To: Trey German, Advisors

From: Team 4, Eric Taylor and Raymond Montgomery

Date: 4/20/2015

Subject: Final Report

Executive Summary

This project's objective was to design an oscilloscope BoosterPack (a hardware extension of a LaunchPad) that is compatible with TI LaunchPads (a programmable micro controller and its peripherals) that is a low cost alternative to the typical desktop oscilloscope. This project was open source so anyone can learn from the hardware and software design and be able to expand upon them. The final product must be able to function as a reliable oscilloscope at an affordable cost to both hobbyists and students. As a low end design, the oscilloscope BoosterPack needs to push its cost down as much as possible while having the features of a typical oscilloscope. The main goal was to create a BoosterPack that has two measurement channels that can take a +/- 15V signal and has a bandwidth of 7MHz for under $50. Future work on a similar project should look into being able to take the full capabilities of the ADC and adjusting the front end so it can be attached to a multitude of probes.

1. Introduction and Project Overview

Our client Trey German from Texas Instruments (TI) wants a BoosterPack that can function as a low cost oscilloscope for TI's series of LaunchPads. This project would be available to both hobbyists and professionals so they can easily buy and attach this BoosterPack to a LaunchPad and have a low cost oscilloscope. This BoosterPack is compatible with the Tiva C Connected LaunchPad so TI can expand its market for LaunchPad, BoosterPack, and Energia (TI's open source C++ programming language) products by utilizing resources made by TI. With the successful completion of the oscilloscope BoosterPack there will be a lower cost alternative for the current oscilloscopes that are available on the market. The client would like the designs and code to be open source, the coding to be done in Energia, a user's manual, a prototype of the design, and the code and designs used to create the prototype. We were able to create an oscilloscope BoosterPack that was able to take inputs from two channels and trigger off one. The signals can range from -1.5V to 1.5V and has a bandwidth of 200k. These shortcomings can be solved in software with some additional hardware as you will read later.

Contents

2. Accomplishments

The project was to create an oscilloscope BoosterPack for TI's Launchpad series which had the following features: two measurement channels, hardware triggering, user control, 6.5 MHz bandwidth, and +/ 15V input swing for all under $50. The reasoning behind the selection of these features can be seen below. In our final product we were able to accomplish most of what was needed but not all. The BoosterPack did have two working channels and a hardware trigger for under $50, however the software could not sample fast enough to get the 6.5 MHz bandwidth and adjustments are needed on the front end to get a full +/- 15 V input swing. The final board we made had a 200 kHz bandwidth and +/- 1.5V input swing.

2.1 Description of the Primary Stakeholders and Features

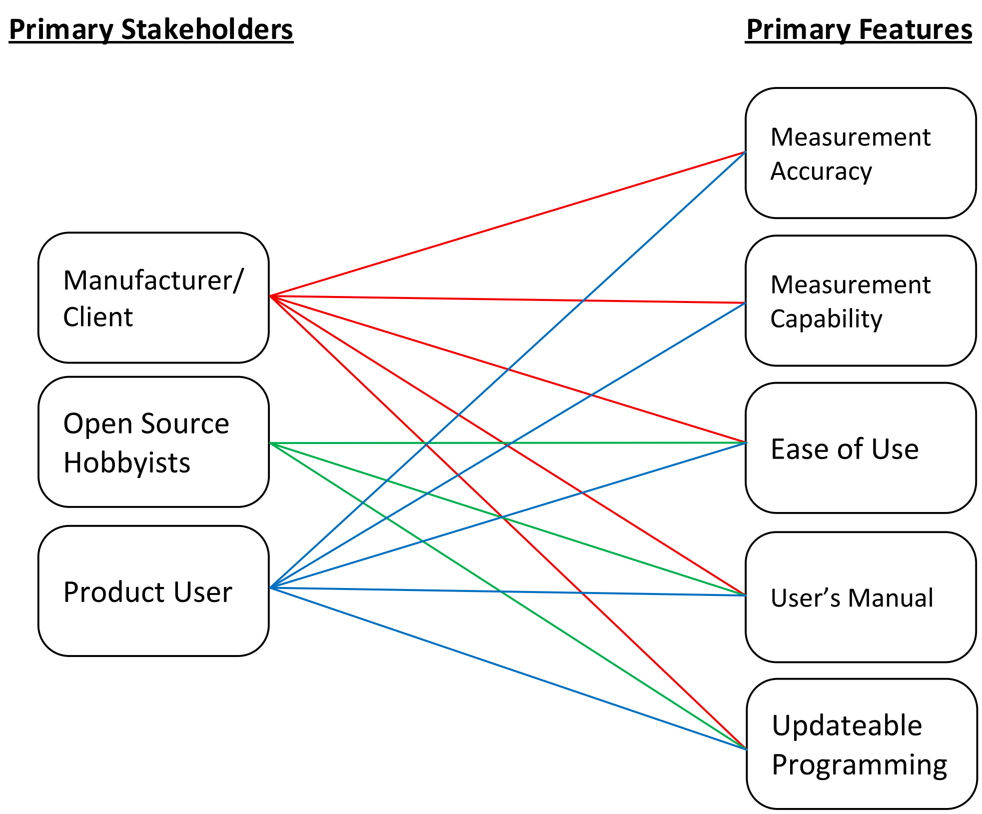


Figure 1. Primary Stakeholders and Features

The final product which consists of our physical circuit, the code that runs it, and the open source material all of which are determined by the primary stakeholders and features of our system. The client, TI, provided this project submission and therefore cares about all the deliverables they requested. Anyone who uses the oscilloscope BoosterPack wants a functional final product and would want to reference the open source material for debugging errors and exploring the design of the product. Those who do own the product (like hobbyists and other recreational researchers) can still view the open source materials for studying circuit and code designs. The remaining features describe the actual function of the oscilloscope BoosterPack. 'Measurement Accuracy' and 'Measurement Capability' are distinct and necessary features for the final product. The accuracy describes the how well the oscilloscope BoosterPack's measurements are to the actual signal being measured, while capability is a necessary step in determining signal accuracy because we need confirm that the data displayed on the oscilloscope is measurement data. Since the program on the circuit's microcontroller can be changed, the user can see how making changes to the program can affect the operation of the oscilloscope and other programs can be loaded onto the LaunchPad so it can be used for different projects. As the project becomes easier to use, the user enjoys using the oscilloscope BoosterPack more which is why ease of use is a primary feature.

2.2 Description of the Solution

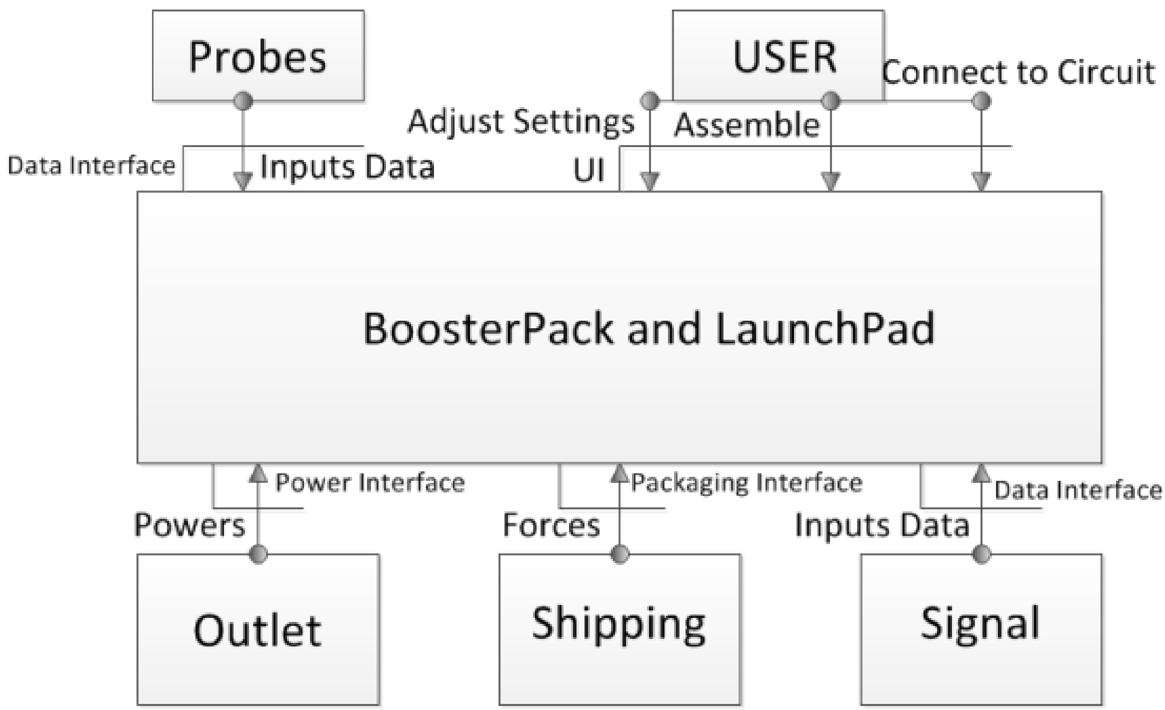


Figure 2. Domain Diagram

In figure 2 the domain model of the project is presented. In this model the outside actors of the system are identified along with their interactions with the system. The first actor are the probes that are used in conjunction with the system. This directly related to measurement accuracy, ease of use, price limit, and measurement capabilities. The probes are what connects the signal to the circuit and have characteristics like input impedance and signal attenuation. These can effect what type of signal that could be measured and how accurate the system can be. The probes are also a separate component to reduce cost of the final package, and the user can use ones to their specification. For the final board design any BNC probe could be attached to measure signals. However when the 10x setting is used the signal does not go through. Further research is needed to figure out why this happens.

The next outside actor is the user which adjusts the settings, assembles/updates, and in general uses the scope. This directly relates to the ease of use, instruction manual, measurement capabilities, and price limit. The user needs to be able to operate the scope with ease, and should have a similar interface to other scopes on the market. This coincides with the user manual which explains the use of the scope to the user. Finally the user wants to be able to buy the product at a reasonable price given the performance the scope has. This was satisfied using buttons that came attached to the LaunchPad and a potentiometer attached to the BoosterPack. These controls allowed the user to adjust time and voltage per deviation, and also adjust the trigger level. Using controls that came with the LaunchPad also reduced the total cost of the board.

The next outside actors are outlet which directly effects power consumption, shipping which involves how the product is packaged, and the signal which related to accuracy and capability. The outlet determines how much power the scope can use. For power the final board can be powered by any micro usb source including portable battery packs. The shipping of the product relates the manufacturability and how the product is packaged. This was accounted for in the hardware design of the board. Finally the signal shape, size, and characteristics need to be known so the scope can be made to measure the variety of signals that it needs.

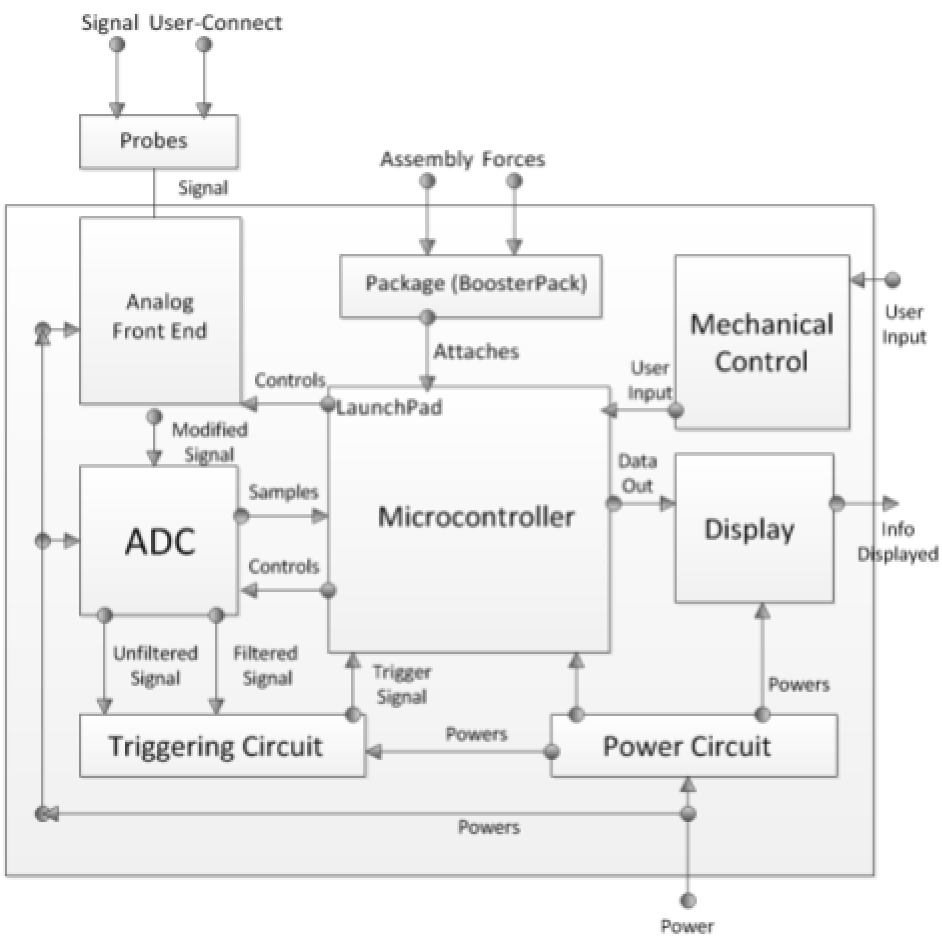


Figure 3. Logical Architecture

In figure 3 we see the logical architecture of the system which describes how the scope will respond to the outside actors and shows how the system will function in general. Following the flow of the signal first comes the analog front end which accepts the signal from the scopes and proceeds to attenuate/amplify the signal, apply the proper common mode voltage, and make it differential. The signal is also put through a filter to reduce high frequency noise. The signal then proceeds to the ADC where it is sampled and then read into the memory of the microcontroller. The microcontroller the uses these samples and based on the user input displays the signal on a LCD screen.

The front end involves many parts, first of which is the THS4121 which does the single to differential conversion. This part was a cheap general part that is able to handle +/- 1.5V swings which was appropriate because we planned 10x probes working with the board which they did not. With 10x probes the +/- 1.5V swing would be enough for a +/- 15V input. This part also had the necessary bandwidth to handle 10 MHz signals.

The next part used was the programmable gain amplifier, LMH 6882. This part was first suggested by the client and worked well for our purpose. This amplifier has up to 25dB gain allowing for the measurement of small signals. This part also had two channels which reduced the part count on the board reducing cost.

Next came the sampling system or ADC. The ADC chosen was the ADS5237. This part had a sampling rate of 65 MSPS which allowed the measurement of signals up to 7MHz assuming the industry guideline of having 10 samples per period to have a good measurement on a signal. It also was selected because it had two channels which reduced part count and was relatively cheap compared to other ADCs that were up for consideration. Finally it had 10-bits of resolution which the client stated he wanted in the planning process.

The microcontroller which takes in the samples was satisfied using the Tiva C connected LaunchPad from TI. This board was needed because of the extra pins that were included which were needed to satisfy all of the requirements. This board also had EPI which was needed to receive the 20-bit data signal for both channels at appropriate speeds.

Other blocks include the triggering circuit which takes in the filtered and unfiltered signal and tells the microcontroller when to start sampling based on a desired trigger level. This was done using cheap general purpose op-amps because of their low cost, and had satisfactory bandwidth for our features. The power circuit takes in the power from the outlet or USB and provides the microcontroller and the circuit with power. The power circuit was on the LaunchPad itself and no further circuitry was needed. The package block includes how it has to be manufactured to be able to interact with the Launchpad. This will be done by following BoosterPack templates and specifications. Finally the mechanical control which includes buttons which are on the Launchpad and a potentiometer which is on the BoosterPack.

Finally the display requirement was satisfied by an external BoosterPack made by a third party. This allowed us to focus on other features while satisfying a requirement at low cost. A simple 2.2" LCD controlled by SPI was used because of its low cost and simplicity to control.

This solution is able to deal with all of the major features which includes measurement accuracy, ease of use, measurement capabilities, updateable programming, and user manual. The measurement accuracy and capabilities are determined by the front end and ADC. Ease of use is taken care of by the mechanical control, display, and probes. However it couldn't fully handle the features because the software wasn't able to take in samples fast enough. The hardware could handle this requirement but software could not. Other than this detail the hardware selected was able to satisfy all of the requirements

2.3 Data and Verification of Requirements

Some requirements that relate to the primary stakeholder features are shown below.

Black Box

Interaction	ID	Actors	Requirement
Inputted Signal	BBDI-1	Probes, Signal	The inputted signal must be between +15V and – 15V
Inputted Signal	BBDI-2	Probes, Signal	The inputted signal must be below 7 MHz to be properly sampled and measured.
Adjust Settings	BBAS-2	USER	The user must be able to change the time scale of both channels.
Adjust Settings	BBAS-3	USER	The user must be able to change the voltage scale of both channels.

White Box

Interaction	Req-ID	Blocks	Requirement
Measuring Signals	WBMS-2	Triggering Circuit	The signal input to the Triggering Circuit should be scaled down to a range of 0V to 2V.
Measuring Signals	WBMS-4	Triggering Circuit	The output signal should stay within the range of 0V to 5V.
Measuring Signals	WBMS-6	Triggering Circuit	The potentiometer should be controlled by the user with an external, mechanical interface.
Measuring Signals	WBMS-7	Triggering Circuit	The output signal should range from 0V to 3.5V (due to op-amp saturation).

Most of these requirements deal with ease of use and how the user is able to interact with the scope. The measurement accuracy and capabilities are also touched upon in the requirements. The block box requirements directly relate to how the user can adjust the settings and the measurement capabilities of the scope. These were primarily tested using the analog front end because that is what determines these characteristics. The white box deals with the triggering circuit and how the user is able to adjust the trigger level of the circuit.

White Box Testing

As said before for the white box requirements we tested the triggering circuit. First to test these requirements we had two input signals are averaged and are compared to a trigger level voltage controlled by a disk potentiometer. Power supplies of -5V and +5V are used. The averaged output voltage, trigger level voltage, and the output voltage of the system (output of comparator) are measured using an oscilloscope. These measurements help prove the 'linearity' of the trigger level voltage, the limits of the input range, and the propagation delay. The following diagram was the result.

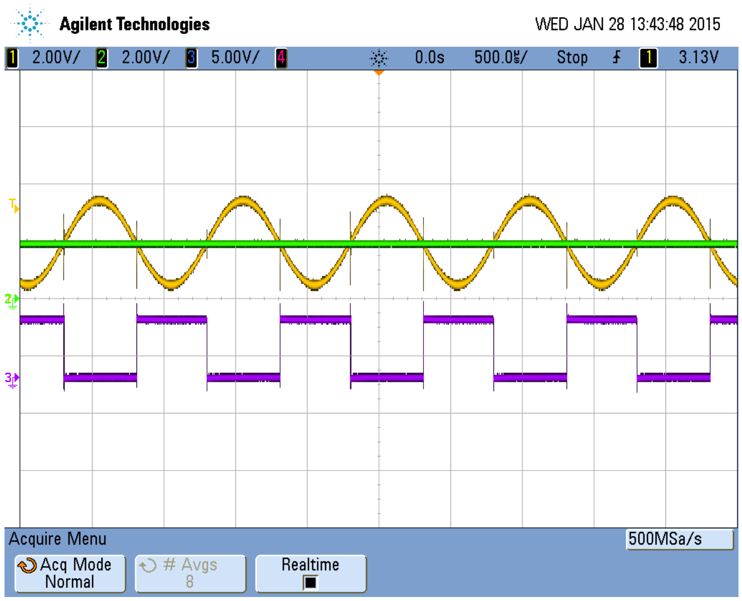


Figure 1: Highest input voltage. Both input signals have f = 1 kHz and their values range from -1.5V to +1.5V. (Green – Trigger Level, Yellow – Signal, Purple – Output)

The averaged output has an appropriate frequency (f = about 1 kHz) and an appropriate amplitude (about 3Vptp). These results agree with the requirements and expectations of the system. The trigger level voltage is correctly shaping the logical output of the comparator.

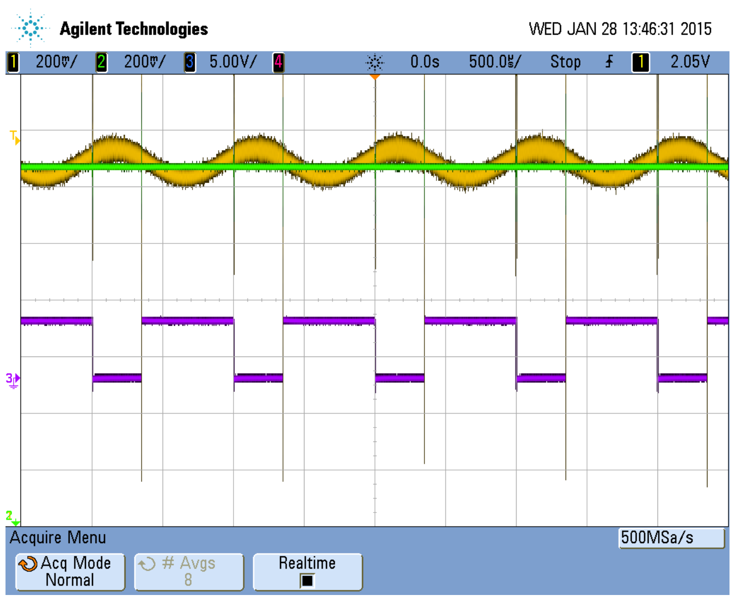
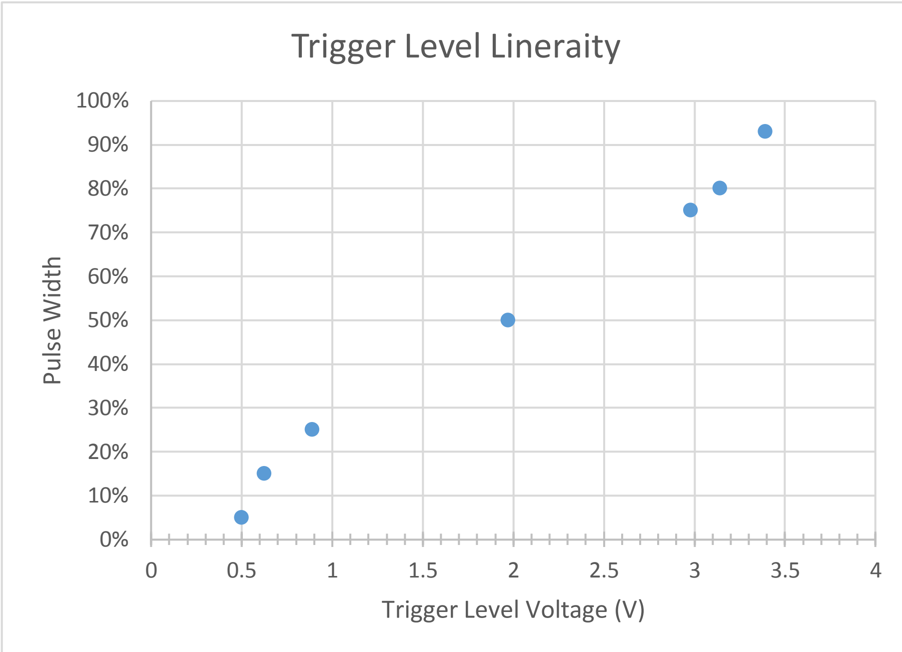


Figure 2: Lowest input voltage. Both input signals have f = 1 kHz and their values range from -50mV to +50mV.(Green – Trigger Level, Yellow – Signal, Purple – Output)

The averaged output has an appropriate frequency (f = about 1 kHz) and an appropriate amplitude (about 100mVptp). These results agree with the requirements and expectations of the system. The trigger level voltage is correctly shaping the logical output of the comparator.

Graph for Trigger Level 'Linearity':



Trigger Level Voltage	Duty Cycle
500mV	5%
624mV	15%
890mV	25%
1.97V	50%
2.98V	75%
3.14V	80%
3.39V	93%

The variation of the pulse width of the logical output of the comparator shows that the trigger level voltage can appropriately be compared with the averaged output signal at all (numerous) values of the trigger level voltage.

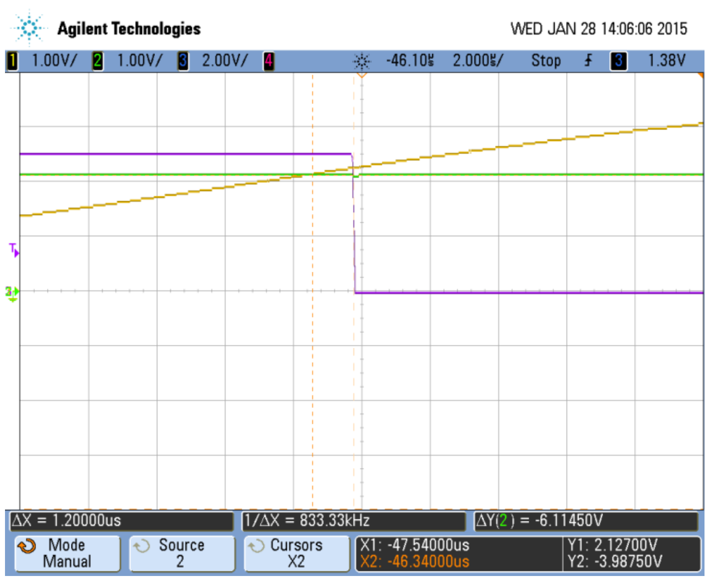


Figure 4: The propagation delay of the logical comparator output voltage is shown. (Green – Trigger Level, Yellow – Signal, Purple – Output)

The propagation delay is shown to be ΔX = 1.2 us. This propagation delay is too high because our oscilloscope should measure signals up to 7 MHz whose period is shorter than the propagation delay which causes a problem with sampling the signal at inappropriate times.

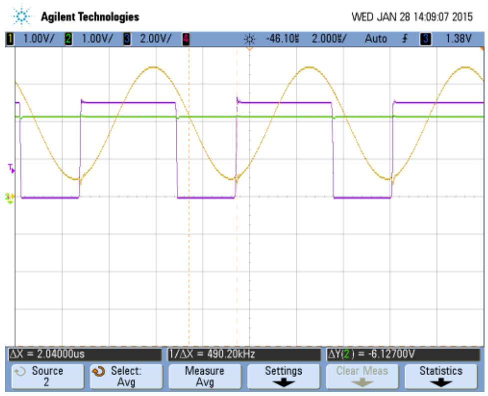


Figure 5: The result of having the maximum input frequency is shown. (Green – Trigger Level, Yellow – Signal, Purple – Output)

The maximum frequency that the system can handle and still maintain desired operation is 150 kHz. This much too low of a frequency (150 kHz << 7 MHz). This low maximum frequency is caused by the slew rate on the comparator amplifier. The limits of the comparator amplifier also affect the propagation delay.

We concluded that the comparator amplifier can be replaced with the amplifier that used to average the input signals. This will improve the propagation delay to an appropriately small value. This will also increase the maximum operation frequency of the system. Our final product included this amplifier and worked as intended.

Black Box Testing

For the black box testing we wanted to confirm the input requirements to the scope. This includes features like how high frequency of a signal can be inputted to the scope, and how large of a signal. This testing revolved around the front end because that is what takes the input signal and delivers it to the ADC for sampling.

For the setup of this testing the final board was made so a scope probe can take an input signal and there were testing wires soldered to the output of the analog front end right before the ADC. This allows us to see when a certain signal is inputted that the signal gets to the ADC correctly to be sampled. Here we are mostly looking for shape because depending on the settings of the programmable gain amplifier the true amplitude is unknown and is only known to the microcontroller which provide the correct gain factor to the samples. For the sake of this testing the lowest settings of gain were used for the programmable gain amplifier.

To start testing the functionality was confirmed with a 50mV input which is reality simulates a .5 V input because of the 10x probes (probes used were set at 1X). At 50 mV a sine wave was put through at 1kHz, 100kHz, 1MHz, and 10 MHz in addition to a square wave at 1MHz and a ramp wave at 200kHz. Again here we want to confirm the correct shape going into the ADC.

These test address the requirements of BBDI-1 and BBDI-2 which both describe characteristics of the input signal.

Here are the results of the first round of testing. (Yellow – Input, Green – Output)

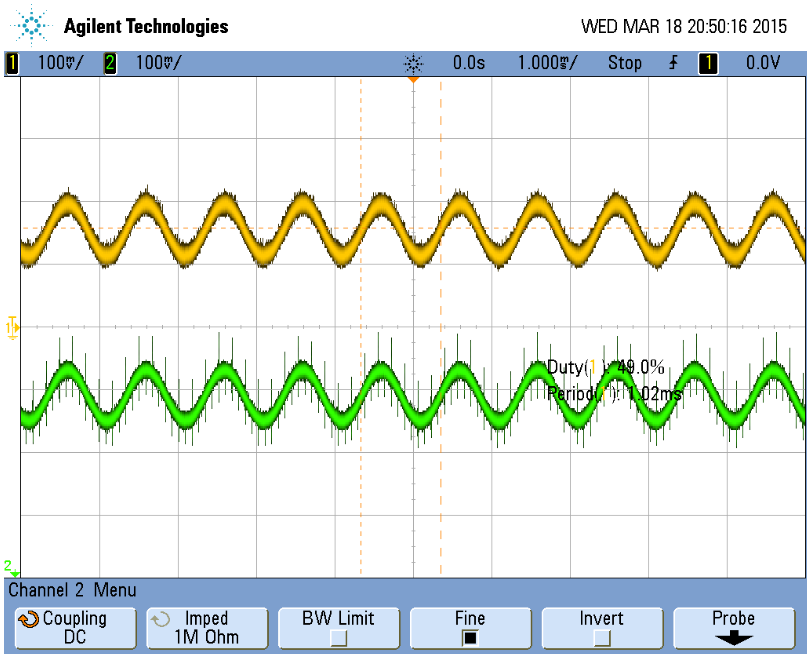


Figure 1. 50 mV Sine at 1kHz

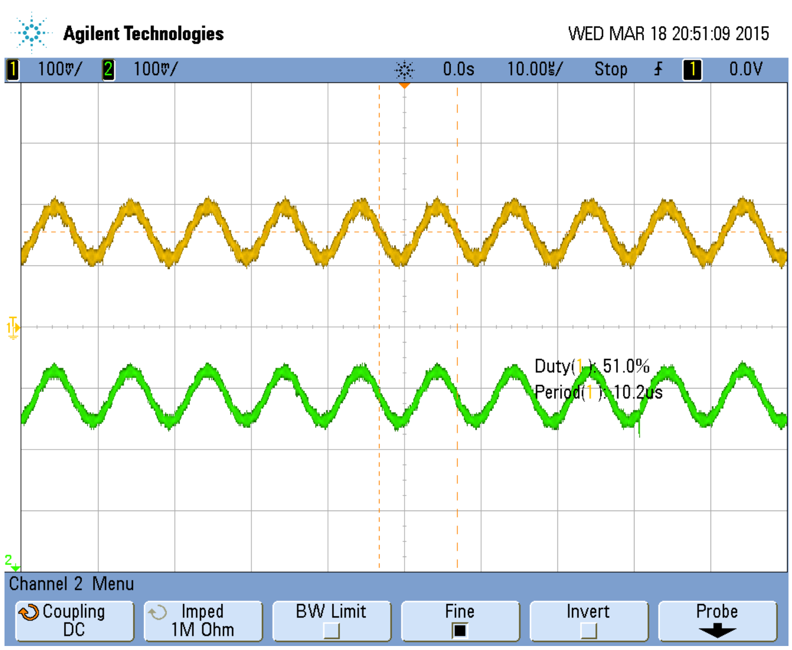


Figure 2. 50mV sine at 100kHz

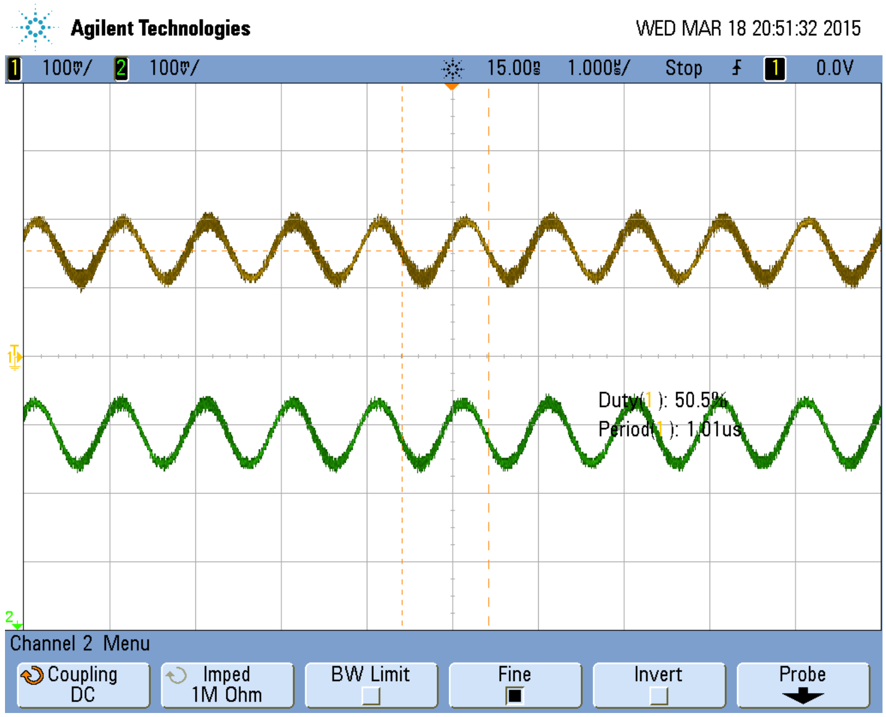


Figure 3. 50mV sine at 1Mhz

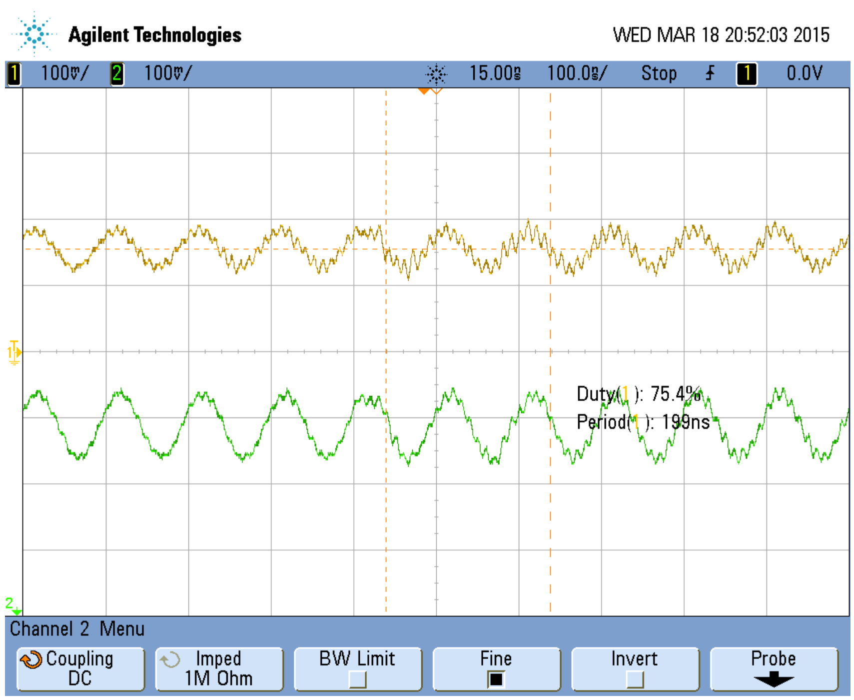


Figure 4. 50mV sine at 10MHz

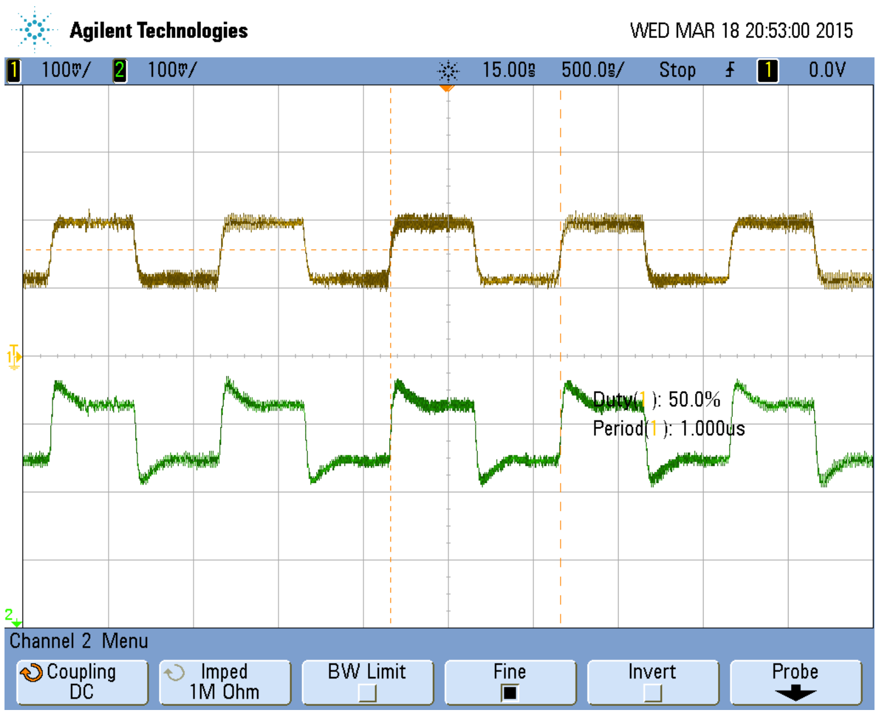


Figure 5. Square Wave at 1MHz

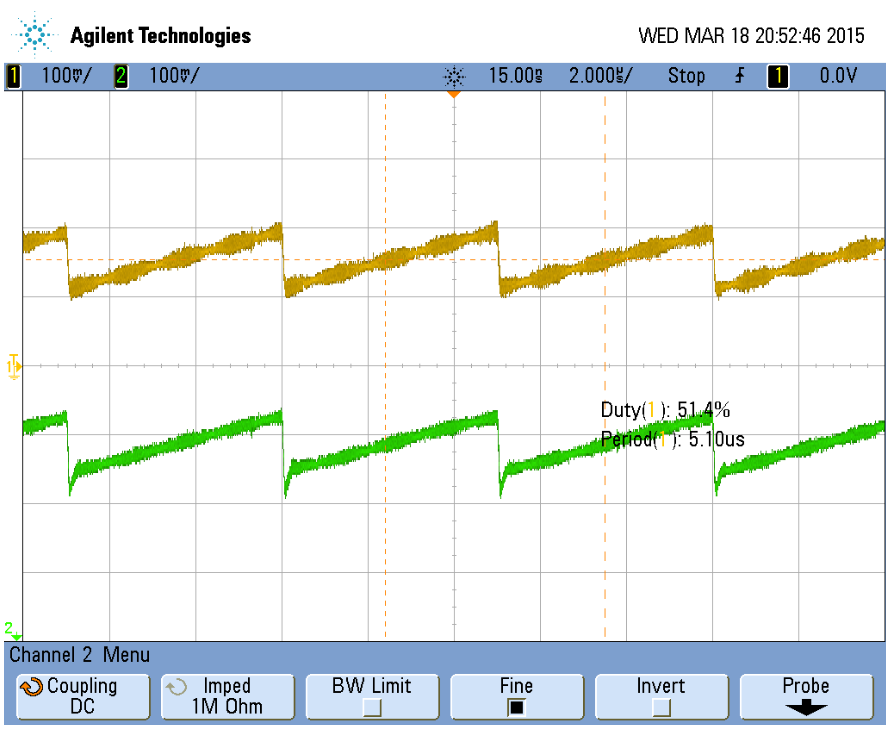


Figure 6. Ramp Wave at 200kHz

From these plots we can conclude that the front end functions properly at small signals and at high enough frequencies. For the next set of testing the limits of the requirements were tested to see if there was any degradation of the signal at the limits of the PGA.

The second round of testing includes an input signal of 1.4V simulating a 14V input on 10x probes. 1.5V was tried but the signals saturated failing the 15V goal. However the behavior still should be tested at the max input level. The same tests were performed as before. The only change was the input level of the signal.

Here are the results (Yellow – Input, Green – Output):

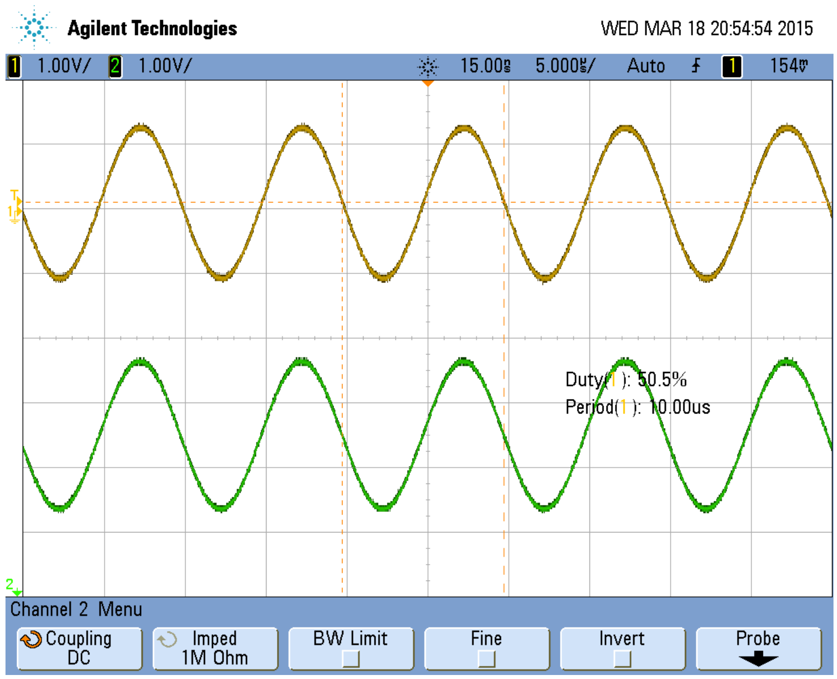


Figure 7. 1.4V Sine at 100KHz

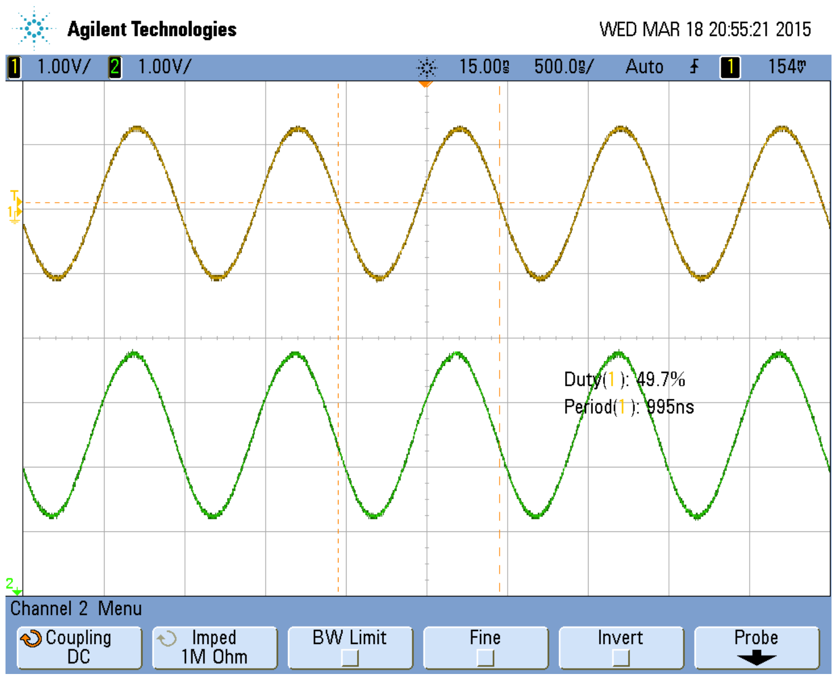


Figure 8. 1.4V Sine wave at 1MHz

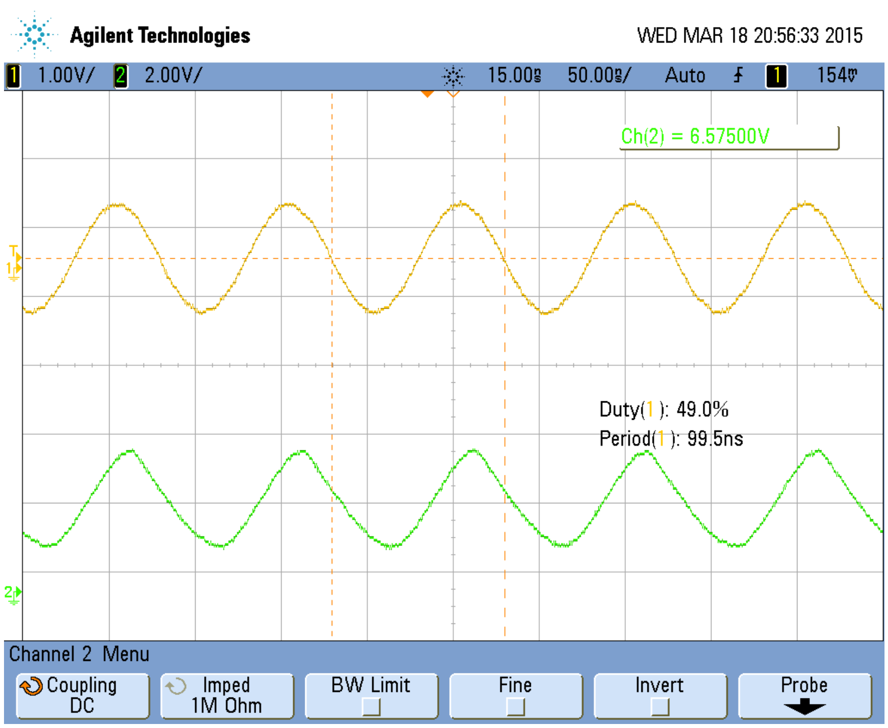


Figure 9. 1.4V Sine wave at 10MHz

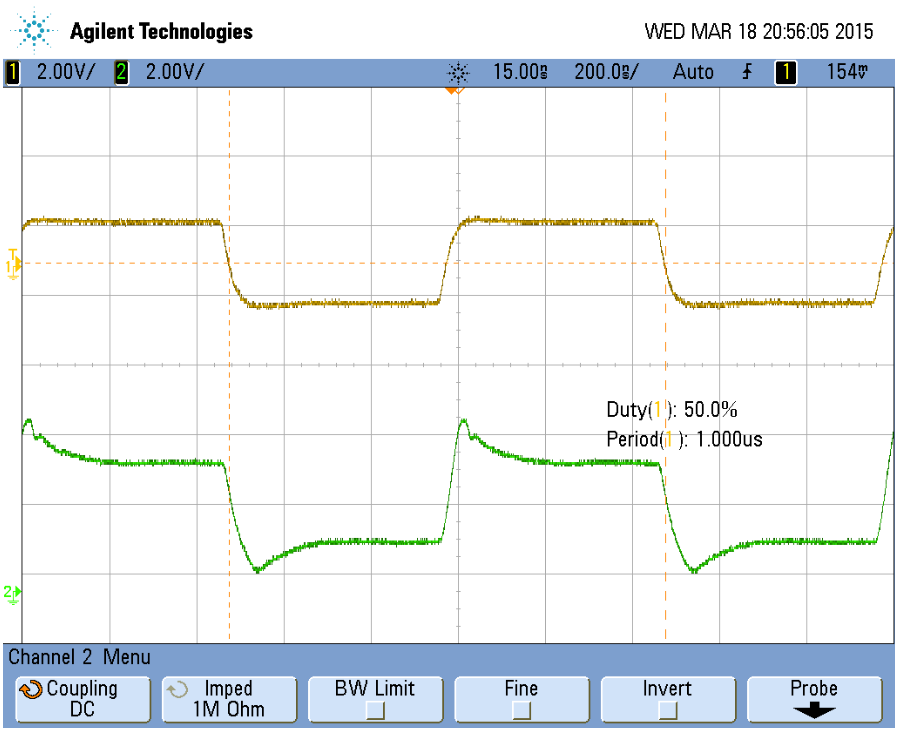


Figure 10.1.4V Square wave at 1MHz

Figure 11. 1.4V Ramp at 200kHz

Conclusions:

For the first round of testing all the signals were able to be seen through the PGA with minimal distortion. When the frequencies were increased to 10MHz the tests were approaching the limits of the signal generator which can be seen in the input signal causing distortion on the output signal. This can be seen in the yellow input signal on the graphs. These tests also show the low pass filter has to be looked at to get rid of some of the noise on the input signal.

For the second round of testing where the amplitude was increased the signals became much clearer and more defined. In general a lot better results were seen in terms of the shape of the original signal. This shows us at smaller signals the gain settings may have to be increased to get the optimal shape of the output signal.

Overall the requirements were not met perfectly, but with fixes to the low pass filter with a 10 MHz bandwidth, using the correct gain settings on the PGA controlled by software, and putting a small 1/10th voltage divider to allow the full +/- 15V range, the front this system can achieve its requirements. These were implemented on the final board. However since the 10x probes didn't work as intended the full range could not be used. This could be fixed by adding a smaller voltage divider on the front end to reduce the signal more coming in essentially doing the attenuation a 10x probe would do.

3. Project Plan and Timeline

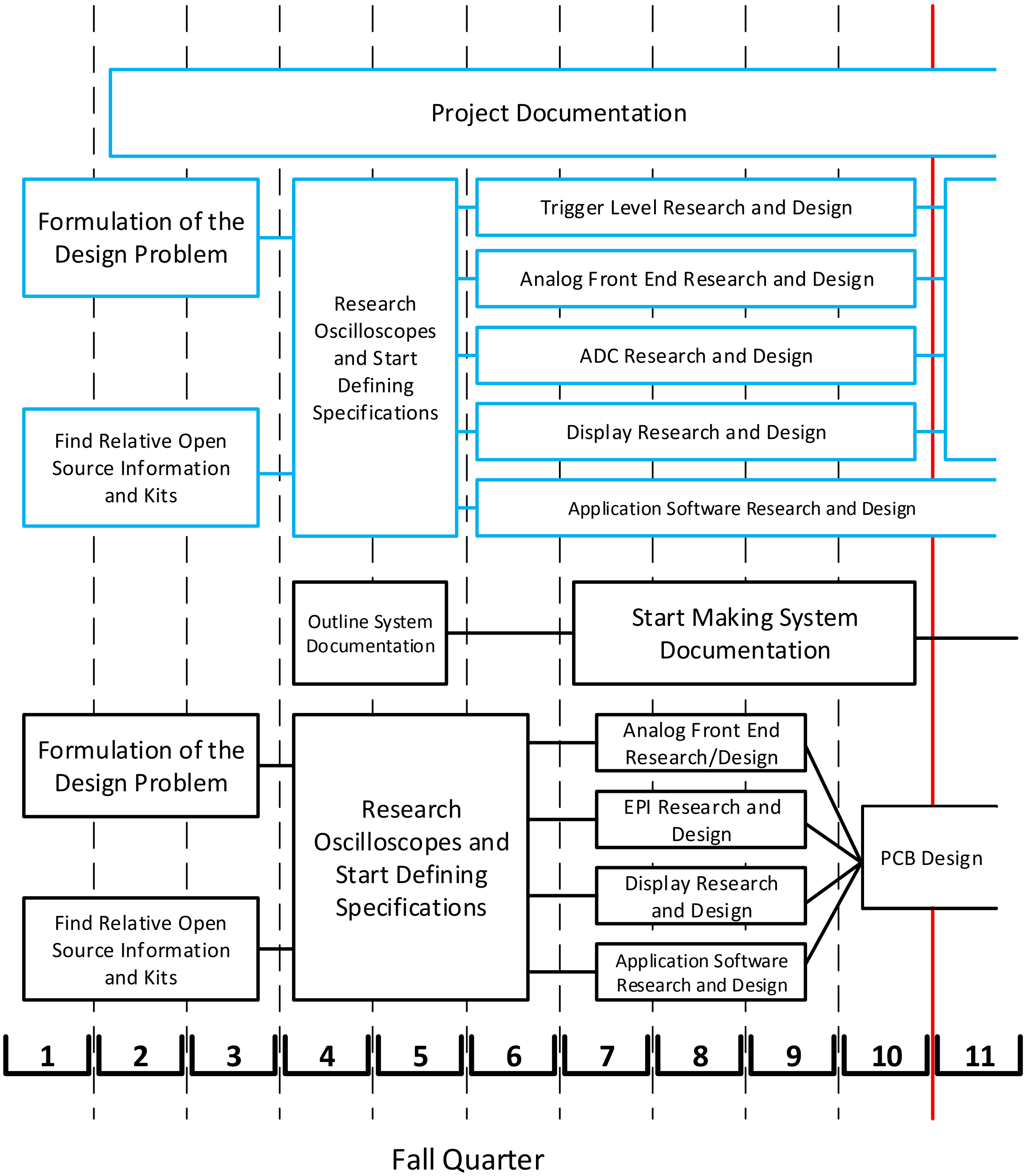


Figure 1. *This section of the timeline shows the initial plans and the actual progress made during the first 10 weeks of work on our project (50% of our allotted time to work on the project).*

The original timeline, shown in black at the bottom, has four major categories. Weeks 1 to 3 initialize the project team and help define the goals of the project. The rest of the time consists of documentation, hardware, and software progress. Documentation includes all reports required of the project for the ECE460 and ECE461 Senior Design classes. Several PCBs needed to be designed to efficiently test the hardware subsystems of the oscilloscope BoosterPack. Then these subsystems are all connected on a final board for testing the final, complete hardware design. The code for the software is all done with Energia, a TI software application. Hardware is the most vital part of the project because all project goals depend on the hardware. Software needs hardware as an interface and therefore cannot be fully tested without it. Data used in documentation is only collected from hardware.

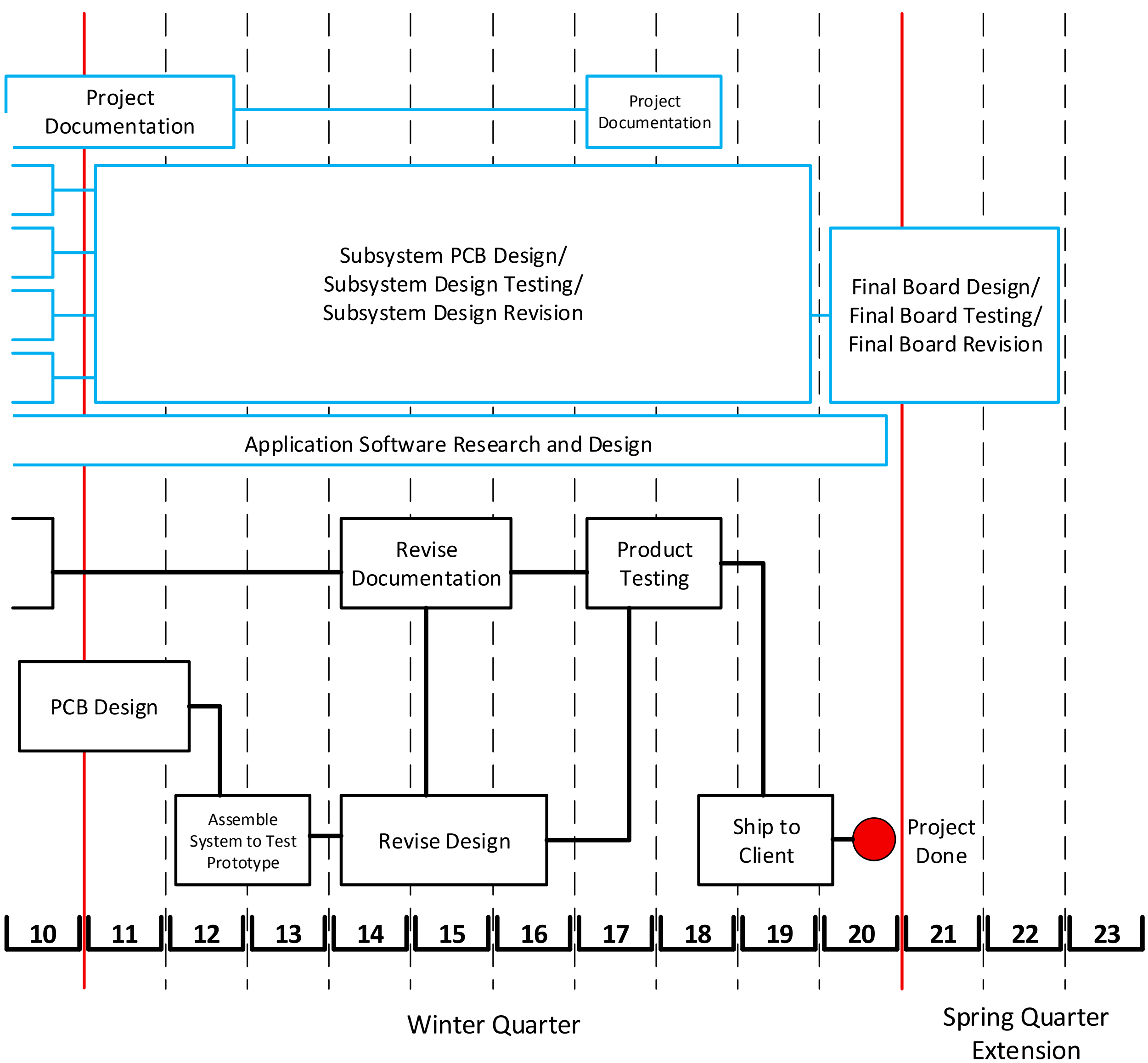


Figure 2. *This section of the timeline shows the initial plans and the actual progress made during the last 10 weeks of work on our project (50% of our allotted time to work on the project) but also shows our progress during our 3 week extension for our project.*

Our actual progress, shown in blue at the top, definitely has differences from the original. Our client explained some helpful block diagrams during our client drop-in and this helped us to become ready to start designing hardware and software earlier. Project documentation took more time out of the quarter than expected and it felt like a distraction from developing software and hardware, increasing the span of time spent on research and design. PCB design involved a large amount of debugging caused by numerous sources (soldering errors, PCB file design errors) and pushed back the design for the final board/product. While burdened with hardware difficulties, we made minimal progress on the software. There are deviations from our original plan that cannot be seen in the timeline. There was some confusion about the definition of our project in the first few weeks which delayed our preliminary research. Originally group of 3 people, we lost a group member as soon as Week 11 started. This made it even more difficult to put in enough hours to match the development of 4 people when we are only 2 people.

Certain deviations from our original timeline were easy to see but others could be undetected because they lack due dates or checkpoints to remind us of where our progress should be. To improve detection of deviations, there could be an assigned person to constantly monitor the progress of all assignments or every person can report their shortcomings or difficulties as soon as they arise. The best way to prepare for unknown problems is to welcome every opportunity of the problem. In our case, one person could have made a PCB as soon as possible to discover what problems can arise with PCB design. Then the impact of the problems with one PCB would only be a fraction of the problems with multiple PCBs, therefore saving time by not solving the same problems multiple times.

4. Recommendations

Our project has fallen short of its expectations and its goals. The hardware is capable of handling the range of input signals (frequencies up to 7MHz) but the software can't handle samples fast enough. A micro DMA method in software would help to handle samples faster and enables the oscilloscope BoosterPack to appropriately handle and display the higher frequency signals by writing the samples directly to memory when they are received. The software also doesn't dynamically change the gain of the PGA to amplify smaller signals. However the control signals to do so are in hardware. More software would have to be added to allow the oscilloscope BoosterPack to measure the range of signals that we designed for. Finally adding a selectable attenuator to the front end would allow the hardware to accept larger signals. These recommendations would help the project to better meet the stakeholder features for Measurement Accuracy. Overall the core functionality works, meeting the Measurement Capability, Open Source Material, Ease of Use, and Updateable Programming features, but adding more software would allow the board achieve all its goals, and adding some hardware could help the project to meet these goals.

5. Going Further

5.1 Standards

Many standards went into our project. The BoosterPack interface design is standard because every BoosterPack and LaunchPad need to have certain dimensions and locations for pin headers so the BoosterPacks can be stacked on top of the LaunchPad. Our project is taking advantage of this to not only attach the oscilloscope hardware to the LaunchPad, but also the display on top of our BoosterPack.

The power coming into the BoosterPack is supplied through a standard 5V at 1A USB power supply converter on the LaunchPad. This powers all of the hardware on the board including the display.

Signals are measured through standard mechanical BNC connectors and 10x attenuation capable probes.

The display used for the BoosterPack has a SPI display driver and the code for the LaunchPad is configured specifically for this type of display driver.

If the product reaches the end of its life then the materials used to fabricate and populate the PCB are ROHS (Restriction of Hazardous Substances Directive) certified so the product can be disposed in an environmentally friendly manner.

5.2 Manufacturability/Safety

Many features of our project took into consideration the manufacturability of the product. All ICs used to populate the board are TI brand ICs and all parts can be bought from one supplier, DigiKey, which makes it easy and cost efficient to supply components. The types of ICs and the different values of resistors, capacitors, and inductors were minimized to have less variation in the components therefore making it easier to supply them.

There are however areas of improvement in terms of manufacturability of the project. The BNC connectors have electrical connections and physical connections to the PCB board. The pins are connected to the circuit but there are stubs on the bottom of the connectors that increase the stability of the mount on the PCB. This alone doesn't provide enough support and the connectors can be more secure by placing an adhesive between the bottom of the connectors and the mask on the PCB. Test points should be added for the AFE and other areas to help with debugging the hardware. Finally the PGA has a heat pad on the bottom which should be soldered with IR to reduce the temperature of the chip.

There are also some safety concerns. There are places where we have soldered components so each solder point is an exposed electrical connection. After the PCB is populated, a mask can be placed over the board to cover the points.

5.3 System Failure Mode Analysis

If the system is used inappropriately the product could fail and cause permanent damage to itself. The PGA on the BoosterPack could overheat if too high power of a signal is inputted or the scope is left on for an elongated period of time. This is because the bottom thermal pad of the PGA could not be soldered by us, however in manufacturing would be able to be soldered making this problem moot\. This could burn the chip and the component would need to be replaced. A user error could measure signals outside the specified amplitude range which could burn components by supplying too much power in terms of the input signal. This error shouldn't be happen if the user the BoosterPack under the specified conditions. This error would be hard to detect and debug because it depends on which component burns first. Another user error could be an incorrect orientation of the BoosterPack on the LaunchPad while power is on (plugged in). This might occur somewhat frequently if the user is not paying attention to the arrangement of the pin headers when the BoosterPack and LaunchPad are connected. An incorrect connection due to this error could cause a short and burn a component. This error would be hard to detect and debug because it also depends on which component burns first.

5.4 Societal Impact

The oscilloscope BoosterPack should make the reliable function of an oscilloscope more available to the general public. Mainly students or hobbyists doing electrical work would benefit from having this product on the market because this gives a low cost solution to measuring signals. With the open source material and the function of our product, there will be an increase in the exploration of the science behind electronics. People might be interested in engineering at an earlier age because of the affordable price and the open source information that can aid in teaching the user. This also opens up the possibility of a portable scope that every student can have to do in class or out of class labs with.

5.5 Economic Impact

There will be an increase in the number of people that have access to equipment that has a reliable oscilloscope function. With lower cost oscilloscopes in the market, there will be less purchases for higher end oscilloscopes. The cost of higher end oscilloscopes might fall.

5.6 Environmental Impact

The BoosterPack is ROHS certified and can be disposed and recycled properly. The owner should take the product to an appropriate electronics recycler. A failure to recycle or dispose properly could harm the environment. Some parts will never break down on the environment and other may decompose, releasing chemicals that could harm the environment.

6. Bibliography

Annotated List of Research Memos

[1] Yaohui Wang, *Research of Analog Front End Design*. October 7, 2014.

Description of the purpose and operation of an analog front end and looked into characteristics our group should look at when making our analog front end.

[2] Eric Taylor, *Hold-Off Triggering,* September 28, 2014.

A description of what hold off triggering is and how it works. This provided understanding of an oscilloscope feature that could be put into the scope at a later date.

[3] Raymond Montgomery, *Oscilloscope Triggering.* October 15, 2014.

This provided research into how our project will handle the triggering in hardware and gave understanding into which parts we should use and the general circuit subsystem that had to be made. This deals more with triggering hardware whereas the previous memo is software triggering features.

Annotated Biblliography

[1] I. King , *High Performance Analog Front Ends,* Analog Edge, Vol. IV Issue 1.

This source was used when the group didn't have a good understanding of the purpose of an analog front end, and what characteristics of one made it a high performing one. This provided characteristics for the analog front end that our group could shoot for and design around.

[2] Microchip Technology Inc. *Non-Inverting Summing Amps* August 25, 2014. [Online]

This webpage explains the operation of amplifier circuits that sum signals together. This is useful in the triggering circuit to sum together the filtered and unfiltered signals.

[3] Circuits Today. *Voltage Comparator.* November 25, 2011. [Online]

This article was used to explain the user of voltage comparator circuits used in the triggering subsystem of our design.

[4] EEVBlog. *Oscilliscope Trigger Holdoff Tutorial.* March 29, 2011. #159 [Online]

This video provided understanding of holdoff triggering and how we could add it as a feature ein our final scope.

[5] Texas Instruments. *Oscilloscope Solution.* [Online]

This is a compilation of resources by Texas Instruments that describes solutions and systems needed to make an oscilloscope. This was useful to learn all the systems we needed for our final project.