Low-cost Ocean Current and Temperature Sensor (LOCATS)

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Like all major planetary systems, the earth’s cryosphere is extremely dynamic and is influenced by many variables that are yet to be quantified. Antarctica is a good example of this, where floating ice shelves hold back massive glaciers. The warm ocean water flowing under the ice melts it away from the bottom as environmental conditions melt it from the top. Unfortunately, there is sparse data to profile the oceanic system below the ice shelves, and very little of it can be used to truly describe how the system changes with seasons and tidal harmonics. This is of concern recently, as ice shelves in Antarctica are showing signs of collapse. The goal of the LOCATS project is to design and build a prototype sensor to gain a better understanding of the energy flow below the ice. The sensor is designed to be deployed in large arrays to gain macro scale measurements of Antarctic ocean currents and temperatures. Each low cost individual sensor will be designed to withstand and collect data in the harsh polar environment for a year at minimum. In order to run a year long mission the sensor is designed to log data periodically and run on low power. As of March 2016 the LOCATS team has developed a working prototype.

Nomenclature

- **LOCATS**: Low Cost Ocean Current and Temperature Sensor
- **ADC**: Analog to digital converter
- **ADCP**: Acoustic Doppler Current Profiler
- **Biofouling**: Detrimental effect on equipment in long term biological exposure.
- **CDW**: Circumpolar Deep Water - Oceanic water surrounding Antarctica
- **DITL**: Day In The Life test

1. Introduction

The goal of LOCATS is to develop a low cost prototype oceanographic instrument to measure the temperature and velocity of circumpolar deep water. The data will be used to further develop understanding and models of the Antarctic oceanic system.

The Antarctic oceanic environment is a complex system subject to many different variables, for example water temperature, salinity, and mixing. Ice shelves are part of this dynamic oceanic energy system. It is a place where glaciers and ice streams flow off of the continent into the sea to form and feed ice shelves that may last for thousands of years along coastlines protected by rocky peninsulas and islands. The constant overland flow of ice adding to the shelves, along with frequent fracturing of shelves into icebergs, forms a dynamic stability. However, the ice shelves are now showing signs of breaking up and collapsing completely. This would cause their source glaciers and ice streams to flow completely into the ocean, thus increasing the sea level. Unfortunately, the ocean’s own influence on this system is poorly understood. Currently available commercial sensors are highly accurate and equally expensive. As a result, creating an entire network of sensors to record the environment is extremely difficult and high-risk. The goal of this project is to create a sensor specifically to allow for low-cost and low-risk array deployment while retaining a usable level of precision.

Glenn Grant, the project’s principal investigator, proposed the project to Space Grant teams prior to the fall 2015 school year. Once accepted, a team was created to design and build a prototype for the project.
The first few weeks of the project were spent defining the mission that the sensor would carry out. Once this was accomplished the team moved on to develop a first iteration design. The first iteration design was completed by November 2015 and work began in construction of a working prototype. The team’s efforts in March 2016 have been focused on characterization of the sensor. Summer plans for the sensor include a short term ocean deployment and further testing.

2. Design

The best way to measure water currents in the ocean for this project is to use a drag tilt sensor. Other methods may be prohibited by complexity, expense, or power consumption. A drag tilt sensor measures the velocity of a fluid indirectly by correlating speed to orientation. The temperature will be measured directly by sensors in the pressure vessel. The design of the sensor can be broken into two major systems. The electronics system takes care of sensing and data handling. The structural system is designed to protect the electronics while operating in extreme conditions. Both systems must work in conjunction to meet the project requirements.

I. Requirements

Major requirements are explained below, while all requirements can be found in the appendix. Each individual sensor shall cost no more than $1000. For the collected data to be scientifically useful the temperature must be accurate to within 0.05 degrees Celsius between -2 to 10 °C. The current speed must be accurate to 0.25 cm/s from 0 to 25 cm/s. The heading must be determined to within 5 degrees and the time and date accurate to within 5 minutes over the course of a year. The sensor shall be designed to log data for a minimum duration of one year in a circumpolar deep water environment.

II. Commercial Sensors

Traditionally, accurate water velocity measurements along a water depth profile have been taken using Acoustic Doppler Current Profilers (ADCP). ADCPs cost several thousand dollars and their high cost can limit the spatial granularity of many projects’ measurements. A few low cost alternatives to ADCPs have been developed. However, as of now, none of these alternatives have been able to achieve accuracies comparable to ADCPs. Furthermore, many of the low-cost ADCP alternatives have not been designed to withstand the pressures present at large depths underwater and still remain above one thousand dollars per unit. For these reasons, our project has set out to develop a sub-one thousand dollar ADCP alternative, with comparable accuracy and one that can deployed at large depths and pressures. The low-cost and small form factor of our design will allow our project to achieve high measurement density and therefore give researchers greater insight into the spatial variation of ocean current and temperature below Antarctic ice shelves.

III. Functional Block Diagram

The functional block diagram outlines how components of the design interact with one another. The structure encloses the electronics, serving as protection from the environment as well as an attachment point to the mooring line that will string several sensors together. The electronics package includes a power supply, sensors, and a command and data handling system. Raw voltage from the power system is regulated to the operating potential of 3.3V and fed to the microcontroller, real time clock, and the power distributor. The microcontroller sends a signal to the power distributor when necessary to wake the sensors and write data. The microcontroller takes readings from the sensing package which includes a real time clock, temperature sensors, and orientation sensors. This data is finally saved to solid state storage. The functional block diagram is represented in Figure (1).

IV. Concept of Operations

A graphical representation of the concept of operations is given in Figure (2). The sensor has been designed with a large scale deployment in mind. When this time comes, the initial assembly and integration of the mechanical and electrical subsystems will be taking place at Colorado Space Grant Consortium in Boulder Colorado at least two months before being sent for deployment. Quality assurance tests will be performed
Figure 1. Functional Block Diagram
prior to delivery. Once all the safety checks are passed for both subsystems, integration of all components will occur a week before shipping the complete sensor, and a complete inventory will be created. Once delivered to the research vessel, travel to the deployment site may take several weeks. Hours before deployment in the research vessel, the person in charge of the sensor deployment will follow the deployment checklist to ensure that each sensor is fully operational. The sensors will be deployed in a predetermined location and left for the mission duration. The sensor will periodically log data until it is either recovered or runs out of electrical power. When weather allows the sensors will be recovered and the data sent to Boulder for analysis.

![Figure 2. Antarctic Concept of Operations](image)

V. Structure

1. Outer Structure

The pressure vessel is designed to protect the electronics system in the circumpolar deep water environment. It will encounter pressure up to 12 MPa, a high salinity, temperatures near zero degrees Celsius and biofouling. The shell of the vessel is made of two flanged cylindrical halves with an o-ring interfacing between the two. Both halves have an inner diameter of 3.125 inches and a wall thickness of 0.2 inches. These dimensions were chosen to ensure the air pocket within the vessel was large enough to ensure neutral buoyancy in saltwater. The upper half is one half inch taller than the lower half in order to accommodate an eyebolt which interfaces with the mooring line attachment system. The lower half includes an o-ring groove along its upper face. The seal is detailed in the next section. Eight 8-32 bolts are tightened in a star pattern to their respective locking nuts along the flange, sandwiching the o-ring between the two halves (Figure (3)). For the current version of the prototype, all machining was done on a lathe so that parts are radially symmetric.

2. Pressure Seal

The seal is comprised of a single 90 durometer 2-240 nitrile o-ring fitted into a static face seal groove. A high durometer o-ring was chosen so that at high pressure it does not deform. A nitrile o-ring is used to combat degradation from salt water. The o-ring cross sectional size was chosen so that it can be accommodated between the bolt holes and inner diameter of the flange, as well as being large enough to be compressed
before the seal faces make contact. A static o-ring seal is used due to its reliability at high pressures and ease of machining (Figure (4)). The contacting vessel faces have been polished to a mirror finish to ensure the seal is not obstructed by uneven surfacing or sharp micro ridges.

### 3. Inner Structure

The inner structure is designed to achieve several goals. It must maintain ample separation between the accelerometer/magnetometer and other components to avoid interference. Additionally it must hold the thermistors in contact with the outer structure to aid in thermal conduction. Finally it is designed to be lightweight so that it does not compromise the neutral buoyancy of the sensor. Two designs are in contention for the final model. The first is a traditional design using three columns of aluminum standoffs with several hardware plates. Being made from off the shelf parts this design has the advantage for a large scale production run but it is heavier than the other model. The second option is a 3D printed frame for the same hardware plates. This design is significantly lighter, more than half, but not suitable for large scale production.
VI. Power

The power system must be capable of driving the sensor for the full mission duration of a year. Furthermore, it must be resilient in harsh thermal conditions as there is no thermal control system onboard. The batteries will experience temperatures near zero Celsius continuously for a year or more on end. Due to tilt sensitivity the sensor must remain positively buoyant, therefore, the mass of the sensor is restricted. After extensive testing and modification the active current was determined to be 40 mA. The quiescent (sleeping) current is $10.7\mu$A. Over the course of a year it is expected that the sensor will require 1.75 Ah. The sensor is currently powered by three Energizer Ultimate Lithium AA size cells in series. The maximum voltage is 5.4V which is adequate to guard against voltage sag in cold temperatures. The energy capacity is between 3 and 4 amp hours.

VII. Command and Data Handling

The electronics system is based around an ATmega328 microcontroller in an Arduino Pro Mini. The Arduino controls all of the sensors through the Arduino programming language, and sensor communication is performed through the I2C and SPI buses as well as the digital and analog inputs/outputs. For design ease and data protection, data is written to a microSD card onboard. To save power, the processor will enter sleep mode, and data is taken only during the active portion of the duty cycle, which can be seen in the accompanying diagram (Figure (5)). A typical duty cycle has the following structure: processor wake up with the alarm from the real-time clock; power up of power rail; sensor poll for data collection and subsequent data writing to the SD card; power down of power rail; setting of RTC alarm; and entering sleep.
VIII. Sensing

The temperature sensing system is comprised of thermistors, a wheatstone bridge, analog to digital converters, and of course the microcontroller. Thermistors are a kind of electrical resistor that predictably decrease in resistance when heated. With a circuit to measure the resistance this effect can be transduced into a temperature measurement. The resistance measuring circuit is used in LOCATS is called a Wheatstone bridge. It offers high precision and low sensitivity to changes in temperature. The Wheatstone bridge provides a differential voltage based on the input voltage and the resistance of the thermistor. Sixteen bit analog to digital converters then provide the microcontroller with a digital interpretation of the differential. The digital value is stored on the SD card and can be translated into a temperature measurement in post-processing.

The ocean current sensor is designed as a high sensitivity drag-tilt device. This means that it relies on the current to impart a drag force on the pressure vessel that will cause a measureable tilt. This tilt is then recorded as a change in the ambient direction of the acceleration of gravity by the onboard three axis accelerometer. The correlation between the tilt measurement and the velocity of the current is highly dependent on physical qualities of the sensor such as its coefficient of drag, shape, mass distribution and buoyancy. The effect of these parameters has been modeled as a guide but to achieve the required precision the final sensor must be characterized empirically. Additionally the sensor is equipped with a three axis magnetometer. In conjunction with the readings from the accelerometer, this data allows the sensor’s orientation relative to a fixed Earth coordinate system to be determined.

3. Test Methods and Results

I. Temperature

Several temperature tests were performed in order to calibrate the sensors. Furthermore, the tests provide a sense of the precision that could be obtained from the temperature sensing system. A well stirred mixture of ice and freshwater was used for the tests as its temperature is known to be zero degrees Celsius. The first test, only designed to test the thermistors, lasted approximately half an hour and took one reading every second. The second test incorporated the thermistors into their location in the pressure vessel and lasted for nearly 18 hours. In this test one thermistor was left near the electronics in an effort to measure heat buildup. Furthermore this day in the life test (DITL) took the average of 30 samples as one reading every minute.

To perform analysis of the temperature test results a MatLab script was written. For a specified period the script calculated the mean, median, and standard deviation of the data. The results from the first test showed that over a period of ten seconds the standard deviation of measurements was 0.01 degrees Celsius. In the long term test the standard deviation over a period of ten minutes was 0.005. The increase in accuracy in the DITL test could be explained by the larger mass of water used or by the improved sampling strategy. Assuming that the water temperature was constant over these periods shows that the system is between five and ten times as precise as required.

Figure (6) is a brief statistical report on the temperature measurement precision from the day in the life test. The sample is eleven measurements over the course of eleven minutes in the middle of the night. Because of the short period and steady environmental factors it is fair to assume that the temperature of the water was constant for this period. In the top row one will find plots of the ADC value and the calculated temperature with respect to time. The next row contains statistical results in terms of ADC value and temperature. Over this period the greatest standard deviation of temperature reading was less than 0.0051 of a degree Celsius. This means that 99.7% of temperature readings were within 0.015 °C. Finally histograms are presented for the temperature readings from each thermistor. These results suggest that the sensor meets temperature precision requirements. It can be seen that the average thermistor readings vary by up to 1 °C but this offset can be removed by calibration to a known source. The thermistors responded similarly throughout the test. Their responses were compared by taking the difference in differences between readings. Over the course of 500 minutes, the two exterior thermistors experienced an average rate difference of $7 \cdot 10^{-4}$ °C.
II. Orientation

To test the precision of tilt measurement the team obtained an azimuth-elevation tilt rig. It is mechanically geared so that each turn of the crank wheels corresponds to one degree of rotation. The test platform was leveled with a bubble level, and the pressure vessel was secured to the platform. A rest period was allowed to mark the beginning of the test and to allow for a calibration reading. Thirty data samples were averaged and recorded every second. Every 20 seconds, the rig was rotated one degree in elevation until 90 degrees was reached. A similar test will be performed in the azimuth axis to determine the accuracy of the heading reading.

The data from the tilt test was plotted in MatLab (Figure (7)). Visual inspection found that the test was insufficient to characterize the precision of the tilt measurement. The cause of this failure comes from ambiguity between the resolution of the ADC and the step size used in the test. Discrete steps of approximately one degree are visible in the plot of inclination with respect to time though few data points lie in between. It is hard to tell from this data whether the maximum resolution of the orientation measurement system is fine enough to meet requirements. A better test will be carried out in which the sensor is rotated by less than a quarter degree. This data will help identify the maximum resolution of the orientation measurement system.

III. Future Tests

The pressure vessel is ready to be tested to its full operating pressure of 12 MPa. This test will occur this summer, most likely at the University of Washington. The results will verify whether or not the pressure vessel is capable of protecting the electronics up to 1000 meters below the surface of the ocean.

Several electrical current consumption tests have been performed on the first iteration hardware. As the second iteration hardware is completed, it will be similarly characterized. Furthermore, once the system has settled into its second iteration, a long term power consumption test will be performed to identify the performance of the power system against requirements. The project will forego a clock accuracy test as the results are not of incredible importance and the effort required to perform a quality test would be too great.

4. Errors and Uncertainties

I. Temperature

To calculate temperature at any given time, one must use circuit theory to determine the resistance of the thermistors in the Wheatstone bridge and then use the thermistor equation. The uncertainty in this method can be directly calculated for each data point, and the sensitivity of it to its various variables can be determined. The explicit equations can be found in the appendix. For highest clarity, the uncertainty equation was plotted four times with respect to the four variables that could affect it with all others remaining constant. These graphs can be seen in the appendix.

Interesting, there is no sensitivity to $T_0$ (the temperature at which the thermistor was calibrated) or $V_{in}$ (the voltage incoming to the Wheatstone), and the sensitivity to $R$ (the resistance of all resistors on the bridge) and $\beta$ (a thermistor property) is linear, as expected.

After the temperature test was performed, a sample of ADC values from a reasonably stable time frame was examined to determine the resolution of the ADC. During the assessment, it was discovered an ADC value change of 1 gave a temperature change of $2 \cdot 10^{-3}$ °C.

II. Orientation

There are several factors affecting the attitude determination system that present a significant challenge. A general model of these effects was determined mathematically and used to guide the design. Figures (8) and (9) show a free body diagram of the sensor and the results of the sensitivity analysis given a particular state of the variables in the free body diagram. The 3D surface in Figure (9) represents the measured tilt angle across a range of drag forces $F$ and center of pressure $d$. The first of the challenges is that the calculation of direction and velocity from each reading assumes a static state at the time of record. If the sensor were to be in motion at the time, then the accelerometer readings would not fall in line with the assumptions and therefore would skew the results. Fortunately the environment is not expected to change rapidly or oscillate on a small scale, and the sheer amount of data recovered will help to reduce the error from non-static effects.
Furthermore the recorded tilt angle depends heavily on the buoyancy of the sensor. Even if every sensor had an identical mass, changes in salinity in the water column could perhaps cause significant variations in readings at identical water velocities. Yet another challenge is due to the precision of the measurements by the accelerometer. The values are limited by the resolution of the onboard analog to digital converter. This causes problems near vertical and horizontal orientations. Near vertical the heading reading is unstable and near horizontal the velocity reading is too stable. This implies that there is a range of velocities in which the orientation may be trusted. The sensor must be tuned to operate in that specific range of current velocities.

III. Next Steps and Future Improvements

As of March 2016, the sensor has yet to be tested in a saltwater or high pressure environment for buoyancy or structural strength. The longevity of the sensor has also yet to be tested, and finer tests have yet to be performed. These tests are planned for the summer of 2016.

In this iteration it is necessary to assume that the ocean currents are horizontal. In a future version of the sensor, knowing both the salinity and tension at the attachment point of each sensor in the mooring line would provide enough data to model the current in 3D along the entire water column. Future iterations of the sensor would also incorporate a magnetometer and accelerometer of higher precision to increase precision of current velocity measurements and calculations.

5. Conclusion

The goal of the LOCATS project is to develop and test a prototype oceanographic instrument capable of measuring water current and velocity. The project has so far built a first iteration drag-tilt prototype and begun preliminary testing. An individual unit can be produced for under $300, well below the cost of a commercial sensor. The sensor has been determined to exceed temperature measurement requirements. More testing is scheduled for Summer 2016 to validate or invalidate orientation measurement, mission life, and operating condition requirements. Future plans for the Low Cost Ocean Current and Temperature Sensor project include building and testing a second iteration design in a short term ocean deployment.

Appendix

Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>The sensor shall record current velocity, water temperature, geographic location, and time.</td>
<td>Initial Requirements</td>
</tr>
<tr>
<td>0.2</td>
<td>The data logging mission shall last one year at minimum.</td>
<td>Initial Requirements</td>
</tr>
<tr>
<td>0.3</td>
<td>The sensor shall be deployed in the Antarctic Ocean up to a depth of 1000 meters on a mooring line.</td>
<td>Initial Requirements</td>
</tr>
<tr>
<td>0.4</td>
<td>The production sensor shall be completed by December 11 2015.</td>
<td>Initial Requirements</td>
</tr>
<tr>
<td>0.5</td>
<td>The production sensor shall cost less than $1000 per unit.</td>
<td>Initial Requirements</td>
</tr>
<tr>
<td>0.6</td>
<td>The prototype sensor shall be tested and calibrated to ensure proper function in mission environment.</td>
<td>Initial Requirements</td>
</tr>
</tbody>
</table>

I. Temperature Calculation and Uncertainty Equations

To calculate the temperature in Kelvin from raw thermistor values, the following equations are used:
<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>The sensor shall record one sample per hour at minimum.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.2</td>
<td>The current velocity shall be recorded to within 0.25 cm/s in the range of 0 to 25 cm/s.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.3</td>
<td>Temperature measurements shall be made to within 0.05 °C in the range of -2 to 10 °C.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.4</td>
<td>Compass direction of current shall be known to within 5 °.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.5</td>
<td>Time shall be known within five minutes over the course of a year.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.6</td>
<td>Data collected from sensors shall be recorded in their most basic forms.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.7</td>
<td>Each sensor shall write a data file including a header that specifies the serial number, and calibration values.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.8</td>
<td>Battery voltage shall be recorded with each data sample.</td>
<td>0.1</td>
</tr>
<tr>
<td>1.9</td>
<td>Thermistor bridge source voltage recorded with each sample.</td>
<td>0.1</td>
</tr>
<tr>
<td>2.1</td>
<td>The sensor shall carry enough energy to power data logging systems for the full logging mission length of one year.</td>
<td>0.2</td>
</tr>
<tr>
<td>2.2</td>
<td>Loss of power shall not jeopardize any previously collected data.</td>
<td>0.2</td>
</tr>
<tr>
<td>2.3</td>
<td>Memory shall be allocated to store all collected data for the duration of the mission.</td>
<td>0.2</td>
</tr>
<tr>
<td>2.4</td>
<td>Environmental factors shall not interrupt data collection.</td>
<td>0.2</td>
</tr>
<tr>
<td>2.5</td>
<td>Biofouling shall not affect the precision of measurements.</td>
<td>0.2</td>
</tr>
<tr>
<td>3.1</td>
<td>The sensor shall be designed to operate up to 1000 meters below the surface in circumpolar deep water.</td>
<td>0.3</td>
</tr>
<tr>
<td>3.2</td>
<td>Several sensors shall be attached to the same mooring line.</td>
<td>0.3</td>
</tr>
<tr>
<td>3.3</td>
<td>Each sensor shall include a method for attaching to the mooring line.</td>
<td>0.3</td>
</tr>
<tr>
<td>3.4</td>
<td>Each sensor shall be designed to operate at -5 °C.</td>
<td>0.3</td>
</tr>
<tr>
<td>3.5</td>
<td>The sensors shall be designed stay submerged for up to two years.</td>
<td>0.3</td>
</tr>
<tr>
<td>3.6</td>
<td>The sensor shall be capable of sealing and resealing on a ship with limited lab resources.</td>
<td>0.3</td>
</tr>
<tr>
<td>6.1</td>
<td>The sensor shall be tested to a pressure of 1200 meters CDW.</td>
<td>0.6</td>
</tr>
<tr>
<td>6.2</td>
<td>The sensor shall be tested to -5 °C.</td>
<td>0.6</td>
</tr>
<tr>
<td>6.3</td>
<td>Magnetic sensitivity shall be tested to 5000 nT.</td>
<td>0.6</td>
</tr>
<tr>
<td>6.4</td>
<td>Drag tilt sensor shall be calibrated to be accurate to within 0.25 cm/s of current flow.</td>
<td>0.6</td>
</tr>
<tr>
<td>6.5</td>
<td>Temperature sensor shall be calibrated to within 0.05 °C.</td>
<td>0.6</td>
</tr>
<tr>
<td>6.6</td>
<td>Magnetic sensor shall be calibrated to within 5°.</td>
<td>0.6</td>
</tr>
</tbody>
</table>
\[ R = R_k \left[ \frac{V}{V_0} + \frac{R_1}{R_1 + R_2} \right]^{-1} - R_k \]  \hspace{1cm} (1)

where \( R \) is the resistance of the thermistor; \( R_1, R_2 \) are resistances on the Wheatstone bridge; \( V \) is the voltage measured across the bridge; and \( V_0 \) is the input voltage to the bridge.

\[ T = \left[ \frac{1}{T_0} + \frac{1}{\beta} \ln\left( \frac{R}{R_0} \right) \right]^{-1} \hspace{1cm} (2) \]

where \( T_0 \) is the temperature at which the thermistor was calibrated in Kelvin, \( \beta \) is the thermistor's intrinsic beta value; \( R \) is the resistance of the thermistor as calculated above; \( R_0 \) is the base resistance of the thermistor; and \( T \) is the temperature in Kelvin.

The uncertainty is calculated in the following way:

\[ \delta T = \sqrt{\left( \delta R \frac{\partial R}{\partial R_k} \right)^2 + \left( \delta V \frac{\partial R}{\partial V} \right)^2 + \left( \delta V_0 \frac{\partial R}{\partial V_0} \right)^2 + \left( \delta R_1 \frac{\partial R}{\partial R_1} \right)^2 + \left( \delta R_2 \frac{\partial R}{\partial R_2} \right)^2} \hspace{1cm} (3) \]

where:

\[ \frac{\partial R}{\partial R_k} = -1 + \left[ \frac{V}{V_0} + \frac{R_1}{R_1 + R_2} \right]^{-1} \hspace{1cm} (4) \]

\[ \frac{\partial R}{\partial V} = \frac{-R_k V_0}{V_0 \left( \frac{V}{V_0} + \frac{R_1}{R_1 + R_2} \right)^2} \hspace{1cm} (5) \]

\[ \frac{\partial R}{\partial V_0} = \frac{R_k V}{V_0 \left( \frac{V}{V_0} + \frac{R_1}{R_1 + R_2} \right)^2} \hspace{1cm} (6) \]

\[ \frac{\partial R}{\partial R_1} = \frac{-R_k \left( \frac{1}{R_1 + R_2} - \frac{R_1}{(R_1 + R_2)^2} \right)}{\left( \frac{V}{V_0} + \frac{R_1}{R_1 + R_2} \right)^2} \hspace{1cm} (7) \]

\[ \frac{\partial R}{\partial R_2} = \frac{R_1 R_k}{(R_1 + R_2)^2 \left( \frac{V}{V_0} + \frac{R_1}{R_1 + R_2} \right)^2} \hspace{1cm} (8) \]

II. Temperature Measurement Sensitivity Plots
Figure 5. Logic Flow Chart

- **Start**
- **Setup**
  - Create global objects
  - Setup SD file
  - Begin ADC/Digital Temp comm
  - Begin Accel/Mag comm
  - Begin RTC comm

- **Take and Log Data**
  - Poll RTC
  - Poll Accel/Mag
  - Poll Temp
  - Write data to SD

- **Prep for Sleep**
  - Power down power rail
  - Set RTC alarm

- **Sleep**

- **Wake Up**
  - Clear alarm
  - Power up power rail

- Return to top of loop
Figure 6. Temperature Test Data Analysis

<table>
<thead>
<tr>
<th></th>
<th>Therm1</th>
<th>Therm2</th>
<th>Therm3</th>
<th>Therm4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.0145</td>
<td>0.0046</td>
<td>1.1948</td>
<td>0.2946</td>
</tr>
<tr>
<td>Median</td>
<td>1.0131</td>
<td>0.0039</td>
<td>1.1942</td>
<td>0.2940</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.0051</td>
<td>0.0010</td>
<td>0.0042</td>
<td>9.4494e-04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Therm1</th>
<th>Therm2</th>
<th>Therm3</th>
<th>Therm4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.2233e+04</td>
<td>1.1731e+04</td>
<td>1.2323e+04</td>
<td>1.1874e+04</td>
</tr>
<tr>
<td>Median</td>
<td>12232</td>
<td>11731</td>
<td>12323</td>
<td>11874</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>2.5334</td>
<td>0.5045</td>
<td>2.1019</td>
<td>0.4671</td>
</tr>
</tbody>
</table>
Figure 7. Tilt Test Data
Figure 8. Free Body Diagram of Sensor on Mooring Line

B = Buoyant force
F = Drag force
W = Sensor weight
phi = Angle of incidence of flow
theta = Measures tilt angle of the sensor
b = Distance to center of buoyancy
d = Distance to center of pressure
w = Distance to center of gravity
Figure 9. Tilt Angle Against Drag Force and Center of Pressure Location

Figure 10. Temperature Sensitivity wrt $\sigma T_0$
Figure 11. Temperature Sensitivity wrt $\sigma_{Vin}$

Figure 12. Temperature Sensitivity wrt $\sigma_R$
Figure 13. Temperature Sensitivity wrt $\sigma_\beta$
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