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(SURF Report)

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Automated Measurement of Sideband Power in the 2K Interferometer

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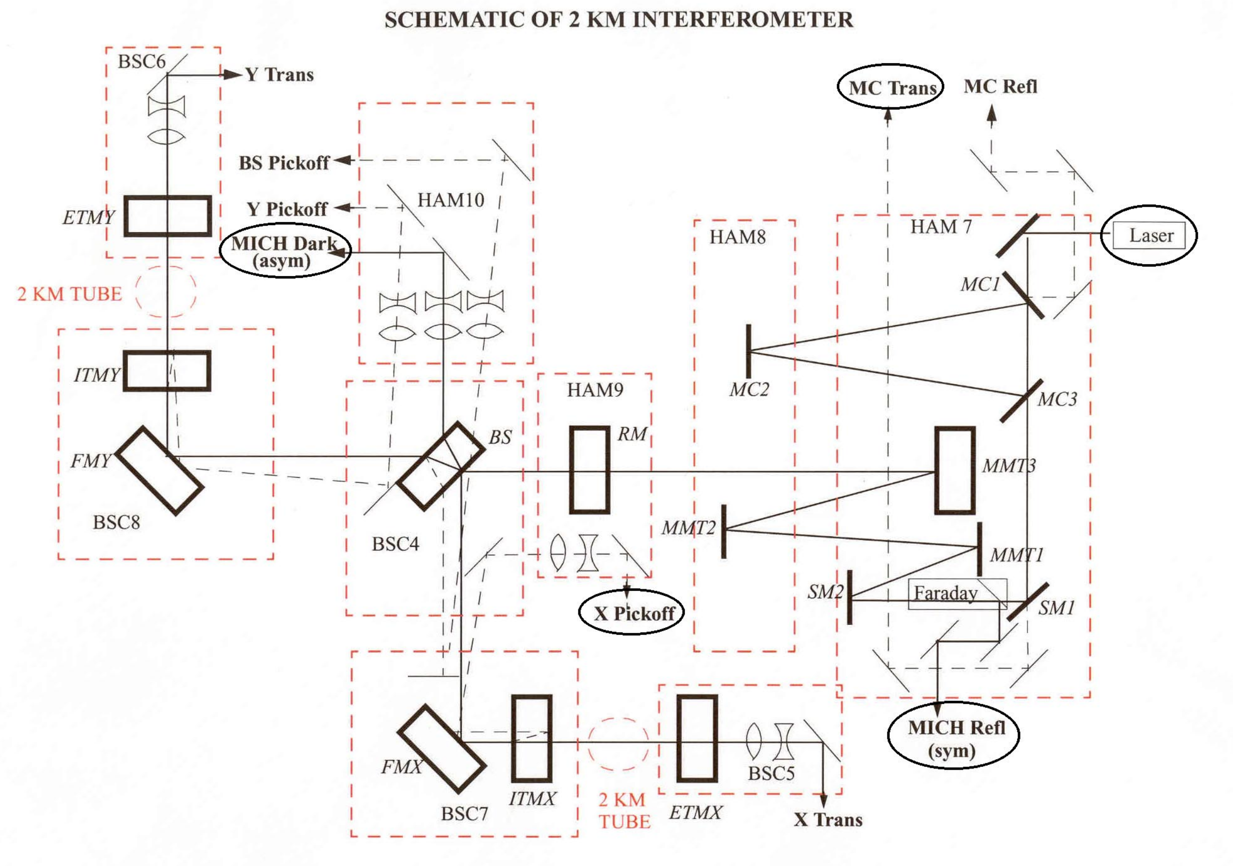
Abstract:

The interferometers at the LIGO Hanford Observatory utilize phase modulation to produce rf sidebands that are used in the detection of gravitational waves. The sidebands and carrier resonate at different levels in the various optical cavities of the interferometer. In order to fully understand the operation of the interferometer, it is necessary to measure sideband power relative to carrier power in each optical cavity. Because of alignment drifts, it is desirable to perform these measurements in parallel. A system consisting of optical spectrum analyzers and remote controlled digital oscilloscopes and ramp generators has been implemented to automate the measurement process in the 2K interferometer. Data has been obtained with the interferometer in several configurations. Similar systems will also be installed for the Hanford 4K interferometer and the Livingston 4K interferometer.

1 Introduction

The Laser Interferometer Gravitational wave Observatory (LIGO) project utilizes a power-recycled Michelson interferometer with Fabry-Perot arm cavities in the detection of gravitational waves. Phase modulation is used to produce sidebands that are used in controlling the length of the cavities in the interferometer[1] with the Pound-Drever-Hall technique[2]. Great care was taken in the design of the interferometers to control the levels at which the sideband and the carrier frequencies resonate in the cavities. To fully understand the operation of the interferometer and to analyze its performance, it is necessary to measure sideband power relative to carrier power, and determine their levels of resonance in each optical cavity nearly simultaneously (**Figure 1**). The interferometers are also designed so that the upper and lower sidebands resonate at the same level, and it is necessary to look for and measure any asymmetries in the sidebands. It is not desirable make these measurements manually, however, because it requires tasks such as physically adjusting the equipment, connecting and disconnecting cables, etc., which are both time consuming and likely to interfere with the operation of the interferometer by creating noise and possibly causing a cavity to lose its lock. To avoid these problems, a system consisting of remote-controlled oscilloscopes that automatically measure relative sideband and carrier power has been installed for the Hanford 2K interferometer. Similar systems are also planned to be installed on the Hanford 4K and Livingston 4K interferometers. The system has been tested and been found to work reliably (low levels of light, high levels of noise) and quickly (less than 5 seconds for a measurement at each location under ideal circumstances, less than a minute under bad circumstances, which result from a low light level and high noise level) with little interaction from the operator. Several improvements to the system, such as automating support equipment and increasing the speed of the measurement, will likely be implemented in the future, but are not immediately required.

Figure 1. Measurement locations. There are five measurement locations, but only four oscilloscopes because the measurement from the mode cleaner (MC) transmitted beam and the laser pickoff beam are essentially the same measurement. In most situations, the laser pickoff measurement will not be used, and the MC transmitted measurement will take its place as the initial condition of the laser being input to the interferometer. Occasionally, a measurement may be made at each location to determine if a problem is arising from the mode cleaner. The other measurements are taken at the asymmetric port (the Michelson dark port), the symmetric port (the Michelson reflected beam), and the X-pickoff beam



2 Materials and Methods

2.1 Theoretical Considerations

Certain materials have the property that their refractive indices change under the influence of an electric field. A beam passing through such a material will acquire a phase shift proportional to the electric field. A Pockels Cell utilizes a material in which the change in the refractive index is proportional to the change in the electric field. By passing a laser beam of frequency ω through a Pockels Cell, being driven by a sinusoidal electric field of frequency Ω, the original electric field of the beam,

$$\tilde{E} = E_0 e^{i\omega t} \qquad \textbf{(Equation 1)}$$

is altered to become

$$\tilde{E}' = E_0 e^{i\omega t + i\Gamma\cos(\Omega t)} \qquad \textbf{(Equation 2)}$$

where Γ is the modulation depth and depends on the amplitude of the driving signal. This process is called phase modulation, as the phase is modulated at a frequency Ω. This signal may be expanded in terms of Bessel functions using the following Fourier expansion,

$$e^{-iz\sin t} = \sum_{n=-\infty}^{n=+\infty} J_n(z) e^{-int} \qquad \textbf{(Equation 3)}$$

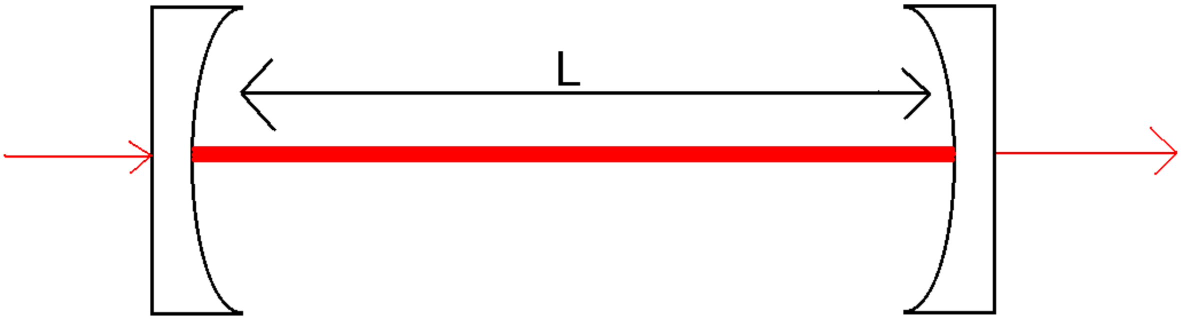
to obtain

$$\begin{aligned}\tilde{E}' &= E_0 e^{i\omega t}\left[J_0(\Gamma) + J_1(\Gamma)e^{i\Omega t} - J_1(\Gamma)e^{-i\Omega t} + J_2(\Gamma)e^{2i\Omega t} - J_2(\Gamma)e^{-2i\Omega t} + \ldots\right] \\ \tilde{E}' &= E_0\left[J_0(\Gamma)e^{i\omega t} + J_1(\Gamma)e^{i(\omega+\Omega)t} - J_1(\Gamma)e^{i(\omega-\Omega)t} + \ldots\right]\end{aligned} \qquad \textbf{(Equation 4)}$$

where J_n is the Bessel function of first kind of order n. The $J_0(\Gamma)$ term is called the carrier, and the $J_1(\Gamma)$ terms are called the first order sidebands. The LIGO interferometers use Pockels Cells, or electro-optic modulators (EOMs) to produce sidebands that are essential in the detection of gravitational waves. LIGO uses three different EOMs, but the only one of current interest has a modulation depth of 0.44, and at this modulation depth, sidebands of order greater than one are small and may be neglected.

To obtain a measurement for the modulation depth, it is desirable to measure the component of the beam that is present at a certain frequency. It is only possible to measure the power of the beam, which is related to the square of the electric field, so it is necessary to isolate the component of the field at a given frequency. To accomplish this, a scanning confocal Fabry-Perot cavity, also called an optical spectrum analyzer (OSA), is used. A confocal Fabry-Perot cavity consists of two confocal mirrors, as shown in **Figure 2**, having amplitude reflectances r_1 and r_2 respectively and having transmittivities t_1 and t_2 respectively. They are separated by a distance L, with the focus of each mirror lying on the surface of the other mirror.

Figure 2. Optical Spectrum Analyzer



The transmittance of power into such a cavity is derived as follows. The electric field in the cavity, E, is the sum of the beam that just entered the cavity and all the beams that have been reflected within the cavity. Each time a beam is reflected back to the left mirror, it will lose some light due to the reflectance of the mirrors and acquire a phase shift due to the distance traveled. The resulting electric field in the cavity is therefore:

$$\tilde{E}_c = E_0 t_1 \left[1 + re^{i\varphi} + \left(re^{i\varphi}\right)^2 + \left(re^{i\varphi}\right)^3 + \ldots\right] = E_0 \sum_{n=0}^{n=\infty} \left(re^{i\varphi}\right)^n = \frac{E_0}{1 - re^{i\varphi}}$$

$$\varphi = \left(\frac{2L}{\lambda}\right) \cdot 2\pi, \qquad r = r_1 r_2 \qquad \textbf{(Equation 5)}$$

where λ is the wavelength of the incoming light. The electric field transmitted through the right mirror is therefore:

$$\tilde{\mathrm{E}}_t = \frac{\mathrm{E}_0 \mathrm{t}}{1 - \mathrm{re}^{i\varphi}}, \qquad \mathrm{t} = \mathrm{t}_1 \mathrm{t}_2 \qquad \textbf{(Equation 6)}$$

The power is proportional to the absolute magnitude squared of the electric field, so the transmittance of power can be defined as the ratio of the absolute magnitude squared of the transmitted field to the square of the input field:

$$T = \left| \frac{\tilde{E}_t}{E_0} \right|^2 = \frac{t^2}{1 - 2r\cos\varphi + r^2} = \frac{t^2}{(1-r)^2 + 4r\sin^2\left(\frac{\varphi}{2}\right)} = \frac{\left(\frac{t}{1-r}\right)^2}{1 + \frac{4r}{(1-r)^2}\sin^2\left(\frac{\varphi}{2}\right)}$$

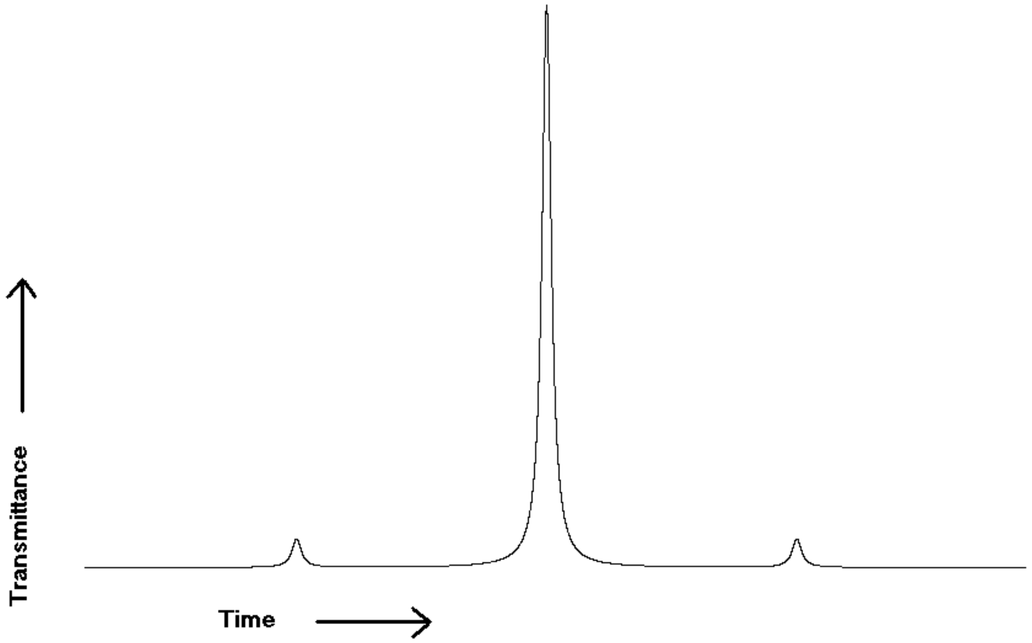
which reduces to

$$T = \frac{T_0}{1 + \left(\frac{2F}{\pi}\right)^2 \sin^2\left(\pi \frac{\upsilon}{\upsilon_r}\right)} \qquad \textbf{(Equation 7)}$$

$$T_0 = \left(\frac{t}{1-r}\right)^2, \quad F = \frac{\pi\sqrt{r}}{1-r}, \quad \upsilon_r = \frac{c}{2L}$$

The cavity allows for high transmittance when the frequency of the light is near the resonance frequency of the cavity. One of the mirrors on an OSA is mounted to a piezo-electric device, and by applying a voltage to the mount; the mirror may be moved slightly, altering the resonance frequency of the cavity. By applying a ramp voltage, the cavity effectively scans over a range of frequencies, transmitting power when the resonance frequency passes near a frequency present in the input light.

Figure 3. Theoretical plot of transmittance of power through an OSA as a function of time. The finesse of the cavity is 200.



Because this is a linear system, each component of the light may be considered separately and the results may then be summed. This property allows for the individual frequency components of the light to be isolated, and their power measured independently. By measuring the transmitted power versus time of a phase modulated signal, three spikes in the power will be observed as in **Figure 3**. The two small spikes are caused by the sidebands and the high central peak is a result of the carrier. As the power depends on the square of the electric fields, the ratio of the height of the carrier peak to the height of the sideband peaks is given as follows:

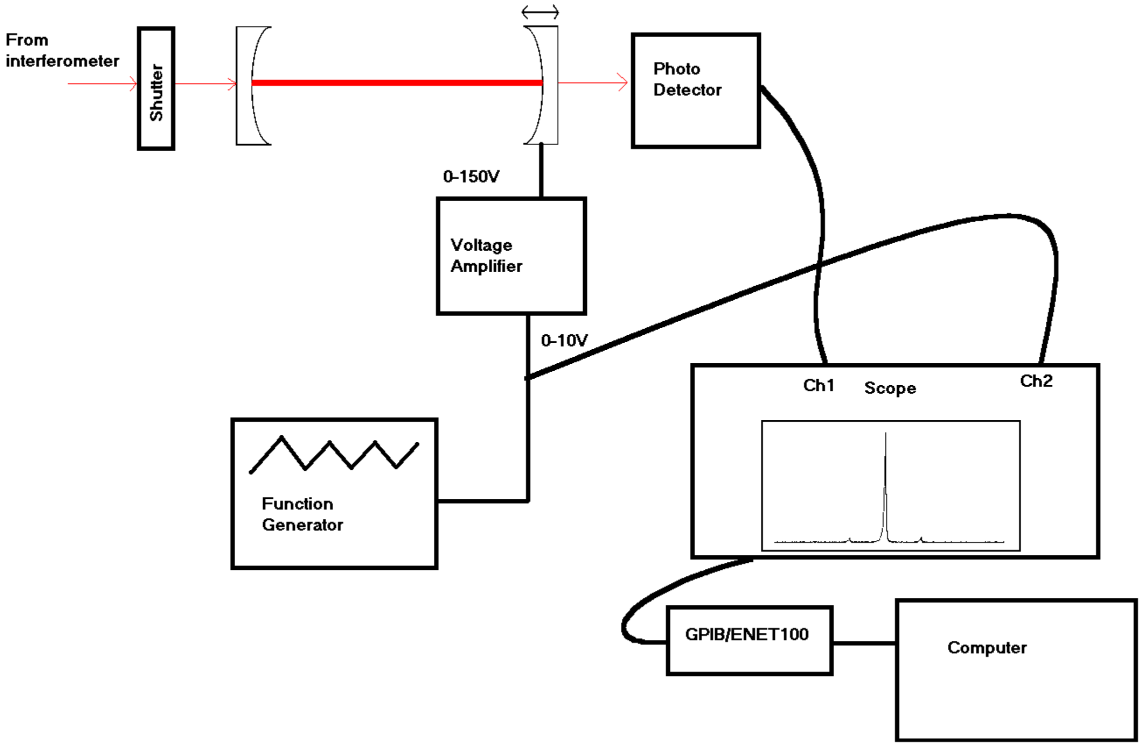
$$\frac{P_{\text{Sideband}}}{P_{\text{Carrier}}} = \left(\frac{J_0(\Gamma)}{J_1(\Gamma)} \right)^2 \qquad \textbf{(Equation 8)}$$

After obtaining a measurement for this ratio, it is possible to use numerical routines to determine the modulation depth, as described in **Section 2.3.1**.

2.2 Physical Implementation

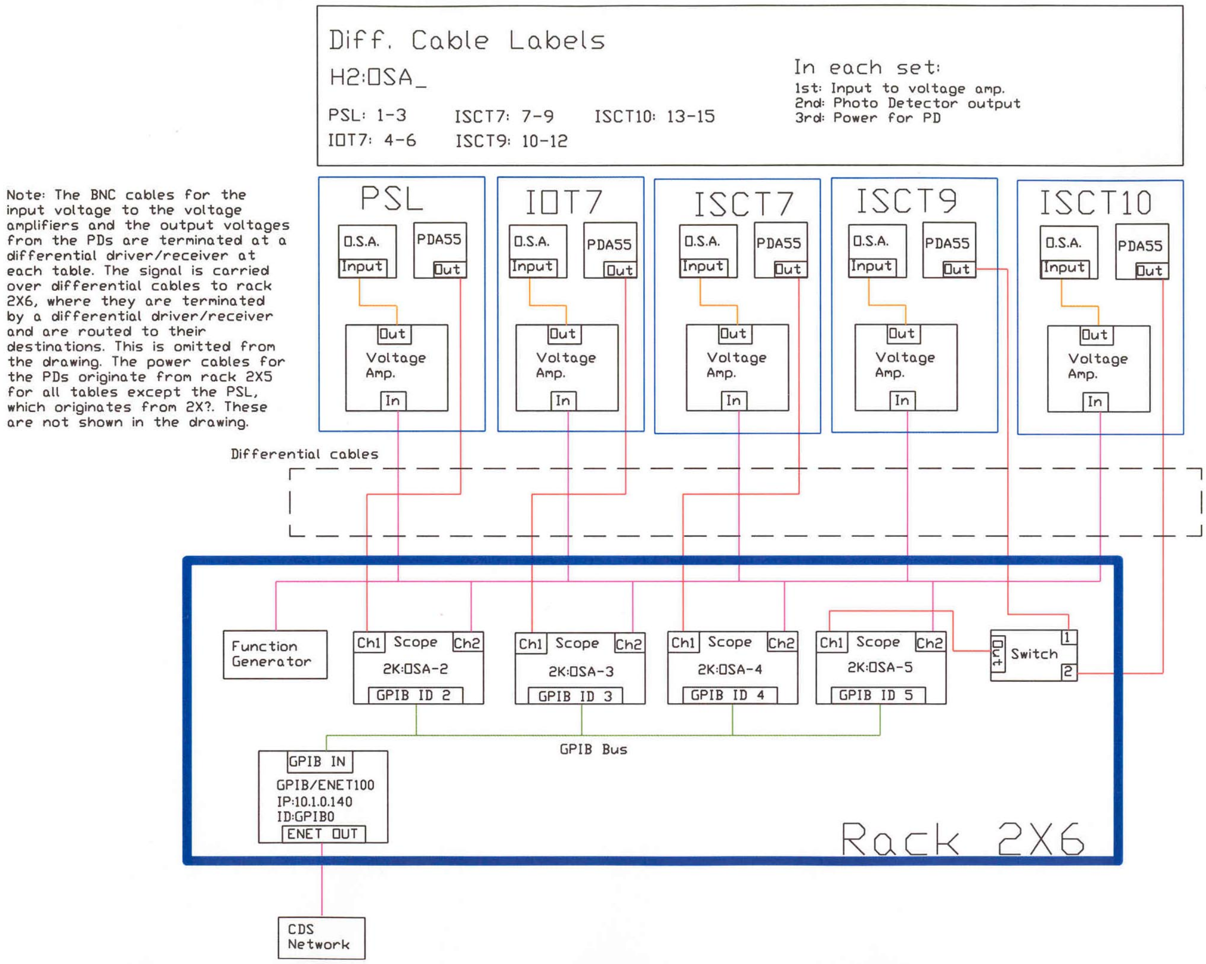
To measure the ratio of carrier power to sideband power with an OSA, there is a fair amount of equipment required. The OSA requires a ramp voltage of about 0 to 150 volts, so a function generator and voltage amplifier are required. A photo detector must measure the transmitted light, and the signal from the photo detector must be connected to an oscilloscope. The oscilloscope uses the signal from the function generator as a trigger that can be adjusted to keep the relevant part of the signal in view. The oscilloscope is connected to a computer network through a GPIB/ENET100 converter, which allows a computer to control its settings, and collect and analyze data. The OSA will reflect light back to its source, which will produce undesirable interference. To avoid this problem under normal circumstances, a shutter is installed between the OSA and its source. The shutter, when open, allows light to pass freely through, but when closed, reflects light to a beam dump. This prevents the OSA from reflecting light to its source when it is not in use. A generic diagram showing the basic connections is shown in **Figure 4**.

Figure 4. Basic layout of equipment necessary to measure relative sideband power at one location.



An OSA, photo detector, voltage amplifier and shutter are required to be present at each measurement location. The remaining equipment - the oscilloscopes, the function generator and the GPIB/ENET100 converter - are placed in a central location. A single voltage amplifier could have been used to drive every OSA, but doing so would require running long, high voltage cables, which are undesirable for safety reasons. Instead, a single function generator drives several voltage amplifiers, which are located near an OSA. The oscilloscopes must also be placed in this location because they must be connected to a single GPIB/ENET100 converter, and GPIB cables are limited to several meters in length. The length of the cables that the signals from the function generator and photo detectors must be carried also tends to produce noise in the signals. To avoid this, differential cables, which send the signal relative from one wire to another, as opposed from one wire to the ground, are used in place of BNC cables. The differential cables result in much less noise being produced and also avoid ground loops. A schematic of the equipment is shown in **Figure 5**. Each optical table is a large, conducting body, and all electrical devices in contact with the table will also be in contact with each other, which would result in additional ground current loops that produce noise. Therefore, all equipment is installed on the table using insulated screws and tape, which prevents electrical connections being made.

Figure 5. Schematic of equipment layout for all locations. PSL corresponds to the laser pickoff beam, IOT7 to the MC transmitted beam, ISCT7 to the Michelson reflected beam, ISCT9 to the asymmetric port and ISCT10 to the X pickoff beam.



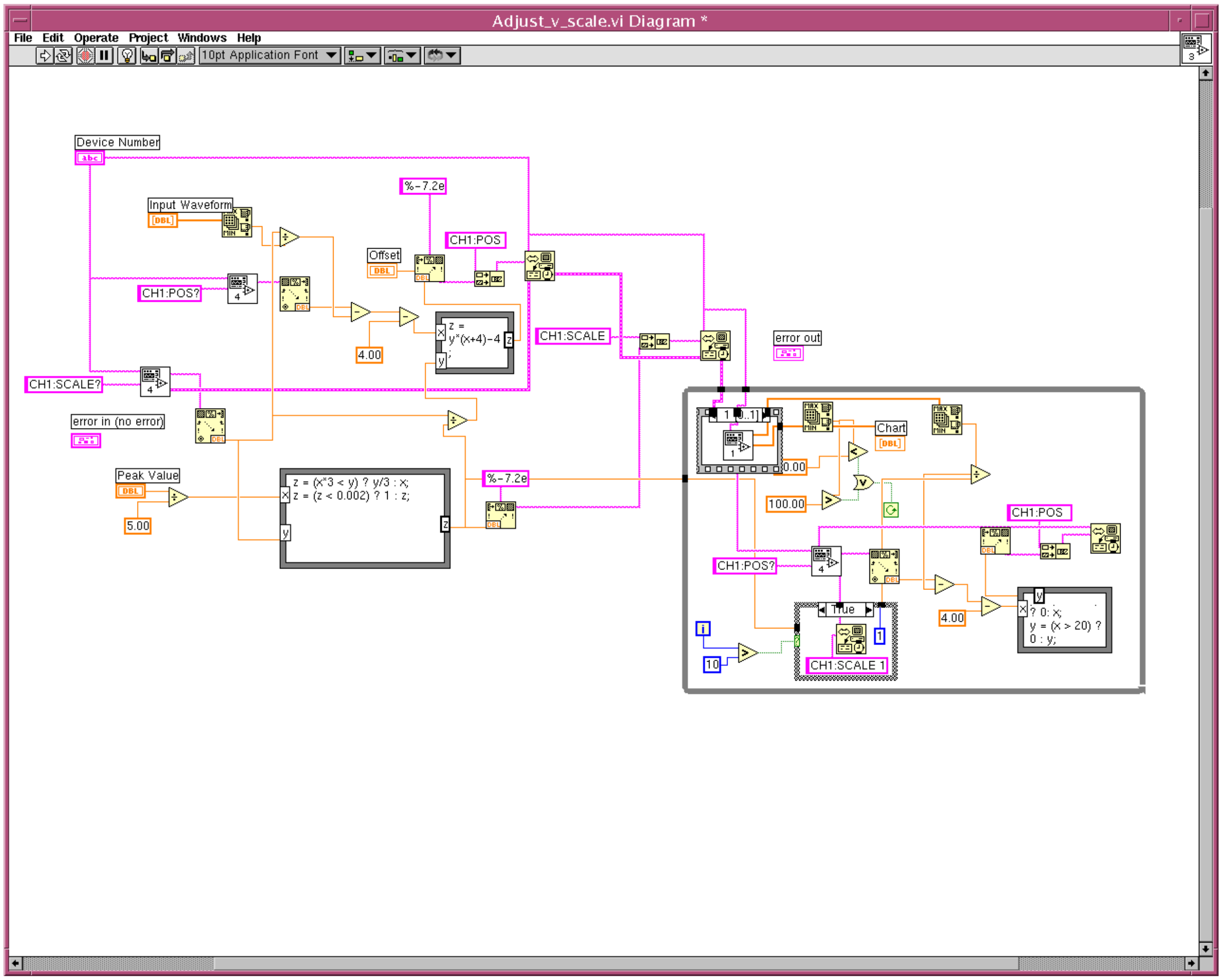
Note: The BNC cables for the input voltage to the voltage amplifiers and the output voltages from the PDs are terminated at a differential driver/receiver at each table. The signal is carried over differential cables to rack 2X6, where they are terminated by a differential driver/receiver and are routed to their destinations. This is omitted from the drawing. The power cables for the PDs originate from rack 2X5 for all tables except the PSL, which originates from 2X?. These are not shown in the drawing.

2.3 Software

2.3.1 Modulation Depth Measurement

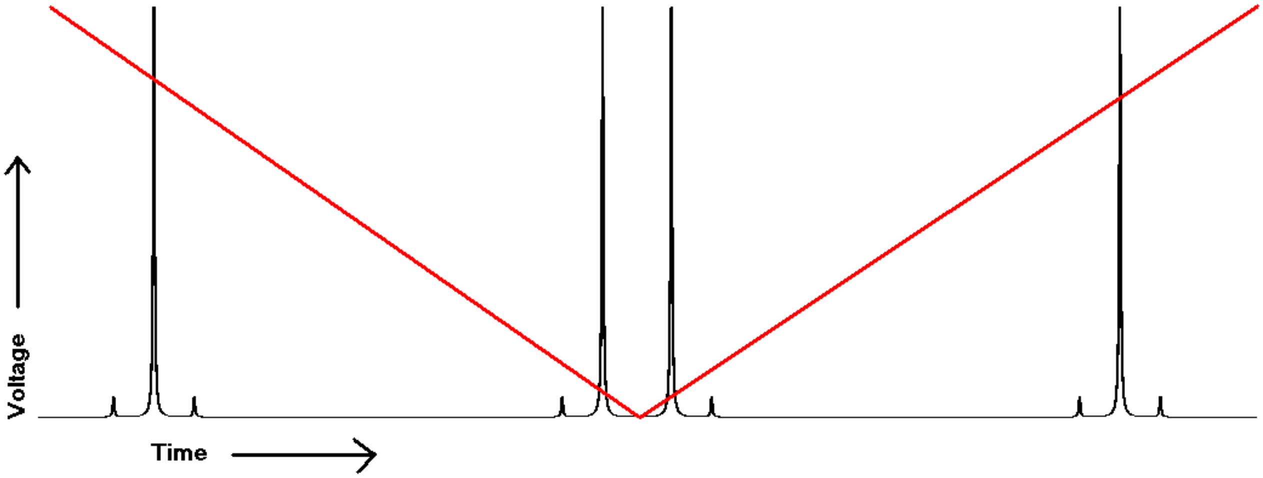
The software was written in LabVIEW, a graphical programming language. A typical diagram of a LabVIEW program is shown in **Figure 6**.

Figure 6. Typical LabVIEW application. The purpose of this one is to adjust the vertical scale of the oscilloscope for obtaining the best measurement.



The primary function of the software is to communicate with the oscilloscope, measure the heights of the peaks of the sidebands and of the carrier, calculate their ratio, and determine the value of the modulation depth. The software communicates with the oscilloscope through GPIB, or the NI-488 standard. The first step of the software is to initialize the settings of the oscilloscope, including the voltage scale, the time scale, the trigger source and level, and other various settings, as shown in **Appendix A** . The oscilloscope is set to obtain an average of 128 measurements, taken over approximately three seconds, to reduce noise. The next step is determining the heights of the sideband peaks and the carrier peak. There are two methods that the software uses to find these heights. Note that the piezo mount on the OSA tends to drift over time, so the horizontal position of the signal will also tend to drift. The software finds the position of the signal (simply the position of the maximum value), and if it drifts too far in either direction, will adjust the trigger value to move it back towards the center. Essentially, it will decrease the trigger if the carrier is too far in one direction, and increase the trigger if the carrier is too far in the other direction. In some cases, the software may center a carrier, but one of the sidebands may be cut off, as shown in **Figure 7**.

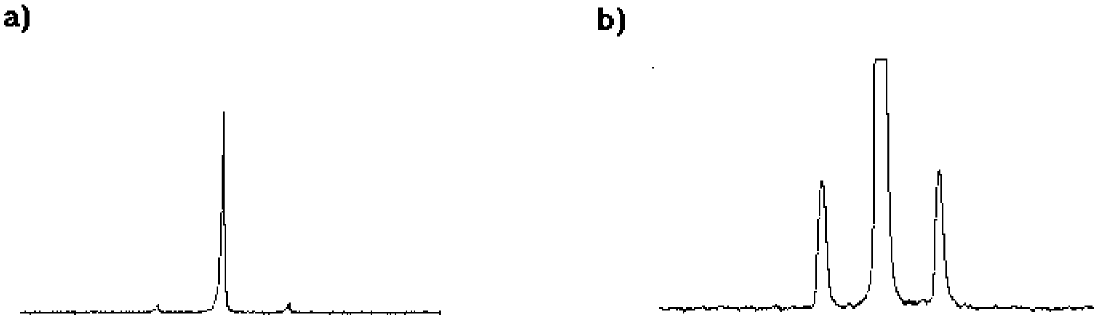
Figure 7. The red signal represents the driving voltage on the OSA. The black signal is the output signal from the photo detector, as seen on the oscilloscope. When the voltage on the OSA goes to zero, the right sideband is cut off. The oscilloscope and software only look at one fifth of what is shown here, which is enough to see both the carrier and sidebands in one plot.



If the carrier becomes too close to the rails of the driving signal, the software will automatically look to the other end of the waveform, in order to avoid this problem. It is guaranteed that there will be another carrier signal here because the OSA's mirror is moved approximately 1.5 wavelengths, or 1600 nm by the driving signal. The trigger adjustment is done in both methods. Note that there is only one method for extracting the heights from the waveform data; it is the method for obtaining the data that changes. The heights are obtained from a built-in peak-finder in LabVIEW, under the assumption that the two sidebands and the peaks will be the largest peaks in the data obtained.

The first method is the slower of the two, but also the more precise. It begins by adjusting the vertical scale and vertical position of the oscilloscope so that the carrier height is over half of the available scale, as shown in **Figure 8a**:

Figure 8. Part a is a typical graph that the software obtains when measuring the carrier height. Part b is a typical graph that the software obtains when measuring the sideband height.



There tends to be a significant amount of amplitude noise in these measurements, so the carrier is measured a certain number of times without the need of further adjustment. The operator can adjust the number of averages taken. After the carrier height has been obtained, the software lowers the vertical scale, until the sideband height is over half of the available scale, as shown in **Figure 8b**. The sideband measurement is averaged over the same number of measurements as the carrier measurement. The ratio of the sideband power to the carrier power is calculated from the results of both measurements.

The second method is much quicker (taking approximately 1 second as opposed to 10-30 seconds), but is also less accurate and cannot be used if the ratio of sideband power to carrier power is too small. This method simply adjusts the vertical scale so that the carrier height is over half the available scale, as shown in **Figure 8a**, and then measures both the carrier height and the sideband height from this data. This method will obviously be much faster because it does not need to adjust the vertical scale to measure the sidebands, but loses accuracy because the sideband height is given on a small scale. The oscilloscope transfers the data in an 8-bit format, giving each point a 0 to 255 scale. Typical sideband measurements performed in this way will give values of 5 to 15, which allow for a large degree of uncertainty in the measurements.

However, since this method can be performed much more quickly, many more measurements can be performed using this method and their results averaged, producing a more accurate result than a single measurement.

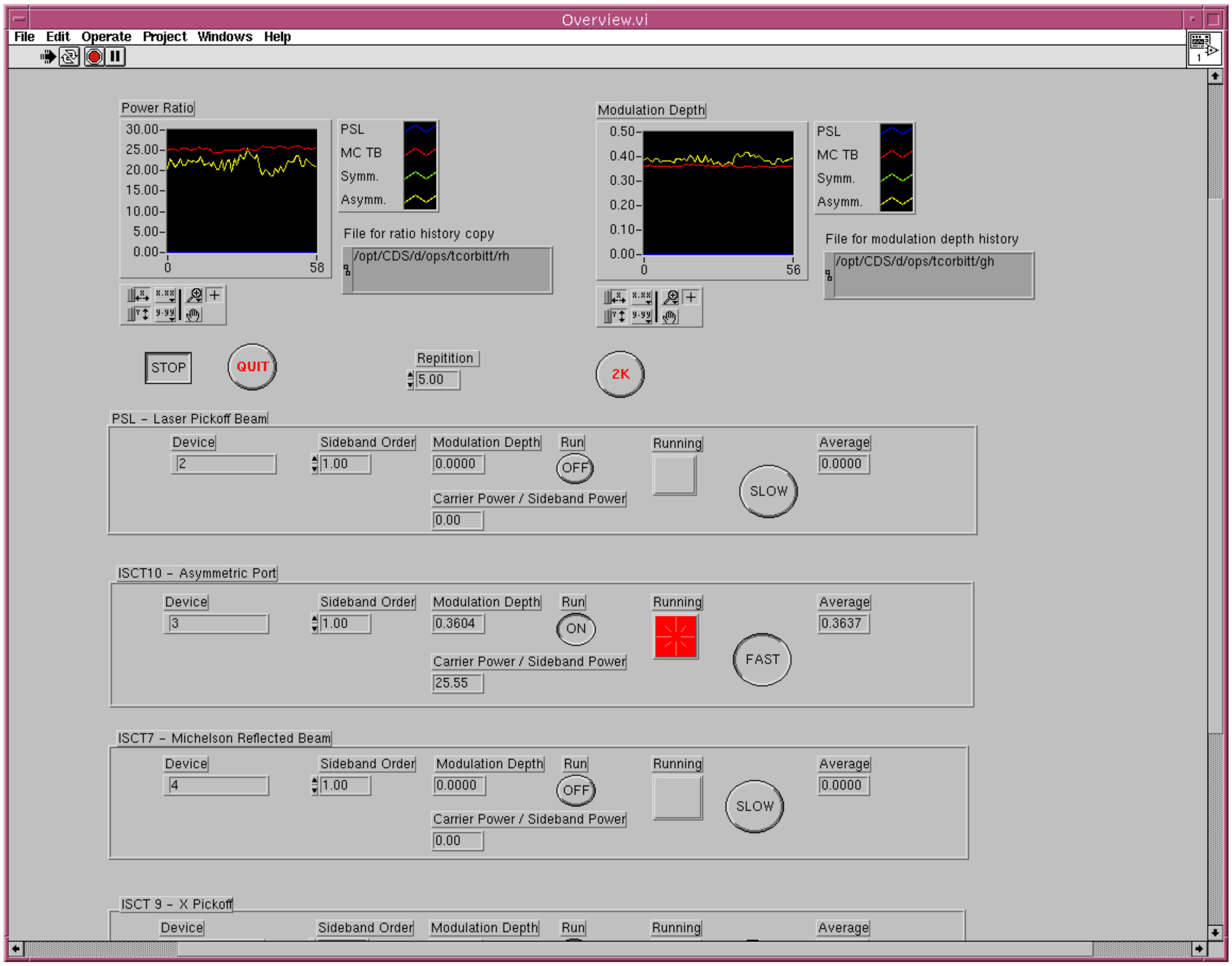
After the ratio of heights is obtained, the software uses numerical approximations of the Bessel functions of zero and first order[3] to obtain a value for the modulation depth. Beginning at zero, the software obtains the value by incrementing upwards in steps of 0.1, calculating the expected ratio of heights, as given by **Equation 9**. If the calculated ratio is less than the measured ratio, the software continues to increment in steps of 0.1. If the calculated ratio is more than the measured ratio, then the last step of 0.1 is removed, and the process is repeated in increments of 0.01. This process is repeated until five significant digits are obtained. Note that the operation of the interferometer does not strictly change the modulation depth, but rather the individual components at any given frequency. That is to say that the power present in the second and third order sidebands may be changed in such a way that they are not consistent with the measured modulation depth. In this case, the ratio of the powers of the first order sidebands to the carrier will be more useful. For this reason, both the ratio of the powers and the modulation depth will be displayed by the software. A screen of the software is shown in **Figure 9**. A record of the measured ratios and modulation depths along with the current time (specified in seconds since 12:00 AM, January 1, 1904 in Universal time) are saved to two user specified file. The format of the file is as follows:

<ratio/modulation depth of 1st measurement><TAB><2nd measurement><TAB><3rd measurement><TAB><4th measurement><TAB><time><EOL>

The data from these files can be read into any program and analyzed further. If a certain measurement is turned off, it will return a default value of zero.

Appendix A also shows a list of the routines the program uses, with a list of their input and output variables and a brief description of their functions.

Figure 9. Screenshot of the relative sideband power measurement program.



File for ratio history copy: /opt/CDS/d/ops/tcorbitt/rh

File for modulation depth history: /opt/CDS/d/ops/tcorbitt/gh

Repitition: 5.00

PSL – Laser Pickoff Beam
Device: 2
Sideband Order: 1.00
Modulation Depth: 0.0000
Run: OFF
Running
Average: 0.0000
Carrier Power / Sideband Power: 0.00
SLOW

ISCT10 – Asymmetric Port
Device: 3
Sideband Order: 1.00
Modulation Depth: 0.3604
Run: ON
Running
Average: 0.3637
Carrier Power / Sideband Power: 25.55
FAST

ISCT7 – Michelson Reflected Beam
Device: 4
Sideband Order: 1.00
Modulation Depth: 0.0000
Run: OFF
Running
Average: 0.0000
Carrier Power / Sideband Power: 0.00
SLOW

ISCT 9 – X Pickoff
Device
Sideband Order
Modulation Depth
Run
Running
Average

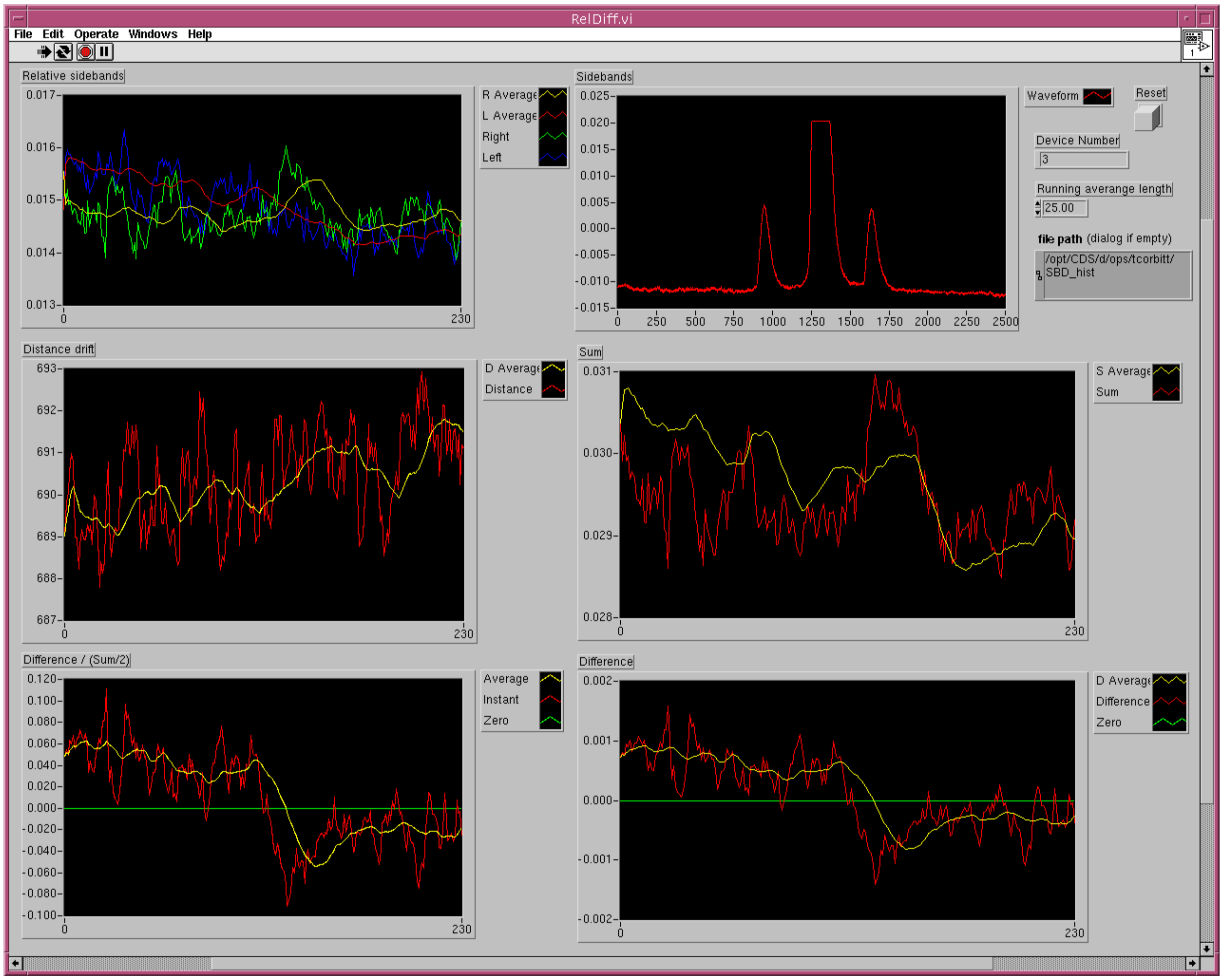
2.3.2 Comparing Sidebands

The LIGO interferometers were carefully designed so that both the lower and the upper sideband would resonate at the same levels in the cavities. Any asymmetry between the two is an indication that this is not the case. To test the sidebands against each other, software was developed that compares the heights of the sidebands to each other. The software first adjusts the vertical scale so that the sideband height is approximately half the available scale, then continually tracks the sideband heights, their difference in heights, the distance between them, their sum, and their difference over their average, as shown in **Figure 10**. To reduce noise in the signal, a running average, of user specified length is also displayed. The data from these measurements, along with the current time (specified in seconds since 12:00 AM, January 1, 1904 in Universal time) is saved to a specified file in the following format:

<left sideband><TAB><right sideband><TAB><running ave. left><TAB><running ave. right><TAB><time><EOL>

This data can then be read in any external programs and the data further analyzed.

Figure 10. Screenshot of the sideband difference measurement program.



Device Number
3

Running averange length
25.00

file path (dialog if empty)
/opt/CDS/d/ops/tcorbitt/SBD_hist

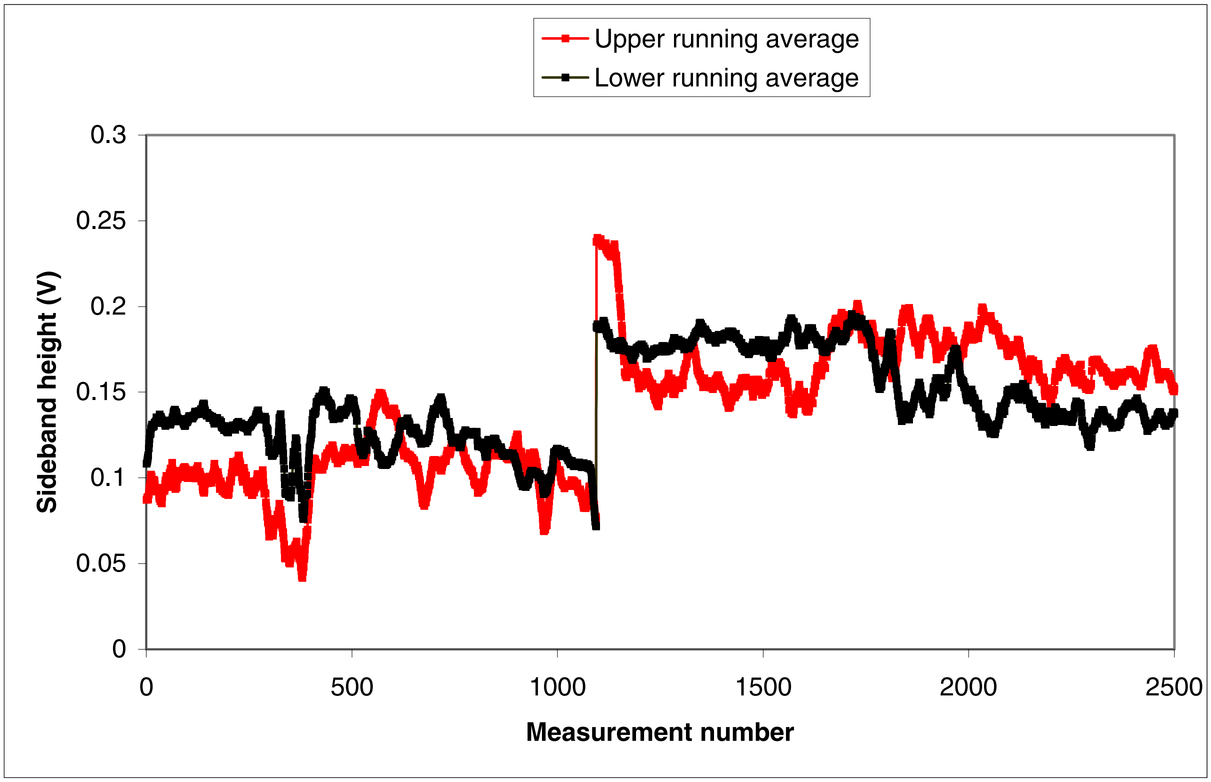
3 Results

The system has been tested with the Hanford 2K interferometer in several configurations. In most locations, the amount of light available to be used for the measurement is very low. Measurements must be taken with as little as 10 microwatts of light. Such a low power signal only allows for a carrier peak voltage of about 20 millivolts from the photo detector. While this is sufficient for measuring the carrier, the sidebands will ordinarily only have about 5% of the power of the carrier, which results in a 1 millivolt signal from the sidebands, which is too low to reliably and accurately measure. To overcome this problem, pre-amplifiers are used to both amplify and filter the signal from the photo detector. A gain ranging from 20 to 100, depending on how much light is being used, and a low pass filter with 3 kHz bandwidth must be used in three of the five locations to obtain a good signal.

Once the equipment is in place, it takes only several minutes to prepare the system for use. The equipment may be left in a ready state all the time, with the exception of the shutters. For making the modulation depth and ratio measurement, the amount of time necessary per measurement will vary somewhat. For the quick measurement, which obtains data for both the carrier and sidebands simultaneously, several seconds are required to first find the carrier, center it, and adjust the vertical scale and position. After this is done, each subsequent measurement will take approximately 0.8 seconds. The limiting factor is the transfer speed of data from the oscilloscope to the computer. The slow system records an average value of the modulation depth and the ratio of powers over a user-specified number of measurements. With the default number of five measurements, the system takes approximately 25 seconds to record values, resulting in an average measurement time of 5 seconds. The overhead in this method – adjusting the vertical scale to focus on the carrier and then the sideband – is a constant time delay, so as the number of measurements is increased, the average time per measurement will decrease asymptotically towards twice the time for the fast system. This occurs because the slow system must transfer two sets of data for each measurement. The relative sideband measurement takes approximately 0.8 seconds, as it as limited by the transfer speed as well.

The ratio of powers and modulation depth measurements were found to work reliably, with reasonably accurate measurements being obtained in all cases that were tested, with measurements for the ratio of carrier power to sideband power ranging from 2 to 50. The measurements have been repeated over a hundred times for the both the fast system and the slow system (the slow system actually made 30 iterations, making 5 measurements each iteration), with no user intervention, and a proper result was obtained for each measurement. The sideband asymmetry measurements were made several thousand times, with no user intervention, without losing tracks of the sidebands. A simple graph showing the sidebands' behavior over this time is shown in **Figure 11**.

Figure 11. Sideband heights over time. The sudden jump in the heights was a result of the arms of the interferometer losing, and regaining lock.



4 Discussion

There are several improvements that can be made to this system. The most important will be the ability to remote control the safety shutters. Currently, opening the shutters requires physically going to the optical tables and flipping a switch. A better setup would have the shutters controlled by the software, so that the operator has no need to enter the vicinity of the interferometer. Additionally, investigation into improving the transfer speed of data between the oscilloscope and the computer should be made. The GPIB bus is rated at 10 megabits per second, and the computer network at 100 megabits per second, but the effective transfer speed is only 50 kilobits per second. The massive discrepancy in transfer speeds appears to be a result of the oscilloscope requiring time to prepare the data to be transferred (transferring 100 data points requires 75% as much time as transferring 2500 data points), although a more detailed study is needed to confirm this.

Measurements have been made for the ratio of carrier power to sideband power with the interferometer in several configurations. The results of these measurements are shown in **Table 1**:

Table 1. Measurements made of carrier power to sideband power in various interferometer configurations. Infinite values refer to there being no detectable sidebands found. Zero values refer to there being no carrier.

	Recycling cavity locked to carrier frequency (arm cavities not locked)	**Recycling cavity locked to sideband frequencies (arm cavities not locked)**	**Both arm cavities locked**
Initial Ratio (PSL)	22.78	22.73	22.65
Michelson Reflected	∞	0	5.26
Asymmetric Port	8.13	26.91	7.25
X-Pickoff	∞	0	97

The data has only been taken recently and there has been insufficient time to analyze it. Further work should include both analyzing this data, as well as taking further data with both arm cavities in the interferometer locked. Taking additional data in this configuration, and investigating how the ratios change over periods of time and how the ratios change when the interferometer loses and regains lock are necessary steps to understand the interferometer's operation.

5 Conclusions

The automated system to measure relative sideband power and to look for asymmetries in the sidebands has been both developed and installed on the Hanford 2K interferometer. The system currently provides an effective, expeditious and practical method for making these measurements. For ideal operation, it will be necessary to automate control of the safety shutters, and improve the transfer speed of data from oscilloscopes to the computer as much as possible. There are already plans for installing systems on the Hanford 4K and Livingston 4K interferometers.

6 Acknowledgements

I would like to thank Daniel Sigg for being my mentor and helping me work through the problems encountered with the project. I would also like to thank everybody in the EE laboratory who helped with the installation of the equipment and cables.

Appendix A

Table 1. Initial commands set to oscilloscope

Command	Note
HEADER:OFF	Header is no longer returned in queries
CH1:SCALE 1	
CH1:COUPLING DC	
CH1:BANDWIDTH OFF	
CH1:PROBE 1	
CH1:INVERT ON	Signal becomes inverted by cables, this is needed as a fix
HORIZONTAL:DELAY:POS 0	
TRIGGER:TYPE EDGE	
TRIGGER:MAIN:EDGE:COUPLING DC	
TRIGGER:MAIN:EDGE:SLOPE FALL	
TRIGGER:MAIN:EDGE:SOURCE CH2	
TRIGGER:MAIN:EDGE:MODE AUTO	
ACQUIRE:NUMAVG 128	
ACQUIRE:MODE AVERAGE	
HORIZONTAL:MAIN:SCALE 5E-4	

Table 2. VIs constructed for program.

Name	Inputs	Outputs	Function
Adjust_Trigger	Device Number, Max Index, Max Value(unscaled),	Trigger Level	Adjusts trigger of specified oscilloscope so the Max Index becomes the center of the domain.
Adjust_V_Scale	Device Number, Peak Value, Input Waveform	Error Out	Adjusts vertical scale of specified oscilloscope, so that the specified peak value will occupy about 60% of the available range.
Average	Input Array	Average	Returns average value of the input array.
GPIB_query	Device Number, Query String	Output String	Queries specified device with query string. Reads output in “block format.” Currently only used for retrieving curve data.
Get_Curve	Device Number	Waveform Array, Unscaled Data	Reads waveform data(scaled) and unscaled data from specified device.
Get_Mod	Device Number, Number Repititions, Sideband Number	Modulation Depth, Carrier Power/Sideband Power	Retrieves data from oscilloscope, and analyzes it to obtain the modulation depth and ratio. Performs the measurement the specified number of times and returns the average. (Slow system)
Get_N_Order	Device Number, Order Peaks	Right Sideband, Left Sideband, Diff. Index, Area, Output Peak, Scaled Data	Gets the specified sideband number (0 for carrier) and returns relevant information.
Get_Peak3	Input Array, Order	Peak, Right Sideband, Left Sideband, Distance, Indices, Difference in Power, Max	Analyzes the data to extract the information. Peak is the average of the two sidebands, distance is the difference in the indices, Indices is a four member array, containing the starting indices and length of the peaks, Max is the maximum of the two peaks.
Menu	N/A	N/A	Top-level interface. Allows user to open Overview or Reldiff
Overview	N/A	N/A	Top-level interface. Allows user to choose settings and measurements for taking modulation depth and ratio measurements.
Reldiff	N/A	N/A	Reads data from specified oscilloscope and compares sidebands to determine their degree of asymmetry.
TrailingAverage	Array, Number	Output Array, Average	Truncates input array to reduce its size to match the input number, if necessary, and returns the average of the new array, as well as the new array. To use this VI, append new data into an array, pass array through VI, and replace the source array with the output array.
Gpib_q	Device Number, Query String	Output String	Queries specified device with specified string and returns the result.
Side	Device Number, Sideband Number	Modulation Depth, Ratio	Retrieves data from oscilloscope and analyzes it to obtain information. (Fast system)
Suminterval	Input array, Start, Length	Sum	

Appendix B

Instructions for relative sideband measurement software

1. Select the measurements to make by pushing the “Run” button in each desired frame. The device number which corresponds to each measurement location is determined by the connections made by the cables in rack 2X6, so it is required to check the cables to know which device numbers to use.
2. Select “SLOW” or “FAST” measurements for each location. “SLOW” measurements are recommended in most cases because of greater reliability and accuracy.
3. Press the run button to begin taking measurements. Measurements will continue to be taken until the button is pressed again, with the results being shown numerically, graphically, and being saved to a specified file.

Instructions for sideband asymmetry measurement software

1. Select the device to take measurements from, select the running average length and press the continual run button (two arrows in a circle at the top left of the window).
2. Press the reset button to clear the graphs, if desired.

Note: To run the software, you must be logged in to “control3,” and the software is located at “/opt/CDS/d/ops/tcorbitt/SBM3.”

References

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3. W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, *Numerical Recipes in C* (Cambridge Univ. Press, New York, ed. 2, 1997), pp. 232-3.
