UAS Operations in Extreme Weather Environments
Case Studies and Technological Solutions
Enable uncrewed aircraft systems (UAS) to operate year round to provide rich data sets in any weather condition.

The inability to operate safely in all terrain, weather conditions, and over long distances is becoming an increasingly limiting factor in the adoption of UAS for commercial applications.

Specialized vehicle design, subsystems, and control algorithms to produce industrial grade equipment.

Platforms that simplify operations through true autonomy while providing 24/7 operational capabilities.
End-to-end UAS IP including the user interface, ground station, communications protocol, avionics, control algorithms, and vehicle design

- Advanced sensing capabilities
  - Airdata systems capable of mitigating ice and heavy precipitation
  - Vision based systems for GPS denied navigation and automated emergency landing
  - Machine learning based system for fault prediction and detection

- Extreme weather based design
  - Tool-less assembly designed to be used with gloves
  - Ingress protection from abrasive volcanic ash and corrosive gasses

- Industry leading wind based control and path planning
  - Energy aware warning system for rapidly evolving flight conditions
  - Energy extraction through dynamic soaring to extend mission duration

- Years of experience designing vehicles for observations of weather events
MULTI-MISSION FIXED WING UAS

S2 UAS

- Rugged, modular design
- Mature, field proven SwiftCore avionics
- Multi-sensor payload configurations possible
- BVLOS proven
- Field fixable
- NASA and NOAA certified

Modular Field-Swappable Payload System

Enables rapid changes of the payload in the field using a common power, data, and mechanical interface without any specialized tools.
## S2 UAS SPECIFICATIONS

### Mission Capabilities

<table>
<thead>
<tr>
<th>Capability</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Ceiling</td>
<td>4500 m (14,000 ft)</td>
</tr>
<tr>
<td>Max Winds Endured</td>
<td>15 m/s (30 kts)</td>
</tr>
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</table>

### Flight Characteristic (6 kft density alt)

<table>
<thead>
<tr>
<th>Capability</th>
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<tbody>
<tr>
<td>Flight Speed</td>
<td>12 m/s (24 kts) stall, 19 m/s (37 kts) cruise</td>
</tr>
<tr>
<td>Flight Time</td>
<td>110 max, 90 min nominal</td>
</tr>
<tr>
<td>Range</td>
<td>110 km (60 nm) max, 92 km (50 nm) nominal</td>
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</table>

### Vehicle Characteristics

<table>
<thead>
<tr>
<th>Capability</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>9.3 kg (20.5 lbs) max takeoff weight</td>
</tr>
<tr>
<td>Wingspan</td>
<td>3.0 m (10.0 ft)</td>
</tr>
</tbody>
</table>

### Payload Capabilities

<table>
<thead>
<tr>
<th>Capability</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Nose Cone Dimensions</td>
<td>20.3 cm (8 in) diameter, 63.2 cm (24.9 in) length</td>
</tr>
<tr>
<td>Power available</td>
<td>50 W total</td>
</tr>
<tr>
<td>Payload Weight</td>
<td>2.3 kg (5 lbs) max with rail launch</td>
</tr>
<tr>
<td>Geotagging Accuracy</td>
<td>Typically &lt; 1m in all directions</td>
</tr>
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SENSOR SUITES AND APPLICATIONS

Typical UAS Payload Offerings

**Visual or thermal spectral cameras** provide high resolution data that can be combined into an orthomosaic or three-dimensional map.

**Lidar / Multispectral** specialized applications make use of scanning lidar or multi/hyperspectral cameras for data capture.

The S2 UAS Modular Payload System Simplifies Sensor Integration - Some Examples of Flown Payloads

**High-altitude, high-latitude atmospheric research studies in Greenland** operating in temperatures near -20°C at altitudes up to 14,000 ft. analyzing water vapor.

**Coastline monitoring** using a combination of thermal and hyperspectral payloads with a multispectral camera array for Landsat-8 OLI and S-NPP VIIRS instrument calibration.

**Airborne measurements of trace gases** including carbon dioxide (CO2), sulfur dioxide (SO2), methane (CH4), and hydrogen sulfide (H2S) as well as generation of arthomasic, thermal and 3D data products.

**Nighttime in situ measurements of wildfire plumes** and remote measurements of wildfire properties utilizing multiple sensors capable of research-quality measurements of CO2, CO, aerosol, RH, p and T.

**Volcano plume monitoring** with sensors specifically designed to measure selected gases and a nephelometer to assess volcanic particle size and distribution.

**Soil moisture mapping** (up to 600 acres per flight) using multiple sensors including an L-band radiometer capable of measuring soil moisture content up to 10 cm below the ground.
SAFE TO LAND

AUTOMATED HAZARD MITIGATION

- System runs continuously during a flight
- Segmentation map is converted to map of hazards and safe areas
- The system attempt to fit a landing corridor in the map
- If a landing area can be safely fit, its GPS coordinates are estimated and saved
- If an engine failure is detected the landing plan memory is searched and the closest landing area is selected and sent to the autopilot
- The pilot has the final say in choosing to execute the emergency plan
SAFE TO LAND

SUBURBAN EXAMPLE

Improving Guesses
GPS DENIED NAVIGATION

COMBINING VISION AND RADIO SIGNALS
AUGMENTED ONBOARD INTELLIGENCE
NASA ARMSTRONG SBIR
BENCH TESTING SUBSYSTEMS
CHARACTERIZATION OF FAILURE MODES
Outliers easily identified out of large amounts of data
Quickly identifies subsystem issues
Potential solution for icing detection
BST's proprietary and intuitive SwiftTab GUI focuses on data gathering, allowing the operator to focus on the mission at hand rather than extraneous information.

Safety is built into the system, including an electronic centralized aircraft monitor-like system to simplify identifying and addressing failures using fault trees.

The system also contains a stand-alone simulator with the ability to inject faults during training.
MAKUSHIN VOLCANO MONITORING

- Black Swift S2 fixed wing UAS
- Pathfinder BVLOS UAS operations
  - No string of observers
  - No special ground equipment
- Adverse conditions
  - > 50kt winds
  - > 1600 ft/min downdrafts
- Precipitation and clouds
- Near freezing conditions
- Sensor directed flight control
FLIGHT AREA

Requested TFR Boundary (staring 2 miles southwest of runway)

Planning, notification, and safety
- FAA COA with NASA Airworthiness
- Contact with local operators and NOTAM
- CTAF Monitoring
- Onboard ADS-B
- Visual Line of sight near airport
FLIGHT PLANNING

AIRSPACE AND TERRAIN
FLIGHT PLANNING

WIND ESTIMATION

Trace Gas Payload

Photogrammetry Payload

Summit Time

Go-No/Go Winds
3D Wind Probe Designed at BST to be accurate yet rugged
- Has been used on both manned and unmanned aircraft for studies.
- Low cost achieved through accurate 3D printing.
- Full sensor suite with co-located IMU, magnetometer and GPS
- Operated in a variety of conditions: Arctic, tornadic thunderstorms, etc.
9th order polynomial fit seems to provide good results

- Computation of $c_\alpha$, $c_\beta$, and $c_q$
- Non-linear, but has good symmetry.

- Probe positioned at 900 points
  - +/- 15° $\alpha$ & $\beta$ at 1° intervals
  - > 1000 measurements at each position.
- ~$10^6$ total measurements
- 3 hour total run time.
The S0 is a small, low cost, modular, electric fixed-wing UAS for air deployment from a P-3 Orion “Hurricane Hunter” aircraft. This purpose-built autonomous flight aircraft provides essential measurements in the atmospheric boundary layer of the eyewall of a hurricane.

### SO UAS

- **Air Deployment**
- **Swivel Wing**
  - Simple, Reliable Deployment
- **In Situ Atmospheric Probe**
  - Pressure, Temperature, Humidity
- **AVAPS Compatible**
  - Integration with Current NOAA Systems
- **S0 Air-Deployed UAS**
  - Robust, simple to operate, scientific platform
- **Flush-Air Sensing Nosecone**
  - Three-Dimensional Winds
WIND MEASUREMENT
Accurate Measurements in Precipitation
S0 AIRFRAME DESIGN
STABILITY ANALYSIS

Short Period

Roll Subsidence

Phugoid

Dutch Roll
## S0 VTOL - PERFORMANCE IN A SMALL PACKAGE

Capable of fitting into a backpack or including several into a small case for persistent measurements, the S0 represents a revolutionary set of capabilities for small UAS.

<table>
<thead>
<tr>
<th>Multi-Mission</th>
<th>Despite its small size, the S0 can be outfitted with either a real time video system or an atmospheric monitoring setup</th>
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<tbody>
<tr>
<td>Performance</td>
<td>Capable of dashing &gt; 100mph with a climb rate of &gt; 3000 fpm</td>
</tr>
<tr>
<td>Industry Leading Accuracy</td>
<td>Calibrated against standardized equipment for the measurement of atmospheric thermodynamics</td>
</tr>
<tr>
<td>Time on Station</td>
<td>Flights up to 90 minutes, providing monitoring capabilities that far exceed multirotors</td>
</tr>
<tr>
<td>Silent</td>
<td>Barely audible even at 200'</td>
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</table>
Volcanoes in Costa Rica have been leaking CO2 into the overlying ecosystems similar to future atmospheric concentrations.

This provides a fortuitous natural experiment with which to test the ecosystem responses.

First flights in mid January measured CO2 and plant response around volcanoes in Costa Rica in order to understand the ecosystem response in the tropics, the lungs of the planet.
VOLCANO MONITORING

NASA SBIR

- Trace gas (S02, H2S, CO2)
- Particle size and count
- P,T,RH, 3d Winds
- RGB and Thermal Imagery
- Sample Cassettes

NASA SBIR NNX16CP42P
Technical Monitor: Dr. Dave Pieri, JPL
VOLCANO MONITORING

NASA SBIR
Deployment to Greenland
- 6 sample flasks
- Telemetry in their own UI
- Valve control through Python
- Rated to -20 C
- Flights up to 14,000’
FIRE WEATHER PREDICTION

NOAA NIGHTFOX

Ru-Shan Gao, Troy Thornberry, Karen Rosenlof, Brian Argrow, Sher Schranz, ESRL/CSD, CU, ESRL/GSD
Objective

▸ Design a glider for exploring the Venus upper atmosphere
  ▸ Remain aloft for a minimum of 1 month
  ▸ Harvest energy from upper atmospheric shear through dynamic soaring
    ▸ Does not require sunlight
    ▸ Allows targeted sampling
    ▸ Can be performed automatically

Work to Demonstrate Feasibility

▸ Developed a aircraft simulation
  ▸ Makes use of probe data as well as the latest GCM's
▸ Designed a simple controller to perform dynamic soaring
▸ Performed several runs through different regions of the atmosphere
▸ Demonstrated net energy increase over time
▸ Demonstrated ability to overcome downdrafts