INTEGRATING EXPERIMENTATION AND INSTRUMENTATION IN UPPER-DIVISION PHYSICS

by

QI ZHANG

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Major Professor
N. Sanjay Rebello

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QI ZHANG

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Abstract

Over the past 20 years there have been limited efforts to improve students' interest and knowledge of electronics and to offer students experiences to integrate and apply their knowledge of electronics with experimental physics. None of the reform efforts cited in the literature have performed a careful assessment of student learning and attitudes, and most of them report anecdotal success. These programs share several commonalities. They typically have a capstone project experience in which students apply their knowledge and skills in electronics and instrumentation to a particular context.

The KSU Physics Department has embarked on an endeavor to improve the PMI (*Physical Measurement and Instrumentation*) class taken by physics majors. Capstone project experiences for students in PMI will provide them with an opportunity to revisit experiments they completed in previous courses. They then apply the knowledge and skills in electronics and instrumentation learned at the beginning of the PMI course to automate these experiments. The use of LabVIEW™ and NI ELVIS™ provides a range of opportunities to students due to their visual interface and easy learning curve. However, they do have some disadvantages such as speed and resolution when compared to more traditional measurements with oscilloscopes.

Three specific capstone experiences have been developed in PMI. These include saturated absorption in Rubidium, the Franck-Hertz experiment, and the speed of light measurement. In each case, students first complete the traditional experiments and then use NI ELVIS™ and LabVIEW™ to automate these experiments. Students are provided minimal explicit guidance in completing the capstone projects. These include one-page handouts describing the goals, basic procedures and questions that students have to answer for themselves. Comparing data from traditional experiments and those from automated using LabVIEW™ and NI ELVIS™ provides a context in which to discuss the trade-offs between the traditional and automated experiments.

Future efforts include the development of more experiments as well as careful assessment of student learning and attitudes as a result of the capstone experiences in the PMI class. This project can potentially inform similar efforts at other institutions in the future.

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Dedication

I dedicate this report to my family back in China who has always supported my education.

CHAPTER 1 - INTRODUCTION

There appears to be a general agreement that all physics majors need to have a solid background in electronics and instrumentation. This is especially true for physics majors who may plan to pursue research in experimental physics, where they will often be called upon to build circuits, use electronic instruments and even write the programs that interface these instruments with computers.

This report was written as part of a project funded by the National Science Foundation to reform the learning experiences of physics undergraduates at Kansas State University. In the KSU Physics Department, there are two laboratory courses offered to the undergraduate physics majors: *Modern Physics Lab* (MPL) in their sophomore year and *Advanced Physics Lab* (APL) in their junior or senior year. After these two classes, a course titled *Physical Measurement and Instrumentation* (PMI) follows in the junior year. The MPL and APL courses cover several classic modern physics experiments. PMI is a basic course in analog and digital electronics. Presently the PMI course is unrelated to the MPL – APL sequence. When students take MPL and APL they focus almost exclusively on the physics and not on the instrumentation. Later they take the PMI course that focuses on the electronics that underlies laboratory instrumentation. Students often see these courses as disconnected and often tend to 'forget' what they had learned in a previous course when asked about it in a later course.

For the students to learn the measurement and instrumentation as well as to refresh the experimental physics, the PMI course needs to better connect instrumentation to experimental physics. In the second half of the PMI class, students are asked to design their own electronic interfaces and write computer programs with LabVIEW™ to control, measure and a set of selected experiments in MPL and APL. By connecting the PMI course directly to the experiments that the students have already preformed in MPL and APL, the students will make the connection much more directly. Reflecting back on their experiences in MPL and APL while taking PMI later will meet the following goals.

1. Provide students an opportunity to re-learn the physics concepts underlying common experiments in modern physics that they had completed one or two years prior to taking this class.

2. Create a context in which students can apply their newly acquired knowledge and skills in…
   - Design, simulation, building and testing of electronic circuits that are commonly used in electronic instrumentation.
   - Programming using LabVIEW™ to control instruments, collect, analyze and display data and control instrumentation
3. Enable students to see how their learning experiences in the three classes: MPL, APL and PMI relate to and reinforce each other.

Structure of This Report

In Chapter 2, we provide a literature review of efforts to teach electronics and instrumentation in the undergraduate physics. The literature review was prepared from a search for "Electronics" and "Laboratory" in the archives of the American Journal Physics (AJP) within 20 years, and will be listed chronologically from 1988 to 2009. In Chapter 3, we will provide a brief introduction to our capstone project, especially focusing on the NI-ELVIS™ and LabVIEW™ software and hardware that students will use in PMI class. In Chapter 4, we will illustrate specifically our work on developing instructional materials for the capstone project in the PMI class at KSU. These will include write-ups and handouts for three experiments from MPL and APL that students revisit during their capstone project experiences in the PMI course. These three experiments are saturated absorption in Rubidium, the Franck-Hertz experiment, and the measurement of the speed of light and sound. Finally, in Chapter 5, we summarize the report and provide plans for the future work on this project. The Appendix contains the LabVIEW™ programs including both the front panel and block diagram codes for the saturated absorption and Franck-Hertz experiments. An electronic circuit diagram for the speed of sound experiment is also attached.

CHAPTER 2 - LITERATURE REVIEW

Electronics has become an important subject in undergraduate physics, with courses that emphasize topics that have overlap with experimental applications. These courses also emphasize analog and digital electronics, partially because the experimental physics research requires students to at least be able to understand and operate the devices and also understand their underlying electronic and engineering principles. Sometimes students who may decide to pursue a career in experimental physics may even need to become electronics technicians themselves and build their own systems before they can focus on the physics. However, in most cases, the electronics courses for physics students are often considered to be easier and less rigorous than those in the electrical engineering curriculum.

In the following sections of this chapter we present a literature review specific efforts to teach electronics and instrumentation in physics undergraduate programs in the U.S. over the past 20 years.

Overview of Teaching Electronics in Physics Departments

The resource letter by Henry [1], briefly recalls the history of instruction in electronics in the undergraduate physics curriculum. Henry provides a summary of the range of classroom and laboratory activities in the physics curriculum, which includes many aspects in analog and digital electronics including data acquisition and computer interfacing. Data acquisition and computer interfacing software, such as LabVIEW™ or BASIC, has often been covered in the electronic classes. Recently there has been a trend toward integrating computer programming and equipment interfacing into the traditional electronic class.

One of the main barriers to this change is the lack of qualified instructors teaching electronics and out-of-date textbooks. Finally, an extensive collection of textbooks, reference books, supplementary texts, articles, laboratory experiments manuals, instructional and design software, videos, and related websites were listed in this paper. Overall, this paper offers a general overview of the history and current situation of teaching electronics in physics departments and sets the backdrop for the project at KSU.

Using Automation in Advanced Physics Laboratory Experiments

Nornes and Tu [2] provide an early example of using computer interfaces (IEEE-488 and RS-232) and electronics to automate several experiments in advanced laboratories. The authors describe their goals for students to better understand the physics in the experiments and to develop the necessary experimental skills and creativity to be successful experimentalists.

LabVIEW™ software is used in this laboratory course,however, the goals and principles were quite similar to the ones we have for our project, which is to repeat the previous experiments in traditionally taught laboratory classes with computer interfacing or any other electronic circuitry. While the computer interfacing and programming were used to enhance the experiments' performance, the author particularly argued that these changes were focused on enabling the students to better understand the physics of the experiments.

The students should not only learn everything from the classroom, but also need to be given an opportunity to set up a connection between physical theories and real world experiments. Computer automation provides a useful tool for the process of gaining experimental skills from performing physics experiments. It also stimulates student interest and deepens the connection between physics theories and real world experiments.

There were three specific experiments in advanced laboratory classes reported in this paper: the Franck-Hertz Experiment, the mass spectrometer experiment, and the multi-channel analyzer. The IEEE-488 standard interface and programming with BASIC are also briefly discussed in this paper. But they are not the essential parts to our focus in the current context, since these techniques have been improved greatly with the use of new hardware and software.

In summary, the results of those experiments were inspiring, but more importantly, the concept of computer interfacing and control of instrumentation, which was still new in 1989, provided important impetus for future developments in this area toward the improved learning of these laboratory skills by physics undergraduates.

Laboratory Course in Computer Interfacing and Instrumentation

Kocher [3] describes a laboratory course using computer interfacing and instrumentation. Computer-aided measurements and the process of analog-to-digital or digital-to-analog conversion were emphasized. There were several techniques such as parallel and serial communication and others were taught to students in this class. This highly integrated class was

adapted by Oregon State University to develop students' ability to perform scientific measurements with the assistance of computer interfacing, analog and digital electronics, and other instruments and devices.

The structure of this laboratory course is interesting. This class requires students to complete a prerequisite course in digital and analog electronics since there is not much time used in the class to teach that basic knowledge. The course is designed to supply students with multiple opportunities of performing and operating scientific devices and electronics. In the first week, students get familiar with the instruments including computer software and interfacing that could be used during the measurements. This is then followed by a study of parallel and serial communication. Particular operation skills and experiences are gained by students according to their chosen field through spending large amount of time with computer interfacing and scientific instruments. Finally, all the students are asked to design their own electronics systems that perform the function of measurement and instrumentation, and to report their efforts to the class.

In the whole process, students are quite independent from instructor's "teaching" and able to choose between different options according to their own interests and capabilities. Teachers are not the only grader or evaluator any more, but everyone in the class has their own opportunity of reviewing, evaluating and learning other students' original work.

This type of course is very dependent on students' motivation and thus can potentially stimulate their interests. The capstone project in the PMI class also is also a very open project to every student in the class. They learn pieces of knowledge of electronics and LabVIEW™ programming, and then are informed of those experiments which they might want to perform. They are not limited to those chosen experiments and projects, but also encouraged to make a choice according to their own interests. Further, even during their projects, students are allowed to make changes to original goals and tasks.

Computer-based Data Acquisition Laboratory for Undergraduates

Maps [4] describes a computer-based laboratory class using computer interfacing, software and data acquisition equipment at the University of Maryland. The goal of the class is to prepare undergraduate students for future employment in research and industry, where the skills of

integrating computers for data acquisition and physical measurement and instrumentation are important.

The class provides an environment where students can gain hands-on experiences in integrating computers into laboratory work. The goals of this class are to (1) enable students to transition from the use of breadboard electronics to the use of commercially available data acquisition boards and programmable instrumentation, and (2) to learn the use of high level integrated data acquisition software as opposed to assembly language. Indeed in the future research work for undergraduates physics major, it is a common case that they are required to be able to get acquainted with particular instruments and/or devices quickly which they have never met before. So this class is in some level a real research class, which provides research experience to undergraduates even before they go into a graduate research project.

Students learn the above skills in the context of four open-ended projects: time of flight measurements of the speed of sound; frequency response measurement of piezoelectric; and two others. Among these experiments the speed of sound experiment is also one of the chosen experiments in our capstone project in PMI class. This experiment is very open and students have come up with varied ideas for the measurements. Even further, with the help of higher resolution of data-acquisition cards and computer interfacing, students can also adapt the experiment to measure the speed of light.

Contemporary Electronics: A Focused Concept Laboratory

Panitz [5] describes an integrated laboratory course titled "Focused Concept Laboratory" which implements integrated circuits and operational amplifiers instead of discrete components, and printed circuit boards instead of conventional wiring techniques during the entire class. This class includes a one hour lecture and four hours laboratory exercises every week. In the class, students build electronic systems which can measure the input current from a tunneling diode from 10nA to 1μA. During this process, students learn about diodes, transistors, operational amplifiers, and many other electronic components that are necessary in building the circuits on circuit boards.

This contemporary electronics class contains two segments. The first segment focuses on analog electronics, transistors, and other electronics. The second segment concentrates on digital electronics, as well as computer interfacing with LabVIEW™ software. By writing LabVIEW™

programs, students are able to perform the measurement of tunneling current automatically in the front panel of the LabVIEW™ application. Then, in the mid-term exam students are asked to compare their result of measurements to the manually recorded data. By comparison, students learn the benefits as well as shortcomings for computer-aided experiments and LabVIEW™ data acquisition.

This is a very similar class to our PMI class at KSU. In the PMI class, students also will learn basic knowledge of analog and digital electronics and LabVIEW™ programming in the first segment. Then in the second segment, students apply their knowledge about electronic measurements and data acquisition to several experiments which most of the student have done in previous laboratory class. In PMI too, students are asked to compare their results from the automated experiments with ones obtained with the original experiment. Thus students are encouraged to think about how to further improve the experimental results.

The Bug: A Temperature Controlled Experiment on a Protoboard

Dixon [6] describes a fully automated experiment for the undergraduate laboratory class. This experiment implements data acquisition and control using LabVIEW™ programming for computer interfacing with experimental devices, and electronics circuits. This experiment is based on a simple physical principle, is less expensive than many other experiments, and requires a wide range of knowledge and implementation of analog and digital electronics, computer-aided data acquisition and control, and other relevant skills. The objective of this laboratory course is to prepare students to be skilled experimentalists in a typical advanced undergraduate or graduate research laboratory setting. The main software is LabVIEW™. Similar to the courses described in several papers before, the first half of this course is dedicated to training the students in electronic skills and LabVIEW™ programming. And once the students have developed a command of the programming languages, they construct an experimental measurement and instrumentation with LabVIEW™. The paper provides a detailed description of the experimental system, measurement and noise analyses and the automated control of the experiment.

Summary

Through this literature review, we can clearly see that many physics departments adopt the projects similar to the one we are currently pursuing at K-State. These projects are designed

to improve the students' interest and the knowledge of electronics and/or to offer their students experiences in which they can integrate and apply their knowledge of electronics with experimental physics. Although none of these course reform efforts cited in the literature have performed a careful assessment of student learning and attitudes, most of them did anecdotally find that those projects helped their students be better prepared for the future advanced undergraduate or graduate research.

The projects described in the literature above all share several similarities with the PMI course. First they all focus on automation and control of electronic equipment and experiments that students may cover in their undergraduate curriculum. There are some projects, however, that go beyond the typical experiments and focus instead on non-standard experiments such as measuring tunneling current. However, even these experiments are not entirely unrelated to modern physics and often cover topics that students would have learned in their modern physics class.

Second, most of the courses rely on students acquiring certain knowledge and skills prior to starting their project. The only exception is the focused concept laboratory project in which students were given a particular task – measure current from a tunnel diode. The students learned the electronics in the context of the project. This approach is significantly different from the approach that we currently use in PMI. It has some advantages and disadvantages over the more traditional approach. The advantage is that when students are expected to learn about an electronic circuit or concept within the larger context of a project that they have to accomplish, they are more likely to be motivated to learn it. The disadvantage is that the students may not necessarily learn the concept or electronic circuits in sufficient detail and may not know all of the applications of it, other than the one in the project.

Finally, almost all of the courses required the use of some kind of programming language. The older courses, before LabVIEW™ was developed used more basic programming languages, but more recently LabVIEW™ appears to be the programming language of choice in upper-division electronics laboratory.

The challenges and barriers highlighted in the article by Henry still exist in many of these courses. Most importantly there are no good textbooks that can cover all of the materials. Some text books that are commonly used in electronics courses offered by physics departments, such as *The Art of Electronics* [7] can serve as excellent reference books. However, they are not

effective textbooks for students who are trying to learn the material for the first time, because they tend to use jargon and often use tricks that may not be familiar to students who typically have not had prior experience in electronics before they take these courses. Finally, the time to learn electronics and apply that knowledge to a project is rather limited.

Given these constraints, the PMI capstone project has tried to accomplish several goals that are similar to the goals of the reform efforts described above. The capstone project in the PMI class is designed to improve student understanding of modern physics experiments in the APL and MPL courses, as well as to develop students' instrumentation skills. The previous efforts described in this chapter inform our studies such efforts have been developed elsewhere. However, because there is a lack of systematic research on the effectiveness of these efforts in fostering student learning of physics and instrumentation, we cannot say for sure that these efforts have met their stated goals. Therefore, the PMI reform efforts can serve as a context for research on whether these efforts have met their stated goals.

In the following chapter, we describe the efforts in the PMI course. These efforts are similar to those described in previous studies. Students learn the concepts of analog and digital electronics in the first half of the semester. They use NI ELVIS™ , which is an interface that allows them to collect real data from electronic circuits using a computer. They also learn LabVIEW™, a visual programming language. In the second half to the semester they apply their knowledge and skills in electronics with NI ELVIS™ and LabVIEW™ to complete a capstone project that automates a physics experiment from the APL or MPL courses. In the next chapter we describe several features of NI ELVIS™ and LabVIEW™ and discuss how and why they are used in the capstone project efforts.

CHAPTER 3 - USING NI-ELVIS™ AND LabVIEW™ IN THE PMI CAPSTONE PROJECT

At Kansas State University, most of the undergraduates in physics major take Modern Physics Lab (MPL) in the first semester of their sophomore year, an Advanced Physics Lab (APL) in the second half of their sophomore year, followed by the Physical Measurements and Instrumentation (PMI) class. Although there are several students that do not follow this sequence of courses, a large number of students do. The reform efforts in the PMI class can however be beneficial to both groups of students. Students who have taken APL and MPL previously get an opportunity to relearn concepts that they had previously learned in these courses. Students who have not taken these courses before learn these concepts for the first time.

The PMI class covers basic concepts of analog and digital electronics such as transistors and amplifiers. Students use NI-ELVIS™, (National Instruments - Educational Laboratory Virtual Instrumentation Suite) to collect data from circuit measurements. They also use MultiSim™, a circuit simulation program to simulate circuits before they build them. During the first half of the semester students are also provided an introduction to LabVIEW™ programming and write simple programs using the software. In the second half of the semester, students use their concepts in electronics as well as their skills in measurement with NI ELVIS™ and LabVIEW™ programming to revisit automate in APL and MPL. In this chapter we will briefly introduce NI-ELVIS™ and LabVIEW™ programming. We will discuss why we choose them for our project and the advantages and disadvantages of using them.

Introduction to NI ELVIS™

NI ELVIS™ is a design and prototyping environment for university science and engineering laboratories. It uses [8] LabVIEW™-based software instruments, and a custom-designed workstation and prototyping board to provide the functionality of a suite of common laboratory instruments.

Along with using the NI ELVIS II™ (a new version of NI ELVIS™, which we refer to as NI ELVIS for simplicity), students also use NI ELVISmx in the computer, which is the software that supports NI ELVIS II™ Series Hardware. It provides the following LabVIEW™ soft front panels (SFPs):

- Arbitrary Waveform Generator (ARB)
- Bode Analyzer
- Digital Reader
- Digital Writer
- Digital Multimeter (DMM)
- Dynamic signal Analyzer (DSA)
- Function Generator (FGEN)
- Impedance Analyzer
- Oscilloscope (Scope)
- Two-Wire Current Voltage Analyzer
- Three-Wire Current Voltage Analyzer
- Variable Power Supplies

In addition to the SFP instruments, NI ELVIS™ has a set of high-level LabVIEW™ functions, which one can use to customize one's display and experiments, to control the NI ELVIS ™workstation using LabVIEW™.

Figure 3-1 Rear View of NI ELVIS II™ Workstation [9]

1	Prototyping Board Power Switch	4	USB Connector
2	Workstation Power Switch	5	Cable Tie Slot
3	AC/DC Power Supply Connector	6	Kensington Security Slot
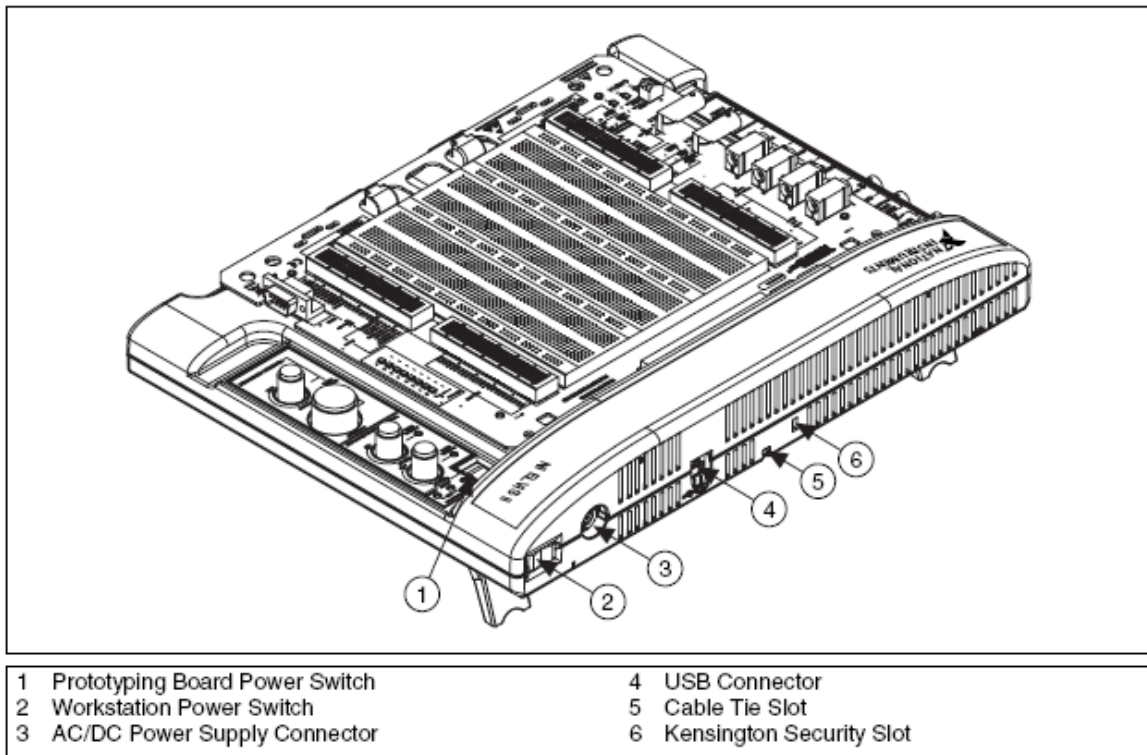
The picture above shows the NI ELVIS II ™ workstation. Due to the functionality of all the instruments described above, we find that NI ELVIS™ is very suitable for our students in PMI class to perform laboratory exercises which can show how electronics component properties can be measured, how to produce variable power supply, how one can utilize the NI ELVIS™ tools for AC circuits[10]. Circuits can be built on the protoboard and later measured with the NI ELVIS™ software suite of LabVIEW™ based SFPs. In addition, students can also perform those functions using NI ELVIS™ within a LabVIEW™ programming environment. The latter option provides students with a range of options, but it is considerably more difficult to use as it requires the understanding of LabVIEW™ programming. However the combination of NI ELVIS™ and LabVIEW™ provides our students the flexibility of first learning to use NI ELVIS™ for simple tasks with the pre-built SPFs and later, when they have learned LabVIEW™, use the NI ELVIS™ instruments as part a larger project.

Although NI ELVIS™ offers several advantages, such as connectivity with the computer to allow for seamless transfer of data into the computer as well as the ability to use its SPFs in a variety of non-traditional ways, there are also several limitations.

These limitations are mainly related to the range and resolution of the voltage output and input that instructors should also consider carefully. For instance, in the saturated absorption experiment, students are expected to use NI ELVIS™ to produce a triangular sweeping signal as a function generator does. To calibrate the signal to the highest possible accuracy, students need to limit the maximum voltage that the NI ELVIS™ can measure. The step size of digital to analog conversion by NI ELVIS™ must be such that it is much smaller than the smallest voltage difference between different peaks from the spectrum that we expect to measure. The DAQ card used in this experiment has 12 bit accuracy, so we can calculate the minimum voltages in this way. So the minimum step size of voltages in analog to digital conversion is given by

$$\text{Step Size in Analog to Digital Conversion} = \frac{\text{Maximum Voltage measured to NI ELVIS}}{2^{12}}$$

Based on this formula, if we set maximum voltage as 5V, the step size is around 0.001V which is adequate for these measurements in saturated absorption experiment. However, students are expected to check this while they are working on this experiment. If they use a higher maximum voltage for the NI ELVIS™, then the step size may be too large for accurate measurement of the peaks.

Another example is the speed of light experiment (we will give further explanation of it in the Chapter 4 and Appendix C). In that experiment, the time difference between two laser signals that students are asked to measure is around 100ns. Thus we would require at least 10ns definition of counting time from NI ELVIS™ which exceeds its capability. The sampling speed of the NI ELVIS™ is at best 10^8 samples/sec, which corresponds to a time resolution of barely 10ns, which in fact adequate for a good measurement. In fact, the traditional way of doing the experiment, which uses a digital oscilloscope works very well in this case.

In summary, even considering possible shortcomings of using NI-ELVIS™, we still insist that adopting NI-ELVIS™ for students to perform their electronic exercises is the best choice, because it affords several conveniences and learning opportunities described above. So in the

PMI class, students will use NI ELVIS™ and computer interfacing to automate experiments in Modern and Advanced Physics Lab.

Introduction to LabVIEW™ programming

LabVIEW™ is a graphical programming language that has been widely adopted throughout industry, academia, and government labs as the standard for data acquisition, instrument control software, and analysis software. [11] LabVIEW™ programs are called Virtual Instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeters. There are three main reasons why we believe that students must learn the knowledge and functionality of LabVIEW™ programming:

First, LabVIEW™ programming is a graphic language which is fun and more attractive to students than other text coded programming languages. It is also relatively easy to learn and master in a limited amount of time, compared to some other programming languages such as C++. In the PMI class, we use the training materials provided by National Instruments [12] and introduce basic concepts and simple applications of VIs in the LabVIEW™ environment. It also turns out that, as we expected, students show quite an interest in learning this new programming language.

Second, given that we are using NI ELVIS™, it is our best choice to adopt LabVIEW™ as the standard programming tools because the NI ELVISmx, the software that supports the NI ELVIS™ hardware, works in the LabVIEW™ environment. It is reasonable that because they are both product of National Instruments Corporation.

Third, there is a wide range of uses of LabVIEW™ in industry and in academia. Undergraduate students in the Physics Department usually go on to conduct further research or land jobs in engineering or industry. In both cases they may commonly need to use LabVIEW™. So in the PMI class, we provide students training in using LabVIEW™ and thus help them get prepared for a variety of future employment and careers.

Also there are some disadvantages of covering LabVIEW™ in PMI class. For example, LabVIEW™ is a product from National Instruments Company which updates itself very often. So it caused a little trouble when we decided to install LabVIEW™ onto all the computers that students were going to use, because the versions changed almost every semester. But this is just

a small shortcoming and cannot overwhelm the obvious advantages which teaching and learning LabVIEW™ offers.

CHAPTER 4 - CAPSTONE PROJECT MATERIAL

In this section we present write-ups for two capstone project experiments in the PMI class. These project write-ups were developed when we performed the experiments ourselves, so that we would be better prepared to guide the students when they worked on these capstone projects.

The materials described below are *not* provided to students, since the students have to figure out for themselves how to the complete the project. Rather, the students are provided with a sheet with some important goals for each capstone project and a list of questions that must be answered for the project that they choose to complete. These handouts are provided in the next chapter.

Capstone Project Write-Up: Saturated Absorption

Introduction

The objective of this experiment is to review the Saturated Absorption Spectroscopy currently used in Advanced Physics Laboratory and to create a capstone project based on it. The goal of high resolution spectroscopy is to measure narrow features in atomic spectra with high accuracy. Unfortunately, there are many sources of broadening (Doppler effect, pressure, Zeeman/ Stark effect, self-absorption) in atomic spectra which prevent high resolution measurements in all but the most sensitive spectrometers. In the Saturated Absorption Spectroscopy Lab, we explore a common technique to circumvent Doppler free spectra and the ability to easily measure hyperfine structure. As a capstone project, we plan to let the students review the experiment first, and then, instead of using the oscilloscope and function generator, connect a DAQ card to the computer, write a LabVIEW™ program, automates the whole experiment and finish it.

Review of Saturated Absorption

When a beam of photons is passed through a vapor, photons whose energy matches transition energies from the ground state to excited states in the atoms or the vapor will be resonantly scattered. This means they are removed from the beam, but appear at other angles. By measuring the apparent absorption in the beam as a function of photon energy, one can thus map out excited level structures of the absorbing vapor atoms. In this experiment, students will use the absorption of light from a variable frequency, and tunable, laser by Rb to explore the level structure of Rubidium. The energy level scheme for Rb is shown below.

Figure 4-1 Rubidium energy level scheme (Reproduced from Figure 1 of Ref. 13)
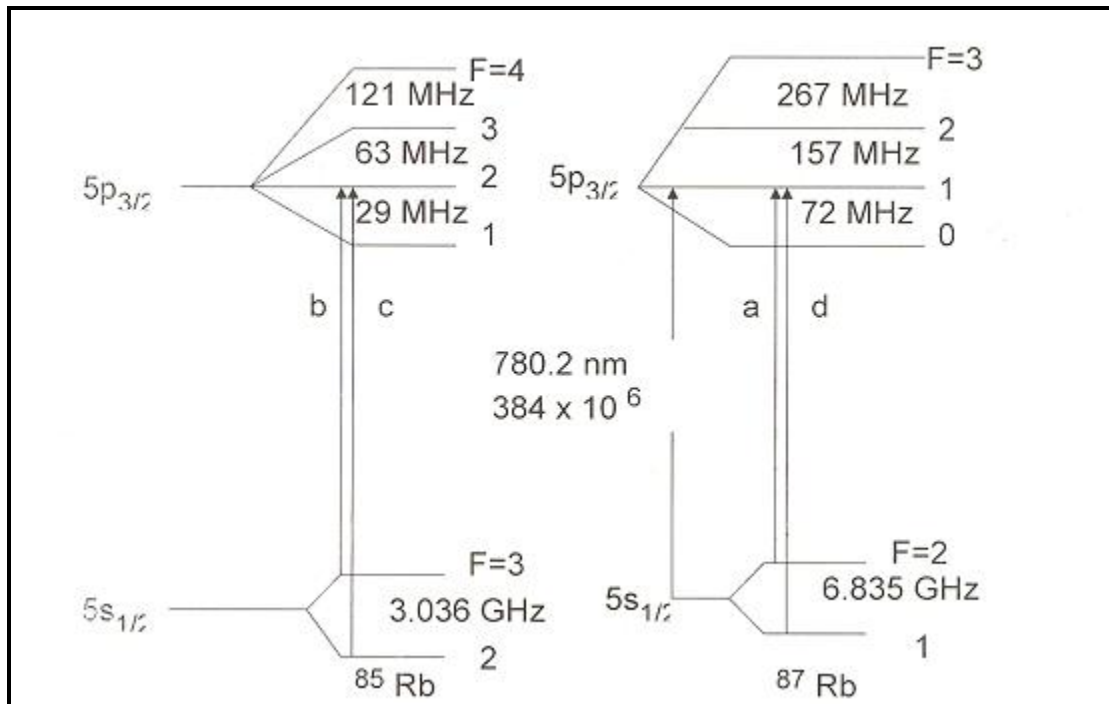
Figure 4-2 Absorption spectrum of Rubidium (Reproduced from figure 2 of Ref. 13)
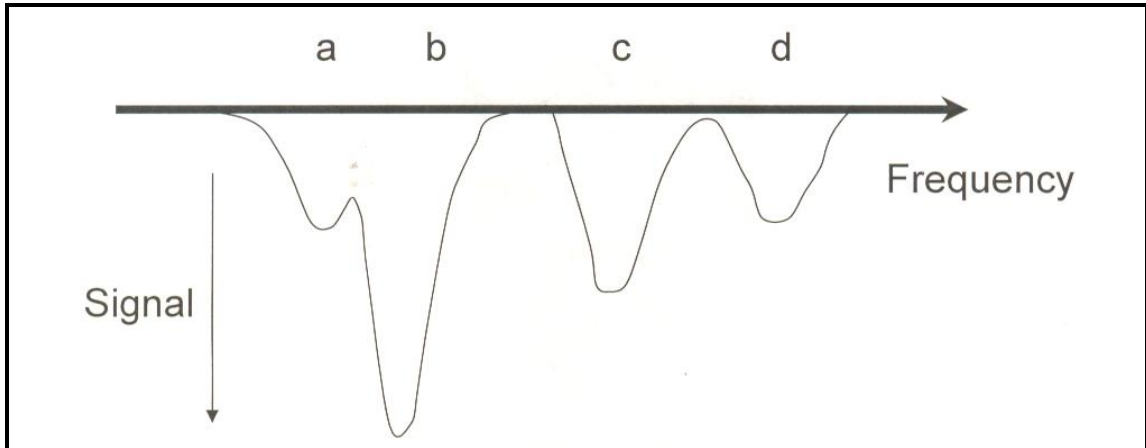
We see that an absorption signal is shown above and the four peaks correspond to the transitions indicated on the schematic diagram. These absorption lines are broad and overlap due to the Doppler effect. At room temperature, atoms of Rb will have thermal motion with speed in all the directions. Due to the Doppler Effect, the laser frequency will be different for those atoms with different speeds. So it gives a broad curve.

Then we observed saturated absorption in a vapor containing ^{85}Rb and ^{87}Rb. Making use of a variable frequency laser tuned to the transition between the $S_{1/2}$ and $P_{3/2}$ states of rubidium, we calibrated the frequency vs. voltage dependence of the laser with a Michelson interferometer. Then we used the calibration result to measure the hyperfine splitting of the ground and excited states of rubidium.

Theory

There are several mechanisms by which the degenerated energy levels of an atom can be split. Hyperfine splitting of atomic energy levels is one of them. [14] It is caused by hyperfine coupling, the weak magnetic interaction between electrons and nuclei. The total electron angular momentum $\vec{J} = \vec{L} + \vec{S}$ and the nuclear spin $\vec{I}$ get coupled $\vec{F} = \vec{J} + \vec{I}$. For ^{85}Rb, the nucleus has spin I=5/2, while the ^{87}Rb nucleus has spin I=3/2. For the $S_{1/2}$ and $P_{1/2}$ state, only two hyperfine splittings will result, while state $P_{3/2}$ will split into four levels (you can see the energy level splitting in the level scheme of Rb, Figure.4-1)

For a laser beam passing through a vapor of rubidium atoms, absorption will occur at the frequencies of transition between the ground states and each of the excited states. We use a pump beam passing through the vapor cell so that the pump and probe beams cross nearly anti-parallel. Using this method, we conveniently solve the Doppler broadening problem and make the hyperfine splitting observable both on the ground state and excited state.

Experiment

Figure 4-3 Saturated Absorption experimental set up (Reproduced from Figure 3 of Ref. 13)
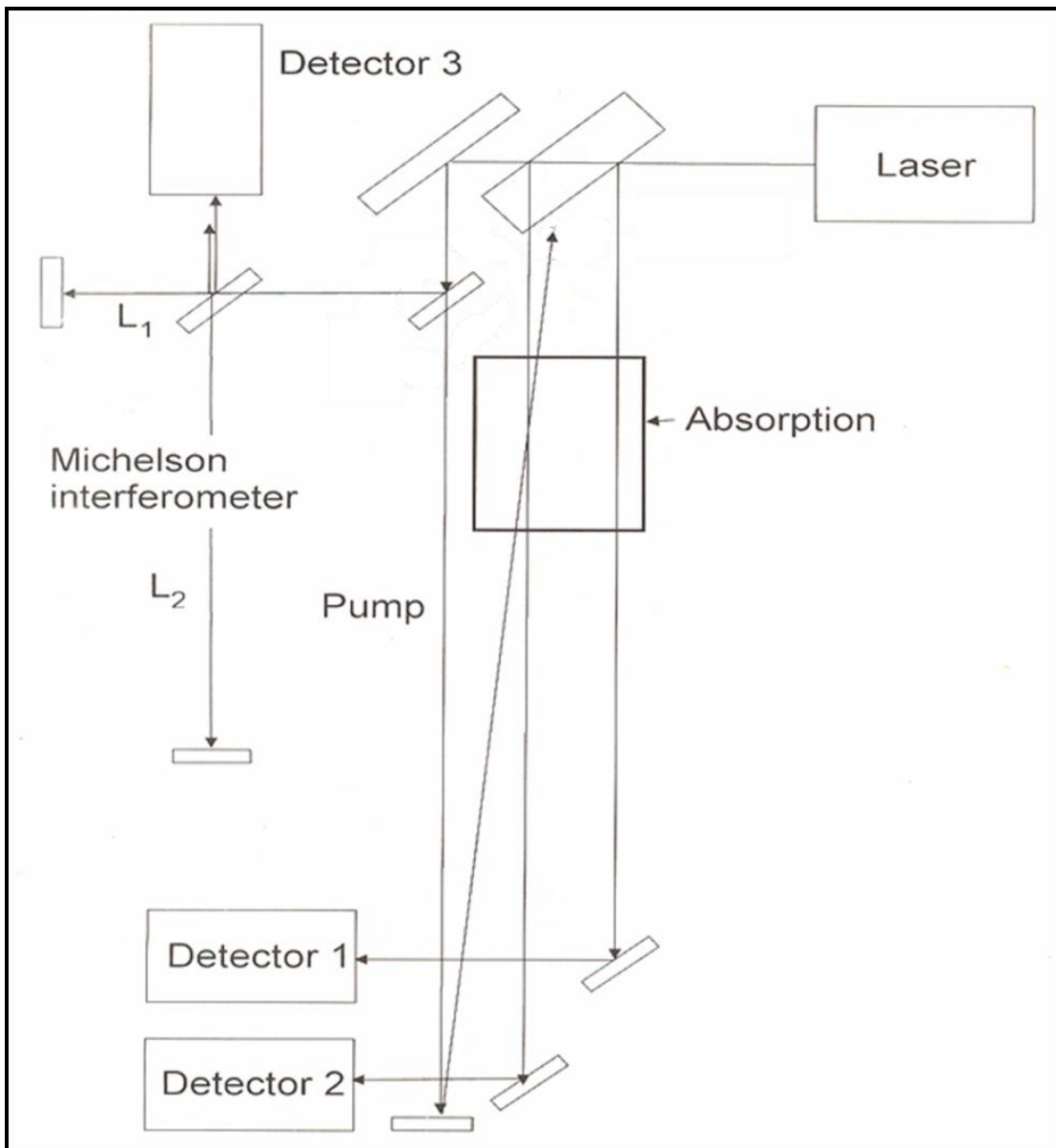
The experimental setup is shown above. A laser, with variable frequency controlled by the position of a diffraction grating, was split into two weak probe beams and a stronger pump beam. Part of the pump beam was further split into a Michelson interferometer. A photodiode was used to measure the intensity of the interference pattern from the interferometer. Two additional photodiodes were used to measure the intensity of the probe beams after traversing a rubidium vapor cell. Using a card, we traced the laser beams through the schematic shown above. If the beams did not follow the schematic, we adjusted the mirror so that they did.

The photodiode signals were amplified and fed to an oscilloscope.[13] Then we set the oscilloscope in YT mode at a slow sweep speed. We set the function generator to create a triangular wave with a frequency of about 3Hz, and checked to ensure that the output was connected to the "laser frequency "input of the laser controller. The voltage from the function generator, added to the voltage set on the controller box, determined the angle of the grating inside the laser which in turn determined the frequency of the laser light. Scanning this voltage scans the frequency. We thus set the function generator to scan the maximum range (0-10V) in a triangular waveform and adjusted the gains and offsets of the amplifiers so that we obtained a signal from the photo detectors. We adjusted the DC offset and/or the voltage setting on the laser control box until we found absorption features, as shown in the previous figure.

Calibration

Figure 4-4 Screen Capture from the oscilloscope for the calibration
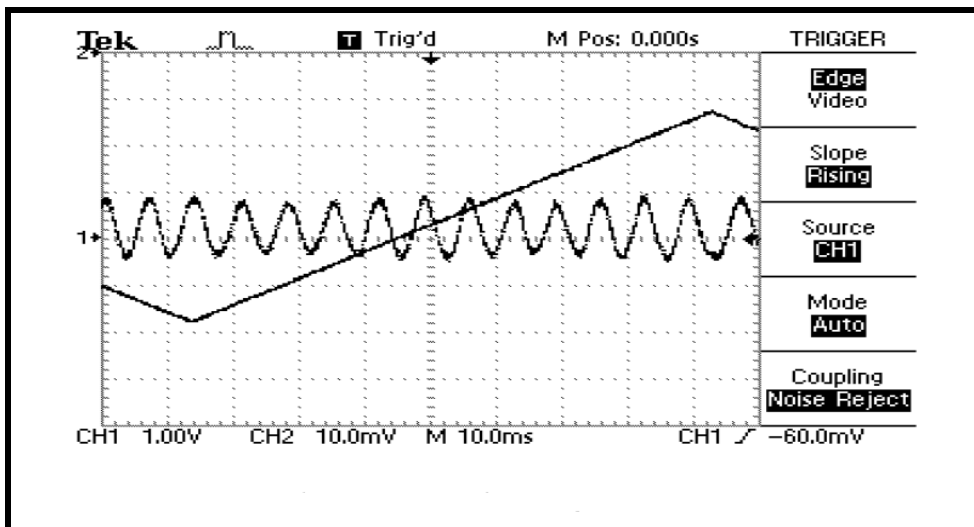
To calibrate the relationship between the laser frequency and the applied voltage, we used a Michelson Interferometer setup, seen on the left hand side of the schematic diagram of the apparatus setup.[13] We pass the signal from Detectors 3 through one channel of the amplifier and adjusted the mirrors of the Michelson Interferometer so that both beams hit the center hole on Detector 3 and the two beams were parallel to each other. We sought a signal from each arm of the interferometer. When both signals were present, we could see the interference oscillations as the wavelength was swept as shown in the figure above. Below, we explain this interference phenomenon in further detail and derive the formula to use for frequency calibration in the following paragraph.

Using the Michelson interferometer, we first calibrated our apparatus. Different applied voltages to the piezo-electric motor in the laser controller resulted in different frequencies. In order to determine the frequency difference between two transitions, we require a calibration factor to convert our voltage measurements into frequency. The optical path length difference between the two arms of the interferometer is $n\Delta L = 2n(L_2 - L_1)$. By changing the frequency and holding ΔL constant, the optical path length difference between two arms changes, and minima /maxima are scanned across the face of the diode detector. Maxima occur when the phase difference is a multiple of 2π. The frequency difference between two adjacent maxima is given by $c/\Delta L$. From this, we can derive the formula that we use for calibration as shown below. Here, ΔV is the voltage difference, n is the number of maxima, and c is the speed of light. In our case, ΔV=0.12Volts, n=3, c=3×10^8m/s, L_2=35.3cm, L_1 =1.3cm. We now apply the formula:

$$\frac{\Delta f}{\Delta V} = \frac{c/2n(L_2 - L_1)}{\Delta V}$$, and find that $\Delta f/\Delta V$=1.39GHz/V. This is the calibration constant.

Now we perform an error analysis on this calculation. We start with the relationship,

$$\delta\left(\frac{\Delta f}{\Delta V}\right) = \frac{c}{2(L_2 - L_1)^2}\delta L$$. In our case, the measurement uncertainty in both lengths is about 0.1 cm, so δL_2= δL_1=0.1 cm; Then δ (L_2-L_1) = 0.14 cm due to the formula $\delta L = \sqrt{(\delta L_1)^2 + (\delta L_2)^2}$ [15] Thus we get: δf= =5.445MHz We also know the voltage error from reading the voltage

difference on the oscilloscope δV=0.02V, then use the equation $\frac{\delta q}{q} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2}$ when $q = \frac{x}{y}$

and calculate the error for the calibration, which is 0.24GHz/V.

So the final calibration should be written as $\Delta f/\Delta V$=13.9$\pm$0.24GHz/V. This calibration process should be completed carefully by the students, because they have to use this value in future measurements.

Ground State Splitting

Next, we observed the hyperfine splitting of the rubidium ground states. For transitions between the $S_{1/2}$ and $P_{3/2}$ states, the hyperfine splitting of $S_{1/2}$ yields 2 transitions for each isotope of rubidium. For ^{87}Rb , the transitions are label A and D in our figure. A corresponds to a transition from the J=1/2, F=2, to J=3/2, F', while D corresponds to a transition from F=1 to F'. For ^{85}Rb , the transitions are label B and C in the figure below corresponds to a transition from the J=1/2, F=3, to J=3/2, F', while C corresponds to a transition from F=2 to F'. We set the function generator voltages to obtain a spectrum in Detector 2, similar to the one seen in Figure 4-2. This is what the students were expected to observe using the oscilloscope.

Figure 4-5 Ground state splitting
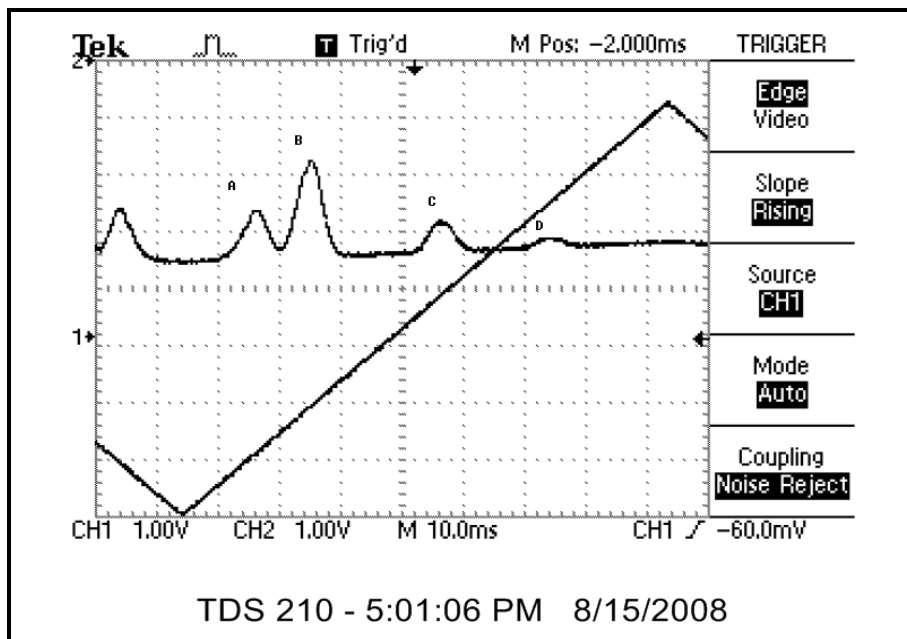
The above figure shows four peaks corresponding to the energy splittings of the ground states of both isotopes of Rb. According to the spectrum that we recorded, the energy differences between each peak are in the table below.

Table 4-1 Voltage and frequency differences for ground state splitting

Peaks	Energy Difference	Frequency Difference
B – C	0.22 $\pm$0.002V	2.78$\pm$0.054GHz
A – D	0.43$\pm$0.002V	5.977$\pm$0.107GHz

Comparing this to the accepted values of 6.385GHz[12] (A-D) and 3.036 GHz (B-C), we have discrepancies of 11.7% and 8.4% respectively.

Hyperfine Splitting P 3/2 Excited States

In order to watch the hyperfine splittings on P3/2 excited states, first we block the pump beam, let the oscilloscope show the subtracted signal from two probe beams, and make sure the two probe beams perfectly cancel each other, which means that we are supposed to observe the signal as a horizontal line on the oscilloscope. Then, we unblock the pump beam, adjust the laser DC control voltage and play with the wave function amplitude and offset to focus on a single transition (A,B,C,or D). Then we can observe the subtracted spectrum from both photodiodes on the oscilloscope. Unfortunately, not all the hyperfine splittings can be clearly observed and measured, so some peaks are visually approximated. The spectrum we recorded is shown below.

Peak A

The splitting for Peak A is shown below.

Figure 4-6 Hyperfine splitting for peak A
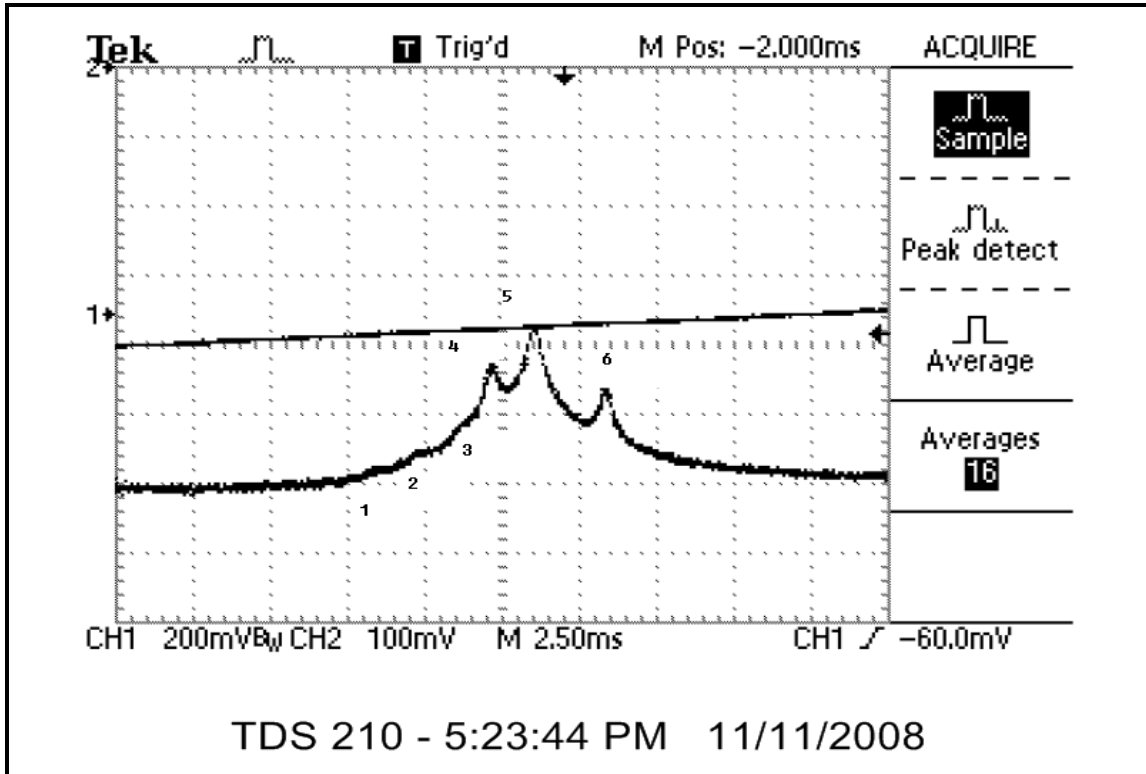
We calculated the corresponding frequency and energy difference shown in the table below Notice: The expected values of frequency for each peak are from Lab manual of Advanced Physics Lab course [12].

Table 4-2 Frequencies and voltage differences for hyperfine splittings of Peak A

$f_n - f_m$	ΔV (Volts)	Δf (MHz)	Δf (MHz) Expected
$f_6 - f_1$	0.0035 ± 0.0004	486.5 ± 52.3	424.0
$f_6 - f_2$	0.0028 ± 0.0004	389.2 ± 57.7	345.5
$f_6 - f_3$	0.0020 ± 0.0004	278.0 ± 60.3	267.0
$f_6 - f_4$	0.0016 ± 0.0004	222.4 ± 59.1	212.0
$f_6 - f_5$	0.0012 ± 0.0004	166.8 ± 55.6	133.5

We can see that errors of frequency are quite large, mainly from the large errors of measuring voltage differences.

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Peak B

We do the same thing to Peak B, C, and D. The peaks 1,2, and 3 are difficult to identify, so we just visually approximated them. The hyperfine splittings for Peak B are shown the figure below

Figure 4-7 Hyperfine splitting for peak B
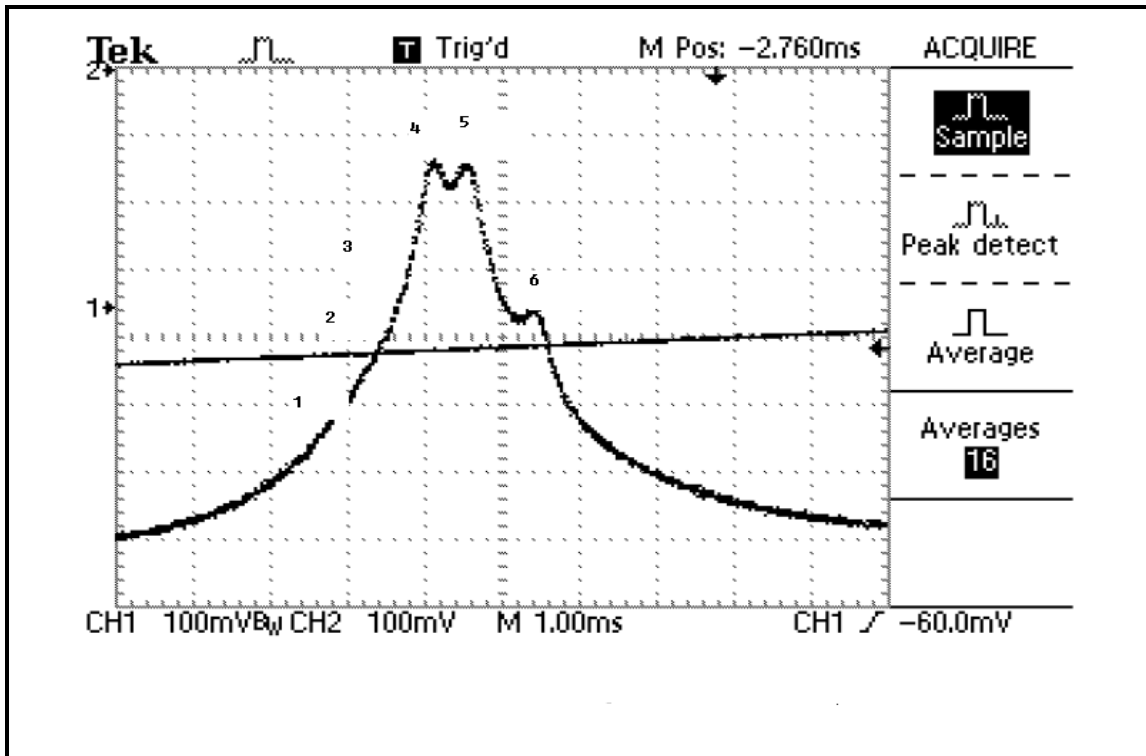
The corresponding frequency and energy differences are shown in the table below.

Table 4-3 Frequencies and energy differences for hyperfine splittings of Peak B

$f_n - f_m$	ΔV (Volts)	Δf (MHz)	Δf (MHz) Expected
$f_6 - f_1$	--	--	184.0
$f_6 - f_2$	--	--	152.5
$f_6 - f_3$	--	--	121.0
$f_6 - f_4$	0.0009 ± 0.0004	125.1 ± 53.7	92.0
$f_6 - f_5$	0.0006 ± 0.0004	83.4 ± 55.6	60.5

Peak C

For transition 3 only a single peak is seen, so the hyperfine structure of the F=2 to F' transition in Rb 85 could not be analyzed. The splittings are shown below.

Figure 4-8 Hyperfine splitting for peak C
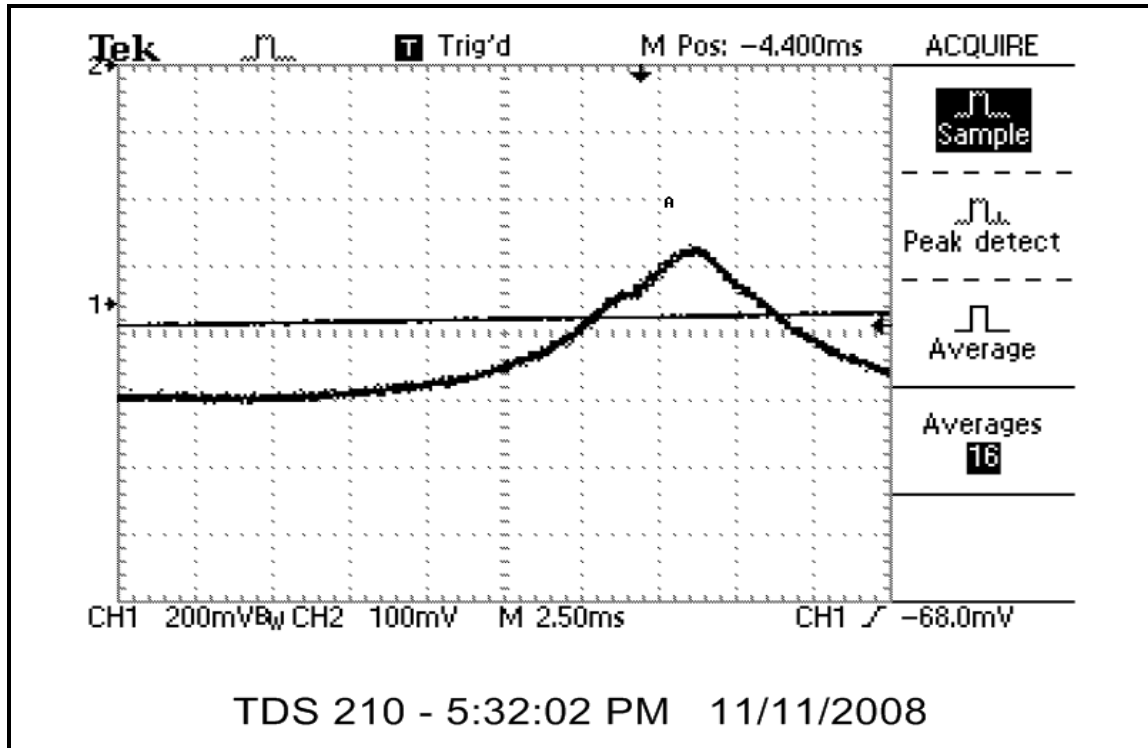
Peak D

For peak D, we could see that around peak 2 and 3, there may be another small one.

Figure 4-9 Hyperfine splitting for peak D
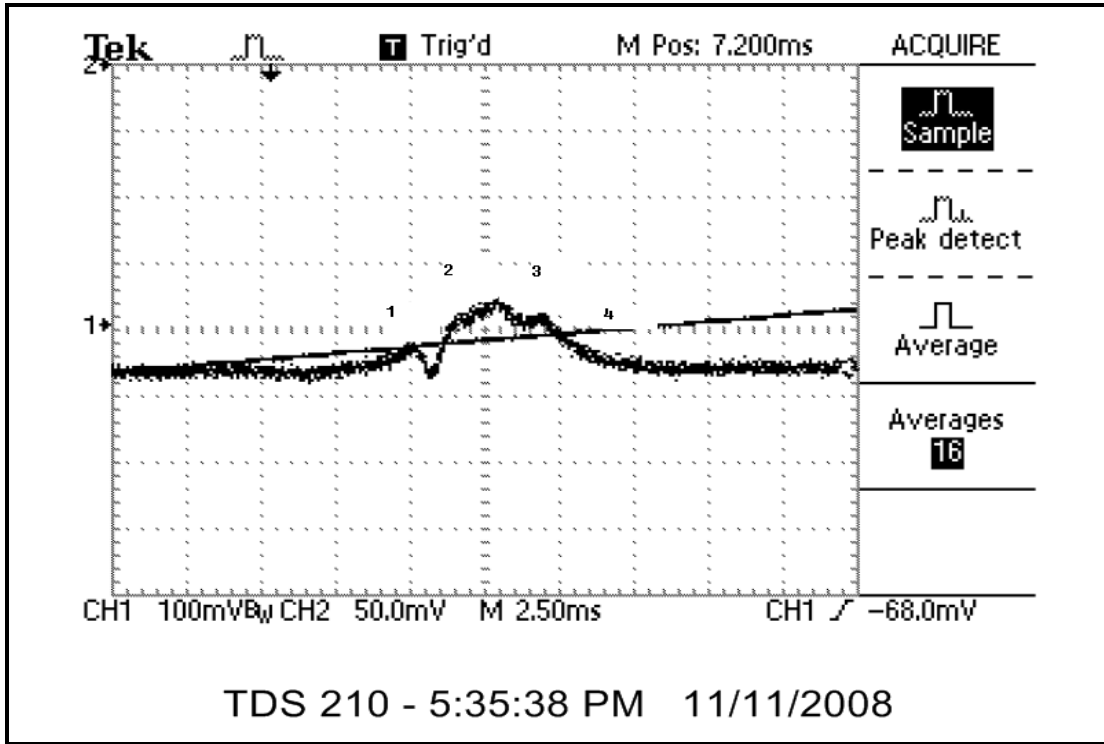
From the figure above, we calculated the voltage difference, and then compared them to the expected ones as shown in the table below

Table 4-4 Frequencies and energy differences for hyperfine splittings of Peak D

$f_n - f_m$	ΔV (Volts)	Δf (MHz)	Δf (MHz) Expected
$f_2 - f_1$	0.0006 ± 0.0004	83.4 ± 55.6	72.0
$f_3 - f_1$	0.0010 ± 0.0004	139.0 ± 55.8	150.5
$f_4 - f_1$	0.0016 ± 0.0004	222.4 ± 56.0	229.0

Saturated Absorption Using LabVIEW™

     In this PMI capstone project, we used the DAQ card output to generate the ramp that scans the laser frequency and to record both photo detector outputs. We wrote a LabVIEW™ program using the NI ELVIS™ to control the experiment and to record the data, obviating the oscilloscope and function generator completely. A part of the LabVIEW™ program (block diagram) is shown below.

Figure 4-10 Block diagram of the LabVIEW™ program used in Saturated Absorption
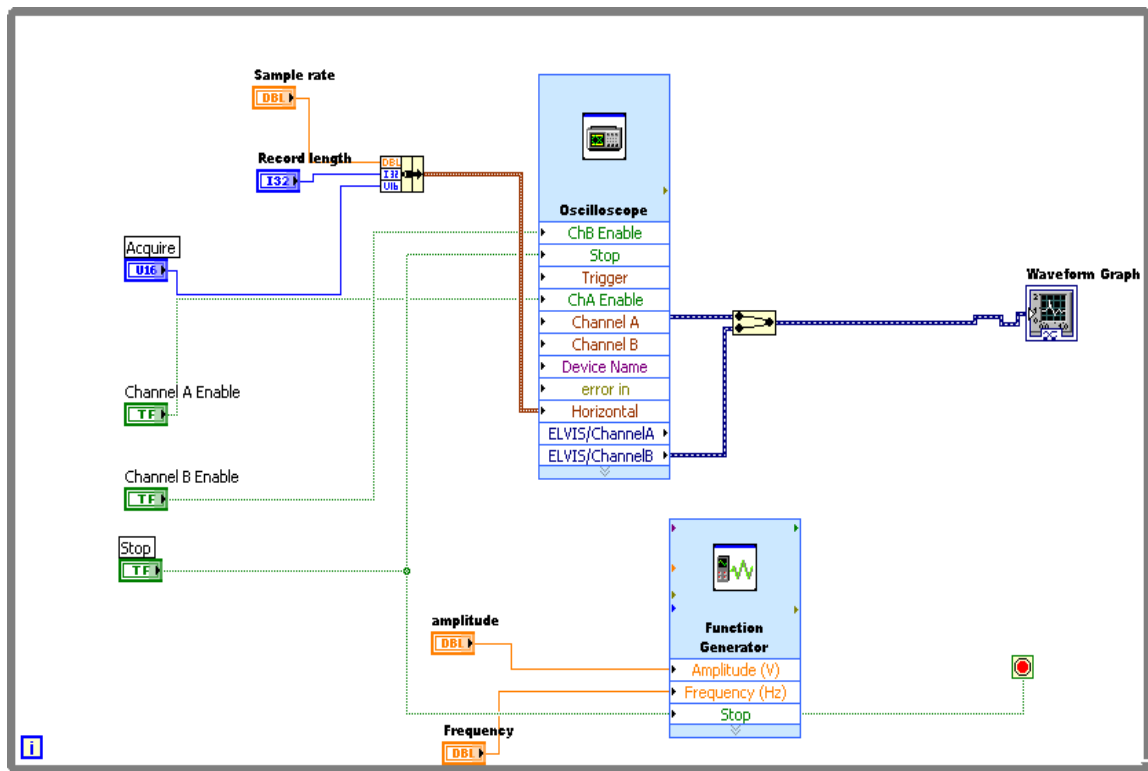
     From this, we can see that we run the oscilloscope and function generator at the same time. The data that we recorded from the front panel of the LabVIEW™ program are discussed below.

Ground State Splitting

     We obtained the two figures below. Each one is capable of being used to calculate the energy difference between each peak.

Figure 4-11 Waveform showing the ground state splitting in LabVIEW™
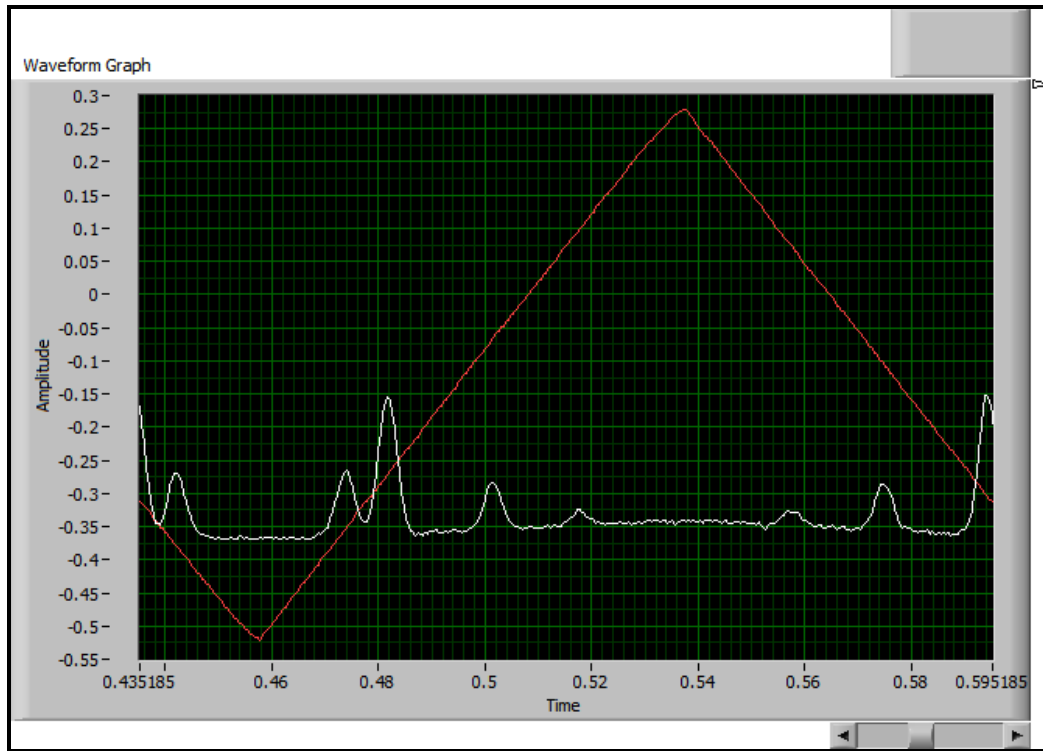
Figure 4-12 Another waveform showing the ground state splitting in LabVIEW™
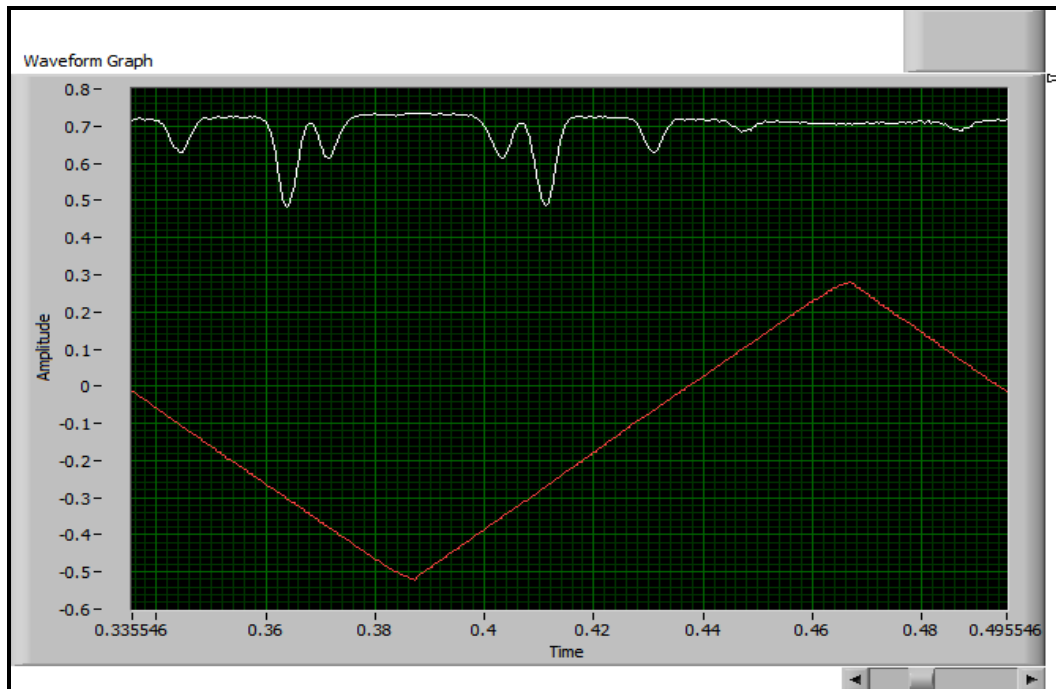
The energy and frequency differences calculated from these peaks are shown in the table below. Notice that due to the damage of the Michelson Interferometer when we were using the NI ELVIS™ and LabVIEW™, we directly use the calibration results of previous experiment.

Table 4-5 Energy and frequency differences for ground state splitting

Peaks	Energy Difference	Frequency Difference
A – B	0.077±0.001V	1.077±0.019GHz
B – C	0.235 ±0.001V	3.267±0.034GHz
C – D	0.154±0.001V	2.141±0.033GHz
A – D	0.467±0.001V	6.491±0.067GHz

There is a 2.0% discrepancy from expected value[12]. Comparing this result with the one from oscilloscope, it is better. But we think this closer result may just come from better alignment of laser or calibration error. The systematic error of energy difference is also a little smaller.

Hyperfine Splitting P$_{3/2}$ Excited States

We obtained the following hyperfine splitting for each of the peaks: A, B, C and D.

Peak A

For Peak A, we obtained the splitting shown in the figure below.

Figure 4-13 Hyperfine splitting for peak A
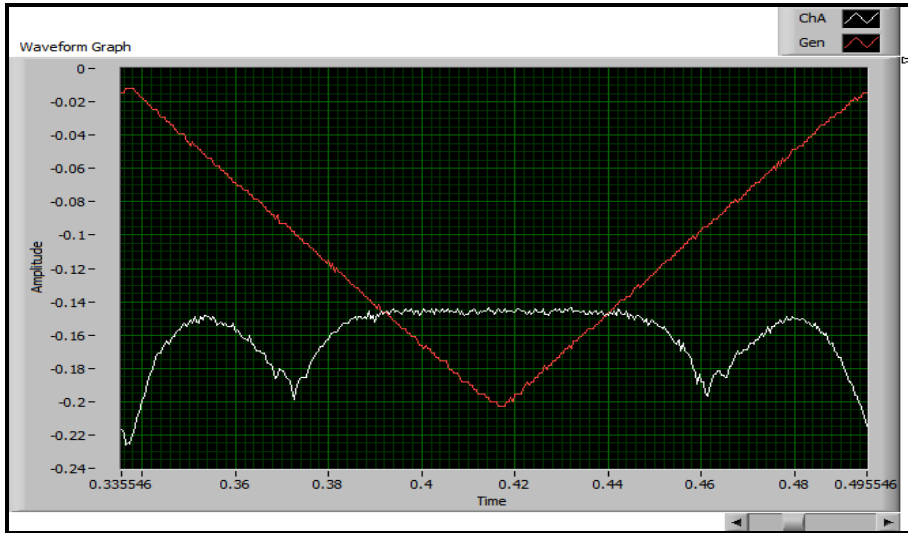
We calculated the corresponding frequency and energy difference shown in the table below.

Table 4-6 Frequencies and energy differences for hyperfine splittings of Peak A

$f_n - f_m$	ΔV (Volts)	Δf (MHz)	Δf (MHz) Expected
$f_6 - f_1$	0.0040±0.001	556.5±133.3	424.0
$f_6 - f_2$	0.0037±0.001	514.2±212.4	345.5
$f_6 - f_3$	0.0035±0.001	486.5±209.6	267.0
$f_6 - f_4$	0.0026±0.001	361.4±168.4	212.0
$f_6 - f_5$	0.0020±0.001	277.8±140.5	133.5

The large error comes from that we cannot easily recognize the exact position of each peak due to limited resolution of NI ELVIS output voltage.

Peak B

For Peak B, we obtained the splittings shown in the figure below.

Figure 4-14 Hyperfine splitting for peak B
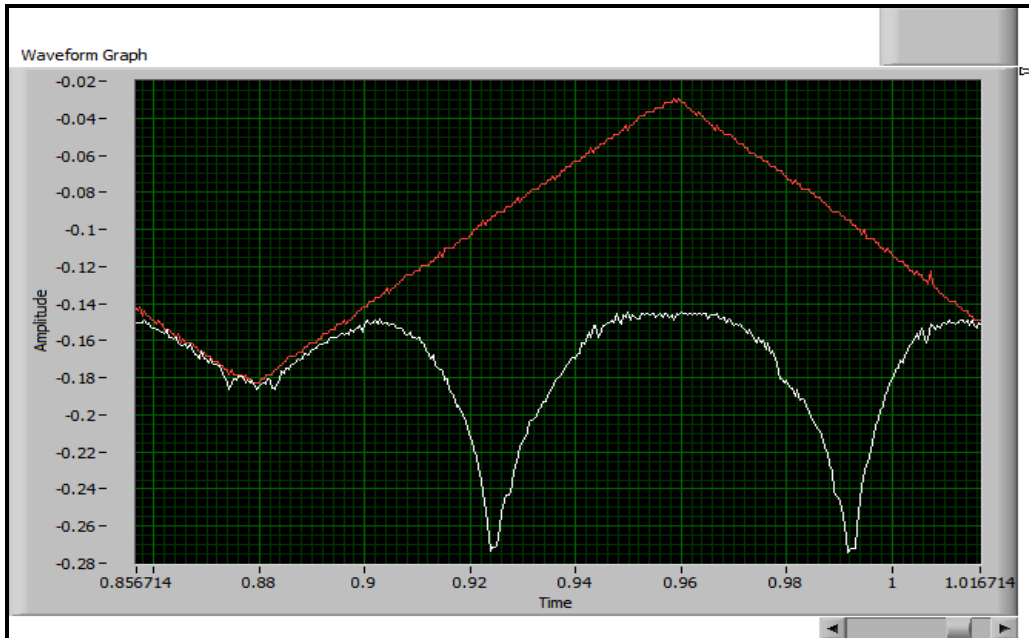
Since the voltage difference between those peaks (which we cannot recognize them clearly) are nearly only 0.002 V, and our minimum voltage step produced by NI ELVIS is 0.001V, we will not table the voltage and corresponding difference between each peaks due to large error. And it is the same situation for Peak C and Peak D. we will only paste all the graphs which we observed in the LabVIEW front panel.

Peak C

For Peak C, we obtained the splittings shown in the figure below. We could barely see the splittings on this peak and it was not sufficient for measurement and calculation.

Figure 4-15 Hyperfine splitting for peak C are barely visible
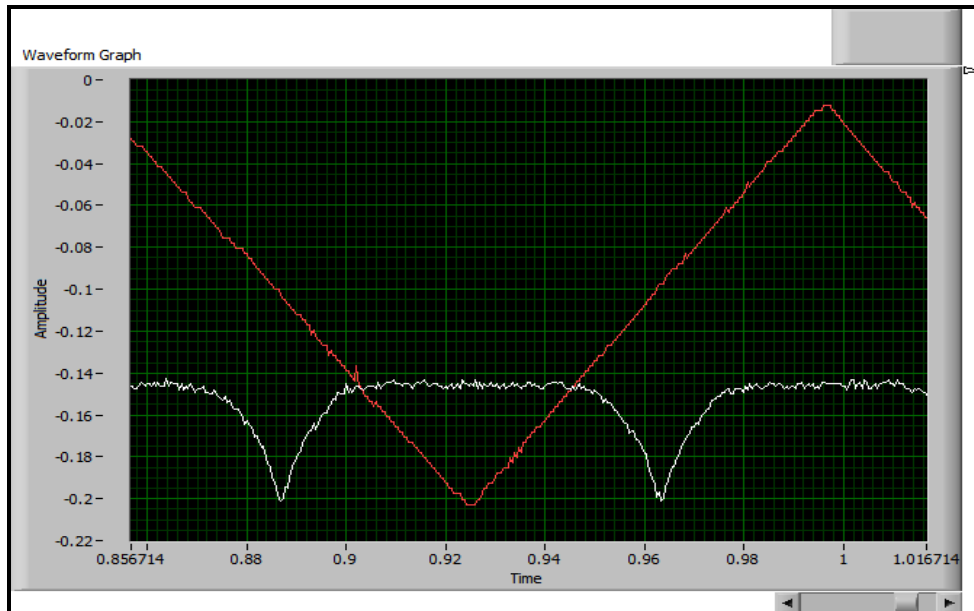
Peak D

The signal amplitude of this peak is really small comparing to the noise. So we turn the signal to 100 times bigger, rather than 10 times that we used to the first three peaks. The obtained hyperfine splittings for Peak D are shown in the figure below

Figure 4-16 Hyperfine splitting for peak D after magnification by a factor of 100, as opposed to 10 for the previous splittings
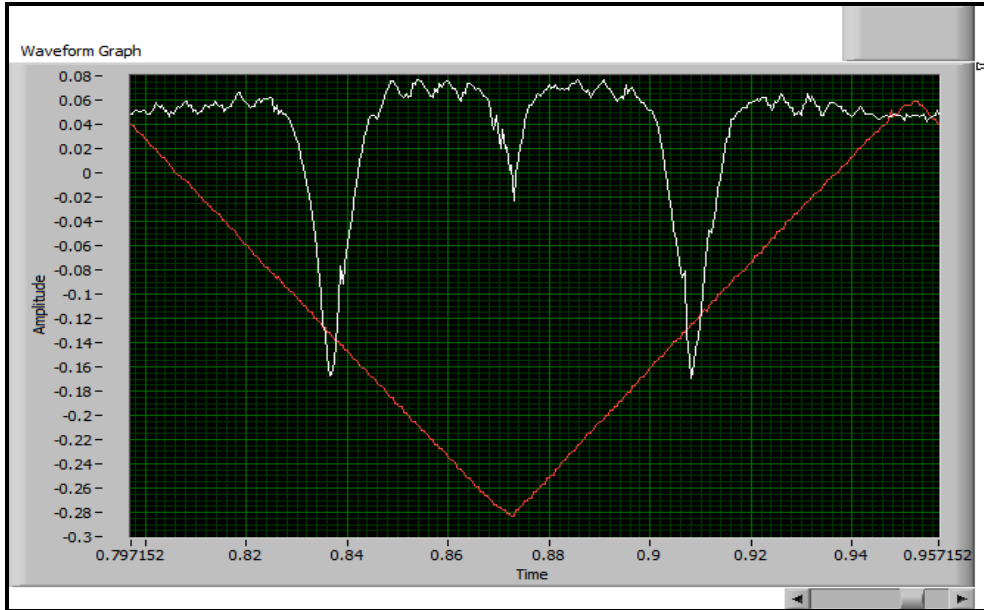
Saturated Absorption: Conclusions

We were able to successfully complete the Saturated Absorption Spectroscopy experiment and also a capstone project based on it that utilized a LabVIEW™ interface to control and collect data. The result returned from the LabVIEW™ front panel are fairly good for measuring ground state splitting, whereas its limited resolution stopped us from measuring the excited splitting. Please see the table below for a direct comparison between the frequency difference of ground state splitting from the oscilloscope and LabVIEW™.

Table 4-7 Comparison of ground state splitting frequency difference

Peaks	Frequency Difference(oscilloscope)	Frequency Difference(LabVIEW)
A – B	1.112±0.037GHz	1.077±0.019GHz
B – C	2.78±0.054GHz	3.267±0.034GHz
C – D	2.085±0.045GHz	2.141±0.033GHz
A – D	5.977±0.107GHz	6.491±0.067GHz

After we compare those results, we find that there has been no apparent improvement from our automated experiments. And if we take another table of frequency difference of excited state of $P_{3/2}$ of Rb:

Table 4-8 Comparison of ground excited splitting frequency difference

$f_n - f_m$	Δf (MHz)(LabVIEW)	Δf(MHz)(Oscilloscope)	Δf (MHz)Expected
$f_6 - f_1$	556.5 ± 133.3	486.5 ± 52.3	424.0
$f_6 - f_2$	514.2 ± 212.4	389.2 ± 57.7	345.5
$f_6 - f_3$	486.5 ± 209.6	278.0 ± 60.3	267.0
$f_6 - f_4$	361.4 ± 168.4	222.4 ± 59.1	212.0
$f_6 - f_5$	277.8 ± 140.5	166.8 ± 55.6	133.5

We find that LabVIEW™ turns out to give much larger error that the oscilloscope does. That can be understood in this way: the error mainly comes from voltage differences that we read from the measurement, because the fractional uncertainties of voltage differences are way larger than that of calibration[14]; and fractional uncertainties of voltage differences from NI ELVIS™ are much larger than it from real function generator and oscilloscope. We can also see the limitation of NI ELVIS™ in the experiment of Speed of Light discussed later.

And we also want to pay attention to the experience of applying electronics and computer interface that students can gain through this process. The assessment of the capstone project will be the main point of our future work.

Capstone Project Write-Up: The Frank-Hertz Experiment

Introduction

This experiment demonstrates the quantization of energy levels of isolated atoms. Electrons are emitted from a hot filament of a vacuum tube and accelerated across a gap to the anode in the presence of a fill gas. They then go through a short deceleration region and are collected on the collector of the tube. The current through the tube is measured. When the acceleration voltage gives the electrons energy sufficient to excite the first excited state of the fill atoms, the electrons may lose a quantum of energy in the collision, thereby losing enough energy that they can no longer reach the anode. Thus a dip in the observed tube current will occur. As

the acceleration voltage is raised further, the electrons may lose two or three quanta of energy at voltages corresponding to multiples of the excitation energy.

Thus a plot of tube current versus acceleration voltage displays regular dips. From this plot the excitation energy of the atomic energy level of the fill gas can be calculated. The capstone project that we create on this experiment is a straightforward one. We use NI ELVIS™ and LabVIEW™ programming to record and analyze data. Basically, we use LabVIEW™ instead of a real oscilloscope.

Review of the Franck-Hertz Experiment

One can demonstrate the 1926 Nobel Prize Winning Franck-Hertz Experiment with this alternate method that uses a neon-filled tube. The concepts of quantum theory are verified as several well-defined minima that can be observed on your oscilloscope screen, as the electrode current produced by the control unit excites the neon resonance line

Experimental Set Up

The apparatus consists of a neon-filled Franck-Hertz tube, a control unit with power supplies, reverse voltage source and DC preamplifier; and a shielded cable with BNC connectors. The DC amplifier included in the control unit consists of two cascaded operational amplifiers, the first of which is connected as an electrometer amplifier. The current to be measured is applied to the non-inverting input. The input impedance is 680 KΩ. The gain can be adjusted with a variable negative feedback resistance. The subsequent second operational amplifier further amplifier the signal and inverts it. The output display voltage is proportional to the measured current. A voltage of one volt output corresponds to an input current of 0.7A in the minimum sensitivity setting and to an input current of 7 nA in the maximum sensitivity setting. Connections to the operating unit and the voltage source must be made as shown in the figure below.

Figure 4-17 Frank Hertz experiment set up
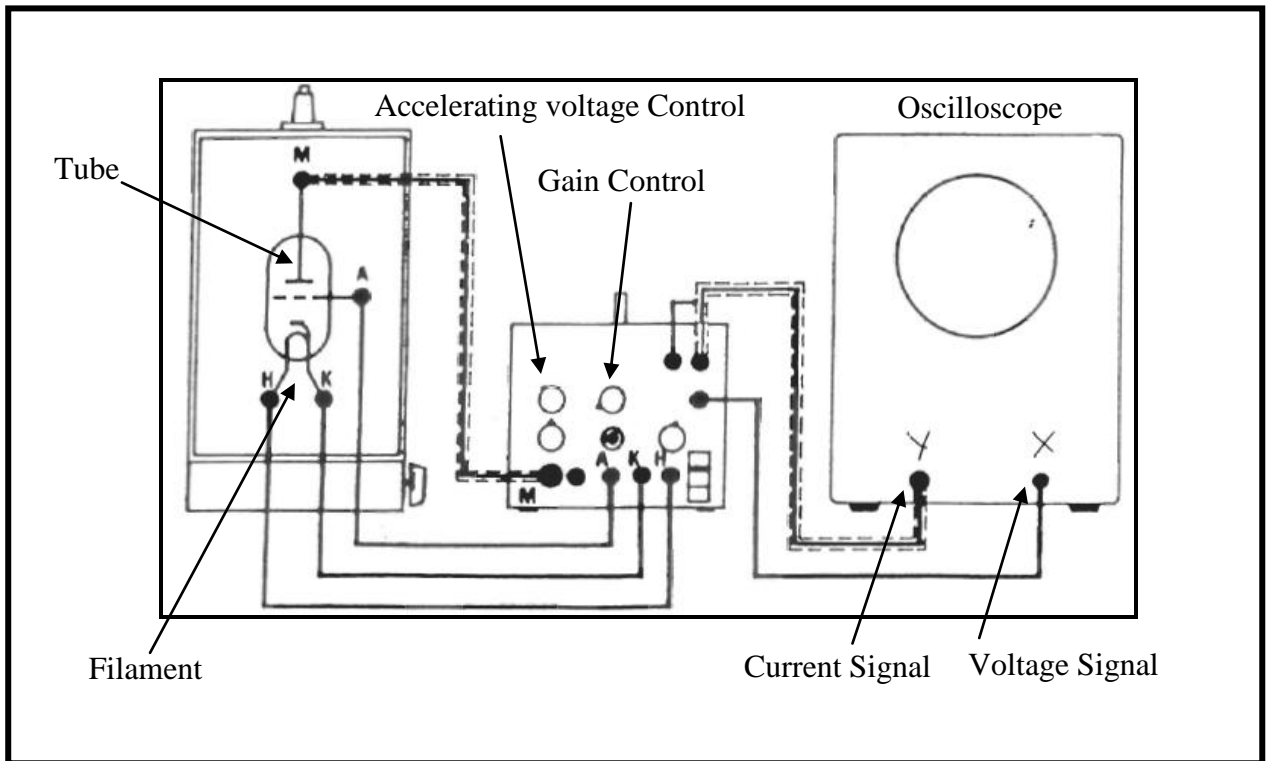
Procedure

The basic steps for setting up the experiment are as follows:

1. Connect the oscilloscope:

    a.) From (V+) to Channel 1(Y-Deflection);

    b.) from U_b /10 to Channel 2 (X-Deflection);

    c.) From ground (V-) to ground of Channel 1.

2. Set switch U_b to position O

3. Slowly increase the saw tooth voltage amplitude with the control knob U_b .

The indirectly heated cathode requires a warm-up time of about 90 seconds after you switch on the operating units. Slowly increase the accelerating voltage (starting from 0 volts to 70 volts), while reducing the "gain" setting, to keep the output reading within the meter range. A current on the order of 10 nA then flows from the collector electrode to the anode. Amplification gain or current sensitivity should then be set to suitable levels.

Experimental Results and Discussion

The data recorded directly from the multimeter is shown in the table below and is plotted in the figure that follows. The uncertainties of both the Franck-Hertz experiment output (proportional to the current through the diode) and applied voltage (Accelerating Voltage) are 0.01V.

Table 4-9 Data from Frank-Hertz experiment

The Franck-Hertz Experiment Output (Volts)	Applied Voltage /10 (Volts)
0.03	1.15
0.17	1.50
0.27	1.84
0.31	2.21
0.24	2.36
0.19	2.44
0.09	2.58
0.05	2.65
0.03	2.78
0.19	3.02
0.39	3.28
0.85	3.95
0.76	4.18
0.56	4.36
0.49	4.72
0.76	4.99
1.23	5.31
1.47	5.52
1.77	5.87
1.63	6.31
1.62	6.63

The Franck-Hertz Experiment Output (Volts)	Applied Voltage /10 (Volts)
1.81	6.96
2.24	7.39
2.59	7.87
2.74	8.15
2.88	8.53
3.19	8.96

Figure 4-18 Plot of the Franck-Hertz experiment data
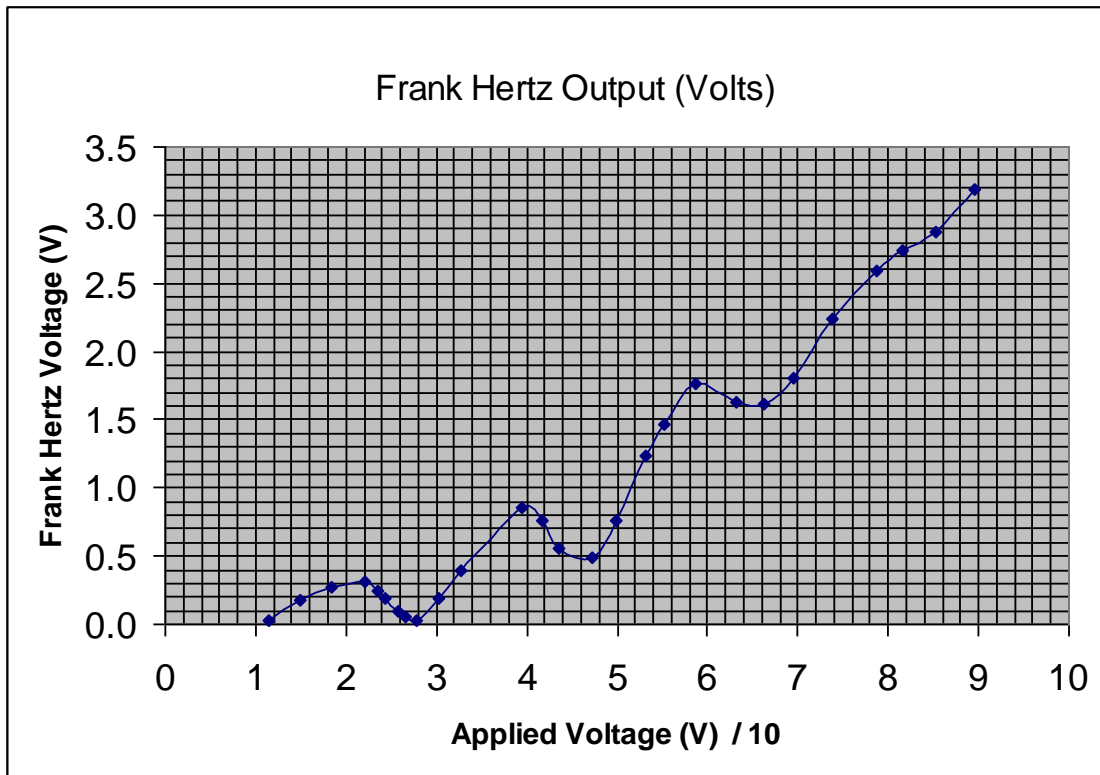
We measured the difference between consecutive peaks and obtained the a peak to peak difference of $P_a - P_b = 1.93 \pm 0.014$V between the 1st and 2nd peaks, and $P_c - P_b = 1.99 \pm 0.014$V between the 2nd and 3rd peaks. The average of the peak to peak voltage difference is 1.96V. This corresponds to a real voltage difference of 19.6 V, (due to the gain factor of 10 on the set up)

which corresponds to the energy difference of 19.6eV between energy levels. This value is close to the observed energy difference.

The Franck-Hertz Experiment: Capstone Project

Instead of using a real oscilloscope, we use NI ELVIS™ and a LabVIEW™ program to collect the data. Unlike the Saturated Absorption experiment NI ELVIS™ and LabVIEW™ are not used for controlling the experiment. They are only used to collect the data.

The block diagram for the LabVIEW™ program is shown below

Figure 4-19 LabVIEW™ program for data collection in the Franck-Hertz experiment
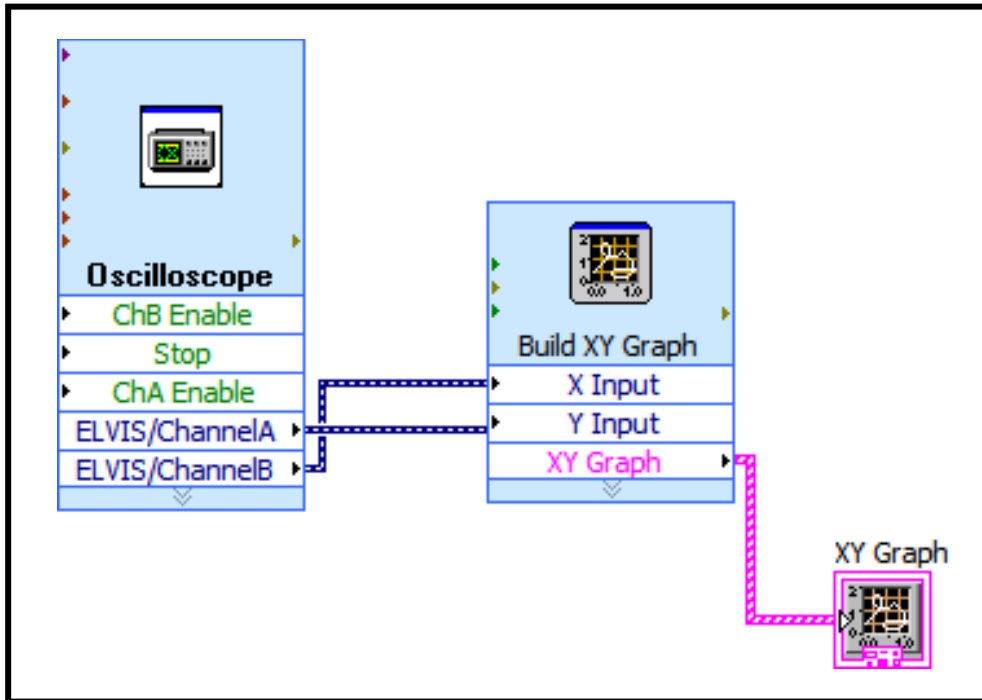
The block diagram above shows that in this VI, we collect data through oscilloscope LabVIEW™ program and totally replace the real data. Then this data flows to a Graph VI and be displayed in the front panel. A completed version of the LabVIEW™ program in this experiment including both front panel and diagram code can be found in the Appendix.

As expected, we can see that as the acceleration voltage is raised from an initial value of zero to the maximum 70V, different levels of reduction in the collector current occur. In the four

figures below, the X-axis represents the accelerating voltage, and the Y-axis represents the FH signal which is proportional to the current through the diode.

The first reduction is shown in the figure below.

Figure 4-20 The first reduction of the Franck-Hertz experiment output.
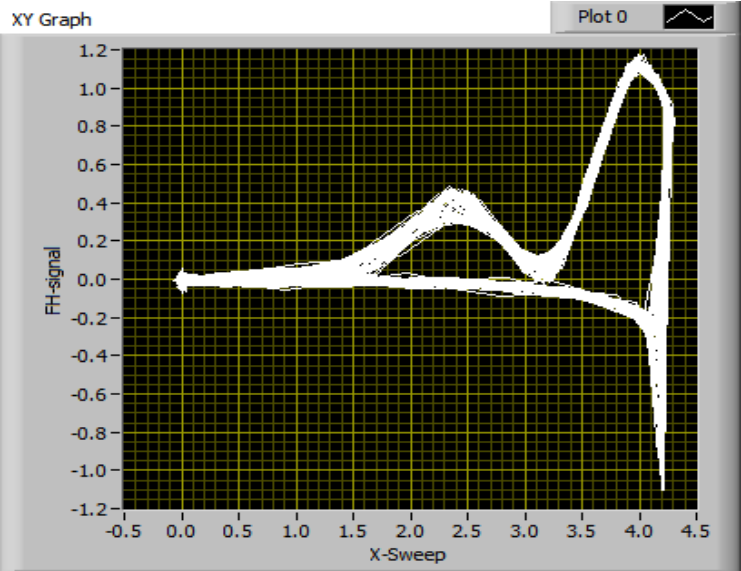
The second reduction is shown in the figure below.

Figure 4-21 The second reduction of the Franck-Hertz experiment output

The third reduction is shown in the figure below.

Figure 4-22 The third reduction of the Franck-Hertz experiment output
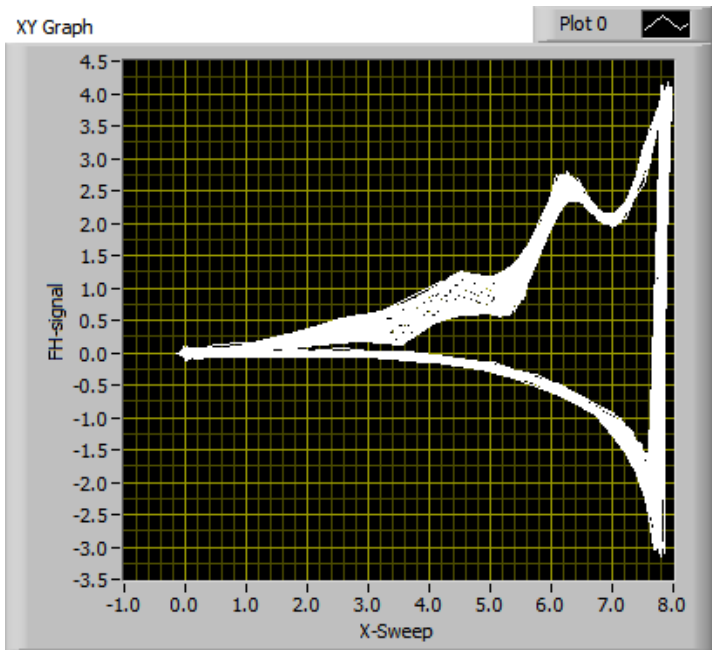
Finally, the fourth reduction is shown in the figure below.
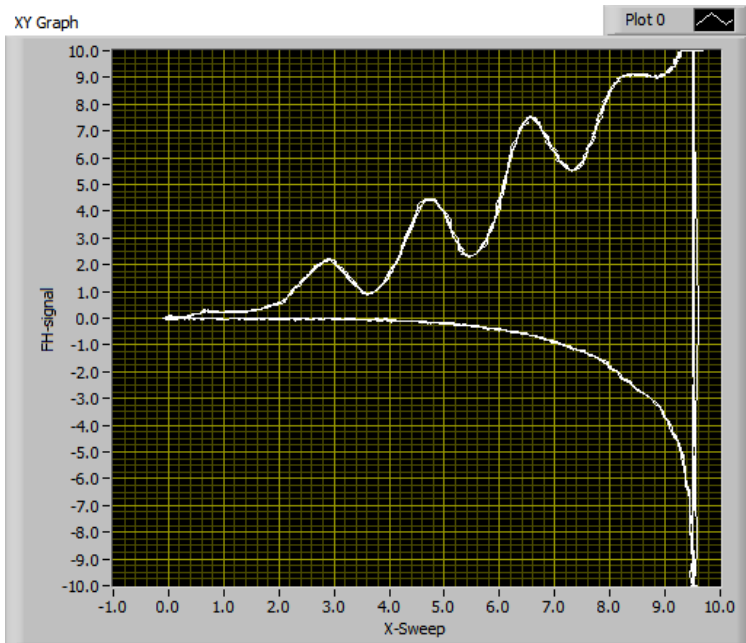
We notice that the FH signal goes down below zero when the accelerating voltage reaches its maximum. One possible explanation could be that the accelerating voltage is sweeping automatically, and when it reaches the maximum value, it cannot 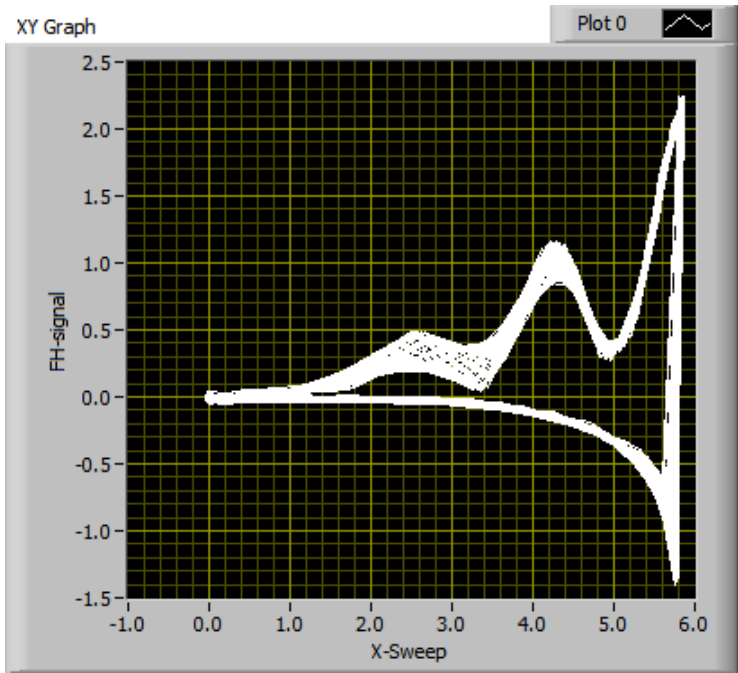immediately go down to zero volts due to a capacitive effect of an internal capacitor in the measuring circuitry in NI ELVIS™. There is a time delay due to time constant associated with the capacitor

The Franck-Hertz Experiment: Conclusion

We can visually approximate the energy difference between the first and second peaks in the NI ELVIS™/LabVIEW™ experiment from the figures to be 1.89 V, and difference between second and third to be 1.88V. The average value is 1.885V. When we compare it to the result of the direct measurement (1.96V) we find that they agree within 4%. The result is also consistent with the energy diagram for neon if we assume that the electrons preferentially excite the states between 18.3 and 18.9eV. Below is the table that directly compares those differences:

Table 4-10 Comparison of Voltage Differences between LabVIEW™ and Multimeter

Peak to Peak	Voltage Difference (V) (LabVIEW)	Voltage Difference (V) (multimeter)
1st—2nd	1.89$\pm$0.02	1.96$\pm$0.02

2nd—3rd	1.88$\pm$0.02	1.90$\pm$0.02
3rd—4th	1.88$\pm$0.04	1.94$\pm$0.04

We give the voltage difference between third and fourth peaks a bigger uncertainty because basically the fourth peak is hard to detect and thus its position is more uncertain than the other peaks. Besides that, we see that the two types of measurements are pretty close to each other, which is expected because the resolution limit of NI ELVIS™ does not play an important role in the measurement.

Capstone project Write-Up: Measuring the Speed of Light

Introduction[12]

When Michelson did his experiment to measure the speed of light he "pulsed" the light by sending it off a rapidly rotating mirror. Technology has progressed since then, and by using a pulsed laser beam instead this experiment can be done more easily. The laser source is based on a pulsed nitrogen laser operating at 337 nm at about 20 Hz with a pulse length near 10 ns. Part of the beam is deflected by a glass slide, after just a few centimeters, into a photodiode, while the main beam travels across the room and back into the same photodiode. If you trigger an oscilloscope with the synchronization pulse from the source, both pulses appearing on the trace and you can measure the time interval between them. By measuring this time difference, and the distance, you can calculate the speed of light.

Apparatus and Procedure [12]

The apparatus list includes:
- A pulsed nitrogen laser.
- A photodiode and preamplifier.
- An optical table with provision for mounting a partially reflecting glass slide.
- A dual-channel oscilloscope.
- Appropriate BNC connectors and cables
- Mirrors at both ends of the room, with which to vary the distance that the pulses travel.
- Tape measure.

The procedure is:

1) Familiarize with the general operation of the laser, oscillator and oscilloscope

2) Adjust the laser so that it hits the center of the mirror at the far end of the room and then adjust that mirror angle so that the laser returns exactly onto the face of the laser (it will be a much more diffuse spot when it returns)

3) Place a microscope slide at 45 degrees to deflect a portion of this intensity out at 90 degrees toward the photodetector. Insert the lens about 6cm in front of the photodetector, and look for a bright spot on the detector box. Adjust the box so that this spot enters the detector hole, and adjust the lens, looking at the scope, until you get a nice strong modulated photodetector signal.

4) Measure the position in time of the maximum (or any point of reproducible phase) relative to the scope trigger. Put the trigger on one channel and the photodetector on the other.

5) Now turn the mirror so that it goes directly into the lens instead of the distant mirror. The signal will be huge, so deliberately misadjust the lens so that you get about the same amplitude on the scope as you did in part (3). Measure the new phase, and use the difference to calculate c. You will have to measure the flight paths.

6) Now readjust for a double-bounce measurement: sent the laser to the distant mirror, adjust this mirror so the return beam hits the wall above the laser, adjust this mirror to return this beam to the far mirror and find the resulting spot (now very diffuse) on the surface of the laser. Use the mirror and lens to reflect and focus about half of this onto the detector, and again measure the speed of light. Your will have to repeat step (5) again, with even more maladjustments to match the weaker signal from the double bounce path. Calculate 'c' from the results.

Data and Error Analysis

This table below shows the data we recorded

Table 4-11 Speed of light measure data and calculation

| Measured length	Time Delay	Calculated Speed of light	Error to expected value
45.5 ft	93.4×10^{-9}s	2.95×10^{-8}m/s	1.7%

We know this simple equation D=V×T, where D, V, T represent distance, velocity and time difference separately. So V=D/T, so in our experiment, C=X/T. The calculated speed of light equals to time delay multiply measured length. Due to error analysis[14], we have this formula: $\frac{\Delta c}{c} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$. Through this equation, we can calculate uncertainties of our result. In our case, Δx=0.1 m, Δt=0.1 ns, And we can calculate the error Δc=0.051×10^{-8}m/s. So the final result should be written as c=2.95±0.051×10^{-8}m/s.

Now we want to see if it is possible to use NI ELVIS^{TM} workbench to build a circuit that can take in the laser signal directly from photodetector. The basic idea of doing this is shown below.

Figure 4-23 Measuring and Manipulating signal from photodetector
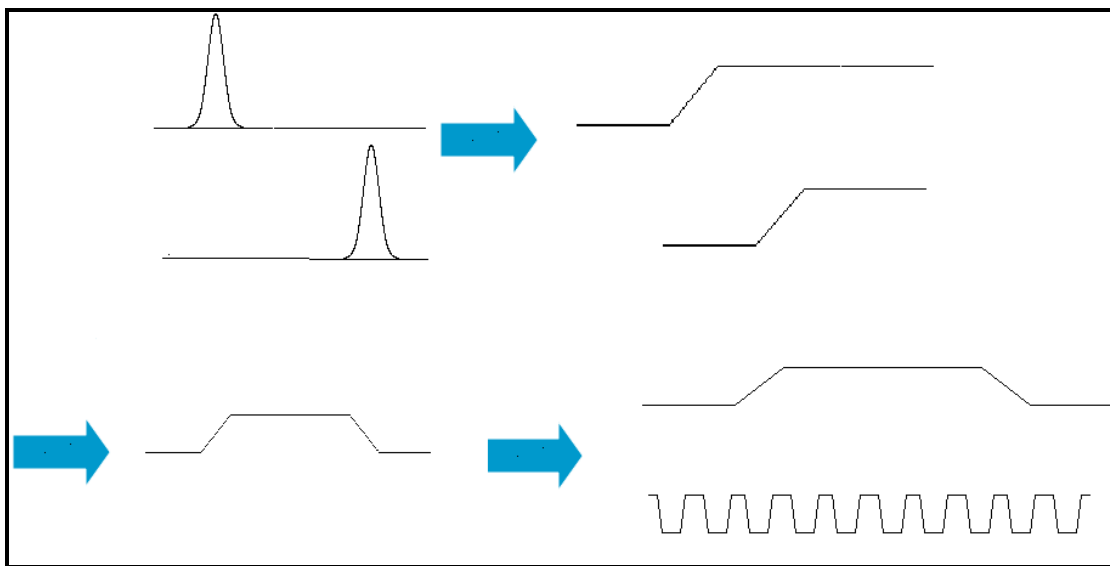
As shown in the above figure, two signals with certain time delay (around 100 ns) go to our electronic system and each of them will be amplified and maintained to the maximum value. Then the two signals will go to an XOR gate and a square pulse with a period around 100 ns will be produced. Then we can use another series of square pulses with much shorter duration to count the duration of the square pulse from the XOR gate, and measure the exact time of the duration of this square pulse. This in turn will be the time delay in the experiment of speed of light.

It turns out to us that this approach requires a counting square pulse with a period of around 10 ns (one tenth of 100 ns) while the NI ELVIS[TM] cannot supply or respond to such a short pulse. [16] Another problem is our circuit which have TTL and CMOS chips, cannot respond as fast as 10 ns. So we finally reached a conclusion that the NI ELVIS[TM] counter-timer circuitry is not capable of measuring the speed of light in this configuration. We then came up with an idea of measuring the speed of sound. It uses the same time of flight principle, as the speed of light experiment. A noise source with NI ELVIS[TM] is used instead of the nitrogen laser, and a pair of microphones is used rather than a photodetector. The speed of sound is much smaller than the speed of light, and the time delay over 1 meter is only around 3.3 ms which is long enough for us to using the electronics and NI ELVIS[TM] to process the signal as shown in the Figure 4-23. A complete diagram of electronic circuit is pasted in the Appendix.

CHAPTER 5 - CAPSTONE PROJECT HANDOUTS

The handouts were provided to the students as a guide for completing the Capstone projects. The handouts provide minimal information and no detailed instructions on how to do the experiments. Students are expected to read through the necessary instructions for each experiment. These instructions are provided to the students as part of the APL and MPL courses. In this capstone project, we once again provide students with these instructions for each experiment.

Students are first expected to complete the 'real' experiment i.e. just as they did it in APL or MPL. After they have been able to successfully complete that task, they are then asked to do the capstone project that involves interfacing and automating these experiments with NI ELVIS[TM] using LabVIEW[TM].

Each section below provides the handout that students were provided for each of the Capstone project experiments in spring 2009. In addition to the saturated absorption and Frank-Hertz experiments, students were also provided hand outs for two other experiments. These were X-Ray spectrometer and measuring the speed of light and sound.

Saturated Absorption Experiment Handout

Overview

In Advanced Physics lab of Saturated Absorption, students use the absorption of light from a tunable diode laser to explore the energy levels of Rubidium. By measuring the absorption versus laser frequency they observe four broad absorption peaks. Then, by employing standard sub-Doppler techniques, further resolve those peaks to reveal the hyperfine structure.

Objective

1. Relearn the physical concepts in the Saturated Absorption experiment.
2. Write a LabVIEW™ program to control the laser source and to read in the signal output from the photo-detectors (within one program), with the help of NI ELVIS™.
3. Save the data into the computer and analyze the energy levels structure of Rubidium.
4. More specifically, record all the four peaks for the ground state and at least one peak for the excited state of Rubidium.

Capstone Project Procedure

1. Read the write-up of Saturated Absorption to figure out what the original experiment is about and perform most of the experiment without LabVIEW™ program and NI ELVIS™.
2. Based on what you have learned about the experiment, figure out how to connect the experimental apparatus with NI ELVIS™, and then write a LabVIEW™ program in the computer.
3. You should be able to control and run all the experiment in the computer.

Questions

You are expected to address these questions in your final presentation of the project.

Physical Questions

1. What is the use of Michelson interferometer? What is the working principle?
2. How does the Sub-Doppler technique work? Why can it give us higher resolution?

Instrumentation and Programming Questions

3. How can you use NI ELVIS™ and LabVIEW™ programming to replace the oscilloscope and function generator? How could you achieve this within one LabVIEW™ program?

4. Is there any time delay or signal "dead zone" when you are trying to read in the signal from photo-detector? (This happened time to time when we was trying to write the LabVIEW™ program)

5. Can you save the data automatically when you start running the LabVIEW™ program?

6. Except NI ELVIS™/LabVIEW™ program, can you think of other ways (more basic LabVIEW™ function) to achieve the same goal? If not, what is the difficult point?

7. How many points per second should the NI-ELVIS™ be able to record to have sufficient resolution?

8. What is the voltage range the NI ELVIS™ will need to output?

9. What is the minimum voltage step size that NI ELVIS™ will output? What will be the impact on your recorded data? How will you minimize the effect of this minimum step size?

10. Same question for digitization effect on reading in the signal.

11. What is the minimum voltage step size that NI ELVIS™ will input? What will be the impact on your recorded data? How will you minimize the effect of this minimum step size?

The Franck-Hertz Experiment Handout

Overview

The Franck-Hertz experiment demonstrates the quantization of energy levels of isolated atoms.

Objective

1. Relearn the physical concepts in the Franck-Hertz experiments.

2. Learn how analog-to-digital conversion can be used in order for a computer to read and control analog voltages to control an experiment.

3. Learn to write a LabVIEW™ program to read in the amplified tube current.

Capstone Project Procedure

1. Read the write up of the Franck-Hertz experiment and try to figure out how the experiment works. Then perform this experiment in the original way.

2. Use the NI ELVIS™ and LabVIEW™ programming to run the Franck-Hertz Experiment automatically so that the NI ELVIS™ records the Frank Hertz current signal directly.

3. Try to read the data into the computer through the LabVIEW™ program.

Questions

You are expected to address these questions in your final presentation of the project.

Physical Questions

1. What is the principle of the Franck-Hertz Experiment?

Instrumentation and Programming Questions

2. How can you use NI ELVIS™ and LabVIEW™ programming to replace the oscilloscope?

3. How can you write a program to drive the step motor (involving machine handling)?

4. Can you save the data automatically when you start running the LabVIEW™ program?

5. Except NI ELVIS™/LabVIEW™ program, can you think of other ways (more basic LabVIEW™ function) to achieve the same goal? If not, what is the difficult point?

6. How many points per second (reading rate) should the NI ELVIS™ be able to record to have sufficient resolution?

7. What is the minimum voltage step size that NI ELVIS™ will input? What will be the impact on your recorded data? How will you minimize the effect of this minimum step size?

X Ray Spectrometer Experiment Handout

Overview

The X-Ray Spectrometer experiment introduces students to the principles of x-ray production and x-ray diffraction. Futures of both Bremsstrahlung and Characteristic X-Ray spectra are observed then compared with theory result, by way of Bragg Diffraction calculations.

Objective

1. Relearn the physical concepts in the X Ray Spectrometer experiment.
2. Understand the instrumentation used to study the X-Ray production, including Geiger counter and stepper motors.
3. Learn the operation of stepper motors and the hardware that controls them.
4. Learn to write a LabVIEW™ program that can control a stepper motor.
5. Read in an X-Ray spectrum using NI ELVIS™.

Capstone Project Procedure

1. Read the write-up of the X Ray Spectrometer experiment and try to figure out how this experiment works. Then perform the first two experiments to observe Bremsstrahlung and Characteristic X-Ray using just one of the salt crystals.
2. Write a LabVIEW™ program to drive the step motor which is given by your instructor.
3. Install the step motor in the existing X-Ray apparatus.
4. Try to read the data in the computer through the LabVIEW™ program.

Questions

You are expected to address these questions in your final presentation of the project.

Physical Questions

1. What is the principle of the X-Ray Spectrometer Experiment?
2. What is the highest energy photon you expect to observe and why? What gives rise to the characteristic X-Rays?

Instrumentation and Programming Questions

3. How can you write a program to drive the step motor (involving machine handling)?
4. Can you save the data automatically when you start running the LabVIEW™ program?
5. Figure out the format of the y-axis data as it is read into the computer. Can you record data in a similar way with NI ELVIS™?
6. If not, can you use an oscilloscope instead?

Speed of Light/Sound Experiment Handout

Overview

In this lab, the speed of light is measured directly with a pulsed nitrogen laser. Careful attention to laser and eye safety must be paid. By measuring the distance traveled and the time required, students can directly measure the speed of light.

Objective

1. Understand how to measure the speed of light (and speed of sound) in this direct time-of-flight measurement.
2. Understand the essential role of uncertainty in the measurement.
3. Design a high-speed timing circuit.
4. Write a LabVIEW™ program to record a series of timing interval measurements and calculate statistics on the resulting data.
5. Assess the uncertainty in their instrumentation and therefore in the final measurement of the speed of light.

Capstone Project Procedure

1. Read the write up of Speed of Light and perform the experiment in Advanced Lab.
2. Design an electronic timing circuit to receive the laser pulse, count the time difference, and read it into a computer.
3. Calculate the resolution of the timing circuit needed to measure the speed of light.
4. Figure out an analogous measurement of the speed of sound. Design the experimental procedure for measuring the speed of sound, and make the measurement.
5. Design an electronic circuit and LabVIEW™ program to compute the speed of sound from signals in a time-of-flight measurement.

Questions

You are expected to address these questions in your final presentation of the project.

Physical Questions

1. What is the principle of speed of light & speed of sound experiments?

Instrumentation and Programming Questions

2. How can you use NI ELVIS™ and LabVIEW™ programming to display the pulse signal received (Displace the Oscilloscope)?

3. Can you save the data automatically when you start running the LabVIEW™ program?

4. Except NI ELVIS™/LabVIEW™ program, can you think of other ways (more basic LabVIEW™ function) to achieve the same goal? If not, what is the difficult point?

5. How high resolution of the electronic timing circuit do we need to measure the speed of light as well as speed of sound? Can you give out the specific calculating steps?

6. Why do we have to move from measuring the speed of light to the speed of sound?

CHAPTER 6 - SUMMARY AND FUTURE PLANS

The importance of teaching electronics in the physics cannot be overemphasized. In fact there have been substantial efforts in the physics community to teach electronics and integrate it with the teaching of experimental physics. In this report we have summarized the literature on the teaching and learning of electronics in the upper-division physics curriculum of the past 20 years. Our literature review focused specifically on efforts that are similar to the capstone project experiences in PMI. We found that the approaches taken by others are very similar to those that we are taking in reform the PMI course. The challenges are also very similar, such as the time needed to help students learn the basic electronics before starting their projects and the lack of good textbooks in electronics appropriate for physics students. Given those challenges, the physics community has made a good effort in designing experiences that would better prepare our physics undergraduates to learn the necessary experimental and instrumentation skills that are critical to being a researcher in experimental physics.

In designing the materials for the capstone project we kept in mind the prior background of the students. These students have typically had at least one course in which they have learned about classic modern physics experiments. In this capstone projects they revisit one of these experiments and first redo the experiment as it is. Then they design electronics and software using LabVIEW™ to help automate the experiment. They are provided with no detailed instruction, only a one-page handout that outlines the goals, basic procedures and most importantly questions that they have to seek answers to while working on the capstone project. The questions relate to both the physics of the experiment as well as the electronics and instrumentation involved in automating the experiment.

The future plans for the capstone project are basically twofold. First, we will continue this process based on feedback from the current group of students who took the PMI course in spring 2009. We will expand the number of the capstone project experiments as per the ones listed in the proposal to the National Science Foundation. Along these lines we will also design assessments that enable us to investigate the extent to which these capstone experiences have

improved student learning of the underlying physics as well as the electronics and instrumentation.

Appendix A - LabVIEW™ Program of Saturated Absorption

In this Appendix, we provide the complete LabVIEW™ program code including both the front panel and block diagram code used in the Saturated Absorption experiment. LabVIEW™ was used to control the device as well as record experimental data. The Front Panel is shown below.

**Figure A-1 Front Panel of Saturated Absorption Experiment**
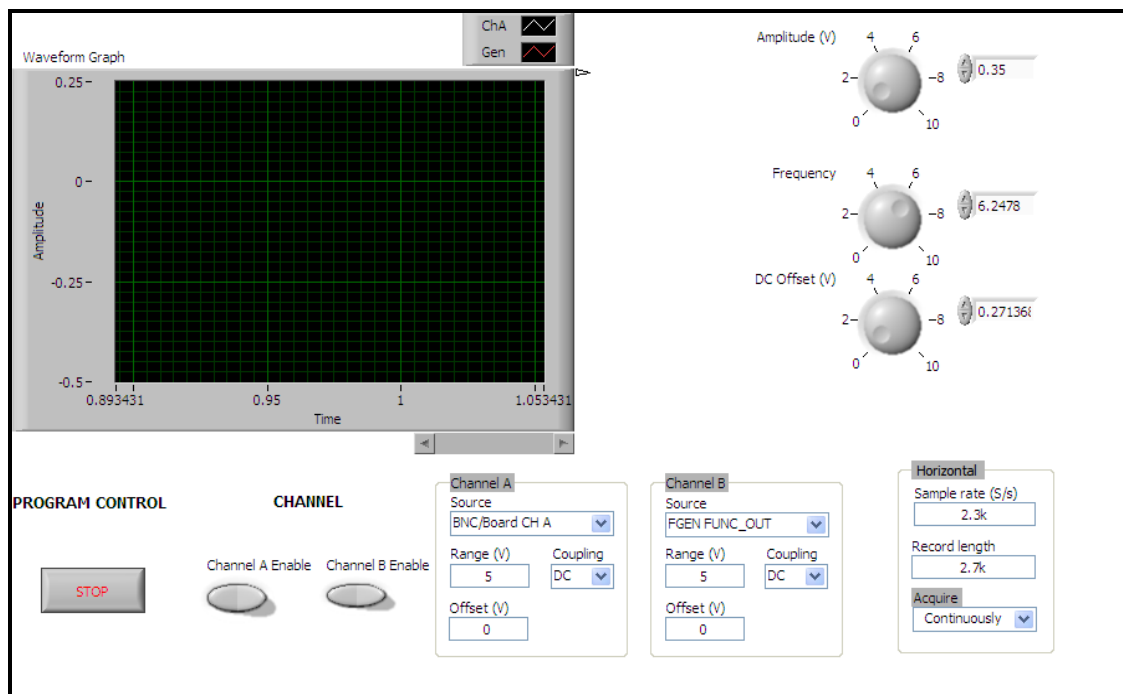
We will briefly explain how this works. The three knobs at the right hand side of the front panel control the amplitude, frequency, and DC offset of the signal produced by function generator which is shown in the diagram code figure later. On the left side of them is a graph which can display two signals from two channels with different colors.

Under the graph, there are two button named "Channel A Enable" and "Channel B Enable." They turn the respective channels on and off. The stop button beside them is the switch of the whole program. And using the "Channel A" and "Channel B" clusters, one can adjust the signal source of each channel, range of the input signal, offset, and coupling. At the right hand

side of two clusters is a "Horizontal" cluster, which is used to determine the sample rate, record length, and acquire modes. In general, these three clusters can determine the format of display of the signal as well as the format with which the signal is recorded.

The corresponding Block Diagram code is shown below.

Figure A-2 Block Diagram code of Saturated Absorption Experiment
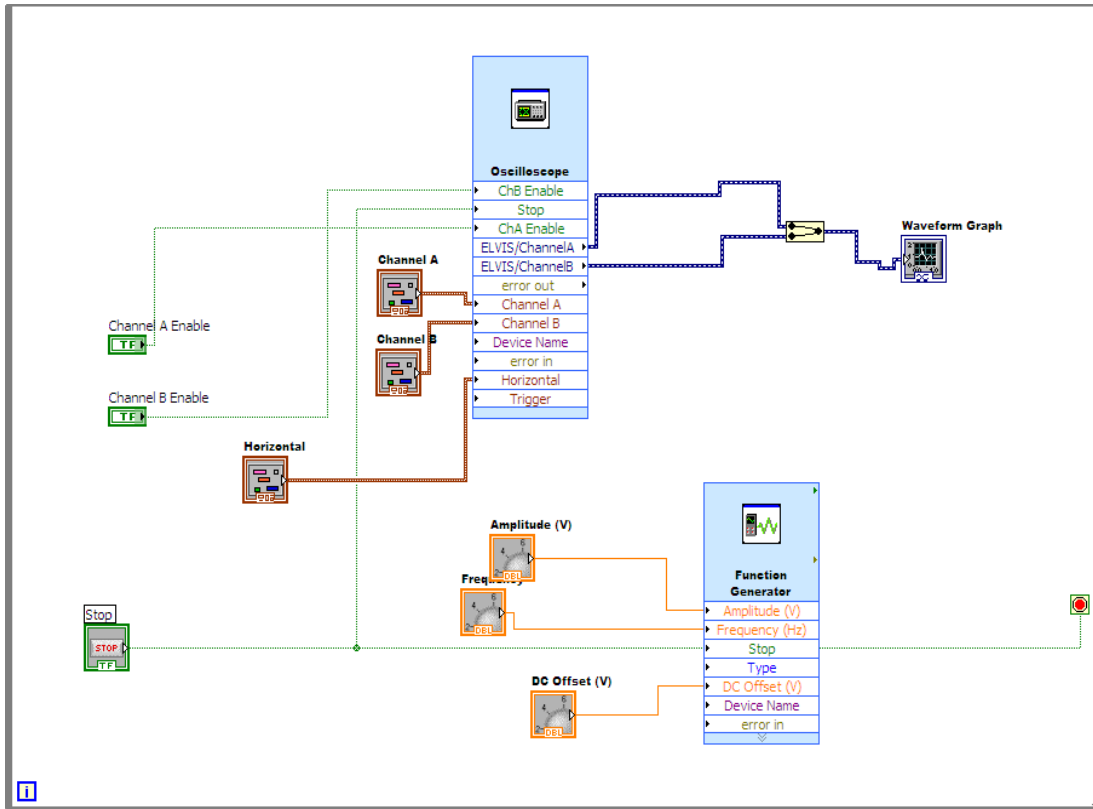
This block diagram code indicates how the data flows in this LabVIEW™ program. We can see that in a while loop, the oscilloscope VI and the function generator VI work simultaneously. The configuration is all set automatically except the trigger part which is shown in the figure below:

**Figure A-3 Configuration required for Trigger option in the Oscilloscope subVI**
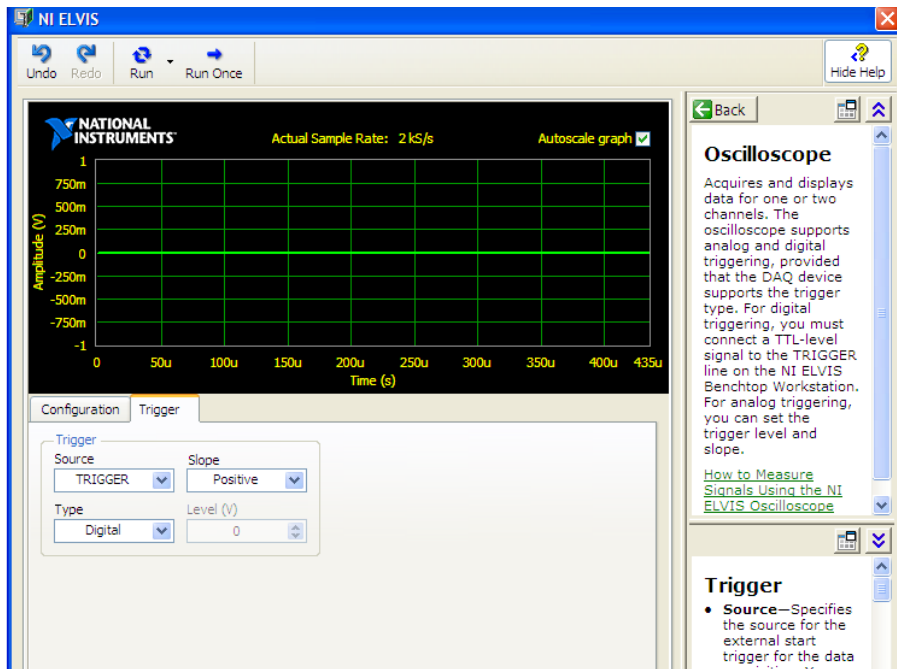
The trigger should be chosen and the "slope" option can be chosen as "Positive" or "Negative" depending on our experimental requirement.

Appendix B - LabVIEW™ Program of the Franck-Hertz Experiment

In this Appendix, we provide the complete LabVIEW™ program including both the front panel and block diagram code used in the Franck-Hertz experiment to display the current vs accelerating voltage as well as to record the experimental data and export them to a chosen file in the computer. The Front Panel is shown below.

**Figure B-1   Front Panel of the Franck-Hertz Experiment**
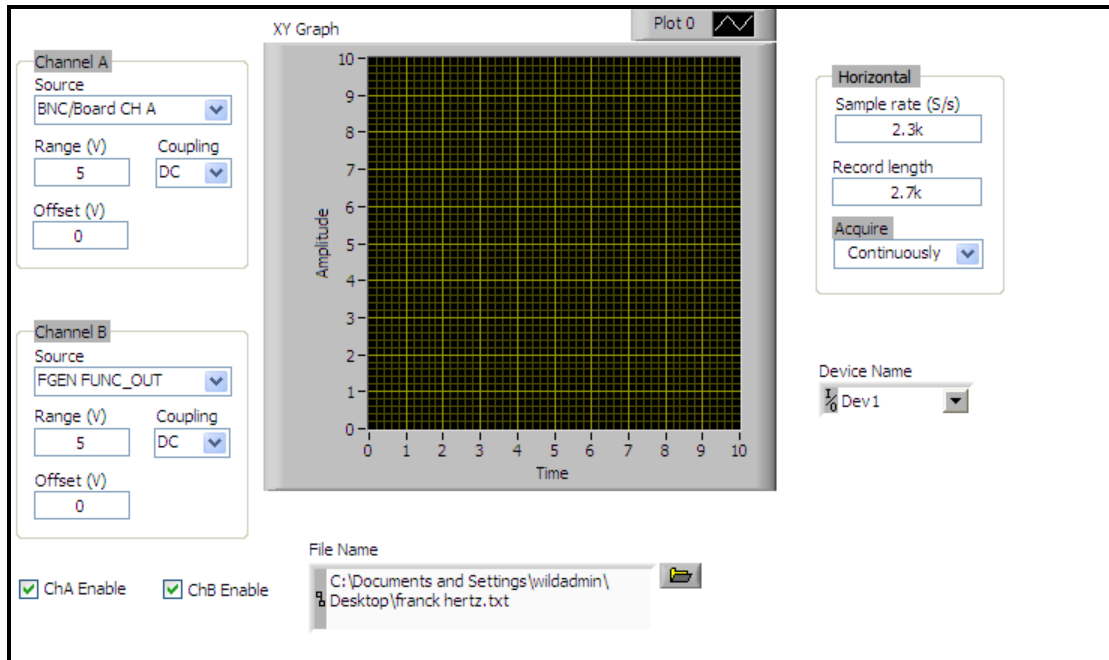
Similar to Appendix A, the Graph displays the signal from oscilloscope VI in the LabVIEW™ program. The three clusters: "Channel A", "Channel B", "Horizontal" also can determine the format of display of the signal as well as the format with which the signal is recorded, just like what they do in the LabVIEW™ program of Saturated Absorption.

The "File Name" text box indicates the location of the file on the computer hard disk.. You can set to program to alert you to type in the file name and address every time the program runs or you can fix them permanently. After you write down all needed data, you can use Excel

or similar software to open it and do the required analysis. The Block Diagram code is shown below:

Figure B-2 Block Diagram code of the Franck-Hertz Experiment
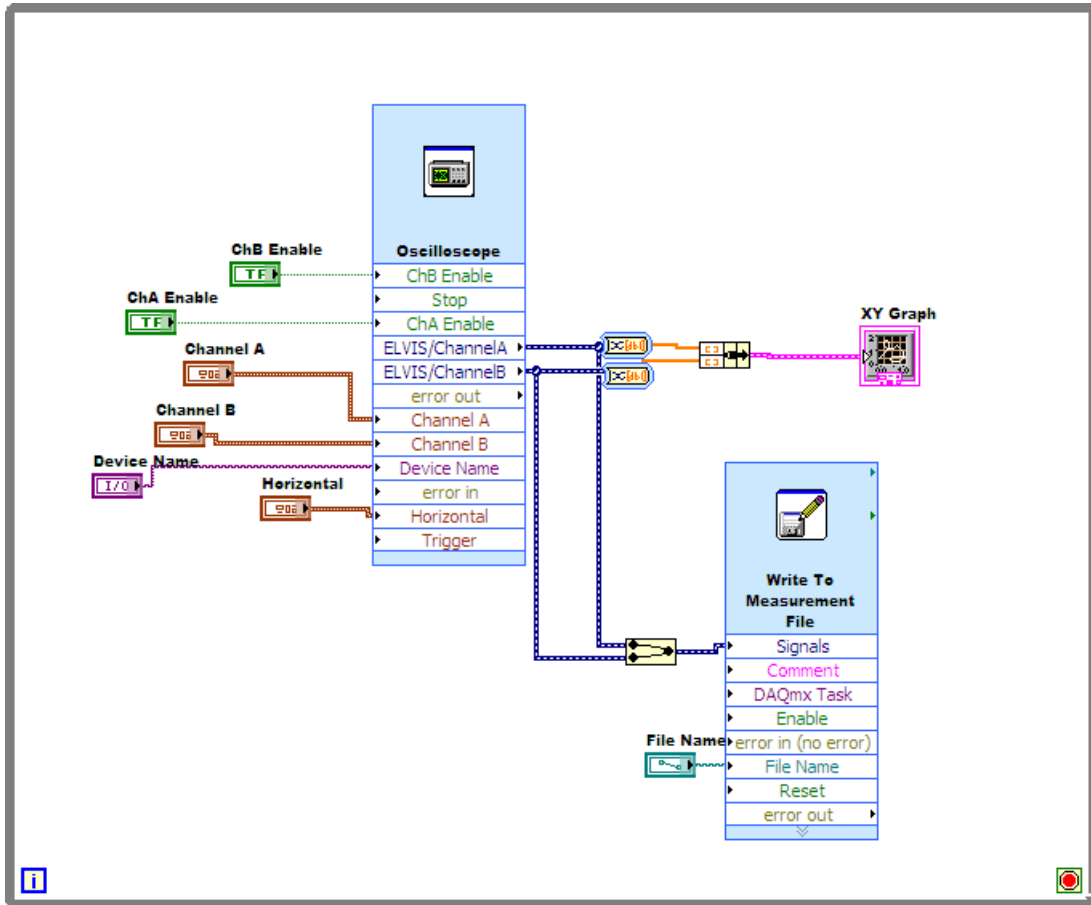

    Again, this Block Diagram code indicates how the data flow in this LabVIEW™ program. A small difference between this code and the one used in the Saturated Absorption is it uses a Write to Measurement File VI and uses the XY mode of Graph.

Appendix C - Circuit for Speed of Sound Measurement

The circuit for the measurement of the speed of sound is shown below.

Figure C-1: Schematic of electrical circuit for Speed of Sound measurement. This circuit is the printout of a MultiSim™ simulation that was built before building the real circuit
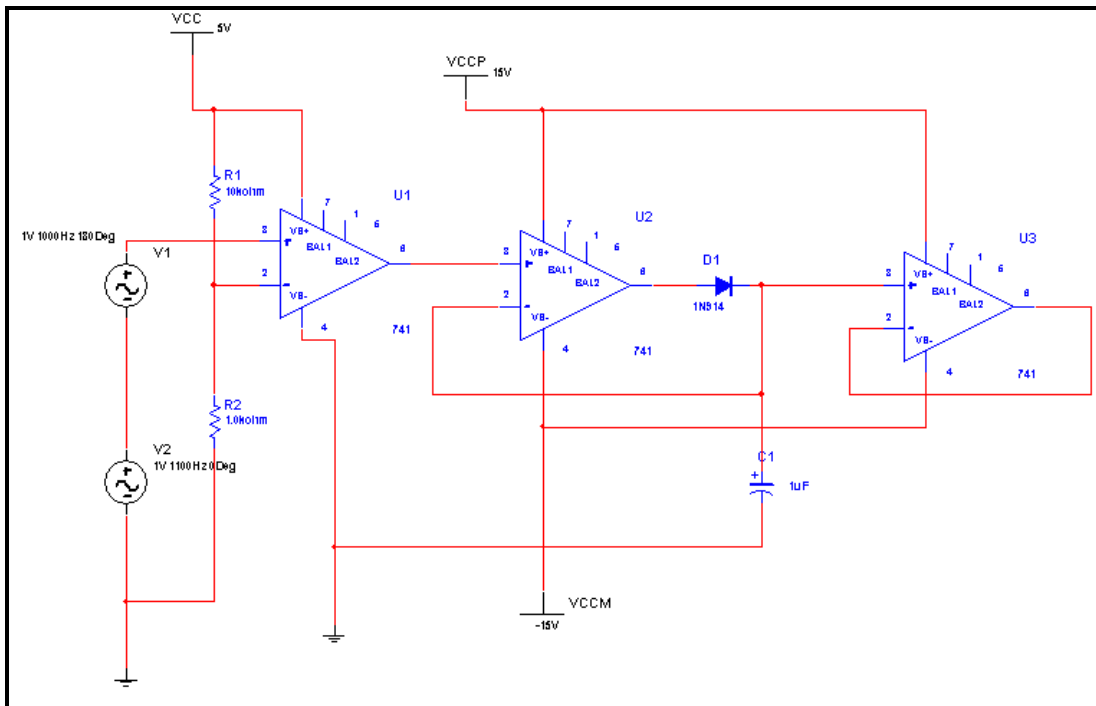

The circuit shown above is from a MultiSim™ simulation file that was created to test whether a real circuit if so built would work. The first stage OPAMP functions as a comparator. It compares the voltage signal from the signal source (V1 + V2) to the voltage of the voltage divider of R1 (= 10kOhm) and R2 (=1kOhm), which in this case is a DC voltage of about 0.5Volts. The output of the first stage is either +5V when (V1 + V2) > 0.1V or 0V when (V1 + V2) < 0.1V. This output is then given to the second stage, which consists of two OPAMPS. Together these two OPAMPS are a sample and hold circuit. This circuit uses a capacitor and diode along with an OPAMP to ensure that when the input voltage (V1 + V2) drops below 2.5V, the output of the second stage does not drop. The third OPAMP is merely a voltage follower. It

is essential, because otherwise the charge from the capacitor can leak out and the sample and hold circuit will not work.

We tested the circuit using an input (V1 + V2) that simulates a signal – a noisy pulse that might be generated by creating a sound, such as a clap, near a microphone. This figure below shows the output waveform at different points in the circuit.

Figure C-2 The output waveforms from different points in the previous circuit are shown in red and pink. The input appears in blue
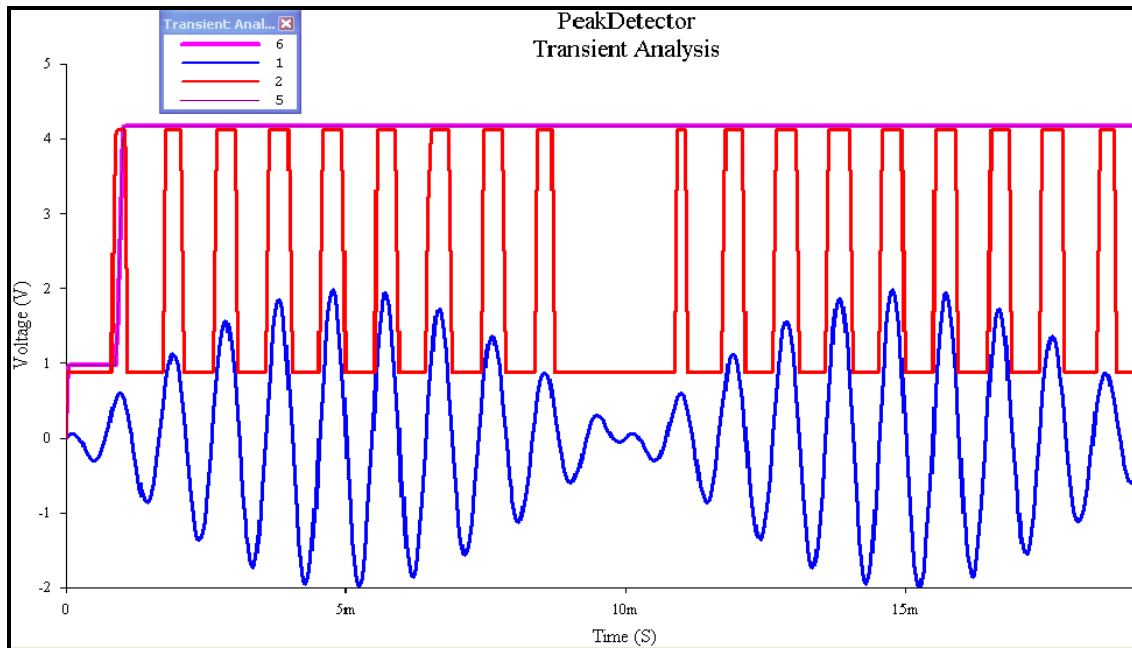
The input waveform (blue) is provided by the sources V1 + V2 which simulate a wave packet train. In reality, if we are looking at the output from a microphone when a loud sound, such as a quick clap of hands, is generated near it, we will not see a wave packet train. Rather we will see a single wave packet. However, a wave packet train suffices for the purposes of demonstrating whether our simulation works. The red waveform is the output of the first OPAMP. Note that it goes high as soon as the blue waveform crosses ~0.5V. This is the threshold, but when the input blue waveform drops to below 0.5V, the output of the first OPAMP also drops to zero. The pink waveform is the final output after the sample and hold circuit. Note that it does not drop to zero and retains the 5V output signal after the first instance when the input passes 0.5V, even though the input may oscillate after that.

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In a real speed of sound measurement, we would need two such circuits – one for each microphone. Then the output of the two circuits would be sent through an XOR gate to create a square pulse whose duration is equal to the time difference between when the output from each microphone went past the threshold.

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