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1 Introduction

The project was to build a cost-effective instrumentation system to measure rapid temperature variations of the atmosphere up to 50,000 feet of altitude. These temperature variations can be used to calculate an estimate of the refractive index of the air. This project is a prototype of a system that can be used multiple times at any given location to determine atmospheric seeing. This document provides information about the high-altitude instrumentation system conceptual design, down-selection process, and final design and implementation.

A background section which contains information about concepts specific to the instrumentation process used in this project is provided. A brief explanation of atmospheric seeing is included as related to the refractive index structure constant, C_n^2. The operations of the sensors and GPS receiver used in the project are explained. The specifications of the project are listed, and the deliverables and the specifics of the design are explained in the design section. A critical path diagram includes major milestones, the dates on which they were completed, and a spending report which details the use of the project budget. A budget is provided to outline the cost of the major components required to complete the project according to specifications.

As light passes through Earth's atmosphere, it gets distorted. The effect is similar to that of a pencil that is partially submerged in water. Just as the light passing through the water makes the pencil look bent, the light passing through the atmosphere causes stars to twinkle (or "scintillate"). This is due to a property called refraction. Refraction occurs when light passes between two different mediums. The light changes in velocity and direction due to density differences between the two media. A large-scale example of density differences is the relative difference between the density of Space and Earth's atmosphere. On a micro-scale, the density of individual pockets of air are not the same, resulting in an atmosphere that is not of a uniform density. These small pockets of air have rapidly changing temperatures, pressures, and humidities, which cause density differences. These density differences are what cause star scintillation.

The point of this project is to measure the small thermal fluctuations taking place throughout the atmosphere, in order to create a vertical profile of its refractive properties. The system is designed to measure only a small vertical column (about one square foot) of temperatures on each flight. The instrument is also designed for reusability so that data from several flights can be combined to create a profile of a wider area. This design technique also allows for multiple areas to be profiled by the same instrument. The system uses a balloon to carry the payload to the specified altitude. During ascent, wind will cause the system to drift horizontally. No horizontal propulsion system is included on the platform due to budget constraints and Federal Aviation Administration regulations. Due to limited controllability of the system, there is no compensation for this drift during a flight. This limitation is again overcome by the reusable design since multiple launches will allow for creation of a full vertical profile of an area. To ensure the system would be reusable, a parachute is included to slow its descent, and padding has been added to the hardware bay to prevent damage to critical components.

The rapid temperature variation sensors were attached at intervals to a cable system hung from the bottom of the hardware bay. These sensors provide data which will be used to calculate the amount of refraction, or bending, that happens to the light in the area in which a launch takes place.

2 Background

This section provides critical background information in support of the project. Necessary information about each of the subsystems required for the functional instrument is included.

2.1 Previous Project

In this project's precursor experiment, Jorgensen et al (2005)[1] implemented a turbulence measurement system to help down-select the option of whether or not to elevate optical telescopes above ground level. The experiment was conducted at the Magdalena Ridge Observatory Interferometer (MROI) in the Cibola national forest in New Mexico, USA. In the experiment, atmospheric turbulence was characterized by microthermal fluctuations at heights of 0.8 to 4.4m above ground. The altitudes of the sensor devices were chosen to correspond to the range of altitudes that the telescopes could be raised above ground. A substantial increase in telescope performance at greater height could justify the increased cost and logistical challenges of raising the telescopes.

Microthermal sensing has been previously implemented in experiments related to atmospheric turbulence (e.g. Jorgensen 2005). Their methods used pairs of thermocouple sensors set at common altitudes with output signals proportional to the difference in temperature between each pair. Sensitivities of roughly 40 micro-Volts per Kelvin required the use of low-noise amplifiers. The need to record very rapid temperature fluctuations (up to 100Hz) requires the use of very fast response temperature sensors.

The MROI experiment concluded that even at heights of 4.4m and below, significant changes in seeing can be found. In addition, the study determined that the fluctuations over a period of several months were not obviously correlated to changing weather conditions. The patterns associated with atmospheric turbulence are not simple to derive and require additional research to be interpreted by scientists.

2.2 Refractive Index

Refractive index is defined as the ratio of an electromagnetic wave's phase velocity in a given medium relative to the same wave's velocity in a reference medium (usually vacuum). A more simple explanation is that the speed of an electromagnetic signal such as light varies depending on the material in which it is propagating. When light moves through a variety of materials with different refractive indices the signal has a tendency to bend and distort. The refractive index of the atmosphere is used as a model of how light entering the atmosphere goes through this process and is distorted before reaching the Earth's surface. The changes in the refractive index of the atmosphere are caused by rapid temperature, pressure, and humidity changes in the air. The changes are not uniform through the entire atmosphere, but instead occur in small pockets of air. The pockets of air undergo rapid variations in density as a result of their temperature and pressure variations, and the result is that light passing from one pocket into another undergoes a change in velocity. The propagation of light from Space to the Earth's surface through variably changing refractive indices causes distortion in the final image received on the ground as seen in Figure 1. A common example

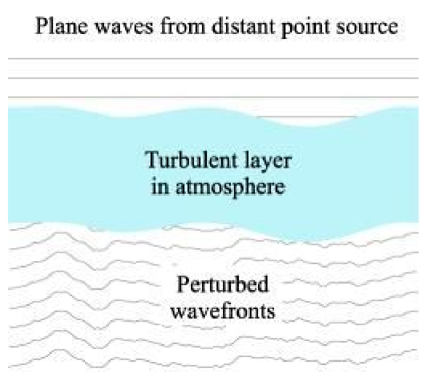

Figure 1: Atmospheric Distortion of Light[2]

of this refraction can be seen in stars that appear to the naked eye as a "twinkle" in the night sky (also known as "scintillation"). The overall degree of refraction in a particular region of atmosphere from space to ground is referred to as the astronomical "seeing" of the area. The refractive index is of interest to astronomers since the sources of undistorted light coming from outside the atmosphere are their primary interest. If a clear image of any stellar object is desired, the refractive properties of the atmosphere must be taken into account, and the distortion caused by these properties corrected for.

By estimating the atmospheric refractive index of a particular area, astronomers can get an idea of the degree of correction that may be needed in order to produce clear images. Rapid thermal variation measurements in the air provide sufficient data to calculate a rough estimate of the refractive index of the atmosphere. The mathematical relationships are found in Background 2.3.

2.3 Atmospheric Seeing

Atmospheric seeing refers to the quality of observing conditions induced by turbulence in Earth's atmosphere. Seeing is caused by variations in the refractive index of the atmosphere. These variations can be estimated by analyzing the rapid temperature fluctuations in the air. Since the variations are also affected by rapid pressure and humidity changes, rapid temperature variation measurements need to be coupled with pressure, humidity, and absolute temperature measurements to obtain a complete seeing measurement. Other factors, such as ground level turbulence induced by thermal currents off of roads and wind flow changes created by buildings and other structural obstacles will cause data taken from lower altitudes to be inaccurate unless measured over a long period of time. Due to induced thermals and temperature changes, daytime seeing values differ from nighttime seeing values.

After collecting a temperature fluctuation measurement, an estimated refractive index structure constant can be calculated at that point in the atmosphere using Equation 1 below, where P, T, and CT are the atmospheric pressure, atmospheric temperature, and the temperature structure constant, respectively. After calculating the full-width-at-half-max (FWHM) atmospheric seeing can be calculated from Equation 2[1].

$$C_n^2 = (80 \times 10^{-6} \frac{P}{T^2})^2 C_T^2 \tag{1}$$

$$\epsilon_{fwhm} = 5.25 \lambda^{\frac{-1}{5}} \left(\int_0^L C_n^2(l) dl \right)^{\frac{2}{5}} \tag{2}$$

2.4 GPS

A Global Positioning System, or GPS, is a tool used to pinpoint locations on Earth. A GPS receiver uses a process called resection to determine its position. The concept of resection involves knowing the distance from an undetermined location to a given number of known locations in order to ascertain the undetermined location. The receiver is able to calculate the distances between itself and the GPS satellites based on how long it takes for the signals to travel from one to the other. There are 24 satellites in orbit used for GPS location. For determination of location, a receiver requires a minimum of 3 satellite links. Having 24 satellites in orbit ensures that at least 4 will be in communication with a GPS receiver at any point on the Earth's surface. To begin the resection process, the GPS receiver determines

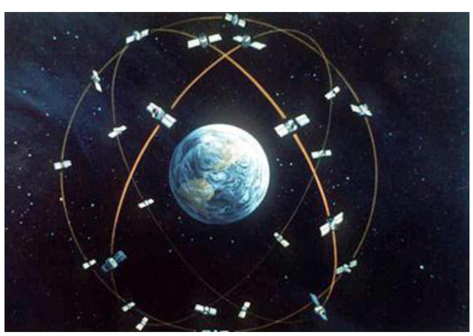

Figure 2: GPS Satellites Orbiting Earth[3]

the distance to a single satellite. This distance shows that the unknown position must lie on the surface of a sphere. Next, the receiver determines the distance to a second satellite and this gives a second sphere. The intersection of these two spheres is a circle. The distance to a third satellite is then determined and the intersection of the third sphere with the circle gives two points in space. It is sometimes obvious which point is incorrect if, for example, it is in the wrong country or in space. This process is illustrated in Figure 3 below. If further clarification is needed, a fourth distance is determined and the intersection of the fourth sphere gives the correct point on the Earth. One limitation to the GPS is selective

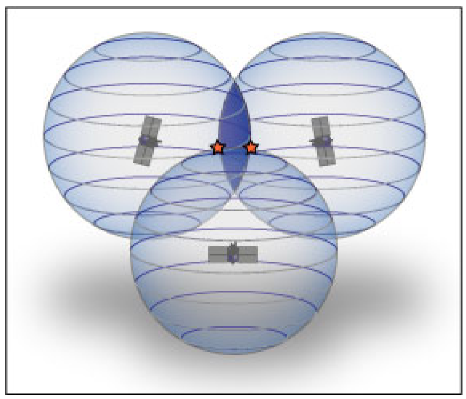

Figure 3: Intersection of Spherical Transmissions[4]

availability which is defined by degradation of the GPS signal intended to create error in commercially available GPS receivers. Selective availability was established to limit the accuracy of the GPS system that could be used for criminal intent. Selective availability was ended by President Clinton in May of 2000. After the attacks on September 11, 2001, there was talk of reestablishing selective availability. However, the government has announced that it has no intent to ever use selective availability again. The abolishment of selective availability allows commercially available GPS to be accurate up to 1 meter[5].

2.5 Thermocouples

A thermocouple is a sensor made up of two dissimilar metals joined together at a junction. Thermocouples are classified by the materials used in their construction. Different types are denoted using capital letters. For instance, a type J thermocouple has one lead made out of Iron and the other made out of Constantan (a Copper and Nickel alloy), whereas a type K thermocouple is composed of Chromel and Alumel (a Nickel, Manganese, Aluminum, and Silicon alloy)[6]. The two leads produce a voltage difference between them that corresponds to a certain temperature. This works on the "Seebeck effect", which states that the temperature difference between two conductors, such as the two types of metal in a thermocouple, is directly proportional to a voltage generated between them. The two metals need to have at least one junction point for this effect to work. The voltage across the thermocouple will generally be anywhere from hundredths of a millivolt to tens of millivolts. Figure 4 provides a diagram of how thermocouples can be wired in parallel.

The thermocouple type effects the temperature range at which the thermocouple can work, and also effects the cost of the thermocouple. Since the voltage generated by the thermocouple is small, amplification is required.

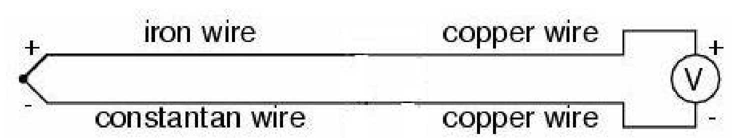

Figure 4: Thermocouple Circuit Diagram[7]

2.6 Piezoresistive

A piezoresistive sensor works by measuring the amount of mechanical stress on the sensor itself. An increase in pressure deforms the sensor, thereby increasing the amount of resistance provided. In a silicon sensor, the conductivity of a crystalline grid changes when the grid is deformed. This type of sensor is highly sensitive to change, and provides a large resistance change with respect to minute pressure changes. This provides a high degree of accuracy for the sensor[12].

2.7 Temperature Sensors

An absolute temperature sensor is able to measure the temperature of a substance with respect to absolute zero. One method of measuring absolute temperature involves using a Zener diode with a breakdown voltage that is proportional to the absolute temperature. This type of temperature sensor is accurate to within 1°C of the actual temperature.

2.8 Batteries

Batteries provide an electrical charge through electrochemical reactions. The amount of voltage that a battery can produce is dependent on the metals and electrolytes used in the reaction. A typical example is a car battery which is a lead-acid battery. For small electronic systems such as a digital camera the two common types of batteries used are nickel and lithium with many different types of electrolytes for each. The batteries can be arranged in serial and parallel configurations to fit the particular device's needs to increase the voltage or current respectively.

2.9 Parachute Descent

The terminal velocity of an object is the velocity of a falling object when it is no longer accelerating. To calculate the terminal velocity we use the following equation where m is the mass of the object, g is the gravitational constant, ρ is the density, A is the area of the object and C_d is the drag coefficient:

$$V = \sqrt{\frac{2mg}{C_d \rho A}}$$

The drag coefficient for a box which has a flat surface is 1.28[13]. This gives a terminal velocity of 194.56 ft/sec when a 4.91 lb box falls from 50,000ft.

Since the box is falling at such a fast rate a parachute can be attached to slow the box while descending to ensure a safe landing. Using a circular parachute with a 6 foot diameter the box will slow to a rate of 14.95 ft/sec. This is calculated using the same equation but with a drag coefficient of 0.75 and using the diameter of the parachute to calculate the total surface area.

3 Design

This section outlines the design process and provides a full description of the final design and its implementation. The first two sections describe the deliverables that were provided to the customer, according to the specifications given by the customer. Next, the preliminary designs of each subsystem are detailed. The final design resulting from the down-selection process and the final implementation are explained in the last subsection.

3.1 Deliverables

3.1.1 Balloon:

A Helium weather balloon capable of altitudes in excess of 50,000 feet was provided.

3.1.2 Sensors:

Turbulence sensors with variable separation were mounted on the outside of the platform. Temperature and pressure sensors were mounted on the platform.

3.1.3 Power Supply:

Batteries able to power the entire system for 12 hours were included.

3.1.4 GPS and Communication:

A GPS receiver was included to facilitate the tracking and retrieval of the platform. A communication system was included on the platform to transmit data back to the ground. A mobile ground station, in the form of a laptop, was provided to communicate with the GPS.

3.1.5 Data Acquisition and Controller:

An on-board computer and external memory were included.

3.1.6 Recovery:

A parachute was included to minimize damage to the platform upon return.

3.2 Specifications

3.2.1 Balloon

A Helium weather balloon able to lift the instrumentation system to an altitude of 50,000 feet.

3.2.2 Sensors

The sensors will measure rapid temperature fluctuations, and must respond at a frequency of 100Hz. The turbulence sensors will be spaced at adjustable distances from the main platform. A pressure transducer and absolute temperature sensor will be included to measure the absolute pressure and ambient temperature of the air at a frequency of 1Hz. All sensors must be able to operate within a temperature range of -60°C to 38°C.

3.2.3 Power Supply

The system will have a power supply that is able to provide power to all subsystems for a period of up to 12 hours.

3.2.4 GPS and Communications

A GPS tracking system will be included to provide three-dimensional position data. A communications system will transmit the GPS coordinates to the ground station over the required distance of 20 miles.

3.2.5 Data Acquisition and Controller

A data acquisition system to gather the sensor data and store it. The system will be able to sample the measurements from the turbulence sensors at a frequency of 100Hz. It will also be able to sample the measurements from the temperature and pressure sensors at a frequency of 1Hz.

3.2.6 Recovery

A landing system to ensure that the platform will land without sustaining significant damage. A flight termination system is to be included so that a flight can be ended when the transmitter is more than 20 miles away or the balloon stops rising and is floating at one altitude.

3.3 Subsystem Design

This section provides the original conceptual designs for the deliverables. The criteria used to down-select from those designs are displayed in decision matrices, where applicable, to show the strengths and weaknesses of each. For each decision matrix, the individual criteria are rated on a scale from 1 to 5, with the highest (best) rating being 5. Each criterion is weighted equally unless otherwise noted. The final design down-selected the best option for each subsystem and implemented it.

3.3.1 Measuring Refractive Index

Estimates of the refractive index of the atmosphere are calculated by applying a system of equations seen in Background 2.3. that relate rapid temperature fluctuations to atmospheric seeing values. This project had a specified measurement sampling rate of 100Hz in order to create an accurate atmospheric profile.

Three conceptual designs were considered as possible solutions to create an atmospheric refractive index profile. Thermocouples used to measure rapid temperature fluctuations were the primary option based on preliminary consultation with the sponsor of the project. Another approach would have included the use of anemometers to measure wind speed and direction for use as an approximation of turbulence. Finally, a Photo Doppler Velocimeter could also have measured wind speeds to estimate the refractive index. Based on decision matrix in Table 1, thermocouples proved to be the best design approach for measuring the refractive index of the atmosphere.

Item	Reliability	Accuracy	Speed	Weight	Cost	Availability	Power Consumption	Average
Thermocouple	5	5	5	5	4	5	5	**4.86**
Anemometer	3	2	1	4	5	5	5	**3.57**
Velocimeter	5	5	5	1	1	1	1	**2.71**

Table 1: Decision Matrix for Turbulence Sensors

The down-selection process of thermocouples for the best in this application was strictly determined by the specifications set by the sponsor. The sampling rate 3.2.2 demanded a sensor that is capable of fast-changing levels at its output. In addition, according to Specification 3.2.2, the range of operation was required to be within -60°C to 40°C. The thermocouples also needed to be selected for cost optimization.

3.4 Rapid Temperature Variation Sensors

Individual classes of thermocouple are available and each are assigned a letter to help decipher their particular characteristics from the others. Types B, J, R, S, and E were not suitable for the project, as their operation ranges did not include the expected range of temperatures. The accuracy of the thermocouple was also an important factor, since more accurate measurements will create an accurate atmospheric profile. Table 2 shows the ac-

Type	Temperature Range ($^\circ C$)	Voltage Range (mV)	Operation Range ($^\circ C$)	Output (μV/$^\circ C$)
B	0 to 1820	0 to 13.82	50 to 1800	10
E	-270 to 1000	-9.835 to 76.373	0 to 800	68
J	0 to 1200	0 to 69.553	0 to 750	53
K	-270 to 1370	-6.458 to 54.886	-200 to 1200	41
N	-270 to 1300	-4.345 to 47.513	-200 to 1200	38
R	-50 to 1760	-0.226 to 21.101	50 to 1600	10
S	-50 to 1760	-0.236 to 18.693	60 to 1600	10
T	-270 to 400	-6.258 to 20.872	-200 to 400	43

Table 2: Information on Thermocouple Types[9][10][11]

curacy of each thermocouple type that met the temperature specification. The accuracy of each type is represented in terms of the maximum error in degrees Celsius. Types K and N were each equally accurate for the temperature range that they would have been used for, but both were less accurate than type T. Type T, K, and N thermocouples each cost as low as $34 per thermocouple (in order to get thermocouples that meet the sampling frequency requirement). Of types T, K, and N, type T has the highest output per degree, which reduces the effects of noise on the output. Based on this information, type T thermocouples were the optimal choice for the project. As a precaution, the type T thermocouple is non-magnetic, and is thus effective when strong magnetic fields are present[11].

These thermocouples met Specification 3.2.2. They had also been proven reliable in the precursor experiment conducted by Dr. Anders Jorgensen. Due to this, they were the optimal thermocouple choice for this project. A drawing depicting the thermocouple and operational amplifier set up can be seen below in Figure 5.

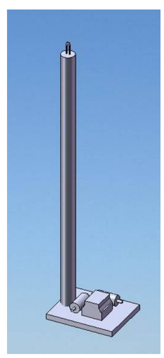

Figure 5: Thermocouple Circuit Drawing

3.5 Temperature Sensor

The absolute temperature sensor was required to operate at a specified range of -60°C to 40°C. The sensor used was a silicon diode analog temperature sensor. An analog temperature sensor is lightweight and can simply be mounted on the exterior of the platform. To meet specifications, cryogenic sensors, or sensors that are able to measure extremely low temperatures, were used. While generally expensive, a cryogenic temperature sensor was donated to the project. The donation of this sensor allowed the allocated portion of the project budget to be used elsewhere. This sensor had been previously used in experiments, and had proven reliable. According to the specification sheet, the sensor was known to be reliable at cryogenic temperatures (below -150°C), which was well beyond the requirements of Specification 3.2.2. The sensor is shown below.

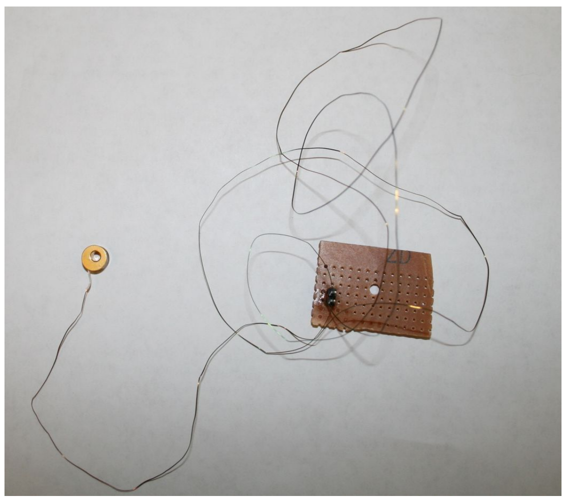

Figure 6: Temperature Sensor

3.6 Pressure Sensor

Sea level air pressure, the lowest possible launch altitude is 14.7 pounds per square inch (PSI). Pressure at an altitude of 50,000 feet is estimated to be 10% of the sea level pressure, or 1.47 PSI. The pressure sensor used in the project was selected to work over a range of 0 to 15 PSI in order to meet this criteria. Further, it was specified to operate at temperatures above -15°C. Due to this, it was necessary to provide insulation to the sensor. This insulation was provided by housing the sensor inside the insulated hardware bay (IHB), which was not pressurized. The sensor used in the project was a piezoresistive sensor, which means that it operated by measuring mechanical stress forces. More information on piezoresistive sensors can be seen in Background 2.6. The TO-5 case that housed the sensor component itself allowed for easy interfacing with signal conditioning electronics. This sensor met all requirements of Specification 3.2.2. An instrumentation circuit was needed for implementation of the

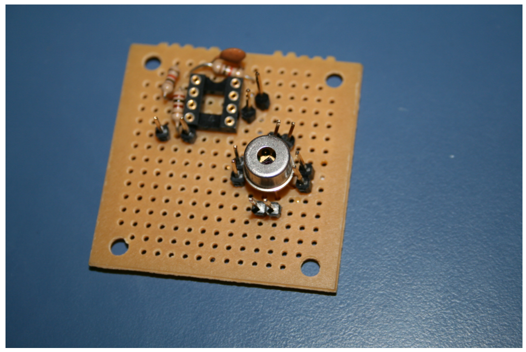

Figure 7: Pressure Sensor

pressure sensor. The pressure sensor is a type of strain gauge that outputs analog electric signals that correspond with the pressure of the surrounding environment. To do this, the pressure sensor acts as a Wheatstone bridge. The Wheatstone bridge circuit is depicted in the schematic in Figure 8, along with the instrumentation circuit for measuring the voltage changes delivered by the sensor. The pressure sensor has a variable resistance on one leg of the Wheatstone bridge that changes resistance by an amount that is proportional to the pressure. The instrumentation circuit is able to use this change in resistance to change its voltage output. With amplification and signal conditioning, the differential voltage from the sensor can be seen at the output of the circuit as a single-ended voltage with reference to ground. It is important to note that the first stage of this circuit acts only as a buffer to the system. The potentiometer labeled VR1 is responsible for changes in the offset voltage and the potentiometer labeled VR2 controls the overall gain of the circuit.

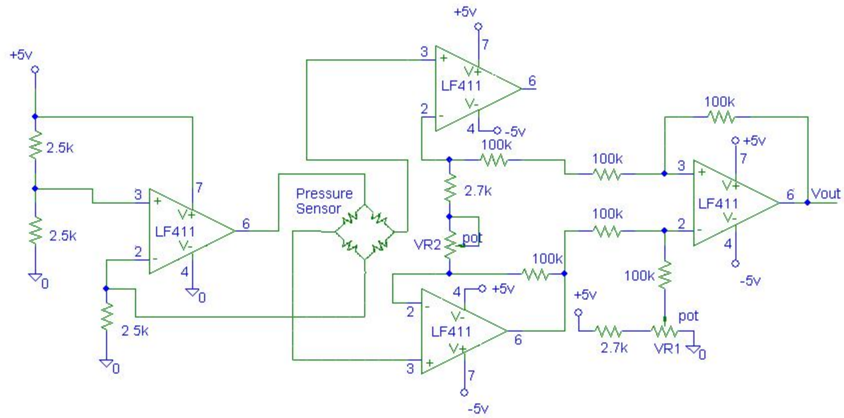

Figure 8: Instrumentation Circuit Required for Pressure Sensor
[14]

3.7 Sensor Corrections

The thermocouples deliver an output in the microvolt range, and the absolute temperature and pressure sensors deliver outputs in the millivolt range. All three sensor types required signal amplification in order for the voltages to be in a readable range for the analog to digital (A/D) converters. An amplification of 1000 was used to provide adequate amplification while still preventing higher output values from reaching the saturation levels of the operation amplifiers. The temperature sensor was amplified by 20. In order to minimize the amount of noise introduced to the signal, low noise amplifiers were used. Further explanation of low noise amplification can be seen in Section 4.2. The amplification circuit can be seen in Figure **??**.

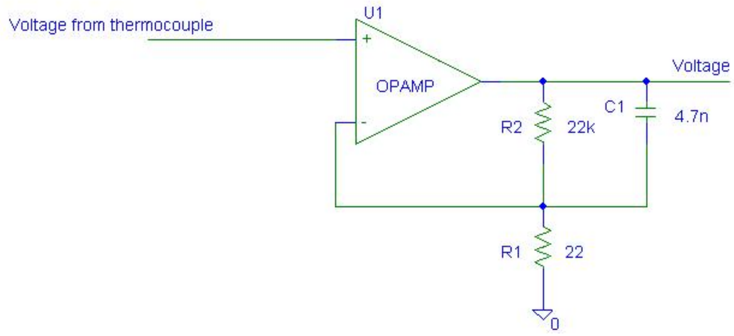

Figure 9: Amplification Circuit Required for Thermocouples

The outputs of the amplifiers were multiplexed to reduce the number of necessary A/D converters. Two 8-to-1 multiplexers were used, since a total of 12 sensor signals needed to be multiplexed. Both multiplexed systems were controlled by the microcontroller. The multiplexer outputs were converted to digital signals, which provided the data to the computer system. The computer then input the data, timestamped it, and stored it in memory.

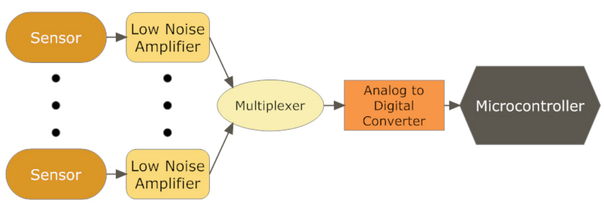

Figure 10: Graphical Representation of Sensor Signal Conditioning

3.8 GPS and Tracking

A GPS receiver was required to track and recover the platform, according to Specification 3.2.4. Since the GPS receiver was accurate to within 5 meters, no other tracking equipment was necessary. However, buzzer and strobe light were included to aid recovery of the platform. For security reasons, commercial GPS receivers are limited in their applications. One

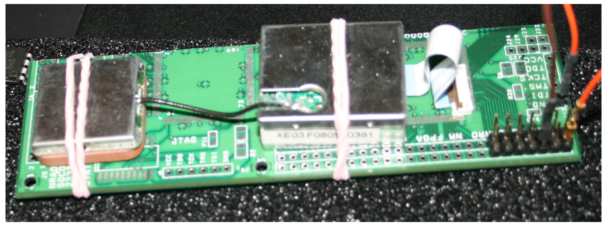

Figure 11: GPS Receiver

limitation is that the GPS receiver must not exceed a velocity of 1,000 knots (or approximately 1,150 miles per hour) and an altitude of 60,000 feet at the same time[8]. If both of these missile-like conditions are met, the GPS receiver will automatically power down. This was not a concern for this application, since the platform cannot reach a velocity beyond its own terminal velocity, as discussed in Background Section 2.9. A second limitation is that the GPS receiver has limited transmitting power, and thus required a transmision system to communicate over the expected 20 mile distance to the ground-based tracking station. For more on the transmision system see Section 3.9.

The GPS receiver also functioned as part of the time-stamping mechanism for collected data. It supplied day, hour, minute, and second information for the data. The GPS receiver was selected due to its small size and low power consumption compared with other models (.07W compared to .1W).

3.9 Transmitter

The transmitter, used in conjunction with the GPS receiver, has been used and proven reliable in previous high-altitude balloon projects. It transmits in the 900MHz band with 1W of power, which was sufficient power to transmit over the specified distance.A high gain directionalantenna was used by the base station to increase the range of the transmission system. The antenna is a 15-element Yagi antenna with a specified gain of 13dBi (13dB with reference to an isotropic radiator). The performance of the transmission system was

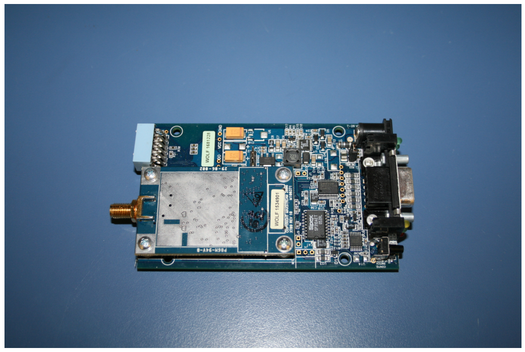

Figure 12: Transmitter

tested to determine its limitations. The receiver was taken to Magdalena Ridge and the transmitter positioned with clear line of sight to the receiver. The receiver was put into range test mode which made the receiver retransmit the signal back to the transmitter. The test revealed that with a 36 mile total transmission range the received signal could attenuate 30dB to 40dB lower and still be above the -110dBm minimum signal level specified by the manufacturer of the receiver.

The transmission system is dedicated solely to the communication of GPS coordinates to the ground based tracking station. No data are transferred through the transmission system.

3.10 Computer

The on-board computer collected data from all sensors and stored it on an MMC (multimedia card). An MMC is often referenced as a secure digital card (or SD card) and is commonly used in digital cameras. The data was tagged with time and location received from the GPS receiver at a rate of once per second. Using the GPS data and the known sensor sampling rate, accurate timestamps for each sensor sample were obtainable, as required by Specification 3.2.5.

The three options considered for the on-board computer and data acquisition system were a microcomputer, a microcontroller, and a PC motherboard. To down-select from these three options to the final design, price, availability, familiarity, power consumption and size were taken into account as depicted in the decision matrix of Table 3. Based on the outcome of the decision matrix the microcontroller was down-selected as the best option for the specifications.

Type	**Price**	**Power**	**Availability**	**Familiarity**	**Size**	**Average**
Microcomputer	4	5	5	3	5	**4.4**
Microcontroller	5	5	5	5	4	**4.8**
PC Motherboard	3	1	5	5	1	**3**

Table 3: Decision Matrix for Onboard Computer

3.10.1 Microcontroller

The particular microcontroller used for this application was one that was previously used by the team and did not require purchasing and budget expenditure. The internal clock was a 50MHz crystal oscillator, which was enough to meet Specification 3.2.2. 5V regulated power supplies were available to provide power to other components. The 10 bit A/D converters on the development board determined the precision of the data stored from the measurements taken by the sensors. This microcontroller met Specification 3.2.5. The data written to the MMC is stored in 512 byte partitions, which means that 512 bytes of data are stored in flash memory before being transferred to the MMC. The system must be recovered to collect the MMC and the data stored on it.

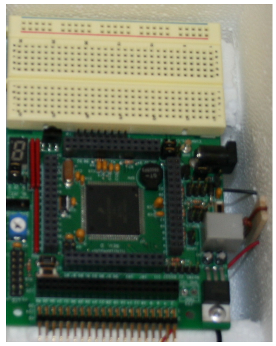

Figure 13: Microcontroller

3.11 Power System

The power system was composed of lithium batteries which each output 3.7V. Since the microcontroller and the sensors needed 5V to operate, a minimum total supply voltage of 7V is required for proper functionality of the on-board voltage regulators. To achieve this supply voltage, the batteries were combined in a series-parallel combination to output an additive 7.4V. The parallel combination is required to ensure proper output power for the operating time constraint of Specification 3.2.3. The voltage loss was dispersed as heat, which was needed to help keep the entire hardware bay warm, since the outside temperature was predicted to be -60°C. Another regulator circuit was designed to provide 3.3V to the GPS and the MMC that operate at LVTTL (low-voltage transistor-transitor logic) levels.

LiSOCl2 (Lithium Thionyl Chloride) batteries were used for this project. The battery pack is specified to provide 7.4V and 5.2Ah (Amp hours)[15]. This equated to 38.5Wh (Watt hours) of power which met the requirement listed in Specification 3.2.3. Their temperature operating range is -55°C to 85°C, which ensures they will work for the project even with minimal insulation. Table 4 provides the power budget for the instrument. The total power demanded by the system is 2.3W. For a 12 hour run time the system required 28Wh. Therefore a single battery pack was sufficient to power all of the electronics. The use of a backup

Part	**Power Consumption**
Transmitter	1W
Microcontroller	1.08W
GPS	0.07
Interfacing Hardware	0.15W
Total	**2.3W**

Table 4: Power Budget

power source in case of failure would have been desirable, but was not an option due to budget constraints.

3.12 Recovery System

A recovery system was required to facilitate retrieval of the platform and the data stored on the hardware within it. The three options considered were a glider, a parachute and an elaborate padding method. The options were down-selected using the following decision matrix: The 6 foot circular parachute slowed the descent of the platform to prevent excessive

Type	**Cost**	**Availability**	**Weight**	**Complexity**	**Average**
Glider	1	1	4	1	1.75
Parachute	5	5	5	4	4.75
Padding	2	5	2	5	3.5

Table 5: Decision Matrix for Recovery System

damage upon landing. The protection offered by the parachute to the fragile internal components was increased by adding padding to the inside of the hardware bay. The parachute was able to decrease the rate of descent of the platform down to a calculated 14.95 ft/sec upon impact. The GPS receiver and transmission system were used to ensure that the platform coordinates were known at the point of impact. To further the chances of recovery once within the vicinity of the GPS coordinates, visual and audio aides were added to the platform. An audio alarm and a strobe light were used to distinguish the platform from the

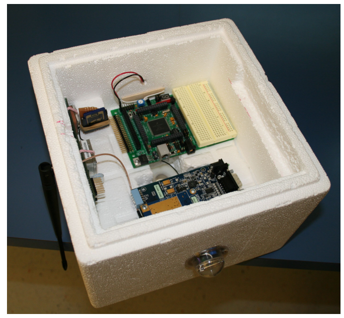

Figure 14: Insulated Hardware Bay

surrounding terrain.

3.13 Platform

The balloon attaches to the parachute's top-dead-center by 20 feet of nylon cord. The tension in the cord keeps the parachute in a non-inflated state until the balloon bursts due to lack of atmospheric pressure. The flight termination device consisted of a resistive heater coil that melted through the nylon cord directly above the parachute when activated. The parachute attaches to the insulated hardware bay by 6 feet of nylon cord in addition to the parachute rigging lines. The insulated hardware bay contained the microcontroller, the batteries, the MMC, the GPS receiver, the transmitter, and the pressure sensor. All interior components were securely stowed inside the bay. The absolute temperature sensor was mounted on the exterior of the bay. The thermocouples sensors were attached at intervals to a cable system that hung from the bottom of the hardware bay to minimize turbulence caused by the balloon's wake. One mandatory addition to the platform was a radar reflector. This was to ensure the safety of airplanes that may be in the vicinity of the platform's lower altitude flight range. Radar reflectors come in a wide variety of sizes, shapes, and weights. The radar reflector used for this project was 1 foot in diameter.

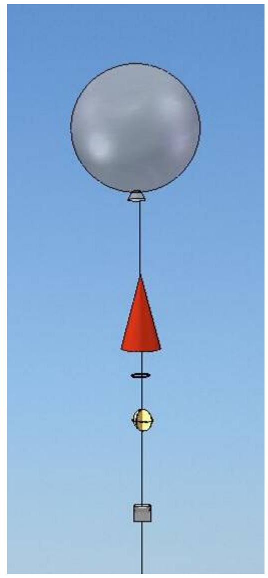

Figure 15: Platform Drawing

Figure 16: Radar Reflector

3.14 Final Design

To measure rapid temperature variations and estimate the refractive index of the atmosphere, 10 thermocouples, a barometric pressure sensor, and an absolute temperature sensor were used. These sensors were fed through signal conditioning circuitry into a microcontroller, which timestamped the data and stored it. A GPS receiver was used to provide timestamping data and GPS coordinates to the microcontroller. The data was stored on a MMC. The GPS receiver was also connected to a transmitter, which sent coordinates to a portable ground station. The final design met all the deliverables and specifications agreed upon with the sponsor.

3.15 Code

The code was written in C language using a program called EmbbededGNU (written by Eric Engler). It is organized into four separate functions. The main function contains initialization code and a continuous loop. The sensor data are read from a function called readsensors, the GPS data are read in a function called GPSread, and the data are written to the MMC in a function called MMCwrite.

The analog-to-digital (A/D) code uses the microcontroller's on-board analog-to-digital converters to convert the signal from the sensors into a format that can be stored on the SD card. It takes the output of the multiplexers, converts it, then stores it. The A/D is set to be in 10-bit mode, which means that it uses 10 bits to encode the voltage levels received. The converter estimates the voltage and uses 10 bits to describe the level. If the voltage is not exactly on a level, it is rounded to the nearest one. This is called "quantization". The GPS

Figure 17: Block Diagram of A/D code

code uses the asynchronous Serial Communication Interface (SCI) on the microcontroller. The two devices are asynchronous which means that they have independent clocks. In order to communicate, the baud rates must be equal or the data will not be valid. The baud rate of the GPS is 9600 bits per second, so the SCI on the microcontroller was set to match this. SCI communication is able to transfer one byte at a time over a data line. The byte, sent out by the GPS, is received by the microcontroller one bit at a time and stored in a buffer. Once the full byte has been received, the buffered data is stored in a data array. The MMC

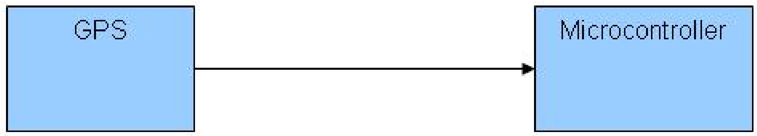

Figure 18: Block Diagram of GPS code

code uses the Serial Peripheral Interface (SPI) of the microcontroller to communicate with the MMC. This is similar to the Serial Communication Interface, except that the clocks on the microcontroller and the MMC are synchronized. The microcontroller is set in "master" mode, which means that the serial data transfer will work using its clock. The clock polarity and clock phase of the SPI interface are set such that the data will be valid on the first rising edge of the clock. The MMC has a "chip select" pin that is active low. This means that the MMC will recognize communication over the SPI interface while the chip select pin is grounded.

The MMC requires that all its pins be connected to a 10kΩ pull-up resistor. The maximum input voltage of each pin is 3.6V, which is 0.3V higher than the operating voltage of the MMC. The card has separate pins for reading and writing data. Pin 7 is used to read data from the card and pin 2 is used to write data to the card.

In order for the microcontroller to communicate with the MMC, a set of commands must be sent to initialize the card in SPI mode. Each command sent to the MMC is 6 bytes long, and must be followed by a waiting period. The waiting period is coded by sending 8 bytes of 0xFF to the MMC. This allows the card to acknowledge the command and respond to it. A wait period must accompany every command sent. A command sequence consists of a command byte, followed by 4 argument bytes, followed by a Cyclic Redundancy Code (CRC). The CRC is disabled in SPI mode, since it is known that the data sent over the line is valid. To start the initialization process, the chip must first be reset. The arguments of the reset command (the middle 4 bytes) can all be 0. The card is not in SPI mode upon reset, so a CRC of hexadecimal value 95 (0x95) is required. After a wait period, the command must be sent a second time in order to be acknowledged by the MMC. After the card is reset, an initialization command must be sent to the card. This command has the same arguments and CRC as the reset command (0s in the middle 4 bytes followed by a 0x95 CRC). This command must also be sent twice. Once the initialization is completed, the card will be in SPI mode. In this project, the MMC initialization all takes place in the main function, since it only needs to be run once.

To write to the MMC, a write command must be sent. A byte of 0xFF must first be sent to ensure the card is ready to accept the write command. The write sequence must start with the write command, followed by the starting address of the empty block that is being written to, followed by a one byte CRC. Since the card is in SPI mode, the CRC can be 0. Once the command is sent and a wait period is completed, another byte of 0xFF is sent. Next, a byte of 0xFE is sent to indicate the start of a block of 512 bytes of data. If 512 bytes of data are not available to be written, junk bytes must be written in to fill the space. Once the data is written, 2 CRC junk bytes must be sent. A final byte of 0xFF is sent to end the writing process.

The MMC stores its file structure information at the beginning of the writable blocks (starting at address 0x00000000, which is the first valid address). If it is required that the data be readable directly from the MMC using a computer, this file structure data cannot be overwritten. The file structure data is not protected, and can be overwritten by data being sent to the memory blocks it occupies. The end of the file structure block must be located, and the data writing must begin on the next block. However, this project did not require that the file structure be preserved. The data writing began at the first available block (0x00000000), and the file structure data was overwritten. To recover the data, either a Linux machine or a microcontroller is required.

This project implemented a "send command" function (called send_sd_cmd in the code) to aid the debugging process. A command, its arguments, and a CRC are stored in a command buffer. The contents of this buffer are sent to the MMC in the "send command" function. After the contents of the buffer are sent, a waiting period occurs. When the next command needs to be sent, the command buffer can be changed and the "send command" function can be called again.

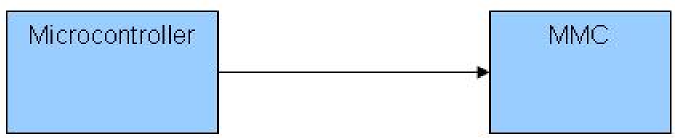

Figure 19: Block Diagram of MMC code

3.16 Graphical User Interface

The graphical user interface (GUI) was made in Labview. Labview has a built-in RS232 interfacing program, reducing the amount of work needed to build a functional GUI. The GUI allows tracking coordinates to be displayed. The user designates the source for the serial read, the amount of information to be read and rate at which information is read.

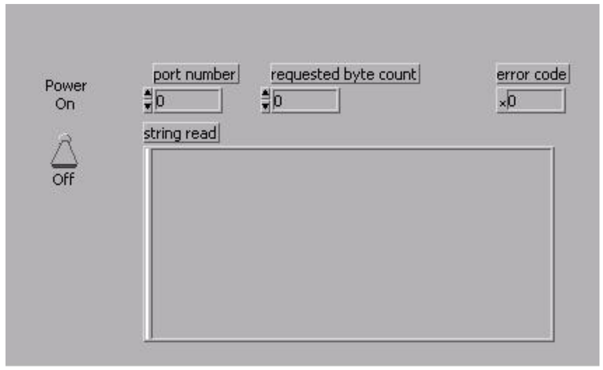

Figure 20: GUI Screenshot

4 Results

This section addresses the results of the project. This includes an explanation of the problems that have led to the indefinite postponement of the launch of the balloon-borne instrument, and an engineering analysis of the project.

4.1 Problems

Several problems were encountered during the implementation of the instrument design. Delays were caused by hardware interfacing issues, problems with the microcontroller, and software complexities. Other problems encountered during the design and implementation of the project include the desired balloon being out of stock, incompatibility of surface mount (SMT) parts without a printed circuit board (PCB), accounting for horizontal drift and minimizing cable weight. The most significant problem that limited the success of the project was the interfacing of all the subsystems with the microcontroller. The original microcontroller, which was donated by the customer, did not interface with the laptop used as the basestation and the microcontroller programming interface. The software license provided by the sponsor for use with the programming software for this microcontroller expired in the middle of the development of the instrument. When renewed, the software was of a different, limited version that did not allow the unit to be programmed in C. Because of this problem, the decision was made to switch to the MiniDragon+ microcontroller used earlier in the electrical engineering curriculum. This introduced problems of limited I/O ports, the lack of serial RS-232 interfacing, and the lack of voltage regulation circuitry that were previously included on the original board. The micocontroller problems were solved with additional hardware and the familiar interface of the secondary board.

The system launch was ultimately delayed due to problems with the GPS and MMC interfacing code. The GPS interface was completed in time for the next scheduled launch date of May 1, 2008 due to the help of Dr. William Rison of the New Mexico Tech Electrical Engineering Department, who had previous experience with similar devices. Dr. Rison aided in the debugging of the code and provided equipment used to test the output of the GPS receiver. The MMC code caused further delay of the launch of the instrument. Dr. Rison also provided assistance in debugging the MMC code, written in assembly language. The code was never completed, and the lack of data storage led to the failure to launch the system.

The integration of surface mount components without a PCB also caused delay in the project. SMT devices were chosen for efficiency and small size early in the project, without consideration of their mounting possibilities. The GPS receiver had a 16-pin flex cable with very small (0.5mm) spacing between its SMT pins. As a rather lucky solution to this surface mount problem, a circuit board from the National Radio Astronomy Observatory (NRAO) was discovered in a scrap heap that just happened to have the exact pin configuration and ground plane connections required for our application. The multiplexer ordered for this projet was a 16 to 1, 28 pin surface mount component that also needed to have a board made for it. No board could be found for this surface mount part, so 2 breadboard mountable 8 to 1 dual in-line package (DIP) multiplexers were used instead.

The desired balloon size was out of stock at the time of order, and the lead time was longer than acceptable in order for completion of the project. This forced a decision to up-size or down-size the balloon, and caused a budget issue since the larger-size balloon cost nearly three times what the the smaller one did, and would have put the project over budget. After consultation with the balloon manufacturer, it was concluded that the smaller balloon would satisfy the specification of altitude for this application.

Cable weight was an issue because Part 101 of FAA regulations stipulate that the payload cannot exceed 6 lbs. The cabling is the heaviest component, so weight quickly became a problem as the original design required a separate cable for each thermocouple. To reduce the amount of cabling, voltage and ground bus lines were used for the thermocouples. This led to a redundancy problem for the thermocouples since the thermocouple circuits would lose power in the event of a bus failure. This risk was acceptable, however, since the weight of the payload was restricted.

4.2 Engineering Analysis

To ensure the reliability of the instrument, several factors were taken into account. The first of these was redundancy. Parallel batteries were included in the design for the project to ensure that sufficient power would be provided if one of the batteries should fail. GPS and transmission system redundancy was evaluated but not employed due to budget constraints.

Another factor to be considered was signal noise. Excessive noise in the system renders the data useless. Reduction of noise was critical for the reliability of the instrument. To reduce the amount of noise introduced into the system, low noise amplifiers were used to amplify the thermocouple voltages. Linear regulators were used instead of switching regulators, again to reduce the noise of the system.

To ensure reliability, testing was also performed on each subsystem of the project. The transmitter was tested and proved to work reliably at a distance of 36 miles. All other subsystems, such as the sensors and the code, were also tested.

To ensure that the amplifiers did not introduce a significant amount of noise, calculations were done using information from the specification sheet. The amplifiers were rated at $\frac{3nV}{\sqrt{Hz}}$. To calculate a worst case scenario, a 500 kHz bandwidth was used. With this bandwidth, the expected error comes out to 2μV. The smallest expected change in voltage from a thermocouple was 22 μV. The expected amount of temperature error is 0.095°F.

4.3 Budget

The total budget for the project was $1000. A breakdown of the budget can be seen in Table 6 below. The majority of the budget for the project was spent on the sensors. The GPS receiver, which includes an antenna, amounted to only 8% of the total budget. The recovery system which includes the parachute and padding amounted to approximately 8% of the budget. The miscellaneous portion of the budget was allotted for circuit components. The MMC was only 5% of the total budget. Overall the cost of the entire project was $894.50 which left approximately 11% of the original budget.

Component	Price
Thermocouple	392
GPS	96.45
Adapters	31.26
MMC	16.48
Antenna	68.50
Balloon	80
Parachute	65
Batteries	81.44
Radar Reflector	29
Miscellaneous	34.25
Total	**894.50**

Table 6: Budget

4.4 Tasking and Critical Path

The subsystems were divided into specific tasks. Each team member led certain tasks. After deliberation over the skill sets of each member, the task leads were appointed as follows in Table 7. The critical path, as presented in Appendix A, shows the flow of tasks which were completed in sequence for the project. Each task had a completion date associated with it, at which time work was begun on the following task. If the best solution had not been found by the completion date, then any functional solution was used.

John Gallegos	Ted Schuler-Sandy	Chad Stephenson	Kristy Stong
Balloon	Sensors	Platform	GPS
Recovery System	Software	Power System	Budget
Platform		Software	Communications

Table 7: Task Allocation

5 Conclusion

The individual subsystems presented in this thesis each met specification requirements. The full integration of all subsystems and launch of the instrument have not yet been completed as of May 7, 2008. The completed project will be used by the customer to map an estimate of the seeing for multiple locations. The future work of this project would include the completion of the code integration and multiple launches of the instrument. This would most likely be done by integrating a PCB for the amplification circuitry. The data from these launches should be analyzed to provide an estimate of the seeing of the area where the launches occurred.

References

[1] Jorgensen, A.M. et al, *Design and test of an instrument for measuring microthermal seeing on Magdalena Ridge*, Magdalena Ridge Observatory, 801 Leroy Place, Socorro, NM 87801

[2] http://en.wikipedia.org/wiki/Image:Atmos_struct_imaging.png

[3] Marshall Brain, http://electronics.howstuffworks.com/gps.htm

[4] http://www.sco.wisc.edu/gps/gps_graphics/inter_spheres.jpg

[5] http://www.ngs.noaa.gov/FGCS/info/sans_SA/docs/statement.html

[6] ISE Inc, http://instserv.com/rmocoupl.htm

[7] Tony R. Kuphaldt, *Lessons In Electric Circuits*, http://www.eng.cam.ac.uk/DesignOffice/mdp/electric_web/DC/DC_9.html

[8] http://www.tycoelectronics.com/gps/glossary.asp

[9] ISE Inc., http://instrumentation-central.com/TechNotes/TypeKTableC.pdf

[10] *Thermocouple*, http://www.sensorsweb.com/thermocouple

[11] Heaton Co., http://www.heatonc.com/TCletter.php

[12] http://www.maxim-ic.com/appnotes.cfm/an_pk/871

[13] http://www.grc.nasa.gov/WWW/K-12/airplane/shaped.html

[14] http://www.metrodyne.com.tw/application%20note.pdf

[15] http://www.batteryspace.com/index.asp?PageAction=VIEWPROD&ProdID=2867