A Platform for Active Stabilization of High-Altitude Balloon Payloads

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ABSTRACT: Weather balloon payloads are commonly used by atmospheric researchers and enthusiasts to gain insight about the upper atmosphere. Balloon payloads are often unstable during flight due to high wind speeds that are experienced in both the troposphere and the lower stratosphere. High Altitude Visual Orientation Control (HAVOC) is a platform of cold-gas thrusters designed to control the azimuth of high-altitude balloon payloads to counteract high wind conditions. HAVOC’s active control scheme uses valves that direct the flow of pressurized gas into two sets of nozzles that can generate torque in either a clockwise or counterclockwise direction. This counteracts the rotation induced by wind and other forces encountered during a high-altitude balloon flight. The HAVOC design is discussed including its methods of measuring and controlling balloon payload rotation. Data from preliminary flights are presented, demonstrating the system’s ability to reduce payload rotation to a user-defined ±40° s⁻¹ for a duration of 1 h 49 min and to maintain a fixed payload azimuth within ±30° for 1 h. In addition, we present possible uses for the HAVOC system tailored to the type of user, including atmospheric researchers, videographers, and students.

KEYWORDS: Atmosphere; Instrumentation/sensors; Measurements; Remote sensing; Soundings; Education
Payload stability is a prevalent issue in balloon-aided Earth observation systems. Payloads attached to balloon lines will often excessively spin during flight, which can distort visual-based instrumentation data. A solution to this issue is to implement motorized gimbals that can mechanically stabilize the balloon payload. Unfortunately, the rotation of the payload package itself can sometimes exceed the maximum controllable rate of rotation for gimbal systems, which are not designed for unlimited rotation of the platform (Jaworski et al. 2011). Low-cost, passive stabilization methods, such as designing the payload body to be more aerodynamically stable or isolating the payload from the balloon line with swiveling joints, can potentially help improve payload stability. Even though passive methods can reduce excessive rotation, they cannot ensure a desired orientation of an instrument or payload package. This would require an active control system that can directly influence payload rotation.

A balloon payload with active stabilization capabilities would be similar to the control systems of a spacecraft, where these systems would need to generate torque to control rotation in a low-pressure environment. For this reason, we looked to current attitude control systems found on spacecraft as reference for our designs. Common spacecraft attitude control systems, such as gas thrusters and reaction wheels, have been applied for use in balloon-based payloads (Brownell 2014; Furey et al. 2016). Reaction wheels stabilize platforms by momentum exchange; rotational energy is stored by conserving angular momentum and then released to provide stability to a platform when needed (Jin et al. 2008). On balloon platforms, reaction wheels are not common because wheels capable of withstanding forces from high winds are often heavy, which can exceed the Federal Aviation Administration (FAA) part 101 exemption limit of 6 lb (~2.7 kg). Gas thruster systems offer the most versatility, as they have a higher torque output and can be scaled to either lighter or heavier payloads alike (Abdellatif et al. 2013). Cold-gas thrusters are commonly implemented into the attitude control systems of satellites and manned spacecraft where orientation control is critical. Moreover, the use of a bang–bang control scheme, also referred to as a “on–off” thruster system, is commonly used in small satellites and is notable for its simplicity (Serpelloni et al. 2016; Kuntanapreeda et al. 1994). In the case of balloon flights, the use of gas thrusters allows for control at higher altitudes (>10,000 m) and better stabilization when passive approaches become less effective with a more turbulent, lower pressure atmosphere.

The solution. The High Altitude Visual Orientation Control (HAVOC) platform is a system of cold-gas thrusters that can actively control balloon payload azimuth at high altitudes. Visual data collection was the initial motivation for creating this system, including photography and videography. However, this system’s usefulness is not limited to purely visual data and additional applications are discussed throughout this paper alongside visual data collection. HAVOC utilizes two sets of opposing nozzles that can influence payload rotation about the axis of the balloon line, stopping the rapid spinning that can compromise the collection of visual data. Deployment and testing of weather balloon stabilization systems are currently lacking in published literature, where there are no hallmark studies explaining both the design and accompanying flight results from a stabilized weather balloon payload.
A stable and controllable balloon platform has potential to aid researchers and enthusiasts in many fields of study. Figure 1 depicts several operation concepts of stabilized balloon payloads using the HAVOC system. Stable balloon platforms have some advantages over other land surveying/observation platforms, such as drones, satellites, and aircraft observations. Drone flight is heavily regulated and requires special training for flights outside visible line of sight, reducing the effective imaging area possible for amateurs. Aircraft imagery is less restrictive, but the altitude ceilings of civilian aircraft are superseded by the heights achievable by latex balloons. Global satellite imagery is available through online services, but real-time targeted images are not always accessible for researchers requiring time dependent observations. Different types of payload sensors could also benefit from a HAVOC-like system. Sensor data processing on balloon payloads, most notably temperature, includes minor corrections to account for solar-radiation heating, which is a function of altitude and location. In the stratosphere, solar radiation causes significant temperature errors during the day. The constantly changing position of the payload due to pendulum motion and rig rotation has been shown to produce quasi-periodic structures in balloon data, particularly in the temperature profile (Philipona et al. 2013; von Rohden et al. 2016). A HAVOC payload could reduce quasi-periodic errors in temperature data by reducing the rig rotation.

A HAVOC payload would also excel in collecting imagery or other data of astronomical events when equipped with gimbal systems to control camera/sensor elevation and roll. This could include solar eclipses (Sibbernse and Sibbernse 2019; Orvis et al. 2017; Liberty 2017; Harrison and Hanna 2016) or meteor showers (Vaubaillon et al. 2021). In addition, HAVOC could be used to avoid sun glint and would allow for images with longer exposure times, ideal for nighttime flights observing stars in the absence of light pollution from the ground (Francisco et al. 2016). An active orientation control system on a balloon payload grants the ability to adjust its line of sight, thus enhancing its tracking capabilities. For example, this technology finds practical application in tethered disaster response balloon telecommunications networks, where pointing directional Wi-Fi antennas on balloon-based systems could assist with cell sectoring (Renganraju et al. 2021). Finally, high-altitude balloon photography and video have been used frequently in science, technology, engineering, and mathematics (STEM) education (Coleman and Mitchell 2014; Yelamarthi et al. 2007; Dooley et al. 2017; Yokoo et al. 2018; McCollum 2011). The ability to collect steady video at balloon altitudes could promote education and public interest in atmosphere science fields.

In this paper, we describe the current design of the HAVOC system and performance data from multiple balloon flights. The second section introduces the design considerations of the
HAVOC platform. In the third section, the mechanical, pneumatic, and control subsystems are further explained. The fourth section contains the results of two test missions of the current cold-gas system, where we demonstrate HAVOC’s ability to successfully reduce payload rotation and control payload azimuth. The fifth section concludes with a summary of results as well as outlook for the future of the HAVOC system.

System overview
During development of the HAVOC system, we had four primary design goals: the system should be easy to use, it should be relatively inexpensive [less than $1,000 (U.S. dollars)], and it should be capable of both rotational velocity stabilization and azimuth control for a duration of 1 h or more. Ease of use would allow amateurs, including students, to utilize the system for research and education purposes. A hardware cost of $1,000 would allow HAVOC to be accessible to most researchers, and likewise would be comparable in cost to most entry-level drones. To achieve these two goals, the HAVOC system is primarily built with consumer off-the-shelf components and follows requirements set by the FAA. Satisfying FAA requirements is extremely important when designing a system meant for many different research applications.

While most of the requirements of the FAA are simple to satisfy, the weight limit of no balloon payload being heavier than 2,720 g (6 lb) (FAA 2021) was the biggest design challenge when ensuring ease of use. The duration goal of at least 1 h was set by considering the average ascent duration of a latex balloon flight being approximately 90–120 min. This goal would ensure stabilized observations for at least 50% of the ascending portion of a balloon flight.

HAVOC was also designed to have two different control modes: velocity stabilization or orientation control. The goal for the velocity stabilization mode is to limit payload rate of rotation about the Z axis to within a predefined threshold throughout flight. We present flight data in the “Stabilization control test flight” section for a ±40° s⁻¹ rotational velocity threshold. The second mode is defining a fixed orientation for a certain azimuth. The “Orientation control test flight” section presents flight data where the HAVOC system was programmed to point at a single azimuth direction within a ±30° margin.

Subsystems
Mechanical system. The HAVOC system is built to be both sturdy and lightweight. The body of the payload is a rectangular–cylindrical Styrofoam container. This was chosen since it matched the profile of the air supply tank and the vertical stacking of components better balanced the payload by keeping the center of mass closely aligned to the vertical Z axis (Fig. 2). This helped to ensure that the torque produced by each thruster pair was equal.

The payload, as shown in Fig. 3, generates torque using two pairs of nozzles, with one pair at each end of a carbon fiber rod that runs through the center of the payload. These nozzles are encased in Styrofoam balls which were included to increase the torque from rotational drag on the payload. Since the rotational drag always opposes the rotational motion, this serves to fight against the payload’s tendency to accumulate large angular velocities due to atmospheric forces. Many of the structural components have been 3D printed for rapid prototyping and to reduce weight by using plastic parts instead of machined metals. The central rod is attached to the payload body by two 3D-printed anchors and runs through a 3D-printed core containing the solenoid valves and a high-pressure air (HPA) regulator. Attached to the bottom of this apparatus is a carbon fiber over wrapped compressed air tank. The electronics of the payload rests atop the main payload core in an insulated box.

Pneumatic system. The pneumatic system controls the output of HPA through two pairs of nozzles. The gas output is controlled by two normally closed solenoid valves that are opened according to the control loop run by the onboard microcontroller. The force generated by
gas output through each nozzle counteracts rotation of the payload, this is shown in Fig. 2. The pneumatic system that distributes HPA to accomplish the main payload control is displayed in Fig. 4. Table 1 lists the name/brand of the parts used in the HAVOC pneumatic system as well as their operating pressures. High-pressure air is stored in an 820 cm$^3$ (50 in.$^3$) tank at a pressure of 31,000 kPa (4,500 psig). This tank sits at the bottom of the payload body and supplies HPA to the system through the tank regulator, which reduces the tank output pressure to 6,200 kPa (900 psig). A secondary regulator further reduces the pressure to a range between 0 and 690 kPa (0–100 psig). Pneumatic tubing then routes the supplied air into the solenoid valves, each of which supplies air to its corresponding nozzles through flexible tubing and push-to-connect-type fittings.

**Control system.** The current HAVOC control system utilizes common consumer electronics (Fig. 5). The system is controlled using a Paul J. Stoffregen and Robin C. Coon (PJRC) Teensy 4.0 microcontroller with the addition of a Bosch BNO-055 Smart Sensor breakout board for rotation data. These components were selected for ease of use, as both have readily accessible documentation and open source code. The BNO-055 sensor is notable for being a very capable sensor that automatically fuses inertial measurement unit (IMU) data and magnetometer data to output three-axis orientation. This greatly reduces the difficulty of programming the system. All of these components are relatively inexpensive (<$100), and by using a capable programming environment, such as Arduino Integrated Development Environment (IDE), programming becomes simple.

The HAVOC control system is capable of choosing when to limit angular velocity based on altitude. Using a BMP-388 barometer to calculate altitude, the HAVOC payload can activate its control system once a certain altitude threshold has been met. Once activated, the HAVOC IMU continuously measures the angular velocity about the $Z$ axis of the payload. If this value becomes higher than the predefined value, bang–bang control is used by turning on the solenoid that will apply torque opposite of the motion until the angular velocity is adequately reduced. This system was successfully proven in the test flight outlined in the “Stabilization control test flight” section. The HAVOC payload can also continuously look in a given direction. A proportional-derivative (PD) controller for payload orientation is implemented in the payload. Proportional-derivative control is based on the proportionality and rate of range of system error. The error of the system is the difference between the current system states and the desired system output.
For 1D angular rotation we consider two states. The angle position offset $\theta_e$, which is the difference between the current payload angle and the desired payload azimuth, and the angular velocity error $\omega_e$, which is defined by the current velocity of the payload as a stable payload, should have zero angular velocity. These errors are used to continuously calculate thrust duration required to stabilize rotation to our desired bounds. The PD control law for directional orientation control follows the proportional-derivative control law, with

$$t_b = K_p \theta_e + K_d \omega_e + \tau,$$

(1)
where is $t_b$ the solenoid burst time, $K_p$ and $K_D$ are proportion and derivative gain constants, and $\theta_e$ and $\omega_e$ are the orientation and angular velocity error. Since a solenoid valve does not open instantly upon receiving the electrical signal to open, there is a need to account for this delay within the PD loop such that the system does not consistently underrespond. An offset $\tau$ is included in the equation to account for this factor.

### Table 1. Complete list of HAVOC pneumatic parts including operational pressures. The part number column references annotations in Fig. 4. Maximum allowable pressure (MAP) defines the point at which components cease operation due to either failure or malfunction. Maximum expected operating pressure (MEOP) values are the maximum pressure a component is expected to experience during normal operation.

<table>
<thead>
<tr>
<th>No.</th>
<th>Part</th>
<th>MAP (psig)</th>
<th>MEOP (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tank (Ninja LITE 50 cu/4,500 psi HPA Tank)</td>
<td>13,500</td>
<td>4,500</td>
</tr>
<tr>
<td>2</td>
<td>Tank regulator (Ninja Std. Regulator)</td>
<td>13,500</td>
<td>4,500</td>
</tr>
<tr>
<td>3</td>
<td>Sys. regulator (Boulder Co. 90 Pneumatic Reg.)</td>
<td>9,000</td>
<td>900</td>
</tr>
<tr>
<td>4</td>
<td>Tee MxFxF fitting (Palmer’s Pursuits 1/8″ NPT)</td>
<td>2,900</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>Relief vent (1/8″ NPT 1093KS2)</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>Tee push to connect (1/4″ OD)</td>
<td>217</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Solenoids valves (1/8 NPT 2-Way 20HL98)</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>Tubing (Utah Pneumatics 1/4″ OD)</td>
<td>600</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>L push to connect (Utah Pneumatic 1/4″ OD)</td>
<td>435</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>Nozzle (custom 3D print)</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>
The value of $\tau$ was found experimentally during a ground test by progressively reducing $t_b$ in the control loop until the solenoid no longer had enough time to open properly and no air was released from the system. This test was a simple laboratory-based electrical test achieved by continuously pulsing the system’s solenoid valves at increasing small time intervals until no gas flow was achieved. This is a physical limitation of the solenoid hardware itself and so no simulations of atmospheric conditions were required. It is important to note that the addition of an offset means that the estimated thruster burst time is always at least $\tau$. When thruster burst time is close to $\tau$, the solenoids can open and close rapidly, risking damage to the system. To account for this, a cutoff of an extra 0.5 ms was applied such that if the burst time $t_b$ is less than $\tau + 0.5$ ms, no solenoids would fire.

**Flight data**

*Stabilization control test flight.* The first HAVOC flight was undertaken on 11 April 2021 from the Severe Weather Institute and Radar and Lightning Laboratories (SWIRLL) at 196 m AMSL. The purpose of this flight was to demonstrate HAVOC’s ability to limit the rate of rotation of the payload body to a predefined threshold. For this flight, a target rotation threshold was set as ±40° s⁻¹, where upon activating the stabilization system, the payload should not exceed this threshold. The direction of the rotation was not specified; this means the payload was allowed to either rotate clockwise or counterclockwise within the defined maximum rate of rotation. For this test, the balloon line consisted of three payload packages top to bottom: a small radiosonde payload for atmospheric data collection, a camera payload equipped with a 360° camera for observing the HAVOC payload’s performance, and the HAVOC payload equipped with a horizontally fixed camera. Photos of HAVOC in flight are shown in Fig. 6.

The payload train was deployed on a Kaymont 1,200 g latex balloon with an approximate 5 m s⁻¹ ascent rate. Ball-bearing swivel hooks were installed between each payload on the
balloon line to decouple their rotation from one another. This prevented the balloon, or the other payloads, from influencing the rotation of the HAVOC payload. This balloon-line configuration is illustrated in Fig. 7. A SPOT Trace GPS tracker was placed within the HAVOC payload body and was used to locate the flight train once it had returned to the ground. The weather conditions on launch day included clear skies with constant eastward-moving winds. A fast upper-level jet was located between 10,000 and 15,000 m. We have observed that flying at altitudes with high wind gradients cause the most excessive spinning for weather balloon payloads. Knowing the altitude of the upper jet on this day, the launch team programmed the HAVOC payload to activate stabilization at 15,000 m. The HAVOC payload uses its onboard altimeter to measure altitude and is programmed to automatically activate stabilization once exceeding the target altitude. The code for this day subsequently instructed the stabilization system to activate at the most turbulent period of the flight (15,000 m).

During the payload’s ascent, rate of rotation (shown in Fig. 8) stayed within the defined threshold without the use of active stabilization. However, as the balloon line reached 10,000 m and the upper-level jet, the payload began to spin excessively, reaching rates of ±100° s⁻¹. The stabilization system was activated at the intended altitude of 15,000 m. At the time of activation, the payload was rotating at a rate of 71° s⁻¹. The cold-gas thrusters were able to reduce this rotation within the ±40° s⁻¹ threshold in just 320 ms, where it did not exceed its rotation threshold for the remainder of the ascending flight.

At around 23,000 m, balloon burst occurred, causing the HAVOC system to descend. The stabilization system was still active after the balloon burst. Due to the violent nature of the balloon burst, the system was not able to maintain rotation within the target threshold, exceeding the bounds at several points. Once the descent grew less turbulent, which was
about 1,000 m below burst altitude, the system was able to recover the payload’s rotation for the remainder of the flight (also shown in Fig. 8). This is especially of interest because video observations are often distorted during descent, since the line experiences free-fall where a payload is not in constant tension with the balloon line. This unconstrained state allows payloads to move more freely, which is further affected by an increased descent velocity prior to full parachute deployment. The HAVOC system was able to greatly reduce these effects during its descent. For studies wanting to maximize data collection during balloon flights, a HAVOC stabilized platform could double the amount of useful observations, where reliable visual data could come from both ascent and descent of a weather balloon payload.

From the provided flight data, we have shown that the HAVOC system could actively influence payload rotation during flight for a considerable amount of time. Payload rate of rotation was effectively controlled and limited to an acceptable defined target threshold. The initial success of controlling velocity led us to attempt the more demanding challenging of maintaining a fixed payload azimuth (“Orientation control test flight” section).

**Orientation control test flight.** On 23 July 2022, HAVOC was flown two times from SWIRLL to test the payload’s ability to maintain a fixed azimuth within a defined margin. Both flights were undertaken on 1,500 g Kaymont balloons at an ascent rate of 5 m s\(^{-1}\). Z-axis data collected from these two flights are shown in Fig. 9. The first flight served as a control reference, flown with no active stabilization. In this flight, shown in Fig. 9a, payload azimuth direction changes randomly throughout the entire flight. There was no period of the flight where the payload rested or ceased rotation. This is in line with other balloon payloads with no stabilization systems. Rate of rotation did decrease for higher altitudes, but no steady azimuth was achieved. After completion of the first flight, HAVOC was recovered and launched from the same location as the prior flight within 2 h. The objective of the second flight was to activate thruster stabilization above 10,000 m and maintain a fixed azimuth within ±30° for as long as possible. The target payload azimuth was based on the orientation of the payload after completing pre-flight sensor calibration. These data are shown in Fig. 9b. Ground testing in a laboratory environment showed that with 60 psig output the thruster force was too strong for precise azimuth control, as the system would tend to oscillate and become unstable. This is due to...
the minimum burst time of the solenoid valves ($\tau$) limiting the minimum amount of torque impulse the system can produce. This problem would only become worse at higher altitudes as atmospheric pressure decreases and the pressure difference across the nozzle becomes larger. Our current facilities lack a pressure chamber large enough to test the HAVOC system at simulated high-altitude pressures and so only sea level performance can be verified on the ground. To better prepare the system for the new objective of maintaining a fixed azimuth at high altitudes we chose to decrease the system pressure until sea level performance became stable and then further reduced output pressure until corrections became considerably under damped to account for increased thruster force at high altitudes. This series of test resulted in a pressure setting of 10 psig.

Fig. 9. Z-axis data from two HAVOC flights. (a) Control flight, with no stabilization. (b) With stabilization. ±30° bounds are plotted with dotted lines. Wind speed and direction measured from radiosonde are denoted by wind barbs.
Prior to activation, the rotation of the payload in the second flight closely matched what occurred in the control flight with no active stabilization. Immediately following activation, the payload attempted to stabilize its azimuth but was initially unable to. This is likely due to the decreased pressure output of the thrusters as well as the presence of fast-moving jet streams at this altitude. Attempts to stabilize payload azimuth continued and the payload gained proper control authority starting at 12,000 m, and was able to bring its azimuth into the target threshold. Payload propellant was then exhausted at 22,600 m after operating for 1 h. After this point no more active corrections could be made to maintain azimuth, causing the payload to rotate freely for the remainder of the ascending flight. The patterns of this rotation match closely the trends shown in the control flight in the time leading up to balloon burst.

Analysis of data from the remaining two rotational axes (X and Y) was used to determine the HAVOC system’s impact on the pendulum motion of the balloon line. Since the system is calibrated in an upright vertical position, the offset of the X and Y axes corresponds to the angle of the system relative to the surface of Earth. Swing of the balloon line is measured through these angle measurements. Values and trends of the X and Y axis were found to be nearly indistinguishable for these flights, and so for brevity only Y-axis data have been presented here.

The Y-axis offset of the HAVOC payload prior to stabilization varied between ±10° of vertical. This was consistent between both flights for altitudes below 10,000 m, shown in Fig. 10. When the payload reached 10,000 m, fast-moving winds led to a higher offset in the Y axis, reaching offsets of up to 51°. This was the maximum disturbance experienced prior to balloon burst. Stabilization of the Z-axis offset was activated at 10,000 m and initially the system was unsuccessful at maintaining azimuth within the ±30° threshold. The period in which the system was unable to minimize this rotation appears to correlate with regions of high offset in the Y axis, as shown in Fig. 10b. One possible reason could be that the payload was highly canted and not normal with Earth’s surface, and so the thruster system would need to work partially against gravity in order to maintain its desired Z-axis position.

After exiting the regions of high winds, the Y-axis offset returns to prestabilization levels as the payload now actively corrects Z-axis offset within the desired mission threshold. Values for Y-axis offset between the inactive (Fig. 10a) and active stabilization (Fig. 10b) flights do not appear to differ in any significant way. Since both flights involved identical hardware and only differed with the presence of Z-axis stabilization, there appears to be no major effect, either positive or negative, of the HAVOC system on pendulum type movement of the balloon line. Additional payloads equipped with IMUs might be used to better characterize motion along the balloon line, but since the HAVOC payload was mounted to the bottom of the line its rotation should be characteristic of the entire line.

Although azimuth control was achieved, we have shown there are some challenges with using thruster controls on balloon payloads. Atmospheric pressure decreases with altitude, causing thruster output to increase with altitude. A simple solution to this issue is to optimize the thruster pressure output for the operating flight altitude. The HAVOC team is currently developing methods to modify thruster output with altitude using the onboard flight computer. This solution would allow the payload to operate in fast and slow wind conditions over a wider range of altitudes. In the future, additional control schemes could be tested that directly impact tilting of the payload body and possibly pendulum motion of the balloon train.

**Future development and conclusions**

More test flights will be conducted with the current payload and control system design to further evaluate the HAVOC system’s performance. We believe that the current bang–bang control system could reduce payload rotation below the ±40° s⁻¹ target that was previously tested.
We also plan to improve upon HAVOC's azimuth control mode by using past-collected flight data to optimize our control code and achieve azimuth accuracy below ±30°. For payloads using external cameras or observation equipment, an independent gimbal system could be utilized alongside the HAVOC stabilization and orientation system. We plan to develop our own gimbal system and incorporate it into our current payload design. Utilizing these two systems, we plan to execute some of the operation concepts outlined in this paper, such as observing the upcoming 2024 North American solar eclipse at high altitudes. The authors hope that this paper will be a foundational stepping stone for others who want to develop and deploy their own actively stabilized weather balloon platform.

Fig. 10. HAVOC Y-axis rotation data for (a) uncontrolled and (b) controlled azimuth flights. Wind speed and direction measured from radiosonde are denoted by wind barbs.
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Data availability statement. For information regarding HAVOC’s design and flight code, please email the first author.

References


