ANALYSIS OF WIRELESS TILTMETERS FOR GROUND STABILITY MONITORING

Kenneth Scott Logan

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Dr. Erik C. Westman, Chairman
Dr. Mario G. Karfakis
Dr. Antonio V. Nieto

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ABSTRACT

Tiltmeters can be used in the mining environment to monitor slope stability by making use of gravitational force to measure angles of inclination relative to horizontal. Tiltmeters typically use accelerometers, which output a voltage measurement that can be related to angle of tilt. Though wireless tiltmeters already exist today, they lack certain ruggedness and sensitivity preventing use in mines. The purpose of this project was to investigate the feasibility of using already existing wireless tiltmeters in the mining setting. Additionally, a new wireless tiltmeter was designed which could be specially tailored for the needs of monitoring hazardous rock bodies in both surface and underground mines. By recording angles of any slope, either in a surface mine or underground, over extended periods of time, changes in readings can infer instabilities in the rock mass underlying the slope being measured. By placing many tiltmeters in a mesh on a surface slope or underground roof, rib, or other face, the entire surface can be monitored. Compared to the measurements of a single point using one instrument, a dense network can be extremely useful in detecting rock movement.

Many monitoring techniques are in use already in mines. Traditional methods of monitoring, though undeniably useful, are often time consuming. By utilizing wireless devices that transmit data back to a single location, data acquisition and analysis time can be minimized, saving the mine employee hours as well as down time. As surface mines continue to deepen, and underground mines continue to progress further from the surface, the extent of necessary monitoring continues to increase: this widening range will require greater time for proper monitoring, unless an automated system is implemented. With proper wireless equipment, real time monitoring of an entire mine is possible.

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Next, I could not have completed this research without the love and support of my family, especially my wife, Caroline. Thank you for supporting me through my academic career.

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CHAPTER 1: INTRODUCTION

Ground control accidents are among the leading cause of fatalities in the mining industry. Around 50% of fatalities in underground mines are caused by ground control failures. Between 1995 and 2001, about 15% of fatalities in surface mines occurred as a result of slope instability (McHugh & Girard, 2006). Whether slope stability incidents occur in underground mines or in surface mines, unexpected rock movement can cause serious injuries, fatalities, and potentially mine catastrophes. For the purpose of this project, the term "slope" can refer to both surface surfaces and underground surfaces: anything that has a measurable angle. The depth of surface mines can increase the dangers of slope stability issues, but deep open pit quarries are not the only victims of surface mining slope failure. Even relatively shallow mines can experience destructive consequences from undetected slope instabilities. Extent of underground mines also produces a higher probability of failure, but as with surface mines, even smaller production underground mines are susceptible to failures. (NIOSH, Slope Stability, 2007)

Proper monitoring of slopes and rock masses can help a mine operator recognize when the probability of a failure is higher than usual. This pre-failure warning can help the mine in many ways. Not only do slope failures wreak havoc on production capabilities, they are able to seriously damage equipment, and in the worst cases, kill or injure people too close to the point of failure. The objective of slope monitoring is to detect, before failure, possible instabilities to allow the operator to take appropriate remedial measures. The main concern and main purpose of monitoring is the protection of men and equipment (Larocque, 1977).

Conventionally, underground mine roofs have been monitored using rod extensometers or convergence monitors. Subsurface measurements are also taken using inclinometers and extensometers. Surface mines usually use surveying equipment to observe the location of physical monuments (surveying stakes, permanent structures, etc.), map tension cracks, and use wire extensometers to monitor rock movement over time, which pertains to the overall slope stability. (Girard, Mayerle, & McHugh, 2006)

With the ever growing size and depth of surface mines, and with the extent of underground mines continuing to escalate, manual extensometer measurements and surveying techniques are becoming less feasible. Smaller mines may only incorporate a few instruments monitoring, in which case the time required for physically reading and recording each piece of equipment is not significant. However, with increasing mine size and equipment quantity, the time required by an individual to physically check gauges on extensometers or convergence monitors continues to grow, and will eventually become too great. When the mine is losing time, the mine is losing money, and a change is necessary. A system is needed that will relay the condition and readings of monitoring instruments back to a base where the operator can view multiple points, if not the entire mine quickly and easily. The relays needed to link equipment to a central station might traditionally use wires, however the wires could span long distances, and the wire costs can become unfeasible. Another form of signal transfer is using wireless devices. Any digital signal can be transmitted wirelessly. The cost of wireless equipment is usually higher than conventional wired equipment; however the high cost of wire seen in conventional equipment is non-existent when using wireless technology.

The stability and condition of many civil structures, including buildings and bridges, can be monitored in real-time with wireless, micro electrical mechanical systems (MEMS) (MicroStrain, 2007). These wireless sensors are placed at the area(s) of interest, and their readings are relayed back to a gateway. The sensors can also be arranged to form a mesh network, of which an illustration can be seen in Figure 1.1, in which the sensors communicate with each other, while transmitting data back to the gateway. If one sensor is too far from the gateway to transmit directly, it simply sends data to a closer sensor, which “hops” the data along to the gateway or other nodes. The gateway is connected to either a data storage device or uses the Internet to transmit the data to operators in real-time. Unfortunately, MEMS have not been tailored specifically to the mining industry.

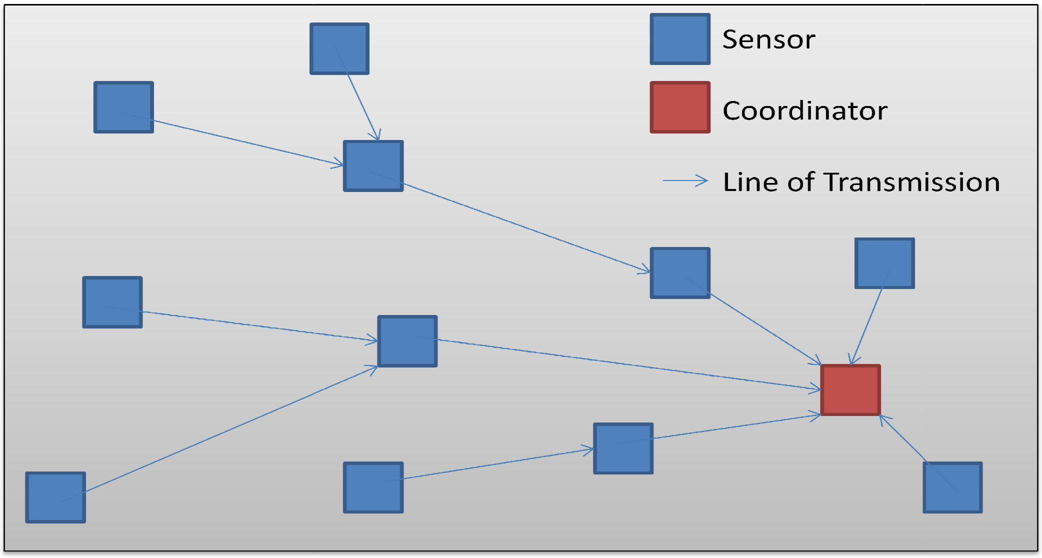

Figure 1.1: Mesh Network

There are two contrasting circumstances with existing wireless MEMS. One method is to purchase individual components of MEMS equipment separately at minimum cost. Though cost effective, the end result is difficult to construct and program, and requires a high degree of effort by the user before it is production-ready. The other option is to purchase previously assembled MEMS equipment preconfigured or designed for specific functions by an already existing company. Though the second option is often simpler and quicker to put into operation, it is generally more costly than designing the sensor from individual components. For example, the products from Crossbow are less expensive, but more difficult to use out of the box, while the products from Accsense and MicroStrain are much more user-friendly, while costing considerably more. (Crossbow, 2007), (MicroStrain, 2007), (Accsense, 2007) Outside of these companies, it is more cost efficient to purchase components through electronic manufacturers to design a new sensor. The process of fabricating a unique design to suite the desired situations will be further discussed in the duration of this project.

At the time of this writing, the technology is too expensive to be widely accepted by the mining industry. Before the industry can accept the wireless MEMS technology, it must be proven reliable and the cost must be relatively comparable to existing technologies. With continually advancing technology, the cost of the sensors, as well as the cost of manufacturing the products, is expected to drop within the next 10 years. Advancements as such would allow mining operators to continually monitor, in real-time, areas of interest using dense meshes created of multiple wireless sensors. The use of wireless sensors to monitor slope stability would help to improve the understanding of rock behavior, as well as increase predictability of failure(s).

This project will discuss the current technologies used to monitor slope stability, as well as evaluate the performance and cost of wireless inclinometers for monitoring ground stability at surface and underground mines. This project will also include designing, building, and testing a new prototype tiltmeter based on the theory of using accelerometers for tilt measurement.

CHAPTER 2: LITERATURE REVIEW

In order to understand the need for this project, it is important to understand the underlying issues of rock mechanics, as well as a history of current and past monitoring systems. This literature review should serve as a prelude to the project to follow. Key terms, ideas, and topics such as rock failure, current monitoring systems, and wireless technology will be addressed in the following Literature Review.

2.1- Failure of Rock

Properly planning the layout of a highwall plays a critical role in the slope stability of highwalls (Sjöberg, 1996). For example, analyzing the rock strength to determine the appropriate powder factor (the quantity of explosive used per unit of rock blasted) can minimize backbreak (unwanted fracturing of material behind the desired face). Determining the appropriate bench height and slope angle is also crucial. If the overall pit and bench slopes are too steep, instabilities have a much higher probability of becoming an issue. An important factor to consider is the alignment of fault planes in the host rock. Fault planes are fractures in the rock which occur because of in situ forces (shear and compression) in the rock (Brady & Brown, 1985). They occur in almost all types of rock, and with proper engineering, hazards related to the fault layout(s) can be minimized.

While thorough engineering of slope design and support systems can greatly improve the overall stability of the rock mass, even a carefully planned slope could be subject to instability. Most engineering materials are designed to have homogeneous properties throughout the material. Rock is different from these materials because it contains fractures throughout which make its structure discontinuous (Brady & Brown, 1985). Unexpected rock failures due to these fractures can result in fatalities, loss of equipment, major changes to the mining plan, and high costs to the operating company. (Girard, Mayerle, & McHugh, 2006)

When loading any material, whether in a laboratory or in a real life scenario, a point of failure is eventually reached. At the time of this failure point, a distinct surface is formed on each of the resulting two pieces. Any weak planes or discontinuities in rock formations are where rock structures are weakest, having little or no tensile strength (Brady & Brown, 1985), and are more likely to fail when loaded. Some of the more common failures due to fault geometry are described in this section.

2.1.1- Potential Slope Failures

Plane failures often occur when the fault strikes and dips parallel to the slope face. Generally the dip of the fault is greater than the angle of friction. Small scale failures of individual benches are usually not significant in an open pit mine. However, if the failure disrupts the traffic of a major haul road, the consequences are higher (Girard J. M., 2006). Primarily, the operator is more concerned with large scale plane failures, and should be more interested in minimizing the risk of an overall slope failure. A theoretical example of plane failure can be seen in Figure 2.1 below (after Girard J. M., 2006).

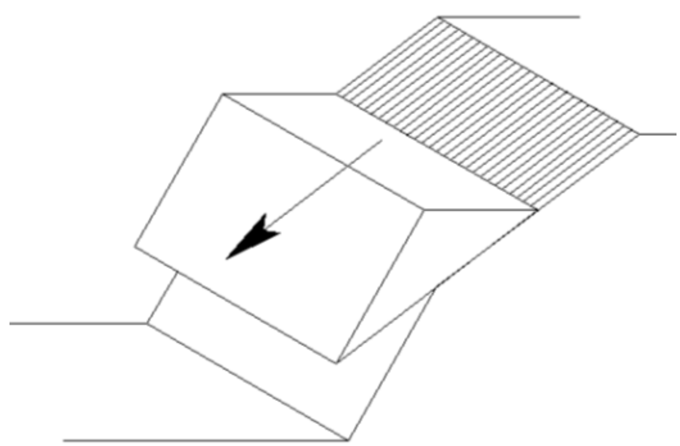

Figure 2.1: Plane failure (after Girard J. M., 2006)

Wedge failures occur when two fault lines or other discontinuities intersect near the face. The resulting "wedge" of rock is loosened by blasting vibrations, weathering cycles, excess water presence, or other causes (Hoek & Bray, 1981). Figure 2.2 depicts a wedge failure (after

Girard J. M., 2006). Wedge failures are more common than true plane failures, as fault lines normally intersect each other, creating a mesh of fractures in the host rock (Hoek & Bray, 1981).

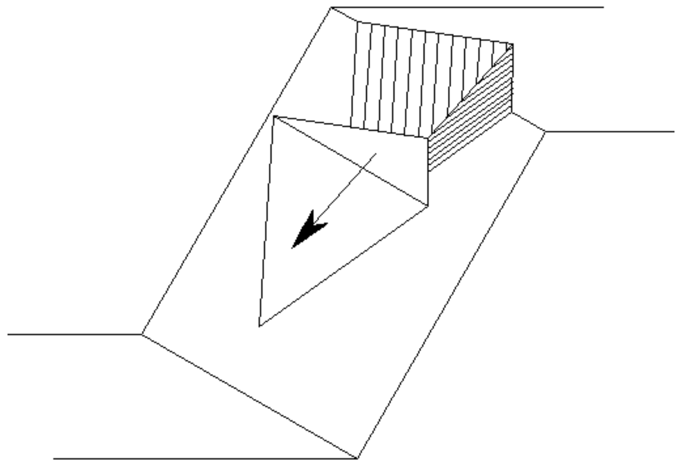

Figure 2.2: Wedge failure (after Girard J. M., 2006)

Another common instability is raveling. Raveling is caused by a combination of weathering of material and the expansion and contraction associated with yearly freeze-thaw cycles (Girard J. M., 2006): as seasons change from warm to cold, water contained within the pores and faults of the host rock freezes and expands. As the temperature increases, the ice melts and more water fills the expanded cracks. As the cycle repeats, slab-like pieces of rock are formed (Hoek & Bray, 1981). Over time, this weathering creates a highwall arranged of loose rock blocks. The composure and integrity of the highwall is severely decreased by the presence of the blocks; this rock condition generally involved small rock falls and not massive failures (Girard J. M., 2006).

The aforementioned failure scenarios are some of the more common conditions; however the preceding list does not describe all possible failure mechanisms. The diagrams depict failures in surface mining, but similar situations occur underground. When discontinuities run parallel with the roof of an underground mine, or if discontinuities intersect in the immediate roof, plane and wedge failures can occur underground. Many preventative measures are taken underground (roof bolting, pillar wrapping, etc.), to help prevent major roof (and rib) failures.

These preventions do not solve all problems, but provide more protection for the miners than if no measures were taken.

2.1.2- Common Warning Signs

Initial rock movement rates are often small, and occur over long durations of time before the resulting failure. The displacement rate, as seen in Figure 2.3, accelerates as the failure approaches (after Larocque, 1977). By recognizing initial slope instabilities, large and small scale failures can be planned for, and possibly prevented (Larocque, 1977).

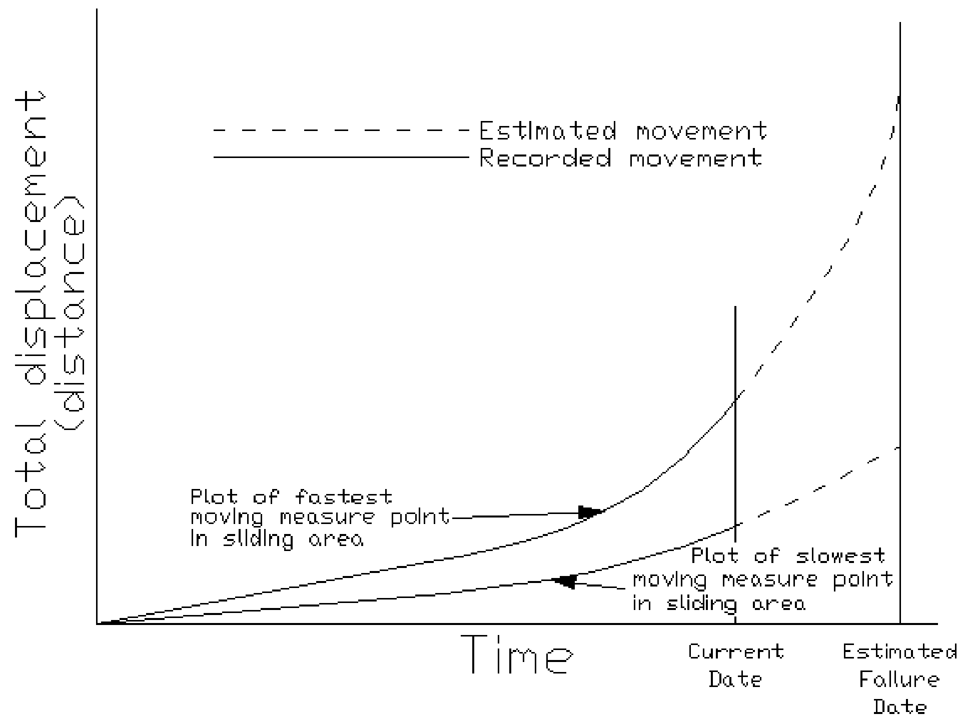

Figure 2.3: Plot of cumulative displacement vs. time for a slope failure (after Larocque, 1977)

A typical open pit mine may only suffer two or three slope failures throughout the life of the operation: how can the few slopes which have a potential for danger be detected in the midst of all the other slopes created during mining? Certain combinations of geological faults, slope geometry, and groundwater conditions create high risk slope environments (Hoek & Bray, 1981). If high risk combinations of such parameters can be recognized during the planning and development stages of a mine, precautions can be taken to deal with the slope issues of these special areas.

Acknowledging the possibility of slope failures and knowing the warning signs of different slope failures can contribute greatly to the safety of the mining operation. After evaluating the geological structure of an area prior to excavation, it must be expected to expose undetected discontinuities as the pit is excavated. Upon encountering discontinuities outside of the initial mine plan, new planning and provisions must be made (Hoek & Bray, 1981). Some of the more common warning signs of slope instability are described below.

The formation of tension cracks at the top of a slope can be an obvious sign of rock moving slightly toward the open pit. This displacement is not easily detected from the pit floor, so it is important to monitor the crests of highwalls near areas of activity. Monitoring the spread of tension cracks can prove useful in determining the extent and severity of the fracture (Girard, Mayerle, & McHugh, 2006). Tension crack monitoring can be found in more detail in the current monitoring methods section.

Finding fresh rubble at the toe of a highwall or on the pit floor should be a very strong indicator that something is not stable on the slope. When abnormal rubble is noticed, extra monitoring should be assigned to the respective highwall(s) (Hoek & Bray, 1981).

The presence of water is to be expected in a mine, because generally the mining progresses below the water table. However, if unexpected and sudden changes in groundwater levels occur, it may be a warning sign of subsurface movement (Hoek & Bray, 1981). The perched water table or a water bearing rock mass could be intersected, which would in turn change the amount of water or water pressure observed by the monitoring instruments. A sudden intersection of water bearing rock could mean that new fractures are being created, or existing fractures are extending. Even if the presence of water suddenly disappears, new fractures could be forming that could divert the water elsewhere. Though this lack of water may be welcomed by the Pit Forman, slope stability issues may be at hand.

Bulging material seen on a highwall, sometimes known as bulges, creep, or "cattle tracks" can indicate slow subsurface movement of the slope. Another warning of slower subsurface movement is the location of vegetation: movement of tress and/or other vegetation at the crest of an incline can be an indicator of instability (E&MJ & Anonymous, June 2007).

The purpose of this project is to detect minute changes of surface inclination. Theory deduces that as rock material shifts and begins to move, small changes can be seen at the surface. By using tiltmeters, it is hoped that wireless sensors will be able to accurately show changes of angle. By monitoring the change of surface angles, it may be possible to locate prime areas where failures are likely.

2.2- Current Monitoring Systems

The objectives of a slope monitoring program are to: 1) maintain safe operational practices; 2) provide advance notice of instability; and 3) provide additional geotechnical information regarding slope behavior (Sjöberg, 1996). Monitoring physically takes place during the operating stage of mining, however proper planning is essential. The monitoring systems and location of such system(s) should be included in the mine design (Larocque, 1977).

2.2.1- Monitoring at Surface Mines

One of the most widely used surface mining methods is open pit mining. "Open pit mining is a very cost-effective mining method allowing a high grade of mechanization and large production volumes." (Sjöberg, 1996) Because of the low cost of open pit mining, it is economically viable to mine lower grade mineral deposits, which would be considered uneconomical when using underground methods. Given the current decreasing trend in production costs and the relatively constant level of ore prices, it can be assumed that open pit mining will continue to be an important factor in the extraction of minerals needed in today's industrial society.

As open pit mining continues, so the depth of the pits will increase. A major issue with increasing mining depths is the costs associated with stripping (mining waste, "the material associated with an ore deposit that must be mined to get at the ore and must then be discarded." (Hartman & Mutmansky, 2002)), which influences the economy of the mining operation. Highwalls should be designed as steep as safely possible to minimize the volume of material removed to access the ore. However, inherent slope stability risks are associated with increasing highwall slopes.

After planning properly, it is still important to monitor the highwalls regularly. In surface mining, the most common type of slope monitoring is measuring displacement. A very common method is using surveying techniques. Survey networks consist of multiple locations of observation points. Areas where instability is anticipated are equipped with stations including target prisms (Hoek & Bray, 1981). There must also be station(s) anchored in control point(s) or areas where instability is not expected. These control points should be as constant as possible, as they will be the base for all measurements taken using the survey network (Larocque, 1977). The control stations should also have a clear view of all other stations in the network to allow easier reading of the instruments. A backsight must be used to reference the angles measured using the Total Station Unit, or other surveying equipment. The backsight, anchored in stable ground, provides a constant and known location for the surveying of the reflector prisms, and provides correction for atmospheric effects (Larocque, 1977). An example of a survey network can be seen in Figure 2.4.

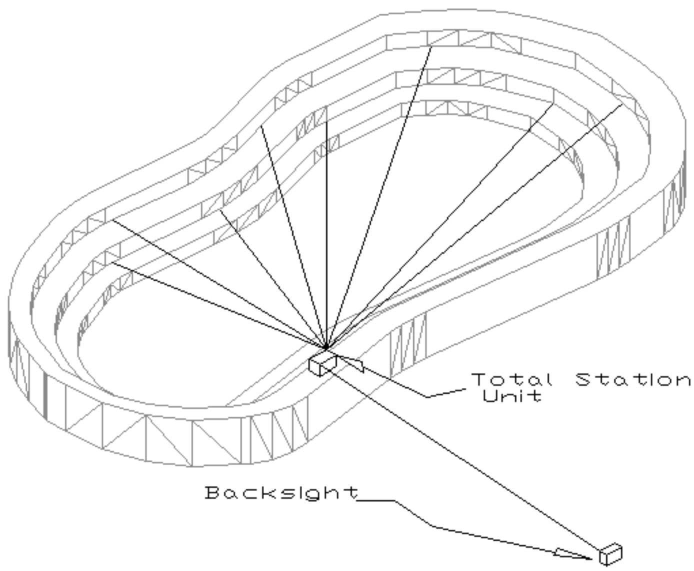

Figure 2.4: Example survey network

The angles and distances from the control station to each station of interest in the network are measured on a regular basis to establish a history of movement on the slope. When/if changes occur in the readings, the operator knows that movement has occurred and further exploration of the cause of this movement is necessary. Errors such as dust, haze, extreme temperatures, equipment deterioration and/or malfunction, and human error can have an effect on the accuracy of the readings, but repeated measurements often minimize these factors.

Another method of stability monitoring is mapping tension cracks. The formation of cracks is a somewhat apparent sign of instability in a slope. "Measuring and monitoring the changes in crack width and direction of propagation is required to establish the extent of the unstable area." (Girard, Mayerle, & McHugh, 2006) One downfall to monitoring cracks is that the rock has already shifted: cracking of the rock can loosen the entire area which has the potential to weaken the ground, making measurements inaccurate. Another issue with tension crack monitoring is the reality that the cracks seen on the surface may not accurately reflect the extent and seriousness of the potential failure. This can be one of the more dangerous methods of monitoring as well, as the operator who is measuring the cracks must enter a known instability area, placing himself/herself at possible risk.

Wire extensometers are simple systems which have capabilities of alerting nearby personnel in case of increased failure probability. The simple system has more than one configuration. One of these setups consists of a wire anchored in the questionable area, which runs over a pulley anchored in stable rock. The wire suspends a weight on the stable end, which moves up or down along with the movement of the unstable rock. These wire extensometers can be fitted with triggering mechanisms to alert nearby miners if a significant amount of displacement occurs, although it is not common practice to do so. A sample setup of a wire extensometer can be seen in Figure 2.5 below (after Girard, Mayerle, & McHugh, 2006).

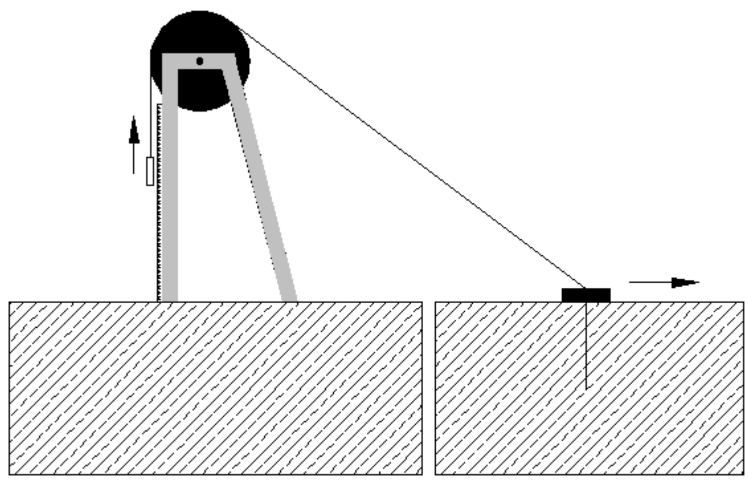

Figure 2.5: Extensometer setup (after Girard, Mayerle, & McHugh, 2006)

One problem with wire extensometers is sag in the wire. The length of wire should be limited to minimize the effects of sag. The counter weight is also matched to the type and length of wire. Another setup of extensometer use involves anchoring two steel stakes into the host rock, one on each side of the fracture in question. An invar tape extensometer is then fitted to the stakes, and the displacement can be monitored. As daily displacement increases, less precise tape equipment with a greater displacement range can be substituted (Larocque, 1977).

Inclinometers are also used to monitor the stability of highwalls in open pit mines. Inclinometers (also known as tiltmeters) measure the inclination of an object with respect to gravity. As seen in Figure 2.6 (after Girard J. M., 2006), the inclinometers give the operator an estimate of how the rock is moving beneath the surface. The angles displayed on each inclinometer can be combined to give a cross-section of the borehole they are monitoring, and thus estimating the movement of the bench. In Figure 2.6 multiple sensors are displayed, however to save money, the operator can use one inclinometer, which will decrease accuracy and resolution in data. A single inclinometer can also be used in alliance with a track laid along the walls of the borehole to allow the inclinometer to travel vertically and measure the inclination of the entire borehole.

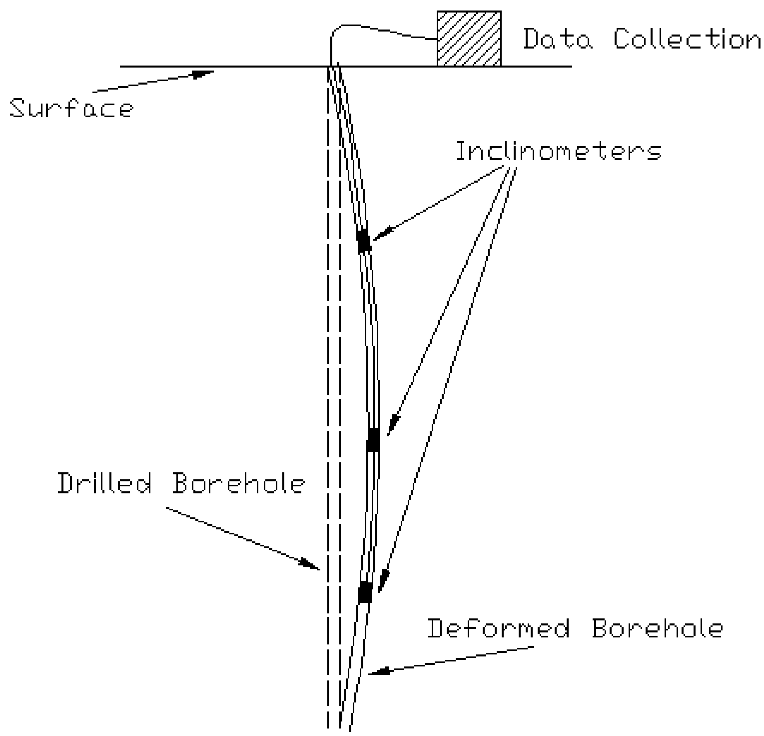

Figure 2.6: Monitoring slope stability with inclinometers (after Girard J. M., 2006)

Microseismic monitoring is used in open pit mines located in seismically active areas. Here, microseismic monitoring can help warn operators of possible slope failure by detecting seismically active zones which can cause rockbursts and earthquakes (Sjöberg, 1996). Seismic events underground, either caused by a controlled event (explosion, hammer strike, etc.) or microseismic events, can be examined to find areas of high stress in the earth. This procedure is explained further in the *subsurface* section.

2.2.2- Monitoring at Underground Mines

The stripping ratio is often too great to economically mine using open pit methods. In cases such as these, as well as in certain types of ore body formations, underground mining is utilized to access the mineral deposit. Underground mining is more expensive than surface mining, production is slower, and the cost of mining is higher (Hartman & Mutmansky, 2002). In terms of ore production, subsurface mining extracts less than 5% of metals and nonmetals, and since 1995, approximately 35% of US coal. However, the United States depends heavily on underground mining for most of its supply of potash, lead, trona, zinc, molybdenum, salt, and silver. (MSHA, 2007)

Surveying is used heavily in underground mines, and when performed properly, can be of great use in mapping the mines progress as well as directing further production movement. However, surveying, is not a major source of monitoring in underground mines, as it is time consuming and can hinder progress of the production team. Surveying for monitoring slope stability in surface mines can mostly be accomplished by setting up equipment at two or three positions at the very minimum, while in underground mining, hundreds of points would be needed.

The use of borehole extensometers is fairly common in underground measurements. Borehole extensometers measure rock deformation parallel to the borehole and can only withstand very small shear displacements normal to the borehole (CSMRS, 2006). If shear displacements exceed the limits of the extensometer, the equipment becomes useless. The system consists of a rod or wire (or multiple rods or wires) extending between the reference head gauge and the anchor point. The instrument is grouted in the borehole leaving the reference head on the rock surface. Figure 2.7 shows a typical borehole extensometer (after CSMRS, 2006).

Borehole inclinometers, also used for subsurface measurements, assess the angular deflection of the borehole. They can be used to locate a failure surface in a sloped area that is moving. Inclinometers are not the easiest equipment to monitor routinely, but can be very useful in finding hazardous areas.

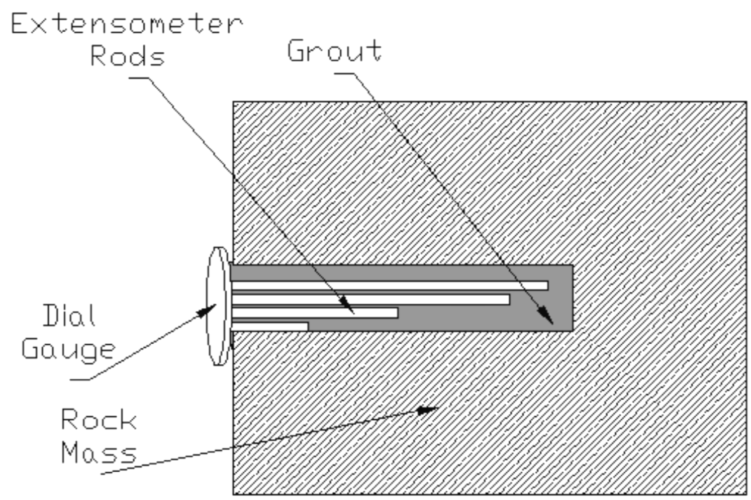

Figure 2.7: Borehole Extensometer (after CSMRS, 2006)

Observations by the National Institute for Occupational Safety and Health (NIOSH) have shown that a limited degree of roof monitors are actually in use beyond the typical inspections of sight and sounding. Inclinometers and extensometers are equipment that can relay data, but require a miner to physically read the instrument, potentially placing him/her in an area of danger. NIOSH has realized the need for an inexpensive monitor with the capability of recording data at a distance from the mine roof. This equipment should allow operators to obtain data without sending an employee into a potentially hazardous area, while still allowing the mine to keep records of reliable and steady data (Iannacchione & Bajpayee, 2006).

The Roof Monitoring Safety System (RMSS) was introduced in 1999 by NIOSH. This modified mechanical extensometer can provide an initial indication of movement in the roof, with the added capacity to be read remotely (Iannacchione & Bajpayee, 2006). The RMSS is used to monitor the sag, or vertical movement of the roof. The equipment can be adjusted to alert the operator of movement as low as 0.001 in (0.003 cm). To read the RMSS, the operator will need a multimeter, which reads the resistance of the equipment. A resistance conversion chart is provided with the equipment, allowing the operator to transform the resistance readings to measurements of sag (Marshall, Prosser, & Iannacchione, 2006).

Typical installations of the RMSS are conducted by NIOSH personnel. The steps of installation include: selection of site for installation, drilling a 2-in (5-cm) diameter hole;

typically about 13 ft (3.9 m) into the roof, inserting the RMSS in the hole and attaching and extending the cable along the roof and down the rib (Prosser, Marshall, Tadolini, & Iannacchione, 2006).

Microseismic monitoring experience has shown that there is some correlation between measurable rock noise and slope movement, but quantitative criteria are still lacking (Sjöberg, 1996). Even though the technical equipment needed for microseismic monitoring is currently available, microseismic monitoring is not completely reliable: setbacks include filtering out the noise from mining equipment and correcting arrival times for the actual length of travel for the wave. Research and experimentation is being performed to help solidify the use of microseismic monitoring in underground mining. In "Time-Lapse Tomography of A Longwall Panel: A Comparison of Location Schemes", by Kramer Luxbacher, the process of using microseismic events to map out areas of high and low stress underground is described. As the P-waves travel through the earth, they travel through many layers of rock, as well as many areas of differing stress. Assuming homogenous rock content, the speed of the P-waves can be related to the stresses in different areas of the rock mass, and with an array of sensors, a 3-dimensional diagram, as well as 2-dimensional maps can be created mapping high and low stress areas. An example of this method is seen in Figure 2.8 below, shows the inferred stresses on a longwall face while the shear is operating (Luxbacher, 2007). The higher velocities are represented by darker shades.

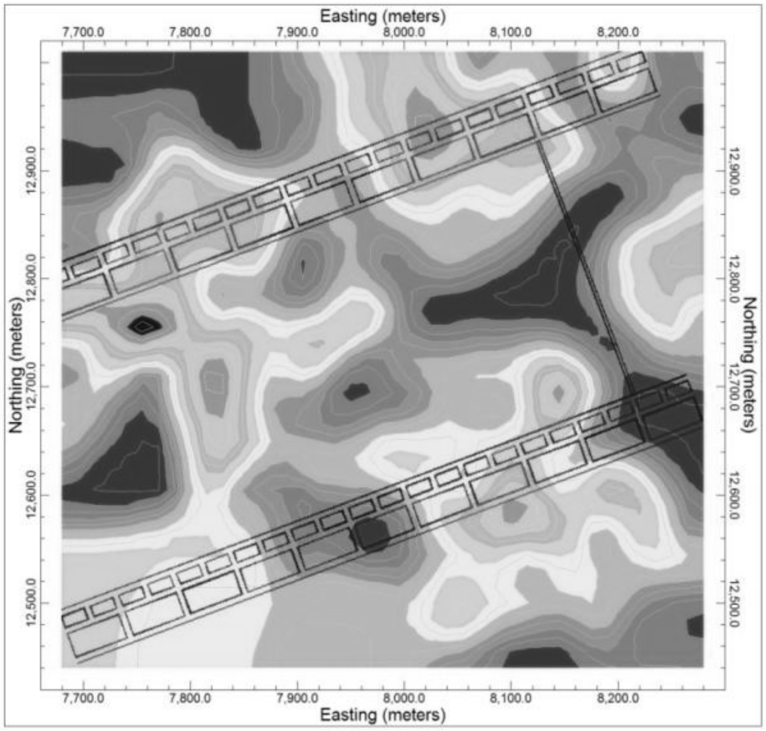

Figure 2.8: Plan view velocity tomograms at seam level

In a different case study, 15 geophones were used to study the microseismic events in an underground limestone mine, where 2 distinct roof falls were observed. Over 700 microseismic emissions were collected, and analyzed manually. After the occurrence of both roof falls, it could be seen that within 48 hours of first signs of roof failure, a large increase in filtered seismic activity was present. In general, monitoring microseismic activity has potential to locate future roof fall events, although determining the exact timing of these event is much more difficult and may prove to be beyond the capabilities of the technology (Iannacchione, Batchler, & Marshall, 2006).

2.3- Wireless Instruments

As the primary goal of this project is to study, design, and test wireless tiltmeters, it is important to have an understanding of wireless technology. This section will give a brief history of wireless technology, and describe current wireless products.

2.3.1- History of Wireless Technology

'Communication without the use of wires other than an antenna' is a fair definition of wireless technology. This definition is shared by the radio. It should be known that the wireless technology known and loved today has spawned from its ancestor, the radio (Dubendorf, 2003).

Guglielmo Marconi was one of the first individuals to develop commercial workable radio communication, purportedly sending and receiving his first radio signal in Italy in 1895. In early 1896, Marconi journeyed from Italy to England to demonstrate to the British telegraph authorities his developments in operational wireless telegraphs. With the help of W. H. Preece, a British electrical engineer, radio signals were transmitted wirelessly over a distance of 1.75 miles in July 1896. Less than one year later, the distance had been more than quadrupled to 8 miles, between Lavernock Point and Brean Down England (Dubendorf, 2003).

Though America was not among the first to realize the potential of wireless technology, US scholars soon realized the commercial possibilities of the European technologies. In September 1899, during the International Yacht Races held off of New York harbor, reports were transmitted intermittently via radio devices by Marconi: the steamer *Ponce* was equipped with radio devices and two receiving stations were equipped. Though this demonstration was not very successful, it brought interest in the still new wireless technology to the United States.

Perhaps one of the greatest events of early radio was the reception by Dr. Marconi at St. John's, Newfoundland, of a transmitted test signal from his English station. This became known as the famous letter "S", which was successfully transmitted from England to Newfoundland on December 11, 1901 (Dubendorf, 2003).

With the introduction of "Packet Data", information was able to be sent wirelessly more efficiently than before.

The transmission range is influenced by the power of the transmitter and the type and location of the antenna. The length of the antenna and the frequency transmitted also play a factor in the transmission range.

Voice transmission was accomplished in the 1920s, but the technology needed for such equipment as wireless telephones or pagers was not readily available for public use. It was not until the 1980s that the technology was perfected to the point that they became widely available as consumer products (Dubendorf, 2003).

2.3.2- Current Wireless Technology

Many companies produce instruments that take physical measurements and transmit data wirelessly. These instruments can potentially monitor any physical occurrence and transmit digital data wirelessly to a receiver. Properties including (but not limited to) acoustic levels, vibration, inclination, humidity, temperature, acceleration, pressure changes, and light exposure can all be monitored. Wireless devices can be designed with event counters to record and transmit the patterns and frequencies of set trigger mechanisms. Though the wireless transmitting range is limited by the antenna type and size, the ability to transmit over long distances is possible by using multiple relay stations, or even multiple sensors with the ability to mesh together and transmit data to a single (or multiple) station. More powerful antennas can also be used to increase the transmitting distance and reliability.

Wireless, micro electrical mechanical systems (MEMS) have proven to be useful in monitoring the integrity of many civil structures. Philadelphia, PA is connected with Camden, NJ, via the Ben Franklin Bridge. This 1927 suspension bridge, which supports seven lanes of traffic, used to be monitored with wired instruments, but has recently changed to a MicroStrain wireless sensor system. When using the wireless sensors, the engineers in charge observed an increased ease and speed of installation. They also found that when switching to the new MicroStrain system, they reduced the need for cable and its protection, realized a lower overall system cost, and reduced pre-mature equipment repairs (MicroStrain, 2007).

Civil engineering is not the only industry to utilize the wireless inclinometers. In November, 2006, a MicroStrain micro-sensor was successfully implanted in an artificial knee replacement. This new "smart knee" has the ability to report digital, 3 dimensional torque and force data back to computers. The sensor provides information on twisting, bending, compressive and shearing loads across the human knee. These transmissions not only help doctors monitor the stability of the knee replacement, they also help them better understand how the human knee operates (MicroStrain, 2007).

The automotive industry is able to use wireless inclinometers custom designed for the needs of automobile testing and qualification. Crossbow offers a complete inertial reference system designed to allow automobile manufacturers and examiners to measure and analyze a vehicle dynamic response. Tri-axial inclinometers coupled with accelerometers are used to measure the pitch, roll, and yaw of automobiles as well as their respective dynamic information: angles, rates, and accelerations (Crossbow, 2007).

Though traditional monitoring instruments have been used in mining for years to monitor the stability of surrounding rock bodies, wireless technology is not yet widely accepted. Wireless monitoring technology has benefits and setbacks when compared to traditional scheduled monitoring.

One benefit of wireless instrumentation is the capability of real-time monitoring. When using the traditional scheduled monitoring a quantity or quality is monitored at a scheduled time. The reliability of the data depends greatly on the sampling rate, the amount of samples per given unit of time. Some traditional instruments have the capability of measuring in real-time, but many do not. One problem with scheduled monitoring is the consequences of an event occurring between scheduled recordings. If a physical measurement changes between readings, the operator has no knowledge about it until the next scheduled monitoring session. With real-time monitoring, the status of a quantitative variable can be measured continuously. Recorded data can also be viewed by the operator so that after a significant event, much more accurate time can be delegated to changes in the measurement(s); which could allow the operator to determine what actually caused the event in question. Graphs of measurement history are readily available to any user with access to the recorded data, so trends in the data can be analyzed. The data can be transmitted via the Internet to allow operators to view the status of monitored physical measurements at any time, from any place, simply requiring an Internet connection (Accsense, 2007).

Another benefit of real-time monitoring is the ability to set up alarms when monitored levels are exceeded. Triggers can be set up to alert staff via email and/or voicemail alarms if a monitoring device records an extreme or unexpected measurement (Accsense, 2007). Also, the instruments continue to monitor, even when the work crew is off duty. Information from the sensors has the capability of being posted on the Internet for access on nights, weekends, and holidays when no-one else is even in the vicinity of the sensor. This allows the operator to be constantly alert of the status of their project.

An obvious benefit of wireless instrumentation is the lack of wiring costs. Wired instruments spaced in larger areas require vast amounts of cables. With the rising costs of precious metal commodities, the cost of cable will expectedly continue to increase. Wireless instruments have no need for these expensive wires, so using wireless technology could save the operator on costs.

Setbacks are also apparent in current wireless monitoring devices. The transmitting range of most devices is not extremely impressive. Generally the upper limit of wireless transmitting is around 250 ft, but the distance is dependent on line of sight. There are transceivers that will operate as far as one mile from its receiving antenna, but distances like these are not incredibly common. As with any wireless devices, barriers and objects between the transmitter and the receiver often interfere with the quality and reliability of the transmission.

These setbacks present a real issue to be considered in mining. Surface mining often takes place on a large scale, so distances between highwalls and structures is generally greater than 250 ft. One of the more common types of subsurface mining is room and pillar mining, which incorporates support pillars of the host material. The wireless signals used in the devices in question will not penetrate these roof supporting barriers. To resolve both issues in the described situations, a network of multiple sensors would need to be used, to allow multiple relay stations before the signals are finally transmitted to a central data storage device.

Another issue comes with the power source of the device. Though most instruments can be powered by an external power source, the instrument would need to be battery powered in situations that require truly wireless monitoring. The life of the batteries used in many sensors is not much more than 6 months (varies with different sampling rates and other settings within individual sensors), which would require the operator to replace batteries at least twice a year, if not more. This could cause minute disruptions in the work cycle unless planned into the schedule properly. To reduce the probability of sudden sensor loss due to battery failure, alarms on the sensors can allow the operator advance notice of lowered supply voltage, and provide ample time to replace the batteries.

Mining conditions are often very rugged, and the instruments available today may not be ready for the mining environment. In underground coal mines, the ever present coal dust and rock dust may interfere with the instrumentation in the device. In surface mining, the possibility of minor rock falls occurring above a sensor on a highwall exists: even though fist sized rocks may only fall short distances, the momentum generated by the falling material could be enough to damage current wireless instruments. The ever presence of water could also provide unwanted short circuiting in equipment.

CHAPTER 3: PRELIMINARY DATA COLLECTION

The *Accsense* A1-01a sensor pod was tested for reliability (continuity of wireless transmissions), ease of use, and sensitivity. The following chapter discusses the procedure and some results of preliminary testing of already existing equipment, as well as testing the accelerometer chosen for use in the circuit board. For more information on the circuit board, refer to Chapter 4: Designing a Wireless Tiltmeter.

3.1- Accsense Wireless Systems

The *Accsense* A1-01A sensor pod is designed for general measurements. Within the pod casing, there are several different internal sensors, as well as an exterior terminal for wiring additional instruments to the pod. The pods have the ability of storing up to 255 data points before transmitting, and have a range of approximately 260 ft (80 m). The internal sensors include equipment to measure ambient temperature, vibration, humidity, acoustic level, and ambient light (Accsense, 2007).

3.1.1- Testing the Accsense A1-01a

To analyze the functionality of the *Accsense* wireless MEMS technology, simple testing was performed outside of a formal laboratory. A board of wood was angled between 5° and 25° in increments of 5°. At each increment, an *Accsense* A1-01a sensor pod, as seen below in Figure 3.1, was placed on the board and left to gather and transmit data.

Figure 3.1: Accsense A1-01a Sensor Pod

After sufficient time, the sensor was rotated 90° on the plank to test the sensitivity of the internal accelerometers for each axis, positive and negative, X- and Y-. As the pod was rotated, any measurements taken during the time of rotation were ignored. As mentioned before, the pods were placed on a plank of varying angle from the horizontal plane. At each angle, the sensors were tested with four rotations, denoted as antenna NE, SE, SW, and NW for continuity. These rotations would allow testing of both the X- and Y- axes, as well as positive and negative angles for each axis. The headings given as descriptions to the antenna arrangement have no relation to true North, but were simply a descriptor to help repeat the same measurements for each angle. As the sensor pod was rotated, or the angle of inclination was altered, the time of day was recorded to aid in data analysis.

The *Accsense* A1-01a sensor pods operate by transmitting a wireless voltage reading to a "gateway", which can be purchased through *Accsense* (Accsense, 2007). The gateway used for the purpose of this experiment is the *Accsense* B1-01, as seen below in Figure 3.2.

Figure 3.2: Accsense B1-01 Gateway

The gateway is connected to the Internet via an Ethernet cable on its rear panel (same panel as antenna as seen above in Figure 3.2). With this Ethernet connection, the *Accsense* B1-01 has the ability to post real-time data on the *Accsense* website (Accsense, 2007). With a valid username and password, an operator has the ability to check on his active sensors from anywhere in the world, provided a PC with Internet connectivity.

The *Accsense* website automatically takes the data transmitted from the gateway and forms a number of visual aids for viewing the data. The website allows the operator to view data on a time-based level. Charts are automatically loaded for the last 4 hours of recorded measurements, but the duration of data points can be changed easily. Hours, days, weeks, even months of data can be viewed using the built in scatter plots. The actual data numbers can also be viewed on a separate tab, as well as saved and downloaded onto your own PC. The minimum, maximum, average, median, and standard deviation for the selected duration of data points are also displayed on the same page, making a quick assessment of the data. If a further analysis of the data is required, as was the case in this project, the data values can be downloaded and viewed in *Microsoft Excel*.

3.1.2- Accsense Results

After analyzing the data collected by the *Accsense* A1-01a sensor pod, it was decided the sensitivity of the included accelerometer was not sufficient for the purpose of this project. Desired sensitivity was around 0.5°, and the *Accsense* sensor pods were only displaying obvious visual and statistical changes of between 1 and 2 degrees. The standard deviation of the readings were simply too high for accurate angle measurements.

A major problem with the design of the sensor pod was the output reading was a sum of all axis measurements. The resulting voltage could represent a variety of angles given the same output. In a perfect situation where an angle was to change on one axis, as well as change equally negative on the other, no voltage difference would be detected. This misrepresentation of angle was observed a number of times during the testing stages of the *Accsense* A1-01a. Figure 3.3 below shows an example of the readings from the sensor pod and illustrates how two angles can have the same (or similar) outputs. As visible in the chart, the 5° and 10° readings are very similar, where the 15°, 20°, and 25° are distinctively different, even varying what could be estimated as linearly. Also visible in Figure 3.3 is the level of noise, which was somewhat significant. Because each measurement varied so heavily, a change may not be as easily noticed.

Data tables were compiled containing measurements at each inclination. Tables containing the relation of alignment, (NE, SE, etc.) were also constructed from the data, however this data was not used; ergo it was not included in the appendixes. Figures were created to visually display the relationships of the four antenna bearings at each angle, as well as comparing the angular readings for each accelerometer alignment. The data tables can be found in Table A.1 through Table A.4 in Appendix A.

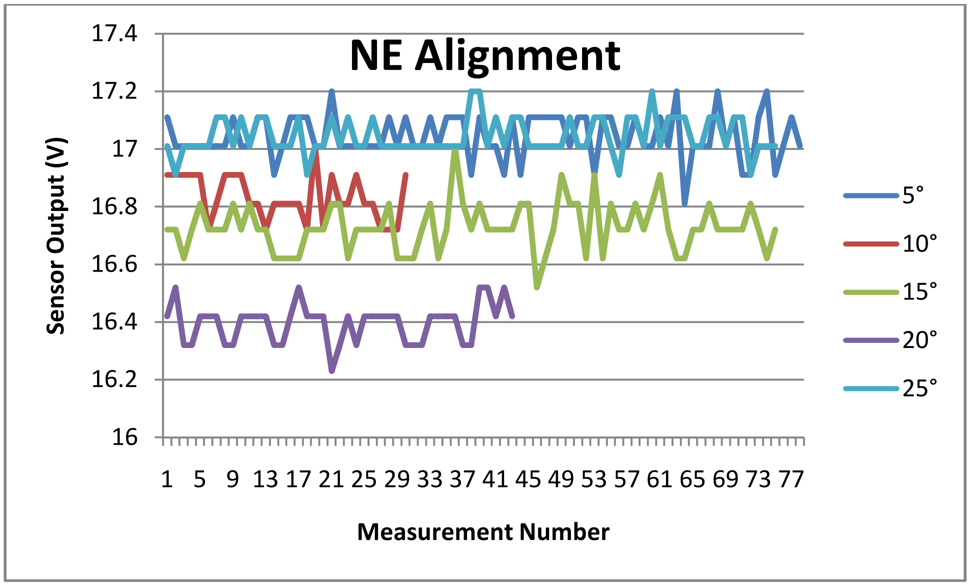

Figure 3.3: Accsense A1-01a output voltage

3.2- Other Wireless Systems

Crossbow and MicroStrain, among other companies, manufacture wireless MEMS sensors that could feasibly be used in the mining environment; however these products were not tested for this project. Crossbow sensors, as seen below in Figure 3.4, were available for use, but because of software installation issues, they were not able to be tested. MicroStrain sensors were not available for testing, and the budget for this project did not allow for their purchase. Therefore an analysis of the MicroStrain sensors could not be performed.

Figure 3.4: Crossbow Sensors

3.3- MEMSIC Accelerometers

Aside from testing the already existing equipment, individual accelerometers were tested for design of a new product. The *MEMSIC* accelerometers tested for the purpose of this project were ordered online from the *MEMSIC* website. The MXR6999M accelerometer was chosen because of its posted sensitivity and other product ratings found online. The MXR6999M is a thermal accelerometer with 2 axes of measurements and a claimed sensitivity of 1000 mV/g. A sensitivity of 1000 mV/g simply means that for each g force, there are 1000 increments of 1 mV. For most accelerometers, 1 g is seen when 1 of the axes is aligned perpendicular to the horizontal plane. Therefore, a sensitivity of 1000 mV/g claims to have 1000 digital steps from horizontal to vertical, or 90°. If assumed linear, each increment would represent a change of 0.09° in theory.

The change in voltage, in reality, is not linear to the change in tilt. The accelerometer is most sensitive to changes in tilt when the accelerometer is perpendicular to the force of gravity and least sensitive to changes in tilt when the accelerometer is parallel to the force of gravity. In other words, when one axis of the accelerometer is vertical, changes in inclination are less obvious. The MXR6999M datasheet includes a table of approximate voltage readings for axis orientations. The table found on the datasheet has been recreated below in Table 3.1 (after MEMSIC, 2008).

Table 3.1: Changes in Tilt for X- and Y- Axes

X-Axis Orientation to Earth's Surface (deg.)	X-Axis		Y-Axis	
	X Output (g)	Change per deg. of tilt (mg)	Y Output (g)	Change per deg. of tilt (mg)
90	1.000	0.15	0.000	17.45
85	0.996	1.37	0.087	17.37
80	0.985	2.88	0.174	17.16
70	0.940	5.86	0.342	16.35
60	0.866	8.69	0.500	15.04
45	0.707	12.23	0.707	12.23
30	0.500	15.04	0.866	8.69
20	0.342	16.35	0.940	5.86
10	0.174	17.16	0.985	2.88
5	0.087	17.37	0.996	1.37
0	0.000	17.45	1.000	0.15

3.3.1- Testing the MEMSIC MXR6999M

The MXR6999M was tested using a simple experiment consisting of a simple straight board and a moving fulcrum. The angle of the board was changed in half degree increments by raising the adjacent leg of the triangle to predetermined lengths. Simple trigonometric calculations allowed the vertical leg to be measured, keeping a constant hypotenuse, as seen below in Figure 3.5.

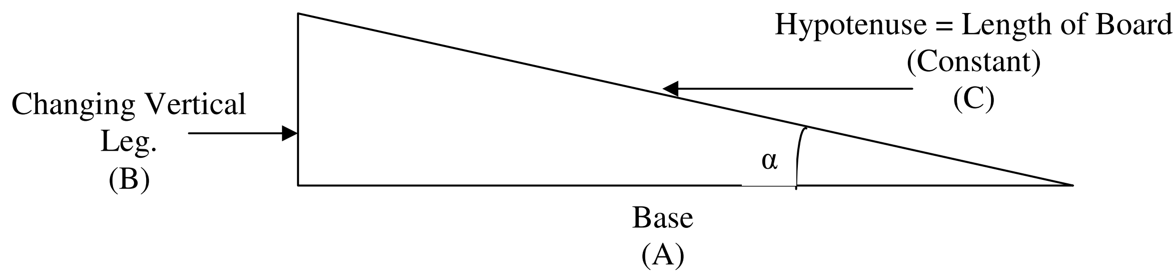

Figure 3.5: Testing the MXR6999M

Using the equation: $\left\{ \sin(\alpha) = \frac{B}{C} \right\}$ a given angle (α) could be measured by keeping a constant hypotenuse (C) (or length of the board), and changing the vertical leg (B) as seen above in Figure 3.5.

The MXR6999M Accelerometers were soldered to special evaluation boards, which were purchased from the *MEMSIC* website. Each evaluation board (here-in referred to as EB) had a solder pad for each respective pin on the MXR6999M. These solder pads connected the pins of the accelerometer to easier accessible pads where wires were soldered for the purpose of analysis. The accelerometers were hand soldered to the EB's, and tested using the simple board experiment described above. An image of the EB and accelerometer, with attached wires, can be seen below in Figure 3

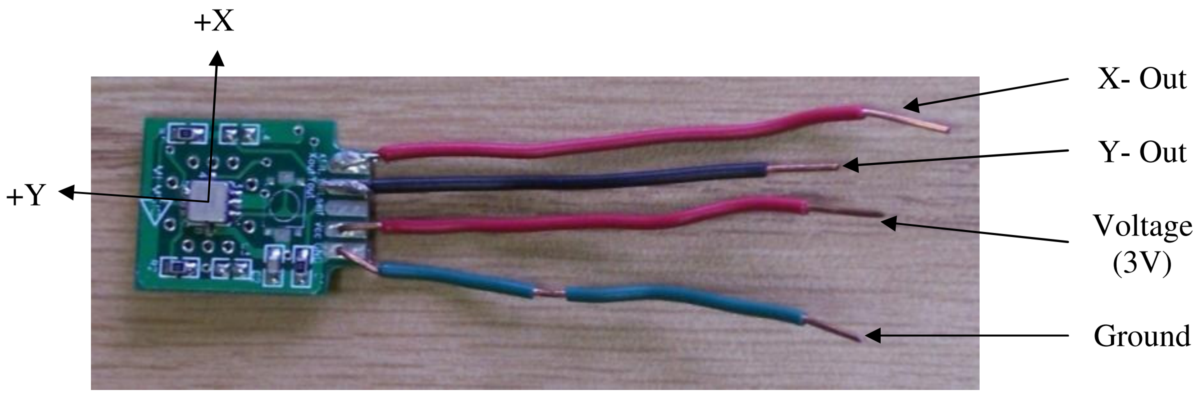

Figure 3.6: MXR6999M and Evaluation Board

As mentioned in the MXR6999M datasheet, the accelerometer has an arrow as a logo, indicating the negative X- Axis. The positive X- Axis therefore is in the opposite direction of the *MEMSIC* logo, and the Y- Axis follows the right hand rule (MEMSIC, 2008). The X- and Y- Axis are labeled above in Figure 3.6 for visual reference. Refer to the MXR6999M datasheet for a Pin Diagram and Pin Spacing figures (MEMSIC, 2008).

To test the *MEMSIC* accelerometers, an experiment was designed so that only one axis would change at a time. This experiment consisted of a plank of stiff wood, with one end anchored. The other end was lowered and raised to attain angles of 0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°, 4.0°, 5.0°, 10.0°, 15.0°, and 20.0° from horizontal. The MEMSIC accelerometer is capable of reading angles at varying frequencies, so for the purpose of consistency, it was necessary to find the optimal operating frequency for both axes.

By testing the mean and standard deviation of the readings at 0° using frequencies of 1 Hz, 10 Hz, 50 Hz, 100 Hz, 500 Hz, 1,000 Hz, 5,000 Hz, and 10,000 Hz, it was determined that the optimal operating frequency was 100 Hz. The data table containing all 100 samples for all frequencies can be found in Table A.5 and Table A.6 in Appendix A. The charts displaying the mean and standard deviation for an inclination of 0° and the aforementioned frequencies can be seen below in Figure 3.7 and Figure 3.8 (X- and Y- axes respectively). This experiment was only performed once for each frequency: repeadability was assumed. As is visible in the figures below, 100 Hz is a fair frequency for both the X- and the Y-axes: the standard deviation (as seen in the error bars) for both axes is significantly lower at this sample rate. With a lower standard deviation, the sensitivity of the accelerometer is increased, allowing the user to determine smaller changes in inclination.

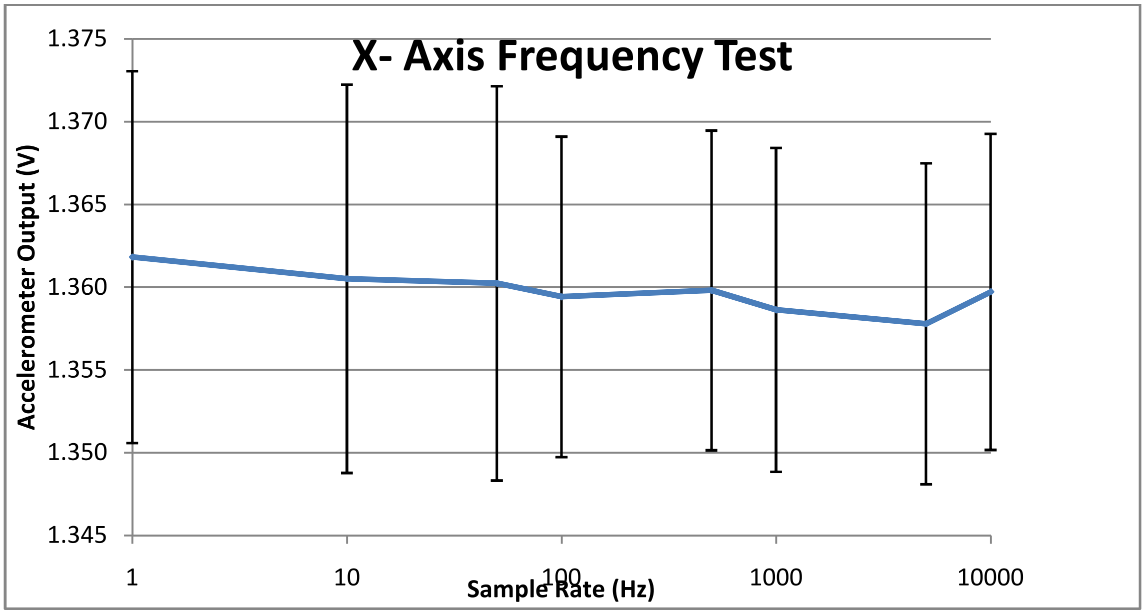

Figure 3.7: X-axis frequency test with ±2 standard deviation error bars

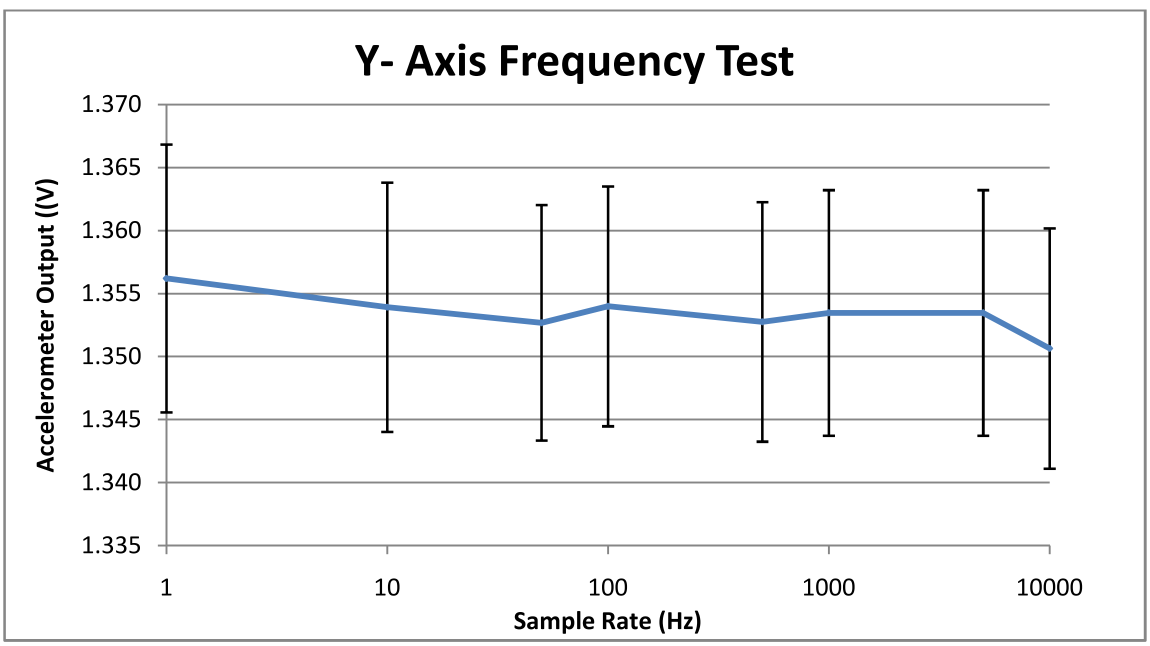

Figure 3.8: Y-axis frequency test with ±2 standard deviation error bars

Using the determined accelerometer frequency of 100 Hz, 100 samples were recorded at each of the previously stated angles (0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°, 4.0°, 5.0°, 10.0°, 15.0°, and 20.0° from horizontal). During testing it was found that for the X- axis, as the angle increased, so did the voltage output linearly. The Y- axis was found to have a negative correlation, but was also linear. This would prove useful in future testing of the accelerometer, especially when using the output to determine angle change in a non-laboratory environment. The tables with all 100 accelerometer outputs and all angles can be found in Table A.7 and Table A.8 (X- and Y-axis respectively). In Figure 3.9 and Figure 3.10 below, the graphs depict the linear relationship between the angle tested and the voltage output.

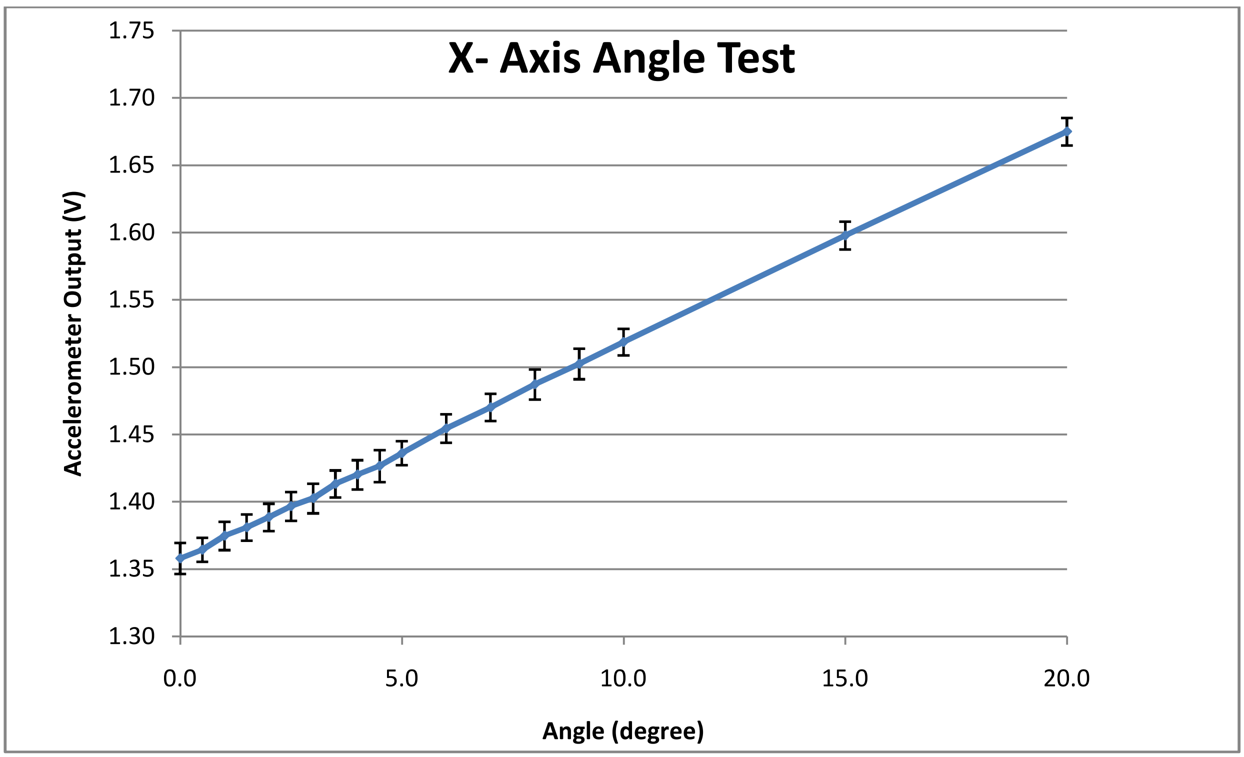

Figure 3.9: X-axis MEMSIC angle test with ±2 standard deviation error bars

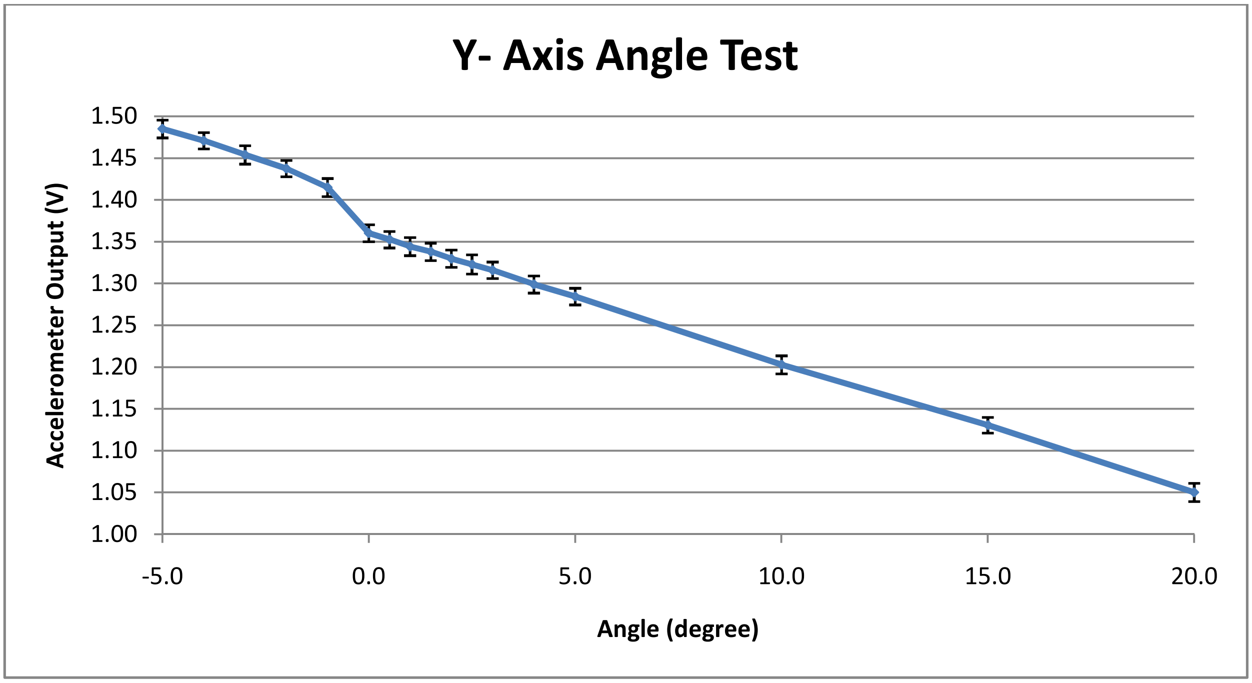

Figure 3.10: Y-axis MEMSIC angle test with ±2 standard deviation error bars

This simple test of increasing the inclination of the accelerometer was performed to check the reliability of the *MEMSIC* MXR6999M. The test was performed once: had additional time been available the test would have been repeated to check the validity and repeatability of angle measurements. The desired sensitivity of the accelerometer would allow the user to detect a change in angle of ±0.5°. The main test involved measuring the output of the accelerometer at angular measurements of 0° to 5.0° in 0.5° increments. To check linearity of the measurements of the accelerometer, further voltage readings were taken at 5° through 10° (at 1.0° intervals), as well as at 15° and 20°. The greater angles of inclination proved to fit linearly with the finer changes observed at the beginning of the experiment. As most angles measured for the purpose of this project are unlikely to be greater than 20°, further measurements were not taken in this test. However, the MXR6999M is capable of measuring angles up to ±90° inclusive on each axis. Though vertical measurements are possible, the sensitivity of the accelerometer decreases as the angle increases. The closer the accelerometer is to horizontal, the more sensitive the equipment will be (MEMSIC, 2008).

In addition to the aforementioned angles, the accelerometer was tested at negative angles to ensure continuous linearity of voltage vs. inclination. As the negative angles were plotted alongside the positive angles, a slight jump in voltage reading was encountered. This jump remains unaccounted for; further research should be attempted before finalizing a design for mass production. As seen in Figure 3.10, the slope of the linear correlation for the negative angles was relatively the same as correlation in the positive data points.

As visible in Figure 3.9 and Figure 3.10, the standard deviation of the readings remained somewhat constant. This is beneficial in serving the purpose of the accelerometer, for the user can understand the error range of the equipment while reading the output data. With greater standard deviation comes greater uncertainty of accuracy in measurement, so the relatively low standard deviation found in this experiment are reassuring of the prospective success of the MXR6999M accelerometer.

3.3.2- MEMSIC Results

Upon conclusion of the tests described in 3.3.1- Testing the MEMSIC MXR6999M, it was found that within one standard deviation, a change of inclination of roughly 0.4° could be detected. With this conclusion, the MXR6999M accelerometer was approved for use in the design of the circuit board, as described in Chapter 4: Designing a Wireless Tiltmeter.

3. 4- Other Accelerometers

Aside from the *MEMSIC* MXR6999M, a number of other accelerometers produced by *Analog Devices* were considered for use in the project design. The ADXL330 was a candidate because it is a 3-axis accelerometer. 3 samples were provided by *Analog Devices*, but were not tested due to the package of the accelerometer. The term package refers to the size, shape, pin location, and pin spacing of the equipment. A specific connection port would have been needed to test the ADXL330, and budgeting and timing for this project did not allow for such a purchase. Also, the sensitivity of the ADXL330 was not sufficient. A mere 300mV/g would most likely have not yielded the results desired for this project. (Analog Devices, 2008)

The ADXL103 was also provided by *Analog Devices*, but no evaluation boards (EB) were provided with the accelerometer. Unfortunately, without an EB, the 5 ADXL103 units provided as samples from *Analog Devices* could not be tested. The ADXL103 is a single axis accelerometer, so even if an EB was available and the device was tested, it was not ideal for use in this project. (Analog Devices, 2008)

Another product very similar to the ADXL103 is the ADXL203, which is a dual axis accelerometer made by *Analog Devices*. The ADXL203 was not available for samples until late in the project lifeline. Even though *Analog Devices* was kind enough to provide 5 ADXL203 units with already mounted on EB's, the timing was unfortunate as the *MEMSIC* MXR6999M had already been selected for use and ordered in quantity 10 for mounting on the circuit boards. The ADXL203 is very similar to the MXR6999M in specifications. Both have sensitivities of 1000 mV/g, have similar voltage supply requirements, and are bi-axial accelerometers with analog output. The package for the ADXL203 is also very similar to that of the MXR6999M; meaning that some of the 8 pins on the accelerometer have the same designated function. Voltage and ground pins are almost identical, even the X- and Y- axis output pins were the same (Analog Devices, 2008)(MEMSIC, 2008). If the size of the accelerometer package, as well as the exact distance between pins were identical, the ADXL203 could be substituted for the MXR6999M on the circuit board design and the functionality of the sensor would most likely remain intact.

CHAPTER 4: DESIGNING A WIRELESS TILTMETER

In an effort to tailor the instrument to the specific requirements of this project, it was decided to design a new and unique device. To link the MXR6999M accelerometer with the XBee wireless transceiver, a circuit board was needed. Refer to 4.1.1- Transceiver selection for more on the XBee transceiver. Since circuit boards are not easily purchased for such a specific task, especially in smaller quantities for prototype models, it was decided to construct a unique circuit board for the purpose of this project using *Eagle* software.

4.1- Circuit Board Design

Eagle is a German made computer program allowing users to create circuit boards using devices that exist in previously created "libraries" or conglomerations of user created components. It is also possible to design new "parts", or components, to suite the user's specific requirements. These devices are added and linked together in a schematic using *Eagle*. From the schematic, a digital copy of a circuit board can be created. This digital blueprint of the circuit board contains all the components of the project needed to make the entire board function properly: the accelerometer, the transceiver, the processor, and all resistors, capacitors, diodes, and transistors needed to make all the components function properly. These devices can be moved, rotated, and connected together using *Eagle*, to create a compact and functional circuit board. In the case of this project, almost all devices (resistors, capacitors, transistors, transceivers, etc) existed in previously created libraries and could be accessed for use without copyright infringement; the only device that needed to be designed from scratch on this program was the connection for the accelerometer. (Bird, Eagle Software, 2007)

4.1.1- Transceiver selection

As this circuit board was desired primarily for wireless use, a transceiver would be the key component in its design. For the purpose of this project, multiple transceiver manufacturing companies were researched online, and *Digi International*'s XBee transceiver was selected.

A low cost ($21 each), low power (2.1 – 3.6V), mesh networking capable device, the XBee transceiver was considered ideal for the purpose of this project. The XBee selected has an indoor range of up to 133 ft (40 m) and an outdoor range of up to 400 ft (120 m). If this distance is deemed too short, XBee PRO transceivers are available at $34 each, and have an indoor range of up to 300 ft (100 m) and an outdoor range of up to 1 mile (1.6 km). For the purpose of this project, the normal XBee transceiver was selected, as distances greater than 100 ft (30 m) were not expected. (Digi International, 2008)

The XBee transceivers have a serial data rate of 1200 – 230,400 bps, which greatly exceeds the data rate expected for this project. Multiple baud rates are supported by the transceiver which would prove useful when programming, as described in 4.3- Programming the Circuit Board. The XBee transceiver has capabilities for sleep mode, which was not used for this project, but is recommended for further research and development of the tiltmeter. (Digi International, 2008) The XBee transceiver can be seen below in Figure 4.1.

Figure 4.1: XBee Transceiver

Please refer to Figure 4.1 for scaling purposes of all images of circuit boards throughout the remainder of this document. A Pin Diagram for the XBee can be found on the *Digi International* website (Digi International, 2008).

4.1.2- Prototype Circuit Board

To properly design the circuit board, an initial prototype board was designed for analytic purposes. Using Eagle, the circuit board was laid out and organized for ideal analysis in the testing stages, with solder test points (to test voltage readings) for important connections, LED diodes for visual confirmation of sending and receiving data, and switches for testing different XBee transceiver settings. Test points would also prove useful for connecting additional components if errors in the planning of the board were made. These additions to the board would not be necessary in a production model, but proved useful in the testing stages. This initial prototype would be tested using a CR2032 cell battery, and after fine tuning of the switches, observing the patterns of the diodes and test point indication, modifications to the schematic and board would be made. The schematic and board for this initial prototype model can be seen in Figure 4.2 and Figure 4.3 respectively.

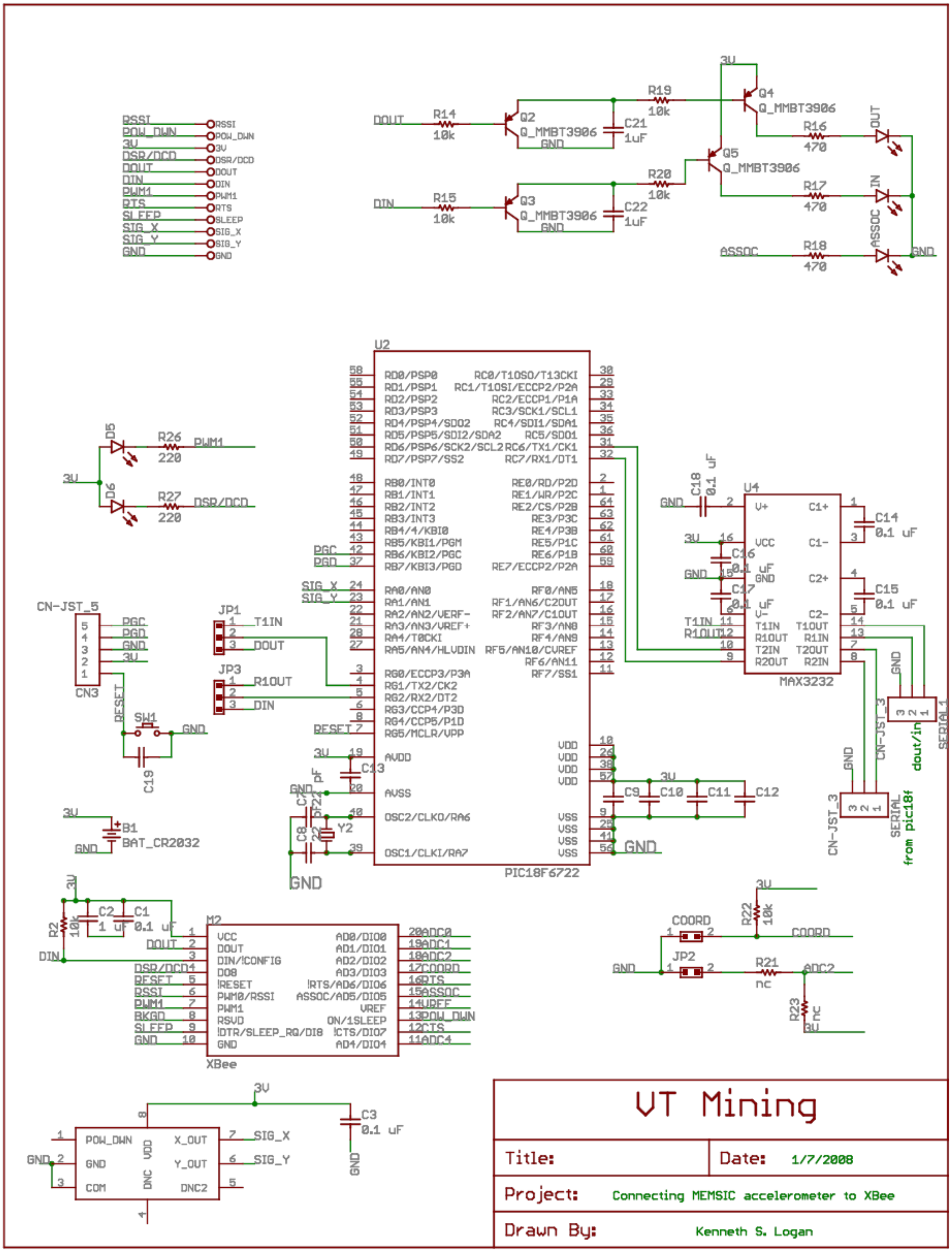

Figure 4.2: Initial Prototype Schematic

The blue rectangle that contours the border of the board is known as a ground plane, which will fill all empty space on the bottom of the board when created. The ground plane allows for easier routing as well as provides a more consistent and better quality ground to all components.

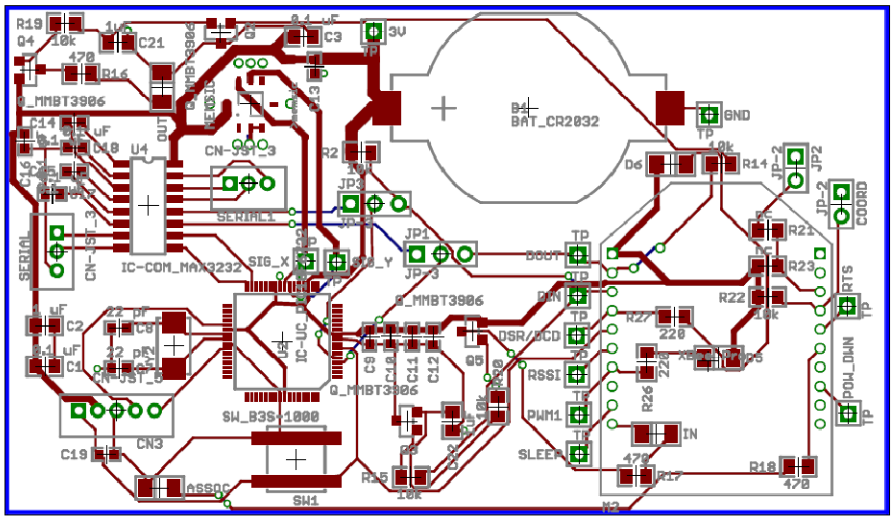

Figure 4.3: Initial Prototype Board

After designing the prototype circuit board in *Eagle*, a group of different layer files were generated to be sent to a circuit board manufacturing company. Seven layers including drill holes, top and bottom copper connections, top and bottom solder mask, and top and bottom silk-screen were created and uploaded to *Advanced Circuits* (Advanced Circuits, 2008). *Advanced Circuits* took the provided layers and manufactured the circuit board represented in Figure 4.3.

Once the circuit board was completed in *Eagle*, additional components were necessary for its operation. Capacitors, resistors, transistors, diodes, and other electronic components were ordered from *Digi-Key* online (Digi-Key, 2008). Some of the parts were available as samples from other manufacturing companies. *Texas Instruments* provided samples of the MAX3232, *Microchip* provided samples of the PIC18F6722, and *Mill-Max* provided samples of headers for the XBee transceivers (Texas Instruments, 2008)(Microchip, 2008)(Mill-Max, 2008). Also, the accelerometer used in this design came from *MEMSIC*, and the XBee transceiver was ordered from *Digi International,* formerly *MaxStream* (MEMSIC, 2008)(Digi International, 2008). A list of all the necessary components for the prototype board, along with their product numbers and company from which they were purchased or ordered can be found in Table C.1 in Appendix C.

Once all components arrived from their respective manufacturing companies, they needed to be soldered to the circuit board. To accomplish this, the hot plate and solder syringe at the Virginia Tech Unmanned Systems laboratory were used. A solder paste containing miniscule spheres of solder in a liquid flux was applied using a syringe, to fasten all components to their designated board locations. The board (with loosely attached components) was then placed upon the hot plate to activate the solder in the flux, and permanently attach all components to the board. A few minutes after placing the circuit board on the 235° F hot plate, the solder was fully activated, and all surface mounted components were successfully attached. Additional soldering was required for the “through hole” components. The necessary jumpers, headers, and serial connectors were soldered to the board by hand, completing the process. (Bird, Virginia Tech Unmanned Systems Laboratory, 2008) The result was a prototype board ready to be tested for analysis. The prototype board, after soldering, can be seen below in Figure 4.4.

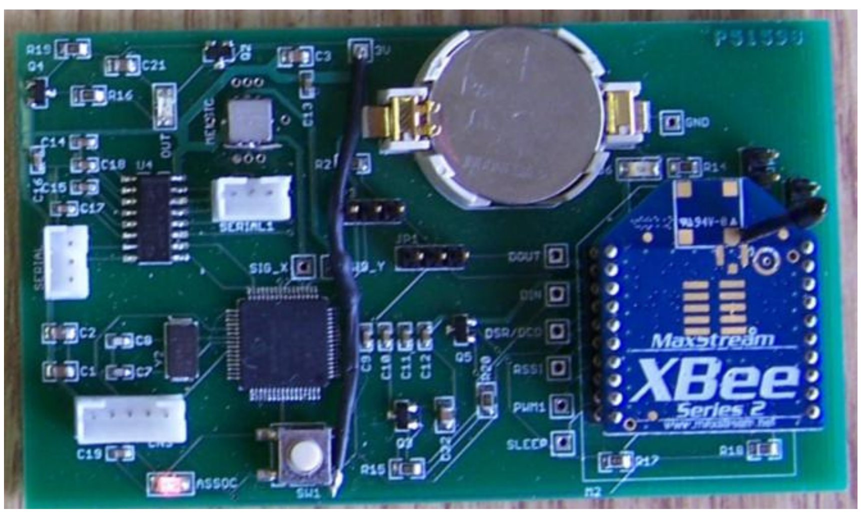

Figure 4.4: Physical Prototype Circuit Board

4.1.3- Revisions to the Circuit Board

After testing the prototype, changes were made to the schematic and board, and a new board was ordered. This new board was also tested and further changes were made. Unfortunately, an error was found in the board layout, and a third board was designed. Because this third board was tested in a live mining environment, it was ordered in quantity five. For more details on the testing of the final revision board, see Chapter 5: Multiple Tiltmeter Testing.

The schematic for the final board was slightly different than the prototype. The prototype board had a total of 5 diodes, while the new board would only have two, one to illuminate when data was sent, and one to illuminate when data was received. The prototype board also had additional jumpers to test specific connections. These were thought to be useful when the board was being designed, but were considered unnecessary after testing of the prototype. Another difference between the prototype schematic and the test product schematic is the number of test points. Test points can be useful, and are relatively small in size; however, during the prototype testing, many existing test points were left untouched. Therefore, their existence on the board was deemed unnecessary. Another change made to the schematic was the power supply. Instead of using a single CR2032 cell battery, the board would be connected to a pair of 3V AA batteries. This modification allowed a significant increase the battery life. The new schematic for the revised circuit board can be seen below in Figure 4.5.

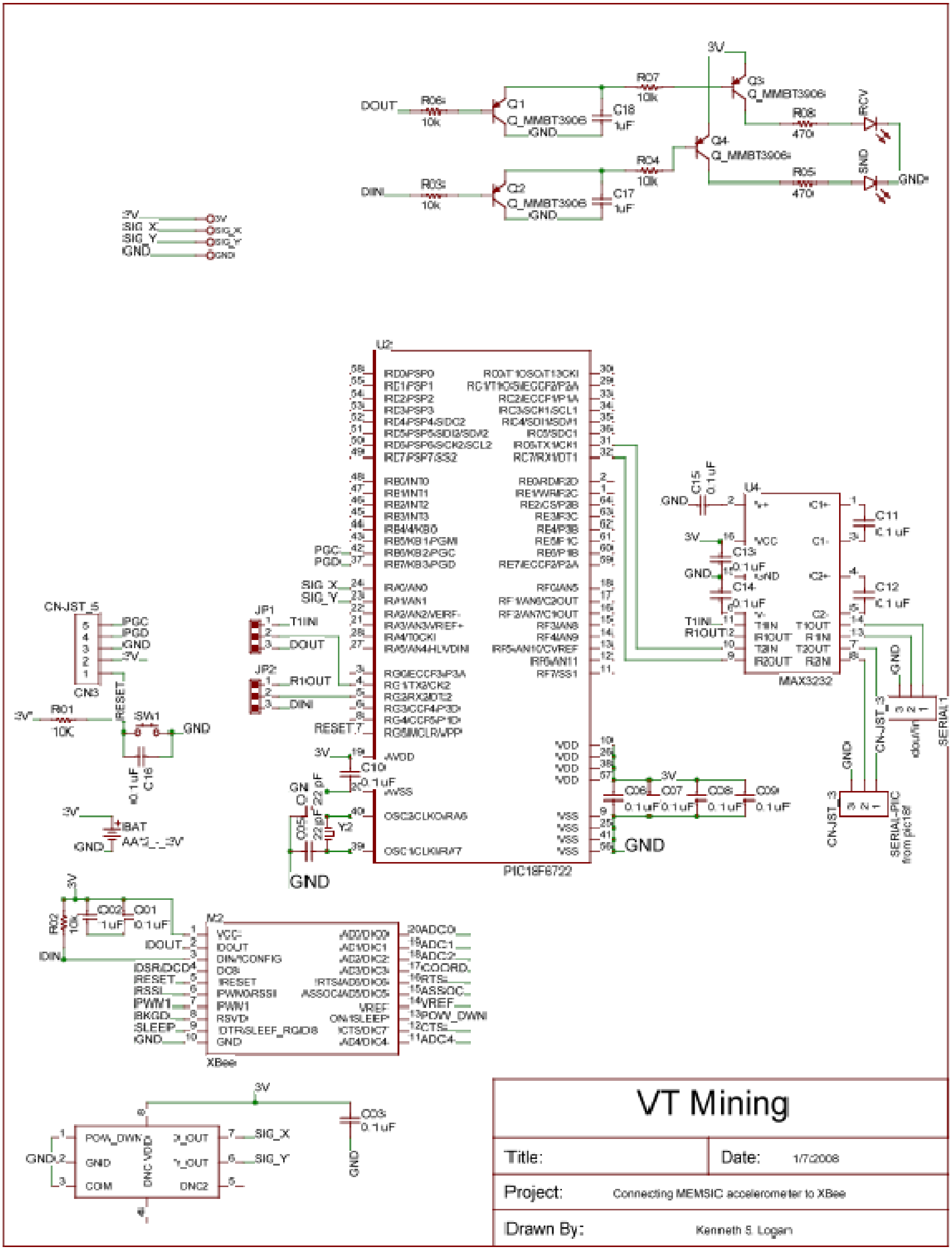

Figure 4.5: Final Revised Schematic

The new board was designed to be smaller and more ergonomic than the prototype board. Experience gained when designing and testing the prototype board helped to dictate the preferred placement of resistors, diodes, and other components. The overall size of the board was reduced to match the dimensions of the twin AA battery housing, and allowed the battery housing to be mounted on the reverse side of the board, gaining space for the rest of the components. The designed board can be seen below in Figure 4.6.

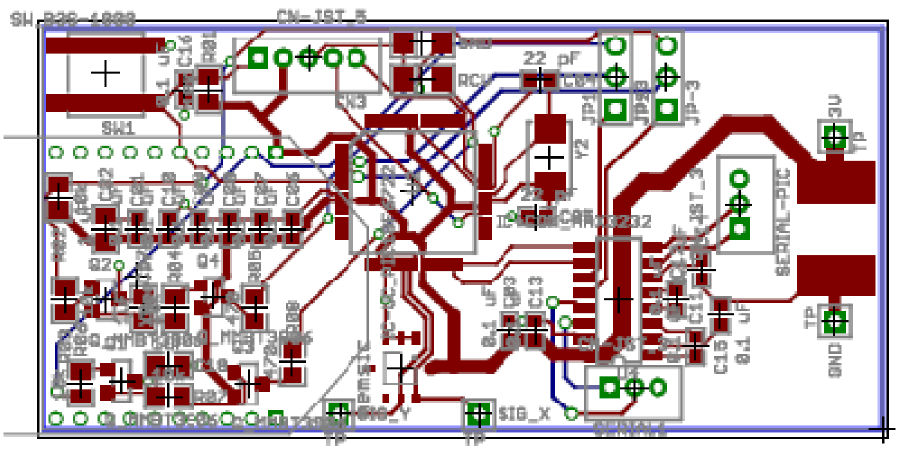

Figure 4.6: Final Revised Board

This final board followed the same procedure of component population as did the prototype board. Refer to 4.1.2- Prototype Circuit Board for details on the soldering process. The soldered final revision of the circuit board can be seen below in Figure 4.7.

Figure 4.7: Physical Final Revised Circuit Board

4.2- Cost Analysis

To analyze the cost of each board, a program in *Eagle*, that allows the user to create a Bill of Materials (BOM), was utilized. This BOM was joined with the component list from *Digi-Key*, *Digi-International,* and *MEMSIC* to accomplish an estimate of the unit cost for the prototype board as well as the final revised production board. Details for the cost analysis of both boards can be found in the following sections.

4.2.1- Cost Analysis for the Prototype Board

A detailed BOM for the prototype board can be found in Table C.1 in Appendix C. The contents of the prototype board's BOM were slightly altered to properly analyze the cost of one circuit board: the columns *Description*, *Part #,* and *Company* were excluded from the analysis, while the preceding columns *Part*, *Value*, *Device*, and *Package* were included for recognition of parts on the order forms.

Table C.3, as seen in Appendix C, was created to show the estimated cost of one unit of each component required for the prototype circuit board. The prices listed in Table C.3 do not include shipping costs, processing fees, sales tax, or any labor costs.

As seen in the final row of Table C.3, the total cost of the components on each prototype board was $53.64. The cost of each blank board from *Advanced Circuits* was $33. Adding these numbers yields a total of $86.64 for each prototype board.

4.2.2- Cost Analysis for the Revised Board

A detailed BOM for the revised board can be found in Table C.2 in Appendix C. The contents of the revised board's BOM were slightly altered to properly analyze the cost of one circuit board: the columns *Description*, *Part #,* and *Company* were excluded from the analysis, while the preceding columns *Part*, *Value*, *Device*, and *Package* were included for recognition of parts on the order forms.

Table C.4, found in Appendix C, was created to display the estimated cost of one unit of each component required for the final revised circuit board. As in Table C.3, the listed prices do not include shipping costs, processing fees, sales tax, or any labor costs.

As seen in the final row of Table C.4, the total cost of the components on each revised board was $52.32. The cost of each blank board from *Advanced Circuits* was $33. Adding these numbers yields a total of $85.32 for each revised board. Although the difference in the cost of each revised board and the cost of each prototype board is not significant, the reduction comes from the changes made in *Eagle* as work on the project progressed.

When future boards are ordered, they will likely be ordered in larger quantities, resulting in a reduction of the cost, significantly reducing the overall cost per unit. The components that populate each board will also be ordered in mass quantity, further reducing the cost per component. Also, with future boards, certain components would not be necessary, as described in 7.1- Future Recommendations.

4.3- Programming the Circuit Board

Once the boards were designed, ordered, and soldered with the necessary components, they needed to be tested. Before testing however, the blank processing units (PIC18F6722) needed a program to guide the operation of all the components in a system to send wireless serial data from one circuit board to another.

4.3.1- Background

As mentioned before, the processing unit for the designed circuit board is the PIC18F6722 (here-in referred to as the PIC). The initials PIC represent a family of microcontrollers manufactured mainly by Microchip Technology. The name PIC is an acronym for "Programmable Intelligent Computer". PIC's are popular because of their wide availability and their relatively low cost. There are many families of PIC's, including the 16F, 18F, and others. Each family has slightly different capabilities and packages (pin layouts and spacing). The PIC18F6722 was selected as the processing unit in this design because of a recommendation from a colleague, John P. Bird, who deals with these processors on a more regular basis (Bird, Eagle Software, 2007). A Pin Diagram for the PIC18f6722 can be found on the Microchip PIC18F8722 Family Data Sheet (Microchip, 2004).

When purchasing a PIC, the processor arrives devoid of code. The user must write the codes or use already existing code to make the processor function to its intended functionality. When the PICs and all other components were soldered to the circuit board, the first step was to install a bootloader. This was done using a "logger" owned by the Virginia Tech Unmanned Systems lab. Loading this bootloader onto the 5-pin serial port allowed any user to utilize a 3-pin serial port to program the PIC. This is beneficial in many ways: without the use of the 3-pin serial port, all commands would need to be written on the logger, one line at a time, and programmed using this special equipment; by using a 3-pin serial port, any PC with standard load software can write code to the PIC. (Bird, Virginia Tech Unmanned Systems Laboratory, 2008)

After loading the bootloader onto the PIC, a series of test codes were written, compiled and loaded to the PIC before the final code was loaded for production use. The first step was writing the code to be loaded. To accomplish this task, a program called *PIC C Compiler* (Custom Computer Services, Inc., 2008) was used. This program allows the user to write the code using the C programming language. The code must be compiled using *PIC C Compiler's* built in compiler to change the C code to hexadecimal (HEX) format, which is what the PIC understands and can run. After the code was developed and compiled using *PIC C Compiler*, the program *Tiny PIC Bootloader* was used to digitally write the code to the PIC. A description of the procedure of the actual cycle of writing the code, compiling the code and then loading the code to the PIC can be found in Appendix B on page 113.

4.3.2- Codes Used for Testing and Programming PIC

A simple code, “toggle”, was written to test the functionality of the PIC. The code “toggle” can be found in the Appendix B-1. “Toggle” simply forces one pin of the 64 pins on the PIC to turn on (showing a voltage of 3V) and then turn off to 0V after 2 seconds. This process repeats so the user can measure the voltage on this pin to confirm the PIC is operating properly. “Toggle” was only used on the first prototype board to test the connection settings; on future boards this was not used, as the connection settings remained basically the same for the PIC.

Once the PIC was determined to function properly, a second program was written to test the serial functionality of the PIC. “Serial Test” was written to force the PIC to output a message every second reading “TEST SERIAL”. This serial message was read by connecting the PC used for this project to the “SERIAL” port on the prototype circuit board, and the “SERIAL-PIC” port on the final revised board. “Serial Test” can be found in Appendix B-2.

After testing the serial functions of the PIC, it was decided to test the functionality of the accelerometer with the PIC, as well as the PIC’s computational abilities. To accomplish both of these tasks, the program “Test ADC” was written. The source code entitled “Test ADC” can be found in Appendix B-3. “Test ADC” forced the PIC to read two pins connected to the accelerometer’s X- and Y- axes, and sum a total of ten measurements, displaying a combination of text and values over a serial output pin.

All of these programs could be tested using the serial ports on the circuit board, so a simple homemade serial extension was used to read the output messages. The serial extension, as seen below in Figure 4.8, was fabricated to connect pins 1, 2, and 3 on the circuit board connecter directly to pins 2, 3, and 5 respectively on the serial port of a common PC. (Bird, Virginia Tech Unmanned Systems Laboratory, 2008)

Figure 4.8: Serial Connector

This serial connector, which simply ties the sending, receiving, and ground pins to each other, was used heavily in the testing of the prior codes. Unfortunately, it would prove useless when testing the wireless capabilities of the circuit board. In order to test the *Digi International* XBee transceiver (here-in referred to as the XBee), a separate device was needed, and was purchased from *Digi International*.

4.3.3- Wireless Transmission

The XBee interface board XBIB-U-DEV, as seen below in Figure 4.9, connects a single XBee unit to a USB-b port, which in turn connects to the USB-a port on a common PC.

Figure 4.9: XBIB Interface Board

After installing the necessary drivers provided by representatives of *Digi International*, the interface board operated exactly as the serial connector, with the exception of the COM port. The serial connector used COM port 1, while the wireless interface board (XBIB) operated on COM port 7. (Digi International, 2008)

Another important step was setting up an association between the XBee modules. This was accomplished by using the program *X-CTU* which was downloaded from the *Digi International* website with the assistance of a *Digi International* associate. For mesh network designs, the sensors in the network need to be programmed as "Routers". This term describes their ability to send original data, as well as relay data received from other "Routers". One XBee, the XBee connected to the PC, needed to be programmed as a "Coordinator". (Digi International, 2008) The "Coordinator" does not send data, but rather receives all transmissions and relays them to the serial program on the PC. It is recommended that the "Coordinator" XBee is marked to differentiate it from the "Router" XBees, as there are no visual differences between the two.

After setting up the wireless Coordinator on the XBee interface board, the next step was to test the board's wireless serial capability. To accomplish, the program entitled "Serial Test 2" was developed. "Serial Test 2" basically performs the same task as "Serial Test", with a change of output pins on the PIC. The circuit board was designed to allow for a variety of methods of reading the PIC serial outputs, so a simple change of output pins was all that was necessary for the XBee to transmit the serial message wirelessly. "Serial Test 2" can be found in Appendix B-4.

4.3.4- Final Code for Production Tiltmeters

After concluding tests with the aforementioned C programs on the PIC, a final code for tiltmeter use was developed. This code was designed so that multiple sensors could be used, therefore requiring the use of an identifier. The code was also developed to allow for easy import into *Microsoft Excel* for data analysis purposes. To accomplish this, software using for-loops was developed, with a final output of simply "Identifier (A, B, C, etc)", "X- Axis output", “Y- Axis output”. Using capital letters as identifiers for the 4 final sensors, their transmissions could be separated from each other using a simple Sort function in *Microsoft Excel*. By using a simple comma separated value (CSV) output for the code, it was easy to import the data for analysis. The final source code, “Final_A” can be seen in Appendix B-5: Final_B, Final_C, and Final_D are identical to Final_A with the obvious exception of their identifier, as previously described.

It was found that true “mesh network” software, where transceivers not only communicated with a base radio, but with each other, was too complex to develop in the allotted time for this project. Taking into consideration this setback, the final software version forces the sensors to form a “star” network, as shown below in Figure 4.10, where each transceiver communicates directly with the coordinating station at the PC. This severely limits the absolute range of the network, as hopping from one sensor to another is no longer possible. Therefore the limits of the network are limited to the range of the transceiver, approximately 133 ft (40 m).

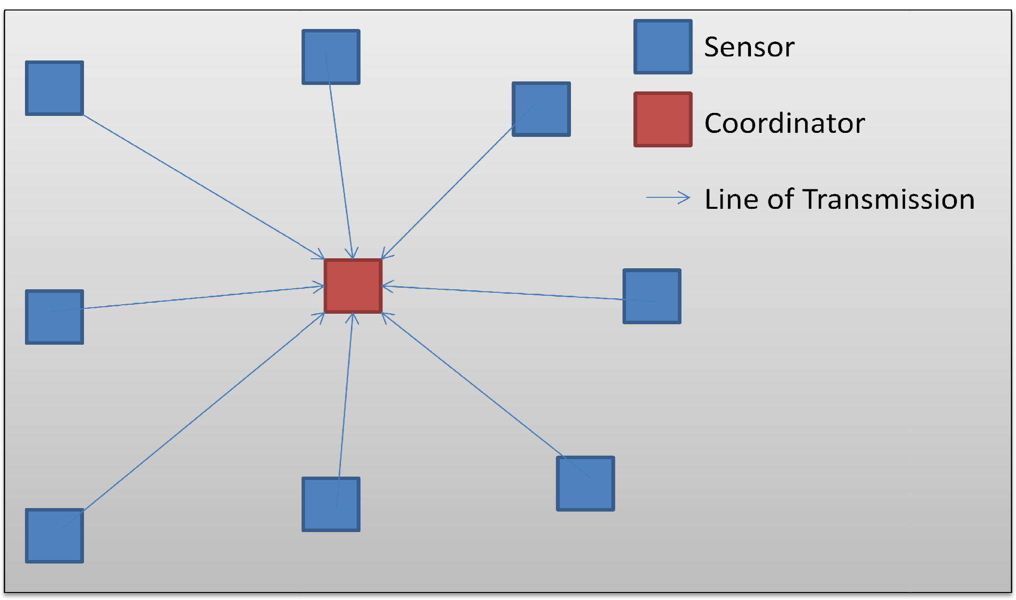

Figure 4.10: Star Network

Chapter 5: Multiple Tiltmeter Testing

After completing the circuit board (as described in Chapter 4: Designing a Wireless Tiltmeter) the completed design required testing in a real world environment. Before installation in a mine however, the functionality of the tiltmeters was tested in a laboratory setting. The completed final revised circuit boards, quantity four, were packed into their cases and left for a time to gather data, sending wireless transmissions back to the PC used for this project. This chapter describes in detail the testing procedure and setup for multiple sensors for the purpose of this project.

5.1- Setup of Multiple Sensor Testing

5.1.1- Location

For the purpose of this project, the terms "tiltmeter" or "sensor" will be used to encompass the circuit board designed and described in 4.1- Circuit Board Design, all components that belong on the circuit board, batteries to power the unit, and an enclosing device. More can be found on the device enclosures in 5.1.2- Sensor Housing.

Before the tiltmeters could be installed in a mine, they required laboratory testing to insure proper functionality of the equipment. For this laboratory testing, the four final revised tiltmeters were arranged in the mining engineering graduate student office, room 115-A, located in Holden Hall at the Blacksburg campus of Virginia Polytechnic Institute and State University (Virginia Tech). This room did not provide ideal conditions for testing the ruggedness of the sensors, but allowed for continuous monitoring of known angles in a controlled environment. The test involved four sensors, each of which were placed in distinctly separate locations to test the effects of different factors.

Sensor A was placed on a bookshelf at an approximate angle of 37° from horizontal. The word "approximate" is used in all measurements because the casing of the sensors were measured, not the exact angle of the accelerometer inside the case. Since sensor A included a damaged accelerometer, which did not output anything on the Y- axis of tilt. Therefore, the unit was placed so that only the X- axis was tilted and measured. The Y- axis was set up at the horizontal for simplicity.

Sensor B was placed on top of a second bookshelf, at an angle of approximately 8.5 degrees. The sensor was aligned so that the X- and Y- axes were similar. After approximately 24 hours of recording the previously given angle, the inclination of the sensor was altered to simulate a change of surface angle of a roof or highwall. By simply placing a thin Compact Disk case under the base of the incline, the angle of inclination was changed to approximately 7.8°, a change of 0.7°.

To observe the interaction of the tiltmeters and a metal structure, which occasionally emits unusual wavelengths, sensor C was placed directly behind a microwave. Sensor C was angled approximately horizontal, to see how the predicted voltage outputs would compare with actual voltage outputs. Theoretically, a horizontal MXR6999M accelerometer should output a voltage of 1.5V on both the X- and Y- axes.

Sensor D was placed in direct sunlight at an approximate angle of 12°. By locating this final sensor directly next to a window, it was intended to determine whether heat provided by sunlight would have an effect on the output of the accelerometer. Since the MXR6999M accelerometer is a thermal accelerometer, (see 3.3- MEMSIC Accelerometers for details), it was considered the effect of heat from sunlight may cause output voltage fluctuation. Conclusive information on any fluctuation would prove useful in mounting sensors on highwalls and other common mining applications.

5.1.2- Sensor Housing

Because the overall plan for this project is to mount sensors in a mining environment, rugged housing for the sensors is necessary. To accomplish the task of ruggedizing the sensors, a few options were explored. Watertight cases could be fabricated using common hardware materials, cases could be manufactured by a specialized contractor to fit the specifications of the sensors, or an already existing case could be purchased from a manufacturer. These options were explored mainly using online research.

Philip's Plastic and Machining LTD provides a custom service of creating unique cases for customer's designs. To employ *Philip's Plastics*, an engineering sketch would need to be mailed or faxed to *Philip's Plastics*, and after a small period of time, the custom enclosures would be returned via mail to the customer. After describing the project to a representative, the product was described as using Polyvinyl Chloride (PVC) sheeting. The cost for manufacturing such an enclosure was estimated at $15 for each case, not including shipping costs. This option provided an escape plan if no other option was found usable. The waiting period for such enclosures required for this project was around a week, so the decision to employ *Philip's Plastics* could be made after exploring other options (Phillip's Plastic and Machining LTD, 2008).

After speaking with a representative from *Philip's Plastics*, it was decided to research the difficulty of fabricating a home-made version of their product. If this option were selected, the case would not look as professional, nor would it likely function as well as a contracted design, but the cost would most likely be less. Local hardware stores were contacted, but none carried sheets of PVC, which was the suggested material by *Philip's Plastics*. Because flat PVC sheeting was not readily available, the option of self-fabricating enclosures was discarded.

Pelican cases were suggested by Dr. Erik Westman, and after researching different products of *Pelican*, the 1010 Micro Case was selected. The inside dimensions of the 1010 Micro Case are 4.37" x 2.87" x 1.68" (11.1 x 7.3 x 4.3 cm) (Pelican Cases, 2008), which were sufficient for the sensor dimensions. Each *Pelican* 1010 Micro Case cost approximately $10, without shipping. The 1010 Micro Case with enclosed sensor can be seen below in Figure 5.1. As larger battery options were explored the 1010 Micro Case allowed sufficient space for the sensor and up to two D-cell batteries.

Figure 5.1: Sensor and Battery Pack in Pelican Case

It was decided to observe the operation of the sensors inside the 1010 Micro Case. The effect of the hard and thick plastic of the case on the transmission capabilities of the transceivers was unknown. In the laboratory testing, the effects of the *Pelican* cases *were* found to be minimal, not hindering the transmission capabilities of the XBee in the least.

5.2- Procedure of Multiple Sensor Testing

As mentioned in 4.3.4- Final Code for Production Tiltmeters, each sensor had a similar, but slightly different source code programmed, compiled, and loaded on its PIC. The goal of testing multiple sensors was to create as realistic an environment as possible given the limited time and location of the testing site. To monitor the sensors as they would be monitored in a mine, the sensors were programmed to transmit a serial message of its identifier, X- axis output, and Y- axis output, separated by commas to allow for easy importation into *Microsoft Excel* for analysis.

Unfortunately, the first code version written to each of the sensors contained a minor flaw or software bug. The serial transmission of each unit contained an additional period at the very end of the line, which upon importation into *Microsoft Excel*, rendered all Y- Axis values useless. A value with two decimal places is viewed as zero in *Microsoft Excel*, so for all Y- Axis transmissions, the data was appearing as zero values. Upon realization of this error, after approximately one day of recording, the sensors were re-programmed and the useless data was discarded. New data was recorded for analysis using the corrected program.

Each sensor was placed again in its proper location, as described in 5.1.1- Location, and left to gather and transmit data. The sensors were allowed to sit for an extended period of time without disruption. After about a day of monitoring, the inclination of sensor B was altered by about 0.7°, as described in 5.1.1- Location. The time of this change was recorded so it could be pinpointed when analyzing the data received by the coordinating XBee. Other than this minute change of inclination, all other sensors were left alone to collect data in a stationary position. This would represent a realistic change in a mining environment, as most of the monitored areas would be unlikely to move.

To insure all transmissions were received and recorded, the program *Terminal* allows the user to "Log" files. As data is received in *Terminal*, the logger records an identical serial transmission in a text document, saved on the PC anywhere the user desires. For the case of this project, the files were stored on the desktop for easy access. While data was being recorded by *Terminal*, the experimenter created additional text files with descriptions included such as exact time of transmission, or time of altered inclination angles. These text files were used when analyzing the data recorded in the Logged file to pinpoint specific transmissions, changes in transmission environment, and to help identify how long each sensor was in operation.

As the program *Terminal* was relied upon heavily for gathering and logging the data, it could not be shut down for the duration of the experiment. Therefore, the PC on which *Terminal* was being used could not shut down. This could potentially cause problems for PC's with automatic updating features, as sometimes they re-boot themselves following an update. In the case of an automatic reboot, all data transmitted, from when the computer shuts down until an operator notices the reboot and restarts *Terminal*, would be lost. To circumvent this problem, the XP Windows Professional based PC running *Terminal* was modified via, the Control Panel to prevent automatically installed updates. This solved the immediate problem at hand, although extensive testing on this issue was not performed.

Each sensor was powered by a pair of AA batteries. Once sensor A's batteries were exhausted, two D-cell batteries were connected in series to create a 3V power supply with greater amp-hour capacity than two AA batteries in series. Both pairs of batteries, AA and D-cell, have an overall voltage of 3V, so the only difference observed was the operating life of the power supply.

5.3- Results of Multiple Sensor Testing

After the sensors had been transmitting data for approximately two days, including the first day where erroneous programming caused flawed data, it was noticed that one of the sensors was no longer sending transmissions. After examining the equipment, it was discovered that the voltage supply had been depleted, showing a voltage of 2.0V. The operating voltage range of the transceiver, as discussed in 4.1.1- Transceiver selection, is 2.1V – 3.6V, therefore as the voltage dropped below 2.1V, the transceiver failed to operate properly. As the second day continued it was noticed that the other three sensors eventually ceased transmitting as well, each sensor having a voltage of less than 2.1V after a failure to transmit was observed.

It was interesting to witness that some of the sensors operated more efficiently than others. Sensor A was the first to deplete its power supply, and then seven hours following, sensor B failed to transmit. Exactly seven hours following sensor B's final transmission sensor C failed. Interestingly, it took an additional six and one half hours before sensor D's final transmission. Each of the measurements (as seen on the X- Axis of Figure 5.2) occurred 30 minutes apart, so the time differences of transmission failure points can be estimated using Figure 5.2. For the raw data collected in this experiment, please refer to Table A.9. Since all sensors used the exact same, brand new, Duracell AA batteries, from the exact same package, it is unlikely this variation of operational duration is a result of the battery. Rather, it is more likely that a small short was present on some of the boards, allowing sufficient voltage-drop to effect battery life, but not enough to alter the operation of the PIC. If a short were present on the pads of the PIC, the original bootloader, as described in 4.3.1- Background, would have failed to load, so it can be assumed that if a short were present, it would be involving another component.

It was also observed that as the sensors began to experience lower than desirable voltage, output voltages were greatly affected. Both the MXR6999M accelerometer and the XBee transceiver operate at approximately the same voltage. As seen below in Figure 5.2, the output was affected severely as the voltage neared the lower limit of their operating range.

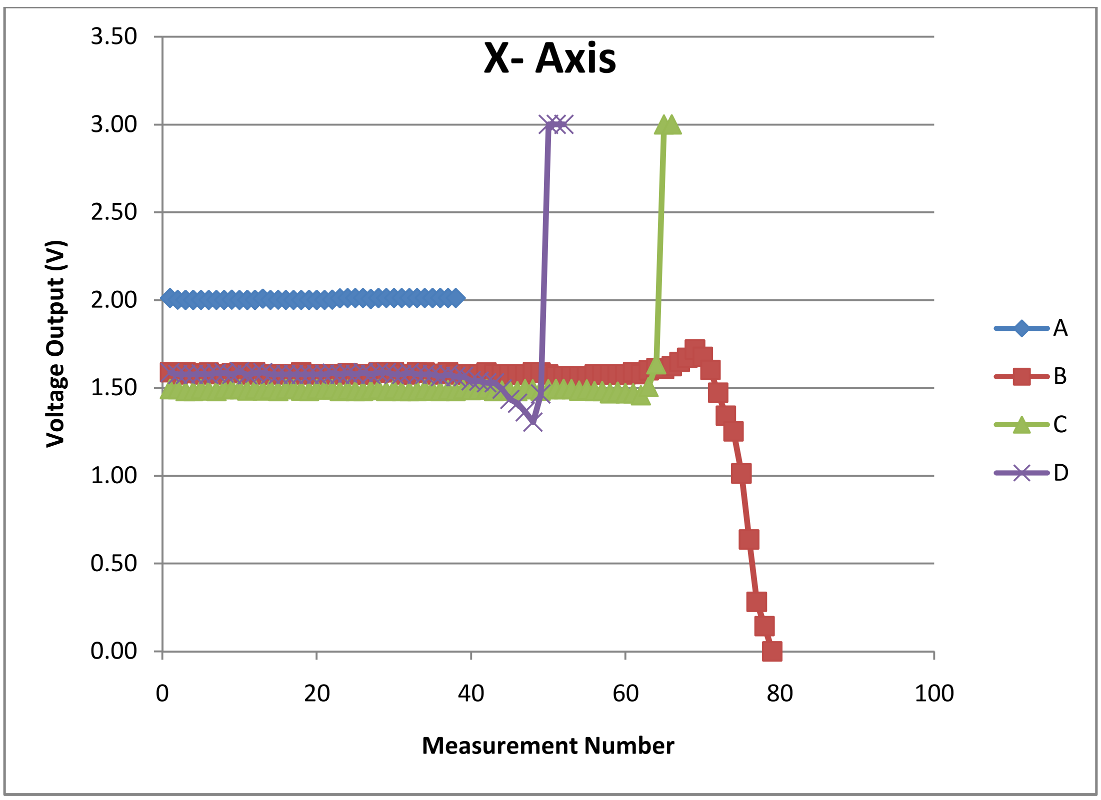

Figure 5.2: X- Axis output as the power supply was depleted

Notice in the above figure with exception to sensor A, as the sensor began to near the end of its transmissions, the voltage output values changed dramatically. If when looking at this graph of output voltages, the viewer was unaware that each sensor's power supply was nearing depletion, an assumption of drastic slope alteration could be deducted.

The life of a power supply depends heavily on the operational status of all components that draw voltage from the power supply in question. The software developed for the sensors under test, as found in Appendix B-5, allows all components to remain active whenever voltage is available. Most of the components have the capability of a sleep mode, which would theoretically stop all component power consumption until the code demands they power on again, or "wake up". For the purpose of this project, sleep mode was not considered, as an external clock would need to be present on the circuit board. This external clock would ensure that all sensors "woke up" at the same time, to allow for proper sending and receiving of data packets. If one sensor were to power on and send data, but the receiving sensor was not yet powered on, the data sent would be lost, and therefore useless. An external clock was not used for this project because the complexity of the code would increase greatly.

Because sleep mode was not incorporated within this project, all components remained powered on for the duration of the testing procedure. The constant operation of all components drew voltage quickly from the simple 3V power supply, and as previously noted, depleted the twin AA batteries in approximately two days. Battery life of this magnitude would be unacceptable in a mining environment, as frequent battery replacement would be required. With a greater span of sensors, and if eventual mesh networking is realized, a mine employee would need to cover extreme distances just to replace the batteries, on a regular basis. Therefore, if this system were to be installed in a mine, additional code development would be required. To solve the problem of battery life for the prototyping stage, two D-cell batteries were connected in series to tiltmeter A on Thursday, March 26, 2008. By connecting the two D-cell batteries in series, a voltage of 3V was obtained with a much greater amp-hour capacity than two AA batteries. The greater amp-hour capacity of the D-cell batteries proved sufficient for the mine environment testing. When testing the D-cell batteries in the lab environment, the voltage was approximately half depleted (a simple multi-meter showed the batteries voltage to be 2.550 on Monday, March 31, 2008) after about 5 days. This insured that a week's data could be collected without need of new batteries. A more powerful Lithium type battery would perhaps be better suited for this type of application, but is beyond the scope of this project.

Upon collection of the data, *Microsoft Excel* was utilized to analyze the importance of each data point. To accomplish this task, the data was simply imported and sorted by sensor identifier. The rearranged data table can be viewed in Table A.10, separated in columns by sensor identifier.

Chapter 6- Field Testing

To properly test the tiltmeters designed and discussed in Chapter 4: Designing a Wireless Tiltmeter, a field test was performed. Raw data was collected for this study between Tuesday, April 1, 2008 and Monday, April 6, 2008 at a surface quarry located in northern Virginia. Blending a mixture of diabase (also known as taprock) and a bordering sedimentary material known as "hornefels", the mine has an annual production of around 2,000,000 tons. The on-site plant operates two pits, here-in referred to as the "Northern pit" and the "Southern pit".

6.1- Site Description

Over the past 10 years, the quarry has experienced slow and small scale failures in their Southern pit. The East-most pit wall in the Southern pit has been slowly raveling due to complex fractures and discontinuities in the host rock. On Thursday, March 13, 2008 a large scale failure occurred at this same location. Figure 6.1 below shows the failure area.

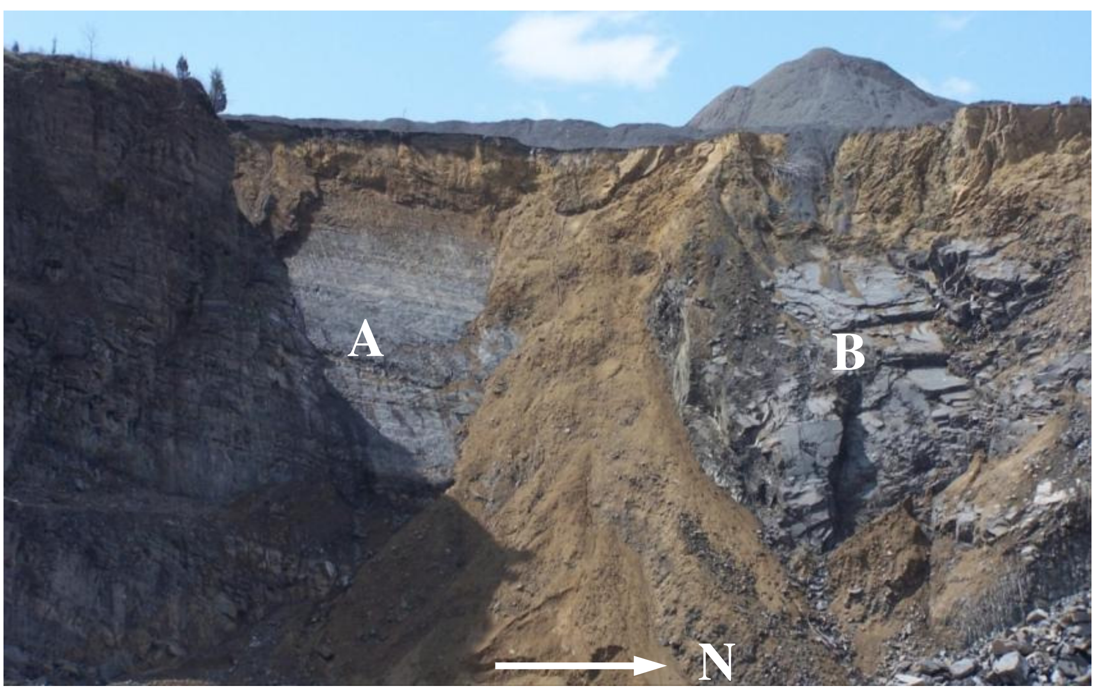

Figure 6.1: Site Failure

When viewing Figure 6.1, it should be noted that the material on the left of the photograph, as marked by A, has been failing over the past 10 years. This slow failure has not caused extreme delays to the mine. The material marked by B, was involved in a more recent displacement which occurred in a large scale failure. As is visible in the photograph, all rubble has not been fully removed from the base of the bench.

To monitor any further movement of material to the right of B, the mine is currently using a simple method of measuring surface cracks using mounted measuring tapes. Measurements are recorded and compared daily to observe any continuous displacement of the highwall.

6.2- Installing the Experimental Tiltmeters

After experimenting with the tiltmeters in the laboratory setting, it was found that some of the sensors failed to operate properly after changing to D-cell batteries. By re-soldering and testing the equipment it was found that the PIC was somehow being inadvertently damaged. This damage was assumed to be caused by static discharge or power surges from prototype connection of the two D-cell batteries. For this reason, only three tiltmeters were available for use for field testing. These three tiltmeters were differentiated by their output code, as described in 4.3.4- Final Code for Production Tiltmeters, using an identifier: either “A”, “B”, or “C”. The code forced each tiltmeter to transmit a simple serial message containing its identifier and the X- and Y- axis accelerometer output voltage values every 30 minutes. This program was set up to run as long as power was available for the tiltmeter.

Two of the three tiltmeters discussed were mounted using simple wooden stakes. Two stakes were driven into the highwall surface, set apart a distance of the width of the tiltmeters’ protective cases. The tiltmeter was then wedged tightly between the two stakes, and secured further by tightening the two stakes with ratchet straps above the tiltmeter. The setup for each tiltmeter can be seen below in Figure 6.2. This design was intended to hold the tiltmeters as motionless as possible, so that any disruption of the voltage output would not be caused by unaccounted for and undesirable factors. These factors include, but are not limited to accidental movement by wind, rain, small animals, or human contact.

Figure 6.2: Securing the Tiltmeters

Two tiltmeters were secured in the fashion shown in Figure 6.2, and one tiltmeter was secured on a metal transfer point using silicone gel to hinder movement. The tiltmeter secured with silicone gel can be seen in Figure 6.3 below. The transfer point can be seen in Figure 6.4, along with the relative positioning of the three tiltmeters used in this experiment.

Figure 6.3: Tiltmeter Secured by Silicone Gel

Unfortunately, the mounting considerations for this project are still in the prototype stages, just as the rest of the tiltmeter design. The securing methods shown in Figure 6.2 hold the tiltmeter theoretically motionless with respect to the topsoil in which the stakes are driven. This however, has no true relation to the host rock below the topsoil. In future use, the tiltmeter would ideally be mounted using extended metal rods directly into the host rock. Better yet, a borehole could be used to place multiple tiltmeters, as shown in Figure 2.6, using a different type of transceiver antenna to insure signal is transmitted.

As seen below in Figure 6.4, tiltmeter A was placed on the transfer point. Upon close examination of the below figure, signs of bent legs supporting the conveyor running to the transfer point are visible. Tiltmeter B was placed near the second bent leg from the left, and tiltmeter C was placed near the third bent leg. Only the tops of these legs are visible, and the tiltmeter cases cannot be seen from this distance, but the reference of these placements will help describe any data found in the results.

Figure 6.4: Tiltmeter Placement

6.3- Site Results

The three tiltmeters were installed in the aforementioned positions on Tuesday, April 1, 2008. A mining company employee agreed to power the sensors off on Monday, April 7, 2008, and send the data back to Virginia Tech via email for analysis. Upon reception of the email containing the data collected during the approximately six days of exposure, *Microsoft Excel* was used to import the text files, as described in Chapter 5: Multiple Tiltmeter Testing. Upon compilation and organizing the data by identifier, it was found that some points at the beginning and end of the test were extreme outliers. It was assumed before the tiltmeters were fully in their final position, a measurement was taken and transmitted. Therefore, these outlying points were discarded. The time of the first true measurements were recorded, allowing extrapolation for the remaining points. Assuming the 30 minute delay operated successfully on each PIC, the times could be estimated for each recorded measurement. The formatted data collected during this six day period can be found in Table D.1.

Upon compilation of the data, simple line graphs were created to visually analyze the data points. The line graphs representing the data collected during the aforementioned test can be found below in Figure 6.5, showing the X- axis results, and Figure 6.6, showing the Y- axis results.

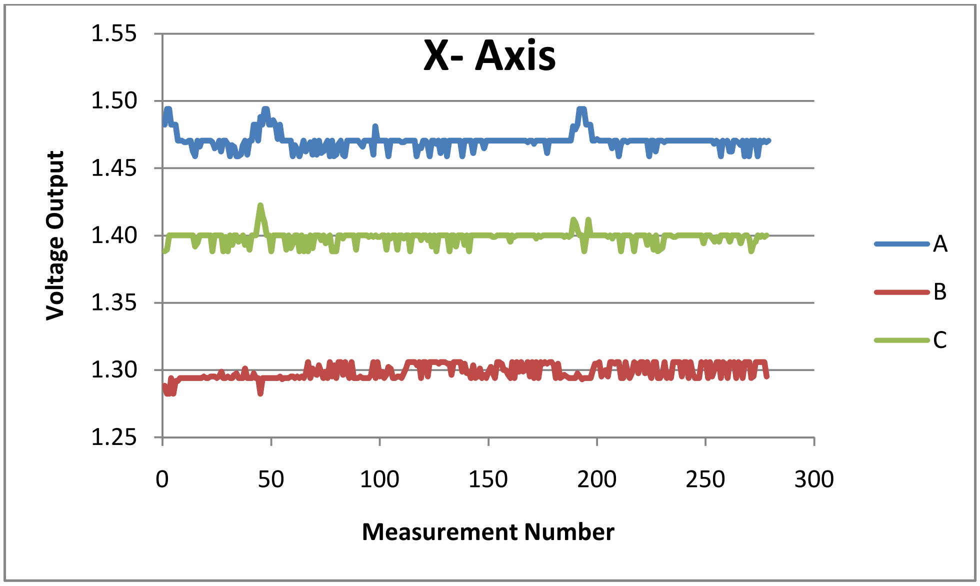

Figure 6.5: X- Axis Results for Field Testing

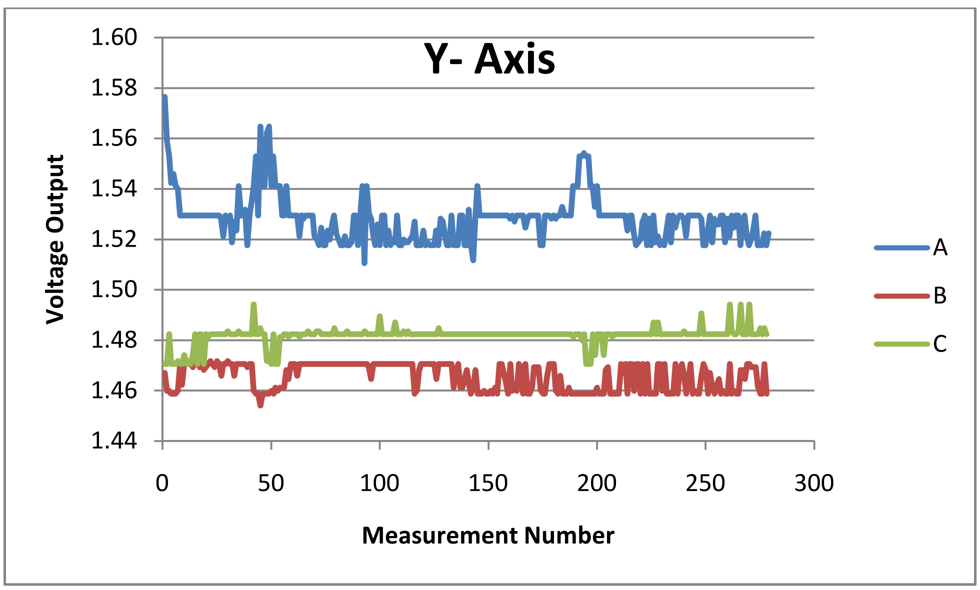

Figure 6.6: Y- Axis Results for Field Testing

As visible in both figures, there were fluctuations of output voltage. Two main fluctuations are visible, the first of which started at around measurement number 35, and ended around measurement number 60. The second major fluctuation began at measurement number 185 and ended at around measurement number 205. These fluctuations were visible in the outputs from tiltmeter A, B, and C, but more so in tiltmeter A. Also, on tiltmeter A, it appears that on the first day of recording, half of a fluctuation was observed. The origin time of this fluctuation is unknown, but ended around measurement number 8.

Other than these fluctuations, the results are fairly consistent. The results of this experiment, other than the variations, represent a currently stable slope. Ignoring the deviations during peak sunlight hours, the mean voltage output appears to remain constant. A certain amount of noise is visible, and should be expected, but averaging the non-fluctuating values should produce a relatively constant mean voltage.

6.4- Discussion of Results

When looking at the table constructed with time estimates, the half fluctuation ended on Tuesday, April 1, 2008 at approximately 5:30 PM. The first major fluctuation began around 7:00 AM, and continued through 7:30 PM on Wednesday, April 2, 2008. The second major fluctuation began around 10:00 AM and continued through around 8:00 PM on Saturday, April 5, 2008. When these times and dates were compared to local weather reports, it was obvious that the fluctuations occurred during times of higher temperatures. On Tuesday, April 1, 2008, a high of 77° F was observed, and while both Wednesday April 2, 2008 and Saturday April 5, 2008 only saw highs of 61° F and 63° F, the skies were not as cloudy as the rest of the week, so ample sunlight could have caused the tiltmeters temperature to increase (The Weather Channel, 2008).

When looking at the days fluctuations were not observed, Thursday April 3, 2008 experienced slight rain, which would have kept the tiltmeters cooler. Friday April 4, 2008 observed fog and some rain in the afternoon, and Sunday April 6, 2008 experienced rain throughout the day. The tiltmeters were collected on Monday, April 7, 2008 before peak temperatures and daylight hours were reached, so no fluctuations on Monday were visible (The Weather Channel, 2008).

As seen in Figure 6.5 and Figure 6.6, the fluctuation of tiltmeter A was the greatest; likely because tiltmeter A was located on a metal structure. Because metal retains heat extremely well, especially during peak sunlight hours, it is understandable why fluctuations of tiltmeter A were more severe. For the purpose of analyzing the fluctuation significance, tiltmeter A was chosen because of its greater variations.

When comparing the output values and angles found in Figure 3.9 and Figure 3.10, a line of best fit was applied in *Microsoft Excel*. Using the trendlines' equations, as seen below in Equation 1 and Equation 2 (X- and Y- axis trendline equations respectively), it could be deduced that the fluctuation in temperature on Wednesday April 3, 2008 represented a change in angle of 2.188° and 2.118° (X- and Y- axis respectively). The variation on Saturday April 5, 2008 represented a 1.875° and 1.471° change (X- and Y- axis respectively), and the half fluctuation seen on Tuesday April 1, 2008 represented a change of 1.563° and 2.765° (X- and Y- axis respectively).

$$y = 0.016x + 1.357 \qquad (1)$$
$$y = -0.017x + 1.400 \qquad (2)$$

$$\{y = voltage\ output\ of\ accelerometer\ (V)\}$$
$$\{x = angle\ of\ inclination\ (degrees\ from\ horizontal)\}$$

The fact that the fluctuations coincided with peak sunlight and temperature hours cannot be ignored, especially since the accelerometers measuring the inclination are thermal accelerometers. It can be concluded from the brief six day test that sunlight and temperature fluctuations cause significant changes in the tiltmeter's output. This fact should not be overlooked, and if tiltmeters such as these are to be installed in a mine permanently, the operator should be aware daily fluctuations such as those described in this chapter are possible. Unfortunately, these fluctuations will likely interfere with any automated alarms if eventually incorporated within the tiltmeter design. How will the tiltmeter differentiate between a change in angle and a hot midsummer's day? The fluctuations described previously showed a change of almost 3°, which would represent a significant movement in the host material. Unless the temperature of the tiltmeters was somehow regulated, daily fluctuations could not be differentiated from actual changes in slope angle.

One possible solution to this fluctuating temperature issue would be to program the tiltmeters to only transmit data during evening hours. This would not give real-time data during the day, but would help minimize the variability of the data.

Another solution would be to incorporate a thermistor in the design of the tiltmeter circuit board. This thermistor would then be used to calibrate the output voltages for the temperature inside the tiltmeter casing.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

After testing products already on the market as well as a tiltmeter designed for the purpose of this project, it was concluded that monitoring slope stability using wireless tiltmeters has great potential. However, at the given stage of research and development, it is not recommended for immediate implication. With more research and development of the tiltmeter described in this project, a wireless mesh could be designed and incorporated in a mine's safety program. Ideally, a dense network of sensors could be set up to extend monitoring capabilities: with multiple sensors in close proximity, an entire surface could be monitored for safety purposes.

During the testing of the tiltmeters, as described in this project, some conclusions are made about the usefulness of the equipment. Though the accelerometer could detect small changes in angles, approximately 0.4°, the significance of a change this minute may not render useful when trying to monitor slope stability. Especially in applications for surface mines, the vertical component of the monitored rock mass greatly affects the sensitivity required to detect small inclination changes. With a more sensitive accelerometer, for example detecting changes as small as 0.01°, much greater possibilities for detecting changes in slope (both surface and underground) are available.

Though simple wireless communication was found possible when designing a new wireless tiltmeter, a true "mesh network" was not established. For the scope of this project, programming the tiltmeters to successfully operate in a mesh network was too complex. Because of this setback, the range and extent of monitoring capabilities is extremely limited at this stage. Once mesh networking is achieved for the tiltmeters described in this project, greater possibilities are available for monitoring longer distances and more complex areas.

Though a simple source code was developed to serve the purpose of this project, a more experienced software developer would be required for further software maturity. With additional programming support, the tiltmeters could include the addition of sleep mode and other clocking functionality, greatly extending the battery life for each tiltmeter. Existing wireless systems already incorporate such functions as sleep mode and mesh networking, but to design a completely new system, a new code required developing, and in the allotted time for the project, the author could not develop such a code.

This project has shown most importantly that the sensitivity of the accelerometers employed for the purpose of this test is lacking. Even if true mesh networking was attained and a sleep mode was incorporated, the tiltmeters for this project would not recognize a significant failure in a surface mine before more conventional methods. Though the *MEMSIC* MXR6999M Accelerometer was among the more sensitive options explored, a greater degree of sensitivity is required to detect smaller changes of angle.

7.1- Future Recommendations

After working on the circuit board and testing the final product, there are a few recommendations that should be noted. It was found that the LED lights were useful in testing, especially when testing the programs written for the PIC. However the LED diodes are not necessary in production models, as they contribute to unnecessary battery depletion. Though they proved useful in testing, most of the readings recorded, sent and received by the sensor will likely go unobserved, thus rendering them obsolete in real world industrial environment.

Another suggestion would be to spend more time in component placement. While much time was spent throughout the duration of this project to find the best component location (resistors, capacitors, switches, etc.), with the lack of LED diodes (see aforementioned suggestion) and their respective components, much board space will be gained underneath the XBee module as seen in Figure 4.6. If a reduction of size was required, removal of the diodes and related components could be the solution. The components on the final revised board as seen in Figure 4.6 were provided enough room for the silkscreen material to be visible during soldering. With production boards, this is not necessary, as more than likely an automated system will be soldering the parts.

The second serial port, "Serial 1", on the final revised board as seen in Figure 4.6 could also be removed, as well as the jumpers labeled JP1 and JP2. These items were left on the final revised board for testing purposes, but after the testing stages they will become obsolete. A simple wire connection on the board could connect the send and receive pins on the PIC to the send and receive pins on the XBee.

Both sides of the board could also be used for component population in a size limiting situation. This would allow further reduction of board dimensions, but would most likely not permit a battery to be mounted to the board. After brief experimentation, a circuit board was able to be drawn using *Eagle* which was no larger than the XBee device. The double sided board consisted of no power supply, so an external battery pack would be needed. The board was close to 1 square inch, approximately the size of the XBee module. The smallest estimated board can be seen below in the digital representation seen in Figure 7.1.

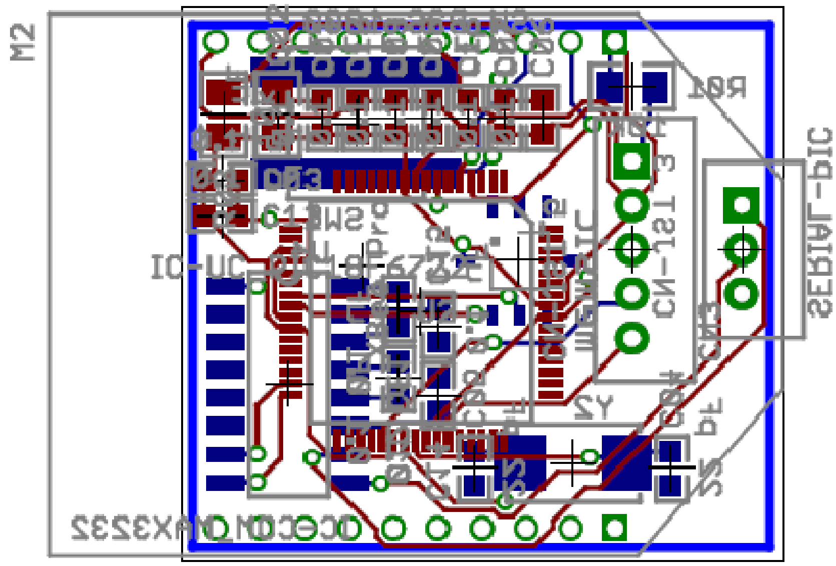

Figure 7.1: Proposed Smallest Circuit Board Design

As visible in Figure 7.1, the blue components are to be soldered on the bottom side of the board, and the red components are to be soldered on the top of the board. The overall dimensions of this completed board are 1.050 in x 0.960 in. The blue rectangle that follows the border of the board is known as a ground plane. For more on the ground plane, refer to4.1.2- Prototype Circuit Board.

The final code, as seen in Appendix B-5, used for the final revised circuit boards does not create a true mesh network. As shown in Figure 4.10, the star network design is limited to the range of each individual transceiver and cannot span great distances, or circumvent obstacles. This arrangement would not be ideal for use in a mining environment, as both large distances and obstacles (such as coal pillars) would be encountered. For future products, a program that allows for true mesh networking would need to be developed and programmed to each sensor. This would greatly extend the usefulness of the sensors created in this project.

The battery life for the sensors was found to be inadequate, as described in 5.3- Results of Multiple Sensor Testing. The final software written for this project does not incorporate any sleep modes for the sensors, so they are in essence running 100% of the time. Transmitting data is by far the greatest consumer of electricity, and although the sensors are not transmitting data at every given moment, the constant operation of the PIC steadily contributes to battery depletion. Once the voltage supply dips below 2.1V, the transceiver no longer functions, as the operating voltage range for the XBee is 2.1V – 3.6V, as described in 4.1.1- Transceiver selection. To resolve this issue, an external clock would need to be incorporated into the circuit board design. This external clock would require additional programming, but would allow the circuit board to essentially cut off all power supply, minus the power needed to run the external clock, and to reboot itself for sending and receiving data at a given time. Every tiltmeter used in this ideal product would need to be powered on at relatively the same time, because if data is sent from sensor A to sensor B, and sensor B is not powered on, the data will not be received, and could possibly be lost. An external clock would also require a separate power supply, probably a 3V CR2032 coin cell battery.

Additionally, a "handshake" must be used, or a proximity guide of all operating sensors, to prevent signals from traveling in opposite directions than the desired endpoint at a PC. Data could theoretically be transmitted to the very extent of a network and be lost due to sensors turning on and off if the signal travels the wrong direction. A proximity network would require additional code, as well as fixed and coordinated locations of each sensor.

Another solution with respect battery life would be to incorporate a small solar panel for use in surface mines. This solar panel would store energy during the daylight hours and use the stored energy at night to power the tiltmeter. This solution would also require a method of relaying wires to the tiltmeter through the protective casing: keeping water and other elements out of the case would be very important so special care would be needed in designing such a setup.

A tiltmeter issue that surfaced during discussions with the mining company, see Chapter 6- Field Testing for details, was the concern that a sensitivity of 0.5° might not provide useful information. It was suggested to find a more sensitive accelerometer, something that could accurately detect changes of approximately one minute of angle, or 1/60° = 0.01666°. This option was explored lightly, and it was found that more sensitive accelerometers are not readily available at this time. Some accelerometers do exist with greater sensitivities than those used in this project, but the associated cost was extreme when compared to the cost of the MXR6999M accelerometer, as well as the other accelerometers discussed in Chapter 3: Preliminary Data Collection.

To solve many of these issues, a simple solution is possible. Instead of designing a new product to replace the tiltmeter of this project, or continuing to experiment and modify the programming and components of the circuit board, the *Accsense* sensor pods could be used with an addition of a more sensitive piece of equipment. As seen in Figure 3.1, the *Accsense* sensor pod comes with connection points for additional equipment. Monitoring devices such as extensometers could be attached to the sensor pod and mounted in such a way that the output would be sent wirelessly through the sensor pods already existing mesh network. These output values could still be accessed online, just as described in 3.1- Accsense Wireless Systems. Though this solution seems rudimentary, it would solve many of the problems associated with the development of a new device.

Appendix A: Equipment Testing Data

Accsense Sensitivity Test
MEMSIC Frequency Test
MEMSIC Sensitivity Test
Multiple Tiltmeter Test Raw Data
Multiple Tiltmeter Test Formatted Data

Table A.1 shows raw data from the Accsense Sensitivity Tests as described in 3.1- Accsense Wireless Systems.

Table A.1: Accsense Sensitivity Measurements for NE Orientation

5°		10°		15°		20°		25°	
Value	Time	Value	Time	Value	Time	Value	Time	Value	Time
17.11	7/6/07 19:31	16.91	7/7/07 10:32	16.72	7/7/07 21:12	16.42	7/8/07 11:08	17.01	7/8/07 18:01
17.01	7/6/07 19:32	16.91	7/7/07 10:33	16.72	7/7/07 21:13	16.52	7/8/07 11:09	16.91	7/8/07 18:02
17.01	7/6/07 19:33	16.91	7/7/07 10:34	16.62	7/7/07 21:14	16.32	7/8/07 11:10	17.01	7/8/07 18:03
17.01	7/6/07 19:34	16.91	7/7/07 10:35	16.72	7/7/07 21:15	16.32	7/8/07 11:11	17.01	7/8/07 18:04
17.01	7/6/07 19:35	16.91	7/7/07 10:36	16.81	7/7/07 21:16	16.42	7/8/07 11:12	17.01	7/8/07 18:05
17.01	7/6/07 19:36	16.72	7/7/07 10:37	16.72	7/7/07 21:17	16.42	7/8/07 11:13	17.01	7/8/07 18:06
17.01	7/6/07 19:37	16.81	7/7/07 10:38	16.72	7/7/07 21:18	16.42	7/8/07 11:14	17.11	7/8/07 18:07
17.01	7/6/07 19:38	16.91	7/7/07 10:39	16.72	7/7/07 21:19	16.32	7/8/07 11:15	17.11	7/8/07 18:08
17.11	7/6/07 19:39	16.91	7/7/07 10:40	16.81	7/7/07 21:20	16.32	7/8/07 11:16	17.01	7/8/07 18:09
17.01	7/6/07 19:40	16.91	7/7/07 10:41	16.72	7/7/07 21:21	16.42	7/8/07 11:17	17.11	7/8/07 18:10
17.01	7/6/07 19:41	16.81	7/7/07 10:42	16.81	7/7/07 21:22	16.42	7/8/07 11:18	17.01	7/8/07 18:11
17.11	7/6/07 19:42	16.81	7/7/07 10:43	16.72	7/7/07 21:23	16.42	7/8/07 11:19	17.11	7/8/07 18:12
17.11	7/6/07 19:43	16.72	7/7/07 10:44	16.72	7/7/07 21:24	16.42	7/8/07 11:20	17.11	7/8/07 18:13
16.91	7/6/07 19:44	16.81	7/7/07 10:45	16.62	7/7/07 21:25	16.32	7/8/07 11:21	17.01	7/8/07 18:14
17.01	7/6/07 19:45	16.81	7/7/07 10:46	16.62	7/7/07 21:26	16.32	7/8/07 11:22	17.01	7/8/07 18:15
17.11	7/6/07 19:46	16.81	7/7/07 10:47	16.62	7/7/07 21:27	16.42	7/8/07 11:23	17.01	7/8/07 18:16
17.11	7/6/07 19:47	16.81	7/7/07 10:48	16.62	7/7/07 21:28	16.52	7/8/07 11:24	17.11	7/8/07 18:17
17.11	7/6/07 19:48	16.72	7/7/07 10:49	16.72	7/7/07 21:29	16.42	7/8/07 11:25	16.91	7/8/07 18:18
17.01	7/6/07 19:49	17.01	7/7/07 10:50	16.72	7/7/07 21:30	16.42	7/8/07 11:26	17.01	7/8/07 18:19
17.01	7/6/07 19:50	16.72	7/7/07 10:51	16.72	7/7/07 21:31	16.42	7/8/07 11:27	17.01	7/8/07 18:20
17.2	7/6/07 19:51	16.91	7/7/07 10:52	16.81	7/7/07 21:32	16.23	7/8/07 11:28	17.11	7/8/07 18:21
17.01	7/6/07 19:52	16.81	7/7/07 10:53	16.81	7/7/07 21:33	16.32	7/8/07 11:29	17.01	7/8/07 18:22
17.01	7/6/07 19:53	16.81	7/7/07 10:54	16.62	7/7/07 21:34	16.42	7/8/07 11:30	17.11	7/8/07 18:23
17.01	7/6/07 19:54	16.91	7/7/07 10:55	16.72	7/7/07 21:35	16.32	7/8/07 11:31	17.01	7/8/07 18:24
17.01	7/6/07 19:55	16.81	7/7/07 10:56	16.72	7/7/07 21:36	16.42	7/8/07 11:32	17.01	7/8/07 18:25
17.01	7/6/07 19:56	16.81	7/7/07 10:57	16.72	7/7/07 21:37	16.42	7/8/07 11:33	17.11	7/8/07 18:26
17.01	7/6/07 19:57	16.72	7/7/07 10:58	16.72	7/7/07 21:38	16.42	7/8/07 11:34	17.01	7/8/07 18:27
17.11	7/6/07 19:58	16.72	7/7/07 10:59	16.81	7/7/07 21:39	16.42	7/8/07 11:35	17.01	7/8/07 18:28
17.01	7/6/07 19:59	16.72	7/7/07 11:00	16.62	7/7/07 21:40	16.42	7/8/07 11:36	17.01	7/8/07 18:29
17.11	7/6/07 20:00	16.91	7/7/07 11:01	16.62	7/7/07 21:41	16.32	7/8/07 11:37	17.01	7/8/07 18:30
17.01	7/6/07 20:01			16.62	7/7/07 21:42	16.32	7/8/07 11:38	17.01	7/8/07 18:31

17.01	7/6/07 20:02
17.11	7/6/07 20:03
17.01	7/6/07 20:04
17.11	7/6/07 20:05
17.11	7/6/07 20:06
17.11	7/6/07 20:07
16.91	7/6/07 20:08
17.11	7/6/07 20:09
17.01	7/6/07 20:10
17.01	7/6/07 20:11
16.91	7/6/07 20:12
17.11	7/6/07 20:13
16.91	7/6/07 20:14
17.11	7/6/07 20:15
17.11	7/6/07 20:16
17.11	7/6/07 20:17
17.11	7/6/07 20:18
17.11	7/6/07 20:19
17.01	7/6/07 20:20
17.11	7/6/07 20:21
17.11	7/6/07 20:22
16.91	7/6/07 20:23
17.11	7/6/07 20:24
17.11	7/6/07 20:25
17.01	7/6/07 20:26
17.01	7/6/07 20:27
17.11	7/6/07 20:28
17.01	7/6/07 20:29
17.01	7/6/07 20:30
17.11	7/6/07 20:31
17.01	7/6/07 20:32
17.2	7/6/07 20:33
16.81	7/6/07 20:34
17.01	7/6/07 20:35
17.01	7/6/07 20:36
17.01	7/6/07 20:37
17.2	7/6/07 20:38

μ	σ
16.83	0.0813118

16.72	7/7/07 21:43
16.81	7/7/07 21:44
16.62	7/7/07 21:45
16.72	7/7/07 21:46
17.01	7/7/07 21:47
16.81	7/7/07 21:48
16.72	7/7/07 21:49
16.81	7/7/07 21:50
16.72	7/7/07 21:51
16.72	7/7/07 21:52
16.72	7/7/07 21:53
16.72	7/7/07 21:54
16.81	7/7/07 21:55
16.81	7/7/07 21:56
16.52	7/7/07 21:57
16.62	7/7/07 21:58
16.72	7/7/07 21:59
16.91	7/7/07 22:00
16.81	7/7/07 22:01
16.81	7/7/07 22:02
16.62	7/7/07 22:03
16.91	7/7/07 22:04
16.62	7/7/07 22:05
16.81	7/7/07 22:06
16.72	7/7/07 22:07
16.72	7/7/07 22:08
16.81	7/7/07 22:09
16.72	7/7/07 22:10
16.81	7/7/07 22:11
16.91	7/7/07 22:12
16.72	7/7/07 22:13
16.62	7/7/07 22:14
16.62	7/7/07 22:15
16.72	7/7/07 22:16
16.72	7/7/07 22:17
16.81	7/7/07 22:18
16.72	7/7/07 22:19

16.32	7/8/07 11:39
16.42	7/8/07 11:40
16.42	7/8/07 11:41
16.42	7/8/07 11:42
16.42	7/8/07 11:43
16.32	7/8/07 11:44
16.32	7/8/07 11:45
16.52	7/8/07 11:46
16.52	7/8/07 11:47
16.42	7/8/07 11:48
16.52	7/8/07 11:49
16.42	7/8/07 11:50

μ	σ
16.4	0.06784207

17.01	7/8/07 18:32
17.01	7/8/07 18:33
17.01	7/8/07 18:34
17.01	7/8/07 18:35
17.01	7/8/07 18:36
17.01	7/8/07 18:37
17.2	7/8/07 18:38
17.2	7/8/07 18:39
17.01	7/8/07 18:40
17.11	7/8/07 18:41
17.01	7/8/07 18:42
17.11	7/8/07 18:43
17.11	7/8/07 18:44
17.01	7/8/07 18:45
17.01	7/8/07 18:46
17.01	7/8/07 18:47
17.01	7/8/07 18:48
17.01	7/8/07 18:49
17.11	7/8/07 18:50
17.01	7/8/07 18:51
17.01	7/8/07 18:52
17.11	7/8/07 18:53
17.11	7/8/07 18:54
17.01	7/8/07 18:55
16.91	7/8/07 18:56
17.11	7/8/07 18:57
17.11	7/8/07 18:58
17.01	7/8/07 18:59
17.2	7/8/07 19:00
17.01	7/8/07 19:01
17.11	7/8/07 19:02
17.11	7/8/07 19:03
17.11	7/8/07 19:04
17.01	7/8/07 19:05
17.01	7/8/07 19:06
17.11	7/8/07 19:07
17.11	7/8/07 19:08

17.01	7/6/07 20:39
17.11	7/6/07 20:40
16.91	7/6/07 20:41
16.91	7/6/07 20:42
17.11	7/6/07 20:43
17.2	7/6/07 20:44
16.91	7/6/07 20:45
17.01	7/6/07 20:46
17.11	7/6/07 20:47
17.01	7/6/07 20:48

μ	σ
17.04	0.07760098

16.72	7/7/07 22:20
16.72	7/7/07 22:21
16.72	7/7/07 22:22
16.81	7/7/07 22:23
16.72	7/7/07 22:24
16.62	7/7/07 22:25
16.72	7/7/07 22:26

μ	σ
16.73	0.08479185

17.01	7/8/07 19:09
17.11	7/8/07 19:10
17.11	7/8/07 19:11
16.91	7/8/07 19:12
17.01	7/8/07 19:13
17.01	7/8/07 19:14
17.01	7/8/07 19:15

μ	σ
17.04	0.06369635

Figure A.0.1 shows the mean and standard deviation of all data points recorded for each angle at the NE orientation.

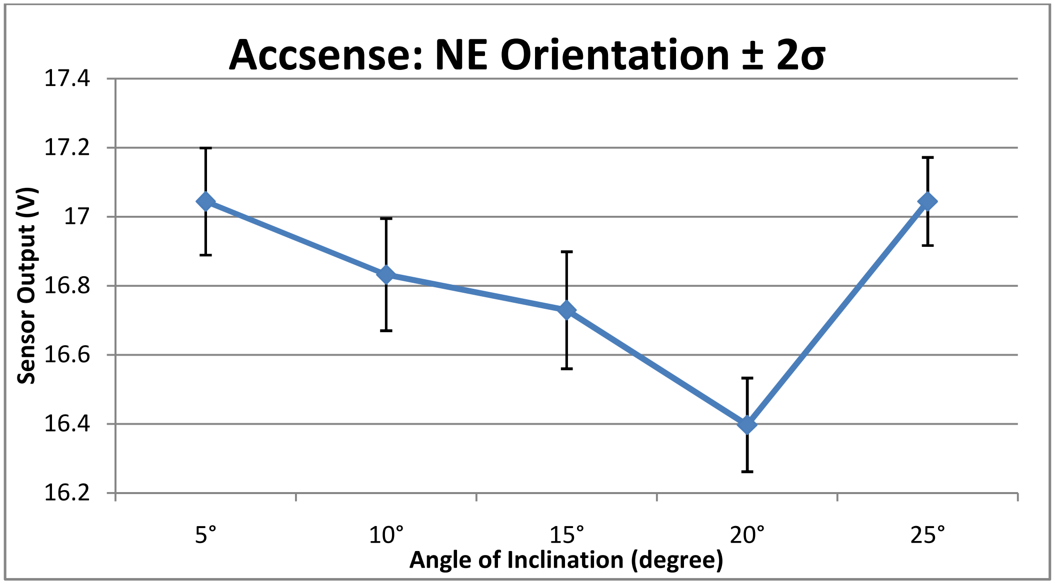

Figure A.0.1: NE Mean with ±2 standard deviation error bars

Table A.2 shows raw data from the Accsense Sensitivity Tests as described in 3.1- Accsense Wireless Systems.

Table A.2: Accsense Sensitivity Measurements for SE Orientation

5°		10°		15°		20°		25°	
Value	Time	Value	Time	Value	Time	Value	Time	Value	Time
15.64	7/6/07 23:06	14.08	7/7/07 11:02	12.41	7/7/07 22:29	10.46	7/8/07 11:51	9.091	7/8/07 19:27
15.64	7/6/07 23:07	13.88	7/7/07 11:03	12.32	7/7/07 22:30	10.65	7/8/07 11:52	9.188	7/8/07 19:28
15.84	7/6/07 23:08	13.78	7/7/07 11:04	12.41	7/7/07 22:31	10.56	7/8/07 11:53	9.188	7/8/07 19:29
15.64	7/6/07 23:09	14.08	7/7/07 11:05	12.41	7/7/07 22:32	10.65	7/8/07 11:54	9.188	7/8/07 19:30
15.74	7/6/07 23:10	13.98	7/7/07 11:06	12.41	7/7/07 22:33	10.65	7/8/07 11:55	9.091	7/8/07 19:31
15.54	7/6/07 23:11	13.98	7/7/07 11:07	12.41	7/7/07 22:34	10.65	7/8/07 11:56	9.188	7/8/07 19:32
15.64	7/6/07 23:12	14.08	7/7/07 11:08	12.32	7/7/07 22:35	10.56	7/8/07 11:57	9.188	7/8/07 19:33
15.64	7/6/07 23:13	13.88	7/7/07 11:09	12.32	7/7/07 22:36	10.65	7/8/07 11:58	9.188	7/8/07 19:34
15.74	7/6/07 23:14	14.08	7/7/07 11:10	12.41	7/7/07 22:37	10.56	7/8/07 11:59	9.188	7/8/07 19:35
15.54	7/6/07 23:15	14.08	7/7/07 11:11	12.41	7/7/07 22:38	10.56	7/8/07 12:00	9.188	7/8/07 19:36
15.74	7/6/07 23:16	13.98	7/7/07 11:12	12.41	7/7/07 22:39	10.56	7/8/07 12:01	9.286	7/8/07 19:37
15.74	7/6/07 23:17	14.08	7/7/07 11:13	12.41	7/7/07 22:40	10.65	7/8/07 12:02	9.286	7/8/07 19:38
15.74	7/6/07 23:18	14.08	7/7/07 11:14	12.51	7/7/07 22:41	10.56	7/8/07 12:03	9.091	7/8/07 19:39
15.44	7/6/07 23:19	13.98	7/7/07 11:15	12.22	7/7/07 22:42	10.46	7/8/07 12:04	9.091	7/8/07 19:40
15.64	7/6/07 23:20	13.98	7/7/07 11:16	12.32	7/7/07 22:43	10.56	7/8/07 12:05	8.993	7/8/07 19:41
15.54	7/6/07 23:21	13.98	7/7/07 11:17	12.41	7/7/07 22:44	10.56	7/8/07 12:06	9.188	7/8/07 19:42
15.54	7/6/07 23:22	13.98	7/7/07 11:18	12.41	7/7/07 22:45	10.46	7/8/07 12:07	9.188	7/8/07 19:43
15.64	7/6/07 23:23	13.88	7/7/07 11:19	12.51	7/7/07 22:46	10.56	7/8/07 12:08	9.188	7/8/07 19:44
15.64	7/6/07 23:24	13.88	7/7/07 11:20	12.41	7/7/07 22:47	10.56	7/8/07 12:09	9.286	7/8/07 19:45
15.64	7/6/07 23:25	13.98	7/7/07 11:21	12.32	7/7/07 22:48	10.65	7/8/07 12:10	9.091	7/8/07 19:46
15.64	7/6/07 23:26	13.98	7/7/07 11:22	12.41	7/7/07 22:49	10.65	7/8/07 12:11	9.091	7/8/07 19:47
15.84	7/6/07 23:27	13.88	7/7/07 11:23	12.41	7/7/07 22:50	10.56	7/8/07 12:12	9.188	7/8/07 19:48
15.64	7/6/07 23:28	13.88	7/7/07 11:24	12.32	7/7/07 22:51	10.46	7/8/07 12:13	9.091	7/8/07 19:49
15.54	7/6/07 23:29	13.98	7/7/07 11:25	12.51	7/7/07 22:52	10.56	7/8/07 12:14	9.286	7/8/07 19:50
15.74	7/6/07 23:30	14.08	7/7/07 11:26	12.41	7/7/07 22:53	10.56	7/8/07 12:15	9.091	7/8/07 19:51
15.54	7/6/07 23:31	14.17	7/7/07 11:27	12.51	7/7/07 22:54	10.56	7/8/07 12:16	9.286	7/8/07 19:52
15.74	7/6/07 23:32	13.98	7/7/07 11:28	12.32	7/7/07 22:55	10.56	7/8/07 12:17	9.091	7/8/07 19:53
15.64	7/6/07 23:33	13.98	7/7/07 11:29	12.51	7/7/07 22:56	10.56	7/8/07 12:18	9.188	7/8/07 19:54
15.74	7/6/07 23:34	14.08	7/7/07 11:30	12.41	7/7/07 22:57	10.75	7/8/07 12:19	8.993	7/8/07 19:55

15.64	7/6/07 23:35
15.64	7/6/07 23:36
15.54	7/6/07 23:37
15.84	7/6/07 23:38
15.74	7/6/07 23:39
15.74	7/6/07 23:40
15.74	7/6/07 23:41
15.64	7/6/07 23:42
15.74	7/6/07 23:43
15.64	7/6/07 23:44
15.74	7/6/07 23:45
15.54	7/6/07 23:46
15.74	7/6/07 23:47

μ	σ
15.66	0.09320715

13.98	7/7/07 11:31
14.08	7/7/07 11:32
14.08	7/7/07 11:33
13.98	7/7/07 11:34
14.08	7/7/07 11:35
13.88	7/7/07 11:36
13.88	7/7/07 11:37
13.88	7/7/07 11:38
13.98	7/7/07 11:39
13.98	7/7/07 11:40
13.98	7/7/07 11:41
14.08	7/7/07 11:42
14.08	7/7/07 11:43
13.88	7/7/07 11:44
13.98	7/7/07 11:45
14.08	7/7/07 11:46
13.98	7/7/07 11:47
13.98	7/7/07 11:48
13.88	7/7/07 11:49
13.78	7/7/07 11:50
13.98	7/7/07 11:51
14.08	7/7/07 11:52
13.98	7/7/07 11:53
13.98	7/7/07 11:54
13.98	7/7/07 11:55
13.88	7/7/07 11:56
13.88	7/7/07 11:57
13.88	7/7/07 11:58
13.98	7/7/07 11:59
13.98	7/7/07 12:00
14.08	7/7/07 12:01
13.98	7/7/07 12:02
13.98	7/7/07 12:03
14.08	7/7/07 12:04
14.08	7/7/07 12:05
13.98	7/7/07 12:06
13.98	7/7/07 12:07

12.41	7/7/07 22:58
12.41	7/7/07 22:59
12.41	7/7/07 23:00
12.51	7/7/07 23:01
12.32	7/7/07 23:02
12.41	7/7/07 23:03
12.41	7/7/07 23:04
12.41	7/7/07 23:05
12.41	7/7/07 23:06
12.41	7/7/07 23:07
12.51	7/7/07 23:08
12.41	7/7/07 23:09
12.41	7/7/07 23:10
12.41	7/7/07 23:11
12.51	7/7/07 23:12
12.41	7/7/07 23:13
12.51	7/7/07 23:14
12.32	7/7/07 23:15
12.41	7/7/07 23:16
12.41	7/7/07 23:17
12.32	7/7/07 23:18
12.51	7/7/07 23:19
12.61	7/7/07 23:20
12.41	7/7/07 23:21
12.41	7/7/07 23:22
12.32	7/7/07 23:23
12.41	7/7/07 23:24
12.41	7/7/07 23:25
12.61	7/7/07 23:26
12.41	7/7/07 23:27
12.41	7/7/07 23:28
12.32	7/7/07 23:29
12.32	7/7/07 23:30
12.41	7/7/07 23:31
12.41	7/7/07 23:32
12.51	7/7/07 23:33
12.51	7/7/07 23:34

10.56	7/8/07 12:20
10.56	7/8/07 12:21
10.56	7/8/07 12:22
10.65	7/8/07 12:23
10.46	7/8/07 12:24
10.46	7/8/07 12:25
10.56	7/8/07 12:26
10.65	7/8/07 12:27
10.65	7/8/07 12:28
10.46	7/8/07 12:29
10.56	7/8/07 12:30
10.56	7/8/07 12:31
10.56	7/8/07 12:32
10.46	7/8/07 12:33
10.65	7/8/07 12:34
10.75	7/8/07 12:35
10.46	7/8/07 12:36
10.65	7/8/07 12:37
10.65	7/8/07 12:38
10.65	7/8/07 12:39
10.65	7/8/07 12:40
10.56	7/8/07 12:41
10.56	7/8/07 12:42
10.65	7/8/07 12:43
10.56	7/8/07 12:44
10.65	7/8/07 12:45
10.65	7/8/07 12:46
10.65	7/8/07 12:47
10.56	7/8/07 12:48
10.56	7/8/07 12:49
10.46	7/8/07 12:50
10.46	7/8/07 12:51
10.56	7/8/07 12:52
10.65	7/8/07 12:53
10.56	7/8/07 12:54
10.56	7/8/07 12:55
10.65	7/8/07 12:56

9.091	7/8/07 19:56
9.188	7/8/07 19:57
9.188	7/8/07 19:58
9.091	7/8/07 19:59
9.188	7/8/07 20:00
9.091	7/8/07 20:01
9.091	7/8/07 20:02
9.091	7/8/07 20:03
9.188	7/8/07 20:04
9.286	7/8/07 20:05
9.188	7/8/07 20:06
9.188	7/8/07 20:07
9.188	7/8/07 20:08
9.091	7/8/07 20:09
8.993	7/8/07 20:10
9.188	7/8/07 20:11
9.188	7/8/07 20:12
9.188	7/8/07 20:13
9.286	7/8/07 20:14
9.188	7/8/07 20:15
9.091	7/8/07 20:16
9.091	7/8/07 20:17
9.188	7/8/07 20:18
9.091	7/8/07 20:19
8.993	7/8/07 20:20
9.188	7/8/07 20:21
9.286	7/8/07 20:22
9.188	7/8/07 20:23
9.091	7/8/07 20:24
9.188	7/8/07 20:25
9.188	7/8/07 20:26
9.286	7/8/07 20:27
9.384	7/8/07 20:28
9.188	7/8/07 20:29
8.993	7/8/07 20:30
9.091	7/8/07 20:31
9.091	7/8/07 20:32

14.08	7/7/07 12:08
14.08	7/7/07 12:09
13.98	7/7/07 12:10
13.88	7/7/07 12:11
13.88	7/7/07 12:12
13.98	7/7/07 12:13
13.88	7/7/07 12:14
13.88	7/7/07 12:15
14.08	7/7/07 12:16
14.08	7/7/07 12:17
13.88	7/7/07 12:18
14.08	7/7/07 12:19
13.98	7/7/07 12:20
13.98	7/7/07 12:21
13.98	7/7/07 12:22
13.98	7/7/07 12:23
13.98	7/7/07 12:24
13.88	7/7/07 12:25
13.88	7/7/07 12:26
13.88	7/7/07 12:27
13.88	7/7/07 12:28
13.88	7/7/07 12:29
13.98	7/7/07 12:30
13.88	7/7/07 12:31
13.98	7/7/07 12:32
13.98	7/7/07 12:33
13.88	7/7/07 12:34
13.98	7/7/07 12:35
14.08	7/7/07 12:36
14.08	7/7/07 12:37
13.98	7/7/07 12:38
13.98	7/7/07 12:39
14.08	7/7/07 12:40
14.08	7/7/07 12:41
13.98	7/7/07 12:42
13.98	7/7/07 12:43

12.32	7/7/07 23:35
12.41	7/7/07 23:36
12.51	7/7/07 23:37
12.32	7/7/07 23:38
12.32	7/7/07 23:39
12.41	7/7/07 23:40
12.32	7/7/07 23:41
12.32	7/7/07 23:42
12.41	7/7/07 23:43
12.32	7/7/07 23:44
12.51	7/7/07 23:45
12.41	7/7/07 23:46
12.22	7/7/07 23:47
12.41	7/7/07 23:48
12.51	7/7/07 23:49
12.41	7/7/07 23:50

μ	σ
12.41	0.07500286

10.65	7/8/07 12:57
10.46	7/8/07 12:58
10.65	7/8/07 12:59
10.56	7/8/07 13:00
10.65	7/8/07 13:01
10.65	7/8/07 13:02
10.56	7/8/07 13:03
10.56	7/8/07 13:04
10.65	7/8/07 13:05
10.56	7/8/07 13:06
10.46	7/8/07 13:07
10.56	7/8/07 13:08
10.56	7/8/07 13:09
10.46	7/8/07 13:10
10.75	7/8/07 13:11
10.65	7/8/07 13:12
10.56	7/8/07 13:13
10.46	7/8/07 13:14
10.65	7/8/07 13:15
10.56	7/8/07 13:16
10.56	7/8/07 13:17
10.75	7/8/07 13:18
10.46	7/8/07 13:19
10.46	7/8/07 13:20
10.65	7/8/07 13:21
10.65	7/8/07 13:22
10.65	7/8/07 13:23
10.65	7/8/07 13:24
10.56	7/8/07 13:25
10.65	7/8/07 13:26
10.56	7/8/07 13:27
10.46	7/8/07 13:28
10.56	7/8/07 13:29
10.56	7/8/07 13:30
10.65	7/8/07 13:31
10.65	7/8/07 13:32

9.188	7/8/07 20:33
9.091	7/8/07 20:34
9.188	7/8/07 20:35
9.091	7/8/07 20:36
9.091	7/8/07 20:37
9.188	7/8/07 20:38
9.188	7/8/07 20:39
9.188	7/8/07 20:40
9.188	7/8/07 20:41
9.091	7/8/07 20:42
9.188	7/8/07 20:43
9.091	7/8/07 20:44
9.091	7/8/07 20:45

μ	σ
9.156	0.07916958

13.88	7/7/07 12:44
13.88	7/7/07 12:45
13.88	7/7/07 12:46
13.98	7/7/07 12:47
13.98	7/7/07 12:48
14.17	7/7/07 12:49
14.08	7/7/07 12:50
14.08	7/7/07 12:51
13.98	7/7/07 12:52

μ	σ
13.98	0.08213859

10.65	7/8/07 13:33
10.46	7/8/07 13:34

μ	σ
10.58	0.07555514

Figure A.0.2 shows the mean and standard deviation of all data points recorded for each angle at the SE orientation.

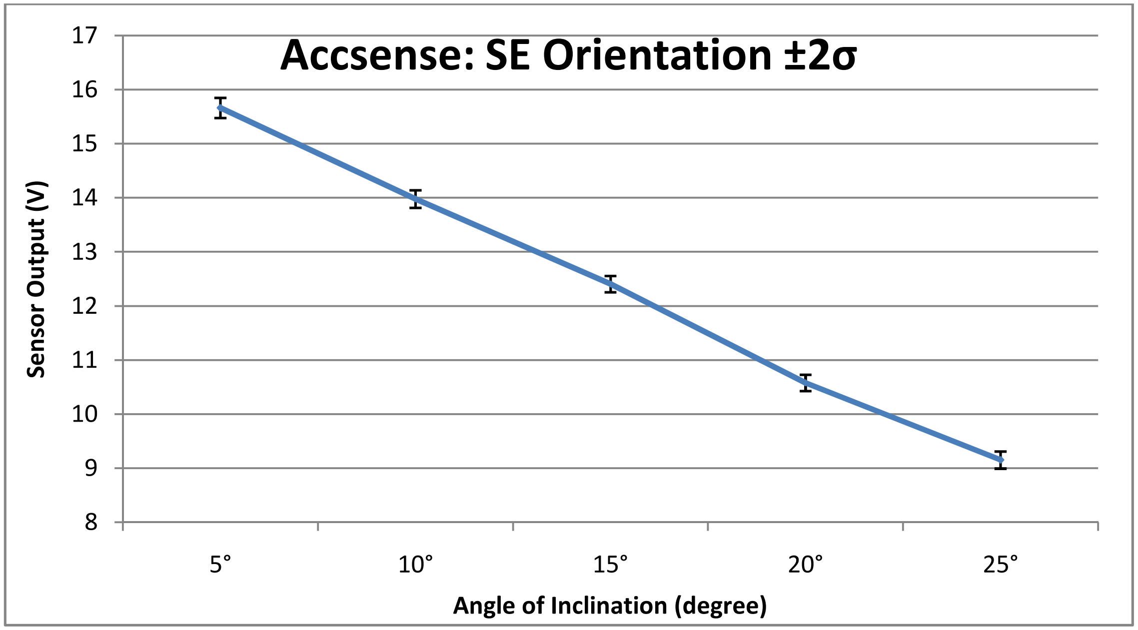

Figure A.0.2: SE Mean with ±2 standard deviation error bars

Table A.3 shows raw data from the Accsense Sensitivity Tests as described in 3.1- Accsense Wireless Systems.

Table A.3: Accsense Sensitivity Measurements for SW Orientation

5°		10°		15°		20°		25°	
Value	Time	Value	Time	Value	Time	Value	Time	Value	Time
17.69	7/6/07 20:51	17.79	7/7/07 18:48	17.3	7/7/07 23:53	17.01	7/8/07 13:46	16.32	7/8/07 20:52
17.69	7/6/07 20:52	17.6	7/7/07 18:49	17.2	7/7/07 23:54	16.91	7/8/07 13:47	16.52	7/8/07 20:53
17.6	7/6/07 20:53	17.6	7/7/07 18:50	17.3	7/7/07 23:55	17.01	7/8/07 13:48	16.32	7/8/07 20:54
17.69	7/6/07 20:54	17.5	7/7/07 18:51	17.4	7/7/07 23:56	17.01	7/8/07 13:49	16.42	7/8/07 20:55
17.69	7/6/07 20:55	17.5	7/7/07 18:52	17.4	7/7/07 23:57	16.81	7/8/07 13:50	16.42	7/8/07 20:56
17.69	7/6/07 20:56	17.6	7/7/07 18:53	17.5	7/7/07 23:58	16.81	7/8/07 13:51	16.42	7/8/07 20:57
17.79	7/6/07 20:57	17.6	7/7/07 18:54	17.2	7/7/07 23:59	16.91	7/8/07 13:52	16.42	7/8/07 20:58
17.69	7/6/07 20:58	17.6	7/7/07 18:55	17.3	7/8/07 0:00	16.91	7/8/07 13:53	16.42	7/8/07 20:59
17.69	7/6/07 20:59	17.6	7/7/07 18:56	17.4	7/8/07 0:01	16.91	7/8/07 13:54	16.32	7/8/07 21:00
17.69	7/6/07 21:00	17.5	7/7/07 18:57	17.3	7/8/07 0:02	16.91	7/8/07 13:55	16.52	7/8/07 21:01
17.79	7/6/07 21:01	17.69	7/7/07 18:58	17.3	7/8/07 0:03	17.01	7/8/07 13:56	16.23	7/8/07 21:02
17.69	7/6/07 21:02	17.6	7/7/07 18:59	17.3	7/8/07 0:04	16.91	7/8/07 13:57	16.42	7/8/07 21:03
17.6	7/6/07 21:03	17.6	7/7/07 19:00	17.4	7/8/07 0:05	16.91	7/8/07 13:58	16.52	7/8/07 21:04
17.79	7/6/07 21:04	17.79	7/7/07 19:01	17.4	7/8/07 0:06	16.81	7/8/07 13:59	16.42	7/8/07 21:05
17.69	7/6/07 21:05	17.6	7/7/07 19:02	17.4	7/8/07 0:07	17.01	7/8/07 14:00	16.42	7/8/07 21:06
17.79	7/6/07 21:06	17.6	7/7/07 19:03	17.4	7/8/07 0:08	17.01	7/8/07 14:01	16.42	7/8/07 21:07
17.79	7/6/07 21:07	17.79	7/7/07 19:04	17.3	7/8/07 0:09	17.01	7/8/07 14:02	16.32	7/8/07 21:08
17.69	7/6/07 21:08	17.6	7/7/07 19:05	17.3	7/8/07 0:10	17.01	7/8/07 14:03	16.52	7/8/07 21:09
17.79	7/6/07 21:09	17.6	7/7/07 19:06	17.4	7/8/07 0:11	16.91	7/8/07 14:04	16.52	7/8/07 21:10
17.69	7/6/07 21:10	17.5	7/7/07 19:07	17.3	7/8/07 0:12	17.11	7/8/07 14:05	16.42	7/8/07 21:11
17.79	7/6/07 21:11	17.6	7/7/07 19:08	17.3	7/8/07 0:13	16.91	7/8/07 14:06	16.52	7/8/07 21:12
17.79	7/6/07 21:12	17.69	7/7/07 19:09	17.2	7/8/07 0:14	17.01	7/8/07 14:07	16.42	7/8/07 21:13
17.69	7/6/07 21:13	17.79	7/7/07 19:10	17.2	7/8/07 0:15	16.81	7/8/07 14:08	16.42	7/8/07 21:14
17.79	7/6/07 21:14	17.6	7/7/07 19:11	17.4	7/8/07 0:16	16.81	7/8/07 14:09	16.42	7/8/07 21:15
17.79	7/6/07 21:15	17.6	7/7/07 19:12	17.4	7/8/07 0:17	17.01	7/8/07 14:10	16.42	7/8/07 21:16
17.79	7/6/07 21:16	17.6	7/7/07 19:13	17.4	7/8/07 0:18	17.01	7/8/07 14:11	16.42	7/8/07 21:17
17.69	7/6/07 21:17	17.5	7/7/07 19:14	17.4	7/8/07 0:19	16.91	7/8/07 14:12	16.32	7/8/07 21:18
17.69	7/6/07 21:18	17.6	7/7/07 19:15	17.2	7/8/07 0:20	16.91	7/8/07 14:13	16.42	7/8/07 21:19
17.69	7/6/07 21:19	17.6	7/7/07 19:16	17.3	7/8/07 0:21	17.01	7/8/07 14:14	16.42	7/8/07 21:20
17.69	7/6/07 21:20	17.69	7/7/07 19:17	17.3	7/8/07 0:22	17.01	7/8/07 14:15	16.42	7/8/07 21:21
17.79	7/6/07 21:21	17.5	7/7/07 19:18	17.4	7/8/07 0:23	17.01	7/8/07 14:16	16.52	7/8/07 21:22

17.79	7/6/07 21:22
17.79	7/6/07 21:23
17.69	7/6/07 21:24
17.79	7/6/07 21:25
17.69	7/6/07 21:26
17.69	7/6/07 21:27
17.69	7/6/07 21:28
17.69	7/6/07 21:29
17.69	7/6/07 21:30
17.79	7/6/07 21:31
17.6	7/6/07 21:32
17.79	7/6/07 21:33
17.69	7/6/07 21:34
17.79	7/6/07 21:35
17.69	7/6/07 21:36
17.79	7/6/07 21:37
17.89	7/6/07 21:38
17.69	7/6/07 21:39
17.79	7/6/07 21:40
17.69	7/6/07 21:41
17.79	7/6/07 21:42
17.69	7/6/07 21:43
17.69	7/6/07 21:44
17.69	7/6/07 21:45
17.79	7/6/07 21:46
17.6	7/6/07 21:47
17.69	7/6/07 21:48
17.79	7/6/07 21:49
17.69	7/6/07 21:50
17.79	7/6/07 21:51
17.69	7/6/07 21:52
17.69	7/6/07 21:53
17.79	7/6/07 21:54
17.79	7/6/07 21:55
17.69	7/6/07 21:56
17.69	7/6/07 21:57
17.6	7/6/07 21:58

17.6	7/7/07 19:19
17.6	7/7/07 19:20
17.6	7/7/07 19:21
17.6	7/7/07 19:22
17.5	7/7/07 19:23
17.5	7/7/07 19:24
17.5	7/7/07 19:25
17.6	7/7/07 19:26
17.69	7/7/07 19:27
17.5	7/7/07 19:28
17.69	7/7/07 19:29
17.69	7/7/07 19:30
17.5	7/7/07 19:31
17.6	7/7/07 19:32
17.69	7/7/07 19:33
17.6	7/7/07 19:34
17.69	7/7/07 19:35
17.69	7/7/07 19:36
17.5	7/7/07 19:37
17.69	7/7/07 19:38
17.5	7/7/07 19:39
17.5	7/7/07 19:40
17.6	7/7/07 19:41
17.6	7/7/07 19:42
17.6	7/7/07 19:43

μ	σ
17.6	0.08137376

17.2	7/8/07 0:24
17.3	7/8/07 0:25
17.3	7/8/07 0:26
17.2	7/8/07 0:27
17.3	7/8/07 0:28
17.2	7/8/07 0:29
17.4	7/8/07 0:30
17.2	7/8/07 0:31
17.3	7/8/07 0:32
17.11	7/8/07 0:33
17.3	7/8/07 0:34
17.3	7/8/07 0:35
17.4	7/8/07 0:36
17.3	7/8/07 0:37
17.4	7/8/07 0:38
17.2	7/8/07 0:39
17.3	7/8/07 0:40
17.3	7/8/07 0:41
17.4	7/8/07 0:42
17.4	7/8/07 0:43
17.4	7/8/07 0:44
17.3	7/8/07 0:45
17.4	7/8/07 0:46
17.4	7/8/07 0:47
17.2	7/8/07 0:48
17.4	7/8/07 0:49
17.2	7/8/07 0:50
17.4	7/8/07 0:51
17.4	7/8/07 0:52
17.11	7/8/07 0:53
17.4	7/8/07 0:54
17.4	7/8/07 0:55
17.3	7/8/07 0:56
17.3	7/8/07 0:57
17.3	7/8/07 0:58
17.3	7/8/07 0:59
17.4	7/8/07 1:00

16.91	7/8/07 14:17
16.91	7/8/07 14:18
17.01	7/8/07 14:19
17.01	7/8/07 14:20
17.01	7/8/07 14:21
16.91	7/8/07 14:22
17.01	7/8/07 14:23
17.01	7/8/07 14:24
17.01	7/8/07 14:25
17.01	7/8/07 14:26
17.01	7/8/07 14:27
17.01	7/8/07 14:28
17.11	7/8/07 14:29
16.81	7/8/07 14:30
17.01	7/8/07 14:31
17.01	7/8/07 14:32
16.91	7/8/07 14:33
17.01	7/8/07 14:34
17.01	7/8/07 14:35
16.91	7/8/07 14:36
16.91	7/8/07 14:37
17.01	7/8/07 14:38
16.91	7/8/07 14:39
16.91	7/8/07 14:40
17.11	7/8/07 14:41
17.01	7/8/07 14:42
16.81	7/8/07 14:43
16.91	7/8/07 14:44
17.01	7/8/07 14:45
16.81	7/8/07 14:46
16.91	7/8/07 14:47
16.91	7/8/07 14:48
17.01	7/8/07 14:49
16.91	7/8/07 14:50
16.91	7/8/07 14:51
16.91	7/8/07 14:52
17.01	7/8/07 14:53

16.52	7/8/07 21:23
16.52	7/8/07 21:24
16.42	7/8/07 21:25
16.62	7/8/07 21:26
16.42	7/8/07 21:27
16.32	7/8/07 21:28
16.52	7/8/07 21:29
16.42	7/8/07 21:30
16.42	7/8/07 21:31
16.52	7/8/07 21:32
16.42	7/8/07 21:33
16.52	7/8/07 21:34
16.62	7/8/07 21:35
16.42	7/8/07 21:36
16.42	7/8/07 21:37
16.52	7/8/07 21:38
16.52	7/8/07 21:39
16.42	7/8/07 21:40
16.42	7/8/07 21:41
16.52	7/8/07 21:42
16.42	7/8/07 21:43
16.42	7/8/07 21:44
16.52	7/8/07 21:45
16.52	7/8/07 21:46
16.42	7/8/07 21:47
16.52	7/8/07 21:48
16.42	7/8/07 21:49
16.52	7/8/07 21:50
16.52	7/8/07 21:51
16.52	7/8/07 21:52
16.62	7/8/07 21:53
16.42	7/8/07 21:54
16.52	7/8/07 21:55
16.62	7/8/07 21:56
16.52	7/8/07 21:57
16.42	7/8/07 21:58
16.52	7/8/07 21:59

17.79	7/6/07 21:59
17.6	7/6/07 22:00
17.69	7/6/07 22:01
17.79	7/6/07 22:02
17.69	7/6/07 22:03
17.79	7/6/07 22:04
17.6	7/6/07 22:05
17.79	7/6/07 22:06
17.6	7/6/07 22:07
17.79	7/6/07 22:08
17.69	7/6/07 22:09
17.69	7/6/07 22:10
17.69	7/6/07 22:11
17.69	7/6/07 22:12
17.6	7/6/07 22:13
17.79	7/6/07 22:14
17.69	7/6/07 22:15
17.79	7/6/07 22:16
17.6	7/6/07 22:17
17.6	7/6/07 22:18
17.79	7/6/07 22:19
17.69	7/6/07 22:20
17.69	7/6/07 22:21
17.6	7/6/07 22:22
17.79	7/6/07 22:23
17.69	7/6/07 22:24
17.79	7/6/07 22:25
17.69	7/6/07 22:26
17.69	7/6/07 22:27
17.79	7/6/07 22:28
17.69	7/6/07 22:29
17.89	7/6/07 22:30
17.79	7/6/07 22:31
17.79	7/6/07 22:32
17.69	7/6/07 22:33
17.69	7/6/07 22:34
17.79	7/6/07 22:35

17.3	7/8/07 1:01
17.3	7/8/07 1:02
17.3	7/8/07 1:03
17.2	7/8/07 1:04
17.3	7/8/07 1:05
17.2	7/8/07 1:06
17.2	7/8/07 1:07
17.11	7/8/07 1:08
17.3	7/8/07 1:09
17.3	7/8/07 1:10
17.3	7/8/07 1:11
17.4	7/8/07 1:12
17.4	7/8/07 1:13
17.3	7/8/07 1:14
17.3	7/8/07 1:15
17.2	7/8/07 1:16
17.11	7/8/07 1:17
17.4	7/8/07 1:18
17.3	7/8/07 1:19
17.2	7/8/07 1:20
17.4	7/8/07 1:21
17.4	7/8/07 1:22
17.3	7/8/07 1:23
17.2	7/8/07 1:24
17.2	7/8/07 1:25
17.2	7/8/07 1:26
17.5	7/8/07 1:27
17.11	7/8/07 1:28
17.2	7/8/07 1:29
17.11	7/8/07 1:30
17.2	7/8/07 1:31
17.3	7/8/07 1:32
17.4	7/8/07 1:33
17.3	7/8/07 1:34
17.3	7/8/07 1:35
17.3	7/8/07 1:36
17.3	7/8/07 1:37

16.81	7/8/07 14:54
17.01	7/8/07 14:55
17.01	7/8/07 14:56
17.01	7/8/07 14:57
16.72	7/8/07 14:58
16.91	7/8/07 14:59
16.91	7/8/07 15:00
17.01	7/8/07 15:01
16.91	7/8/07 15:02
16.81	7/8/07 15:03
16.91	7/8/07 15:04
17.01	7/8/07 15:05
16.91	7/8/07 15:06
17.01	7/8/07 15:07
16.91	7/8/07 15:08
16.91	7/8/07 15:09
16.91	7/8/07 15:10
16.91	7/8/07 15:11
16.81	7/8/07 15:12
16.91	7/8/07 15:13
16.81	7/8/07 15:14
16.81	7/8/07 15:15
16.91	7/8/07 15:16
17.01	7/8/07 15:17
17.01	7/8/07 15:18
16.91	7/8/07 15:19
16.91	7/8/07 15:20

μ	σ
16.94	0.07884056

16.42	7/8/07 22:00
16.32	7/8/07 22:01
16.32	7/8/07 22:02
16.52	7/8/07 22:03
16.62	7/8/07 22:04
16.52	7/8/07 22:05
16.52	7/8/07 22:06
16.62	7/8/07 22:07
16.42	7/8/07 22:08
16.52	7/8/07 22:09
16.52	7/8/07 22:10
16.42	7/8/07 22:11
16.52	7/8/07 22:12
16.42	7/8/07 22:13
16.52	7/8/07 22:14
16.52	7/8/07 22:15
16.52	7/8/07 22:16
16.42	7/8/07 22:17
16.62	7/8/07 22:18
16.52	7/8/07 22:19
16.42	7/8/07 22:20
16.52	7/8/07 22:21
16.52	7/8/07 22:22
16.52	7/8/07 22:23
16.42	7/8/07 22:24
16.52	7/8/07 22:25
16.42	7/8/07 22:26
16.52	7/8/07 22:27
16.42	7/8/07 22:28
16.42	7/8/07 22:29
16.52	7/8/07 22:30
16.52	7/8/07 22:31
16.52	7/8/07 22:32
16.52	7/8/07 22:33
16.42	7/8/07 22:34
16.32	7/8/07 22:35
16.52	7/8/07 22:36

17.79	7/6/07 22:36
17.79	7/6/07 22:37
17.69	7/6/07 22:38
17.79	7/6/07 22:39
17.79	7/6/07 22:40
17.79	7/6/07 22:41
17.79	7/6/07 22:42
17.69	7/6/07 22:43
17.69	7/6/07 22:44
17.79	7/6/07 22:45
17.89	7/6/07 22:46
17.79	7/6/07 22:47
17.69	7/6/07 22:48
17.69	7/6/07 22:49
17.79	7/6/07 22:50
17.69	7/6/07 22:51
17.79	7/6/07 22:52
17.6	7/6/07 22:53
17.79	7/6/07 22:54
17.69	7/6/07 22:55
17.79	7/6/07 22:56
17.6	7/6/07 22:57
17.69	7/6/07 22:58
17.69	7/6/07 22:59
17.79	7/6/07 23:00
17.79	7/6/07 23:01
17.69	7/6/07 23:02
17.69	7/6/07 23:03
17.69	7/6/07 23:04

μ	σ
17.73	0.06748608

17.2	7/8/07 1:38
17.4	7/8/07 1:39
17.4	7/8/07 1:40
17.3	7/8/07 1:41
17.4	7/8/07 1:42
17.5	7/8/07 1:43
17.4	7/8/07 1:44
17.3	7/8/07 1:45
17.3	7/8/07 1:46
17.3	7/8/07 1:47
17.4	7/8/07 1:48
17.2	7/8/07 1:49
17.3	7/8/07 1:50
17.3	7/8/07 1:51
17.11	7/8/07 1:52
17.4	7/8/07 1:53
17.2	7/8/07 1:54
17.3	7/8/07 1:55
17.3	7/8/07 1:56
17.4	7/8/07 1:57
17.3	7/8/07 1:58
17.4	7/8/07 1:59
17.11	7/8/07 2:00
17.3	7/8/07 2:01
17.4	7/8/07 2:02
17.2	7/8/07 2:03
17.2	7/8/07 2:04
17.3	7/8/07 2:05
17.4	7/8/07 2:06
17.2	7/8/07 2:07
17.4	7/8/07 2:08
17.4	7/8/07 2:09
17.3	7/8/07 2:10
17.5	7/8/07 2:11
17.4	7/8/07 2:12
17.3	7/8/07 2:13

16.32	7/8/07 22:37
16.42	7/8/07 22:38
16.42	7/8/07 22:39
16.62	7/8/07 22:40
16.52	7/8/07 22:41
16.32	7/8/07 22:42
16.42	7/8/07 22:43
16.42	7/8/07 22:44
16.52	7/8/07 22:45
16.42	7/8/07 22:46
16.42	7/8/07 22:47
16.62	7/8/07 22:48
16.32	7/8/07 22:49
16.42	7/8/07 22:50
16.62	7/8/07 22:51
16.52	7/8/07 22:52
16.52	7/8/07 22:53
16.42	7/8/07 22:54
16.42	7/8/07 22:55
16.42	7/8/07 22:56
16.42	7/8/07 22:57
16.62	7/8/07 22:58
16.52	7/8/07 22:59
16.52	7/8/07 23:00
16.62	7/8/07 23:01
16.52	7/8/07 23:02

μ	σ
16.47	0.08138806

μ	σ
17.31	0.09182778
	0.18365555

Figure A.0.3 shows the mean and standard deviation of all data points recorded for each angle at the SW orientation.

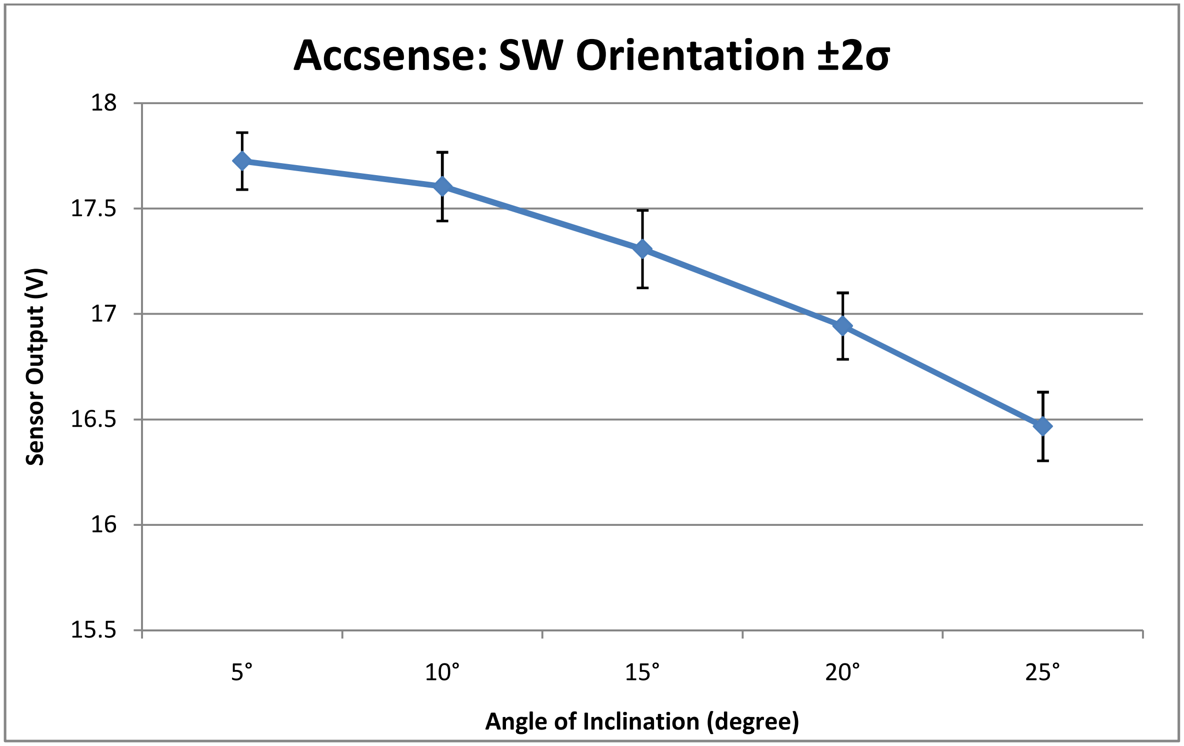

Figure A.0.3: SW Mean with ±2 standard deviation error bars

Table A.4 shows raw data from the Accsense Sensitivity Tests as described in 3.1- Accsense Wireless Systems.

Table A.4: Accsense Sensitivity Measurements for NW Orientation

5°		10°:		15°		20°		25°	
Value	Time	Value	Time	Value	Time	Value	Time	Value	Time
19.26	7/6/07 23:51	20.43	7/7/07 19:46	20.53	7/8/07 4:36	22.58	7/8/07 15:26	23.56	7/8/07 23:08
19.06	7/6/07 23:52	20.33	7/7/07 19:47	20.43	7/8/07 4:37	22.58	7/8/07 15:27	23.66	7/8/07 23:09
18.96	7/6/07 23:53	20.43	7/7/07 19:48	20.63	7/8/07 4:38	22.58	7/8/07 15:28	23.46	7/8/07 23:10
19.06	7/6/07 23:54	20.43	7/7/07 19:49	20.53	7/8/07 4:39	22.58	7/8/07 15:29	23.46	7/8/07 23:11
19.06	7/6/07 23:55	20.43	7/7/07 19:50	20.53	7/8/07 4:40	22.58	7/8/07 15:30	23.46	7/8/07 23:12
19.06	7/6/07 23:56	20.33	7/7/07 19:51	20.53	7/8/07 4:41	22.58	7/8/07 15:31	23.46	7/8/07 23:13
19.16	7/6/07 23:57	20.33	7/7/07 19:52	20.53	7/8/07 4:42	22.58	7/8/07 15:32	23.56	7/8/07 23:14
19.16	7/6/07 23:58	20.33	7/7/07 19:53	20.43	7/8/07 4:43	22.48	7/8/07 15:33	23.56	7/8/07 23:15
19.16	7/6/07 23:59	20.23	7/7/07 19:54	20.53	7/8/07 4:44	22.68	7/8/07 15:34	23.56	7/8/07 23:16
19.06	7/7/07 0:00	20.33	7/7/07 19:55	20.43	7/8/07 4:45	22.48	7/8/07 15:35	23.36	7/8/07 23:17
19.16	7/7/07 0:01	20.23	7/7/07 19:56	20.53	7/8/07 4:46	22.68	7/8/07 15:36	23.46	7/8/07 23:18
19.06	7/7/07 0:02	20.43	7/7/07 19:57	20.53	7/8/07 4:47	22.58	7/8/07 15:37	23.56	7/8/07 23:19
19.06	7/7/07 0:03	20.33	7/7/07 19:58	20.53	7/8/07 4:48	22.58	7/8/07 15:38	23.46	7/8/07 23:20
19.16	7/7/07 0:04	20.33	7/7/07 19:59	20.53	7/8/07 4:49	22.68	7/8/07 15:39	23.56	7/8/07 23:21
19.16	7/7/07 0:05	20.43	7/7/07 20:00	20.63	7/8/07 4:50	22.68	7/8/07 15:40	23.56	7/8/07 23:22
19.06	7/7/07 0:06	20.33	7/7/07 20:01	20.43	7/8/07 4:51	22.58	7/8/07 15:41	23.56	7/8/07 23:23
19.16	7/7/07 0:07	20.33	7/7/07 20:02	20.53	7/8/07 4:52	22.58	7/8/07 15:42	23.46	7/8/07 23:24
19.06	7/7/07 0:08	20.14	7/7/07 20:03	20.53	7/8/07 4:53	22.58	7/8/07 15:43	23.46	7/8/07 23:25
19.16	7/7/07 0:09	20.43	7/7/07 20:04	20.53	7/8/07 4:54	22.68	7/8/07 15:44	23.46	7/8/07 23:26
19.06	7/7/07 0:10	20.43	7/7/07 20:05	20.43	7/8/07 4:55	22.68	7/8/07 15:45	23.56	7/8/07 23:27
18.96	7/7/07 0:11	20.43	7/7/07 20:06	20.53	7/8/07 4:56	22.58	7/8/07 15:46	23.46	7/8/07 23:28
19.06	7/7/07 0:12	20.33	7/7/07 20:07	20.53	7/8/07 4:57	22.68	7/8/07 15:47	23.56	7/8/07 23:29
19.06	7/7/07 0:13	20.33	7/7/07 20:08	20.63	7/8/07 4:58	22.68	7/8/07 15:48	23.56	7/8/07 23:30
19.16	7/7/07 0:14	20.53	7/7/07 20:09	20.53	7/8/07 4:59	22.58	7/8/07 15:49	23.75	7/8/07 23:31
19.16	7/7/07 0:15	20.43	7/7/07 20:10	20.63	7/8/07 5:00	22.58	7/8/07 15:50	23.36	7/8/07 23:32
19.16	7/7/07 0:16	20.33	7/7/07 20:11	20.82	7/8/07 5:01	22.78	7/8/07 15:51	23.56	7/8/07 23:33
19.16	7/7/07 0:17	20.33	7/7/07 20:12	20.63	7/8/07 5:02	22.68	7/8/07 15:52	23.56	7/8/07 23:34
19.06	7/7/07 0:18	20.43	7/7/07 20:13	20.43	7/8/07 5:03	22.68	7/8/07 15:53	23.46	7/8/07 23:35
19.06	7/7/07 0:19	20.33	7/7/07 20:14	20.33	7/8/07 5:04	22.68	7/8/07 15:54	23.46	7/8/07 23:36
19.16	7/7/07 0:20	20.43	7/7/07 20:15	20.63	7/8/07 5:05	22.68	7/8/07 15:55	23.46	7/8/07 23:37
19.06	7/7/07 0:21	20.33	7/7/07 20:16	20.63	7/8/07 5:06	22.58	7/8/07 15:56	23.46	7/8/07 23:38

19.06	7/7/07 0:22
19.16	7/7/07 0:23
19.06	7/7/07 0:24

μ	σ
19.1	0.06567896

20.23	7/7/07 20:17
20.33	7/7/07 20:18
20.43	7/7/07 20:19
20.23	7/7/07 20:20
20.33	7/7/07 20:21
20.43	7/7/07 20:22
20.43	7/7/07 20:23
20.33	7/7/07 20:24
20.33	7/7/07 20:25
20.43	7/7/07 20:26
20.43	7/7/07 20:27
20.14	7/7/07 20:28
20.43	7/7/07 20:29
20.43	7/7/07 20:30
20.43	7/7/07 20:31
20.23	7/7/07 20:32
20.43	7/7/07 20:33
20.33	7/7/07 20:34
20.43	7/7/07 20:35
20.33	7/7/07 20:36
20.43	7/7/07 20:37
20.43	7/7/07 20:38
20.33	7/7/07 20:39
20.43	7/7/07 20:40
20.43	7/7/07 20:41
20.23	7/7/07 20:42
20.43	7/7/07 20:43
20.33	7/7/07 20:44
20.43	7/7/07 20:45
20.53	7/7/07 20:46
20.43	7/7/07 20:47
20.33	7/7/07 20:48
20.43	7/7/07 20:49
20.33	7/7/07 20:50
20.43	7/7/07 20:51
20.33	7/7/07 20:52

20.43	7/8/07 5:07
20.53	7/8/07 5:08
20.53	7/8/07 5:09
20.33	7/8/07 5:10
20.63	7/8/07 5:11
20.63	7/8/07 5:12
20.53	7/8/07 5:13
20.53	7/8/07 5:14
20.43	7/8/07 5:15
20.53	7/8/07 5:16
20.63	7/8/07 5:17
20.53	7/8/07 5:18
20.63	7/8/07 5:19
20.63	7/8/07 5:20
20.43	7/8/07 5:21
20.53	7/8/07 5:22
20.63	7/8/07 5:23
20.92	7/8/07 5:24
20.53	7/8/07 5:25
20.43	7/8/07 5:26
20.63	7/8/07 5:27
20.53	7/8/07 5:28
20.43	7/8/07 5:29
20.43	7/8/07 5:30
20.53	7/8/07 5:31
20.53	7/8/07 5:32
20.53	7/8/07 5:33
20.53	7/8/07 5:34
20.63	7/8/07 5:35
20.43	7/8/07 5:36
20.53	7/8/07 5:37
20.53	7/8/07 5:38
20.53	7/8/07 5:39
20.63	7/8/07 5:40
20.33	7/8/07 5:41
20.53	7/8/07 5:42

22.58	7/8/07 15:57
22.58	7/8/07 15:58
22.58	7/8/07 15:59
22.58	7/8/07 16:00
22.68	7/8/07 16:01
22.78	7/8/07 16:02
22.78	7/8/07 16:03
22.68	7/8/07 16:04
22.58	7/8/07 16:05
22.58	7/8/07 16:06
22.58	7/8/07 16:07
22.58	7/8/07 16:08
22.68	7/8/07 16:09
22.68	7/8/07 16:10
22.58	7/8/07 16:11
22.68	7/8/07 16:12
22.68	7/8/07 16:13
22.58	7/8/07 16:14
22.48	7/8/07 16:15
22.68	7/8/07 16:16
22.58	7/8/07 16:17
22.58	7/8/07 16:18
22.48	7/8/07 16:19
22.58	7/8/07 16:20
22.68	7/8/07 16:21
22.58	7/8/07 16:22
22.68	7/8/07 16:23
22.68	7/8/07 16:24
22.58	7/8/07 16:25
22.58	7/8/07 16:26
22.68	7/8/07 16:27
22.78	7/8/07 16:28
22.68	7/8/07 16:29
22.68	7/8/07 16:30
22.68	7/8/07 16:31
22.78	7/8/07 16:32

23.56	7/8/07 23:39
23.56	7/8/07 23:40
23.66	7/8/07 23:41
23.56	7/8/07 23:42
23.46	7/8/07 23:43
23.46	7/8/07 23:44
23.46	7/8/07 23:45
23.66	7/8/07 23:46
23.56	7/8/07 23:47
23.56	7/8/07 23:48
23.66	7/8/07 23:49
23.56	7/8/07 23:50
23.66	7/8/07 23:51
23.66	7/8/07 23:52
23.46	7/8/07 23:53
23.56	7/8/07 23:54
23.56	7/8/07 23:55
23.56	7/8/07 23:56
23.46	7/8/07 23:57
23.66	7/8/07 23:58
23.56	7/8/07 23:59
23.56	7/9/07 0:00
23.66	7/9/07 0:01
23.56	7/9/07 0:02
23.36	7/9/07 0:03
23.56	7/9/07 0:04
23.36	7/9/07 0:05
23.56	7/9/07 0:06
23.56	7/9/07 0:07
23.56	7/9/07 0:08
23.46	7/9/07 0:09
23.46	7/9/07 0:10
23.46	7/9/07 0:11
23.46	7/9/07 0:12
23.66	7/9/07 0:13
23.56	7/9/07 0:14

20.33	7/7/07 20:53
20.23	7/7/07 20:54
20.33	7/7/07 20:55
20.53	7/7/07 20:56
20.33	7/7/07 20:57
20.33	7/7/07 20:58
20.53	7/7/07 20:59
20.33	7/7/07 21:00
20.43	7/7/07 21:01
20.23	7/7/07 21:02
20.33	7/7/07 21:03
20.33	7/7/07 21:04
20.33	7/7/07 21:05
20.43	7/7/07 21:06
20.43	7/7/07 21:07
20.63	7/7/07 21:08
20.33	7/7/07 21:09
20.43	7/7/07 21:10

μ	σ
20.37	0.08553719

20.53	7/8/07 5:43
20.53	7/8/07 5:44
20.53	7/8/07 5:45
20.63	7/8/07 5:46
20.72	7/8/07 5:47
20.63	7/8/07 5:48
20.63	7/8/07 5:49
20.63	7/8/07 5:50
20.53	7/8/07 5:51
20.63	7/8/07 5:52
20.63	7/8/07 5:53
20.53	7/8/07 5:54
20.33	7/8/07 5:55
20.63	7/8/07 5:56
20.63	7/8/07 5:57
20.53	7/8/07 5:58
20.53	7/8/07 5:59
20.53	7/8/07 6:00
20.53	7/8/07 6:01
20.43	7/8/07 6:02
20.53	7/8/07 6:03
20.63	7/8/07 6:04
20.53	7/8/07 6:05
20.43	7/8/07 6:06
20.53	7/8/07 6:07
20.63	7/8/07 6:08
20.63	7/8/07 6:09
20.53	7/8/07 6:10
20.53	7/8/07 6:11
20.63	7/8/07 6:12
20.43	7/8/07 6:13
20.43	7/8/07 6:14
20.43	7/8/07 6:15
20.53	7/8/07 6:16
20.43	7/8/07 6:17
20.43	7/8/07 6:18
20.43	7/8/07 6:19

22.48	7/8/07 16:33
22.78	7/8/07 16:34
22.78	7/8/07 16:35
22.58	7/8/07 16:36
22.68	7/8/07 16:37
22.68	7/8/07 16:38
22.58	7/8/07 16:39
22.68	7/8/07 16:40
22.58	7/8/07 16:41
22.78	7/8/07 16:42
22.68	7/8/07 16:43
22.58	7/8/07 16:44
22.68	7/8/07 16:45
22.58	7/8/07 16:46
22.58	7/8/07 16:47
22.38	7/8/07 16:48
22.68	7/8/07 16:49
22.58	7/8/07 16:50
22.68	7/8/07 16:51
22.48	7/8/07 16:52
22.58	7/8/07 16:53
22.58	7/8/07 16:54
22.58	7/8/07 16:55
22.68	7/8/07 16:56
22.58	7/8/07 16:57
22.58	7/8/07 16:58
22.68	7/8/07 16:59
22.58	7/8/07 17:00
22.68	7/8/07 17:01
22.58	7/8/07 17:02
22.68	7/8/07 17:03
22.68	7/8/07 17:04
22.58	7/8/07 17:05
22.68	7/8/07 17:06
22.48	7/8/07 17:07
22.68	7/8/07 17:08
22.58	7/8/07 17:09

23.56	7/9/07 0:15
23.56	7/9/07 0:16
23.56	7/9/07 0:17
23.56	7/9/07 0:18
23.56	7/9/07 0:19
23.56	7/9/07 0:20
23.66	7/9/07 0:21
23.56	7/9/07 0:22
23.56	7/9/07 0:23
23.46	7/9/07 0:24
23.66	7/9/07 0:25
23.56	7/9/07 0:26
23.56	7/9/07 0:27
23.56	7/9/07 0:28
23.56	7/9/07 0:29
23.66	7/9/07 0:30
23.46	7/9/07 0:31
23.56	7/9/07 0:32
23.75	7/9/07 0:33
23.56	7/9/07 0:34
23.66	7/9/07 0:35
23.56	7/9/07 0:36
23.66	7/9/07 0:37
23.46	7/9/07 0:38
23.66	7/9/07 0:39
23.56	7/9/07 0:40
23.66	7/9/07 0:41
23.56	7/9/07 0:42
23.66	7/9/07 0:43
23.46	7/9/07 0:44
23.75	7/9/07 0:45
23.46	7/9/07 0:46
23.75	7/9/07 0:47
23.66	7/9/07 0:48
23.66	7/9/07 0:49
23.75	7/9/07 0:50
23.66	7/9/07 0:51

20.33	7/8/07 6:20	22.68	7/8/07 17:10	23.66	7/9/07 0:52
20.53	7/8/07 6:21	22.48	7/8/07 17:11	23.56	7/9/07 0:53
20.53	7/8/07 6:22	22.58	7/8/07 17:12	23.66	7/9/07 0:54
20.63	7/8/07 6:23	22.58	7/8/07 17:13	23.66	7/9/07 0:55
20.63	7/8/07 6:24	22.68	7/8/07 17:14	23.56	7/9/07 0:56
20.63	7/8/07 6:25	22.68	7/8/07 17:15	23.66	7/9/07 0:57
20.53	7/8/07 6:26	22.68	7/8/07 17:16	23.56	7/9/07 0:58
20.53	7/8/07 6:27	22.68	7/8/07 17:17	23.56	7/9/07 0:59
20.63	7/8/07 6:28	22.58	7/8/07 17:18	23.56	7/9/07 1:00
20.53	7/8/07 6:29	22.58	7/8/07 17:19	23.66	7/9/07 1:01
20.63	7/8/07 6:30	22.78	7/8/07 17:20	23.66	7/9/07 1:02
20.53	7/8/07 6:31	22.68	7/8/07 17:21	23.66	7/9/07 1:03
20.63	7/8/07 6:32	22.68	7/8/07 17:22	23.66	7/9/07 1:04
20.53	7/8/07 6:33	22.78	7/8/07 17:23	23.66	7/9/07 1:05
20.43	7/8/07 6:34	22.68	7/8/07 17:24	23.66	7/9/07 1:06
20.53	7/8/07 6:35	22.68	7/8/07 17:25	23.56	7/9/07 1:07
20.43	7/8/07 6:36	22.68	7/8/07 17:26	23.66	7/9/07 1:08
20.43	7/8/07 6:37	22.58	7/8/07 17:27	23.66	7/9/07 1:09
20.63	7/8/07 6:38	22.58	7/8/07 17:28	23.56	7/9/07 1:10
20.53	7/8/07 6:39	22.58	7/8/07 17:29	23.66	7/9/07 1:11
20.53	7/8/07 6:40	22.58	7/8/07 17:30	23.66	7/9/07 1:12
20.53	7/8/07 6:41	22.58	7/8/07 17:31	23.75	7/9/07 1:13
20.53	7/8/07 6:42	22.68	7/8/07 17:32	23.56	7/9/07 1:14
20.43	7/8/07 6:43	22.58	7/8/07 17:33	23.66	7/9/07 1:15
20.53	7/8/07 6:44	22.48	7/8/07 17:34	23.56	7/9/07 1:16
20.53	7/8/07 6:45	22.58	7/8/07 17:35	23.66	7/9/07 1:17
20.53	7/8/07 6:46	22.68	7/8/07 17:36	23.75	7/9/07 1:18
20.43	7/8/07 6:47	22.68	7/8/07 17:37	23.56	7/9/07 1:19
20.53	7/8/07 6:48	22.58	7/8/07 17:38	23.56	7/9/07 1:20
20.53	7/8/07 6:49	22.68	7/8/07 17:39	23.75	7/9/07 1:21
20.53	7/8/07 6:50	22.68	7/8/07 17:40	23.66	7/9/07 1:22
20.63	7/8/07 6:51	22.58	7/8/07 17:41	23.75	7/9/07 1:23
20.63	7/8/07 6:52	22.68	7/8/07 17:42	23.66	7/9/07 1:24
20.53	7/8/07 6:53	22.68	7/8/07 17:43	23.75	7/9/07 1:25
20.43	7/8/07 6:54	22.78	7/8/07 17:44	23.75	7/9/07 1:26
20.63	7/8/07 6:55	22.58	7/8/07 17:45	23.56	7/9/07 1:27
20.53	7/8/07 6:56	22.58	7/8/07 17:46	23.66	7/9/07 1:28

20.43	7/8/07 6:57
20.63	7/8/07 6:58
20.53	7/8/07 6:59
20.63	7/8/07 7:00
20.53	7/8/07 7:01
20.53	7/8/07 7:02
20.63	7/8/07 7:03
20.53	7/8/07 7:04
20.43	7/8/07 7:05
20.43	7/8/07 7:06
20.63	7/8/07 7:07
20.53	7/8/07 7:08
20.43	7/8/07 7:09
20.33	7/8/07 7:10
20.43	7/8/07 7:11
20.43	7/8/07 7:12
20.63	7/8/07 7:13
20.53	7/8/07 7:14
20.53	7/8/07 7:15
20.72	7/8/07 7:16
20.53	7/8/07 7:17

μ	σ
20.54	0.08999084
	0.04499542

22.58	7/8/07 17:47
22.68	7/8/07 17:48
22.68	7/8/07 17:49
22.58	7/8/07 17:50
22.58	7/8/07 17:51
22.68	7/8/07 17:52
22.38	7/8/07 17:53
22.58	7/8/07 17:54
22.58	7/8/07 17:55
22.68	7/8/07 17:56
22.68	7/8/07 17:57
22.78	7/8/07 17:58

μ	σ
22.63	0.07787048
	0.03893524

23.75	7/9/07 1:29
23.66	7/9/07 1:30
23.66	7/9/07 1:31
23.75	7/9/07 1:32
23.56	7/9/07 1:33
23.66	7/9/07 1:34
23.75	7/9/07 1:35
23.75	7/9/07 1:36
23.75	7/9/07 1:37
23.66	7/9/07 1:38
23.75	7/9/07 1:39
23.66	7/9/07 1:40
23.85	7/9/07 1:41
23.75	7/9/07 1:42
23.66	7/9/07 1:43
23.75	7/9/07 1:44
23.75	7/9/07 1:45
23.85	7/9/07 1:46
23.66	7/9/07 1:47
23.66	7/9/07 1:48
23.66	7/9/07 1:49

μ	σ
23.59	0.10024814
	0.05012407

Figure A.0.4 shows the mean and standard deviation of all data points recorded for each angle at the NW orientation.

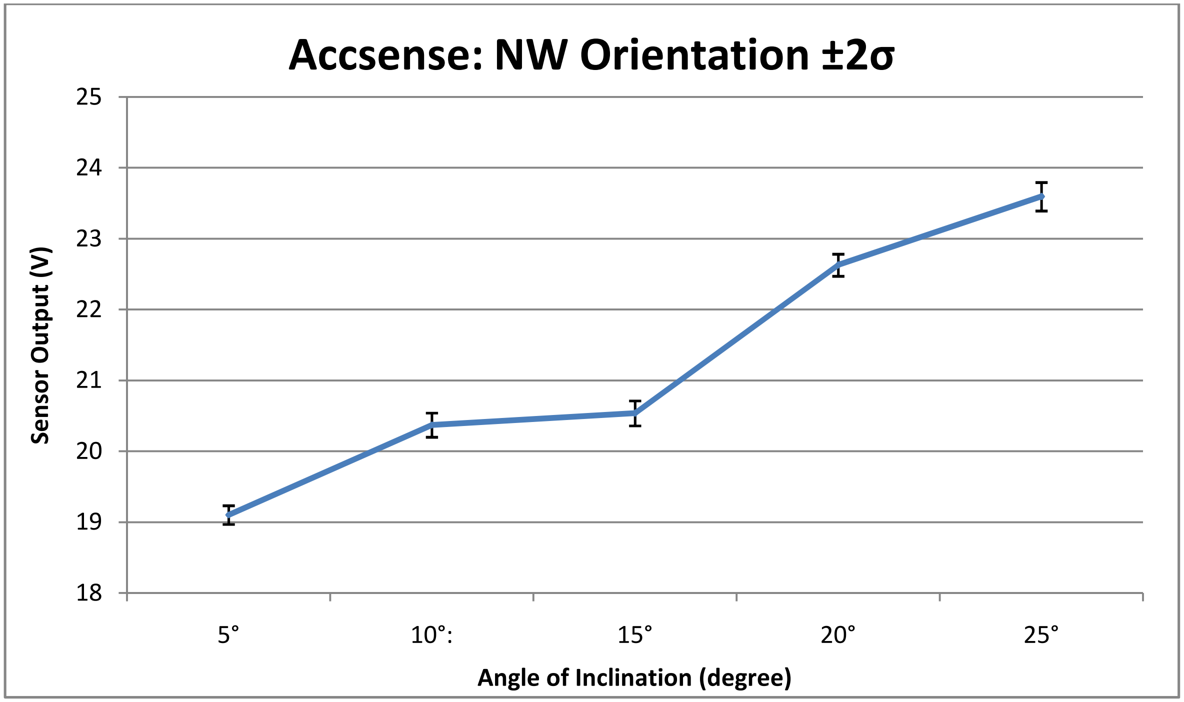

Figure A.0.4: NW Mean with ±2 standard deviation error bars

The following table shows the results of the frequency test of the X-axis on the MEMSIC MXR6999M accelerometer.

Table A.5: MEMSIC Frequency test, X-axis

1	10	50	100	500	1000	5000	10000
1.358	1.36	1.353	1.355	1.358	1.358	1.358	1.365
1.35	1.35	1.35	1.365	1.363	1.355	1.36	1.353
1.355	1.363	1.358	1.35	1.368	1.35	1.355	1.36
1.358	1.355	1.36	1.365	1.365	1.365	1.353	1.358
1.36	1.353	1.368	1.363	1.358	1.36	1.36	1.355
1.365	1.35	1.35	1.36	1.358	1.358	1.365	1.368
1.358	1.355	1.365	1.358	1.355	1.363	1.363	1.36
1.363	1.355	1.363	1.365	1.363	1.358	1.355	1.355
1.37	1.37	1.355	1.358	1.365	1.37	1.365	1.363
1.36	1.365	1.365	1.355	1.368	1.363	1.355	1.358
1.363	1.365	1.355	1.365	1.358	1.363	1.36	1.358
1.365	1.365	1.368	1.355	1.363	1.368	1.358	1.363
1.365	1.358	1.35	1.358	1.355	1.358	1.358	1.355
1.37	1.358	1.36	1.36	1.353	1.363	1.355	1.355
1.36	1.363	1.363	1.358	1.358	1.365	1.353	1.358
1.36	1.36	1.353	1.36	1.365	1.363	1.355	1.353
1.363	1.365	1.365	1.363	1.363	1.37	1.365	1.37
1.353	1.363	1.355	1.355	1.363	1.355	1.353	1.355
1.37	1.353	1.363	1.363	1.358	1.36	1.353	1.36
1.363	1.37	1.36	1.363	1.363	1.358	1.363	1.363
1.365	1.373	1.355	1.363	1.35	1.358	1.365	1.355
1.355	1.358	1.36	1.36	1.355	1.365	1.35	1.355
1.355	1.363	1.368	1.365	1.363	1.353	1.355	1.363
1.36	1.37	1.353	1.358	1.358	1.358	1.363	1.36
1.355	1.353	1.363	1.36	1.36	1.358	1.355	1.355
1.363	1.358	1.358	1.355	1.358	1.355	1.348	1.365
1.37	1.36	1.363	1.36	1.35	1.365	1.355	1.353
1.37	1.358	1.363	1.35	1.358	1.358	1.363	1.358
1.353	1.37	1.365	1.368	1.365	1.36	1.355	1.358
1.35	1.353	1.355	1.358	1.363	1.365	1.358	1.35
1.37	1.37	1.358	1.363	1.358	1.355	1.358	1.365
1.368	1.355	1.363	1.353	1.363	1.358	1.355	1.358
1.363	1.36	1.368	1.358	1.358	1.36	1.35	1.36
1.36	1.363	1.368	1.355	1.363	1.353	1.358	1.36
1.37	1.355	1.353	1.37	1.368	1.368	1.358	1.358
1.37	1.368	1.355	1.36	1.36	1.355	1.355	1.355
1.35	1.358	1.36	1.353	1.355	1.363	1.348	1.368
1.363	1.353	1.353	1.36	1.353	1.363	1.355	1.363
1.36	1.36	1.353	1.365	1.358	1.355	1.358	1.368
1.355	1.365	1.368	1.35	1.365	1.368	1.355	1.365
1.363	1.353	1.358	1.36	1.363	1.353	1.35	1.35
1.365	1.358	1.355	1.36	1.365	1.363	1.363	1.358
1.365	1.358	1.355	1.355	1.355	1.36	1.363	1.358
1.363	1.363	1.355	1.35	1.35	1.355	1.353	1.353
1.363	1.365	1.358	1.358	1.355	1.365	1.353	1.365
1.358	1.373	1.353	1.363	1.358	1.35	1.363	1.358
1.363	1.363	1.373	1.35	1.365	1.355	1.358	1.363
1.373	1.358	1.363	1.368	1.36	1.358	1.35	1.365

	1.365	1.368	1.358	1.363	1.355	1.35	1.355	1.358
	1.365	1.358	1.358	1.363	1.35	1.36	1.363	1.355
	1.365	1.353	1.365	1.363	1.358	1.355	1.355	1.365
	1.363	1.368	1.37	1.358	1.355	1.358	1.358	1.363
	1.35	1.363	1.36	1.353	1.363	1.365	1.355	1.358
	1.365	1.353	1.35	1.358	1.368	1.36	1.36	1.368
	1.36	1.363	1.358	1.365	1.36	1.355	1.358	1.353
	1.365	1.36	1.35	1.36	1.355	1.358	1.358	1.358
	1.36	1.368	1.358	1.355	1.36	1.353	1.363	1.363
	1.363	1.37	1.35	1.355	1.365	1.363	1.355	1.353
	1.355	1.353	1.358	1.358	1.368	1.355	1.35	1.363
	1.363	1.353	1.365	1.355	1.363	1.355	1.355	1.358
	1.355	1.36	1.355	1.36	1.353	1.358	1.36	1.36
	1.363	1.355	1.363	1.365	1.363	1.35	1.355	1.36
	1.358	1.363	1.365	1.358	1.355	1.365	1.348	1.358
	1.36	1.368	1.36	1.355	1.363	1.358	1.365	1.36
	1.37	1.36	1.358	1.36	1.358	1.353	1.365	1.365
	1.358	1.358	1.363	1.355	1.358	1.355	1.353	1.353
	1.363	1.36	1.355	1.365	1.36	1.355	1.355	1.36
	1.368	1.35	1.365	1.358	1.355	1.36	1.363	1.368
	1.358	1.355	1.358	1.365	1.353	1.36	1.355	1.363
	1.365	1.353	1.358	1.35	1.363	1.355	1.353	1.36
	1.363	1.373	1.355	1.36	1.363	1.36	1.355	1.37
	1.358	1.353	1.358	1.365	1.37	1.358	1.355	1.355
	1.353	1.353	1.35	1.363	1.37	1.353	1.355	1.36
	1.358	1.37	1.365	1.358	1.36	1.363	1.358	1.358
	1.365	1.355	1.373	1.358	1.368	1.35	1.358	1.355
	1.365	1.363	1.368	1.353	1.363	1.358	1.358	1.365
	1.358	1.365	1.37	1.363	1.363	1.358	1.353	1.363
	1.368	1.363	1.37	1.355	1.363	1.348	1.358	1.358
	1.355	1.368	1.36	1.363	1.358	1.36	1.358	1.368
	1.37	1.355	1.353	1.365	1.358	1.358	1.36	1.353
	1.363	1.358	1.358	1.36	1.353	1.36	1.358	1.358
	1.355	1.368	1.358	1.358	1.35	1.365	1.355	1.365
	1.355	1.368	1.36	1.36	1.363	1.355	1.358	1.36
	1.36	1.358	1.365	1.365	1.36	1.358	1.355	1.358
	1.37	1.358	1.368	1.36	1.365	1.36	1.363	1.368
	1.376	1.355	1.365	1.37	1.36	1.35	1.368	1.353
	1.363	1.36	1.355	1.355	1.358	1.363	1.363	1.363
	1.36	1.353	1.37	1.358	1.358	1.358	1.355	1.355
	1.355	1.363	1.36	1.365	1.353	1.355	1.36	1.355
	1.37	1.358	1.358	1.35	1.358	1.365	1.37	1.363
	1.36	1.363	1.363	1.365	1.36	1.358	1.363	1.36
	1.365	1.365	1.355	1.358	1.365	1.355	1.355	1.358
	1.365	1.363	1.363	1.355	1.36	1.365	1.365	1.365
	1.355	1.365	1.373	1.36	1.355	1.35	1.368	1.363
	1.365	1.36	1.37	1.365	1.353	1.363	1.355	1.36
	1.355	1.358	1.363	1.355	1.358	1.355	1.36	1.368
	1.358	1.355	1.36	1.365	1.365	1.36	1.365	1.353
	1.36	1.36	1.368	1.363	1.363	1.363	1.363	1.36
	1.37	1.358	1.355	1.35	1.355	1.353	1.355	1.358
	1.365	1.365	1.363	1.363	1.36	1.355	1.368	1.355
Mean:	1.36182	1.36051	1.36023	1.35942	1.35981	1.35863	1.35779	1.35972

Std. Dev:	0.00562	0.00587	0.00596	0.00484	0.00483	0.00489	0.00485	0.00478

The following table shows the results of the frequency test of the Y-axis on the MEMSIC MXR6999M accelerometer.

Table A.6: MEMSIC Frequency test, Y-axis

1	10	50	100	500	1000	5000	10000
1.358	1.345	1.355	1.358	1.35	1.358	1.358	1.353
1.355	1.345	1.358	1.358	1.353	1.355	1.355	1.355
1.35	1.36	1.348	1.36	1.355	1.353	1.353	1.35
1.355	1.355	1.345	1.355	1.355	1.355	1.355	1.358
1.355	1.355	1.345	1.345	1.363	1.35	1.35	1.355
1.353	1.35	1.358	1.35	1.355	1.355	1.355	1.35
1.355	1.353	1.355	1.355	1.355	1.345	1.345	1.353
1.355	1.358	1.358	1.355	1.35	1.345	1.345	1.358
1.358	1.358	1.363	1.345	1.353	1.342	1.342	1.342
1.358	1.363	1.348	1.358	1.342	1.35	1.35	1.342
1.353	1.353	1.355	1.36	1.348	1.35	1.35	1.358
1.35	1.35	1.345	1.355	1.35	1.35	1.35	1.355
1.355	1.355	1.345	1.355	1.355	1.355	1.355	1.345
1.355	1.355	1.355	1.353	1.358	1.353	1.353	1.35
1.348	1.35	1.363	1.355	1.36	1.358	1.358	1.353
1.358	1.35	1.355	1.353	1.355	1.358	1.358	1.345
1.365	1.35	1.35	1.35	1.353	1.36	1.36	1.353
1.355	1.35	1.348	1.35	1.35	1.353	1.353	1.355
1.363	1.355	1.353	1.36	1.345	1.353	1.353	1.345
1.358	1.358	1.353	1.355	1.35	1.353	1.353	1.345
1.355	1.35	1.36	1.348	1.35	1.348	1.348	1.358
1.353	1.355	1.35	1.35	1.358	1.348	1.348	1.35
1.35	1.355	1.348	1.36	1.355	1.353	1.353	1.353
1.355	1.363	1.353	1.358	1.358	1.355	1.355	1.35
1.363	1.35	1.35	1.345	1.36	1.358	1.358	1.353
1.355	1.355	1.355	1.35	1.355	1.36	1.36	1.345
1.363	1.353	1.345	1.355	1.355	1.36	1.36	1.358
1.363	1.348	1.348	1.355	1.353	1.355	1.355	1.355
1.355	1.363	1.355	1.355	1.35	1.355	1.355	1.345
1.363	1.355	1.35	1.353	1.348	1.35	1.35	1.353
1.36	1.355	1.345	1.348	1.36	1.348	1.348	1.355
1.355	1.363	1.355	1.363	1.353	1.345	1.345	1.35
1.358	1.355	1.345	1.365	1.358	1.355	1.355	1.35
1.355	1.348	1.35	1.355	1.358	1.353	1.353	1.35
1.355	1.355	1.358	1.358	1.35	1.35	1.35	1.353
1.355	1.345	1.363	1.36	1.355	1.358	1.358	1.345
1.363	1.35	1.355	1.355	1.348	1.355	1.355	1.35
1.35	1.345	1.36	1.36	1.355	1.358	1.358	1.355
1.35	1.358	1.355	1.353	1.36	1.35	1.35	1.345
1.348	1.355	1.358	1.358	1.365	1.35	1.35	1.35
1.355	1.35	1.355	1.363	1.36	1.355	1.355	1.355

1.358	1.345	1.353	1.363	1.355	1.345	1.345	1.348
1.353	1.353	1.35	1.353	1.355	1.35	1.35	1.35
1.365	1.358	1.35	1.355	1.348	1.35	1.35	1.355
1.355	1.345	1.363	1.348	1.348	1.353	1.353	1.355
1.353	1.358	1.35	1.345	1.348	1.355	1.355	1.345
1.353	1.345	1.345	1.353	1.355	1.353	1.353	1.355
1.358	1.35	1.35	1.358	1.355	1.355	1.355	1.355
1.355	1.358	1.353	1.355	1.358	1.363	1.363	1.345
1.355	1.348	1.353	1.353	1.35	1.363	1.363	1.348
1.365	1.353	1.348	1.353	1.358	1.363	1.363	1.355
1.355	1.36	1.355	1.355	1.355	1.355	1.355	1.348
1.363	1.358	1.348	1.353	1.35	1.358	1.358	1.353
1.348	1.363	1.353	1.355	1.348	1.355	1.355	1.355
1.365	1.35	1.353	1.355	1.345	1.353	1.353	1.345
1.363	1.353	1.353	1.353	1.342	1.353	1.353	1.342
1.363	1.355	1.36	1.35	1.353	1.348	1.348	1.355
1.355	1.355	1.355	1.355	1.353	1.35	1.35	1.35
1.355	1.355	1.348	1.348	1.355	1.348	1.348	1.35
1.358	1.355	1.355	1.353	1.355	1.35	1.35	1.345
1.355	1.363	1.355	1.355	1.353	1.35	1.35	1.35
1.363	1.353	1.355	1.348	1.353	1.355	1.355	1.348
1.358	1.355	1.355	1.345	1.35	1.355	1.355	1.353
1.365	1.363	1.355	1.358	1.348	1.36	1.36	1.355
1.358	1.363	1.35	1.342	1.353	1.358	1.358	1.345
1.348	1.358	1.358	1.358	1.36	1.35	1.35	1.34
1.353	1.345	1.355	1.35	1.358	1.353	1.353	1.355
1.363	1.36	1.355	1.353	1.353	1.345	1.345	1.35
1.348	1.345	1.348	1.348	1.35	1.342	1.342	1.342
1.348	1.345	1.358	1.348	1.353	1.345	1.345	1.348
1.35	1.353	1.355	1.355	1.35	1.345	1.345	1.353
1.348	1.355	1.345	1.355	1.345	1.342	1.342	1.345
1.355	1.355	1.348	1.345	1.358	1.353	1.353	1.35
1.345	1.353	1.35	1.348	1.35	1.353	1.353	1.355
1.348	1.355	1.355	1.353	1.358	1.353	1.353	1.345
1.348	1.355	1.345	1.36	1.355	1.35	1.35	1.345
1.358	1.353	1.353	1.353	1.35	1.353	1.353	1.355
1.363	1.348	1.353	1.358	1.348	1.353	1.353	1.348
1.368	1.35	1.35	1.348	1.353	1.358	1.358	1.35
1.358	1.353	1.35	1.353	1.355	1.355	1.355	1.35
1.345	1.353	1.353	1.36	1.355	1.36	1.36	1.35
1.358	1.358	1.35	1.35	1.355	1.355	1.355	1.342
1.358	1.36	1.348	1.348	1.342	1.353	1.353	1.35
1.355	1.358	1.353	1.36	1.345	1.355	1.355	1.355
1.355	1.355	1.348	1.358	1.35	1.358	1.358	1.342
1.363	1.36	1.358	1.36	1.35	1.358	1.358	1.348
1.355	1.345	1.355	1.355	1.35	1.355	1.355	1.355
1.353	1.355	1.35	1.363	1.355	1.35	1.35	1.353
1.363	1.355	1.35	1.355	1.353	1.355	1.355	1.35
1.36	1.353	1.355	1.355	1.342	1.353	1.353	1.36
1.355	1.35	1.348	1.353	1.35	1.358	1.358	1.35
1.355	1.355	1.363	1.358	1.355	1.355	1.355	1.345
1.358	1.353	1.36	1.355	1.358	1.365	1.365	1.358
1.363	1.355	1.355	1.353	1.35	1.363	1.363	1.358
1.35	1.355	1.355	1.355	1.345	1.363	1.363	1.345

	1.36	1.355	1.353	1.355	1.345	1.355	1.355	1.353
	1.36	1.363	1.353	1.355	1.353	1.355	1.355	1.358
	1.35	1.358	1.353	1.355	1.35	1.355	1.355	1.353
	1.35	1.35	1.345	1.353	1.36	1.355	1.355	1.348
	1.368	1.355	1.353	1.345	1.355	1.353	1.353	1.358
Mean	1.3562	1.35392	1.35269	1.35399	1.35276	1.35347	1.35347	1.35065
Std. Dev.	0.005314	0.004943	0.004675	0.00476	0.004755	0.004873	0.004873	0.004768

The following table shows the X-axis angle readings from the MEMSIC MXR6999M accelerometer.

Table A.7: MEMSIC accelerometer X-axis change in degrees using sample rate of 100 Hz

0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	9.0	10.0	15.0	20.0
1.36	1.36	1.363	1.381	1.391	1.393	1.404	1.416	1.429	1.424	1.432	1.46	1.467	1.49	1.495	1.521	1.608	1.669
1.363	1.368	1.363	1.376	1.393	1.401	1.406	1.411	1.419	1.416	1.432	1.444	1.478	1.493	1.501	1.521	1.59	1.669
1.365	1.358	1.373	1.391	1.393	1.388	1.396	1.411	1.424	1.434	1.439	1.444	1.472	1.48	1.503	1.516	1.59	1.682
1.358	1.36	1.365	1.37	1.386	1.393	1.401	1.421	1.411	1.427	1.434	1.462	1.472	1.49	1.495	1.518	1.61	1.679
1.353	1.36	1.376	1.378	1.391	1.391	1.404	1.411	1.416	1.427	1.444	1.457	1.467	1.478	1.503	1.521	1.597	1.679
1.355	1.363	1.376	1.383	1.386	1.393	1.411	1.404	1.424	1.427	1.437	1.455	1.47	1.485	1.503	1.516	1.592	1.679
1.365	1.37	1.381	1.383	1.381	1.388	1.401	1.414	1.419	1.424	1.437	1.452	1.472	1.498	1.508	1.526	1.592	1.682
1.355	1.365	1.376	1.373	1.386	1.396	1.409	1.414	1.424	1.429	1.437	1.455	1.47	1.495	1.508	1.523	1.597	1.684
1.353	1.365	1.376	1.386	1.396	1.396	1.411	1.409	1.424	1.419	1.437	1.457	1.475	1.485	1.511	1.511	1.592	1.676
1.363	1.365	1.368	1.388	1.396	1.401	1.396	1.419	1.414	1.421	1.442	1.447	1.475	1.488	1.506	1.521	1.595	1.674
1.36	1.363	1.378	1.376	1.393	1.396	1.404	1.411	1.424	1.427	1.434	1.455	1.478	1.488	1.495	1.513	1.605	1.671
1.355	1.363	1.376	1.383	1.391	1.393	1.396	1.411	1.416	1.429	1.432	1.457	1.46	1.493	1.493	1.518	1.597	1.669
1.363	1.358	1.373	1.376	1.399	1.404	1.396	1.406	1.414	1.427	1.442	1.455	1.472	1.493	1.495	1.516	1.592	1.671
1.355	1.365	1.376	1.391	1.393	1.388	1.406	1.406	1.427	1.429	1.437	1.452	1.472	1.49	1.501	1.516	1.597	1.671
1.353	1.365	1.381	1.37	1.393	1.393	1.406	1.414	1.419	1.421	1.434	1.455	1.475	1.478	1.498	1.513	1.6	1.669
1.35	1.36	1.378	1.383	1.396	1.393	1.396	1.414	1.424	1.419	1.437	1.452	1.472	1.48	1.506	1.508	1.597	1.676
1.35	1.355	1.381	1.383	1.376	1.396	1.396	1.406	1.414	1.416	1.437	1.457	1.472	1.488	1.495	1.529	1.6	1.682
1.36	1.368	1.378	1.378	1.391	1.404	1.414	1.414	1.419	1.416	1.437	1.452	1.478	1.493	1.506	1.513	1.595	1.679
1.363	1.363	1.376	1.376	1.386	1.393	1.396	1.411	1.424	1.421	1.434	1.447	1.472	1.478	1.508	1.516	1.597	1.679
1.353	1.363	1.37	1.373	1.388	1.401	1.393	1.411	1.414	1.424	1.429	1.452	1.47	1.488	1.506	1.513	1.595	1.666
1.368	1.365	1.376	1.381	1.388	1.393	1.396	1.419	1.419	1.437	1.437	1.465	1.46	1.483	1.511	1.526	1.61	1.669
1.355	1.365	1.365	1.378	1.391	1.404	1.411	1.414	1.419	1.434	1.427	1.457	1.467	1.485	1.503	1.526	1.592	1.679
1.363	1.37	1.365	1.386	1.383	1.399	1.406	1.411	1.424	1.432	1.437	1.457	1.462	1.485	1.495	1.521	1.6	1.679
1.35	1.37	1.365	1.381	1.393	1.404	1.399	1.411	1.424	1.419	1.439	1.457	1.475	1.485	1.506	1.526	1.602	1.676
1.355	1.363	1.373	1.378	1.386	1.391	1.409	1.414	1.414	1.434	1.437	1.462	1.467	1.488	1.503	1.508	1.6	1.674
1.358	1.36	1.373	1.37	1.388	1.401	1.399	1.411	1.427	1.424	1.442	1.457	1.475	1.488	1.501	1.516	1.597	1.671
1.353	1.36	1.378	1.378	1.388	1.396	1.406	1.416	1.421	1.419	1.437	1.455	1.467	1.485	1.498	1.506	1.592	1.669
1.36	1.36	1.378	1.381	1.386	1.393	1.404	1.424	1.421	1.427	1.432	1.457	1.467	1.495	1.501	1.518	1.595	1.674
1.355	1.363	1.376	1.376	1.388	1.396	1.404	1.411	1.432	1.429	1.437	1.455	1.47	1.49	1.508	1.516	1.6	1.674
1.36	1.365	1.373	1.383	1.388	1.396	1.396	1.411	1.419	1.427	1.439	1.46	1.475	1.501	1.493	1.526	1.597	1.664
1.358	1.365	1.37	1.386	1.383	1.386	1.399	1.406	1.419	1.432	1.432	1.46	1.465	1.488	1.498	1.511	1.595	1.671
1.365	1.365	1.376	1.388	1.378	1.396	1.411	1.416	1.427	1.419	1.437	1.457	1.465	1.478	1.498	1.511	1.6	1.679
1.355	1.373	1.381	1.376	1.391	1.391	1.396	1.416	1.432	1.429	1.434	1.452	1.472	1.488	1.495	1.523	1.602	1.684
1.353	1.376	1.376	1.381	1.383	1.393	1.406	1.416	1.421	1.429	1.432	1.444	1.47	1.498	1.508	1.521	1.597	1.671

1.355	1.358	1.378	1.378	1.391	1.406	1.406	1.414	1.416	1.432	1.439	1.457	1.472	1.49	1.503	1.521	1.597	1.676
1.355	1.363	1.383	1.378	1.381	1.399	1.406	1.414	1.424	1.429	1.432	1.455	1.47	1.488	1.506	1.521	1.59	1.676
1.35	1.355	1.383	1.383	1.396	1.399	1.411	1.406	1.411	1.419	1.434	1.447	1.467	1.493	1.503	1.513	1.597	1.674
1.355	1.373	1.378	1.373	1.391	1.404	1.393	1.424	1.414	1.429	1.437	1.452	1.472	1.485	1.49	1.526	1.602	1.676
1.355	1.358	1.376	1.381	1.388	1.399	1.401	1.404	1.429	1.427	1.447	1.457	1.472	1.488	1.513	1.518	1.595	1.679
1.355	1.37	1.363	1.373	1.381	1.404	1.404	1.414	1.419	1.429	1.437	1.444	1.462	1.488	1.493	1.518	1.61	1.671
1.36	1.363	1.378	1.381	1.386	1.396	1.406	1.416	1.409	1.421	1.427	1.447	1.467	1.485	1.503	1.518	1.592	1.679
1.358	1.365	1.383	1.386	1.386	1.396	1.396	1.416	1.427	1.427	1.439	1.46	1.467	1.483	1.495	1.516	1.602	1.684
1.358	1.368	1.378	1.388	1.391	1.391	1.396	1.421	1.416	1.424	1.437	1.455	1.46	1.478	1.506	1.518	1.592	1.682
1.345	1.358	1.376	1.381	1.381	1.399	1.404	1.416	1.414	1.427	1.437	1.455	1.472	1.485	1.503	1.526	1.595	1.676
1.353	1.365	1.37	1.376	1.383	1.393	1.404	1.406	1.419	1.432	1.439	1.457	1.472	1.485	1.508	1.513	1.592	1.666
1.363	1.36	1.376	1.383	1.381	1.393	1.406	1.419	1.427	1.419	1.432	1.465	1.467	1.493	1.508	1.521	1.6	1.666
1.35	1.37	1.378	1.393	1.386	1.396	1.404	1.416	1.411	1.434	1.432	1.46	1.475	1.488	1.506	1.516	1.597	1.669
1.365	1.365	1.378	1.381	1.388	1.393	1.401	1.404	1.427	1.427	1.434	1.455	1.465	1.488	1.508	1.511	1.597	1.674
1.353	1.365	1.37	1.381	1.393	1.401	1.401	1.406	1.424	1.432	1.437	1.457	1.467	1.488	1.503	1.529	1.6	1.676
1.368	1.36	1.378	1.376	1.378	1.393	1.401	1.416	1.421	1.421	1.437	1.452	1.467	1.478	1.495	1.516	1.592	1.674
1.348	1.36	1.368	1.378	1.388	1.399	1.411	1.419	1.414	1.427	1.437	1.46	1.465	1.48	1.508	1.516	1.59	1.671
1.355	1.355	1.376	1.386	1.393	1.404	1.396	1.406	1.429	1.416	1.447	1.452	1.475	1.488	1.506	1.513	1.592	1.684
1.35	1.365	1.388	1.383	1.388	1.401	1.409	1.414	1.414	1.429	1.437	1.444	1.462	1.493	1.506	1.529	1.597	1.679
1.35	1.365	1.376	1.376	1.393	1.391	1.401	1.411	1.432	1.424	1.442	1.455	1.475	1.49	1.498	1.518	1.595	1.682
1.365	1.363	1.368	1.386	1.388	1.386	1.401	1.404	1.427	1.427	1.444	1.447	1.467	1.478	1.513	1.518	1.6	1.679
1.36	1.365	1.376	1.381	1.388	1.383	1.393	1.421	1.424	1.416	1.429	1.462	1.465	1.485	1.511	1.516	1.602	1.676
1.36	1.365	1.383	1.386	1.396	1.399	1.396	1.416	1.416	1.432	1.437	1.457	1.478	1.483	1.503	1.521	1.602	1.666
1.355	1.358	1.373	1.376	1.386	1.409	1.404	1.409	1.432	1.429	1.439	1.452	1.465	1.478	1.495	1.516	1.6	1.676
1.365	1.378	1.378	1.378	1.391	1.399	1.404	1.419	1.416	1.421	1.437	1.462	1.47	1.478	1.506	1.526	1.61	1.676
1.36	1.365	1.376	1.376	1.391	1.406	1.411	1.411	1.424	1.424	1.429	1.452	1.467	1.498	1.503	1.523	1.597	1.671
1.36	1.365	1.386	1.386	1.391	1.396	1.396	1.416	1.419	1.434	1.434	1.455	1.47	1.495	1.503	1.526	1.597	1.676
1.358	1.37	1.37	1.381	1.399	1.391	1.411	1.416	1.416	1.414	1.437	1.447	1.472	1.483	1.495	1.529	1.59	1.671
1.35	1.363	1.37	1.381	1.391	1.393	1.401	1.424	1.416	1.432	1.442	1.457	1.465	1.49	1.516	1.526	1.59	1.671
1.358	1.36	1.37	1.383	1.383	1.401	1.409	1.411	1.416	1.421	1.439	1.455	1.465	1.488	1.511	1.518	1.597	1.674
1.363	1.358	1.376	1.381	1.386	1.406	1.404	1.416	1.427	1.437	1.442	1.452	1.467	1.485	1.501	1.526	1.602	1.671
1.37	1.365	1.378	1.383	1.386	1.404	1.409	1.416	1.416	1.416	1.434	1.447	1.462	1.485	1.501	1.521	1.595	1.669
1.36	1.363	1.37	1.373	1.396	1.396	1.399	1.409	1.416	1.419	1.439	1.444	1.48	1.478	1.511	1.523	1.597	1.676
1.348	1.368	1.368	1.376	1.391	1.399	1.404	1.406	1.414	1.419	1.434	1.457	1.47	1.488	1.506	1.513	1.592	1.666
1.355	1.363	1.37	1.378	1.383	1.391	1.401	1.414	1.421	1.432	1.447	1.457	1.472	1.49	1.501	1.521	1.597	1.676
1.353	1.365	1.37	1.378	1.386	1.396	1.409	1.419	1.419	1.432	1.432	1.457	1.465	1.478	1.506	1.521	1.597	1.671
1.355	1.355	1.376	1.393	1.386	1.393	1.406	1.416	1.421	1.434	1.439	1.46	1.472	1.488	1.506	1.518	1.597	1.669
1.355	1.368	1.381	1.388	1.391	1.404	1.401	1.414	1.414	1.432	1.447	1.457	1.467	1.493	1.501	1.518	1.605	1.682
1.355	1.37	1.378	1.381	1.383	1.391	1.411	1.416	1.419	1.429	1.427	1.455	1.475	1.485	1.495	1.521	1.592	1.684

	1.358	1.365	1.373	1.383	1.388	1.401	1.401	1.416	1.427	1.419	1.439	1.455	1.47	1.483	1.495	1.518	1.597	1.674
	1.365	1.365	1.376	1.376	1.383	1.399	1.409	1.416	1.427	1.419	1.437	1.452	1.475	1.483	1.511	1.516	1.602	1.679
	1.368	1.365	1.376	1.383	1.388	1.396	1.411	1.414	1.424	1.432	1.439	1.455	1.472	1.495	1.513	1.523	1.595	1.684
	1.355	1.368	1.378	1.378	1.393	1.396	1.393	1.411	1.419	1.437	1.434	1.447	1.48	1.485	1.501	1.518	1.595	1.669
	1.355	1.368	1.376	1.383	1.388	1.396	1.409	1.406	1.427	1.432	1.429	1.447	1.467	1.493	1.503	1.518	1.605	1.676
	1.363	1.358	1.373	1.381	1.383	1.391	1.406	1.421	1.419	1.424	1.442	1.465	1.472	1.495	1.506	1.521	1.59	1.671
	1.355	1.365	1.383	1.378	1.396	1.404	1.411	1.409	1.419	1.432	1.434	1.452	1.475	1.493	1.495	1.518	1.605	1.676
	1.36	1.368	1.373	1.391	1.388	1.391	1.396	1.421	1.419	1.427	1.439	1.452	1.47	1.483	1.501	1.518	1.59	1.684
	1.368	1.363	1.37	1.386	1.388	1.399	1.406	1.414	1.416	1.427	1.437	1.462	1.465	1.478	1.506	1.516	1.602	1.669
	1.373	1.365	1.376	1.386	1.383	1.393	1.396	1.419	1.411	1.432	1.434	1.462	1.467	1.488	1.511	1.511	1.595	1.676
	1.363	1.363	1.378	1.386	1.391	1.393	1.406	1.416	1.416	1.437	1.427	1.457	1.478	1.493	1.495	1.516	1.59	1.676
	1.358	1.363	1.378	1.386	1.396	1.396	1.396	1.406	1.424	1.432	1.437	1.455	1.465	1.483	1.498	1.518	1.592	1.674
	1.358	1.365	1.37	1.381	1.396	1.396	1.401	1.421	1.416	1.427	1.432	1.455	1.47	1.493	1.501	1.518	1.602	1.682
	1.373	1.363	1.376	1.381	1.391	1.404	1.399	1.414	1.419	1.427	1.439	1.455	1.475	1.48	1.498	1.516	1.602	1.669
	1.355	1.365	1.368	1.383	1.391	1.386	1.396	1.419	1.414	1.437	1.437	1.452	1.46	1.495	1.503	1.516	1.6	1.674
	1.353	1.373	1.368	1.381	1.393	1.396	1.406	1.416	1.427	1.419	1.432	1.455	1.472	1.488	1.503	1.516	1.608	1.682
	1.35	1.363	1.37	1.381	1.396	1.391	1.396	1.411	1.414	1.421	1.439	1.455	1.478	1.49	1.501	1.518	1.605	1.676
	1.36	1.373	1.378	1.381	1.383	1.399	1.404	1.404	1.419	1.429	1.434	1.452	1.478	1.495	1.506	1.513	1.595	1.676
	1.365	1.363	1.37	1.381	1.381	1.406	1.399	1.416	1.419	1.419	1.434	1.45	1.46	1.483	1.503	1.521	1.6	1.682
	1.365	1.368	1.365	1.373	1.393	1.401	1.396	1.419	1.419	1.437	1.437	1.46	1.472	1.493	1.501	1.518	1.605	1.674
	1.355	1.365	1.37	1.381	1.388	1.396	1.393	1.409	1.414	1.421	1.429	1.467	1.467	1.48	1.498	1.516	1.6	1.671
	1.368	1.37	1.378	1.383	1.396	1.399	1.406	1.416	1.419	1.434	1.437	1.457	1.478	1.493	1.508	1.516	1.597	1.679
	1.363	1.365	1.376	1.381	1.386	1.393	1.401	1.414	1.421	1.424	1.437	1.45	1.478	1.483	1.506	1.521	1.6	1.682
	1.358	1.363	1.37	1.383	1.386	1.404	1.396	1.404	1.414	1.429	1.432	1.447	1.467	1.49	1.495	1.516	1.597	1.666
	1.355	1.368	1.376	1.383	1.378	1.404	1.406	1.414	1.419	1.429	1.437	1.462	1.48	1.483	1.493	1.521	1.6	1.671
	1.353	1.365	1.381	1.383	1.381	1.401	1.401	1.416	1.424	1.429	1.439	1.447	1.472	1.485	1.498	1.521	1.608	1.676
	1.36	1.368	1.381	1.381	1.393	1.396	1.399	1.409	1.416	1.432	1.427	1.444	1.475	1.483	1.498	1.526	1.605	1.676
Mean:	1.358	1.364	1.375	1.381	1.389	1.397	1.403	1.413	1.420	1.427	1.436	1.454	1.470	1.487	1.502	1.519	1.598	1.675
Std. Dev:	.0058	.0044	.0052	.0049	.0051	.0053	.0055	.0050	.0054	.0060	.0044	.0053	.0050	.0056	.0057	.0049	.0052	.0051

The following table shows the Y-axis angle readings from the MEMSIC MXR6999M accelerometer.

Table A.8: MEMSIC accelerometer Y-axis change in degrees using sample rate of 100 Hz

-5.0	-4.0	-3.0	-2.0	-1.0	0.0	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	10.0	15.0	20.0
1.495	1.472	1.46	1.437	1.416	1.353	1.355	1.342	1.327	1.332	1.325	1.314	1.299	1.286	1.195	1.131	1.059
1.49	1.478	1.457	1.434	1.414	1.365	1.363	1.345	1.34	1.33	1.314	1.322	1.307	1.289	1.202	1.128	1.059
1.485	1.472	1.447	1.432	1.419	1.358	1.345	1.34	1.342	1.337	1.322	1.317	1.297	1.284	1.202	1.136	1.049
1.488	1.462	1.455	1.432	1.411	1.365	1.353	1.337	1.34	1.335	1.325	1.309	1.304	1.289	1.192	1.128	1.049
1.485	1.467	1.452	1.439	1.406	1.368	1.358	1.353	1.345	1.322	1.317	1.314	1.299	1.286	1.205	1.128	1.049
1.495	1.47	1.452	1.442	1.414	1.358	1.358	1.355	1.337	1.34	1.33	1.322	1.294	1.286	1.21	1.136	1.054
1.478	1.462	1.455	1.437	1.421	1.353	1.355	1.348	1.332	1.34	1.327	1.314	1.289	1.276	1.205	1.126	1.044
1.478	1.472	1.457	1.432	1.411	1.358	1.353	1.342	1.345	1.332	1.327	1.307	1.294	1.279	1.207	1.126	1.052
1.493	1.465	1.46	1.437	1.416	1.353	1.35	1.342	1.335	1.342	1.322	1.317	1.302	1.289	1.212	1.131	1.052
1.483	1.48	1.444	1.439	1.411	1.363	1.345	1.335	1.327	1.337	1.322	1.317	1.297	1.289	1.205	1.133	1.042
1.478	1.48	1.452	1.437	1.424	1.355	1.345	1.345	1.337	1.33	1.33	1.317	1.291	1.279	1.21	1.131	1.057
1.483	1.472	1.452	1.432	1.414	1.36	1.353	1.348	1.33	1.332	1.325	1.32	1.299	1.289	1.21	1.131	1.047
1.495	1.472	1.444	1.439	1.411	1.363	1.35	1.335	1.33	1.325	1.314	1.32	1.299	1.291	1.197	1.141	1.049
1.495	1.47	1.457	1.442	1.416	1.368	1.358	1.345	1.34	1.325	1.314	1.32	1.307	1.279	1.212	1.123	1.052
1.483	1.472	1.462	1.427	1.411	1.355	1.35	1.348	1.34	1.327	1.332	1.314	1.302	1.281	1.195	1.131	1.049
1.483	1.472	1.455	1.432	1.416	1.368	1.355	1.35	1.337	1.325	1.325	1.314	1.289	1.284	1.205	1.128	1.059
1.483	1.475	1.455	1.437	1.424	1.37	1.358	1.353	1.332	1.325	1.322	1.304	1.299	1.281	1.207	1.116	1.054
1.485	1.465	1.46	1.442	1.406	1.355	1.353	1.348	1.335	1.327	1.332	1.314	1.302	1.284	1.202	1.128	1.059
1.483	1.475	1.452	1.442	1.409	1.36	1.35	1.348	1.345	1.322	1.327	1.32	1.307	1.284	1.2	1.126	1.052
1.483	1.467	1.457	1.439	1.421	1.36	1.348	1.335	1.332	1.332	1.314	1.317	1.302	1.279	1.207	1.131	1.054
1.485	1.472	1.452	1.437	1.411	1.36	1.35	1.353	1.34	1.332	1.332	1.32	1.299	1.276	1.207	1.126	1.052
1.49	1.472	1.444	1.432	1.404	1.35	1.353	1.348	1.332	1.327	1.314	1.32	1.302	1.286	1.2	1.126	1.054
1.495	1.47	1.455	1.437	1.404	1.36	1.348	1.337	1.34	1.332	1.317	1.309	1.297	1.276	1.212	1.128	1.044
1.488	1.478	1.447	1.447	1.416	1.355	1.355	1.35	1.337	1.335	1.33	1.307	1.302	1.291	1.212	1.128	1.042
1.485	1.467	1.462	1.447	1.416	1.355	1.358	1.342	1.345	1.33	1.322	1.314	1.297	1.289	1.212	1.121	1.057
1.485	1.478	1.447	1.444	1.406	1.363	1.36	1.34	1.332	1.325	1.322	1.32	1.302	1.274	1.205	1.131	1.052
1.49	1.472	1.457	1.437	1.419	1.35	1.353	1.335	1.337	1.327	1.317	1.314	1.297	1.294	1.207	1.136	1.054
1.483	1.475	1.452	1.434	1.409	1.36	1.345	1.345	1.34	1.335	1.312	1.325	1.299	1.276	1.202	1.128	1.047
1.475	1.467	1.45	1.442	1.414	1.355	1.355	1.35	1.345	1.337	1.325	1.32	1.299	1.281	1.202	1.138	1.057
1.483	1.472	1.455	1.444	1.424	1.363	1.358	1.35	1.337	1.33	1.32	1.312	1.291	1.279	1.195	1.133	1.052
1.488	1.467	1.46	1.432	1.411	1.36	1.348	1.345	1.337	1.325	1.33	1.314	1.294	1.294	1.202	1.133	1.047
1.483	1.475	1.447	1.437	1.411	1.36	1.35	1.34	1.34	1.335	1.332	1.322	1.299	1.276	1.2	1.141	1.057
1.483	1.467	1.455	1.439	1.414	1.363	1.353	1.35	1.33	1.33	1.33	1.314	1.294	1.286	1.202	1.131	1.054
1.485	1.472	1.45	1.439	1.416	1.363	1.353	1.337	1.35	1.332	1.322	1.317	1.302	1.276	1.2	1.131	1.044

1.483	1.467	1.455	1.439	1.411	1.358	1.35	1.342	1.34	1.32	1.322	1.32	1.297	1.284	1.195	1.126	1.054
1.485	1.465	1.444	1.434	1.406	1.36	1.355	1.348	1.342	1.33	1.325	1.314	1.299	1.284	1.202	1.133	1.054
1.483	1.475	1.457	1.434	1.406	1.368	1.345	1.337	1.33	1.327	1.314	1.309	1.307	1.284	1.2	1.131	1.047
1.483	1.472	1.457	1.437	1.406	1.363	1.348	1.35	1.345	1.32	1.325	1.322	1.302	1.289	1.192	1.136	1.044
1.478	1.467	1.447	1.444	1.414	1.36	1.355	1.345	1.332	1.335	1.32	1.322	1.297	1.284	1.202	1.141	1.057
1.493	1.48	1.455	1.437	1.406	1.36	1.355	1.353	1.345	1.33	1.317	1.314	1.289	1.284	1.192	1.133	1.044
1.485	1.467	1.457	1.434	1.421	1.365	1.355	1.345	1.335	1.335	1.327	1.32	1.291	1.289	1.192	1.131	1.049
1.478	1.475	1.447	1.432	1.419	1.363	1.353	1.345	1.342	1.33	1.317	1.322	1.294	1.281	1.207	1.128	1.052
1.485	1.47	1.46	1.442	1.414	1.355	1.345	1.337	1.34	1.322	1.33	1.317	1.294	1.289	1.205	1.126	1.044
1.49	1.467	1.457	1.442	1.421	1.355	1.355	1.337	1.335	1.327	1.322	1.317	1.297	1.281	1.21	1.128	1.047
1.485	1.478	1.452	1.442	1.419	1.355	1.353	1.342	1.342	1.325	1.322	1.317	1.299	1.279	1.2	1.131	1.054
1.483	1.472	1.455	1.437	1.411	1.37	1.353	1.345	1.335	1.325	1.332	1.314	1.302	1.286	1.195	1.133	1.049
1.475	1.462	1.45	1.444	1.419	1.358	1.355	1.345	1.337	1.327	1.33	1.325	1.294	1.284	1.207	1.128	1.042
1.478	1.475	1.46	1.442	1.416	1.355	1.342	1.34	1.335	1.337	1.33	1.309	1.299	1.294	1.207	1.136	1.054
1.488	1.467	1.457	1.432	1.406	1.368	1.353	1.353	1.335	1.325	1.33	1.314	1.309	1.279	1.205	1.123	1.047
1.488	1.478	1.457	1.447	1.414	1.355	1.355	1.345	1.337	1.335	1.322	1.327	1.297	1.289	1.2	1.131	1.057
1.48	1.472	1.455	1.439	1.421	1.355	1.348	1.345	1.337	1.322	1.325	1.309	1.297	1.289	1.202	1.133	1.049
1.48	1.46	1.444	1.444	1.414	1.36	1.348	1.355	1.337	1.325	1.312	1.322	1.302	1.286	1.195	1.131	1.059
1.49	1.47	1.447	1.432	1.406	1.363	1.353	1.34	1.33	1.337	1.317	1.314	1.302	1.284	1.2	1.133	1.044
1.493	1.47	1.455	1.437	1.421	1.37	1.348	1.35	1.335	1.33	1.317	1.32	1.304	1.291	1.197	1.128	1.057
1.488	1.472	1.455	1.442	1.411	1.36	1.342	1.342	1.342	1.327	1.317	1.309	1.294	1.281	1.2	1.133	1.044
1.483	1.472	1.444	1.427	1.416	1.36	1.355	1.35	1.332	1.33	1.317	1.32	1.291	1.289	1.202	1.128	1.049
1.488	1.472	1.444	1.437	1.427	1.363	1.363	1.345	1.345	1.34	1.317	1.317	1.299	1.281	1.202	1.133	1.042
1.485	1.467	1.457	1.434	1.416	1.358	1.353	1.337	1.342	1.337	1.317	1.312	1.291	1.294	1.202	1.136	1.052
1.475	1.472	1.452	1.429	1.416	1.363	1.35	1.337	1.33	1.325	1.322	1.322	1.294	1.284	1.202	1.131	1.052
1.49	1.47	1.457	1.437	1.411	1.35	1.35	1.345	1.335	1.332	1.32	1.317	1.294	1.284	1.212	1.138	1.044
1.485	1.465	1.455	1.437	1.419	1.365	1.363	1.35	1.337	1.335	1.325	1.32	1.299	1.281	1.205	1.131	1.059
1.478	1.478	1.46	1.434	1.409	1.363	1.355	1.337	1.337	1.33	1.317	1.314	1.304	1.276	1.207	1.131	1.049
1.485	1.462	1.457	1.437	1.404	1.365	1.36	1.34	1.33	1.332	1.322	1.312	1.299	1.289	1.21	1.131	1.052
1.478	1.475	1.447	1.437	1.409	1.36	1.358	1.342	1.33	1.332	1.332	1.314	1.294	1.284	1.202	1.138	1.047
1.48	1.467	1.457	1.447	1.414	1.365	1.353	1.34	1.345	1.33	1.325	1.325	1.304	1.284	1.2	1.131	1.057
1.493	1.47	1.46	1.439	1.416	1.35	1.35	1.35	1.345	1.335	1.327	1.314	1.297	1.289	1.202	1.131	1.039
1.483	1.465	1.452	1.427	1.424	1.365	1.348	1.35	1.342	1.32	1.325	1.312	1.294	1.289	1.21	1.131	1.052
1.485	1.472	1.442	1.439	1.419	1.363	1.353	1.342	1.332	1.337	1.325	1.317	1.299	1.279	1.205	1.131	1.044
1.483	1.465	1.455	1.439	1.421	1.353	1.353	1.345	1.345	1.332	1.312	1.325	1.309	1.284	1.2	1.123	1.044
1.488	1.47	1.465	1.437	1.416	1.365	1.345	1.345	1.337	1.327	1.317	1.317	1.307	1.286	1.205	1.131	1.054
1.493	1.472	1.462	1.437	1.427	1.355	1.355	1.34	1.342	1.327	1.325	1.314	1.307	1.289	1.197	1.131	1.039
1.48	1.475	1.452	1.437	1.419	1.365	1.345	1.337	1.34	1.327	1.325	1.312	1.304	1.284	1.197	1.136	1.044
1.488	1.472	1.447	1.434	1.411	1.368	1.355	1.35	1.34	1.327	1.332	1.322	1.291	1.279	1.2	1.123	1.059

	1.485	1.47	1.457	1.437	1.414	1.358	1.358	1.337	1.332	1.33	1.322	1.309	1.302	1.294	1.2	1.136	1.057
	1.478	1.472	1.452	1.442	1.411	1.363	1.35	1.342	1.327	1.335	1.317	1.312	1.309	1.291	1.195	1.138	1.044
	1.485	1.475	1.455	1.434	1.421	1.358	1.353	1.355	1.345	1.332	1.317	1.314	1.299	1.286	1.202	1.133	1.054
	1.475	1.462	1.457	1.437	1.419	1.36	1.355	1.348	1.332	1.322	1.322	1.307	1.297	1.284	1.195	1.123	1.054
	1.475	1.465	1.45	1.429	1.416	1.35	1.353	1.337	1.335	1.332	1.327	1.312	1.299	1.286	1.197	1.128	1.047
	1.49	1.478	1.447	1.439	1.414	1.355	1.345	1.34	1.34	1.327	1.327	1.307	1.291	1.284	1.202	1.131	1.057
	1.485	1.472	1.462	1.442	1.416	1.365	1.35	1.348	1.335	1.335	1.325	1.317	1.294	1.284	1.207	1.121	1.042
	1.478	1.478	1.457	1.427	1.421	1.368	1.345	1.335	1.345	1.332	1.325	1.322	1.297	1.286	1.207	1.133	1.059
	1.478	1.48	1.447	1.444	1.416	1.36	1.36	1.355	1.34	1.335	1.32	1.309	1.299	1.286	1.21	1.131	1.044
	1.485	1.467	1.45	1.437	1.414	1.363	1.353	1.345	1.337	1.33	1.325	1.314	1.309	1.284	1.2	1.126	1.049
	1.483	1.478	1.457	1.432	1.424	1.355	1.348	1.342	1.34	1.332	1.32	1.314	1.302	1.284	1.21	1.126	1.049
	1.498	1.465	1.462	1.447	1.414	1.365	1.358	1.35	1.345	1.322	1.322	1.309	1.297	1.289	1.212	1.131	1.044
	1.483	1.462	1.46	1.444	1.411	1.355	1.358	1.348	1.342	1.317	1.317	1.32	1.302	1.284	1.207	1.136	1.059
	1.483	1.467	1.455	1.434	1.416	1.363	1.345	1.345	1.348	1.335	1.317	1.317	1.297	1.279	1.2	1.131	1.044
	1.478	1.472	1.444	1.442	1.419	1.358	1.355	1.34	1.342	1.322	1.327	1.312	1.291	1.284	1.202	1.133	1.054
	1.485	1.462	1.457	1.437	1.424	1.358	1.355	1.345	1.335	1.327	1.327	1.312	1.309	1.284	1.197	1.131	1.054
	1.488	1.475	1.455	1.434	1.414	1.365	1.36	1.345	1.34	1.327	1.327	1.317	1.304	1.276	1.207	1.133	1.059
	1.493	1.472	1.455	1.439	1.411	1.363	1.355	1.345	1.335	1.322	1.317	1.32	1.297	1.284	1.2	1.126	1.049
	1.48	1.467	1.452	1.437	1.409	1.355	1.355	1.353	1.34	1.33	1.33	1.32	1.304	1.289	1.192	1.126	1.049
	1.48	1.467	1.442	1.427	1.414	1.363	1.355	1.337	1.332	1.33	1.332	1.312	1.302	1.274	1.202	1.128	1.042
	1.485	1.478	1.455	1.442	1.419	1.363	1.34	1.342	1.335	1.332	1.332	1.314	1.304	1.281	1.2	1.136	1.049
	1.488	1.467	1.447	1.444	1.421	1.355	1.353	1.342	1.348	1.332	1.332	1.314	1.289	1.279	1.207	1.131	1.042
	1.485	1.47	1.455	1.442	1.414	1.355	1.36	1.337	1.342	1.332	1.325	1.309	1.294	1.279	1.21	1.123	1.049
	1.493	1.472	1.46	1.432	1.416	1.363	1.345	1.345	1.34	1.325	1.317	1.317	1.302	1.291	1.207	1.128	1.047
	1.493	1.472	1.465	1.439	1.419	1.353	1.355	1.342	1.337	1.33	1.317	1.314	1.304	1.294	1.197	1.121	1.052
	1.48	1.475	1.457	1.437	1.416	1.365	1.358	1.342	1.335	1.322	1.314	1.32	1.302	1.279	1.207	1.131	1.047
	1.483	1.472	1.46	1.442	1.409	1.355	1.348	1.342	1.337	1.332	1.317	1.325	1.294	1.289	1.195	1.138	1.047
Mean:	1.485	1.471	1.454	1.438	1.415	1.360	1.352	1.344	1.338	1.330	1.323	1.316	1.299	1.284	1.203	1.130	1.050
Std. Dev.	0.0053	0.0048	0.0055	0.0049	0.0054	0.0051	0.0049	0.0054	0.0052	0.0052	0.0058	0.0049	0.0051	0.0050	0.0054	0.0047	0.0055

Table A.9: Multiple Sensor Test- Raw Data

Terminal log file
Date: 3/25/2008 - 9:40:02 AM

A	2.011764	0.000000
B	1.588235	1.576470
C	1.494117	1.517647
D	1.588235	1.647058
A	2.001176	0.000000
B	1.576470	1.576470
C	1.494117	1.517647
D	1.576470	1.648235
A	2.000000	0.000000
B	1.588235	1.575294
C	1.482352	1.524705
D	1.576470	1.647058
A	2.000000	0.000000
B	1.583529	1.574117
C	1.482352	1.519999
D	1.576470	1.647058
A	2.000000	0.000000
B	1.576470	1.576470
C	1.494117	1.529411
D	1.580000	1.647058
A	2.000000	0.000000
B	1.587058	1.575294
C	1.485882	1.517647
D	1.576470	1.647058
A	2.000000	0.000000
B	1.577647	1.576470
C	1.482352	1.529411
D	1.583529	1.647058
A	2.000000	0.000000
B	1.576470	1.576470
C	1.492941	1.517647
D	1.584705	1.648235
A	2.002352	0.000000
B	1.583529	1.576470
C	1.494117	1.525882
D	1.576470	1.647058
A	2.000000	0.000000
B	1.588235	1.572941
C	1.494117	1.527058
D	1.592941	1.650588
A	2.000000	0.000000
B	1.576470	1.576470
C	1.485882	1.529411
D	1.575294	1.658823
A	2.000000	0.000000
B	1.588235	1.569411
C	1.494117	1.529411
D	1.583529	1.670588
A	2.007058	0.000000
B	1.576470	1.576470
C	1.485882	1.517647
D	1.588235	1.670588
A	2.000000	0.000000
B	1.576470	1.576470
C	1.494117	1.529411
D	1.576470	1.670588
A	2.001176	0.000000
B	1.577647	1.564705
C	1.482352	1.529411
D	1.576470	1.663529
A	2.000000	0.000000
B	1.576470	1.576470
C	1.494117	1.529411
D	1.576470	1.670588
A	2.000000	0.000000
B	1.576470	1.576470
C	1.494117	1.518823
D	1.576470	1.662352
A	2.000000	0.000000
B	1.588235	1.576470
C	1.484705	1.517647
D	1.576470	1.658823
A	2.000000	0.000000
B	1.576470	1.576470
C	1.482352	1.528235
D	1.576470	1.658823
A	2.000000	0.000000
B	1.577647	1.576470
C	1.494117	1.521176
D	1.576470	1.658823
A	2.000000	0.000000
B	1.576470	1.576470
C	1.491764	1.525882
D	1.577647	1.649411
A	2.002352	0.000000
B	1.577647	1.580000
C	1.494117	1.529411
D	1.583529	1.651764
A	2.009411	0.000000
B	1.576470	1.576470
C	1.482352	1.529411
D	1.576470	1.657647
A	2.011764	0.000000
B	1.582352	1.576470
C	1.490588	1.529411
D	1.583529	1.647058
A	2.011764	0.000000
B	1.576470	1.585882
C	1.482352	1.529411
D	1.576470	1.647058
A	2.011764	0.000000
B	1.576470	1.576470
C	1.482352	1.519999
D	1.588235	1.647058
A	2.005882	0.000000
B	1.576470	1.576470
C	1.488235	1.529411

D	1.576470	1.647058
A	2.011764	0.000000
B	1.585882	1.585882
C	1.494117	1.528235
D	1.588235	1.647058
A	2.011764	0.000000
B	1.588235	1.576470
C	1.482352	1.529411
D	1.587058	1.647058
A	2.011764	0.000000
B	1.588235	1.576470
C	1.494117	1.529411
D	1.576470	1.647058
A	2.011764	0.000000
B	1.576470	1.576470
C	1.482352	1.529411
D	1.576470	1.657647
A	2.011764	0.000000
B	1.576470	1.576470
C	1.482352	1.529411
D	1.588235	1.658823
A	2.011764	0.000000
B	1.588235	1.576470
C	1.482352	1.529411
D	1.576470	1.651764
A	2.011764	0.000000
B	1.587058	1.576470
C	1.491764	1.529411
D	1.576470	1.667058
A	2.011764	0.000000
B	1.576470	1.576470
C	1.484705	1.529411
D	1.576470	1.658823
A	2.011764	0.000000
B	1.578823	1.576470
C	1.482352	1.529411
D	1.564705	1.670588
A	2.011764	0.000000
B	1.588235	1.576470
C	1.488235	1.529411
D	1.576470	1.682353
A	2.011764	0.000000
B	1.576470	1.585882
C	1.482352	1.529411
D	1.564705	1.689411
B	1.576470	1.576470
C	1.494117	1.529411
D	1.564705	1.705882
B	1.576470	1.576470
C	1.487058	1.529411
D	1.541176	1.729411
B	1.577647	1.576470
C	1.491764	1.529411
D	1.538823	1.764705
B	1.587058	1.576470
C	1.494117	1.529411
D	1.529411	1.847058
B	1.576470	1.576470
C	1.482352	1.529411
D	1.529411	1.929411
B	1.576470	1.576470
C	1.484705	1.529411
D	1.494117	2.011764
B	1.576470	1.576470
C	1.487058	1.529411
D	1.435294	2.141176
B	1.576470	1.575294
C	1.482352	1.529411
D	1.412941	2.211764
B	1.576470	1.576470
C	1.494117	1.529411
D	1.364705	2.294117
B	1.588235	1.576470
C	1.492941	1.529411
D	1.305882	2.467058
B	1.585882	1.576470
C	1.484705	1.529411
D	1.465882	2.808235
B	1.576470	1.576470
C	1.492941	1.529411
D	3.000000	3.000000
B	1.564705	1.564705
C	1.494117	1.529411
D	3.000000	3.000000
B	1.567058	1.552941
C	1.494117	1.529411
D	3.000000	3.000000
B	1.564705	1.564705
C	1.494117	1.529411
B	1.564705	1.552941
C	1.484705	1.529411
G	2.460000	0.000000
G	2.047058	0.000000
B	1.564705	1.564705
C	1.491764	1.541176
G	2.035294	0.000000
B	1.575294	1.567058
C	1.482352	1.541176
G	2.035294	0.000000
B	1.576470	1.576470
C	1.482352	1.550588
G	2.035294	0.000000
B	1.576470	1.588235
C	1.470588	1.552941
B	1.576470	1.588235
C	1.478823	1.563529
G	2.035294	0.000000
B	1.576470	1.602352
C	1.470588	1.572941
G	2.035294	0.000000
B	1.588235	1.611764
C	1.470588	1.576470

G	2.035294	0.000000
B	1.577647	1.627058
C	1.458823	1.588235
G	2.035294	0.000000
B	1.600000	1.635294
C	1.505882	1.611764
G	2.035294	0.000000
B	1.611764	1.658823
C	1.635294	1.611764
G	2.035294	0.000000
B	1.607058	1.691764
C	3.000000	0.000000
G	2.035294	0.000000
B	1.623529	1.729411
C	3.000000	0.000000
G	2.036470	0.000000
B	1.647058	1.752941
G	2.035294	0.000000
B	1.670588	1.867058
G	2.035294	0.000000
B	1.717646	1.939999
G	2.035294	0.000000
B	1.676470	2.141176
G	2.035294	0.000000
B	1.601176	2.164705
G	2.035294	0.000000
B	1.471764	2.154117
G	2.047058	0.000000
B	1.341176	2.189411
G	2.042352	0.000000
B	1.251764	2.247058
G	2.047058	0.000000
B	1.012941	2.217647
G	2.035294	0.000000
B	0.636470	2.258823
G	2.035294	0.000000
B	0.282352	2.158823
G	2.047058	0.000000
B	0.143529	2.305882
G	2.047058	0.000000
B	0.000000	2.298823
G	2.047058	0.000000
G	2.035294	0.000000
G	2.047058	0.000000
G	2.047058	0.000000
G	2.047058	0.000000
G	2.047058	0.000000
G	2.047058	0.000000
G	2.048235	0.000000
G	2.047058	0.000000
G	2.043529	0.000000
G	2.047058	0.000000
G	2.047058	0.000000
G	2.044706	0.000000
G	2.047058	0.000000
G	2.048235	0.000000
G	2.047058	0.000000
G	2.047058	0.000000

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End log file

The following table represents the raw data found in Table A.9, only formatted to separate each data point by identifier. The formatting was performed in *Microsoft Excel*.

Table A.10: Multiple Tiltmeter Test- Formatted Data

Terminal log file											
Date: 3/25/2008 - 9:40:02 AM											

A	2.011764	0	B	1.588235	1.576470	C	1.494117	1.517647	D	1.588235	1.647058
A	2.001176	0	B	1.576470	1.576470	C	1.494117	1.517647	D	1.576470	1.648235
A	2.000000	0	B	1.588235	1.575294	C	1.482352	1.524705	D	1.576470	1.647058
A	2.000000	0	B	1.583529	1.574117	C	1.482352	1.519999	D	1.576470	1.647058
A	2.000000	0	B	1.576470	1.576470	C	1.494117	1.529411	D	1.580000	1.647058
A	2.000000	0	B	1.587058	1.575294	C	1.485882	1.517647	D	1.576470	1.647058
A	2.000000	0	B	1.577647	1.576470	C	1.482352	1.529411	D	1.583529	1.647058
A	2.000000	0	B	1.576470	1.576470	C	1.492941	1.517647	D	1.584705	1.648235
A	2.002352	0	B	1.583529	1.576470	C	1.494117	1.525882	D	1.576470	1.647058
A	2.000000	0	B	1.588235	1.572941	C	1.494117	1.527058	D	1.592941	1.650588
A	2.000000	0	B	1.576470	1.576470	C	1.485882	1.529411	D	1.575294	1.658823
A	2.000000	0	B	1.588235	1.569411	C	1.494117	1.529411	D	1.583529	1.670588
A	2.007058	0	B	1.576470	1.576470	C	1.485882	1.517647	D	1.588235	1.670588
A	2.000000	0	B	1.576470	1.576470	C	1.494117	1.529411	D	1.576470	1.670588
A	2.001176	0	B	1.577647	1.564705	C	1.482352	1.529411	D	1.576470	1.663529
A	2.000000	0	B	1.576470	1.576470	C	1.494117	1.529411	D	1.576470	1.670588
A	2.000000	0	B	1.576470	1.576470	C	1.494117	1.518823	D	1.576470	1.662352
A	2.000000	0	B	1.588235	1.576470	C	1.484705	1.517647	D	1.576470	1.658823
A	2.000000	0	B	1.576470	1.576470	C	1.482352	1.528235	D	1.576470	1.658823
A	2.000000	0	B	1.577647	1.576470	C	1.494117	1.521176	D	1.576470	1.658823
A	2.000000	0	B	1.576470	1.576470	C	1.491764	1.525882	D	1.577647	1.649411
A	2.002352	0	B	1.577647	1.580000	C	1.494117	1.529411	D	1.583529	1.651764
A	2.009411	0	B	1.576470	1.576470	C	1.482352	1.529411	D	1.576470	1.657647
A	2.011764	0	B	1.582352	1.576470	C	1.490588	1.529411	D	1.583529	1.647058
A	2.011764	0	B	1.576470	1.585882	C	1.482352	1.529411	D	1.576470	1.647058
A	2.011764	0	B	1.576470	1.576470	C	1.482352	1.519999	D	1.588235	1.647058
A	2.005882	0	B	1.576470	1.576470	C	1.488235	1.529411	D	1.576470	1.647058
A	2.011764	0	B	1.585882	1.585882	C	1.494117	1.528235	D	1.588235	1.647058
A	2.011764	0	B	1.588235	1.576470	C	1.482352	1.529411	D	1.587058	1.647058
A	2.011764	0	B	1.588235	1.576470	C	1.494117	1.529411	D	1.576470	1.647058
A	2.011764	0	B	1.576470	1.576470	C	1.482352	1.529411	D	1.576470	1.657647
A	2.011764	0	B	1.576470	1.576470	C	1.482352	1.529411	D	1.588235	1.658823
A	2.011764	0	B	1.588235	1.576470	C	1.482352	1.529411	D	1.576470	1.651764
A	2.011764	0	B	1.587058	1.576470	C	1.491764	1.529411	D	1.576470	1.667058
A	2.011764	0	B	1.576470	1.576470	C	1.484705	1.529411	D	1.576470	1.658823
A	2.011764	0	B	1.578823	1.576470	C	1.482352	1.529411	D	1.564705	1.670588
A	2.011764	0	B	1.588235	1.576470	C	1.488235	1.529411	D	1.576470	1.682353
A	2.011764	0	B	1.576470	1.585882	C	1.482352	1.529411	D	1.564705	1.689411
			B	1.576470	1.576470	C	1.494117	1.529411	D	1.564705	1.705882
			B	1.576470	1.576470	C	1.487058	1.529411	D	1.541176	1.729411
			B	1.577647	1.576470	C	1.491764	1.529411	D	1.538823	1.764705
			B	1.587058	1.576470	C	1.494117	1.529411	D	1.529411	1.847058
			B	1.576470	1.576470	C	1.482352	1.529411	D	1.529411	1.929411
			B	1.576470	1.576470	C	1.484705	1.529411	D	1.494117	2.011764
			B	1.576470	1.576470	C	1.487058	1.529411	D	1.435294	2.141176
			B	1.576470	1.575294	C	1.482352	1.529411	D	1.412941	2.211764
			B	1.576470	1.576470	C	1.494117	1.529411	D	1.364705	2.294117
			B	1.588235	1.576470	C	1.492941	1.529411	D	1.305882	2.467058

				B	1.585882	1.576470		C	1.484705	1.529411		D	1.465882	2.808235
				B	1.576470	1.576470		C	1.492941	1.529411		D	3.000000	3.000000
				B	1.564705	1.564705		C	1.494117	1.529411		D	3.000000	3.000000
				B	1.567058	1.552941		C	1.494117	1.529411		D	3.000000	3.000000
				B	1.564705	1.564705		C	1.494117	1.529411				
				B	1.564705	1.552941		C	1.484705	1.529411				
				B	1.564705	1.564705		C	1.491764	1.541176				
				B	1.575294	1.567058		C	1.482352	1.541176				
				B	1.576470	1.576470		C	1.482352	1.550588				
				B	1.576470	1.588235		C	1.470588	1.552941				
				B	1.576470	1.588235		C	1.478823	1.563529				
				B	1.576470	1.602352		C	1.470588	1.572941				
				B	1.588235	1.611764		C	1.470588	1.576470				
				B	1.577647	1.627058		C	1.458823	1.588235				
				B	1.600000	1.635294		C	1.505882	1.611764				
				B	1.611764	1.658823		C	1.635294	1.611764				
				B	1.607058	1.691764		C	3.000000	0.000000				
				B	1.623529	1.729411		C	3.000000	0.000000				
				B	1.647058	1.752941								
				B	1.670588	1.867058								
				B	1.717646	1.939999								
				B	1.676470	2.141176								
				B	1.601176	2.164705								
				B	1.471764	2.154117								
				B	1.341176	2.189411								
				B	1.251764	2.247058								
				B	1.012941	2.217647								
				B	0.636470	2.258823								
				B	0.282352	2.158823								
				B	0.143529	2.305882								
				B	0.000000	2.298823								

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End log file: Computer Restart

APPENDIX B: C CODES

Code Writing Procedure
"Toggle"
"Serial Test"
"Test ADC"
"Serial Test 2"
"Final_A"

The process of writing each code to the PIC is described in the following list:

1. Write code in *PIC C Compiler*
   a. Can also use another program such as *Microsoft Visual* to write the code, as long as the program uses the C language, not C++.
   b. Use attached codes as guides for writing programs. The symbols "//" indicates a note that does not cause the PIC to read what follows, so follow instructions or take note as to what trails //.
2. Compile code in *PIC C Compiler*
   a. Compiling the code translates what is written in the C language to a HEX format. The PIC reads and understands HEX code, but not C, therefore it is important to compile after any and all changes are made to the code.
3. Use *Tiny Bootloader* to write compiled code to PIC
   a. Attach serial extension, as seen in Figure 4.8, and ensure power to the PIC is on.
   b. Select the HEX file using the Browse button in *Tiny Bootloader*.
   c. Press and hold the reset switch on the circuit board.
   d. Click the "Write" button in *Tiny Bootloader* and then release the reset switch on the circuit board. Tiny Bootloader should then load the program and display a "Write OK" confirmation.
4. Use *Terminal* to read serial messages from PIC
   a. *Terminal* will operate using wireless or wired serial methods. Refer to section 4.3- Programming the Circuit Board for more details.

APPENDIX B-1: "TOGGLE"

The following code shows the "Toggle" code, written to test the functionality of the PIC, as described in 4.3- Programming the Circuit Board.

```
#include <18F6722.h>
#ORG 0xFF00, 0xFFFF{} // vsid bootloader

//* Set configuration bits in the PIC processor *//
//////////////////////////////////////////////////////////////////////////

#fuses HS, NOPROTECT, NOPUT, NOWDT, NOBROWNOUT, NOLVP, NOCPD, NOWRT
#device ADC=8

#use delay (clock=14745600)      /* sets appropriate compiler constants */

#use standard_io (a) // IR sensors
#use standard_io (b) // LED & Power
#use standard_io (d) // Left stepper motor
#use standard_io (e) // Right stepper motor
#use fixed_io(f_outputs=PIN_F3, PIN_F4, PIN_F5)
#use rs232 (BAUD = 9600, XMIT = PIN_C6, RCV = PIN_C7)


//////////////////////////////////////////////////////////////////////////
//* end set configuration bits *//
void main(void) {
  while(1) {
    output_high(PIN_D1); // Turn camera on
    delay_ms(2000); //Goes forward for 2 seconds to release arms
    output_low(PIN_D1);
    delay_ms(2000);
  }
}
```

Appendix B-2: "Serial Test"

The following code shows the "Serial Test" code, written to test the functionality of the PIC, as described in 4.3- Programming the Circuit Board.

```
/* This programs sends out a serial message.
   It can be used as an example of how to do send serial outputs.
   It also will show if the serial port is working. */
#include <18F6722.h>
#ORG 0xFF00, 0xFFFF{} // vsid bootloader
#fuses NOWDT,HS, PUT, NOPROTECT, NODEBUG, BROWNOUT, LVP, NOCPD, NOWRT
#use delay(clock=14745600)
#use rs232(baud=9600,parity=N,xmit=PIN_C6,rcv=PIN_C7,bits=8)

void main()
{
// configure the serial port
   setup_uart(9600);

   while(true)  {

   printf("SERIAL TEST\n\r");

   delay_ms(1000);
   }
}
```

APPENDIX B-3: "TEST ADC"

The following code shows the "Test ADC" code, written to test the functionality of the PIC, as described in 4.3- Programming the Circuit Board.

```
/* This programs reads one of the ADCs and sends the value out on the serial port.
  It can be used as an example of how to read the analog to digital converters.
  It also will show if the ADC and serial ports are working. */

#include <18F6722.h>
#ORG 0xFF00, 0xFFFF{} // vsid bootloader

//* Set configuration bits in the PIC processor *//
///////////////////////////////////////////////////////////////////////////////

#fuses HS, NOPROTECT, NOPUT, NOWDT, NOBROWNOUT, NOLVP, NOCPD, NOWRT
#device ADC=8 //setup the adc for 8 bit values, can be set as high as 10

#use delay (clock=14745600)     /* sets appropriate compiler constants */

#use standard_io (a)
#use standard_io (b)
#use standard_io (d)
#use standard_io (e)
#use fixed_io(f_outputs=PIN_F3, PIN_F4, PIN_F5)
#use rs232 (BAUD = 115200, XMIT = PIN_C6, RCV = PIN_C7)

///////////////////////////////////////////////////////////////////////////////
//* end set configuration bits *//

//*****************************************************************
//Function name: initialization
//Purpose: Initializes motors, timers, interrupts
//                and adc.
//Precondition: void
//Postcondition: void
//*****************************************************************
void initialization() {
  //* Initializes ADC *//
  setup_adc(ADC_CLOCK_INTERNAL);
  setup_adc_ports(ALL_ANALOG); //use all adc pins as adcs (can set some as digital I/O if
needed
}
```

```
//*************************************************************
//Function name: main
//Purpose: 1. Initializing.
//             2. Main sensing loop.
//Precondition: void
//Postcondition: void
//*************************************************************
void main(void) {
  initialization();
  while(1) { //keep running this loop until the PIC is turned off

int32 sum_x = 0;
int32 sum_y = 0;

  set_adc_channel(0); //
  delay_us(10); //delay required after setting adc_channel
  sum_x = sum_x + read_ADC();

  set_adc_channel(1);
  delay_us(10);
  sum_y = sum_y + read_ADC();

  // send out sensor_value in ascii over serial
  printf("The sum_x and sum_y ADC value is \n\r %u, and %u.\n\r", sum_x, sum_y);
  delay_ms(2000);
  }
}
```

APPENDIX B-4: "SERIAL TEST 2"

The following code shows the "Serial Test 2" code, written to test the functionality of the PIC, as well as the wireless capabilities of the XBee, as described in 4.3- Programming the Circuit Board.

```
/* This programs sends out a serial message.
   It can be used as an example of how to do send serial outputs.
   It also will show if the serial port is working. */
#include <18F6722.h>
#ORG 0xFF00, 0xFFFF{} // vsid bootloader
#fuses NOWDT,HS, PUT, NOPROTECT, NODEBUG, BROWNOUT, LVP, NOCPD, NOWRT
#use delay(clock=14745600)
#use rs232(baud=9600,parity=N,xmit=PIN_G2,rcv=PIN_G1,bits=8)

void main()
{
// configure the serial port
   //setup_uart(9600);

   while(true)  {

   printf("SERIAL TEST\n\r");

   delay_ms(1000);
   }
}
```

APPENDIX B-5: "FINAL_A"

The following code shows the "Final_A" code, written for the tiltmeters upon completion of the designing process, as described in 4.3- Programming the Circuit Board. This code was written to each of the sensors installed at the Fairfax Luck Stone mine, with the differentiation of an identifier: "Final_A" output the identifier A, and "Final_B" outputs the identifier B, etc.

```
/* This program reads one of the ADC at 100 Hz and sends the data out on
   the serial port.  It is an example of how to use interrupts */

#include <18F6722.h>
#ORG 0xFF00, 0xFFFF{} // vsid bootloader

//* Set configuration bits in the PIC processor *//
//////////////////////////////////////////////////////////////////////////////

#fuses HS, NOPROTECT, NOPUT, NOWDT, NOBROWNOUT, NOLVP, NOCPD, NOWRT
#device ADC=8

#use delay (clock=14745600)      /* sets appropriate compiler constants */

#use standard_io (a) // IR sensors
#use standard_io (b) // LED & Power
#use standard_io (d) // Left stepper motor
#use standard_io (e) // Right stepper motor
#use fixed_io(f_outputs=PIN_F3, PIN_F4, PIN_F5)
#use rs232 (BAUD = 9600, XMIT = PIN_G2, RCV = PIN_G1)

float sum_x = 0;
float sum_y = 0;
int8 count = 0;
int8 i = 0;
int8 j = 0;
float Avg_x = 0;
float Avg_y = 0;

//////////////////////////////////////////////////////////////////////////////
//* end set configuration bits *//

//*****************************************************************
//Function name: movement
//Purpose: Executes when interrupt timer1 overflows.
```

```
//Precondition: void
//Postcondition: void
//****************************************************************
#int_timer1
void adc_read() {
delay_ms(5000);
while(true)  {
  set_timer1(0x2100); // sets timer interrupt at 100 Hz
  // Clock divisior is 4608 = 0x1200, but order must be flipped to 0x2100(weird compiler bug)

  set_adc_channel(0); //
  delay_us(10); //delay required after setting adc_channel
{for (i=0;i<=9;++i)
  sum_x = sum_x + read_ADC();}

  set_adc_channel(1);
  delay_us(10); //delay required after setting adc_channel
{for (j=0;j<=9;++j)
  sum_y = sum_y + read_ADC();}

Avg_x = sum_x*3/255/i; //(using conversion factor of 3/255 [Voltage/((2^8bits)-1)])
Avg_y = sum_y*3/255/j;

  {// send out X & Y voltages in ascii over serial port
  printf("A, %f, %f.\n\r", Avg_x, Avg_y);
  delay_ms(1800000);} //1800000 ms = 30 minutes.  signal will be transmitted every 30 minutes
  sum_x = sum_y = Avg_x = Avg_y = 0;
  }}
//****************************************************************
//Function name: initialization
//Purpose: Initializes motors, timers, interrupts
//                    and adc.
//Precondition: void
//Postcondition: void
//****************************************************************
void initialization() {
  //* Initializes ADC *//
  setup_adc(ADC_CLOCK_INTERNAL);
  setup_adc_ports(AN0_TO_AN9);
  //* Timer setups *//
  setup_timer_1(T1_internal | T1_DIV_BY_8);  // Timer speed is Fosc/4/T1_DIV_BY_8 =
14.7456 MHz / 4 / 8 = 460.8 kHz
}
//****************************************************************
```

```
//Function name: main
//Purpose: 1. Initializing.
//              2. Main sensing loop.
//Precondition: void
//Postcondition: void
//***************************************************************
void main(void) {
  initialization();
  //* Enable interrupts *//
  enable_interrupts(global);
  enable_interrupts(int_timer1);
  set_timer1(0x2100);
  while(TRUE) {}}
```

APPENDIX C: CIRCUIT BOARD COMPONENTS

Initial Prototype Component List
Final Revised Component List
Prototype Board Cost Analysis
Revised Board Cost Analysis

Table C.1: Initial Prototype Component List

Part	Value	Device	Package	Description	Company	Part #
B1	BAT_CR2032	BAT_CR2032	2032SM	Battery	Digi-Key	BA2032-ND
C1	0.1 µF	CAP-0805	805	Capacitors	Digi-Key	399-1168-1-ND
C2	1 µF	CAP-0805	805	Capacitors	Digi-Key	399-1284-1-ND
C3	0.1 µF	CAP-0805	805	Capacitors	Digi-Key	399-1168-1-ND
C7	22 pF	CAP-0603	603	Capacitors	Digi-Key	399-1053-1-ND
C8	22 pF	CAP-0603	603	Capacitors	Digi-Key	399-1053-1-ND
C9	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C10	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C11	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C12	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C13	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C14	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C15	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C16	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C17	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C18	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C19	0.1 µF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C21	1µF	CAP-0805	805	Capacitors	Digi-Key	399-1284-1-ND
C22	1µF	CAP-0805	805	Capacitors	Digi-Key	399-1284-1-ND
CN3	CN-JST_5	CN-JST_5	JST5	Connector	Digi-Key	455-1707-ND
D1-IN	IN	LED-1206	1206-POL	Diode	Digi-Key	160-1456-1-ND
D2-OUT	OUT	LED-1206	1206-POL	Diode	Digi-Key	160-1456-1-ND
D3-ASSOC	ASSOC	LED-1206	1206-POL	Diode	Digi-Key	160-1405-1-ND
D5	PWM1	LED-1206	1206-POL	Diode	Digi-Key	160-1405-1-ND
D6	DSR/DCD	LED-1206	1206-POL	Diode	Digi-Key	160-1406-1-ND
JP1	JP-3	JP-3	JP3	Jumper	Digi-Key	WM6536-ND
JP2	JP-2	JP-2	JP2	Jumper	Digi-Key	WM6536-ND
JP3	JP-3	JP-3	JP3	Jumper	Digi-Key	WM6536-ND
JP4-COORD	COORD	JP-2	JP2	Jumper	Digi-Key	WM6536-ND
M2	XBee	XBee	XBee	XBee	MaxStream	XB24-BWIT-004
MEMSIC	1000mv/g	MXR6999M	MXR6999M	Accelerometer	MEMSIC	MXR6999M
Q2	PNP	MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
Q3	PNP	MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
Q4	PNP	MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
Q5	PNP	MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
R2	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R14	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R15	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R16	470	RES-0805	805	Resistor	Digi-Key	RHM470ARCT-ND
R17	470	RES-0805	805	Resistor	Digi-Key	RHM470ARCT-ND
R18	470	RES-0805	805	Resistor	Digi-Key	RHM470ARCT-ND
R19	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R20	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R21	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R22	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R23	10k	RES-0805	805	Resistor	Digi-Key	RHM10KARCT-ND
R26	220	RES-0805	805	Resistor	Digi-Key	RHM220ACT-ND
R27	220	RES-0805	805	Resistor	Digi-Key	RHM220ACT-ND
SERIAL	CN-JST_3	CN-JST_3	JST3	Serial	Digi-Key	455-1705-ND
SERIAL1	CN-JST_3	CN-JST_3	JST3	Serial	Digi-Key	455-1705-ND
SW1	SW_B3S-1000	SW_B3S-1000	B3S-1000	Switch	Digi-Key	SW415-ND
U2	PIC18F6722	PIC18F6722	LQFP-64	Processor	Microchip	PIC18F6722-I/PT
U4	MAX3232	MAX3232	SOIC-16	Driver/Receiver	Texas Inst.	MAX3232CDR
Y2	18pF	XTAL-CS10	CS10	Crystals	Digi-Key	300-8094-1-ND

Table C.2: Final Revised Component List

Part	Value	Device	Package	Description	Company	Part #
BAT	AA*2_-_3V	AA_HOUSING	AA_HOUSING	Battery	Digi-Key	SBH-321AS-ND
C01	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C02	1 uF	CAP-0805	805	Capacitors	Digi-Key	399-1284-1-ND
C03	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C04	22 pF	CAP-0603	603	Capacitors	Digi-Key	399-1053-1-ND
C05	22 pF	CAP-0603	603	Capacitors	Digi-Key	399-1053-1-ND
C06	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C07	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C08	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C09	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C10	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C11	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C12	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C13	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C14	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C15	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C16	0.1 uF	CAP-0603	603	Capacitors	Digi-Key	399-1096-1-ND
C17	1uF	CAP-0805	805	Capacitors	Digi-Key	399-1284-1-ND
C18	1uF	CAP-0805	805	Capacitors	Digi-Key	399-1284-1-ND
CN3	CN-JST_5	CN-JST_5	JST5	Connector	Digi-Key	455-1707-ND
JP1	JP-3	JP-3	JP3	Jumper	Digi-Key	WM6536-ND
JP2	JP-3	JP-3	JP3	Jumper	Digi-Key	WM6536-ND
2	XBee	XBee	XBee	MaxStream	MaxStream	XB24-BWIT-004
MEMSIC	Accelerometer	MXR6999M	MXR6999M	Accelerometer	MEMSIC	MXR6999M
Q1	Q_MMBT3906	Q_MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
Q2	Q_MMBT3906	Q_MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
Q3	Q_MMBT3906	Q_MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
Q4	Q_MMBT3906	Q_MMBT3906	SOT-23	Transistor	Digi-Key	MMBT3906FSCT-ND
R01	10K	RES-0805	805	Resistors	Digi-Key	RHM10KARCT-ND
R02	10k	RES-0805	805	Resistors	Digi-Key	RHM10KARCT-ND
R03	10k	RES-0805	805	Resistors	Digi-Key	RHM10KARCT-ND
R04	10k	RES-0805	805	Resistors	Digi-Key	RHM10KARCT-ND
R05	470	RES-0805	805	Resistors	Digi-Key	RHM470ARCT-ND
R06	10k	RES-0805	805	Resistors	Digi-Key	RHM10KARCT-ND
R07	10k	RES-0805	805	Resistors	Digi-Key	RHM10KARCT-ND
R08	470	RES-0805	805	Resistors	Digi-Key	RHM470ARCT-ND
RCV	RCV	LED-1206	1206-POL	Diode	Digi-Key	160-1456-1-ND
SERIAL-PIC	CN-JST_3	CN-JST_3	JST3	Serial	Digi-Key	455-1705-ND
SERIAL1	CN-JST_3	CN-JST_3	JST3	Serial	Digi-Key	455-1705-ND
SND	SND	LED-1206	1206-POL	Diode	Digi-Key	160-1456-1-ND
SW1	SW_B3S-1000	SW_B3S-1000	B3S-1000	Switch	Digi-Key	SW415-ND
U2	PIC18F6722	PIC18F6722	LQFP-64	Processor	Microchip	PIC18F6722-I/PT
U4	MAX3232	MAX3232	SOIC-16	Driver/Receiver	Texas Inst.	MAX3232CDR
Y2	18 pF	XTAL-CS10	CS10	Crystals	Digi-Key	300-8094-1-ND

Table C.3: Cost Analysis for Prototype Board

Part	Value	Device	Package	Unit Cost (USD)
B1	BAT_CR2032	BAT_CR2032	2032SM	1.01
C1	0.1 µF	CAP-0805	805	0.045
C2	1 µF	CAP-0805	805	0.095
C3	0.1 µF	CAP-0805	805	0.045
C7	22 pF	CAP-0603	603	0.036
C8	22 pF	CAP-0603	603	0.036
C9	0.1 µF	CAP-0603	603	0.0137
C10	0.1 µF	CAP-0603	603	0.0137
C11	0.1 µF	CAP-0603	603	0.0137
C12	0.1 µF	CAP-0603	603	0.0137
C13	0.1 µF	CAP-0603	603	0.0137
C14	0.1 µF	CAP-0603	603	0.0137
C15	0.1 µF	CAP-0603	603	0.0137
C16	0.1 µF	CAP-0603	603	0.0137
C17	0.1 µF	CAP-0603	603	0.0137
C18	0.1 µF	CAP-0603	603	0.0137
C19	0.1 µF	CAP-0603	603	0.0137
C21	1µF	CAP-0805	805	0.095
C22	1µF	CAP-0805	805	0.095
CN3	CN-JST_5	CN-JST_5	JST5	0.194
D1-IN	IN	LED-1206	1206-POL	0.105
D2-OUT	OUT	LED-1206	1206-POL	0.105
D3-ASSOC	ASSOC	LED-1206	1206-POL	0.105
D5	PWM1	LED-1206	1206-POL	0.105
D6	DSR/DCD	LED-1206	1206-POL	0.106
JP1	JP-3	JP-3	JP3	0.1875
JP2	JP-2	JP-2	JP2	0.125
JP3	JP-3	JP-3	JP3	0.1875
JP4-COORD	COORD	JP-2	JP2	0.125
M2	XBee	XBee	XBee	21.00
MEMSIC	1000mv/g	MXR6999M	MXR6999M	10.00
Q2	PNP	MMBT3906	SOT-23	0.0676
Q3	PNP	MMBT3906	SOT-23	0.0676
Q4	PNP	MMBT3906	SOT-23	0.0676
Q5	PNP	MMBT3906	SOT-23	0.0676
R2	10k	RES-0805	805	0.0234
R14	10k	RES-0805	805	0.0234
R15	10k	RES-0805	805	0.0234
R16	470	RES-0805	805	0.033
R17	470	RES-0805	805	0.033
R18	470	RES-0805	805	0.033
R19	10k	RES-0805	805	0.0234
R20	10k	RES-0805	805	0.0234
R21	10k	RES-0805	805	0.0234
R22	10k	RES-0805	805	0.0234
R23	10k	RES-0805	805	0.0234
R26	220	RES-0805	805	0.076
R27	220	RES-0805	805	0.076
SERIAL	CN-JST_3	CN-JST_3	JST3	0.12
SERIAL1	CN-JST_3	CN-JST_3	JST3	0.12
SW1	SW_B3S-1000	SW_B3S-1000	B3S-1000	0.55
U2	PIC18F6722	PIC18F6722	LQFP-64	15.68
U4	MAX3232	MAX3232	SOIC-16	1.5
Y2	18pF	XTAL-CS10	CS10	1.013
SUM	-----	-----	-----	53.64

Table C.4: Cost Analysis for Revised Board

Part	Value	Device	Package	Unit Cost
BAT	AA*2_-_3V	AA_HOUSING	AA_HOUSING	0.70
C01	0.1 uF	CAP-0603	603	0.0137
C02	1 uF	CAP-0805	805	0.045
C03	0.1 uF	CAP-0603	603	0.0137
C04	22 pF	CAP-0603	603	0.036
C05	22 pF	CAP-0603	603	0.036
C06	0.1 uF	CAP-0603	603	0.0137
C07	0.1 uF	CAP-0603	603	0.0137
C08	0.1 uF	CAP-0603	603	0.0137
C09	0.1 uF	CAP-0603	603	0.0137
C10	0.1 uF	CAP-0603	603	0.0137
C11	0.1 uF	CAP-0603	603	0.0137
C12	0.1 uF	CAP-0603	603	0.0137
C13	0.1 uF	CAP-0603	603	0.0137
C14	0.1 uF	CAP-0603	603	0.0137
C15	0.1 uF	CAP-0603	603	0.0137
C16	0.1 uF	CAP-0603	603	0.0137
C17	1uF	CAP-0805	805	0.045
C18	1uF	CAP-0805	805	0.045
CN3	CN-JST_5	CN-JST_5	JST5	0.194
JP1	JP-3	JP-3	JP3	0.1875
JP2	JP-3	JP-3	JP3	0.1875
M2	XBee	XBee	XBee	21.00
MEMSIC	Accelerometer	MXR6999M	MXR6999M	10.00
Q1	Q_MMBT3906	Q_MMBT3906	SOT-23	0.0676
Q2	Q_MMBT3906	Q_MMBT3906	SOT-23	0.0676
Q3	Q_MMBT3906	Q_MMBT3906	SOT-23	0.0676
Q4	Q_MMBT3906	Q_MMBT3906	SOT-23	0.0676
R01	10K	RES-0805	805	0.0234
R02	10k	RES-0805	805	0.0234
R03	10k	RES-0805	805	0.0234
R04	10k	RES-0805	805	0.0234
R05	470	RES-0805	805	0.033
R06	10k	RES-0805	805	0.0234
R07	10k	RES-0805	805	0.0234
R08	470	RES-0805	805	0.033
RCV	RCV	LED-1206	1206-POL	0.105
SERIAL-PIC	CN-JST_3	CN-JST_3	JST3	0.12
SERIAL1	CN-JST_3	CN-JST_3	JST3	0.12
SND	SND	LED-1206	1206-POL	0.105
SW1	SW_B3S-1000	SW_B3S-1000	B3S-1000	0.55
U2	PIC18F6722	PIC18F6722	LQFP-64	15.68
U4	MAX3232	MAX3232	SOIC-16	1.5
Y2	18 pF	XTAL-CS10	CS10	1.013
SUM	-----	-----	-----	52.32

APPENDIX D: FIELD TEST DATA

Formatted Data from Mine

The following table includes formatted data from the site test beginning on Tuesday April 1, 2008 and ending on Monday April 7, 2008. The "Estimated Time" column was extrapolated using a recorded initial time of each tiltmeter's first transmission, and adding 30 minutes for the following time. A cell containing "XXXXX" was not used for analysis purposes, as the measurement recorded was either before or after the tiltmeter was securely fastened or removed from its permanent position. Those measurements adjacent to cells containing "XXXXX" were severe outliers when plotting the data.

Table D.1: Formatted Data from Test Mine Site

Terminal log file

Date: 4/1/2008 - 1:08:35 PM

	X- axis	Y- axis	Estimated Time		X- axis	Y- axis	Estimated Time		X- axis	Y- axis	Estimated Time
				B	1.505882	1.447058	XXXXX	C	1.470588	1.472941	XXXXX
A	1.447058	1.494117	XXXXX	B	1.304705	1.435294	XXXXX	C	1.399999	1.482352	XXXXX
A	1.482352	1.576470	4/1/2008 14:05	B	1.294117	1.458823	XXXXX	C	1.388235	1.470588	4/1/2008 14:05
A	1.494117	1.558823	14:35	B	1.288235	1.467058	4/1/2008 14:23	C	1.389411	1.470588	14:35
A	1.494117	1.552941	15:05	B	1.282352	1.460000	14:53	C	1.399999	1.482352	15:05
A	1.482352	1.542353	15:35	B	1.282352	1.460000	15:23	C	1.399999	1.470588	15:35
A	1.482352	1.545882	16:05	B	1.294117	1.458823	15:53	C	1.399999	1.470588	16:05
A	1.482352	1.541176	16:35	B	1.282352	1.458823	16:23	C	1.399999	1.470588	16:35
A	1.470588	1.539999	17:05	B	1.291764	1.458823	16:53	C	1.399999	1.471764	17:05
A	1.470588	1.529411	17:35	B	1.291764	1.460000	17:23	C	1.399999	1.470588	17:35
A	1.470588	1.529411	18:05	B	1.294117	1.470588	17:53	C	1.399999	1.470588	18:05
A	1.469411	1.529411	18:35	B	1.294117	1.462352	18:23	C	1.399999	1.474117	18:35
A	1.469411	1.529411	19:05	B	1.294117	1.470588	18:53	C	1.399999	1.470588	19:05
A	1.470588	1.529411	19:35	B	1.294117	1.471764	19:23	C	1.399999	1.471764	19:35
A	1.470588	1.529411	20:05	B	1.294117	1.470588	19:53	C	1.399999	1.470588	20:05
A	1.462352	1.529411	20:35	B	1.294117	1.470588	20:23	C	1.399999	1.474117	20:35
A	1.458823	1.529411	21:05	B	1.294117	1.469411	20:53	C	1.391764	1.482352	21:05
A	1.470588	1.529411	21:35	B	1.294117	1.470588	21:23	C	1.394117	1.470588	21:35
A	1.465882	1.529411	22:05	B	1.294117	1.471764	21:53	C	1.399999	1.482352	22:05
A	1.470588	1.529411	22:35	B	1.294117	1.469411	22:23	C	1.399999	1.482352	22:35
A	1.470588	1.529411	23:05	B	1.294117	1.470588	22:53	C	1.399999	1.470588	23:05
A	1.470588	1.529411	23:35	B	1.295294	1.468235	23:23	C	1.399999	1.482352	23:35
A	1.470588	1.529411	4/2/2008 0:05	B	1.294117	1.469411	23:53	C	1.399999	1.481176	4/2/2008 0:05
A	1.470588	1.529411	0:35	B	1.294117	1.470588	4/2/2008 0:23	C	1.399999	1.482352	0:35
A	1.469411	1.529411	1:05	B	1.295294	1.471764	0:53	C	1.388235	1.482352	1:05
A	1.464705	1.529411	1:35	B	1.295294	1.470588	1:23	C	1.399999	1.482352	1:35
A	1.465882	1.529411	2:05	B	1.295294	1.469411	1:53	C	1.399999	1.482352	2:05
A	1.470588	1.529411	2:35	B	1.294117	1.471764	2:23	C	1.399999	1.482352	2:35

A	1.462352	1.528235	3:05	B	1.295294	1.470588	2:53	C	1.399999	1.482352	3:05
A	1.470588	1.521176	3:35	B	1.298823	1.465882	3:23	C	1.388235	1.482352	3:35
A	1.470588	1.529411	4:05	B	1.294117	1.470588	3:53	C	1.398823	1.482352	4:05
A	1.468235	1.528235	4:35	B	1.294117	1.470588	4:23	C	1.388235	1.483529	4:35
A	1.458823	1.529411	5:05	B	1.295294	1.471764	4:53	C	1.399999	1.482352	5:05
A	1.467058	1.518823	5:35	B	1.294117	1.470588	5:23	C	1.392941	1.482352	5:35
A	1.465882	1.527058	6:05	B	1.294117	1.470588	5:53	C	1.399999	1.482352	6:05
A	1.458823	1.523529	6:35	B	1.296470	1.465882	6:23	C	1.399999	1.482352	6:35
A	1.458823	1.541176	7:05	B	1.297647	1.470588	6:53	C	1.395294	1.483529	7:05
A	1.460000	1.529411	7:35	B	1.294117	1.470588	7:23	C	1.396470	1.482352	7:35
A	1.467058	1.530588	8:05	B	1.294117	1.470588	7:53	C	1.399999	1.482352	8:05
A	1.470588	1.531764	8:35	B	1.294117	1.470588	8:23	C	1.392941	1.482352	8:35
A	1.460000	1.517647	9:05	B	1.301176	1.470588	8:53	C	1.397647	1.482352	9:05
A	1.470588	1.529411	9:35	B	1.294117	1.469411	9:23	C	1.389411	1.482352	9:35
A	1.470588	1.535294	10:05	B	1.294117	1.470588	9:53	C	1.399999	1.482352	10:05
A	1.482352	1.541176	10:35	B	1.294117	1.470588	10:23	C	1.399999	1.494117	10:35
A	1.482352	1.552941	11:05	B	1.297647	1.460000	10:53	C	1.399999	1.482352	11:05
A	1.470588	1.529411	11:35	B	1.294117	1.458823	11:23	C	1.411764	1.482352	11:35
A	1.488235	1.564705	12:05	B	1.294117	1.458823	11:53	C	1.422353	1.484705	12:05
A	1.482352	1.541176	12:35	B	1.282352	1.454117	12:23	C	1.414117	1.482352	12:35
A	1.494117	1.541176	13:05	B	1.294117	1.458823	12:53	C	1.409411	1.482352	13:05
A	1.494117	1.562353	13:35	B	1.294117	1.458823	13:23	C	1.399999	1.471764	13:35
A	1.482352	1.564705	14:05	B	1.294117	1.458823	13:53	C	1.399999	1.474117	14:05
A	1.482352	1.541176	14:35	B	1.294117	1.458823	14:23	C	1.388235	1.470588	14:35
A	1.485882	1.552941	15:05	B	1.294117	1.460000	14:53	C	1.399999	1.482352	15:05
A	1.482352	1.541176	15:35	B	1.294117	1.458823	15:23	C	1.399999	1.470588	15:35
A	1.471764	1.541176	16:05	B	1.294117	1.461176	15:53	C	1.399999	1.470588	16:05
A	1.482352	1.541176	16:35	B	1.294117	1.460000	16:23	C	1.399999	1.481176	16:35
A	1.470588	1.529411	17:05	B	1.295294	1.461176	16:53	C	1.399999	1.481176	17:05
A	1.470588	1.529411	17:35	B	1.292941	1.461176	17:23	C	1.399999	1.482352	17:35
A	1.470588	1.541176	18:05	B	1.294117	1.461176	17:53	C	1.389411	1.482352	18:05
A	1.470588	1.529411	18:35	B	1.294117	1.468235	18:23	C	1.399999	1.481176	18:35
A	1.470588	1.529411	19:05	B	1.294117	1.464705	18:53	C	1.390588	1.482352	19:05
A	1.458823	1.529411	19:35	B	1.295294	1.470588	19:23	C	1.394117	1.482352	19:35
A	1.467058	1.529411	20:05	B	1.295294	1.470588	19:53	C	1.399999	1.482352	20:05
A	1.463529	1.529411	20:35	B	1.294117	1.470588	20:23	C	1.399999	1.482352	20:35
A	1.458823	1.521176	21:05	B	1.295294	1.465882	20:53	C	1.388235	1.481176	21:05
A	1.464705	1.529411	21:35	B	1.294117	1.470588	21:23	C	1.399999	1.482352	21:35
A	1.470588	1.528235	22:05	B	1.295294	1.470588	21:53	C	1.388235	1.482352	22:05
A	1.462352	1.529411	22:35	B	1.294117	1.470588	22:23	C	1.398823	1.482352	22:35
A	1.465882	1.529411	23:05	B	1.297647	1.470588	22:53	C	1.388235	1.483529	23:05
A	1.469411	1.529411	23:35	B	1.305882	1.470588	23:23	C	1.399999	1.482352	23:35
A	1.460000	1.529411	4/3/2008 0:05	B	1.294117	1.470588	23:53	C	1.390588	1.482352	4/3/2008 0:05

A	1.470588	1.521176	0:35	B	1.301176	1.470588	4/3/2008 0:23	C	1.399999	1.482352	0:35
A	1.460000	1.519999	1:05	B	1.297647	1.470588	0:53	C	1.399999	1.483529	1:05
A	1.470588	1.517647	1:35	B	1.296470	1.470588	1:23	C	1.399999	1.483529	1:35
A	1.461176	1.524705	2:05	B	1.303529	1.470588	1:53	C	1.396470	1.482352	2:05
A	1.462352	1.517647	2:35	B	1.298823	1.470588	2:23	C	1.399999	1.482352	2:35
A	1.467058	1.517647	3:05	B	1.294117	1.470588	2:53	C	1.394117	1.482352	3:05
A	1.470588	1.523529	3:35	B	1.298823	1.470588	3:23	C	1.398823	1.482352	3:35
A	1.458823	1.519999	4:05	B	1.294117	1.470588	3:53	C	1.399999	1.482352	4:05
A	1.470588	1.525882	4:35	B	1.305882	1.470588	4:23	C	1.388235	1.482352	4:35
A	1.458823	1.529411	5:05	B	1.295294	1.470588	4:53	C	1.388235	1.484705	5:05
A	1.460000	1.522353	5:35	B	1.303529	1.470588	5:23	C	1.388235	1.482352	5:35
A	1.468235	1.519999	6:05	B	1.294117	1.470588	5:53	C	1.399999	1.482352	6:05
A	1.470588	1.517647	6:35	B	1.305882	1.470588	6:23	C	1.399999	1.482352	6:35
A	1.460000	1.517647	7:05	B	1.305882	1.470588	6:53	C	1.397647	1.482352	7:05
A	1.458823	1.521176	7:35	B	1.296470	1.470588	7:23	C	1.399999	1.482352	7:35
A	1.470588	1.517647	8:05	B	1.305882	1.470588	7:53	C	1.399999	1.483529	8:05
A	1.470588	1.517647	8:35	B	1.297647	1.470588	8:23	C	1.399999	1.482352	8:35
A	1.470588	1.518823	9:05	B	1.294117	1.470588	8:53	C	1.399999	1.482352	9:05
A	1.470588	1.529411	9:35	B	1.305882	1.470588	9:23	C	1.399999	1.482352	9:35
A	1.470588	1.529411	10:05	B	1.294117	1.470588	9:53	C	1.389411	1.482352	10:05
A	1.470588	1.517647	10:35	B	1.294117	1.470588	10:23	C	1.399999	1.482352	10:35
A	1.468235	1.529411	11:05	B	1.294117	1.470588	10:53	C	1.399999	1.482352	11:05
A	1.465882	1.541176	11:35	B	1.295294	1.470588	11:23	C	1.399999	1.482352	11:35
A	1.470588	1.510588	12:05	B	1.294117	1.470588	11:53	C	1.399999	1.483529	12:05
A	1.470588	1.541176	12:35	B	1.294117	1.470588	12:23	C	1.399999	1.482352	12:35
A	1.470588	1.530588	13:05	B	1.294117	1.470588	12:53	C	1.398823	1.482352	13:05
A	1.470588	1.528235	13:35	B	1.294117	1.469411	13:23	C	1.399999	1.482352	13:35
A	1.460000	1.521176	14:05	B	1.296470	1.464705	13:53	C	1.398823	1.482352	14:05
A	1.481176	1.517647	14:35	B	1.305882	1.470588	14:23	C	1.399999	1.482352	14:35
A	1.470588	1.525882	15:05	B	1.294117	1.470588	14:53	C	1.398823	1.482352	15:05
A	1.470588	1.517647	15:35	B	1.305882	1.470588	15:23	C	1.398823	1.489411	15:35
A	1.470588	1.529411	16:05	B	1.295294	1.470588	15:53	C	1.399999	1.482352	16:05
A	1.470588	1.529411	16:35	B	1.298823	1.470588	16:23	C	1.399999	1.482352	16:35
A	1.470588	1.517647	17:05	B	1.294117	1.470588	16:53	C	1.389411	1.482352	17:05
A	1.458823	1.523529	17:35	B	1.296470	1.470588	17:23	C	1.399999	1.482352	17:35
A	1.470588	1.517647	18:05	B	1.302352	1.470588	17:53	C	1.397647	1.482352	18:05
A	1.470588	1.519999	18:35	B	1.301176	1.470588	18:23	C	1.399999	1.482352	18:35
A	1.470588	1.518823	19:05	B	1.294117	1.470588	18:53	C	1.399999	1.487058	19:05
A	1.470588	1.529411	19:35	B	1.294117	1.470588	19:23	C	1.389411	1.482352	19:35
A	1.470588	1.517647	20:05	B	1.295294	1.470588	19:53	C	1.399999	1.482352	20:05
A	1.469411	1.517647	20:35	B	1.295294	1.470588	20:23	C	1.399999	1.482352	20:35
A	1.469411	1.519999	21:05	B	1.294117	1.470588	20:53	C	1.397647	1.483529	21:05
A	1.470588	1.518823	21:35	B	1.297647	1.470588	21:23	C	1.399999	1.482352	21:35

A	1.470588	1.518823	22:05	B	1.301176	1.470588	21:53	C	1.399999	1.483529	22:05
A	1.470588	1.519999	22:35	B	1.305882	1.470588	22:23	C	1.388235	1.482352	22:35
A	1.470588	1.521176	23:05	B	1.305882	1.470588	22:53	C	1.399999	1.482352	23:05
A	1.470588	1.527058	23:35	B	1.305882	1.470588	23:23	C	1.399999	1.482352	23:35
A	1.458823	1.517647	4/4/2008 0:05	B	1.305882	1.458823	23:53	C	1.399999	1.482352	4/4/2008 0:05
A	1.465882	1.517647	0:35	B	1.303529	1.460000	4/4/2008 0:23	C	1.399999	1.482352	0:35
A	1.464705	1.517647	1:05	B	1.305882	1.468235	0:53	C	1.396470	1.482352	1:05
A	1.470588	1.523529	1:35	B	1.294117	1.470588	1:23	C	1.399999	1.482352	1:35
A	1.470588	1.517647	2:05	B	1.305882	1.470588	1:53	C	1.399999	1.482352	2:05
A	1.468235	1.518823	2:35	B	1.305882	1.470588	2:23	C	1.396470	1.482352	2:35
A	1.458823	1.517647	3:05	B	1.295294	1.470588	2:53	C	1.399999	1.482352	3:05
A	1.470588	1.517647	3:35	B	1.305882	1.470588	3:23	C	1.391764	1.482352	3:35
A	1.470588	1.517647	4:05	B	1.305882	1.470588	3:53	C	1.399999	1.482352	4:05
A	1.468235	1.523529	4:35	B	1.305882	1.470588	4:23	C	1.388235	1.482352	4:35
A	1.470588	1.517647	5:05	B	1.305882	1.464705	4:53	C	1.399999	1.484705	5:05
A	1.461176	1.528235	5:35	B	1.304705	1.470588	5:23	C	1.399999	1.482352	5:35
A	1.470588	1.527058	6:05	B	1.305882	1.470588	5:53	C	1.399999	1.482352	6:05
A	1.470588	1.521176	6:35	B	1.305882	1.470588	6:23	C	1.399999	1.482352	6:35
A	1.458823	1.517647	7:05	B	1.305882	1.470588	6:53	C	1.399999	1.482352	7:05
A	1.470588	1.517647	7:35	B	1.304705	1.470588	7:23	C	1.388235	1.482352	7:35
A	1.470588	1.529411	8:05	B	1.304705	1.470588	7:53	C	1.399999	1.482352	8:05
A	1.470588	1.517647	8:35	B	1.296470	1.470588	8:23	C	1.399999	1.482352	8:35
A	1.470588	1.517647	9:05	B	1.305882	1.461176	8:53	C	1.391764	1.482352	9:05
A	1.470588	1.517647	9:35	B	1.305882	1.468235	9:23	C	1.399999	1.482352	9:35
A	1.470588	1.529411	10:05	B	1.305882	1.470588	9:53	C	1.399999	1.482352	10:05
A	1.458823	1.529411	10:35	B	1.305882	1.461176	10:23	C	1.399999	1.482352	10:35
A	1.470588	1.517647	11:05	B	1.298823	1.461176	10:53	C	1.392941	1.482352	11:05
A	1.470588	1.517647	11:35	B	1.304705	1.464705	11:23	C	1.399999	1.482352	11:35
A	1.470588	1.531764	12:05	B	1.297647	1.468235	11:53	C	1.388235	1.482352	12:05
A	1.470588	1.517647	12:35	B	1.298823	1.462352	12:23	C	1.399999	1.482352	12:35
A	1.461176	1.511764	13:05	B	1.294117	1.458823	12:53	C	1.399999	1.482352	13:05
A	1.470588	1.529411	13:35	B	1.303529	1.461176	13:23	C	1.399999	1.482352	13:35
A	1.470588	1.541176	14:05	B	1.294117	1.468235	13:53	C	1.399999	1.482352	14:05
A	1.470588	1.529411	14:35	B	1.295294	1.458823	14:23	C	1.399999	1.482352	14:35
A	1.470588	1.529411	15:05	B	1.301176	1.458823	14:53	C	1.399999	1.482352	15:05
A	1.464705	1.529411	15:35	B	1.294117	1.458823	15:23	C	1.399999	1.482352	15:35
A	1.470588	1.529411	16:05	B	1.296470	1.460000	15:53	C	1.399999	1.482352	16:05
A	1.470588	1.529411	16:35	B	1.294117	1.458823	16:23	C	1.399999	1.482352	16:35
A	1.470588	1.529411	17:05	B	1.298823	1.458823	16:53	C	1.399999	1.482352	17:05
A	1.470588	1.529411	17:35	B	1.302352	1.460000	17:23	C	1.398823	1.482352	17:35
A	1.470588	1.529411	18:05	B	1.297647	1.458823	17:53	C	1.398823	1.482352	18:05
A	1.470588	1.529411	18:35	B	1.294117	1.461176	18:23	C	1.399999	1.482352	18:35
A	1.470588	1.529411	19:05	B	1.305882	1.458823	18:53	C	1.399999	1.482352	19:05

A	1.470588	1.529411	19:35	B	1.305882	1.470588	19:23	C	1.399999	1.482352	19:35
A	1.470588	1.529411	20:05	B	1.304705	1.470588	19:53	C	1.399999	1.482352	20:05
A	1.470588	1.529411	20:35	B	1.300000	1.467058	20:23	C	1.399999	1.482352	20:35
A	1.470588	1.529411	21:05	B	1.300000	1.463529	20:53	C	1.399999	1.482352	21:05
A	1.470588	1.528235	21:35	B	1.296470	1.458823	21:23	C	1.395294	1.482352	21:35
A	1.470588	1.529411	22:05	B	1.294117	1.470588	21:53	C	1.399999	1.482352	22:05
A	1.470588	1.527058	22:35	B	1.305882	1.460000	22:23	C	1.398823	1.482352	22:35
A	1.470588	1.529411	23:05	B	1.294117	1.461176	22:53	C	1.399999	1.482352	23:05
A	1.470588	1.529411	23:35	B	1.305882	1.460000	23:23	C	1.399999	1.482352	23:35
A	1.470588	1.529411	4/5/2008 0:05	B	1.298823	1.470588	23:53	C	1.399999	1.482352	4/5/2008 0:05
A	1.470588	1.529411	0:35	B	1.305882	1.469411	4/5/2008 0:23	C	1.399999	1.482352	0:35
A	1.470588	1.524705	1:05	B	1.298823	1.458823	0:53	C	1.399999	1.482352	1:05
A	1.469411	1.528235	1:35	B	1.300000	1.470588	1:23	C	1.399999	1.482352	1:35
A	1.470588	1.529411	2:05	B	1.305882	1.458823	1:53	C	1.399999	1.482352	2:05
A	1.470588	1.529411	2:35	B	1.295294	1.458823	2:23	C	1.399999	1.482352	2:35
A	1.468235	1.529411	3:05	B	1.305882	1.461176	2:53	C	1.399999	1.482352	3:05
A	1.470588	1.529411	3:35	B	1.294117	1.469411	3:23	C	1.397647	1.482352	3:35
A	1.470588	1.529411	4:05	B	1.305882	1.469411	3:53	C	1.399999	1.482352	4:05
A	1.470588	1.517647	4:35	B	1.294117	1.469411	4:23	C	1.398823	1.482352	4:35
A	1.470588	1.517647	5:05	B	1.305882	1.460000	4:53	C	1.399999	1.482352	5:05
A	1.470588	1.529411	5:35	B	1.304705	1.458823	5:23	C	1.399999	1.482352	5:35
A	1.461176	1.529411	6:05	B	1.305882	1.458823	5:53	C	1.399999	1.482352	6:05
A	1.470588	1.529411	6:35	B	1.304705	1.465882	6:23	C	1.399999	1.482352	6:35
A	1.470588	1.528235	7:05	B	1.305882	1.470588	6:53	C	1.399999	1.482352	7:05
A	1.470588	1.529411	7:35	B	1.305882	1.470588	7:23	C	1.399999	1.482352	7:35
A	1.470588	1.528235	8:05	B	1.303529	1.470588	7:53	C	1.399999	1.482352	8:05
A	1.470588	1.529411	8:35	B	1.294117	1.460000	8:23	C	1.399999	1.482352	8:35
A	1.470588	1.529411	9:05	B	1.304705	1.458823	8:53	C	1.399999	1.482352	9:05
A	1.470588	1.532941	9:35	B	1.294117	1.465882	9:23	C	1.399999	1.482352	9:35
A	1.470588	1.529411	10:05	B	1.295294	1.458823	9:53	C	1.398823	1.482352	10:05
A	1.470588	1.529411	10:35	B	1.296470	1.458823	10:23	C	1.399999	1.482352	10:35
A	1.470588	1.529411	11:05	B	1.295294	1.458823	10:53	C	1.398823	1.482352	11:05
A	1.470588	1.529411	11:35	B	1.294117	1.461176	11:23	C	1.399999	1.482352	11:35
A	1.481176	1.541176	12:05	B	1.294117	1.458823	11:53	C	1.411764	1.481176	12:05
A	1.478823	1.541176	12:35	B	1.294117	1.458823	12:23	C	1.409411	1.482352	12:35
A	1.482352	1.541176	13:05	B	1.294117	1.458823	12:53	C	1.403529	1.482352	13:05
A	1.494117	1.552941	13:35	B	1.297647	1.458823	13:23	C	1.399999	1.482352	13:35
A	1.494117	1.552941	14:05	B	1.295294	1.458823	13:53	C	1.399999	1.480000	14:05
A	1.494117	1.554117	14:35	B	1.292941	1.458823	14:23	C	1.388235	1.482352	14:35
A	1.482352	1.552941	15:05	B	1.294117	1.458823	14:53	C	1.397647	1.470588	15:05
A	1.482352	1.552941	15:35	B	1.294117	1.458823	15:23	C	1.411764	1.470588	15:35
A	1.482352	1.541176	16:05	B	1.294117	1.458823	15:53	C	1.399999	1.470588	16:05
A	1.470588	1.541176	16:35	B	1.294117	1.458823	16:23	C	1.399999	1.482352	16:35

A	1.470588	1.532941	17:05	B	1.300000	1.458823	16:53	C	1.399999	1.474117	17:05
A	1.471764	1.541176	17:35	B	1.304705	1.458823	17:23	C	1.399999	1.482352	17:35
A	1.470588	1.529411	18:05	B	1.304705	1.461176	17:53	C	1.399999	1.482352	18:05
A	1.470588	1.529411	18:35	B	1.305882	1.458823	18:23	C	1.399999	1.482352	18:35
A	1.470588	1.529411	19:05	B	1.295294	1.458823	18:53	C	1.399999	1.474117	19:05
A	1.470588	1.529411	19:35	B	1.297647	1.458823	19:23	C	1.399999	1.482352	19:35
A	1.470588	1.529411	20:05	B	1.300000	1.468235	19:53	C	1.398823	1.482352	20:05
A	1.470588	1.529411	20:35	B	1.295294	1.469411	20:23	C	1.399999	1.482352	20:35
A	1.464705	1.529411	21:05	B	1.305882	1.458823	20:53	C	1.397647	1.481176	21:05
A	1.470588	1.529411	21:35	B	1.305882	1.458823	21:23	C	1.399999	1.482352	21:35
A	1.470588	1.529411	22:05	B	1.304705	1.458823	21:53	C	1.399999	1.482352	22:05
A	1.458823	1.529411	22:35	B	1.305882	1.458823	22:23	C	1.399999	1.482352	22:35
A	1.467058	1.529411	23:05	B	1.305882	1.458823	22:53	C	1.388235	1.482352	23:05
A	1.470588	1.529411	23:35	B	1.294117	1.470588	23:23	C	1.399999	1.482352	23:35
A	1.470588	1.529411	4/6/2008 0:05	B	1.294117	1.467058	23:53	C	1.399999	1.482352	4/6/2008 0:05
A	1.469411	1.523529	0:35	B	1.305882	1.470588	4/6/2008 0:23	C	1.399999	1.482352	0:35
A	1.470588	1.529411	1:05	B	1.298823	1.458823	0:53	C	1.399999	1.482352	1:05
A	1.470588	1.529411	1:35	B	1.294117	1.470588	1:23	C	1.398823	1.482352	1:35
A	1.470588	1.522353	2:05	B	1.297647	1.470588	1:53	C	1.388235	1.482352	2:05
A	1.470588	1.517647	2:35	B	1.305882	1.460000	2:23	C	1.399999	1.482352	2:35
A	1.470588	1.518823	3:05	B	1.304705	1.470588	2:53	C	1.399999	1.482352	3:05
A	1.470588	1.519999	3:35	B	1.297647	1.470588	3:23	C	1.399999	1.482352	3:35
A	1.470588	1.527058	4:05	B	1.305882	1.458823	3:53	C	1.399999	1.482352	4:05
A	1.470588	1.529411	4:35	B	1.305882	1.470588	4:23	C	1.399999	1.482352	4:35
A	1.470588	1.517647	5:05	B	1.297647	1.458823	4:53	C	1.392941	1.482352	5:05
A	1.458823	1.528235	5:35	B	1.305882	1.470588	5:23	C	1.399999	1.482352	5:35
A	1.470588	1.517647	6:05	B	1.298823	1.458823	5:53	C	1.397647	1.482352	6:05
A	1.470588	1.529411	6:35	B	1.294117	1.458823	6:23	C	1.389411	1.487058	6:35
A	1.462352	1.518823	7:05	B	1.305882	1.458823	6:53	C	1.399999	1.482352	7:05
A	1.470588	1.521176	7:35	B	1.305882	1.458823	7:23	C	1.388235	1.487058	7:35
A	1.470588	1.517647	8:05	B	1.294117	1.470588	7:53	C	1.389411	1.482352	8:05
A	1.470588	1.518823	8:35	B	1.294117	1.470588	8:23	C	1.390588	1.482352	8:35
A	1.469411	1.517647	9:05	B	1.296470	1.460000	8:53	C	1.399999	1.482352	9:05
A	1.470588	1.523529	9:35	B	1.305882	1.470588	9:23	C	1.399999	1.482352	9:35
A	1.470588	1.529411	10:05	B	1.294117	1.458823	9:53	C	1.399999	1.482352	10:05
A	1.470588	1.518823	10:35	B	1.297647	1.458823	10:23	C	1.399999	1.482352	10:35
A	1.470588	1.529411	11:05	B	1.294117	1.458823	10:53	C	1.398823	1.482352	11:05
A	1.470588	1.524705	11:35	B	1.305882	1.458823	11:23	C	1.398823	1.482352	11:35
A	1.470588	1.528235	12:05	B	1.305882	1.470588	11:53	C	1.399999	1.482352	12:05
A	1.470588	1.529411	12:35	B	1.305882	1.458823	12:23	C	1.399999	1.482352	12:35
A	1.470588	1.529411	13:05	B	1.305882	1.468235	12:53	C	1.399999	1.482352	13:05
A	1.470588	1.528235	13:35	B	1.295294	1.470588	13:23	C	1.399999	1.483529	13:35
A	1.470588	1.521176	14:05	B	1.305882	1.465882	13:53	C	1.399999	1.482352	14:05

A	1.470588	1.529411	14:35	B	1.305882	1.458823	14:23	C	1.399999	1.482352	14:35
A	1.470588	1.529411	15:05	B	1.294117	1.464705	14:53	C	1.399999	1.482352	15:05
A	1.470588	1.529411	15:35	B	1.305882	1.470588	15:23	C	1.399999	1.482352	15:35
A	1.470588	1.529411	16:05	B	1.297647	1.458823	15:53	C	1.399999	1.482352	16:05
A	1.470588	1.529411	16:35	B	1.294117	1.460000	16:23	C	1.399999	1.482352	16:35
A	1.470588	1.529411	17:05	B	1.294117	1.458823	16:53	C	1.399999	1.482352	17:05
A	1.470588	1.528235	17:35	B	1.294117	1.458823	17:23	C	1.399999	1.490588	17:35
A	1.470588	1.517647	18:05	B	1.305882	1.465882	17:53	C	1.394117	1.482352	18:05
A	1.470588	1.517647	18:35	B	1.304705	1.470588	18:23	C	1.399999	1.482352	18:35
A	1.470588	1.523529	19:05	B	1.305882	1.468235	18:53	C	1.399999	1.482352	19:05
A	1.470588	1.529411	19:35	B	1.294117	1.458823	19:23	C	1.399999	1.482352	19:35
A	1.470588	1.518823	20:05	B	1.305882	1.467058	19:53	C	1.397647	1.482352	20:05
A	1.468235	1.528235	20:35	B	1.295294	1.461176	20:23	C	1.395294	1.482352	20:35
A	1.470588	1.525882	21:05	B	1.300000	1.458823	20:53	C	1.398823	1.482352	21:05
A	1.469411	1.525882	21:35	B	1.305882	1.462352	21:23	C	1.395294	1.482352	21:35
A	1.458823	1.529411	22:05	B	1.305882	1.464705	21:53	C	1.399999	1.482352	22:05
A	1.470588	1.529411	22:35	B	1.294117	1.458823	22:23	C	1.399999	1.482352	22:35
A	1.469411	1.518823	23:05	B	1.305882	1.460000	22:53	C	1.399999	1.482352	23:05
A	1.470588	1.528235	23:35	B	1.304705	1.458823	23:23	C	1.399999	1.482352	23:35
A	1.462352	1.521176	4/7/2008 0:05	B	1.294117	1.458823	23:53	C	1.395294	1.494117	4/7/2008 0:05
A	1.462352	1.529411	0:35	B	1.305882	1.470588	4/7/2008 0:23	C	1.399999	1.483529	0:35
A	1.470588	1.524705	1:05	B	1.304705	1.458823	0:53	C	1.399999	1.482352	1:05
A	1.470588	1.529411	1:35	B	1.305882	1.460000	1:23	C	1.399999	1.482352	1:35
A	1.469411	1.529411	2:05	B	1.294117	1.458823	1:53	C	1.399999	1.483529	2:05
A	1.467058	1.517647	2:35	B	1.305882	1.458823	2:23	C	1.394117	1.494117	2:35
A	1.470588	1.527058	3:05	B	1.304705	1.468235	2:53	C	1.398823	1.482352	3:05
A	1.458823	1.529411	3:35	B	1.294117	1.468235	3:23	C	1.399999	1.482352	3:35
A	1.470588	1.521176	4:05	B	1.305882	1.464705	3:53	C	1.399999	1.482352	4:05
A	1.458823	1.517647	4:35	B	1.305882	1.470588	4:23	C	1.397647	1.494117	4:35
A	1.470588	1.519999	5:05	B	1.305882	1.470588	4:53	C	1.388235	1.482352	5:05
A	1.470588	1.523529	5:35	B	1.294117	1.469411	5:23	C	1.394117	1.482352	5:35
A	1.470588	1.529411	6:05	B	1.295294	1.469411	5:53	C	1.395294	1.482352	6:05
A	1.458823	1.517647	6:35	B	1.305882	1.469411	6:23	C	1.399999	1.482352	6:35
A	1.470588	1.517647	7:05	B	1.305882	1.461176	6:53	C	1.398823	1.484705	7:05
A	1.469411	1.517647	7:35	B	1.305882	1.458823	7:23	C	1.399999	1.482352	7:35
A	1.470588	1.522353	8:05	B	1.305882	1.458823	7:53	C	1.398823	1.484705	8:05
A	1.469411	1.517647	8:35	B	1.305882	1.470588	8:23	C	1.399999	1.482352	8:35
A	1.470588	1.522353	9:05	B	1.295294	1.458823	8:53	C	1.399999	1.400000	XXXXX

Line charts were created from these data points, and can be found in Figure 6.5 and Figure 6.6 for the X- and Y- axis voltage outputs.

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