Development of a High-Speed Data Acquisition Channel

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Abstract

A set of data acquisition units sample the signals from the LIGO interferometers and supporting sensors such as seismometers. These units convert the analog signals to digital data, sampling at 16384Hz or less. A fast channel, sampling at 262144Hz, was developed and the necessary software changes were made to the data acquisition system. A heterodyne algorithm was developed to sample data from a narrow frequency band and record at a much lower rate. A frequency band of interest is the next free-spectral-range of an arm cavity at 37.520kHz where the gravitational-wave sensitivity peaks again with a full-width-half-max of 200Hz. A calibration was performed to relate the measured digital data to displacement sensitivity of the interferometer.

Introduction

The Laser-Interferometer Gravitational-Wave Observatory at Hanford employs a series of data acquisition units to bring in data from various sources. These sources range from seismometers to the actual detectors on the interferometer. Currently these channels operate at a maximum rate of 16.4kHz, which limits the signal bandwidth to about 8kHz.

For the purposes of diagnostics the observatory team desires a new channel that can record data at a rate of up to 262kHz. This new channel will be used specifically to look at data from the interferometer detectors. The extended frequency range will contain information about several noise sources such as noise from the input beam and the internal modes of the test masses. The primary motivation, however, is to view data from a 200Hz band around 37.520kHz.

The displacement sensitivity of the LIGO interferometer peaks at multiples of the free spectral range of the arm cavities - 37.520kHz[1] for the four kilometer arm - and the new channel will enable observations of this second peak. A frequency band centered at 37.520kHz will have significantly less strain sensitivity than the primary band, but different directional sensitivity, specifically a zero for waves coming from above at the 37.520kHz, so it may contain useful gravitational wave data.[2]

In order to use this data effectively, the new channel heterodynes the sampled data so that the rate written to the network will be manageable. The heterodyne algorithm will be used to tune output channels to specific noise bands.

Methods

Physical Structure

The physical structure of the device is shown in Figure 1. There are four main devices: the whitening board[3], CPU[4], ICS130[5] and the timing board.[6] The whitening board takes the quadrature (Q) and in-phase (I) demodulated signals from the third and fourth photodiodes of the anti-symmetric port and boosts frequencies between 100Hz and 100kHz by a factor of approximately 625.

The timing monitor takes a clock signal from the GPS system and pro-

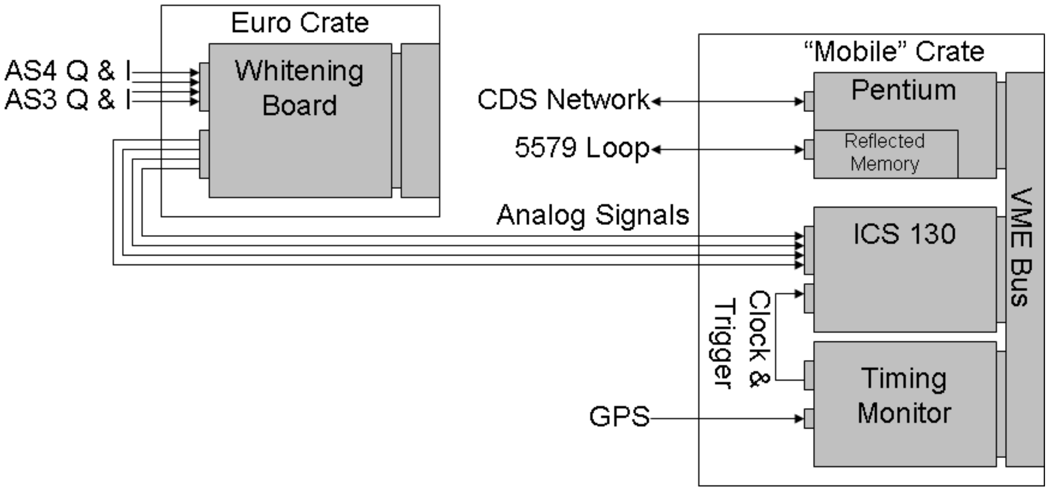


Figure 1: Physical structure of the unit.

duces a 4MHz (2^{22}Hz) clock and a one pulse-per-second signal aligned to UTC. These signals are used for the clock and trigger signals for the ICS130, respectively.

The ICS130 is the analog to digital converter. It takes the output signals from the whitening board and oversamples them at a rate of 4MHz using a sigma-delta type ADC and the clock from the timing monitor. The trigger from the timing monitor is used to line the samples up with the common one second boundary used in the rest of the data acquisition network. The ICS130 filters and decimates the incoming data down to the 262kHz (2^{18}Hz) output rate.

The CPU is where the majority of the data manipulation occurs. This board communicates with the data acquisition network through a reflective memory daughter card.[7] The reflective memory card appears as a portion of the CPU's address space and is connected to a fiber optic network. Every reflective memory card on the fiber loop presents the same data by transmitting anything written to it to the other cards.

The CPU takes the digital data from the ICS130, manipulates it as necessary and sends it out over the reflective memory. The software to be executed is obtained from a standard ethernet connection to the CDS network. Some configuration is obtained from startup scripts on the CDS network and the remainder is obtained from the EPICS configuration management through the reflective memory.

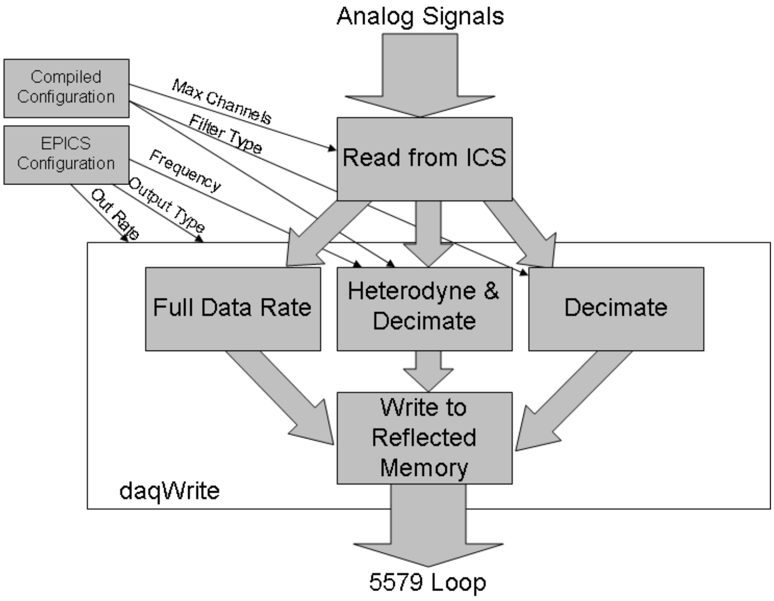


Figure 2: Data flow through the unit.

Data Flow

Figure 2 depicts the flow of data through the CPU. There are two general sets of configuration items – ones that are configured through defines in the code and startup script and ones that are obtained from EPICS at runtime. The digital sample data is read from the ICS130 with a configuration option telling the CPU how many channels (signals) to read. Once the data is in the CPU's memory, the EPICS configuration determines the output format of the data to be sent to the reflective memory. This involves mapping each incoming channel to zero or more output channels each with a given output rate and type.

The output type can concievably be any power of 2Hz from 2^4Hz up to 2^{18}Hz, but currently only 2kHz, 16kHz and 262kHz are supported. The output type may be a 16 bit integer, a 32 bit floating-point number or a complex pair of 32 bit floating point numbers. The complex pair is only valid for heterodyned channels which additionally require a heterodyne frequency.

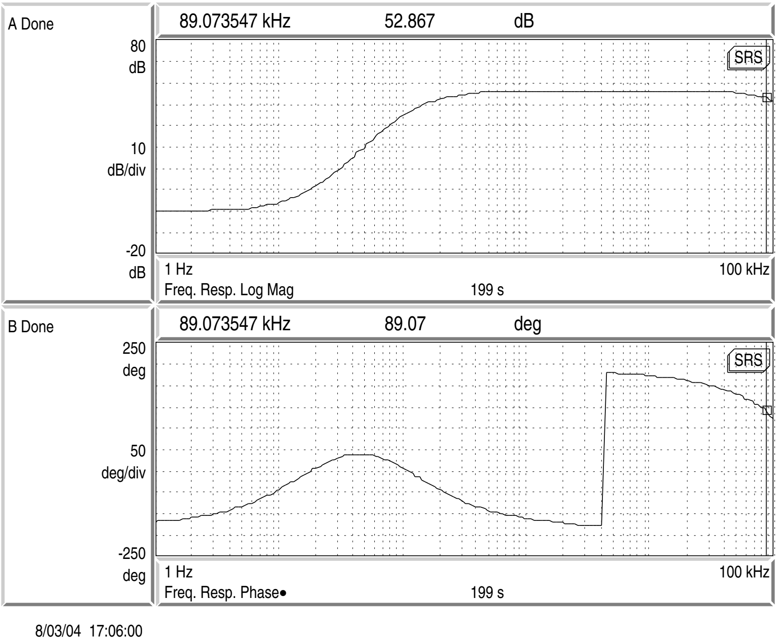


Figure 3: Transfer function of the whitening board.

Whitening Board

The whitening board was designed by Daniel Sigg. A printed circuit board was fabricated and the electronic components were manually soldered on to it. A custom cable was made to connect the 9pin output from the whitening board to the 44pin input to the ICS130. The transfer function has four zeros at 20Hz and four poles at 100Hz in addition to a pole at 150kHz and one at 300kHz. This causes a gain of approximately 625 in the range 100Hz to 100kHz and some antialiasing above that range. The measured transfer function is displayed in Figure 3.

Timing Monitor

The timing monitor was an existing board created for use with the earlier analog-to-digital converters. The one pulse-per-second signal was wired to pin 18 on the output header and a custom cable was made to bring the clock and 1PPS signals from the timing monitor to the clock and trigger signals of the ICS130.

Fast Channels

The 262kHz channels had to be buffered to output data on 16kHz (2^{14}Hz) cycles to prevent disruption of the other devices on the reflective memory loop. To run all eight available channels at the full data rate required rewriting the majority of the reflective memory output routine because the existing routine was not fast enough.

Heterodyned Channels

The heterodyned channels are the most computationally intensive portion of the entire unit. The tasks that must be performed can be divided into decimation and complex heterodyne stages. The heterodyne consists of multiplying by the sin and cos parts of an imaginary exponential of a given frequency. The frequency is required to be a multiple of 128Hz. This allows the precalculation of an array of sin and cos values, removes any possibility of phase drift and greatly reduces the runtime of the heterodyne stage.

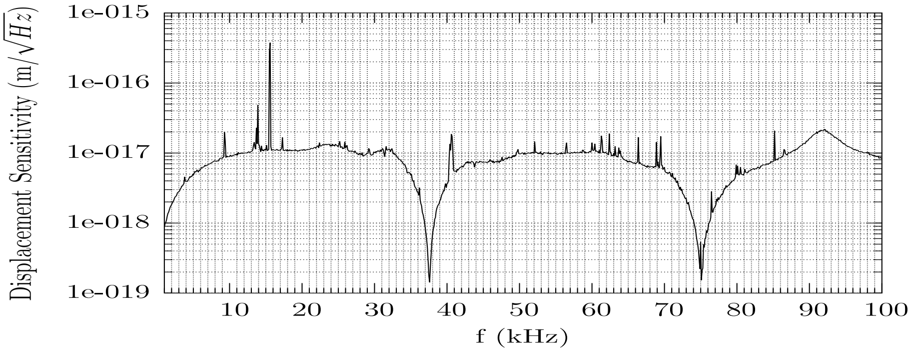
The decimation stage applies a filter to remove frequency components above the Nyquist frequency and then simply takes one out of every N samples, where N is the decimation factor. For efficiency, the heterodyne algorithm will attempt to decimate before the multiplication of the imaginary exponential because the incoming data has only the real part, while after the multiplication, both real and imaginary parts must be filtered.

At this point, the configuration possibilities start to grow exponentially. The preferred filter type would be an FIR filter because it does not affect the phase of the incoming waveform, but it is computationally expensive and so is limited to two channels. Instead it has been decided to use an IIR filter. Specifically, an elliptical filter with 0.1dB passband ripple and 90dB attenuation on the stopband.

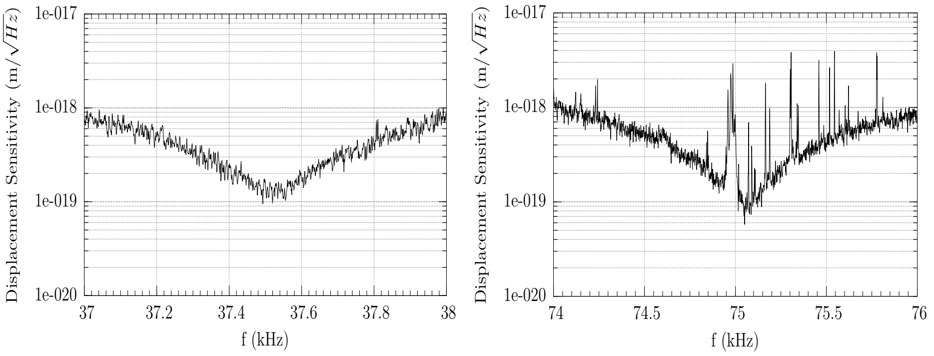
Another consideration is the use of a high pass filter before the heterodyne stage. The algorithm has been constructed to leave open the possibilty of runtime configuration of these various options.

Strain Calibration

As a verification procedure, a strain calibration was performed. The strain calibration is done by causing a known distance change in the interferometer and comparing it to the observed signal. This proportion is then applied to



(a) Broad-spectrum sensitivity.



(b) Sensitivity at the second FSR.

(c) Sensitivity at the third FSR.

Figure 4: Displacement sensitivity on the fast channel.

a measured noise spectrum in combination with the cavity sensitivity curve to produce an overall strain sensitivity.

The precise procedure was as follows: The existing 973.3Hz excitation of 0.015 counts on DARM was used. This excitation produces a $1.44 \cdot 10^{-17}$m-pk differential length change observable at the anti-symmetric port, after correcting for the driving frequency. The signal from the photodiodes was then measured. Due to time and availability constraints, only the AS3 Q signal was used which further implies the lack of any correction for the 13.602° phase offset. A power spectrum was taken of the measured signal and the 973.3Hz calibration line was measured at $1.17 \cdot 10^{-7}$V-rms, after compensating for the whitening board.

The cavity equation has the form $\frac{t_1^2}{1-r_1 e^{-i2\pi f_o/f_{FSR}}}$ where r_1 and t_1 are the reflection ($\sqrt{0.97}$) and transmission ($\sqrt{0.03}$) coefficients of the recycling cavity, f_{FSR} is the free spectral range and f_o is the frequency offset from DC.

A noise spectrum was measured during common mode operation; this spectrum had units of V-rms/$\sqrt{Hz}$. Dividing by the measured voltage, multiplying by the calculated length change and dividing by the normalized cavity equation produces the strain calibration spectrum seen in Figure 4 with units of m/$\sqrt{Hz}$.

Final Configuration

For the final configuration, it has been decided to run with four channels both at the full rate and heterodyned at 37.504kHz, which is the nearest multiple of 128Hz to the second gravitational wave band, centered at 37.520kHz. The heterodyned channels will output at a rate of 2.048kHz. The channels will be connected to the quadrature and in-phase signals from the third and fourth photodiodes on the anti-symmetric port.

Running the fast channels for long periods of time seems to be related to instabilities in the frame builder. This does appear to be a problem with the frame builder, not the data acquisition unit and so its repair is beyond the scope of this project. The interim solution is not to run the faster channels unless they are actively being used. A few days prior to the end of the project, an unknown problem arose with running four fast channels and so the number was decreased to two.

Data Analysis

Near the end of the project, work began on the final project goal of high-frequency data analysis. Only a limited amount of time was spent on this section of the project. Some Matlab code was designed to recreate the combined Q and I signals from the heterodyned channels in the second GW band. Another set of functions was designed to boost the weighting of the center frequencies near the sensitivity peak using an FIR filter and finally to monitor the signal power with an event detection threshold. Insufficient progress was made to produce something useful.

Matlab

Throughout the project, a number of Matlab scripts were produced. These included scripts for the calculation, measurement and analysis of transfer functions of IIR filters, the design of simple FIR filters directly from the desired transfer function, digital dewhitening filters, modulation routines for the heterodyned channels as well as a number of other functions. These scripts will probably not find utility outside this project.

Conclusions

At the end of the project a working data acquisition unit was turned over to Dave Barker. The project goals of a set of fast channels and heterodyned channels have been met completely.

The end products of the project are:

1. The whitening board.
2. The modified timing monitor.
3. The fast ADCU code.
4. The Matlab scripts.

Further

During the course of this project, a number of unidentified lines have been found in the spectrum of the various photodiodes. It may be useful to revisit these features and catalog and identify the more significant ones. This new channel also creates a number of opportunities in terms of data analysis – not just identifying the lines in the spectrum but categorizing their behavior.

Future projects may use the heterodyned channels to lock in on a specific noise source for long-terms studies. And finally, the use of the heterodyned channels provides a practical and potentially permanent observation method for the search for gravitational waves in the second GW band.

Acknowledgements

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