Microwave Power Beaming using Ka-band Radar
Tethered Aerostat Program

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Abstract

Power is transferred wirelessly from a ground based microwave transmitter to a receiver flown on a platform attached to a tethered aerostat. The signal is analyzed using consumer radar detection hardware and developed circuitry. This signal is analyzed by a programmable microcontroller, or Arduino, and data is then transmitted to a logging computer on the ground via flight computer and base station. Eventually, a rectenna and receiver will be developed to convert the microwaves to a useable voltage to power on-board instruments. This technology could be employed as a means to reduce the need for on-board power supplies for CubeSats deployed by the International Space Station, on orbit solar power generation, solar power satellites, etc.

Introduction and Statement of Problem

The term microwave refers to the range of electromagnetic radiation with frequencies between 100 MHz to 1000 GHz. (Pozar, 2012) Wireless power transfer, based on the technology of microwave transmission and reception by rectifying antenna, rectenna, which converts the microwaves to a useable voltage. This concept has been tested and proven on a large scale where 10 kW of power was transferred between a transmitter and receiver. (Lan Sun Luk, Celeste, Romanacce, Chane Kuang Sang, & Gatina, 1997) However, there is also a need for small size applications which could, for example, reduce the design requirements for on-board power supplies of CubeSats, The purpose of this experiment is to receive a microwave signal from a ground transmitter to our airborne receive, amplify the signal, and generate a useable voltage to power onboard electronics.

Equipment

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Aerostat and Winch Powered Spool (WPS). This project used a tethered aerostat (Fig. 1) to suspend a payload equipped with instruments and circuitry required to carry out a specific experiment. When filled with 260 ft^3 of welding grade helium, the aerostat measured approximately 10 ft. in diameter and 7 ft. tall, and provided 10 lbs. of lift. The WPS used electromechanical equipment to deploy/retrieve the aerostat. A wooden wire spool is driven by an electric winch powered by a 12V car battery (Fig. 2).

Figure 1: Aerostat and payload package in flight

Payload platform. Flight instruments were attached to the platform which was suspended below the aerostat (Fig. 3). The instruments and subsystems included on the platform were the Aim Xtra flight computer, an Arduino microcontroller, and electronic circuitry that comprises the Electrical Power and Microwave Beam subsystems, all described next.

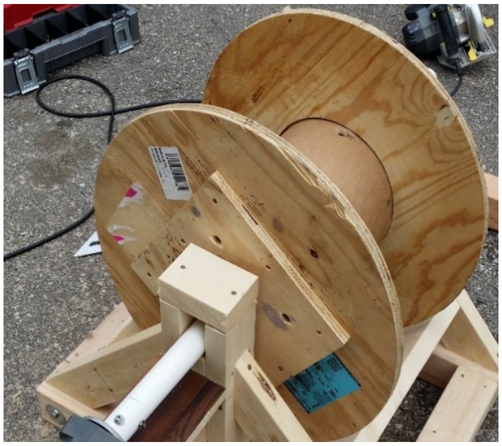
Aim XTRA (AX) and base station. The AX was responsible for real time data viewing during flights and controlled a safety feature that could deflate the aerostat in the event of failure. The AX arrived pre-programmed with its own native software used to view and manipulate data collected. The native AX sensors that were used are discussed later.

Electrical Power System (EPS). This subsystem powers the Arduino, radar detector, and AX.

Arduino. There are multiple inputs and outputs on this microcontroller used to monitor battery power, radar signal strength, and data acquisition from atmospheric sensors. This data was stored to an SD card which could be downloaded at a later time for analysis.

Digital-to-analog converter (DAC). Two voltage divider circuits were combined to one prototype board and allow a conversion from a digital value to an analog voltage that could be easily analyzed.

Microwave beam subsystem (MWB). The microwave transmitter, made by Kustom Electronics Inc., is a FALCON radar gun, a law enforcement tool to detect vehicle speed. It is used to generate 24.15GHz microwaves, 12-40mW output power at 12° beam width (Kustom Signals, Inc., 2011). The receiver is a consumer radar detector with additional circuitry to enables data collection regarding the strength of the signal received.



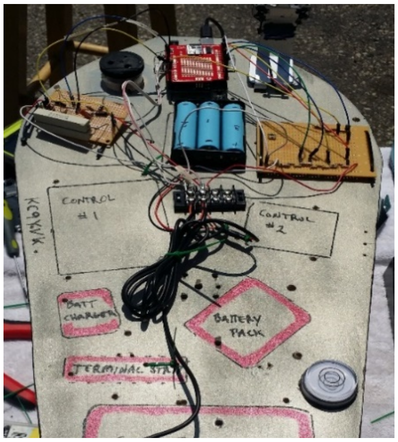


Figure 2: WPS without battery power or tether spooled.

Figure 3: Platform in development prior to launch.

Subsystem Development, Theory of Operation, and Integration

Microwave detection development. The accurate detection of microwave signal strength is crucial when power transfer efficiency calculations are done after a rectenna is developed. It will serve as our baseline measurement. During the first flight, the signal received by the MWB detector was unreliable, which led to the development of the data collection system described here. To accomplish this, a consumer radar detector was used and supporting circuitry was developed. The radar detector had a 7-segment LED display which showed the radar signal strength detected on a scale from 0-5. In order to convert the visual output of the LED display to a useable digital value, the voltage was measured at each of the pins to determine which LED segment was lit. The LED display is a dual inline pin package with 10 pins, 3 of which were not used to generate the display. Five volts is applied to each LED segment. When the segment of the corresponding pin is lit, there is a 2V drop across the LED segment, leaving 3V at the pin. Table 1 shows which LED segments are illuminated for a given signal strength. As shown in Figure 4, when the LED display shows a “5”, LED segments a, c, d, f, and g are lit, causing pins 3, 6, 7, 8, and 10 to have a low voltage.

Signal Strength on LED Display	5	4	3	2	1
Pin 1, Segment B	High	Low	Low	Low	Low
Pin 2	n/a	n/a	n/a	n/a	n/a
Pin 3, Segment C	Low	Low	Low	High	Low
Pin 4	n/a	n/a	n/a	n/a	n/a
Pin 5	n/a	n/a	n/a	n/a	n/a
Pin 6, Segment A	Low	High	Low	Low	High
Pin 7, Segment F	Low	Low	High	High	High
Pin 8, Segment G	Low	Low	Low	Low	High
Pin 9, Segment E	High	High	High	Low	High
Pin 10, Segment D	Low	High	Low	Low	High

Table 1: LED status for specific signal strength
Green=LED on; Red=LED off

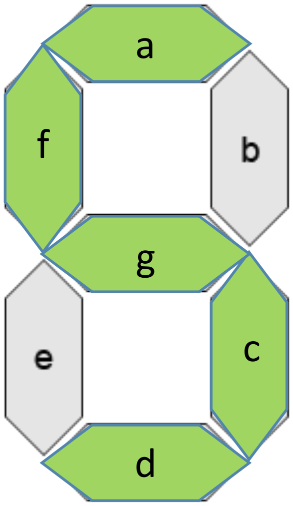
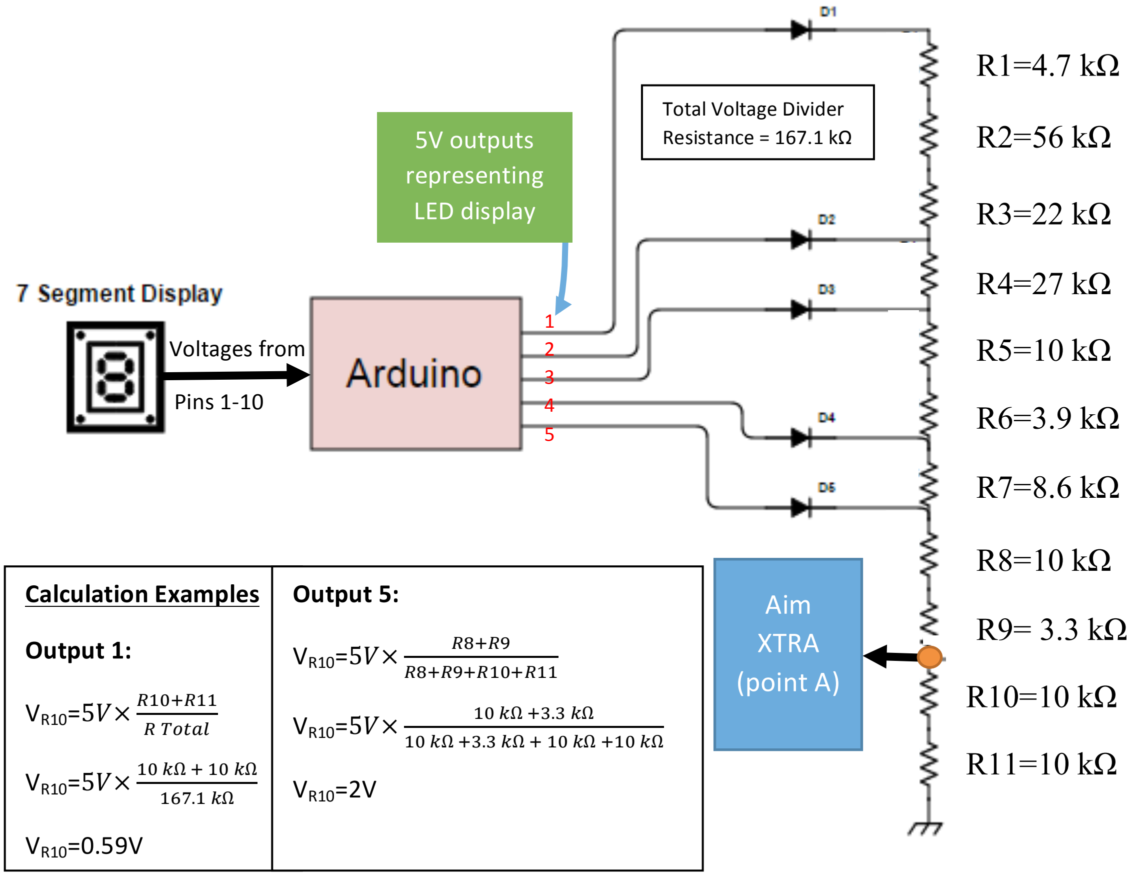


Figure 4: Example of “5” output on LED Display

The 7 voltage values from the LED pins are then sent to analog inputs on the Arduino. The Arduino's code was written to analyze these 7 inputs and provide a 5V output to multiple inputs on a voltage divider, based on which pins are high or low. This worked as a multiplexer/demultiplexer; based on the status of multiple inputs the Arduino will select which output to use. If the LED displays a "1", the 5V output is sent to the top of the voltage divider at D1 and most of the 5V is dropped across resistors 1-9 leaving only a small voltage at the output which is measured at point A (Fig 5). If the LED displays a "5", the output from the Arduino is sent to D5, only a small voltage is dropped, and we read a higher voltage at point A. The output from the voltage divider is sent to the AX, which sends that data in real time to a logging computer on the ground, determining the signal strength that is reaching the aerostat. This information will be critical for future efficiency testing.



Calculation Examples

Output 1:

$V_{R10}=5V\times\frac{R10+R11}{R\ Total}$

$V_{R10}=5V\times\frac{10\ k\Omega+10\ k\Omega}{167.1\ k\Omega}$

$V_{R10}=0.59V$

Output 5:

$V_{R10}=5V\times\frac{R8+R9}{R8+R9+R10+R11}$

$V_{R10}=5V\times\frac{10\ k\Omega+3.3\ k\Omega}{10\ k\Omega+3.3\ k\Omega+10\ k\Omega+10\ k\Omega}$

$V_{R10}=2V$

Figure 5: Simplified schematic of LED/Arduino/voltage divider/AX integration circuit

Electrical power system development. During operation, the Arduino required 7-20 volts, the radar detector required 10-12 volts, and the AX required 3.6-7.4 volts. One battery pack was used to reduce weight and consisted of three lithium ion batteries in series to supply the payload with 12.6 volts peak. Zener regulator circuitry was also developed to supply the AX with 6.8 V (Fig. 6).

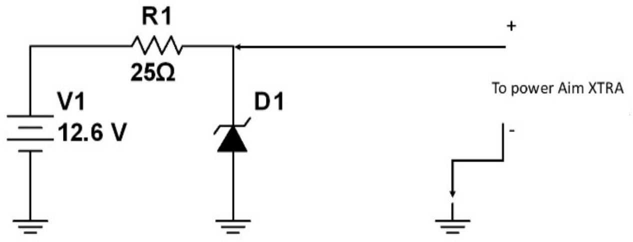


Figure 6: Zener Regulator Circuit

Battery life also needed to be monitored to prevent depleting the battery pack to dangerous levels. This was accomplished using the Arduino to control an NPN transistor circuit (Fig. 7) and voltage divider. To conserve energy the transistor was only forward biased every 5 seconds for one second. The voltage divider was used to step the battery voltage from 0 to 12.6 nominal volts down to 0 to 5 volts to be compatible with the Arduino. After the voltage was stepped down an analog input on the Arduino was then used to measure battery voltage. The measured voltage was used to make calculations, derived from the batteries' power curve that would decide which of four digital pins to turn high (5V). The four pins were designated 25%, 50%, 75%, and 100% battery life (Fig. 8). The pins were fixed to a DAC which depending on the pin that is high will supply the AX a signal voltage from 3.1V (100%) to .8V (25%). This was relayed in real time to the base unit via the AX.

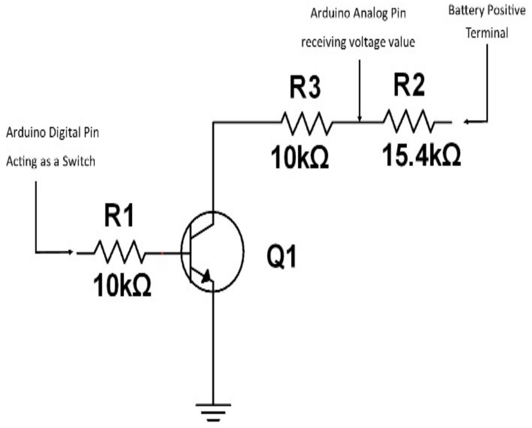


Figure 7: Transistor circuit used to monitor battery voltage. Transistor completes circuit when biased, and produces voltage at point A, which is then sent back to Arduino for analysis.

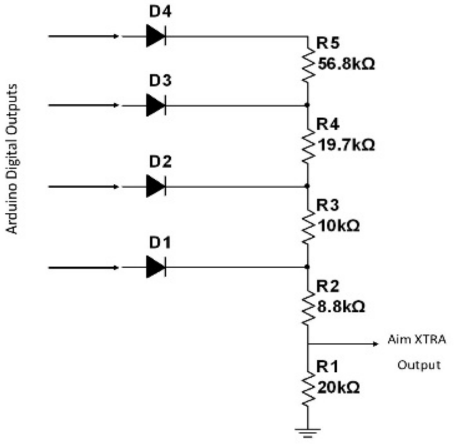


Figure 8: Arduino digital outputs provide 5V to one of 4 inputs to voltage divider depending on battery voltage. AX output received voltage from 0.8-3.1V which indicates battery condition.

Radar efficiency testing. With little background knowledge on the propagation of microwaves, it was important to understand the relationship of signal strength and alignment of the radar gun and detector. To test this relationship, a ground experiment measuring received signal strength versus distance at several offset angles, θ, was performed (Fig. 9). It was found that the maximum signal strength was achieved when the radar horn was pointed directly at the radar gun. The signal strength degraded rapidly when the horn was oriented more than 15° from the axis to the radar gun, which was not surprising due to the 12° beam width of the radar gun (Fig. 10).

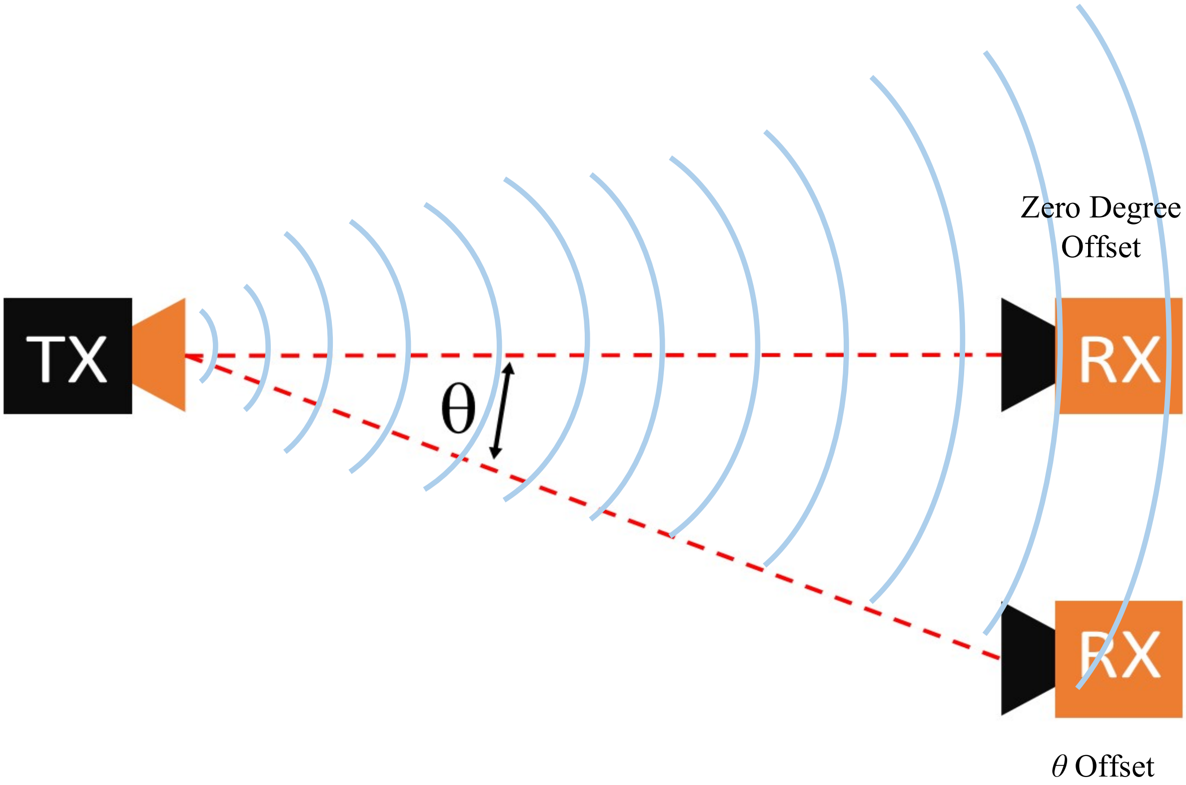


Figure 9: Illustrates the concept of offsetting the receiver (RX) from the transmitter (TX). The horn of the RX remains parallel to the horn of the TX, however, the RX is moved in one direction to create a change in the angle between the center of the TX and RX horns. Microwaves, shown in blue, have greater intensity when the RX is at zero degree offset. Simulated microwaves are shown in blue for visual purposes.

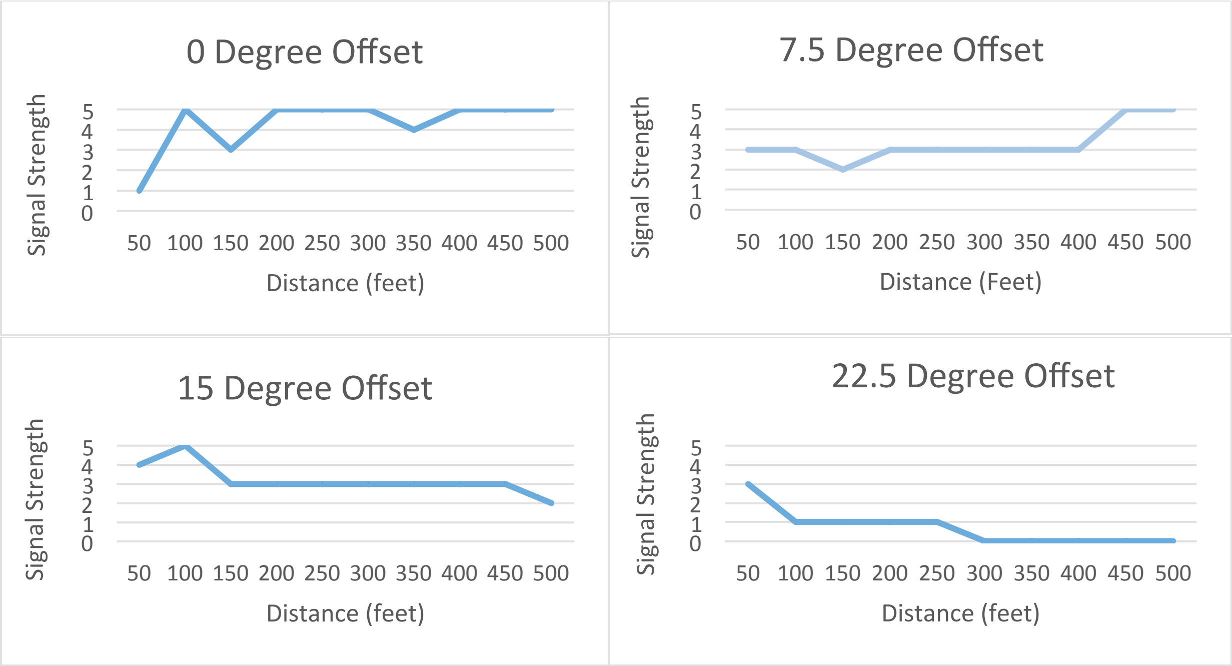


Figure 10: Changes in signal strength, as displayed by radar detector, for varying degrees of offset from transmitter.

Multiple trials were conducted with the radar detector horn facing directly towards the gun and directly away from the gun, or a 180° rotation (Fig. 11). The graph in Figure 12 shows the average signal strength is higher with the horn facing directly towards the gun. It is interesting to note there is still signal detection with the horn facing away from the gun. Perhaps scattered or reflected microwaves could still provide power transfer, but with decreased efficiency. It was also found that there was a direct relationship to signal strength and separation distance. The signal strength dropped, as expected, as the separation distance increase between the gun and detector.

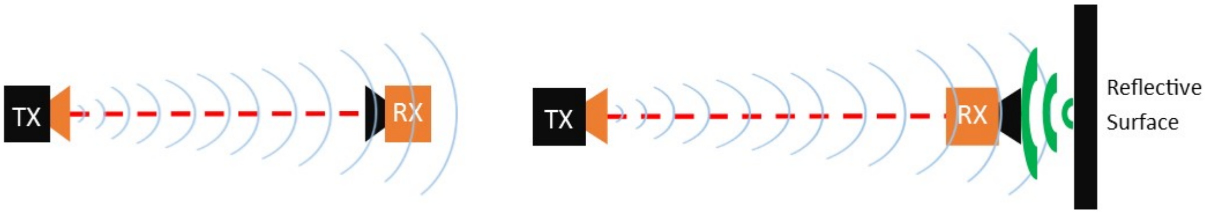


Figure 11: RX and TX orientation during testing. Reflective surface represents microwave scatter from surrounding vehicles, buildings, persons, etc. Reflected microwaves shown in green.

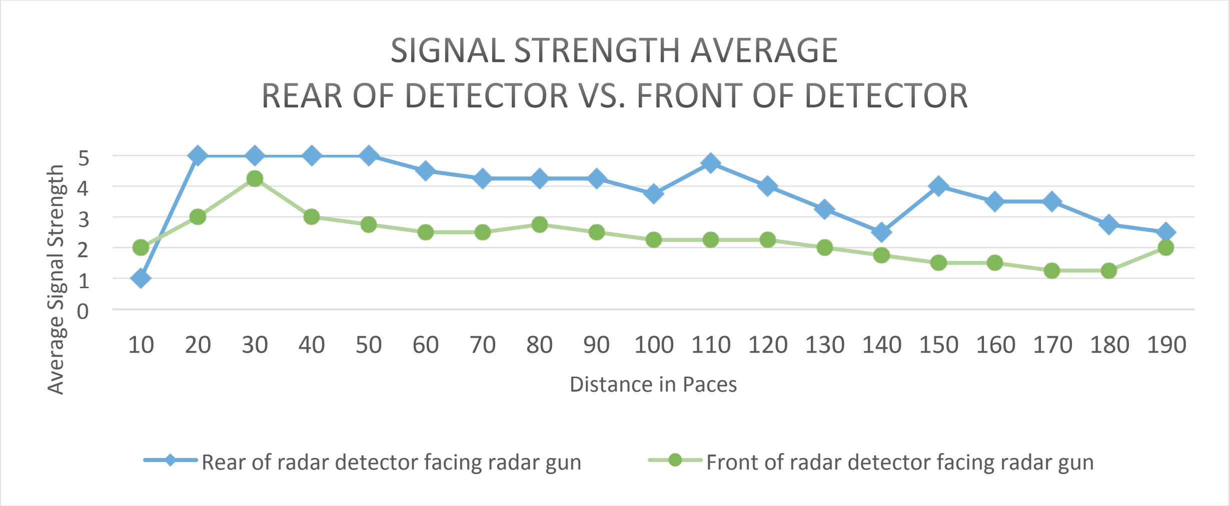


Figure 12: Average signal strength under 2 conditions over multiple trials.

Arduino programmable microcontroller. Weather monitoring was achieved with a Spark Fun HIH6130 chip to record humidity and temperature. These transducers would create a known voltage for a specific condition. Any changes in these voltages would indicate a change in conditions. These values were sent to an analog input on the Arduino for data logging. A Kestrel weather station ground unit was used to monitor weather conditions on the ground to enable comparison to the weather conditions on the aerostat. Any changes in conditions would indicate the conditions the microwaves will be propagating through. This data has not yet been analyzed.

For the data acquisition we used a Spark Fun SD shield. This shield was designed to be used with the Arduino Uno. Due to the need for a larger controller with more I/O pins, an Arduino Mega was implemented. This change required modification to the SD shield by clipping pins 11, 12, and 13, and using jumpers to make new connections to pins 51, 52, and 53. Signal strength, distance from the radar gun, battery power, weather conditions, and time stamps were saved to an onboard SD card in a .txt format. This data was later converted from a .txt file to a .csv file. The .csv file made enabled data viewing in an Excel format.

AX flight computer. The objectives of the AX were to act as the onboard flight computer, log voltage measurements of the EPS and MWB, provide GPS data including location and altitude, as well as provide a means to monitor this data in real time during flight. Some of the data, including atmospheric conditions, GPS, and altitude, were natively programmed sensors and were plug and play. To obtain data regarding the EPS and MWB, the data had to be converted to voltages in the range of 0-3.1V, which is explained under the respective subsystems. Once these voltages were produced, they were sent to the inputs of the AX and then transmitted wirelessly to the base station. These voltages then appeared as a function of time and could be easily analyzed during flight to provide an indication of performance.

Flight 1 Analysis

Pre-flight. While preparing to launch the aerostat, each sub-team was able to efficiently set up the equipment necessary to perform the experiment and collect data. Extension cords were used to power laptop chargers and a DC power supply used for the radar gun. Ground testing of the platform was performed to ensure data transmission, and the aerostat was laid out for inflation. Once the payload had been armed and the aerostat was unpackaged, inflation began. We filled the aerostat to approximately neutral buoyancy to allow us to connect the payload platform and tether.

Flight. During the flight, irregular signals from the MWB and EPS subsystems to the AX base unit required the aerostat to be brought down for troubleshooting. Signals should have been smooth DC values but instead were noisy. 60 Hz noise was present everywhere on payload circuitry as seen on our oscilloscope. This could have been a result of noisy power supplied to the oscilloscope due to the long extension cords, or multiple instruments plugged into the power strip. In the future, a generator positioned near the microwave transmitter would be desirable to reduce line loss in the extension cords and eliminate noisy power. After several attempts to obtain data transmission from the AX to its base station, it was realized that the data was invalid due to wiring connection failure. No useable data from MWB was obtained.

Post flight discussion. The original supplied helium tank was empty, requiring an emergency replacement. Wiring connection failures were present between the AX and Arduino producing unreliable data. MWB circuit produced a noisy, unusable signal. A uniform method to match time between AX, Arduino, and note taking will be required to reduce error in data analysis. The soldering of all connections between subsystems will help eliminate wiring connection failures on a launch day—although significant testing of subsystems prior to soldering will be required. Our team also hoped to compare results from the radar efficiency ground testing to the results from the flight. However, due to the wiring connection failures, we were unable to obtain any useable data, and therefore, unable to compare efficiency results. The WPS worked effectively but mounting WPS to trailer would simplify transportation and eliminate the need for ballast weighting.

Conclusion and Next Steps

One luxury of this project is that it spans 2 years. We have nearly completed year 1, and now have year 2 to refine our processes and techniques. A new platform is in development which will allow for better organization of our instruments and reduction in weight, a gimbal system to aim the radar detector is also in development, and the beginning stages of research are being completed for development of a rectenna for microwave conversion to DC power. All of the developed systems bring the goal of wireless power transmission closer. For example, in developing the radar signal strength circuit, we can compare this data to the voltages produced by the rectenna to determine the efficiency of power transfer. Also, because this technology has been proven on a large scale, our team knows the concept is valid. However, the power of the transmitters used in this experiment was 10 kW, compared to our microwave transmitter which is 10 W. We feel this could present a challenge in reading the small signals we expect to receive at the rectenna.

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