have been used this format since TAMA experiment. The detail of the Frame format is available at its original web site [1]. Frame format is a kind of structure of data. It consists of header structure, pointers to all data parts, instrumental data parts, any kind of data stream, and descriptions. We can add or remove parts of data.

2.3.2 Record Channels

KAGRA data will be derived from DGS subsystem, which is not only the front end of DAQ(data acquisition) system, but also the digital processing part of control system of KAGRA.

stumps The stumps of data epoch will be recorded. GPS time stump of epoc of data. etc.

servo signals Any digital control servo signals will be recorded, including main strain feedback and error signal. Note that raw register values of ADC and DAC have to be recorded with out any reduction or without any calculation. The raw register value record is necessary and indispensably for reliable strain data reconstruction.

Detail of these data were discussed in LCGT design report. It will be cleaned up and revised if it is need for final setting of DGS and DMG system.

environmental data Any environmental data, e.g. temperature, humidity, seismic monitor, acoustic monitor, and any instrumental condition record, e.g. vacuum, power voltage which connected with DGS system will be recorded.

Detail of these data were discussed in LCGT design report. It will be cleaned up and revised if it is need for final setting of DGS and DMG system.

Table 1: default

Tier	Site(s)	Purpose	Raw	Calibrated	Detecter Characterization	Amount of data for 5yrs	event alarts
	Kamioka	DAQ	partial (spool)	partial (spool)	partial (spool)	200TB	partial
0	Kashiwa	Main Storage	○	○	○	5PB	(Not yet discussed)
0.5	Osaka City, Osaka	Low latency	NA or small amount	○	○	500TB	○
1	(undecided)	Full Mirroring	○	○	○	5PB	(Not yet discussed)
2	(Analysis-bases, undecided)	Offline searches	NA	○	○	500TB	NA
3	End users	Development	NA	partial	partial	(Not yet discussed)	NA

quality flags On-line or real time evaluations of data quality will be recored as 'quality flags'. For example, detector characterization results will be included.

calibrate signals Some raw signal data will have to processed and converted to physically calibrated signal as soon as data acquisition, and to be recorded as data file. Most important calibrated signal is the metric strain h (in frequency domain h(f) or in time domain h(t)) which will be converted from main error signal and feedback signal.

These 'calibrated signal' will be recorded.

2.3.3 Kind of Data File Package

raw data all 'raw' data from DGS front-end

processed data (full) all calibrated data in physical values

analysis data calibrated data and some data quality info rations for general use of gravitational wave analysis

low latency data calibrated main signal ($h(f)$ or $h(t)$) and raw data of main signal

simulation data simulated data

2.4 Database of data

Database of data is necessary to manage huge number of data file, to access data at any epoch, and to check correspondence between raw and processed files.

2.5 Tasks

2.5.1 Priority items for this year

- construct hardware of iKAGRA data system
- make software of iKAGRA data system
- data transfer test between Kamioka and Kashiwa / Osaka.
- fix ground design

- Technical problems in data distribution part (GRID or alternative)
- design Tier structure

2.5.2 Mid-term plan toward iKAGRA and bKAGRA

- design Kashiwa main storage for bKAGRA with 5PB (spec, schedule and budget)
- decide Tier-1 site (mirror of observation data)
- fix Tier structure

3 Searches for Coalescing Compact Binaries

Hideyuki Tagoshi (Osaka Univ.)

3.1 Overview

The task of this subgourp is to search for gravitational waves (GW) from coalescing compact binaries (CBC) consisting of neutron stars (NS) and/or black holes (BH).

The CBC signal is usually divided into 3 phases, inspiral phase, merger phase, and ringdown phase. In the case of NS-NS, the end of inspiral phase is around 1.5kHz. The merger and ringdown signals are located at higher frequency than 1.5kHz. Thus, it will be difficult to detect then together with inspiral signal because the detector sensitivity becomes worse than such high frequency. On the other hand, in the NS-BH and BH-BH cases, the inspiral signal ends at lower frequency (which depends on the mass of the BH). Thus, the merger signal, and some times, the ringdown signal comes into the detectors sensitive band. In such cases, merger and ringdown signal will contribute to the total signal to noise ratio, and they can be important for the detection.

The signal duration within the detectors' sensitivity band (10 Hz a few kHz) is about 1000 seconds in the case of $(1.4M_{\odot}, 1.4M_{\odot})$ binaries. Thus, unless we consider the mass lower than $1M_{\odot}$, the effect of the motion of the Earth can be neglected. The inspiral signal is well-modeled (except for the final phase of inspiral just before ISCO). The number of parameters is 9 (distance, two masses, time of coalescence, phase at the coalescence, two angles to specify the sky location of the source, inclination angle, polarization angle) without spins. However, if spins of each stars can not be neglected, the spin parameters (6 in the most general case) will be added to the search parameter, and the search task becomes heavier. The effect of spin is larger for BH, since the spin magnitude can be large. On the other hand, the effect of spin of NS is not large even in the case of most rapidly spinning millisecond pulsars.

It is usually assume that the orbit is in quasi-circular orbit, because the radiation reaction effect make the orbit circular very rapidly. The effect of the eccentricity can not be neglected only when the binary is formed with eccentricity and with very small orbital separation.

Analysis method for the inspiral signal is the matched filtering. If the number of detector is more than one, there are several variation of the analysis method even within the matched filtering analysis. A simple method is the coincidence method in which we compute the output of the matches filter separately for each detector, and then compare the trigger list to find the confident events. More advanced method is a method following the basic principle of the maximum likelihood method faithfully, and this method is sometimes called the coherent method. Usually, the coherent method gives better detection probability than the coincident method. However, computational cost is higher in the coherent method. Thus, in the past, the coincident method is applied at the first step of the analysis. After that, for the small number of candidates derived from the coincident analysis, the coherent method is applied. When KAGRA performs the joint analysis with LIGO and Virgo, we have to determine which analysis method we apply first.

3.2 Science goal

The primary scientific goal of this task is to detect GW from CBC, and reveal the following.

- By detecting gravitational waves from CBC, we can prove that the gravitational radiation is really radiated from CBC. Further, we can prove that the gravitational waves are propagating in the expanding universe. We will investigate whether there are any deviation from the prediction of Einstein's general relativity. If we find any deviation, it will suggest an alternative theory of gravity must be considered.

- The coalescence of NS-NS and/or BH-NS are considered to be the progenitors of the short-hard gamma ray bursts. Thus, to reveal the progenitor of the short gamma ray burst, we will compare the information of CBC gravitational wave events with the information from the electromagnetic observation of gamma ray bursts.

- To reveal whether CBC phenomenon produces EM and neutrino signal together with GW. For this, we need to send out the information of the detection of CBC signal to the other astronomical instruments.

- To obtain the information of the equation of state or the radius of the neutron stars by detecting NS-BH signal during the transition from inspiral to merger phase.
- To obtain the information of the equation of state by detecting GW from hyper massive NS (HMNS) formed after the merger of two NSs.
- To constrain the formation rate and the mass and spin distribution of NS and BH by detecting many CBC signal.

3.3 Tasks

There are mainly 4 tasks in the CBC analysis: online analysis, off-line analysis, parameter estimation of candidate events, and the statistical analysis of the results.

3.3.1 Off-line analysis

The off-line analysis is the analysis which has been done for a long time in the TAMA300 data analysis, and also in the LIGO-Virgo data analysis. The primary tasks of this analysis is the computation of the matched filter signal-to-noise ratio and chi-square for the number of combination of mass parameter (if we include spin, spin parameter must be included). For this computation, we need the following items. Evaluation of the power spectrum density, setup of the template space (i.e., the parameter space), computation of matched filter and chi-square and to make a trigger list. In the case of coincident analysis, the trigger list from each detector is compared and a coincident trigger list is generated. The rate of the accidental coincident events is evaluated with the time shift analysis separately from above main search task. Finally, a statistical analysis applied to compare the number of coincident triggers with the number of accidental coincident events.

In the case of coherent analysis, this process is done for all of the data, and one trigger list is generated. the data from different detector is use to generate the single matched filter output. For veto, chi-square value is computed. In the coherent method, another veto method, called null stream veto can be done. The output of the coherent analysis is a single trigger list. The rate of the false alarm is evaluated with the time shift analysis. The false alarm rate is used to evaluate the statistical significance of the events in the trigger list.

We need to develop these pipelines. Although there are softwares developed and used for the TAMA data analysis. However, these must be revised significantly. We also need to use some of the subroutine in LALSuite. The software is developed using C language at the beginning.

3.3.2 Online analysis

The purpose of the online analysis to obtain candidate gravitational wave signal as early as possible, and send the information of significant events to other astronomical instruments to facilitate the follow-up observation. The items which have to be done in this analysis is similar to the off-line analysis. But in order to finish the analysis quickly, it will be necessary to restrict the parameter range of the search. Further, since the coherent analysis is more expensive, we may need to use the coincident analysis. From the coalescence time at each detectors, the direction to the source is determined.

One issue which must be investigated is the delay of the analysis in the frequency domain matched filtering which is the standard method in the off-line analysis. In the frequency domain analysis, one have to accumulate the data which is longer than the template. Thus, there will be a delay of the start time of analysis measured from the time of coalescence inevitably. One idea to overcome this is to divide the time series data into short data length, and perform the frequency domain matched filtering for each short data, and combine the results to obtain total matched filter output. This kind of method was used for LIGO-S6 and Virgo data. The other idea is to use the time domain matched filtering. The time domain analysis is more expensive than the frequency domain analysis, because of can not use the merit of FFT. Recently, reduction of the computation of the matched filter in the mass parameter space is proposed by using the singular value decomposition of the templates, or the reduced basis method. In both method, any templates in the template space is represented as a linear combination of the smaller number of basis templates. By using these technique, the computation time in the time domain analysis can be reduced to the similar value as in the frequency domain analysis. These methods are now implemented in the LIGO analysis, which is called gstlal_inspiral.

Although these softwares are now developed by LSC and Virgo, we will develop a pipeline for the low latency online analysis by ourselves in order to understand the every details of the pipeline. Information exchange between above mentioned groups will be important.

3.3.3 Parameter estimation of candidate events

Once candidate events are found, plausible range of the parameters of the candidate events have to be evaluated. For this, Bayesian parameter estimation method is usually used. Two kinds of method are mostly used, one is Markov chain Monte Carlo method, and the other is the nested sampling method. So far, we have not much experience of these method. Thus, this item is the item of our mid-term plan. Korean subgroup is very interested in this project, and we expect significant contribution from Korean subgroup.

3.4 Priority items for this year and Mid-term plan toward iKAGRA

Basic KAGALI components

We first develop basic components of KAGALI. These include a wrapper to the FFTW library for FFT, and the wrapper to the FRAME library to read Frame data. These will be done by the end of February.

Offline pipeline

The offline pipeline development will start soon after these basic library are ready. The development of offline pipeline will continue during the FY2014, and it should be finished by the end of March 2015. After March 2015, several tests of the pipeline are done for a several months until June 2015. After data acquisition system of iKAGRA is ready, end-to-end tests of the pipeline which use the hardware of the iKAGRA system will be done until just before the operation of iKAGRA.

Online pipeline

During this year, we continue the basic investigation of the several technique necessary for the low latency online analysis of CBC signals. After some basic components of KAGALI are ready, basic time domain matched filtering codes will be developed. These should be done by the end of March 2013.

After these activities, the development of the full scale online pipeline will starts from April 2014 and will continue by the end of March 2015. After March 2015, several tests of the pipeline are done for a several months until June 2015. After data acquisition system of iKAGRA is ready, end-to-end tests of the pipeline which use the hardware of the iKAGRA system will be done until just before the operation of iKAGRA.

4 Search for Continuous Gravitational Waves

Yousuke Itoh (Univ. of Tokyo)

4.1 Overview

The task of this subgroup is to search for continuous gravitational waves (CW) from isolated compact stars or compact stars in binaries.

Continuous gravitational waves may be emitted from rotating non-axisymmetric compact stars like pulsars, oscillating compact stars, accreting compact stars and wobbling compact stars. Compact stars may be a neutron stars, hybrid stars, or quark stars. Since sensitive band of the ground-based detectors is about 10 Hz - 2kHz, CW targets of those detectors are mainly rapidly rotating compact stars such as millisecond pulsars or r-mode oscillation from Low-Mass-X-ray-Binaries (LMXBs) such as Scorpius X-1. The GW frequency of non-axisymmetric star are twice the stellar rotational frequency while that of the r-mode is 4/3 of the stellar rotational frequency for $l = 2, |m| = 2$. Oscillating neutron stars may emit CWs at higher frequencies for f-mode and may not be detected by ground-based detectors. Neutron stars may wobble and emit CW at the stellar rotational frequency, but such wobbling may decay rapidly so that it may not be a promising GW emission mechanism for those detectors. In any case, we can use mostly the same detection method to search for those CWs.

Continuous gravitational Waves are gravitational waves that last longer than the time scale(s) of the Earth diurnal rotation (day) and/or its orbital motion (year) or the source compact star orbital motion (hours to years). In other words, gravitational waves are continuous when we need to take into account Doppler modulation due to the above orbital/rotational motions. For this reason, any search method must de-modulate Doppler frequency modulation to accumulate enough signal to noise ratio.

To search for CWs, we may use coherent method or incoherent method. In general coherent methods require more computational cost than the incoherent ones but larger signal to noise ratio than the latter ones for a given signal. With coherent methods, signal to noise ratio (SNR) increases as the observation time $T_{\rm obs}$ increases, like SNR $\propto \sqrt{T_{\rm obs}}$, while with incoherent methods, SNR $\propto T_{\rm obs}^{1/4}$ at most.

The coherent methods that LIGO Scientific Collaboration (LSC) uses include F/G-statistic, time-domain complex heterodyning Bayesian search method, and 5n vector method. Incoherent methods use by LSC include pwerflux, stackslide, and hough methods. For LMXBs search, they also use sideband search method that has been used in radio pulsar search in radio astronomy and radiometry search method that is basically stochastic search toward one direction. The sideband search is more sensitive than the radiometry search, while the latter is more robust against possible spin-wandering due to time-variation of the amount of the accreting mass of compact stars in LMXBs. Using those methods, LSC conducted searches for about 200 known pulsars as well as for unknown pulsars over all-sky wide-frequency-band. Here “known pulsars” are pulsars for which we know the rotational frequencies, frequency derivatives, and positions sufficiently accurately so that we do not need parameter search. On the other hand, “unknown pulsars” are those for which we have to conduct parameter search due to lack of precise knowledge on pulsar parameters. Parameters include rotational frequency, frequency derivative, higher order frequency derivative, sky location (e.g., right ascension and declination), GW polarization, GW initial phase, inclination angle between the line of sight and the stellar rotational axis, and gravitational wave strain amplitude. In addition, in the case of LMXB search we need to search over 6 orbital parameters of LMXBs. An “unknown” pulsar search is also called a “blind” search.

The most challenging task in CW coherent search for unknown pulsars is to reduce computational costs. Computational cost is also a big problem in a LMXB coherent search. In general, coherent search is computational cost limited while incoherent search is sensitivity limited. Hence possible long-term research theme may be

- to speed-up the current search codes,
- to find an optimal template placement method (such as random/stochastic template bank),
- to find an optimal combination of incoherent and coherent methods in a hierarchical multi-stage search,
- to find a lower-cost method, and

- to obtain computational resources (such as Einstein@Home, and use of GPGPUs, Intel MICs).

CW search is generally robust against bust-like noises, but is affected by line noise artifacts and non-stationarity of noise floor. CW search team needs help from the detector characterization team to veto out factious events. CW search team needs a list of “known line noise artifacts” which are known to be instrumental origins. On the other hand, the former team can help latter one by developing codes that find those noise artifacts.

4.2 Science goal

The primary scientific goal of this task is to detect continuous GW, and reveal the following items.

- Crust strain of a compact star when its distance is known. If we measure crust strain, we may be able to infer whether the source is a normal neutron star, quark star, hybrid star, or a normal neutron star that has a large toroidal magnetic field.
- If we detect GW from LMXBs, we may be able to verify theories where a neutron star in a LMXB has much lower rotational frequency than the break-up frequency because of GW emission.
- Spatial distribution of sources in the case of a blind search.

4.3 Tasks

Unfortunately, Japanese communities do not have many codes/tools for CW search. As a result, unless we introduce LIGO Algorithmic Library (LAL) software and its applications, we need to develop all the software from scratch. Study on LAL is necessary to reduce tasks.

4.4 Priority items for this year

- Study usability of LAL software/applications
- Develop or introduce from LAL basic coherent search codes for known pulsar search. It may consist of subroutines and codes below
  - a barycentering subroutine that uses the JPL ephemerides,
  - a subroutine that computes a beam pettern function,
  - a subroutine that computes a detector response function,
  - a subroutine that computes GW Phase of a hypothetical pulsar,
  - a subroutine that computes GW strain time series of a hypothetical pulsar,
  - a subroutine that low-pass-filters data,
  - a subroutine that does resampling of data,
  - a subroutine that complex-heterodynes data,
  - a code that generates fake data of a hypothetical detector and noise distribution of which is stationary Gaussian, and
  - a code that computes a detection statistic(s).

4.5 Mid-term plan toward iKAGRA and bKAGRA

We may study possibility of the Intel MIC (Many Integrated Core) or GPGPU (General Purpose Graphical Processing Unit).

5 Radiometry

Nobuyuki Kanda (Osaka City Univ.)

The cross-correlation search for gravitational waves, also known as 'radiometry', has been previously applied to map the gravitational wave stochastic background in the sky and also to target gravitational waves from rotating neutron stars/pulsars.

The detector sites are widely distributed around the globe, which makes independent observation of gravitational waves possible. Since the distributed detectors may not have correlated noise but will have a correlation in the gravitational signal, the cross-correlation of data from two or more detectors makes is a possible way to search for unknown gravitational waveforms. This is a useful property for gravitational wave searches esecially for short duration bursts, or for long duration stochastic gravitational waves. The measurements from spatially separated detectors allow triangulation of the source. The time delay between detectors can be used to determine the incident direction of the gravitational wave in short duration signal analysis. On the other hand, employment of the time delay term in searches for long duration signals or stochastic gravitational waves which come from an arbitrary direction is not simple.

However, we can extract the signal strength if we deconvolve the Earth's rotation from the signal for any point in the sky. Using multiple detectors and long integration times, the deconvolution is possible. This type of directional cross-correlation search for gravitational waves is known as 'radiometry'.

Radiometry and any other triangulation analysis requires widely separated detectors - long baselines, and the variation of orientation (zenith direction, and azimuthal rotation of interferometers) to cover the sky and resolve the polarizations. The recent beginning of the construction of KAGRA[7] in addition to previously constructed advanced detector sites of LIGO[4] and Virgo[5] encourage the development of radiometric analysis.

5.1 Possible Sources for GW Radiometry

According to the benefit and characteristic of the radiometry filter, possible sources are which are localized on the sky, long lived, and be without certain waveform. On the other, power spectrum of the sources might give important information or restriction of optimal filter to search particular sources.

5.1.1 Unresolvable Astronomical Sources

One of the possibility of radiometry detection is unresolvable astronomical sources, such as huge number of neutron starts in galactic clusters.There are huge numbers of single sources which radiate faint gravitational waves which cannot detect independently, i.e., rotating neutron starts, white dwarf binaries, etc. Even they are faint, but sticks up of these faint waves might reach enough power to detect by advanced detectors with a few years integration. However, since each independent stars radiate GW independently, its waves superimpose incoherently.

- Pulsers in galaxy cluster

  In reference [3], we discussed on the stochastic GW from many pulsars in Virgo cluster. Other galaxy clusters might be a GW source for radiometry search.

  In our galaxy, any single sources with out waveform assumption can be targets of radiometry sources.

- LMXB
- Wagoner stars
- Young pulsars in supernova remnant in our galaxy

5.1.2 Anisotropy of Cosmological Background GW]

5.2 Radiometry Filter

Gravitational wave radiometry is a type of stochastic gravitational wave search, but it is also directed or targeted. Radiometric analysis assumes that gravitational waves come from a particular direction such as a point like source or a 'hot spot' in the sky. The radiometry filter uses data from at least two detectors and does not require the knowledge of the waveform. Gravitational waves coming from a particular direction will have a time of arrival delay at two detectors as shown in Fig.4. Since gravitational wave signals at both detectors are coherent in the same polarization component, we can extract gravitational wave signals in the cross-correlation product from two detectors observations with appropriate time delay. Moreover, the signal-to-noise ratio for the gravitational wave will be increased with long integration time, because the two detector noises are independent. By changing the source direction sequentially after every step, we can construct a gravitational wave 'sky map' by radiometric analysis.

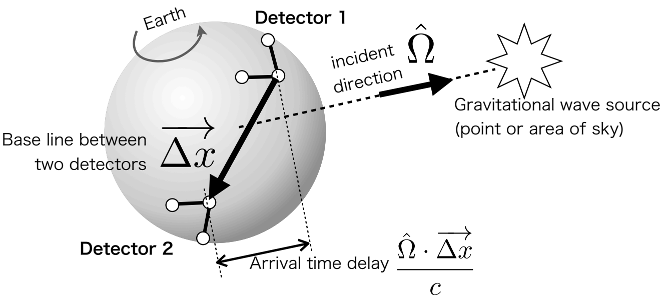


Figure 4: Ideal setup of a radiometry analysis.

Radiometry analysis has been proposed and studied in previous works[10][11]. We explain the radiometry filter briefly here. The source direction or trial direction of the search can be represented by a unit vector $\hat{\Omega}$. The two detectors are labelled as 1 and 2, and the base-line from detector 1 to detector 2 is denoted by the vector $\overrightarrow{\Delta x}$. The arrival time delay for the gravitational wave between the two detectors is $\frac{\hat{\Omega}\cdot\overrightarrow{\Delta x}}{c}$, where c is the speed of light. The output from each detector $s_1(t), s_2(t-\frac{\hat{\Omega}\cdot\overrightarrow{\Delta x}}{c})$ in the time domain has the same gravitational wave timing. In the Fourier domain, this time delay represents a phase difference of the detectors output $\tilde{s}_1(f), \tilde{s}_2(f)$, the Fourier transform of $s_1(t)$ and $s_2(t)$. Therefore, we can define the radiometry filter as follows. A directed overlap reduction function $\gamma(f,\hat{\Omega})$ can be defined to correct the phase difference as

$$\gamma(f,\hat{\Omega}) = \sum_{A=+,\times} F_1^A F_2^A e^{i2\pi f \frac{\hat{\Omega}\cdot\overrightarrow{\Delta x}}{c}} , \tag{1}$$

where $F_{1,2}^A$ are the antenna pattern[6] of detector 1 or 2 for each polarization $A = +$ or $\times$ of the gravitational wave. For optimal filtering, we employ the detectors noise power spectrum $P_{1,2}(f)$ respectively, and assume that gravitational wave spectrum is $H(f)$. The radiometry filter can defined as

$$Q(f,\hat{\Omega}) = \lambda \frac{\gamma^*(f,\hat{\Omega})H(f)}{P_1(f)P_2(f)} , \tag{2}$$

and the filter output is

$$\Delta S(\hat{\Omega}) = \int_{-\infty}^{\infty} df\ \tilde{s}_1^*(f)\tilde{s}_2(f)Q(f,\hat{\Omega}). \tag{3}$$

The base-line $\overrightarrow{\Delta x}$ will change in celestial coordinates according to Earth's rotation in the case of ground-based detectors. Therefore, we calculate ΔS over a short time slice ('chunk') $t-\Delta t/2$ and $t+\Delta t/2$. Therefore the quantities defined in the above equations also become functions of t. Thus the Fourier transforms of detector data can be represented using the short Fourier transforms of $\tilde{s}_{1,2}^*(t;f)$, and $Q(f)$ becomes $Q(t,f)$ and so on. Then

$$\Delta S(t,\hat{\Omega}) = \int_{-\infty}^{\infty} df\ \tilde{s}_1^*(t;f)\tilde{s}_2(t;f)Q(t,f,\hat{\Omega}). \tag{4}$$

Processing many chunks for long duration observational data, we can determine the statistics of ΔS. Since the gravitational wave component will appear in the real part of ΔS, we employ the mean $\mu(\hat{\Omega})$

$$\mu_{\Delta S}(\hat{\Omega}) = \langle \Re[\Delta S] \rangle , \tag{5}$$

and the standard deviation $\sigma_{\Delta S}(\hat{\Omega})$ for the real part of ΔS.

We now need to sum up over the contributions to the SNR, which we denote by $\rho(\hat{\Omega})$, for all the chunks making up the total observation period. The statistic for the full observation time is denoted by $S(\hat{\Omega})$ and its mean and standard deviation by $\mu(\hat{\Omega})$ and $\sigma(\hat{\Omega})$ respectively. The signal-to-noise ratio of particular direction $\hat{\Omega}$ is then given by:

$$\rho(\hat{\Omega}) = \mu(\hat{\Omega})/\sigma(\hat{\Omega}). \tag{6}$$

5.2.1 Implementation on Observed Data Processing

5.3 Tasks

- Priority items for this year
- Mid-term plan toward iKAGRA and bKAGRA

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