Obtaining Accurate Wind and Turbulence Measurements by Small UAS to Fill the Boundary Layer Data Void

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award #1539070

Motivation

- Knowledge of winds are important for many applications:
  - Weather prediction
    - Hazardous weather/aviation safety
  - Mass, momentum or energy transport
    - Pollutants, temperature, humidity
  - Wind loading for structural strength or energy production
- Ground-based measurements can't resolve characteristics at higher altitudes
  - Dynamics and interactions
- Remote sensing tools offer other challenges (cost, portability, ease of use)
  - RADAR – Needs large particulates for return (precipitation/insects)
  - LIDAR – Reflects off smaller particulates (but has shorter range)
- UAS can be used to measure winds for meteorology or research at lower cost and increased flexibility (measure where you want, when you want)

Common Approaches for Measuring Wind using UAS

- Indirect measurement using aircraft dynamics
  - Compare ground speed to airspeed (fixed-wings)
  - Measure motor's response to wind (rotorcraft)

- Direct measurement using sensors
  - Sonic anemometer (often used with multirotor)
  - Multi-hole pressure probe (used by fixed-wings)

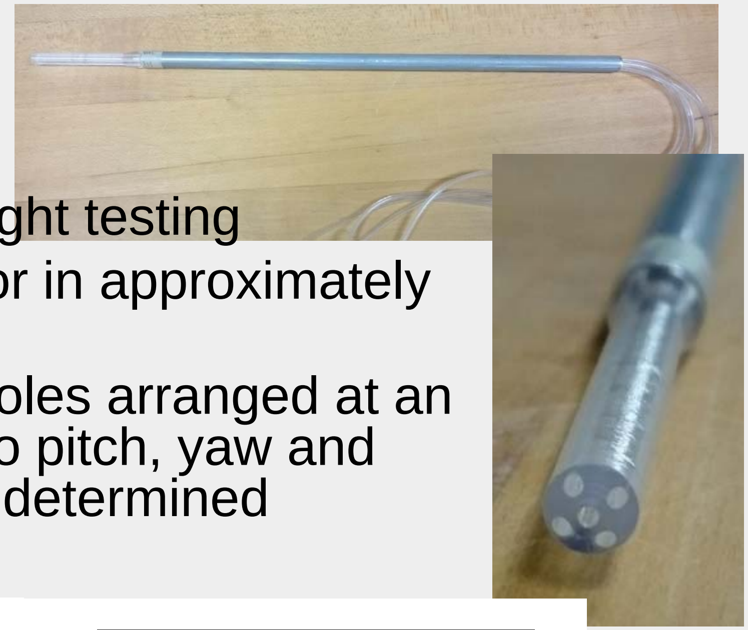
- Less common approaches:
  - Distributed pressure (pressure sensors distributed around aircraft)
  - Hot-wire probes (fast response times 1kHz-10kHz)
  - Acoustic tomography

Fixed Wing Example (BLUECAT5)

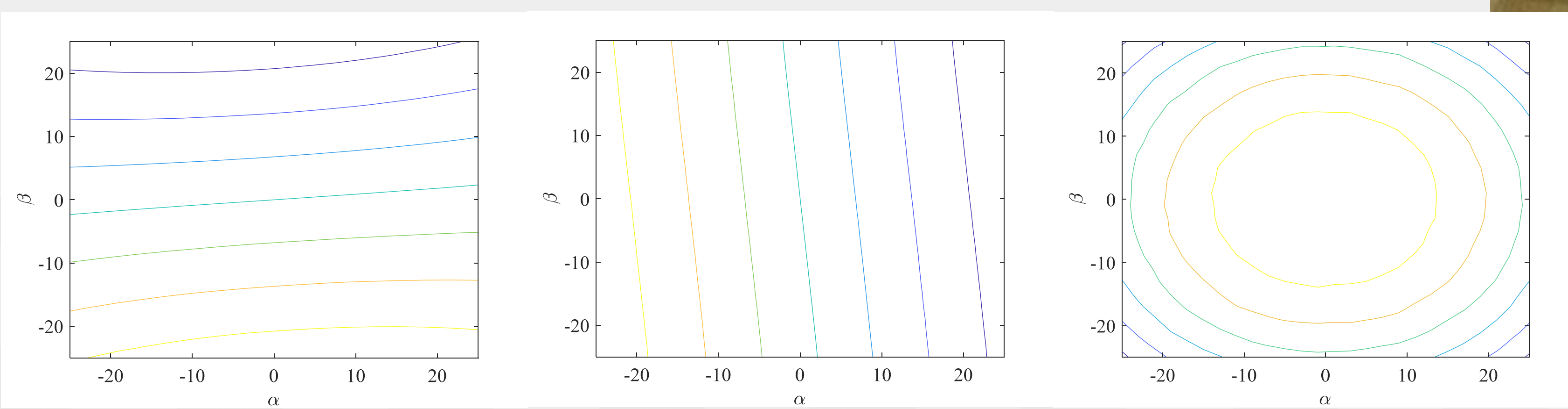
Optimized for horizontal profiles

- Electric motor propulsion
  - Increased reliability
- Pixhawk autopilot
- Custom 5-hole probe
  - 3 components of velocity
- Imet-XQ
  - Pressure, temperature and humidity
- Data Logging – USB-1608FS-Plus
  - Simultaneous logging of 8 channels at 16bit
- Dual GPS INS for 6DOF orientation
- Onboard computer for data acquisition and storage

Multi-Hole Probes

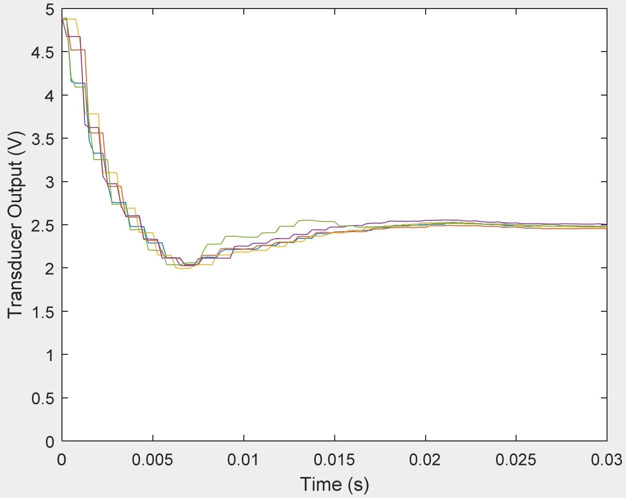


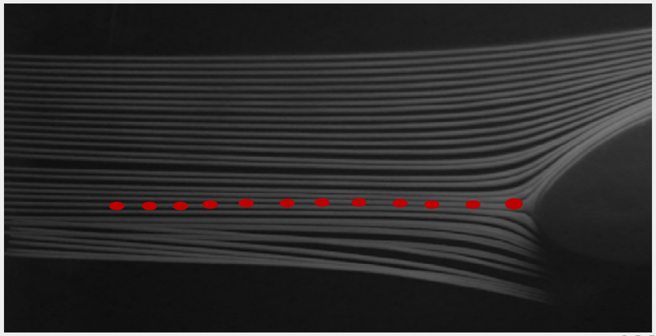
- Multi-hole probes
  - Used in laboratory environments and flight testing
  - Capable of resolving relative wind vector in approximately 45^{o} cone relative to probe axis
  - Relative pressure difference between holes arranged at an angle to the probe axis can be related to pitch, yaw and velocity magnitude through coefficients determined through calibration

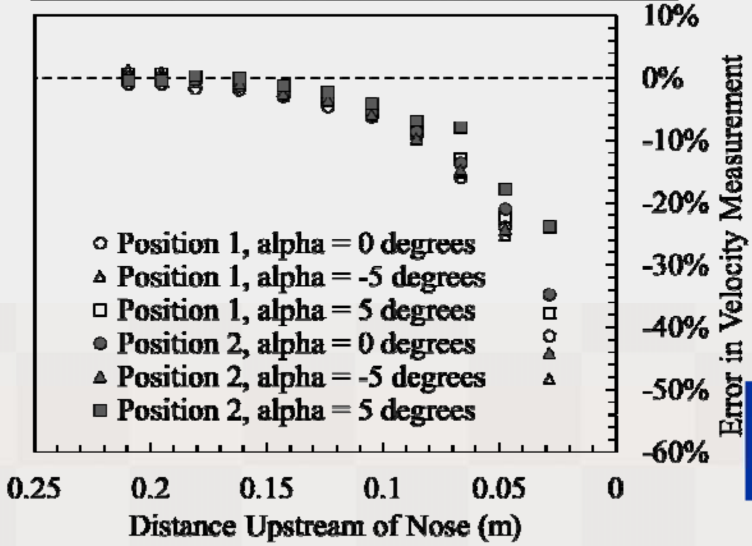


Mitigation of Interference Effects – Fixed Wing

A key concern with the use of pressure probes is disturbance of flow at probe position due to airframe interference





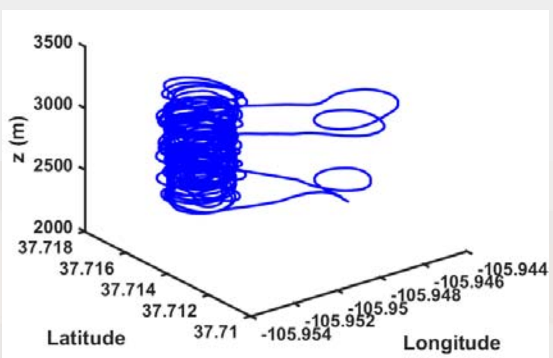


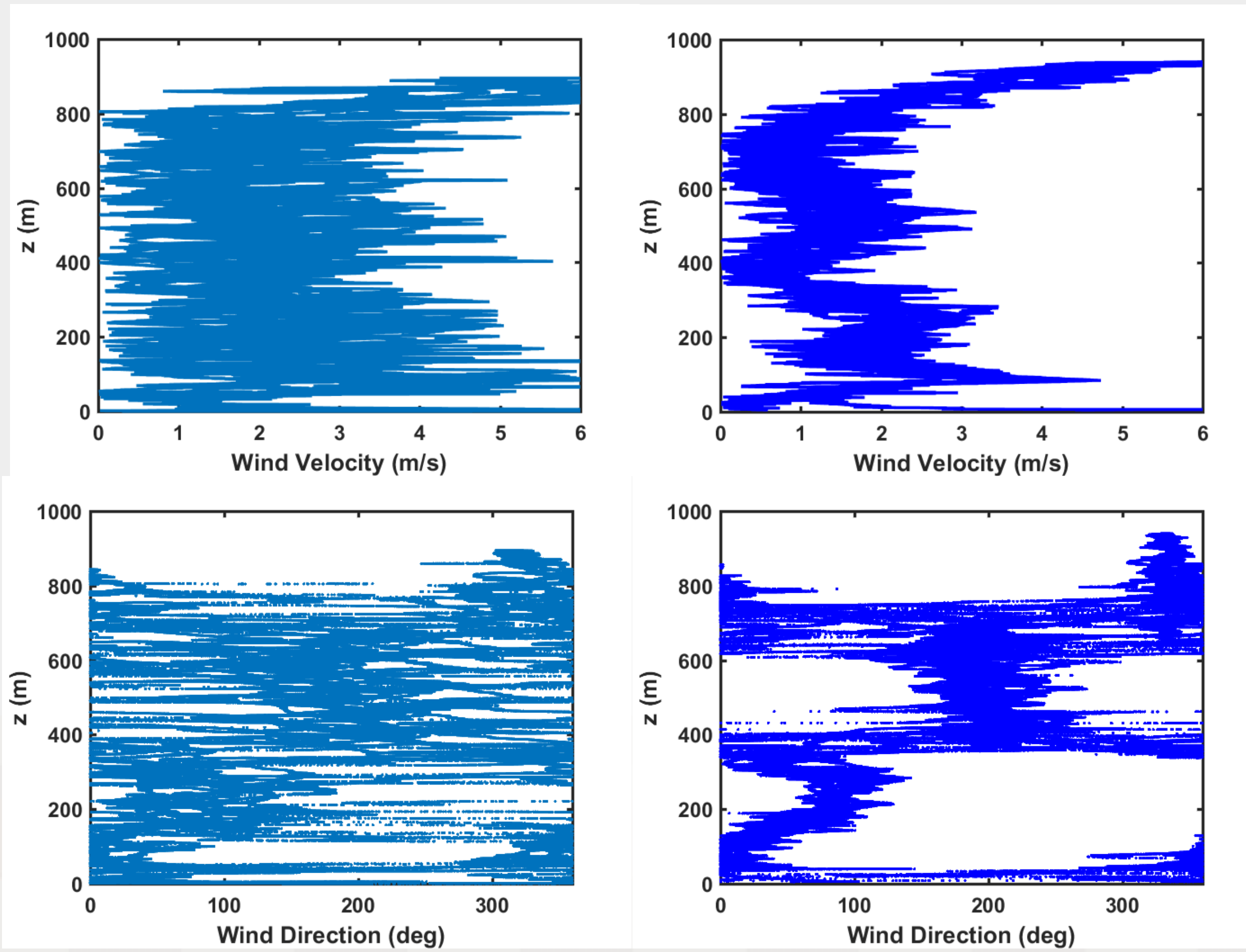
- Time response of 5-hole probe measured to be 60 Hz.
- Water tunnel flow visualization and wind tunnel tests indicate measurement position free of fuselage interference effects

Sensitivity to Misalignment

Five hole probe measurements are very sensitive to misalignments in orientation and time, particularly for measurements conducted in circular trajectories at high data rates.

Right: Before and after correction for 5 degree shift in both pitch and yaw angle of probe relative to the IMU axis





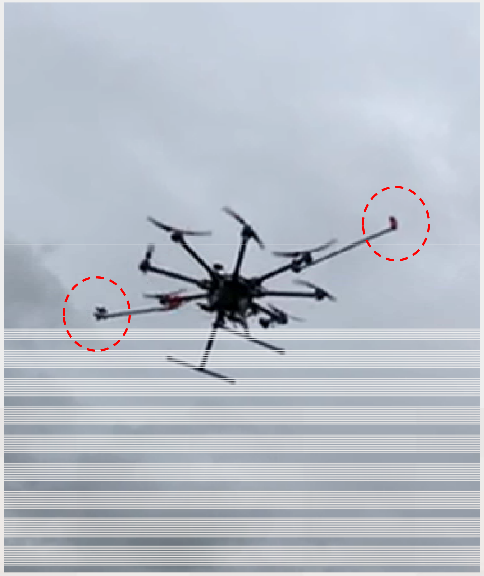
Rotorcraft Examples

Tend to be better suited for vertical profiles. University of Kentucky's fleet include:

- 3DR SOLO quadroter and DJI S1000 octocopter
- Pixhawk autopilot (10 Hz)
  - Aircraft position and orientation
- 3 component sonic anemometer (logged at 10 Hz)
  - Wind velocity and direction
- Imet-XQ (1 Hz)
  - Pressure, temperature and humidity
  - Solar shielded and placed in rotor wash

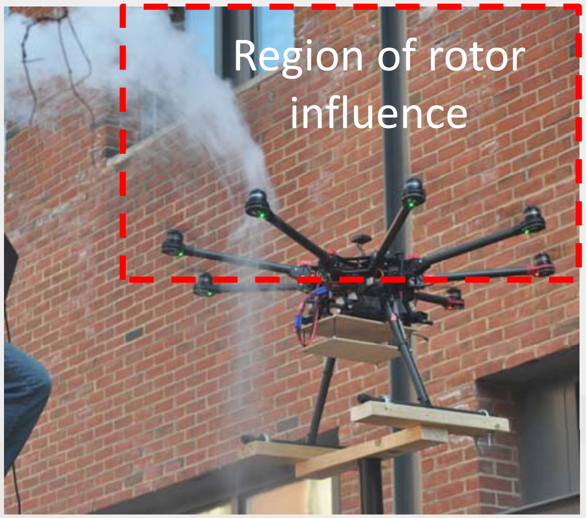
Mitigation of Interference Effects - Rotorcraft

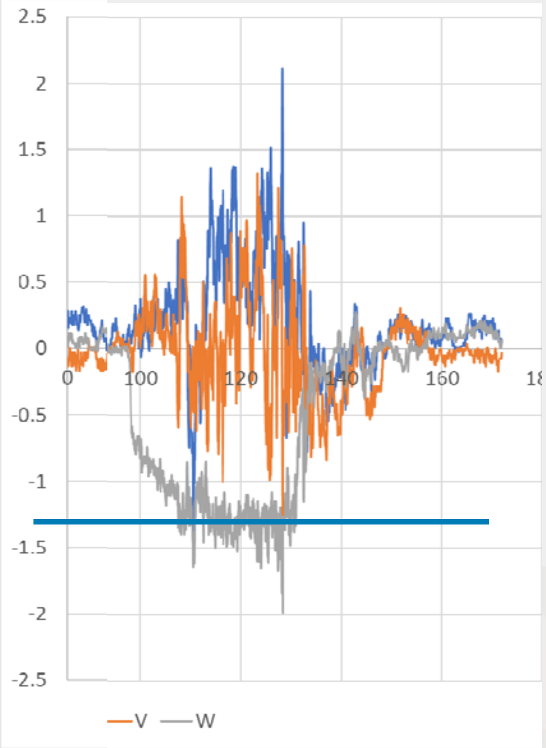
- Interference comes from rotors.
- Can place sonic anemometers outside influence of rotor wash e.g. horizontally or vertically
- Tests using a tethered aircraft can determine where sensor is free of rotor wash



Mitigation of Interference Effects - Rotorcraft

- Sometimes it is not possible to eliminate rotor wash effects at sensor position.
- For these measurements it is also possible to calibrate to determine the bias caused by rotor wash effects at sensor position

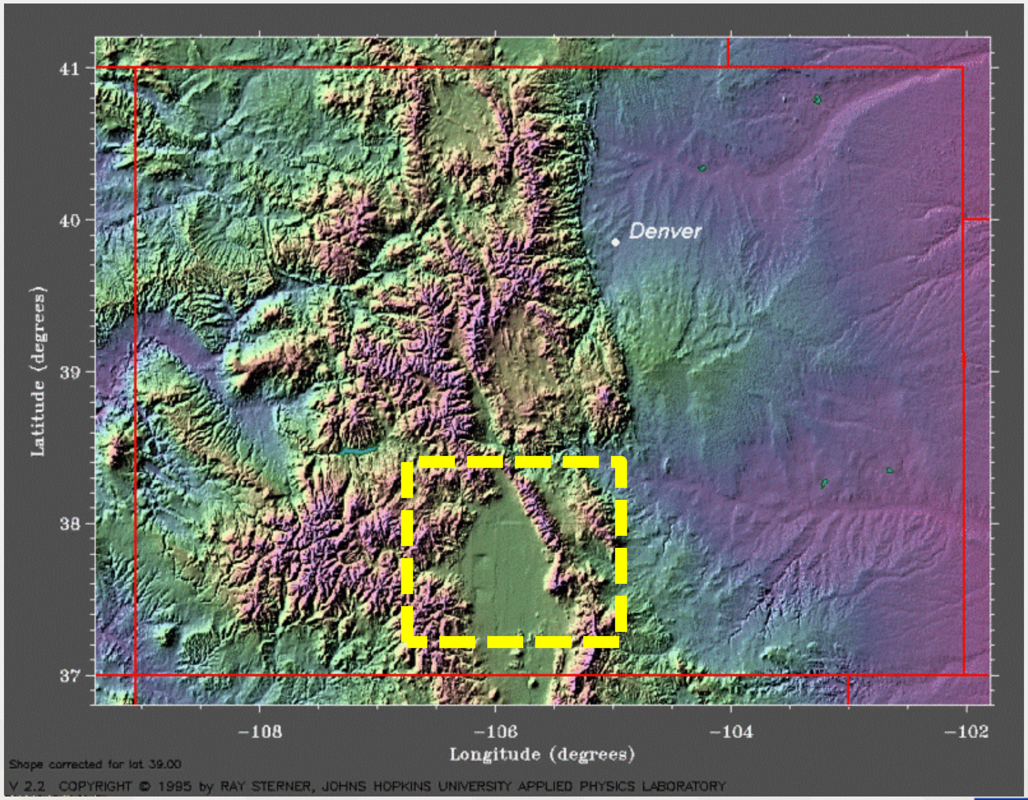




2018 LAPSE-RATE Measurement Campaign

- July 13-20, 2018
  - San Luis Valley, Colorado, USA
  - Between Sangre de Cristo Range and San Juan Mountains
- 8 Universities
- 50 UAS Platforms
  - 1287 Flights
  - 262.38 Hours of Data
- FAA Authorizations for flights to 3,000 ft

- 3 Weather Questions:
  - Convection Initiation
  - Boundary-Layer Evolution
  - Cold Air Drainage
- Sensor Cross Comparison and Calibration Studies
- Comparison to Forecast Models



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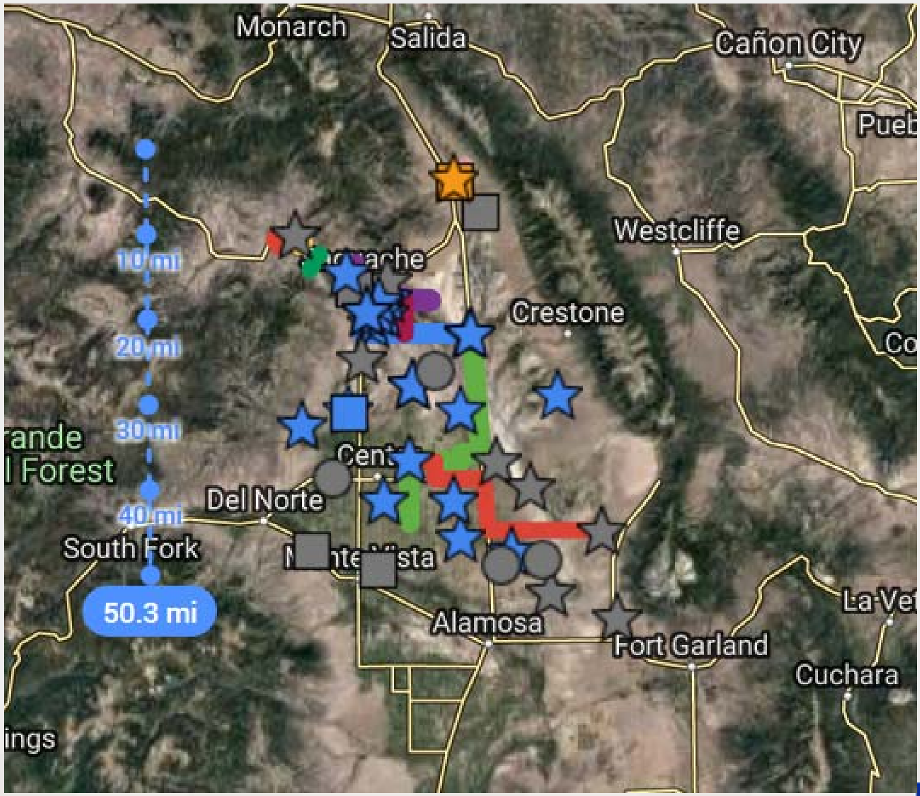
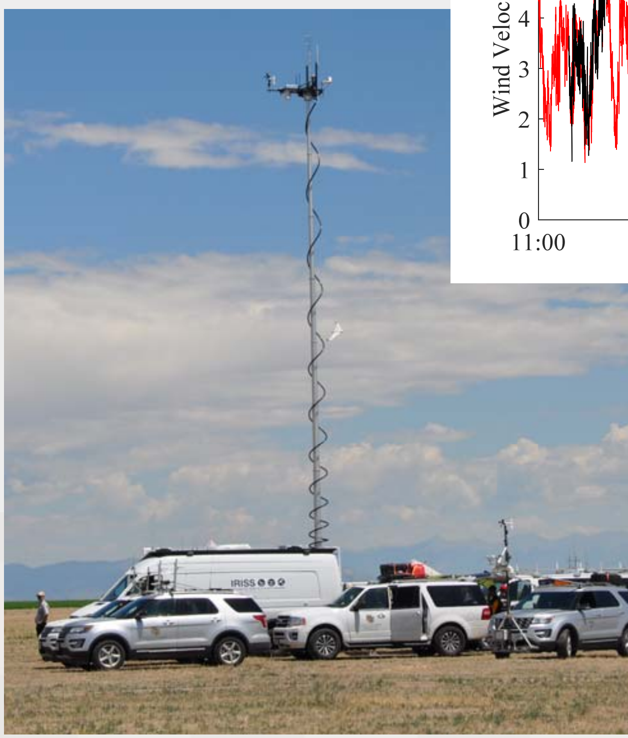
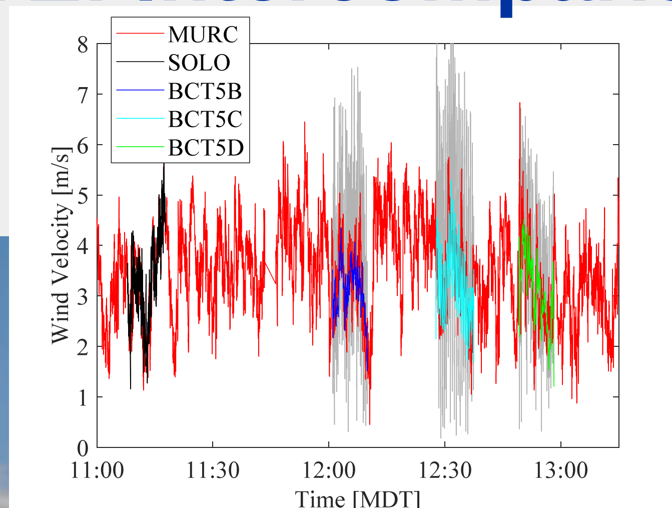
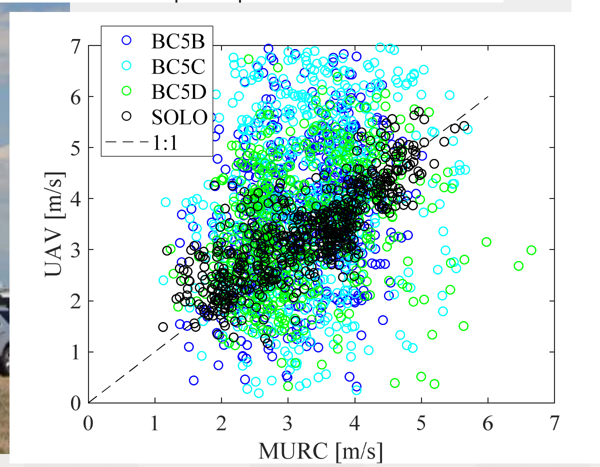
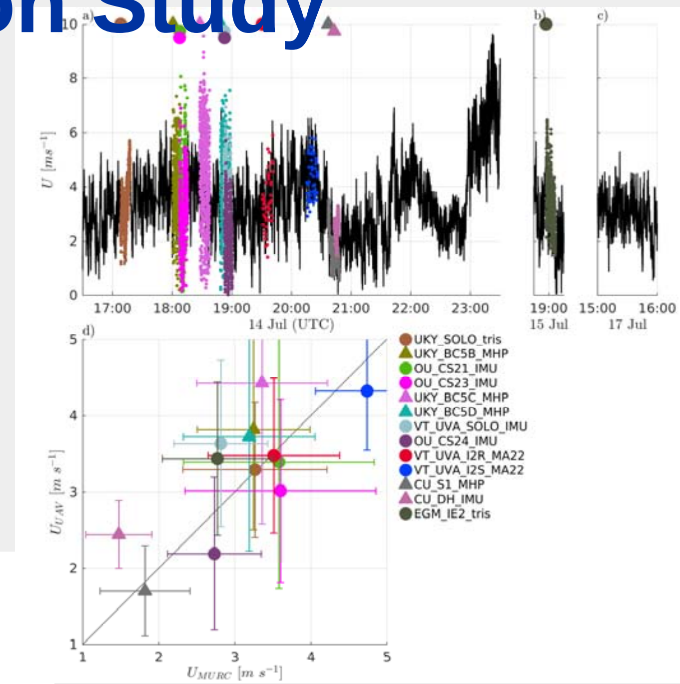


LAPSE-RATE: Intercomparison Study



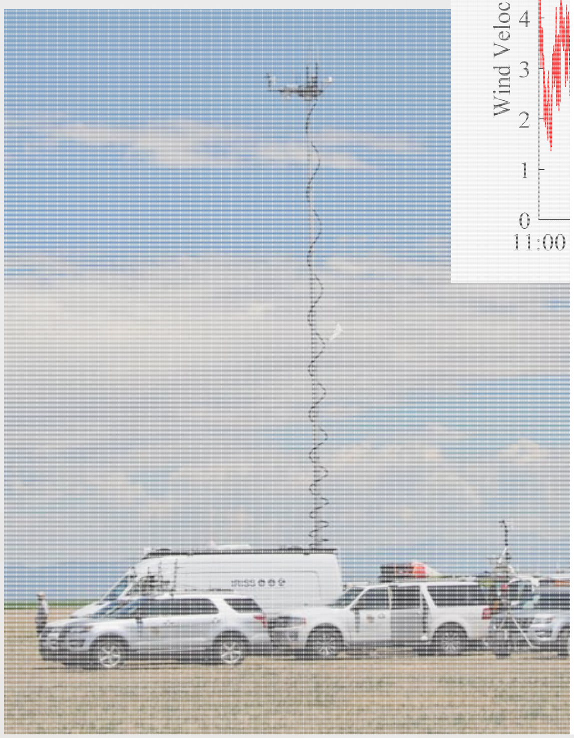


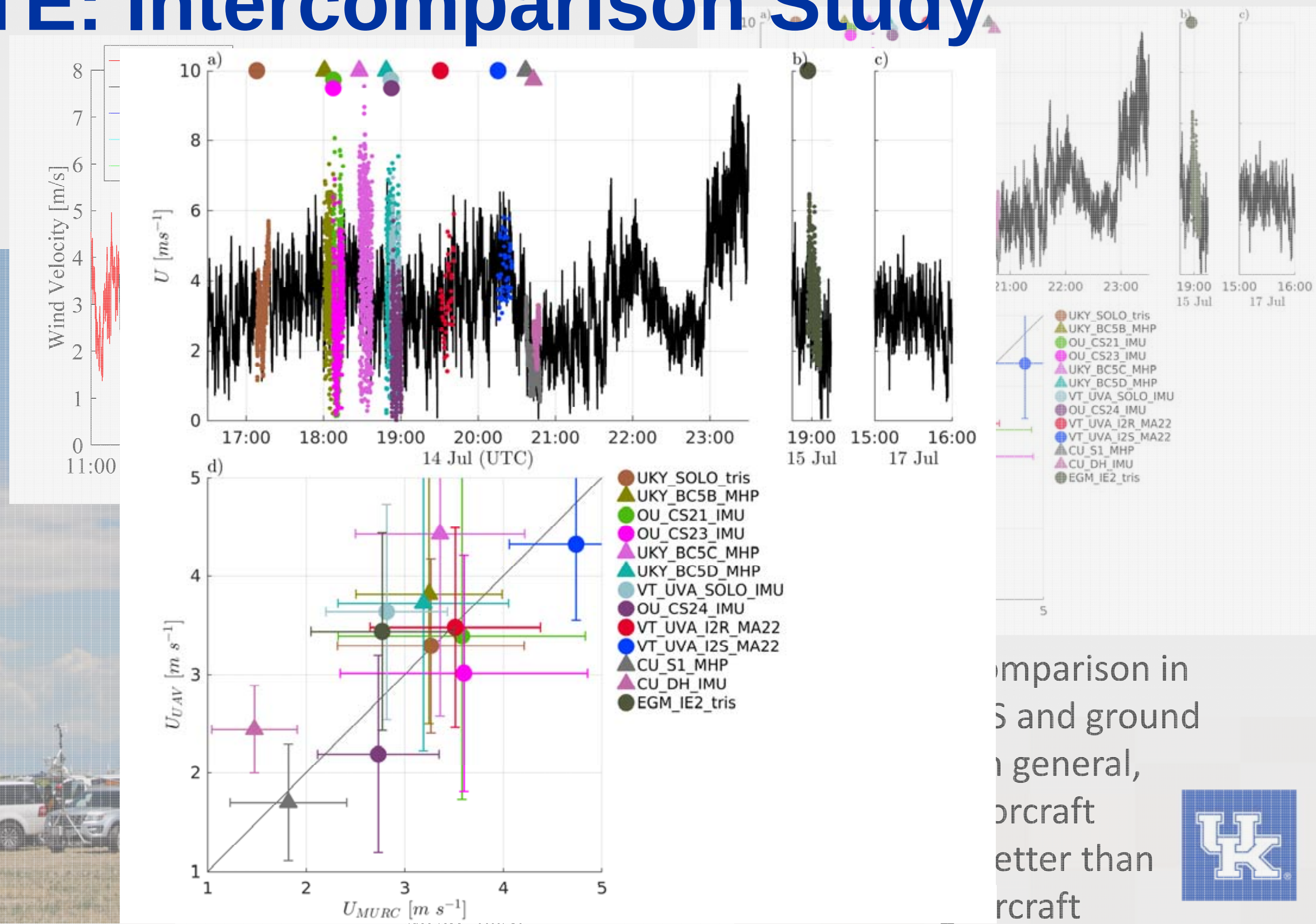




Very good comparison in between UAS and ground reference. In general, hovering rotorcraft performed better than fixed-wing aircraft

LAPSE-RATE: Intercomparison Study





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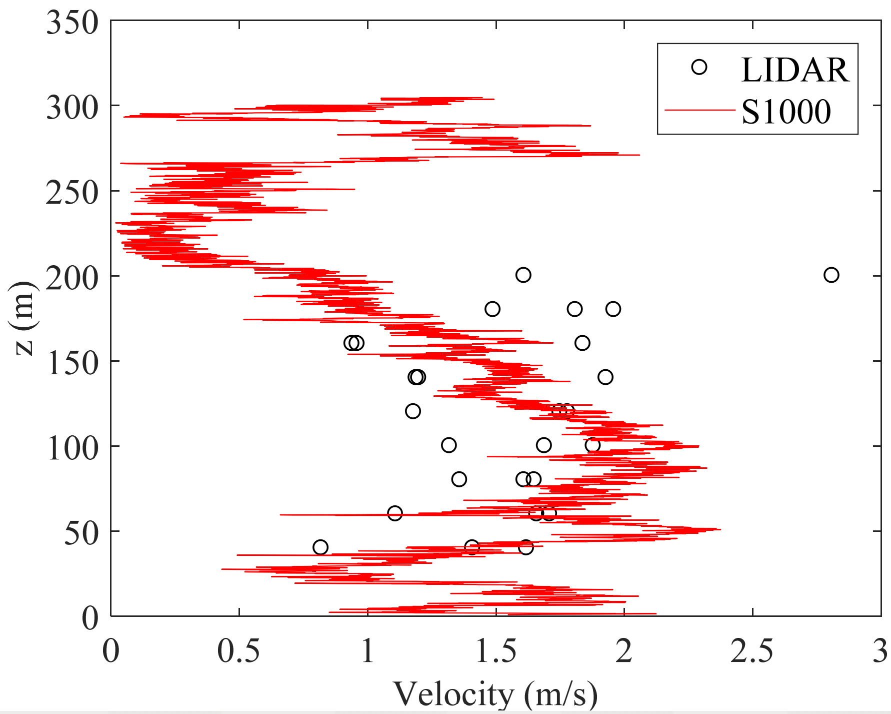
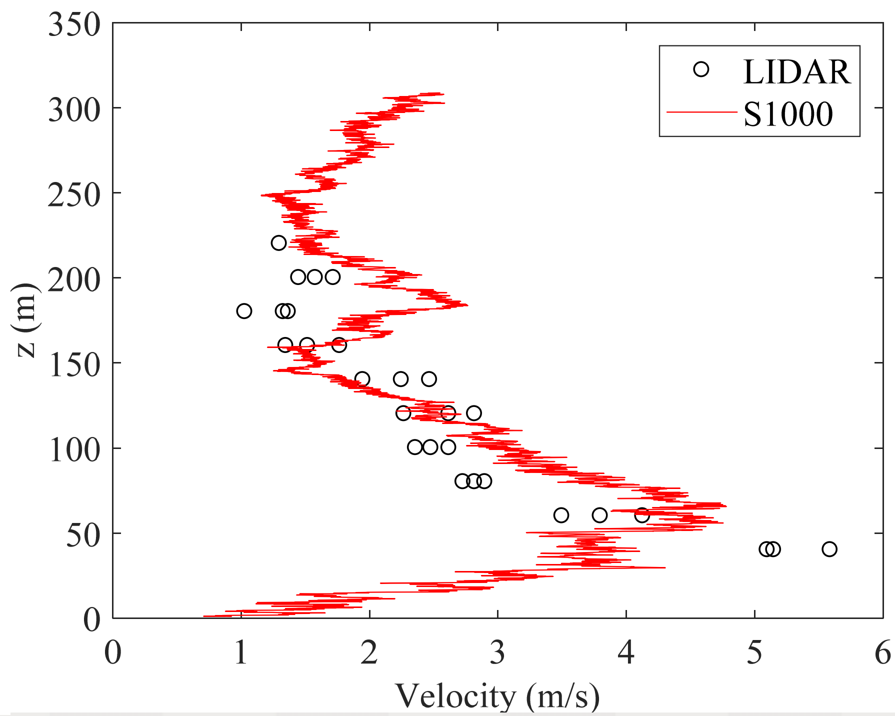
LAPSE-RATE Intercomparison with LIDAR

Comparison between S1000 and LIDAR from Saguache Airport measurements (790 m apart)



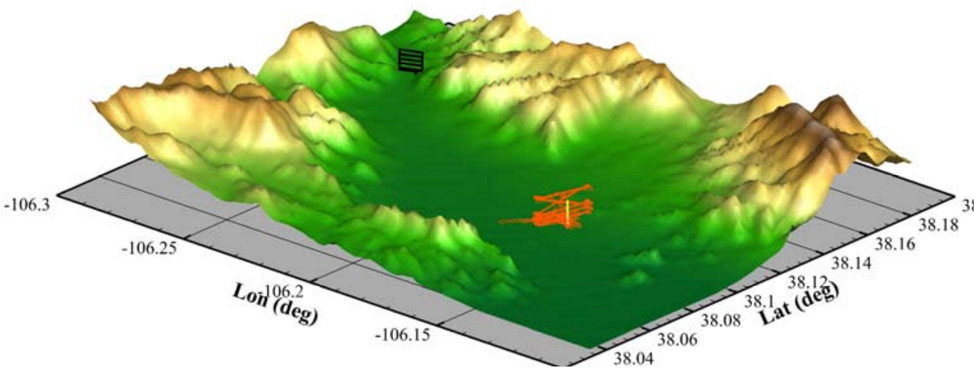
06:07 to 06:13 MDT

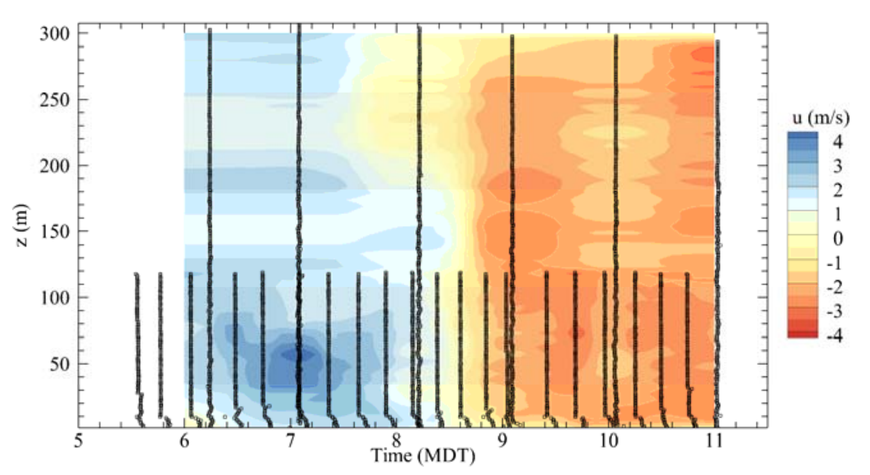


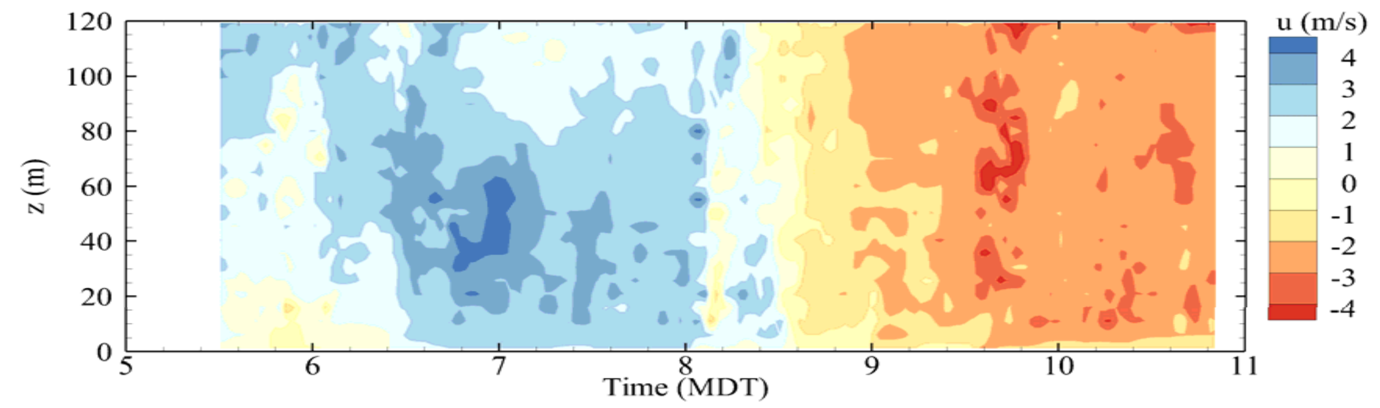
07:00 to 07:04 MDT

LAPSE-RATE Cold Air Drainage Measurements

ROTORCRAFT

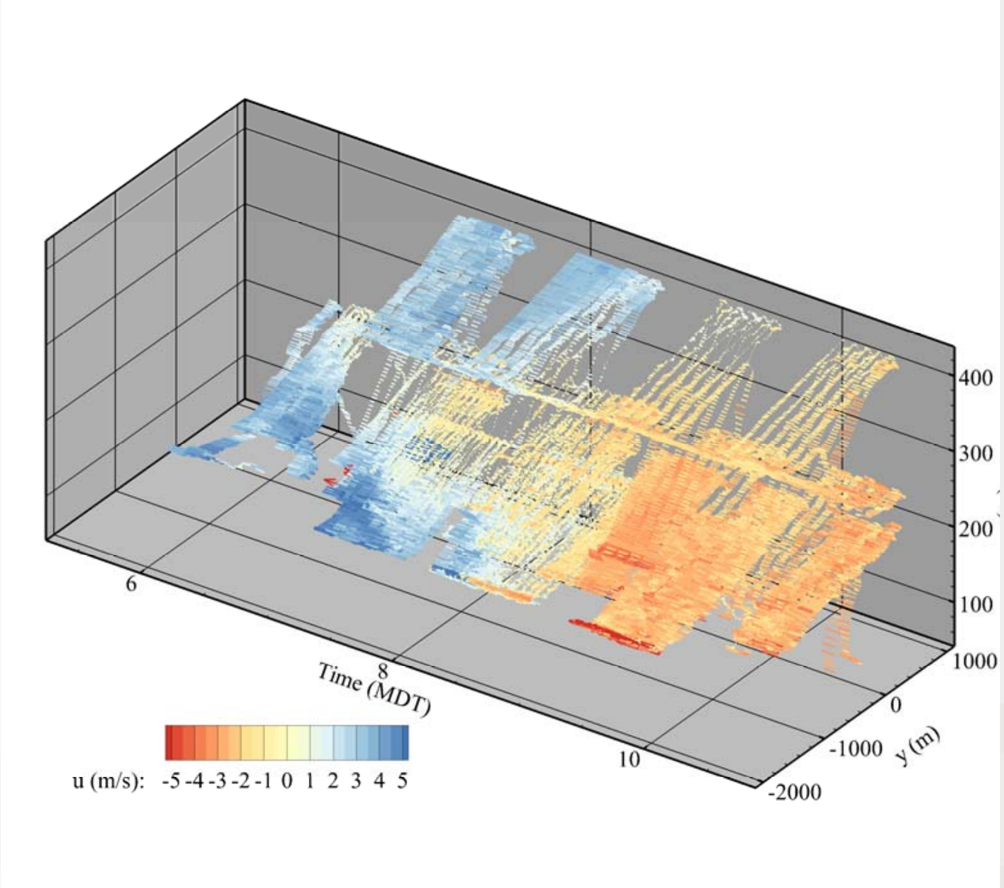






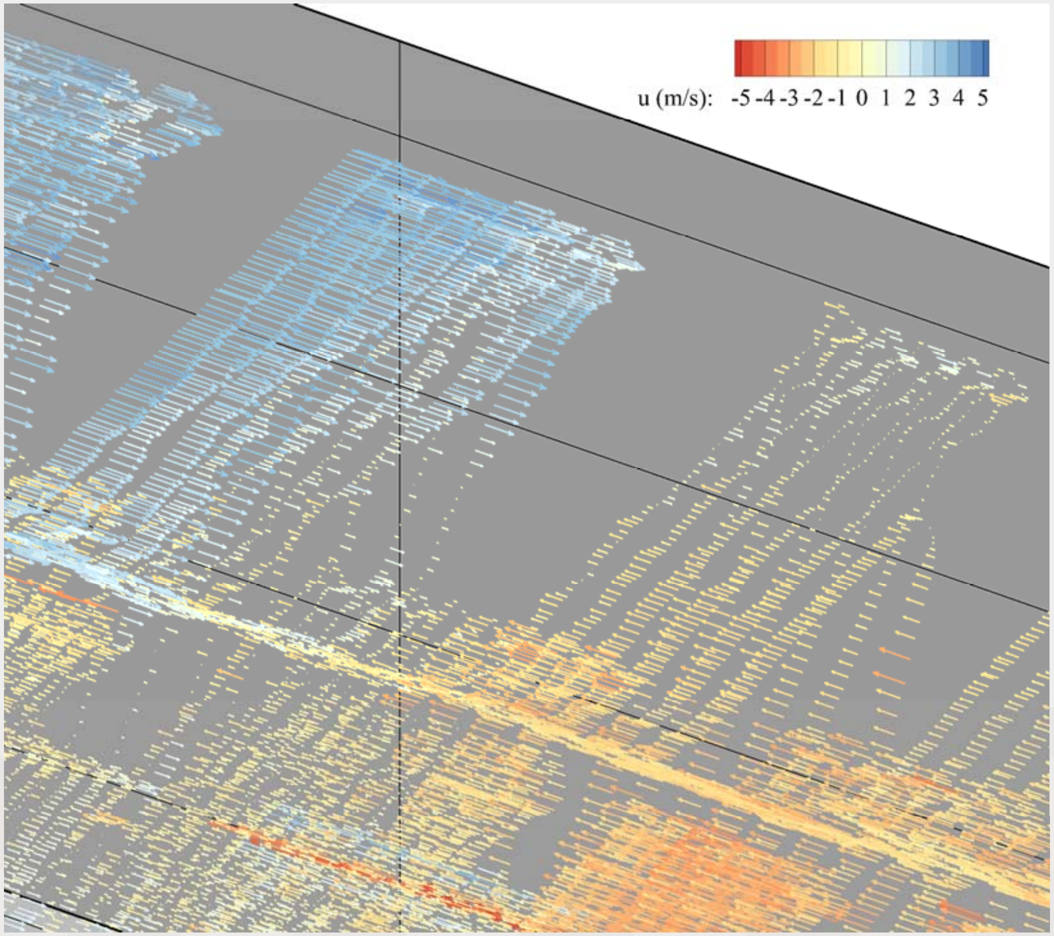
LAPSE-RATE Cold Air Drainage Measurements

Fixed-Wing



LAPSE-RATE Cold Air Drainage Measurements

Fixed-Wing



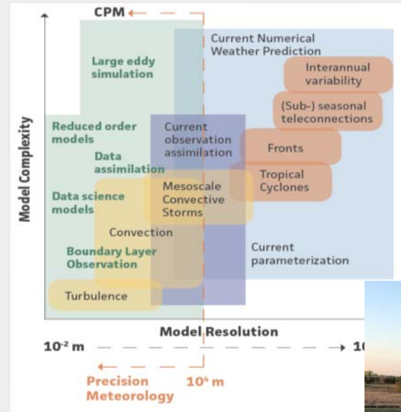
Conclusions

- It is possible to accurately measure the wind speed and direction
  - Different approaches are available
  - Need to mitigate aircraft motion relative to the inertial frame
  - Need to mitigate aircraft interference effects.
- When done correctly the results are reliable
- Benefits of UAS over conventional and remote sensing systems for measuring wind:
  - Cost (LIDAR ~$300k, Rotorcraft ~$10k)
  - Ability to measure over large distances (currently limited by FAA rules)
  - Portability
  - Flexibility
  - Sample rates
- Challenges:
  - Operations can be challenging (pilot training, need to constantly monitor)
  - Not yet at a point where all-weather operations are possible
  - Extended studies are challenging
    - Limitations on duration of measurement (crew endurance)
  - Need to work within regulatory environment
    - Introduces limitations on when flight is possible

Center for Precision Meteorology (CPM)

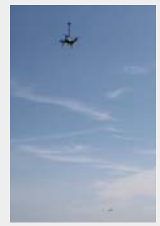
Improved Local-Scale Forecasting with Unmanned Aircraft Systems (UAS) in the Lower Atmosphere

- Practical limits dictate that new paradigms are becoming necessary to achieve accurate weather forecasting at sub-1km scales.
- Meteorological conditions in the atmospheric boundary layer (ABL) are highly complex and variable, so improved local-scale forecasting requires improving ABL observations.
- Researchers at six universities (UK, OSU, OU, UNL, PVAMU and VT) are working with CU and NCAR to combine resources and expertise to engineer new UAS observations and forecasting testbeds to advance modeling, answer key science questions, and improve forecasting for diverse applications



CLOUDMAP












Extras

CLOUD-MAP (2015-2019)

Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

- Four universities: Oklahoma State (OSU), Oklahoma(OU), Nebraska-Lincoln (UNL), and Kentucky (UK) partnered to develop integrated small unmanned airborne systems (sUAS) for enhanced atmospheric physics measurements.
- The team includes atmospheric scientists, meteorologists, engineers, computer scientists, geographers, and chemists necessary to evaluate the needs and develop the advanced sensing and imaging, robust autonomous navigation, enhanced data communication, and data management required to use sUAS in atmospheric physics.
- Annual integrated evaluation of the systems in coordinated field campaigns established benchmarks for technologies, and also required advancing public policy related to adoption of sUAS technology and integration of unmanned aircraft into the airspace.

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Aircraft Dynamics

- Wind speed and direction can be calculated by subtracting the true air speed vector (Pitot-static tube and aircraft orientation) from the ground speed vector (GPS)
  - Evolution of same approach used in manned aviation

- For multi-rotor UAS, autopilot orients the aircraft to follow programmed flight trajectory
  - Required orientation and motor response to follow trajectory will depend on the wind speed and direction
  - IMU/autopilot measure orientation
  - Autopilot measures motor output
  - Through calibration, either response can be used to measure wind speed and direction for specific flight profiles

Direct Measurement

- Sensors measure wind relative to the aircraft, but aircraft is in motion
- Measure position/orientation data (GPS/INS)
- Wind vector then determined from

$$\left[\vec{W}(t,\vec{x})\right]_B = \left[\vec{U}_m(t,\vec{x})\right]_B - \left[\vec{U}_{UAV}(t,\vec{x})\right] - \left[\vec{\Omega} \times \vec{r}_{probe\ \_\ UAV}\right]_B$$

- Convert to earth fixed axis:

$$\left[\vec{W}(t,\vec{x})\right]_I = L_{IB}\left[\vec{W}(t,\vec{x})\right]_B$$

- For spatial measurements can also correct for advection:

$$\left[\vec{W}(\vec{x}^{\,*})\right]_I \approx \left[\vec{W}\left(0, \vec{x} - \overline{\vec{W}(t,\vec{x})}t\right)\right]_I$$