Multi-point Measurement of Thunderstorm Electric Fields by Balloon-borne Dropsondes

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Abstract

Electric field measurements inside thunderstorms are essential to our understanding of thunderstorm charge structure, electrification, and lightning initiation. However, most existing measurements have been made by single instruments carried aloft by weather balloon, thus providing measurements made at a single point that moves through the storm on a timescale of tens of minutes. It is therefore difficult to interpret such data, since a change in observed field strength may be due to motion of the balloon into a region with different field or due to overall evolution of the storm's electrical structure with time. Separation of such spatial and temporal variability requires simultaneous measurements at multiple locations within the storm. This can be accomplished with a single weather balloon by carrying multiple independent electric field dropsondes aloft and releasing them one at a time, separated by short time intervals. The balloon payload design is optimized for low mass and use of off-the-shelf components whenever possible, releasing each dropsonde by a hot wire cut-down mechanism. Each dropsonde spins as it falls, measuring electric field as it rotates and sends data to a ground station in real-time. The dropsondes are designed to fall and rotate stably by use of aerodynamic simulations, with internal components robustly connected along the axis of the instrument to ensure the desired balance and alignment of the principal axes of the moment of inertia. The telemetry transmitters use simple low-cost low-power all-in-one transmitter chips. The telemetry ground station receives signals simultaneously from all dropsondes by a single software-defined radio receiver. Robust long-range communication is enabled by use of spread spectrum techniques and error correcting codes.

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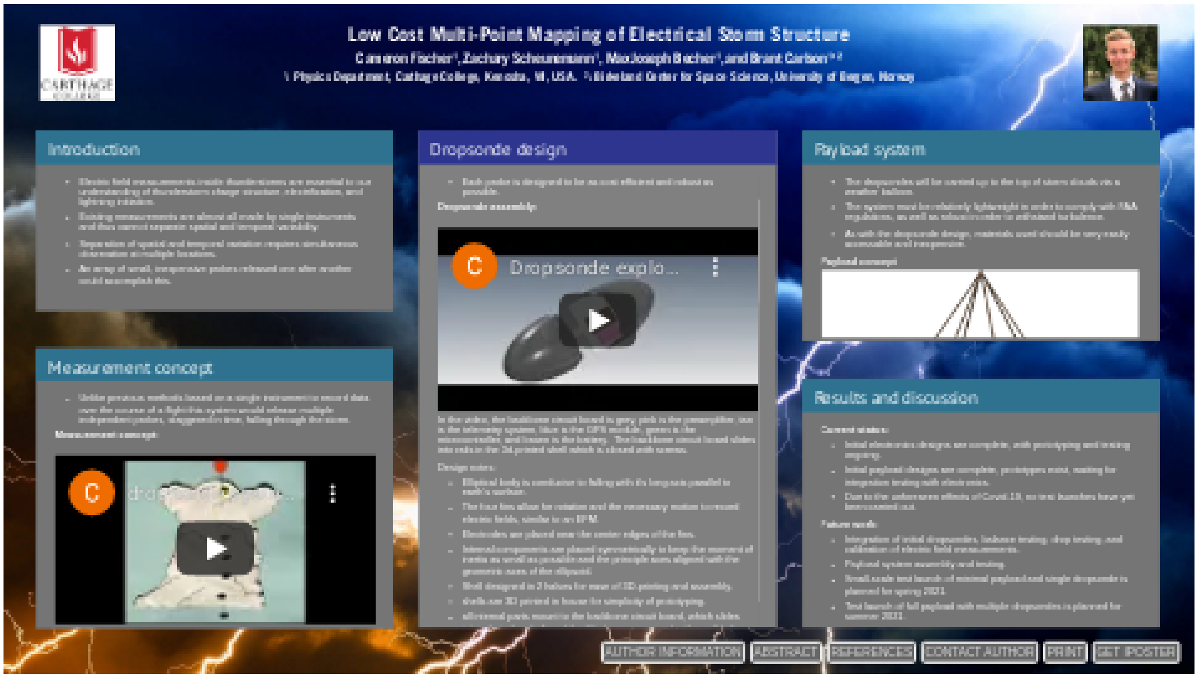
Low Cost Multi-Point Mapping of Electrical Storm Structure



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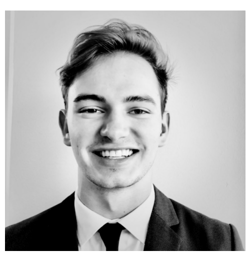

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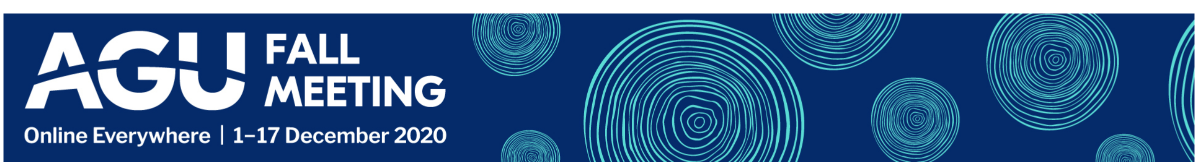


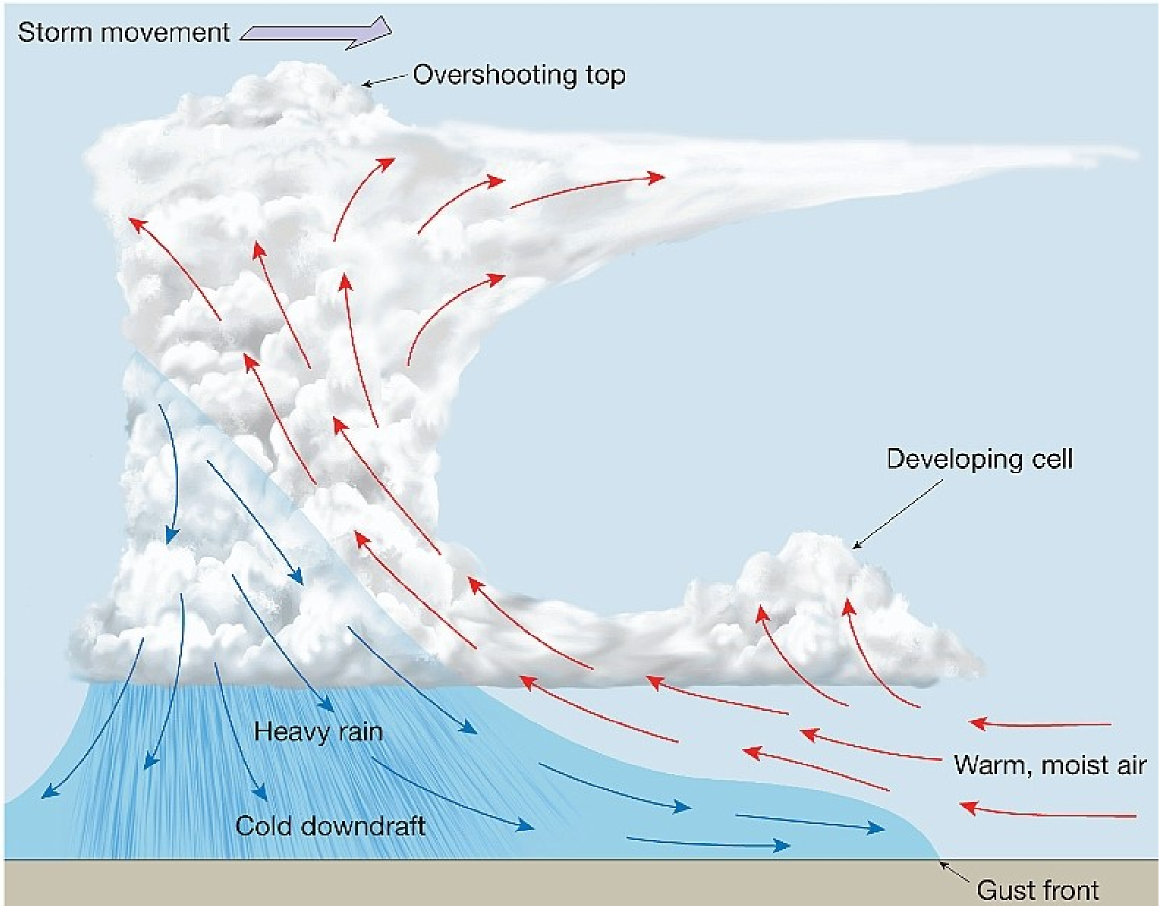
INTRODUCTION

- Electric field measurements inside thunderstorms are essential to our understanding of thunderstorm charge structure, electrification, and lightning initiation.
- Existing measurements are almost all made by single instruments and thus cannot separate spatial and temporal variability.
- Separation of spatial and temporal variation requires simultaneous observation at multiple locations.
- An array of small, inexpensive probes released one after another could accomplish this.

thunderstorm basics

- Thunderstorms form when a mass of warm, moist air rises
- Water vapor condenses, resulting in rain
- Snow, ice, and graupel form in the middle and upper regions
- Collisions between these particles result in electrification
- Charge builds up, resulting in lightning

Thunderstorm anatomy:



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Collision details

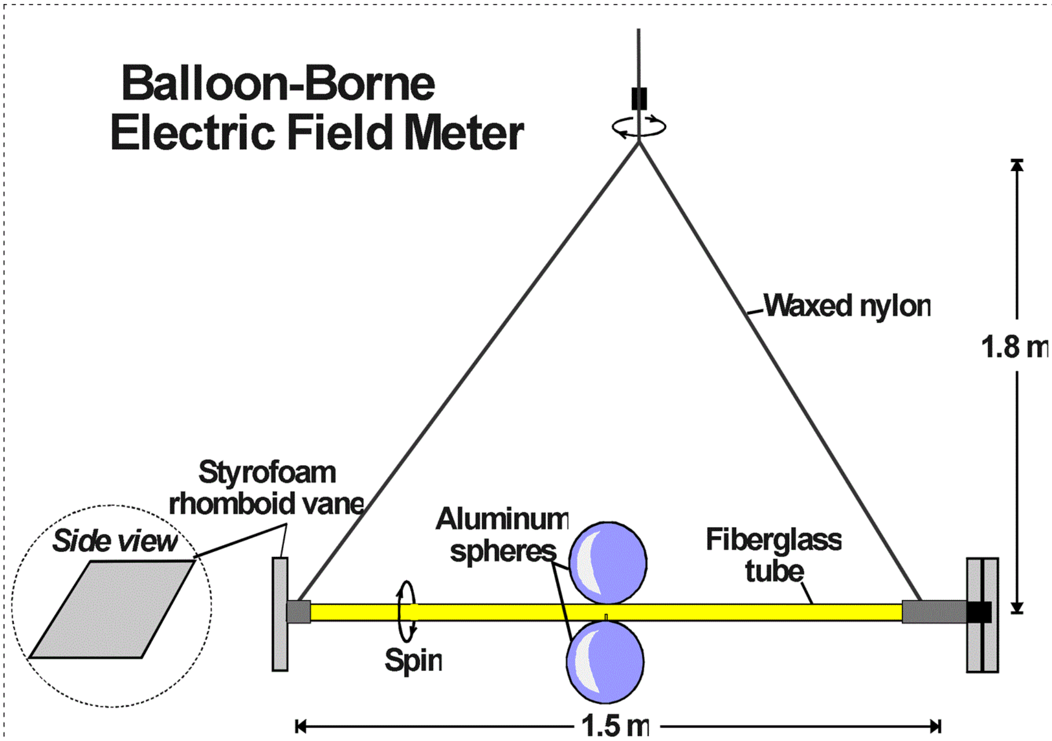
- Both graupel and ice crystals initially have no net charge, though when growing the surface tends to be negatively charged and the interior tends to be positively charged.
- When they collide in the upper region of the storm, the ice crystal gains a net positive charge and the graupel a net negative. In the lower regions the charge transfer reverses.
- Dense graupel falls while ice crystals are carried with updrafts

[VIDEO] https://www.youtube.com/embed/qcf3T8ouZKk?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

- Charges separate and create a potential difference.
- Once electric fields reach a critical strength, discharges occur, which further complicate the electric fields.

Previous Methods

- Most atmospheric measurements have been made with balloon-borne electric field meters (EFM)
- Their general principle relies on induced current through moving electrodes.
- The rotation of conducting spheres is what induces a measurable current in most field meters.



[2]

- If only a single instrument is launched, the results cannot separate spatial and temporal variability.

- Typically, temporal variability is ignored, and the resulting data is treated as a function of altitude. For example, an increase in electric field strength as the balloon rises is treated as a change due to the motion of the balloon into a region of stronger electric field, ignoring the possibility that the electric field is increasing with time due to electrification.

- Here we describe the development of a new measurement technique based on multiple dropsondes, allowing for separation of spatial and temporal variability.

MEASUREMENT CONCEPT

- Unlike previous methods based on a single instrument to record data over the course of a flight this system would release multiple independent probes, staggered in time, falling through the storm.

Measurement concept:

[VIDEO] https://www.youtube.com/embed/YNEytcHGy7I?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

The resulting data can be interpreted in multiple ways:

- **Temporal behavior at an altitude:** with multiple dropsondes moving through the same altitude range at various times, temporal evolution of the electric field at that altitude range can be directly measured.

- **Spatial variability at an instant:** with dropsondes measuring storm electric field at multiple altitudes at a given time, the spatial structure of the electric field structure can crudely be determined.

- **Combined spatial and temporal data:** if the evolution of the storm can be assumed to be approximately steady, spatial and temporal structures inferred by the above methods can be combined into a more complete picture of the full spatial/temporal structure of the storm.

Key components

- Dropsondes: multiple instruments must be carried by a single balloon payload for release into a storm. Information must be transmitted to ground in real-time to relax the requirement for recovery of many instruments.
- Balloon payload: must carry multiple dropsondes and release them once the desired conditions are reached.

Dropsonde concept

- The dropsondes must be lightweight, measure their location, measure electric field, and send such information to ground.

- Instruments must be simple, inexpensive, and robust.

- Electric field measurement requires rotation of electrodes about a horizontal axis. This suggests an a prolate ellipsoidal shape with fins to induce rotation.

Balloon payload concept

- The balloon payload must carry multiple dropsondes, provide some protection, and release them independently according to a pre-determined program.
- This program may be to release the dropsondes once a given altitude is reached, either in rapid succession, after a given time interval, or in multiple groups, depending on the desired goals for the observation.

DROPSONDE DESIGN

- Each probe is designed to be as cost efficient and robust as possible.

Dropsonde assembly:

[VIDEO] https://www.youtube.com/embed/cH_e08e1RGY?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

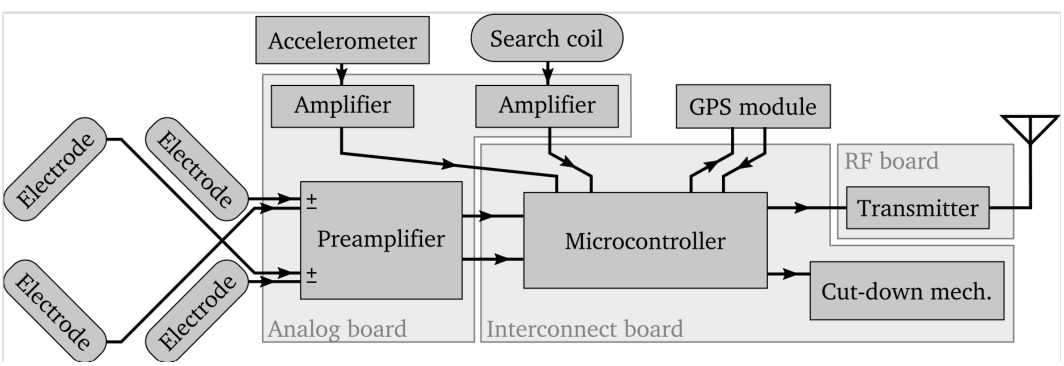
In the video, the backbone circuit board is grey, pink is the preamplifier, tan is the telemetry system, blue is the GPS module, green is the microcontroller, and brown is the battery. The backbone circuit board slides into rails in the 3d-printed shell which is closed with screws.

Design notes:

- Elliptical body is conducive to falling with it's long axis parallel to earth's surface.
- The four fins allow for rotation and the necessary motion to record electric fields, similar to an EFM.
- Electrodes are placed near the center edges of the fins.
- Internal components are placed symmetrically to keep the moment of inertia as small as possible and the principle axes aligned with the geometric axes of the ellipsoid.
- Shell designed in 2 halves for ease of 3D-printing and assembly.
- shells are 3D printed in house for simplicity of prototyping.
- all internal parts mount to the backbone circuit board, which slides into rails in the shell, and the 2 halves are secured with small bolts.

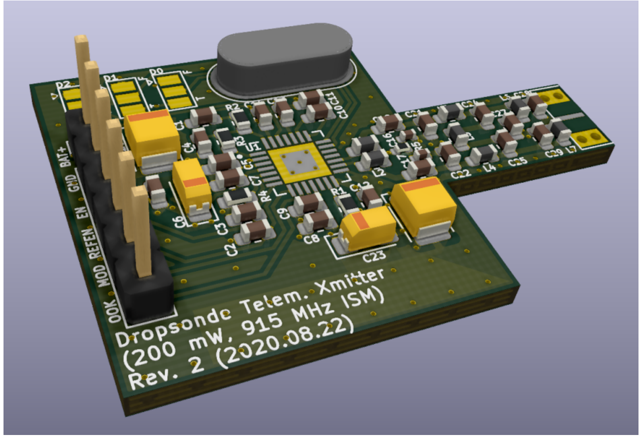
Dropsonde electronics

Block diagram:



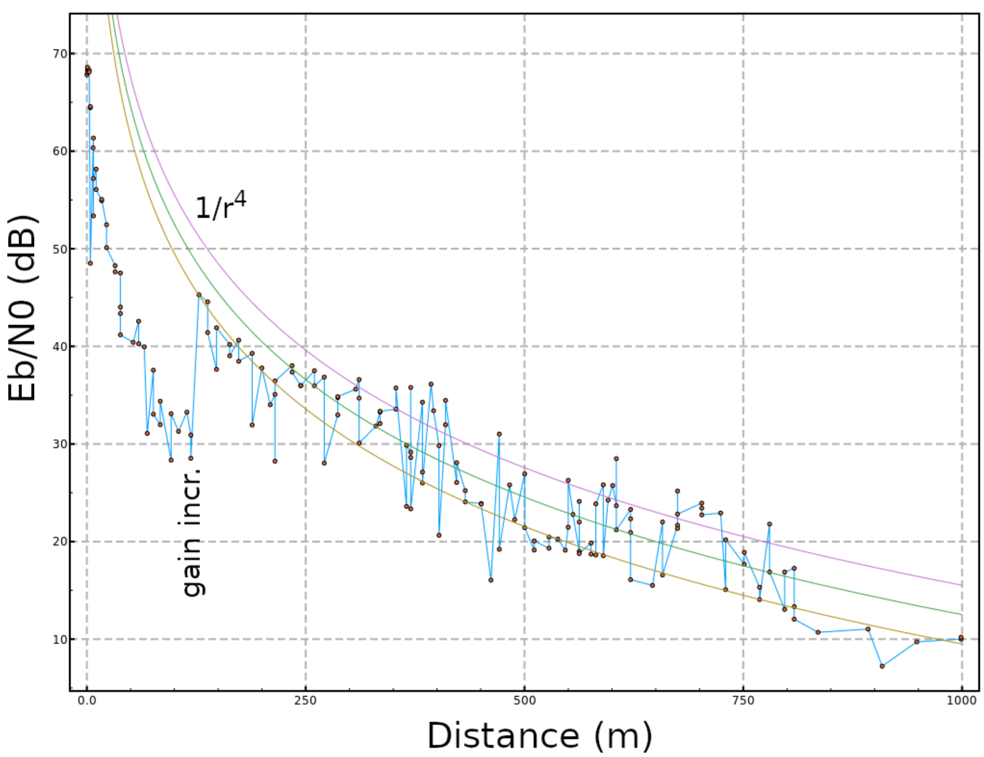
- The Teensy 4.0 is the central microcontroller (used for dropsondes as well as in the payload system).
- It is smaller, lighter, and has more processing power than similarly priced controllers.
- Telemetry system and interconnect board, which all of the components are mounted to, are custom made.

Telemetry system



- Packets transmitted every ~1 s with GPS coordinates and recent E-field measurements, statistics
- Transmitter: MAX2900 (an all-in-one 915 MHz ISM-band transmitter capable of 200 mW), driven directly by the Teensy microcontroller.
- 63-bit PN-code for direct-sequence spread spectrum, process gain
- Interleaved extended binary Golay code for error detection and correction
- Ground-level tests receive signal within ~3 dB of theoretical performance limit
- Extrapolation to airborne performance with a higher-gain antenna gives an estimated range above ~100 km, but further testing is necessary.

Ground-level range test data:

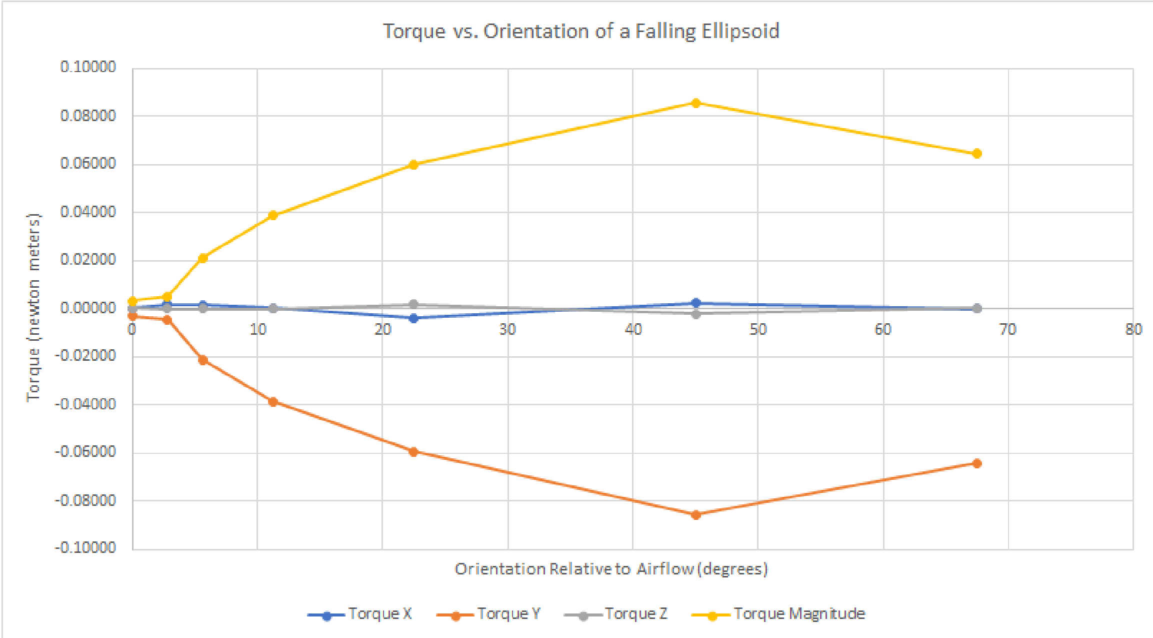


In this figure, dots represent successfully-received data packets with no uncorrectable errors. $1/r^4$ is the expected for line-of-sight near ground communications. (Performance for an airborne instrument will be much improved with reduced interference and $1/r^2$ scaling.)

Aerodynamic simulations

The ellipsoidal shape favors falling with the long axis horizontal. Simulations with a simplified geometry can verify this.

Torque vs orientation



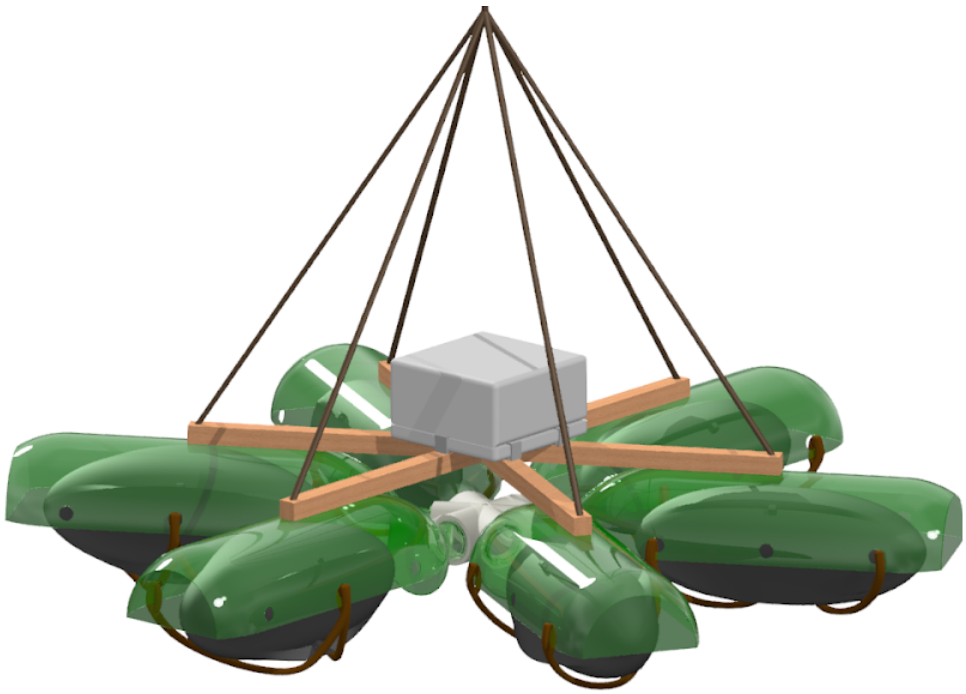
- The negative y component of torque is a restoring torque, suggesting the dropsonde will indeed fall with its long axis horizontal, as desired.

- Simulations give a drag coefficient of ~0.8 and a terminal velocity at sea level of around 13 meters per second, but further mass reductions are possible which would lower the terminal velocity.

PAYLOAD SYSTEM

- The dropsondes will be carried up to the top of storm clouds via a weather balloon.
- The system must be relatively lightweight in order to comply with FAA regulations, as well as robust in order to withstand turbulence.
- As with the dropsonde design, materials used should be very easily accessable and inexpensive.

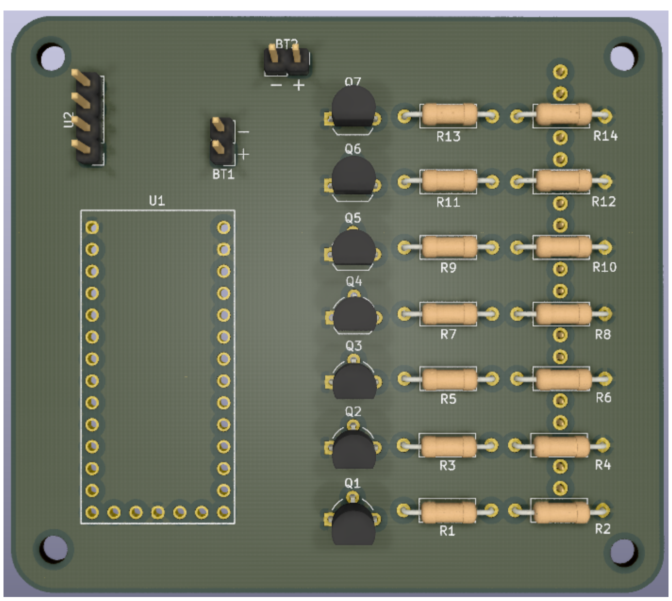
Payload concept



Dropsonde shelters composed of two-litre bottles. Dropsondes are secured by fluorocarbon fishing line (low melting point) and released individually by nichrome hot-wire cut-down mechanisms controlled by the payload electronics.

Payload electronics

- Internal PCB controls when to release dropsondes via an array on nichrome hot wire cut down mechanisms.



- Nichrome system runs current of around 3 amps through 28 AWG nichrome filament to reach temperatures of around 550 degrees celsius.

- Heat melts through length of synthetic cord to release dropsonde as well as help in starting rotation.

flight and release info

- Based on preliminary predictions, a 700g weather balloon will be used with ~16,000 L of helium and neck lift of ~16 Kg. This will yeild a rising flight time of around 25 minutes, with another 15 or so minutes for the probes to fall through the clouds.

- Dropsondes will be released about a kilometer below burst height, at around 15,000 meters, consistent with upper regions of a thunderstorm.

- Timing between each individual dropsonde release is variable and can be altered before launch.

- Normal time between releases would be around 20-30 seconds, however a more complicated drop pattern can be set up with relative ease, for example the first 3 dropsondes launched at 20 second intervals, then a 2 minute pause, then the next 3 released at 30 second intervals.

- Such variety in timings can further help to differentiate spatial and temporal differences.

RESULTS AND DISCUSSION

Current status:

- Initial electronics designs are complete, with prototyping and testing ongoing.
- Initial payload designs are complete, prototypes exist, waiting for integration testing with electronics.
- Due to the unforeseen effects of Covid-19, no test launches have yet been carried out.

Future work:

- Integration of initial dropsondes, balance testing, drop testing, and calibration of electric field measurements.
- Payload system assembly and testing.
- Small-scale test launch of minimal payload and single dropsonde is planned for spring 2021.
- Test launch of full payload with multiple dropsondes is planned for summer 2021.
- Full-scale observation campaign planning is dependent on funding.
- Contact C. Fischer or B. Carlson if interested in collaboration or joint observation campaigns.

Acknowledgments

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Please email me with any thoughts or questions!

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