Development of Photon Calibrator for Hardware Injection Test

Yu-Kuang Chu

國立臺灣師範大學

Recommended for Acceptance

by the Department of

Physics

Adviser: Wo-Lung Lee

June 2018

Abstract

This is a LaTeX template and document class for Ph.D. dissertations at Princeton University. It was created in 2010 by Jeffrey Dwoskin, and adapted from a template provided by the math department. Their original version is available at: `http://www.math.princeton.edu/graduate/tex/puthesis.html`

This is **NOT** an official document. Please verify the current Mudd Library dissertation requirements [**?**] and any department-specific requirements before using this template or document class.

Your abstract can be any length, but should be a maximum of 350 words for a Dissertation for ProQuest's print indicies (or 150 words for a Master's Thesis); otherwise it will be truncated for those uses [**?**].

Dwoskin Ph.D. Dissertation Template — version 1.0, 5/19/2010

Acknowledgements

I would like to thank the Math department for providing the original documentclass file that this class is based upon. I would like to thank my parents, without whom my life would not be possible. I would also like to thank my advisor, my dissertation committee, and my research collaborators because every graduate student needs to do so. And finally, I thank the members of my research group, to whom I leave this template to save you some of the trouble I had to go through getting my dissertation to compile in LaTeX.

Don't forget to ask your advisor if your work was sponsored by a grant that needs to be acknowledged in this section.

To my parents.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction to Gravitational Wave

1.1.1 What is gravitational wave

In the General Theory of Relativity proposed by Albert Einstein. The phenomenon caused by gravity in one frame can be interpreted as the result of curved spacetime.

Furthermore, the field equation of spacetime curvature allows wave-like solution similar to electromagnetic solution in Maxwells equation. In other words, the time-dependent local mass distribution can generate time-depend distortion of spacetime known as gravitational waves. These gravitational waves or the ripple of spacetime can propagate throughout the universe like electromagnetic waves.

However, the physical reality of gravitational wave is not so clear to everyone in the early days, even to Even Einstein himself [**?**]. The main problems is that there exist some gauge degree of freedom in the theory due to the arbitrariness of coordinate choices. We have to know whether the gravitational waves we found are just gauge waves (vibration of coordinate) or the wave can have some observable consequences.

On of the most important observational evidence implying the existence of real gravitational waves is Hulse-Taylor pulsar. .... Finally, in 2015 September 14. GW150914

1.1.2 How to describe gravitational wave

mathematics.

TTgauge There is a very convenient gauge(coordinate) constrain, which is known as Traceless and Transverse gauge. for perturbation of wave like part metic over Schwarzschild background which represent Earths gravity.

How to generate gravitational wave The source of electromagnetic wave is time-dependent electrical charge distribution. Similarly, the source of gravitational wave is time-dependent mass(energy) distribution. Strictly speaking, the lowest order of mass multi-pole which can generate real gravitational waves is mass quadruple because we dont have negative mass, while the electromagnet wave can be generate though time-dependent electrical dipole moment. The gravitational wave strain generated by mass quadruple can be approximately described by famous quadrupole formula: (quadrupole formula) According to our current understand of universe, there are several kinds of astrophysical gravitational wave sources, whose h(t) amplitude is large enough to be detected by current ground based laser interferometer, like advanced-LIGO, advanced-Virgo or KAGRA. Compact Binary Coalescence BNS BBH

1.1.3 How to detect Gravitational wave

The interaction of detector and gravitational wave can have different interpretation due to different coordinate choice. It is quiet similar to that the magnetic force in one observational frame may be electric force in the other frame. However, practically, I would like to use the .., which described in next section.

1.2 Detection of Gravitation wave

Interaction of GW wave when $\lambda_g w$ ¿¿ L of detector Limit of Michelson IFO IFO with dual-recycling and Fabry-Perot arms. Fucking Complex response WE NEED Calibration Calibration Calibration

1.3 Calibration and Reconstruction

Calibration is always the fist step before we measure something by some device. For example, to measure the weight of an apple, you should calibrate your scale by putting a standard kilogram on it. Then, you can either adjust the scale readout to be 1kg, or record the difference showed in scale readout, which may be used to reconstruct real weight of the apple. However, the spring constant of springs inside the scale could fluctuate due to temperature changes. To accurately measure the weight of the apple, we have to measure the calibration factor (scale readout when we put the standard mass on it.) when we measure the weight of apple, if possible, simultaneously.

Due to the complexity of practical interferometer, the response of interferometer itself to external gravitational source is not only complex but also time-dependent. In reality, we inject several calibration lines, which means we shake the End-Test-Mirror by several known frequency and amplitude sine wave. Then, we try to see these standard signal in readout of interferometer. If we can solve .

1.3.1 Transfer function of Laser Interferometer with Fabry-Perot Cavity

1.3.2 Tracking Time-dependent Response by Calibration lines

1.4 Photon Calibrator (Pcal)

1.4.1 Principle of Photon Calibrator

Photon calibrator is an additional laser with high precision intensity modulator. It is installed in front of End-Test-Mass Mirror(ETM) and can push the ETM by radiation force due to its own Laser beam. To generate any artificial h(t) by Pcal, we have to translate desired h(t) into corresponding force F(t) exerting on ETM. This can be done by using equation of motion of the ETM suspend by its suspension system. Then, we control the Pcal Laser output intensity P(t) such that the radiation force exerted on ETM is F(t) we calculated before. If we analyze it frequency domain, the h(f) introduced by P(f) can be describe by eq:

Original Pcal is proposed by Glasgow group [ref!!]. They use single laser beam hitting on the center of ETM. The problem is that it may introduce drumhead mode vibration of ETM surface (just like the vibration mode you see when you hit the center of a drum), which introduce unwanted h(t) effectively. This problem is solved by LIGO group, who separate the Pcal laser beam into two beams, hitting on the nodal point of drumhead mode on the ETM surface[ref!!].

¿ KAGRA

In order to excite same amplitude h(t) in higher frequency regime, we have to give much larger F(t) since the relationship between x(t) and F(t) in an pendulum .

1.4.2 Why do we need Photon Calibrator

1.4.3 Tracking Time-dependent Response by Calibration lines

Chapter 2

Hardware Injection through Photon Calibrator

2.1 Principle

Validate IFO by Pcal (Hardware Injection Test) As I mentioned in last chapter, the practical response of IFO is very complex. To prevent some unexpected problem including no-linear response of IFO and The best way is to provide some test source of expected GW signal.

However, it is impossible to prepare an BBH system in laboratory. Instead, we will generated some test signal by pushing the ETM with Pcal. This procedure is called Hardware Injection Test

Motivation To under whether we can successfully reconstruct the h(t) from our interferometer, the best way is to prepare an artificial signal, sending it to interferometer, reconstructing it, finally, comparing it with original one. However it is quite difficult to generate human made gravitational wave that can be detected by current gravitational wave detector.

Requirement

Low Frequency around 100Hz the nose should below the IFO sensitivity (absolute timing ¡ ?us ns)

High Frequency above 1kHz the transfer function should as flat as possible

Amplitude of Injection Signal

$$\frac{F(t)}{M} = \frac{1}{M}\frac{2P(t)\cos(\theta)}{c} = \ddot{x}(t) \tag{2.1}$$

For $x = x_0 \sin(\omega t)$,

$$\frac{1}{M}\frac{2P_0\cos(\theta)}{c}\sin(\omega t) = -\omega^2 x_0 \sin(\omega t) \tag{2.2}$$

Thus,

$$P_0 = -\omega^2 \frac{Mc}{2\cos(\theta)} x_0 = -\omega^2 \frac{Mc}{2\cos(\theta)} L h_0 \tag{2.3}$$

$$M = 23 \text{ kg}$$

$$L = 3 \text{ km}$$

$$\theta = 0.72 \text{ deg}$$

$$c = 2.998 \times 10^8 \text{ m/s}$$

$$P_0 \text{ (Watts)} \times \frac{Gain_{\text{ Power to OFSPD}}}{2} = \underbrace{V_{\text{OFSPD}}}_{\text{Same as V}_{\text{Injection}}} \text{ (Volts)}$$

Therefore, the overall gain should be set in injection channel, which is in Volt unit, is

$$\omega^2 \frac{Mc}{2\cos(\theta)} L \times \frac{Gain_{\text{ Power to OFSPD}}}{2} \tag{2.4}$$

Chapter 3

Development of Injection Channel

3.1 Requirement of Injection Channel

3.1.1 Noise Requirement

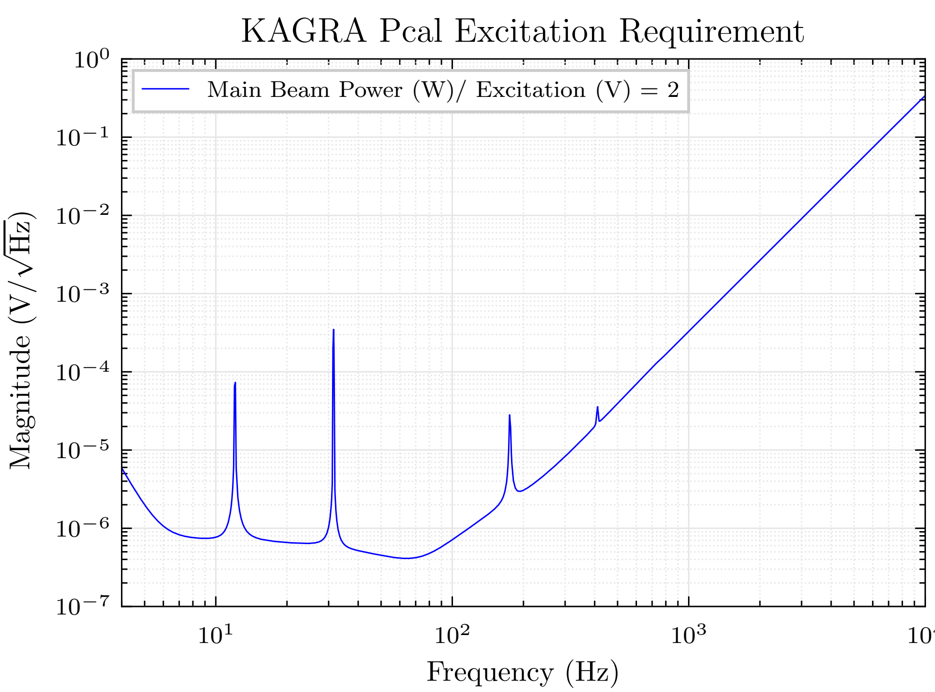

Figure 3.1: Injection Channel Noise Requirement

$$\Delta L(f) < \frac{1}{10} \times (\text{KAGRA length sensitivity}) \tag{3.1}$$

$$\Delta L(f) = \frac{2\Delta P(f)\cos(\theta)}{c} \frac{1}{M(2\pi f)^2} < \frac{1}{10}\Delta h(f)L \tag{3.2}$$

3.2 Noise Source of Excitation channel

3.2.1 Quantization Noise of DAC

The origin of quantization error is coming from the difference between desired analog output and quantized Digital to Analog Converter(DAC) output value. Roughly speaking, it shows like white noise spreading from DC to Nyquist frequency i.e. $Fs/2$. The Root Mean Square value of quantization noise has the order of voltage difference corresponding to last digit or Least Significant Bit(LSB). In time domain, we can calculate standard deviation.

$$\sigma_x = \sqrt{\frac{1}{12}}\delta x_{LSB} \tag{3.3}$$

For a 16-bit 64kHz DAC with output range between ±10Volts,

$$\begin{aligned} \sigma_x &= \sqrt{\frac{1}{12}}\delta x_{LSB} && (3.4)\\ &= \sqrt{\frac{1}{12}}\frac{(+10)-(-10)\text{Volts}}{2^{16}} && (3.5)\\ &= 8.81 \times 10^{-5}\ \text{Volts} && (3.6) \end{aligned}$$

In frequency Domain, the quantization noise is distributed from DC to 32768Hz; therefore, we have ASD

$$
\begin{aligned}
ASD &= \sqrt{PSD} && (3.7)\\
&= \sqrt{\frac{\sigma_x^2}{32768}} && (3.8)\\
&= 8.81 \times 10^{-5}\sqrt{\frac{1}{32768}} && (3.9)\\
&= 4.87 \times 10^{-7}\ \text{Volts}/\sqrt{\text{Hz}} && (3.10)
\end{aligned}
$$

3.3 Noise Reduction through de-whitening filter

Problem of 16kHz excitation channel Implementation of 64kHz Excitation channel in KAGRA digital system

Principle of Analog filter Design of De-Whitening filter Performance test Transfer function measurement Noise requirement Create Inverse De-Whitening filter

Chapter 4

Validation of Injection Channel

Noise measurement around 100Hz the nose should below the IFO sensitivity Transfer Function measurement above 1kHz performance time delay of excitation channel (absolute timing measurement?) Distortion of Scientific Signal BBH BNS post merger

Appendix A

Implementation Details

Appendices are just chapters, included after the *appendix* command.

A.1 Switching Formats

When switching `printmode` on and off (see Section **??**), you may need to delete the output .aux files to get the document code to compile correctly. This is because the hyperref package is switched off for `printmode`, but this package inserts extra tags into the contents lines in the auxiliary files for PDF links, and these can cause errors when the package is not used.

A.2 Long Tables

Long tables span multiple pages. By default they are treated like body text, but we want them to be single spaced all the time. The class therefore defines a new command, *tablespacing*, that is placed before a long table to switch to single spacing when the rest of the document is in double spacing mode. Another command, *bodyspacing*, is placed after the long table to switch back to double spacing. Normal tables using `tabular` automatically use single spacing and do not require the extra commands.

When the documentclass is defined with the 'singlespace' option, these commands are automatically adjusted to stay in single spacing after the long table.

Make sure there is always at least one blank line after the *bodyspacing* command before the end of the file.

Some times long tables do not format correctly on the first pass. If the column widths are wrong, try running the LaTeXcompiler one or two extra times to allow it to better calculate the column widths.

If you want your long table to break pages at a specific point, you can insert the command *pagebreak*[4], to tell LaTeXthat it really should put a page break there. *pagebreak*[2] gives it a hint that this is a good place for a page break, if needed. If there's a row that really should not be broken across a page, use \\\\∗, which will usually prevent a pagebreak.

A.3 Booktabs

The booktabs package is included to print nicer tables. See the package documentation [**?**] for more details and motivation. Generally, all vertical lines are removed from the tables for a better visual appearance (so don't put them in), and better spacing and line thicknesses are used for the horizontal rules. The rules are defined as *toprule* at the top of the table, *midrule* in between the heading and the body of the table (or between sections of the table), and *bottomrule* at the end of the table. *cmidrule* can be used with the appropriate options to have a rule that spans only certain columns of the table.

A.4 Bibliography and Footnotes

The bibliography and any footnotes can also be single spaced, even for the electronic copy. The template is already setup to do this.

Bibliography entries go in the .bib file. As usual, be sure to compile the LaTeXcode, then run BibTeX, and then run LaTeXagain.

To cite websites and other electronically accessed materials, you can use the '@electronic' type of BibTeX entry, and use the 'howpublished' field to include the URL of the source material.

The formatting of bibliography entries will be done automatically. Usually the titles are changed to have only the first word capitalized. If you'd prefer to have your original formatting preserved, place the title in an extra set of curly braces, i.e., "title = {{My title has an AcroNyM that should stay unchanged}},".

A.5 Figures and Tables

The captions of figures and tables take an optional parameter in square brackets, specifying the caption text to be used in the Table of Contents. The regular caption in curly braces is used for the table itself.

Generally captions for tables are placed above the table, while captions for figures are placed below the figure.

Appendix B

Printing and Binding

B.1 Printing

For the library copies of your dissertation, you must use archival quality printing and binding. This means acid-free paper, containing at least 25% cotton fiber. Triangle Repocenter on Nassau Street in Princeton offers both 25% cotton paper and 100% cotton paper. Most people choose the 25% cotton paper, and this is generally recommended by the binders. The 100% copy paper is somewhat thicker and the extra expense is unnecessary.

Triangle offers online submission of your printing and binding order at: `http://triangleprinceton.com/collegiatebinding/thesis/`. If you request binding from them, they will deliver the paper copies to Smith-Shattuck Bookbinding for you and allow you to pick up the completed copies at their store on Nassau Street. The whole process takes 2-3 business days, but check with them in advance during the busy thesis-printing season in April and May.

Currently, your printed and bound dissertation copies can be single spaced. Only the electronic copy submitted to ProQuest must be double spaced. All copies must be printed single-sided, with specific margins.

B.2 Binding

An archival-quality sewn binding is required for the library copies of your dissertation. Smith-Shattuck Bookbinding is highly recommended, and is used by most students. Triangle Repocenter will send your copies there for you, greatly simplifying the process, but you can call Smith-Shattuck with special requests.

The "library standard" sewn binding is sufficient for the copies to be sent to Mudd Library. It uses a black buckram cloth cover, which is the most popular option. For extra copies for yourself and your family members, you can choose "buckram roundback binding", which adds decorative lines on the spine, and printing of the title and author on the front cover. For a small additional fee, you can include the Princeton University shield on the front cover and a ribbon bookmark. Leather covers are also available. See Smith-Shattuck's website for more details at: `http://www.thesisbookbinding.com/`.

Bibliography

[1] S. Fear. Publication quality tables in LaTeX. Available from CTAN, macros/latex/contrib/booktabs, `http://www.ctan.org/tex-archive/macros/latex/contrib/booktabs/booktabs.pdf`, 2005.

[2] R. Lee, D. Karig, J.P. McGregor, and Z. Shi. Enlisting hardware architecture to thwart malicious code injection. *Security in Pervasive Computing, LNCS 2802*, pages 237–252, March 2003.

[3] ProQuest. PQ/UMI GradWorks Guide F2006. `http://www.princeton.edu/~mudd/thesis/Submissionguide.pdf`, 2006.

[4] Seeley G. Mudd Manuscript Library. Submitting your Doctoral Dissertation or Masters Thesis to the Mudd Manuscript Library. `http://www.princeton.edu/~mudd/thesis/`, May 2009.