Dropsonde Design, Calibration, and Testing for Multi-Point Measurement of Thunderstorm Electrical Structures

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Abstract

Electric field measurements are necessary to understand thunderstorm evolution and lightning initiation. However, most existing measurements are made with single instruments carried by weather balloons. It is difficult to interpret such data since a change in observed electric field could be due either to motion of the instrument or charging/discharging currents. In order to decouple these behaviors, it is necessary to make simultaneous measurements at multiple locations. To avoid the complexity of multiple balloon launches, we describe a single balloon instrument with multiple, independent dropsondes to be released at desired time intervals. The dropsondes are designed to rotate and be self stabilizing, enabling them to measure electric fields as they fall. The dropsondes are lightweight, robust, and low-cost, and include a preamplifier, GPS receiver, search coil and accelerometer for orientation sensing, microcontroller, and a telemetry system to transmit data to a ground station. Prototype instruments have been drop-tested to demonstrate aerodynamic stability and rotation and have been calibrated for electric field measurement. A balloon payload set to release a set of such dropsondes via hot-wire release mechanisms can thus accomplish the goal of multi-point measurements of thunderstorm electrical structures.

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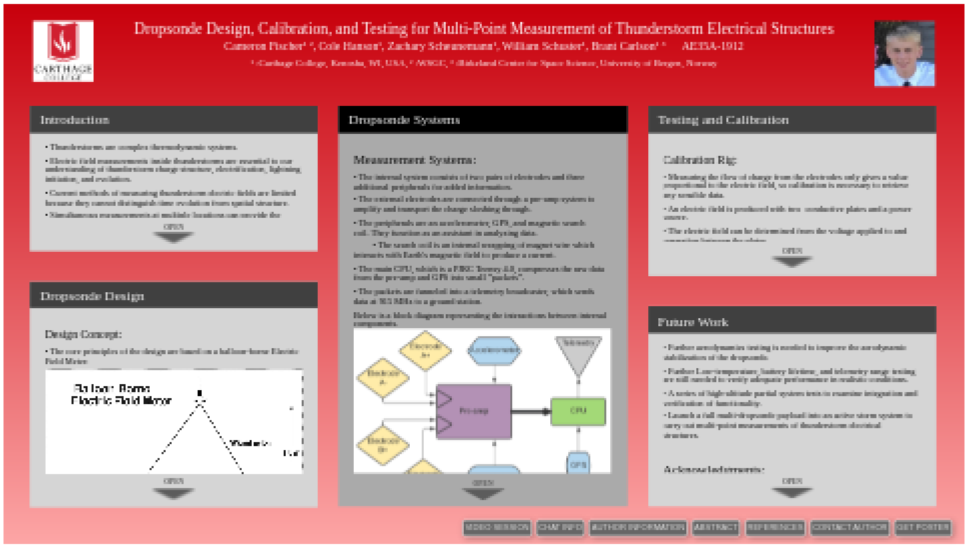

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PRESENTED AT:

INTRODUCTION

• Thunderstorms are complex thermodynamic systems.

• Electric field measurements inside thunderstorms are essential to our understanding of thunderstorm charge structure, electrification, lightning initiation, and evolution.

• Current methods of measuring thunderstorm electric fields are limited because they cannot distinguish time evolution from spatial structure.

• Simultaneous measurements at multiple locations can provide the information necessary to make this distinction. See Schuster et al., AE35A-1911 (https://agu2021fallmeeting-agu.ipostersessions.com/Default.aspx?s=BA-22-F6-13-F3-DE-78-E4-5F-E9-CD-BB-FD-8D-3F-00)

• Such measurements can be made efficiently by releasing multiple probes, known as dropsondes, into the storm.

Thunderstorm Basics:

• Charging mechanisms are poorly understood. Typical structure is shown below.

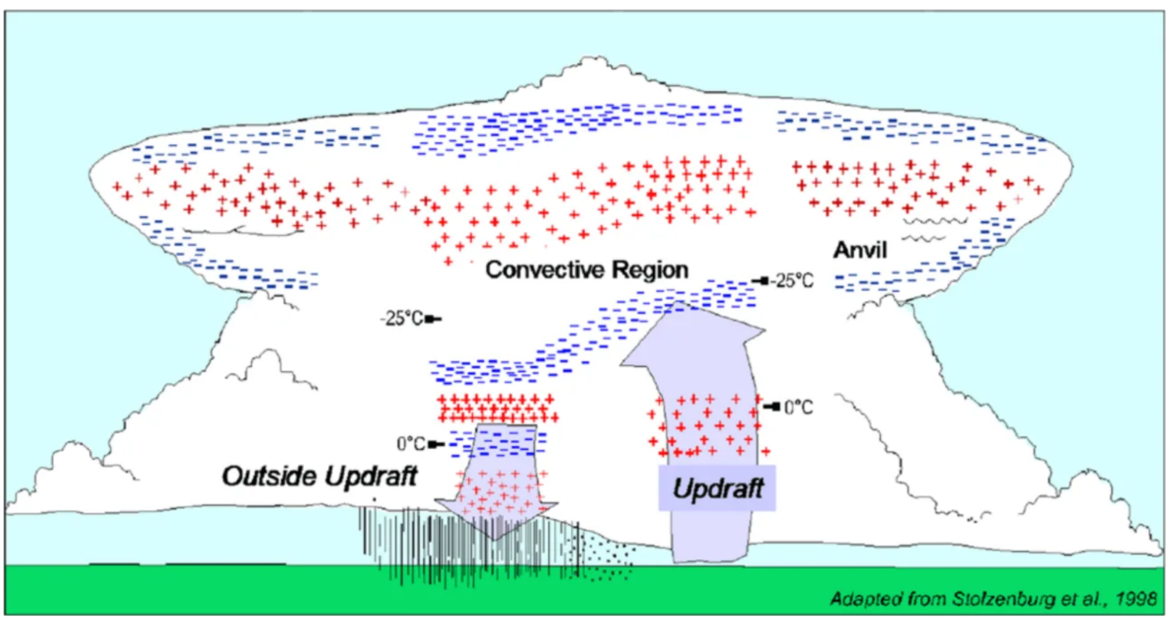
• Thunderstorms form when a mass of warm, moist air rises.

• Water vapor condenses, forming water droplets or ice crystals.

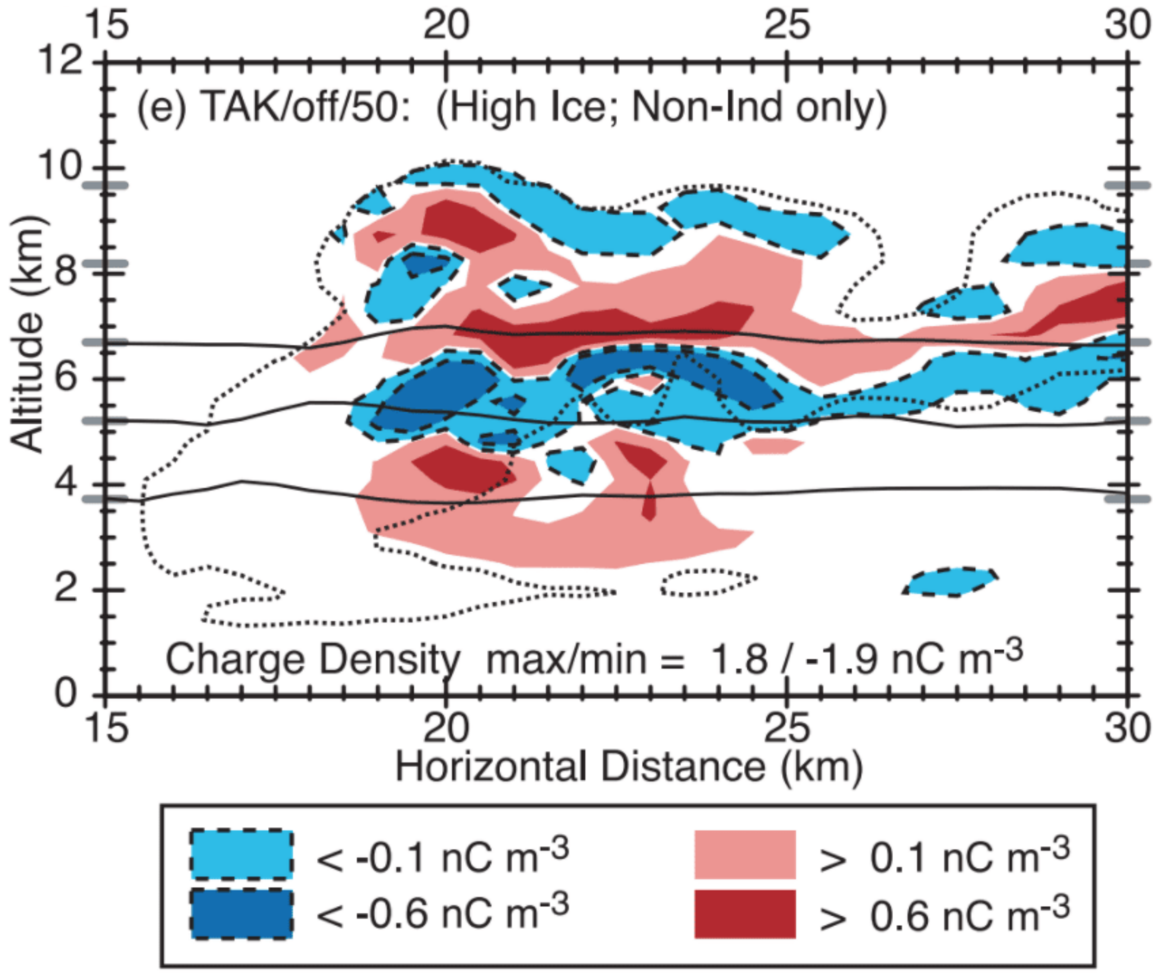
• Snow, ice, and graupel form in the middle and upper regions.

• Collisions between these particles result in electrification.

• Storm gets more charged over time; lightning acts as discharging mechanism.



The above figure depicts a typical storm anatomy, while the below figure depicts a more realistic simulation of the charge distribution.



The stark differences in charge structure above highlight the need for a more complete mapping of the electric fields present in thunderstorms.

DROPSONDE DESIGN

Design Concept:

• The core principles of the design are based on a balloon-borne Electric Field Meter:

[VIDEO] https://res.cloudinary.com/amuze-interactive/image/upload/f_auto,q_auto/v1638982765/agu-fm2021/f9-6a-fe-f9-4c-bc-32-93-91-66-84-a5-4d-5c-cd-88/image/efm_jacmmz.mp4

The above image shows a diagram of a typical Balloon-Borne Electric Field meter, which has been the primary method of measuring thunderstorm electric fields.

• Carried aloft by a balloon, the above referenced fiberglass tube rotates, leading to charge exchange between the aluminum spheres. This charge exchange is recorded, and can be used to infer the electric field strength.

• Our dropsonde concept works on similar principles:

• Small dropsondes are released from the top of storm clouds via a weather balloon transportation system.

• Small electrodes on the dropsonde’s body are used to accumulate charge inside of the storm's electric field.

• A spinning motion is utilized to force the charge accumulated to flow between opposing electrodes.

• That flowing charge can be intercepted and measured to give a quantity proportional to the strength of the electric field.

• Data is then sent to the ground via a telemetry system.

Design Constraints:

• An Ellipsoid shape provides aerodynamic stability, so the dropsondes' long axis is always horizontal.

  • This has been verified by simulation and prototype drop tests.

• Fins designed directly into the body cause rotation while falling, enabling the flow of charge between electrodes.

• Two sets of opposing faces allow for electrodes to be placed directly onto the body.

• The thin, lightweight shell surrounds and protects internal electronics from water and debris.

• Everything must be balanced for proper rotation about the principal axis.

The above image is an AutoDesk inventor rendering of the dropsonde shell.

DROPSONDE SYSTEMS

Measurement Systems:

• The internal system consists of two pairs of electrodes and three additional peripherals for added information.

• The external electrodes are connected through a pre-amp system to amplify and transport the charge sloshing through.

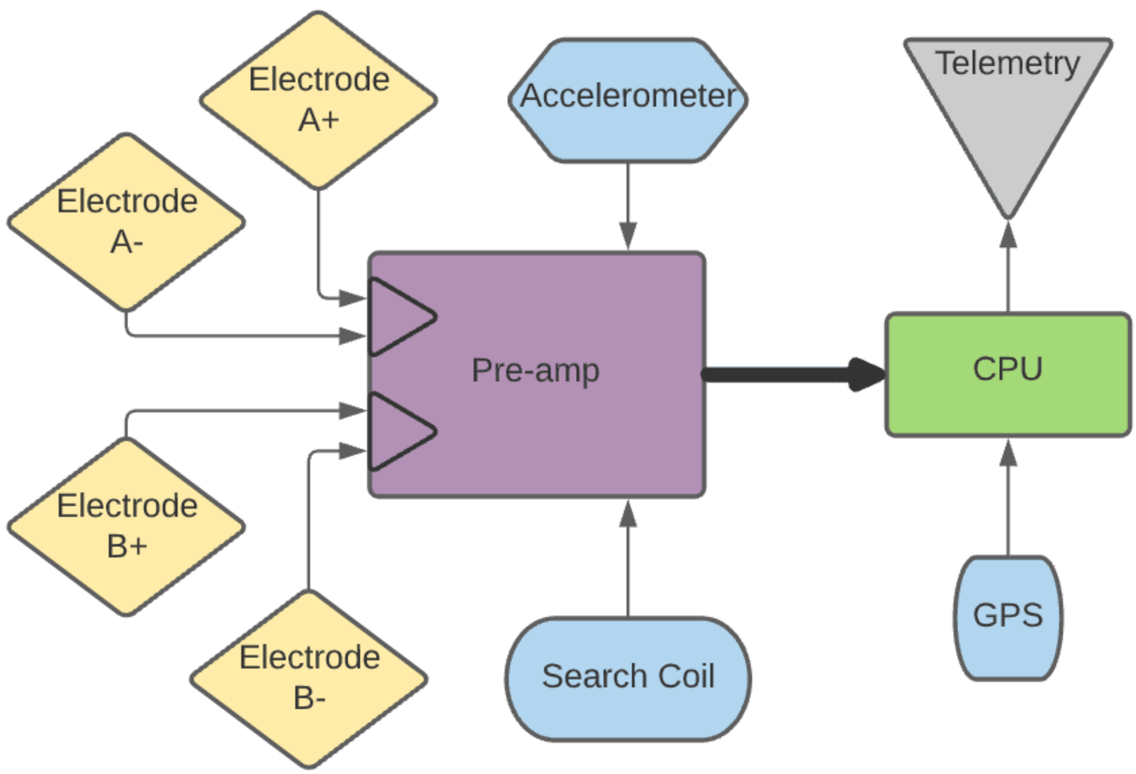
• The peripherals are an accelerometer, GPS, and magnetic search coil. They function as an assistant in analyzing data.

• The search coil is an internal wrapping of magnet wire which interacts with Earth's magnetic field to produce a current.

• The main CPU, which is a PJRC Teensy 4.0, compresses the raw data from the pre-amp and GPS into small “packets”.

• The packets are funneled into a telemetry broadcaster, which sends data at 915 MHz to a ground station.

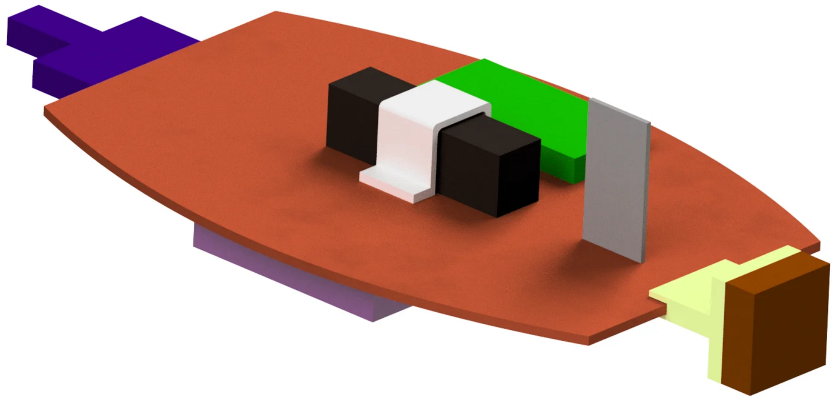
Below is a block diagram representing the interactions between internal components.



Interconnect Board:

• A physical interconnect board supports and connects components, as well as adds rigidity to the shell and keeps the components balanced.

Below is an AutoDesk rendering of the interconnect board and component placement (slightly outdated but shows the general concept)



Data Processing:

• Since the pre-amp is an analog system, the main CPU has to sample data at set intervals.

• The current CPU design intakes around 30,000 data points per component per second.

• This much data cannot be directly transmitted to ground, so data is processed on-board and compressed into packets before transmission

• compressed data packets include spin rate, signal amplitude and phase (via FFT), and simple statistics like minimum, maximum, mean, and variance for electrodes, search coil, and accelerometer.

• Location, time, and signal properties from the GPS are also included in the packet sent to the ground.

• Data from multiple dropsondes can then be combined to infer electric field geometry and time evolution, see Schuster et al., AE35A-1911 (http://agu2021fallmeeting-agu.ipostersessions.com/Default.aspx?s=BA-22-F6-13-F3-DE-78-E4-5F-E9-CD-BB-FD-8D-3F-00)

Transportation System:

• The work for the mothership, or transportation system, was primarily done last year

A quick recap:

• The Mothership is designed to hold six Dropsondes at a time.

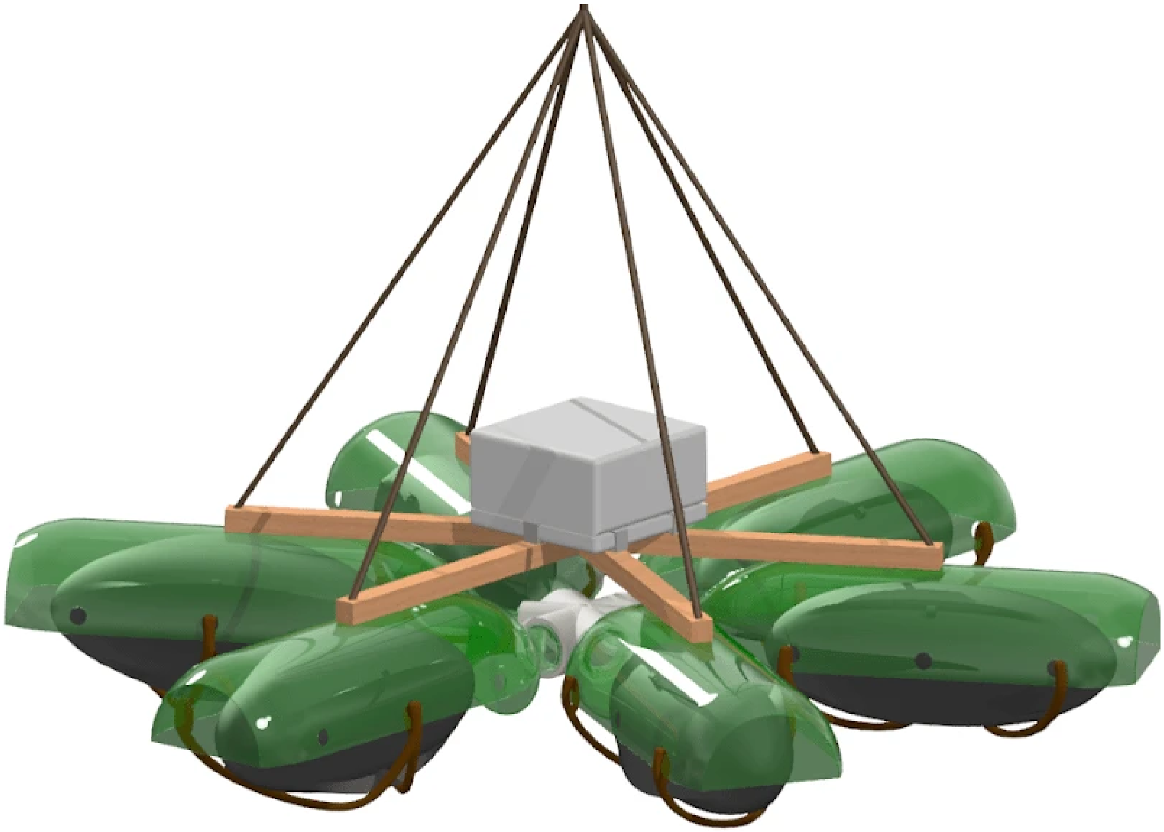
• It is expendable, so it is primarily made of cheap, easy to find materials, but is also robust enough to survive harsh thunderstorm conditions.

• A nichrome hot-wire cutdown mechanism is used to release each dropsonde individually.

• A GPS and microcontroller are used to determine the proper time and location to release each dropsonde

• The whole system is attached to a weather balloon so that it can quickly reach the top of a storm.

Below is an AutoDesk inventor rendering of the Mothership design. Not depicted above the system is a reflector and weather balloon.



TESTING AND CALIBRATION

Calibration Rig:

• Measuring the flow of charge from the electrodes only gives a value proportional to the electric field, so calibration is necessary to retrieve any sensible data.

• An electric field is produced with two conductive plates and a power source.

• The electric field can be determined from the voltage applied to and separation between the plates.

• A crude rig was made to hold the dropsonde rigidly in place while still allowing it to rotate freely.

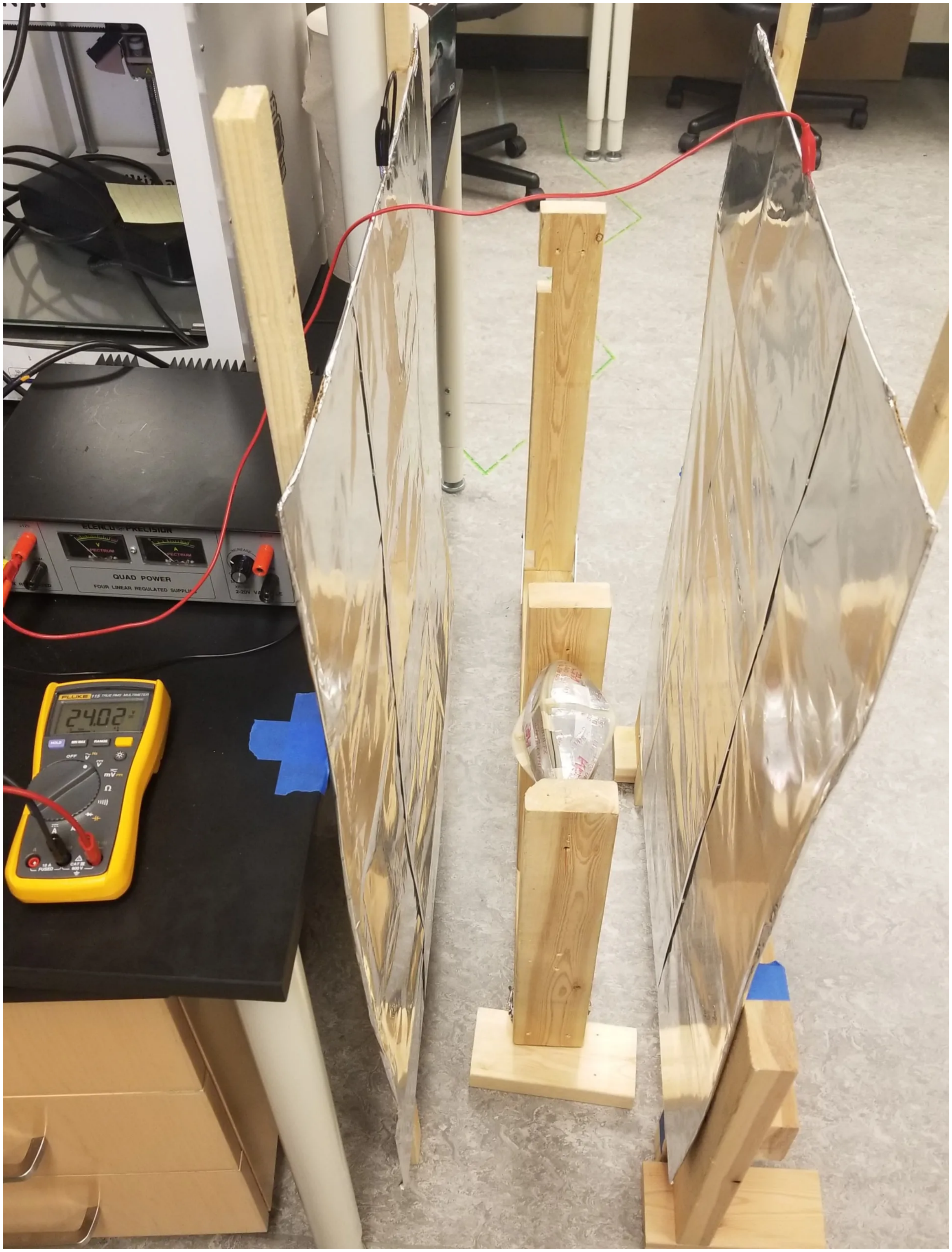
• The spin of the dropsonde is achieved via a leaf blower, to simulate the dropsonde freefalling.

    • Thus far only low voltage, small plate separation tests have been conducted.

• Data is collected using a modified code to intercept the telemetry system.

    • This not only means no hardwiring is necessary, but it also allows for testing of the telemetry data transmission.

Below is an image of the calibration setup.



Calibration Results:

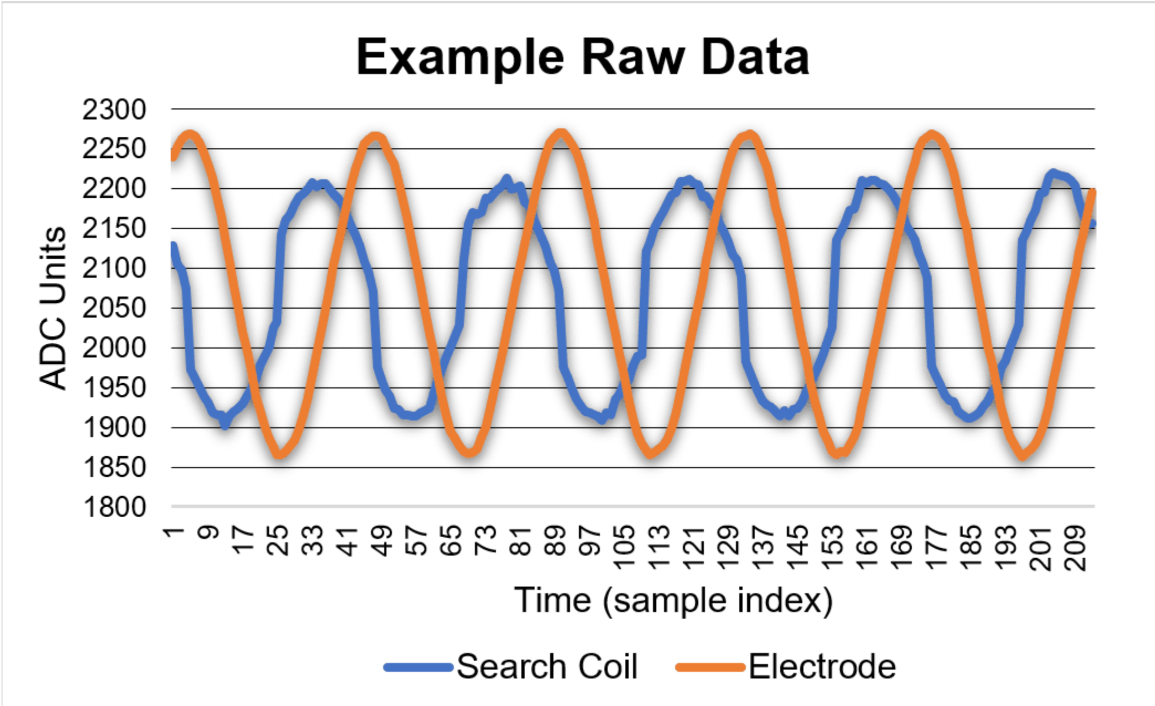
• Data is sampled from the electrodes and various other components at 30 kilo-samples per second (ksps), then transmitted at 1 ksps, all in 12-bit ADC.

• In the figure below titled *Example Raw Data*, roughly ½ a second of data is shown

• The raw data shows clean sinusoidal oscillation from both an electrode channel and search coil.

• The phase shift between these signals provides a relative direction of fields, and therefore the direction the probe is facing.

• signal oscillation is characteristic of the rotation rate for the probe.



• The graph below titled *Signal Strength and Frequency* is 30 seconds of processed data, looking specifically at the frequency of rotation and electrode amplitude, or signal strength.

• This test started with the probe at rest, quickly increasing rotation speed, holding it constant for a few seconds, then letting it slowly come to rest again.

• Both Frequency and Amplitude show very similar trends over time, which is an expected outcome.

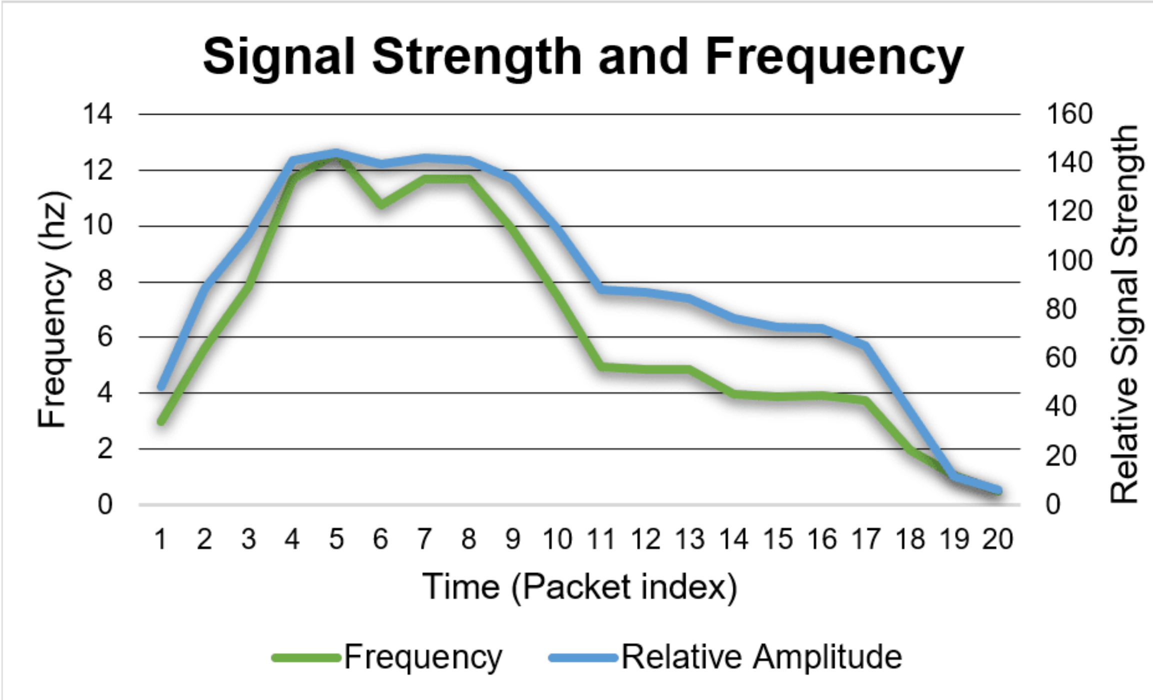
• This shows that both amplitude and frequency data is needed to determine the electric field strength.

• Previous work by a colleague, Max Becher, was done to derive this very relationship.

$$|E| = \frac{A\tau\omega}{\sqrt{\tau^2\omega^2+1}}|V| + E_0$$

Where A, τ, and E_0 are constants to set by calibration.

• Specific values of these constants will be determined using final enclosure and preamplifier designs.



Drop Testing:

• A series of tests were conducted releasing a prototype dropsonde shell from a drone.

• Altitudes ranged from 50 to 150 meters above the ground.

• Overall results were very promising with largely good characteristics.

• Release mechanism had some complications resulting in sub-optimal initial spin rates.

• The shell did not always spin with its long axis horizontal, and occasionally became unstable during the flight.

• Further testing and optimization is necessary, but the overall outcome of the tests was promising.

FUTURE WORK

• Further aerodynamics testing is needed to improve the aerodynamic stabilization of the dropsonde.

• Further Low-temperature, battery lifetime, and telemetry range testing are still needed to verify adequate performance in realistic conditions.

• A series of high-altitude partial system tests to examine integration and verification of functionality.

• Launch a full multi-dropsonde payload into an active storm system to carry out multi-point measurements of thunderstorm electrical structures.

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