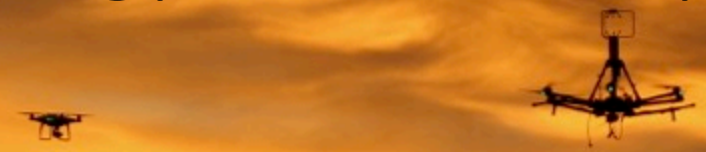
Lessons Learned

Collaboration Leading Operation Unmanned aircraft Development for Meteorology and Atmospheric Physics



Jamey Jacob, *Oklahoma State University*
& Numerous Diverse Hands from the
CLOUD-MAP and LAPSE-RATE Campaigns

CIMMS UAS Workshop
National Weather Center
Oct. 29, 2019

Supported by the National Science Foundation
Award #1539070

CLOUD-MAP Team

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Jamey Jacob
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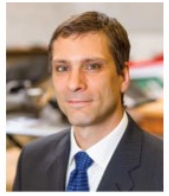
Amy Frazier
Chris Crick













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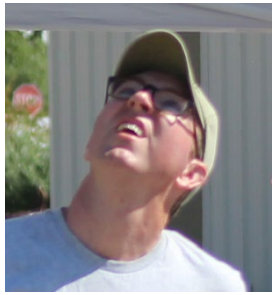
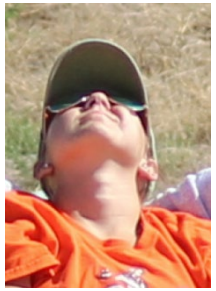
Liz Pillar-Little
Racine Swick
Alyssa Avery


LAPSE-RATE Team

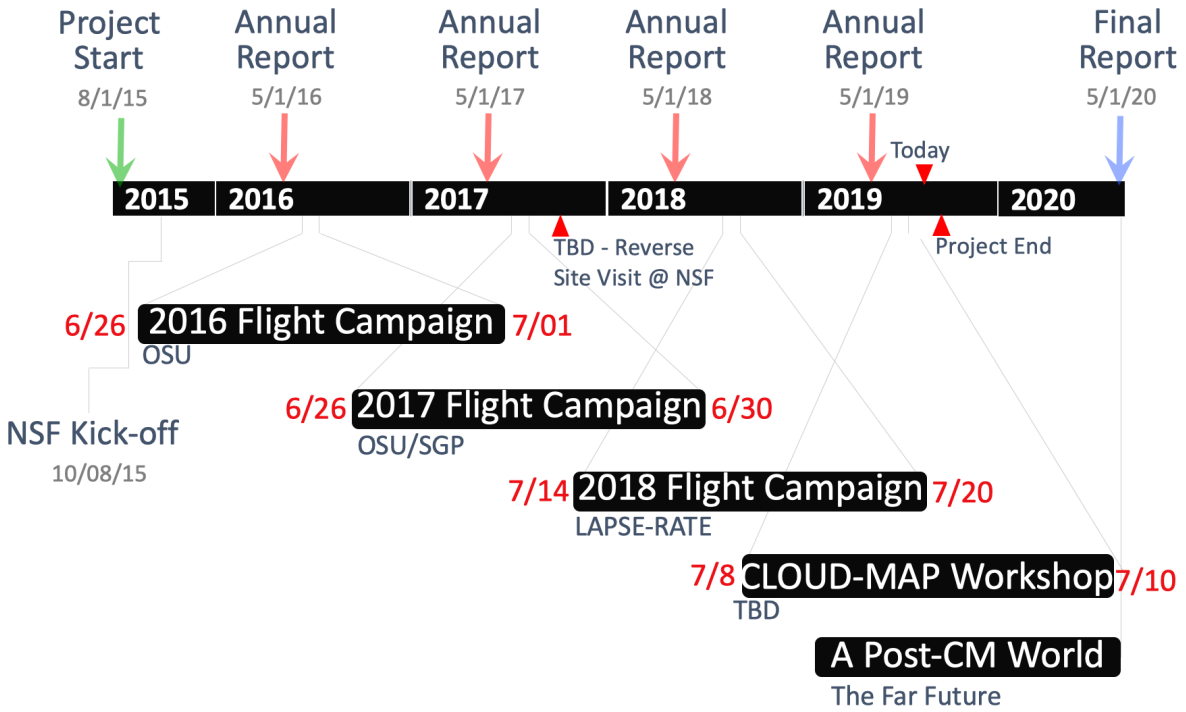
Gijs de Boer
Lindsay Barbieri
Constantin Diehl
James Pinto
Joachim Reuder

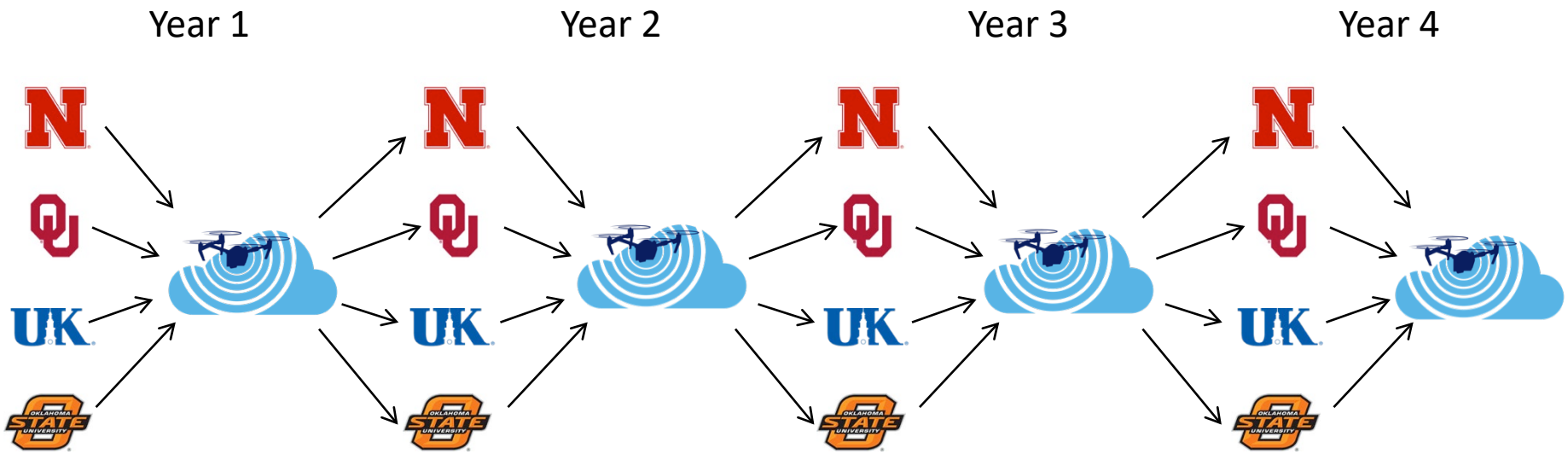




Sean Waugh
Petra Klein
Many, many (many) others

CLOUD-MAP Timeline





2016, 2017, 2018 Flight Campaigns

NCAR/EOL UAS Workshop

THE NCAR/EOL COMMUNITY WORKSHOP ON UNMANNED AIRCRAFT SYSTEMS FOR ATMOSPHERIC RESEARCH

21-24 February 2017
Boulder, Colorado, USA
Final Report 6 February 2018

Senior Editor:
Holger Vömel (NCAR/EOL)

Workshop Report Authors:
B.M. Argrow (CU), D. Axisa (DMT), P. Chlson (OU), S. Ellis (NCAR/EOL), M. Fladeland (NASA/AMES), E.W. Frew (CU), J. Jacob (OSU), M. Lord (NCAR/EOL), J. Moore (NCAR/EOL), S. Oncley (NCAR/EOL), G. Roberts (UCSD), S. Schoenung (BAERI), C. Wolff (NCAR/EOL)

Download the Final Workshop Report

Reference:
H. Vömel, B.M. Argrow, D. Axisa, P. Chlson, S. Ellis , M. Fladeland, E.W. Frew, J. Jacob, M. Lord, J. Moore, S. Oncley, G. Roberts, S. Schoenung, C. Wolff, 2018: NCAR/EOL Community Workshop on Unmanned Aircraft Systems for Atmospheric Research, UCAR/NCAR Earth Observing Laboratory, https://doi.org/10.5065/D6X9292S

WMO UAS Workshop (Toulouse, July 2019)

Government Entities

- NOAA
- NCAR
- UK Met Office
- British Antarctic Survey
- CMA
- DHMZ
- FMI
- Meteo-France
- NMHI
- National Council of Civilian UAV
- DWD
- Hong Kong Observatory
- Met Eireann

International

- WMO
- NMHS/IPET-ABO
- IATA
- ECMWF
- EUMETNET, E-ABO

Industry

- Airbus
- Blackswift
- FLYHT
- Meteomatics
- Singular

Academic

- Technische Universität Braunschweig
- CLOUD-MAP

2016/18 CLOUD-MAP Highlights

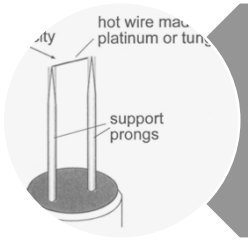
- CLOUD-MAP Field Campaign
  - 2 sites, 15 vehicles, 3 days
  - OSU, Mesonet, and DOE ARM SGP
- 2017 Eclipse ABL Survey
  - 2 sites, 6 vehicles, day long sampling
  - Nebraska and Kentucky, along path of totality
- 2017/18 Targeted Opportunities
  - High wind observations
  - LSS interceptions

Platform Development and Sensor Integration



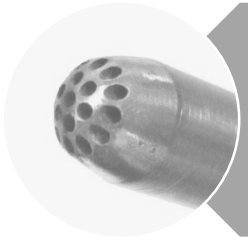



ABL Diagnostics



Fixed wing - hot wires:

- *Velocity magnitude and turbulence*

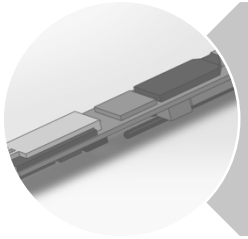


Fixed wing - multi hole probes:

- *Full 3D velocity vector*

Rotary wing solutions

- *Ultrasonic probes*
- *IMU derived velocity*

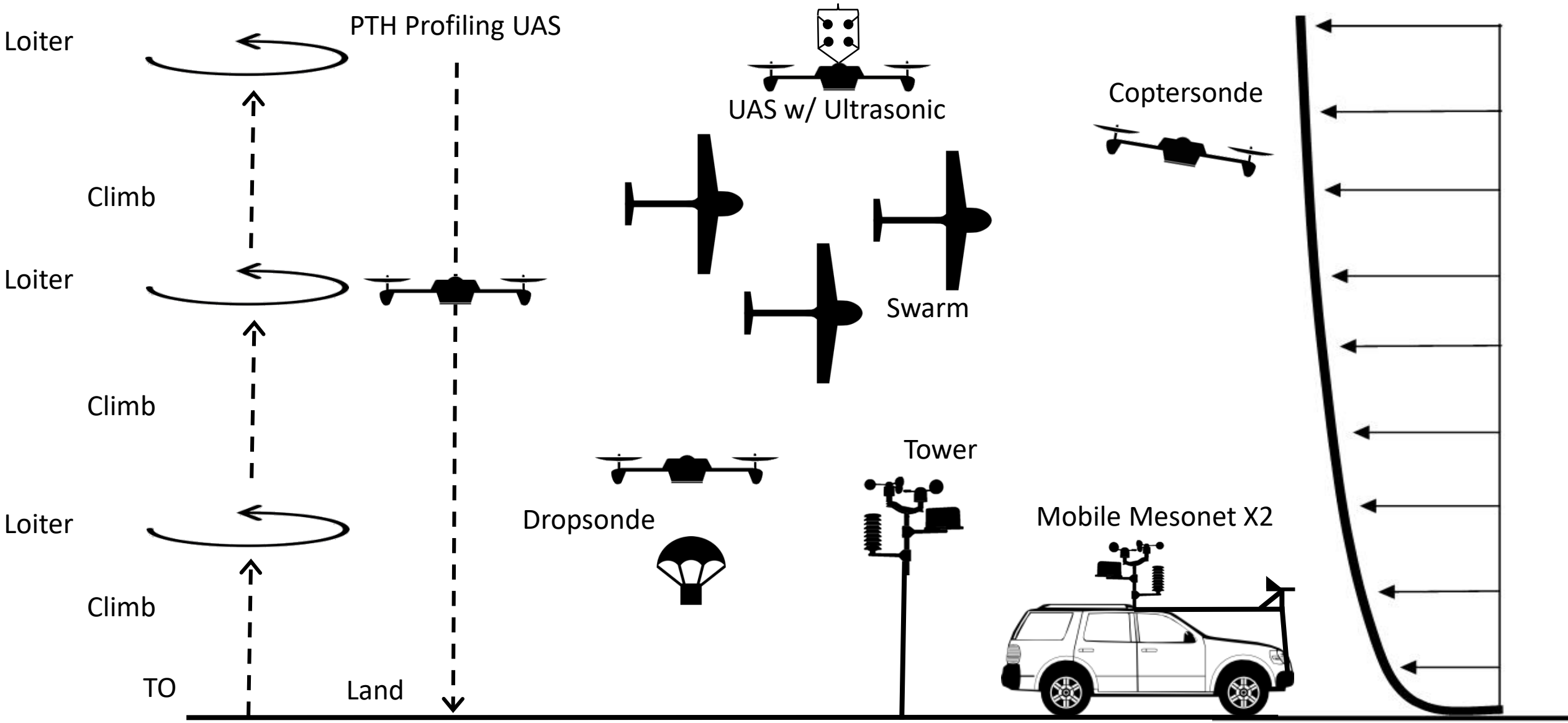


Universal observations
- PTU
- Gas concentrations (CO_2, CH_4)
- IMU

2016-2017 Flight Campaigns

- Annual flight campaign serves as an opportunity to exchange information, compare systems, and evaluate progress throughout year
- 4 teams – 3 flight days each year
- >60 participants with >20 systems
- 767 separate flights
- 91 hrs. total flight time

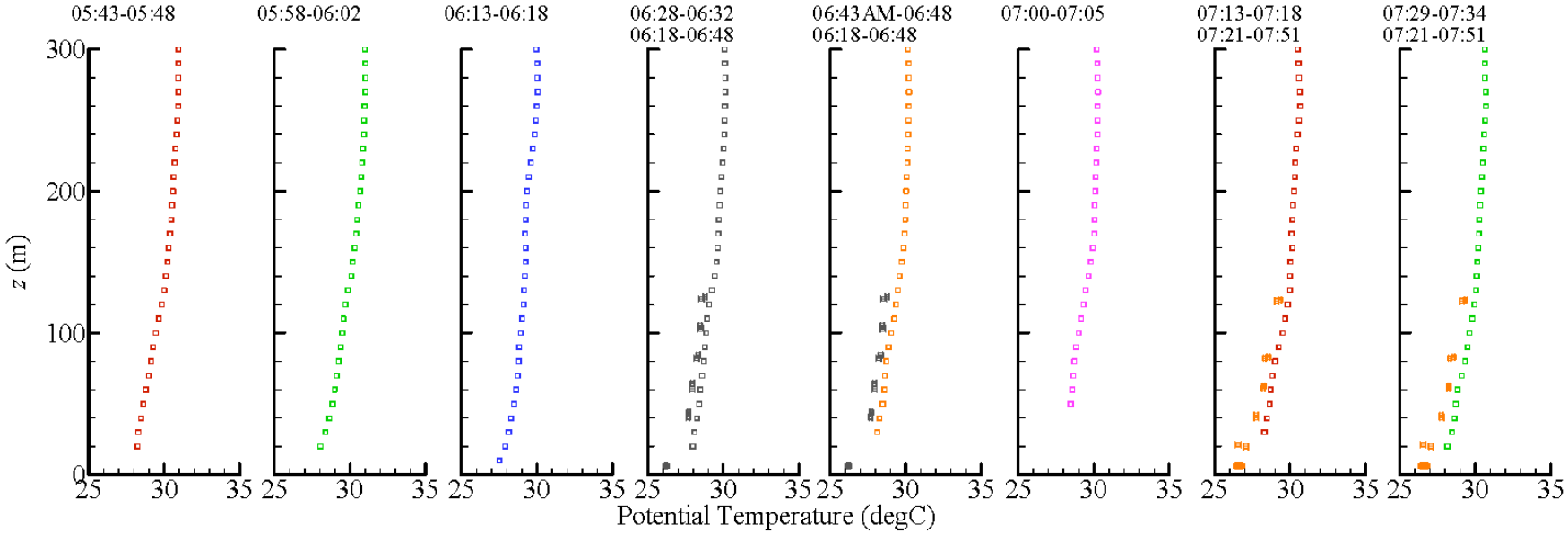
2016/17 CLOUD-MAP Field Campaigns

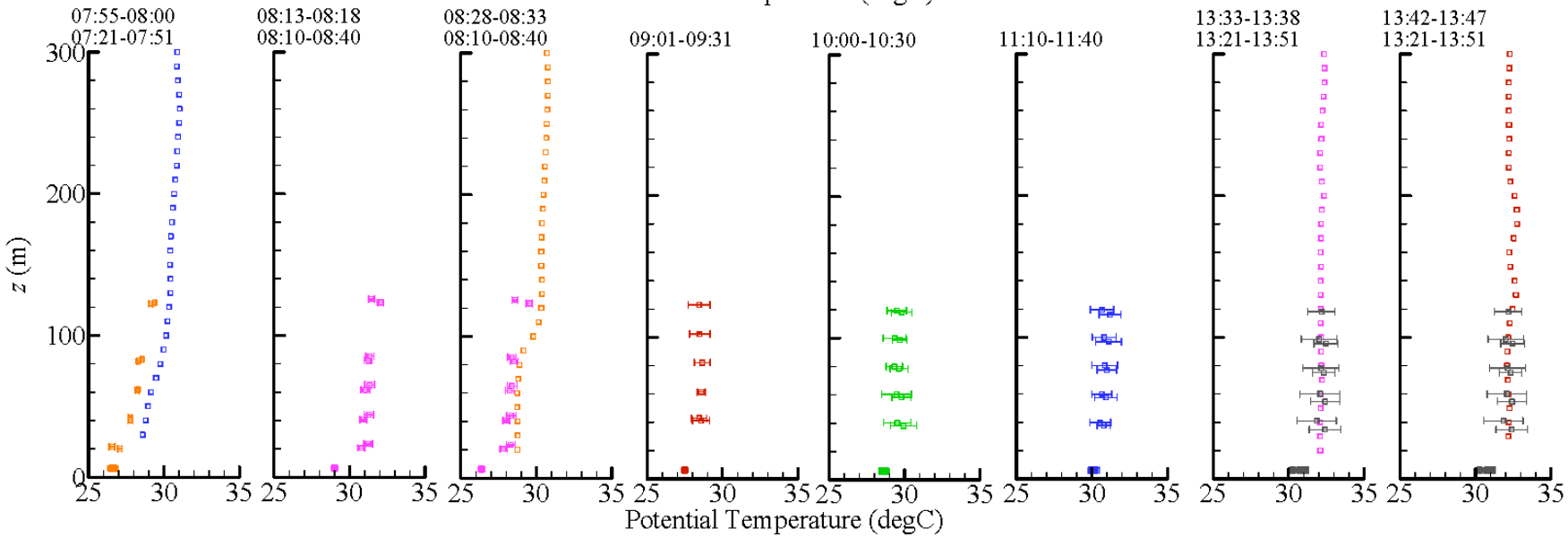


Profiling Prototypes

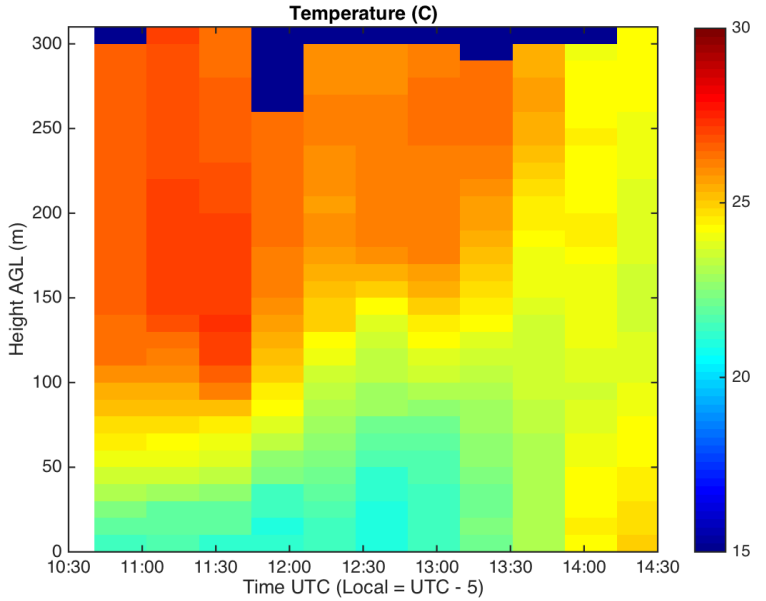
- GPS/IMU
- Pressure, Temp., Humidity
- Winds aloft (direction, magnitude)
- Turbulence

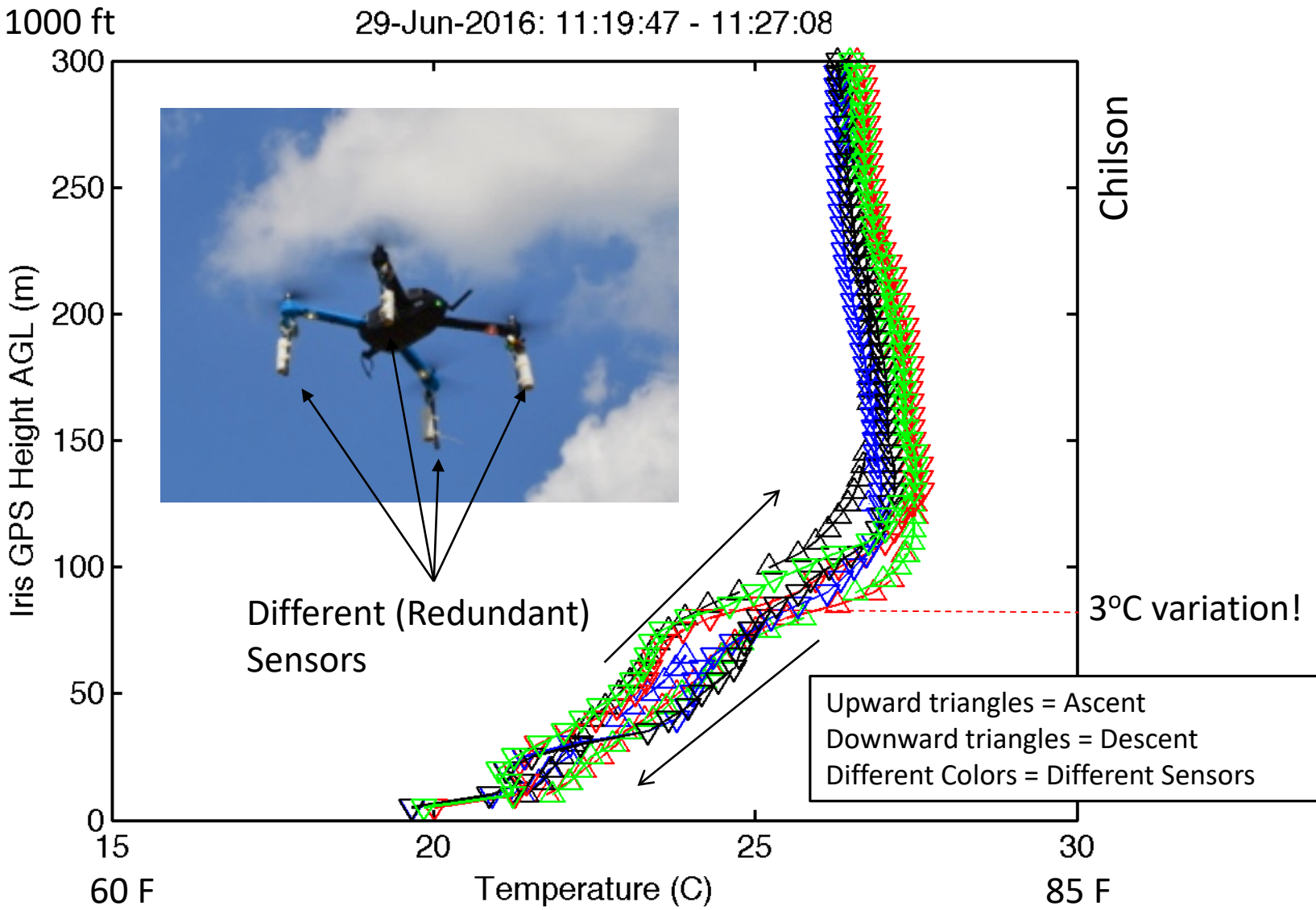
Thermodynamic Observations





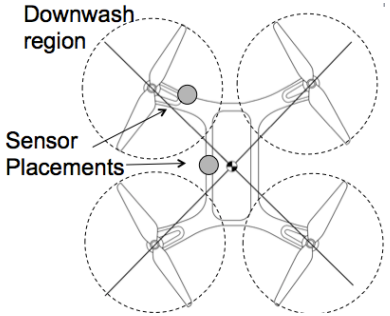
Uncertainties from 2016 Campaign

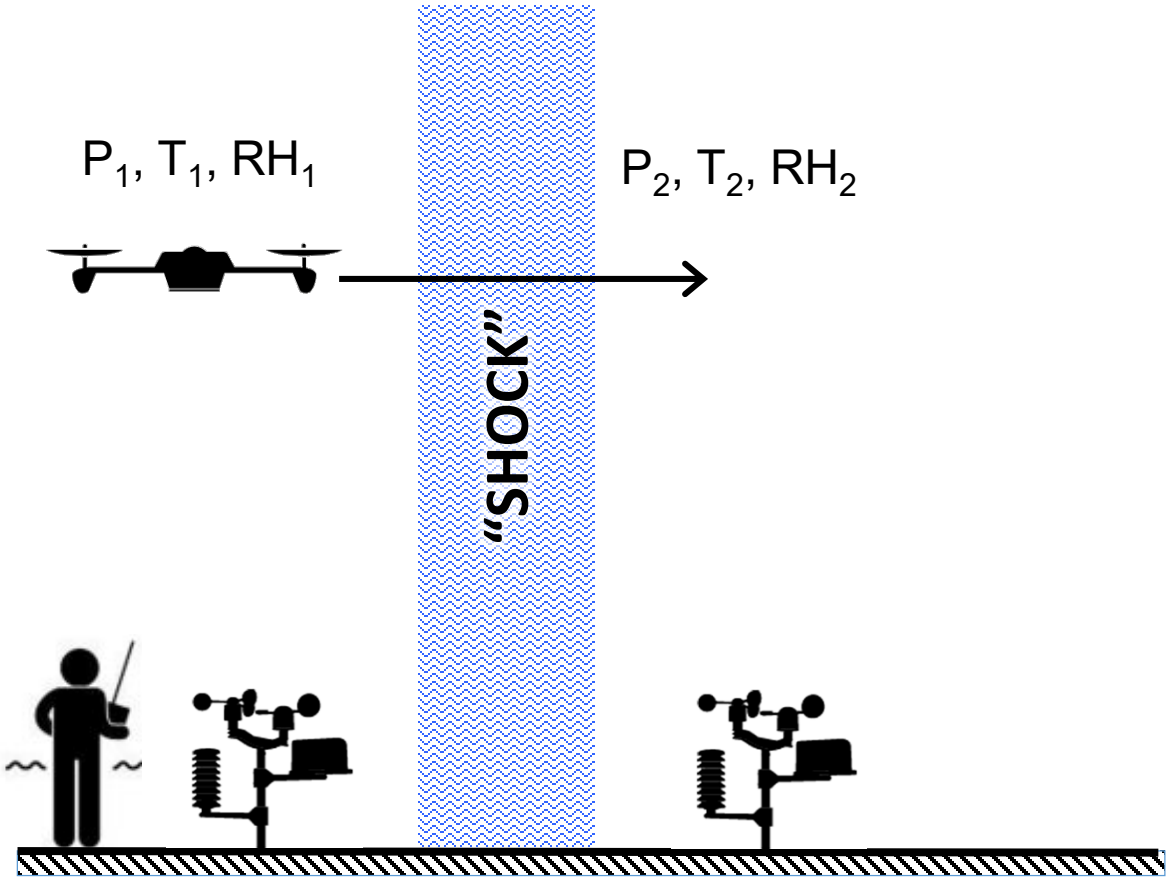




Coptersonde

PTU Calibration/Validation

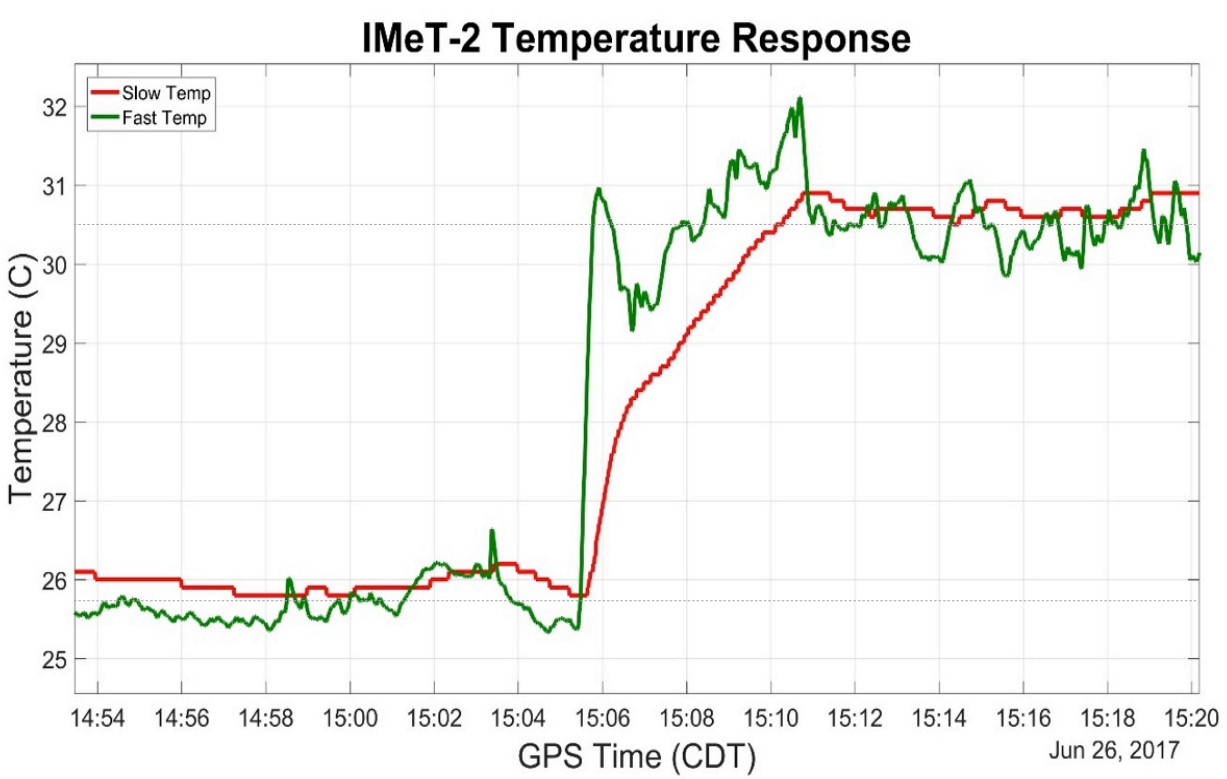


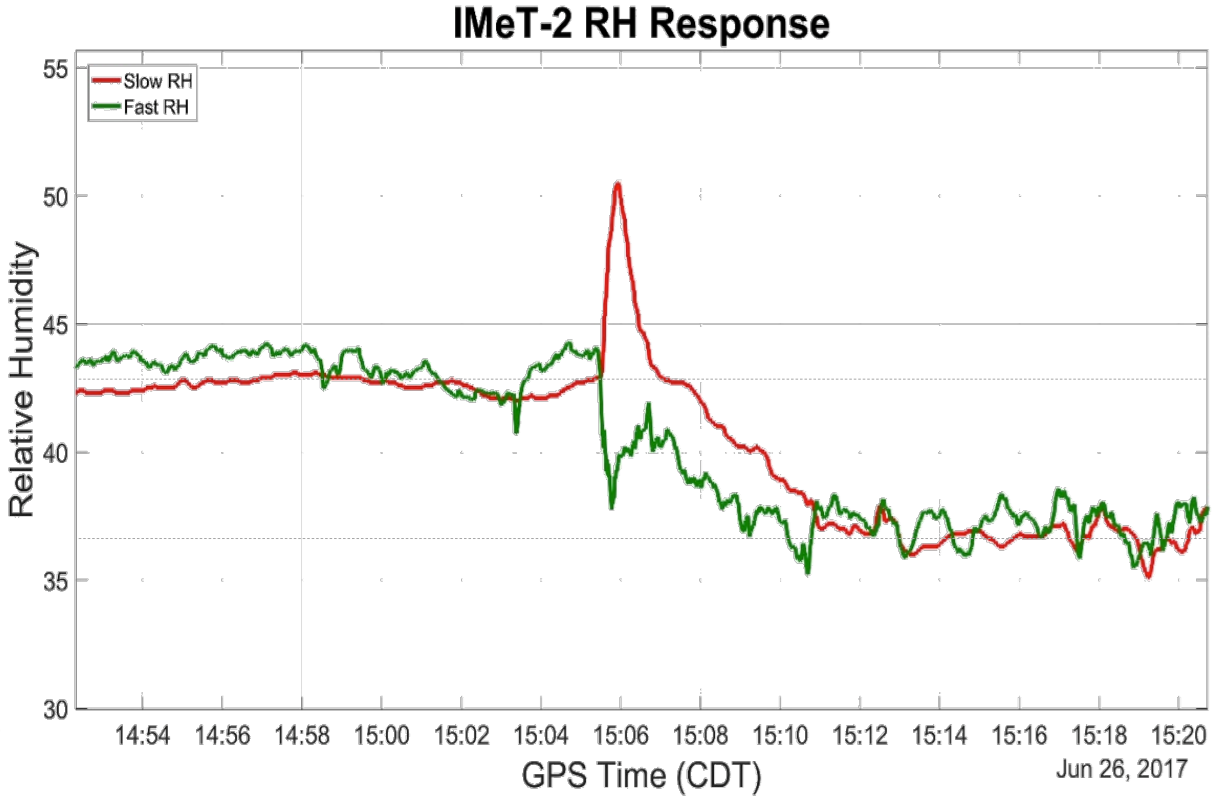


Houston


TOSS
TOSS

Shock


IMeT-2 Temperature Response
Slow Temp
Fast Temp
Temperature (C)
32
31
30
29
28
27
26
25
14:54
14:56
14:58
15:00
15:02
15:04
15:06
15:08
15:10
15:12
15:14
15:16
15:18
15:20
GPS Time (CDT)
Jun 26, 2017


IMeT-2 RH Response
Slow RH
Fast RH
Relative Humidity
55
50
45
40
35
30
14:54
14:56
14:58
15:00
15:02
15:04
15:06
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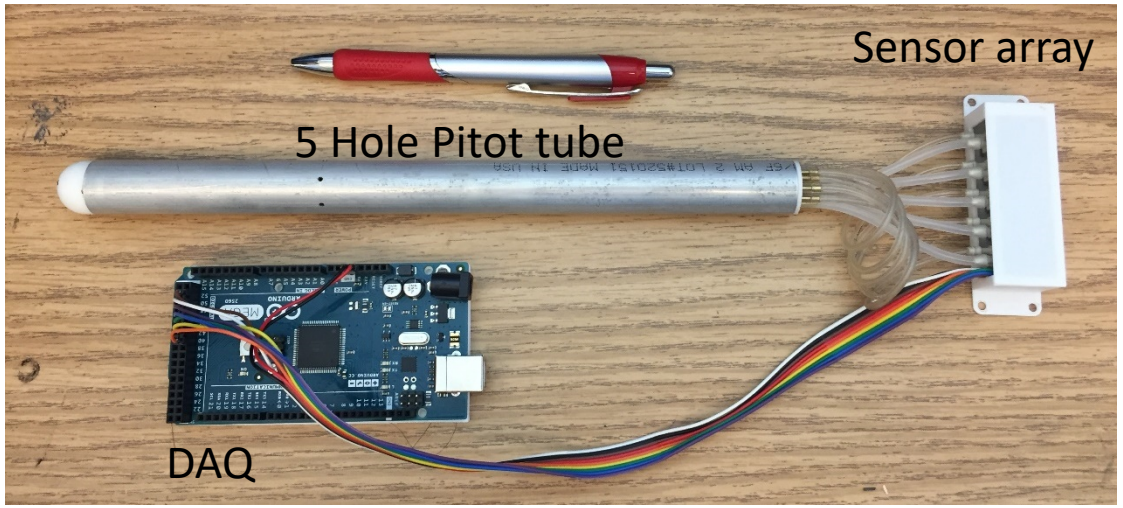
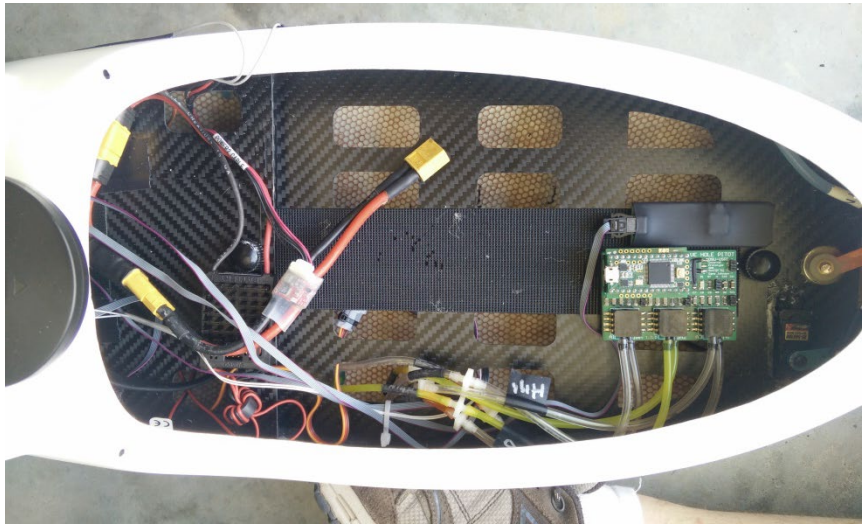
15:16
15:18
15:20
GPS Time (CDT)
Jun 26, 2017

5 Hole Probes





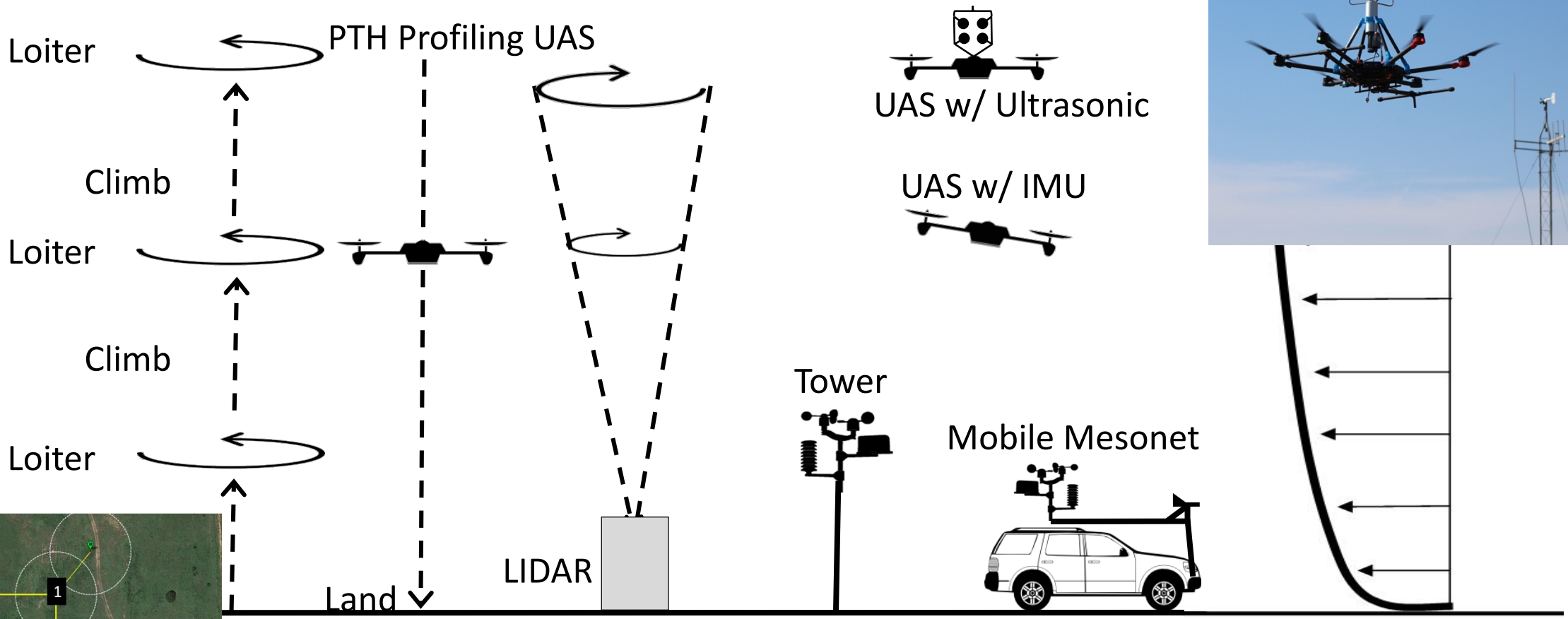
Probes

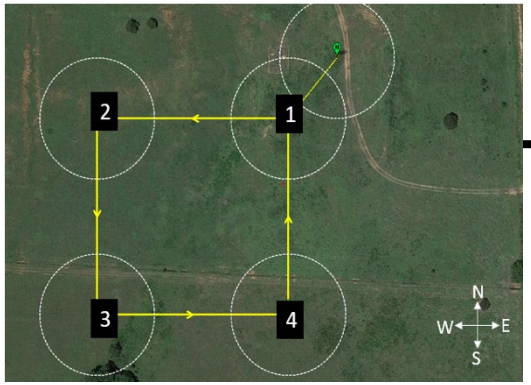
Ultrasonic Anemometer Integration

Anemometer Integration

Field Validation

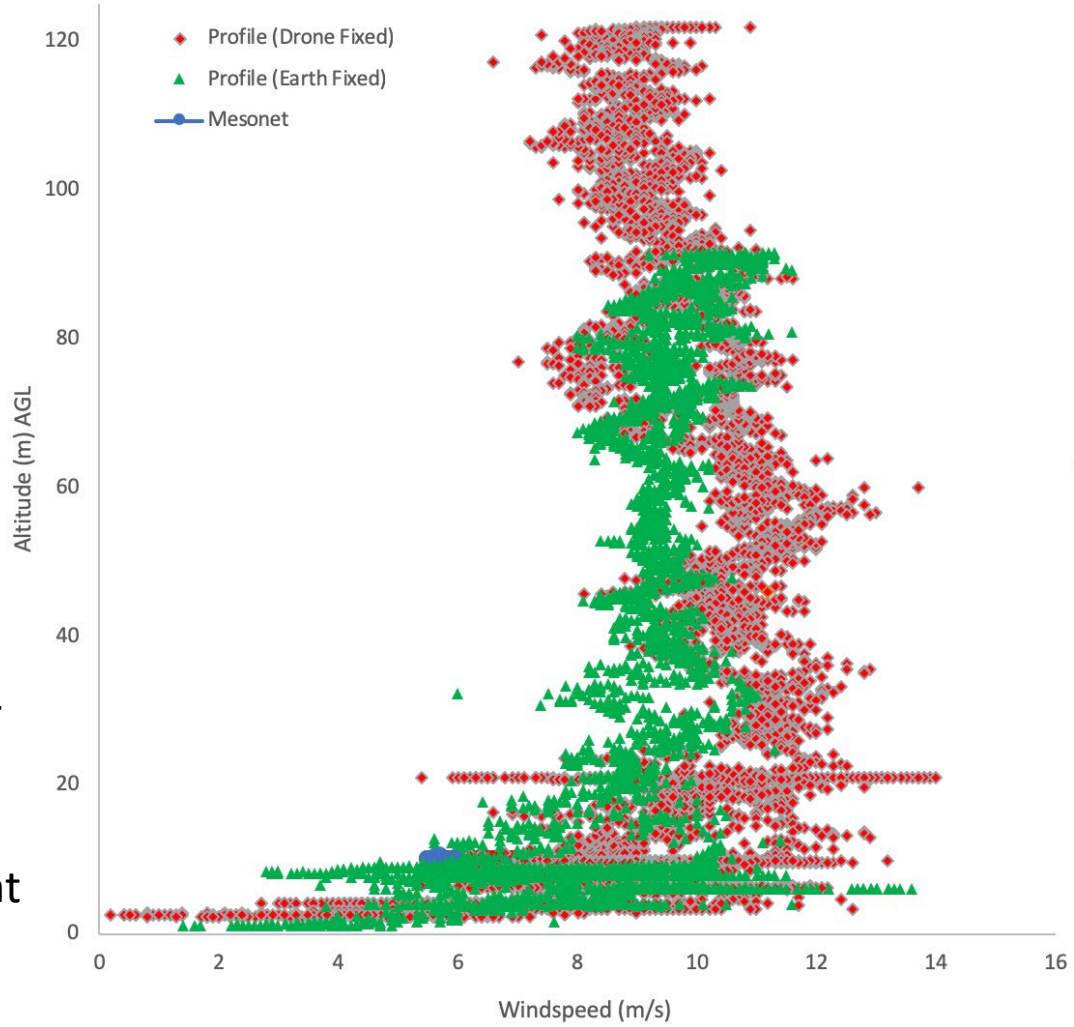
- Mesonets, ARM, MMURC





Further Anemometer Improvements

Gimbaled ultrasonic anemometer for improved turbulence measurement



Mobile Disdrometer for Radar Calibration

FW Launching & Recovery

Runway

- Gear required
- Heavy aircraft
- Infrastructure

Launcher

- Medium to heavy
- Consistent
- Equipment setup & transport
- How to land?

Hand Launch/Belly Land

- Small-medium aircraft (~10 lb max)
- Flexible, little space required

VTOL

- Point launch & recovery
- Large hit to endurance
- Need battery reserve

Bungee

- Small-medium (10+)
- Increases accuracy
- Increased weight
- Larger space needed

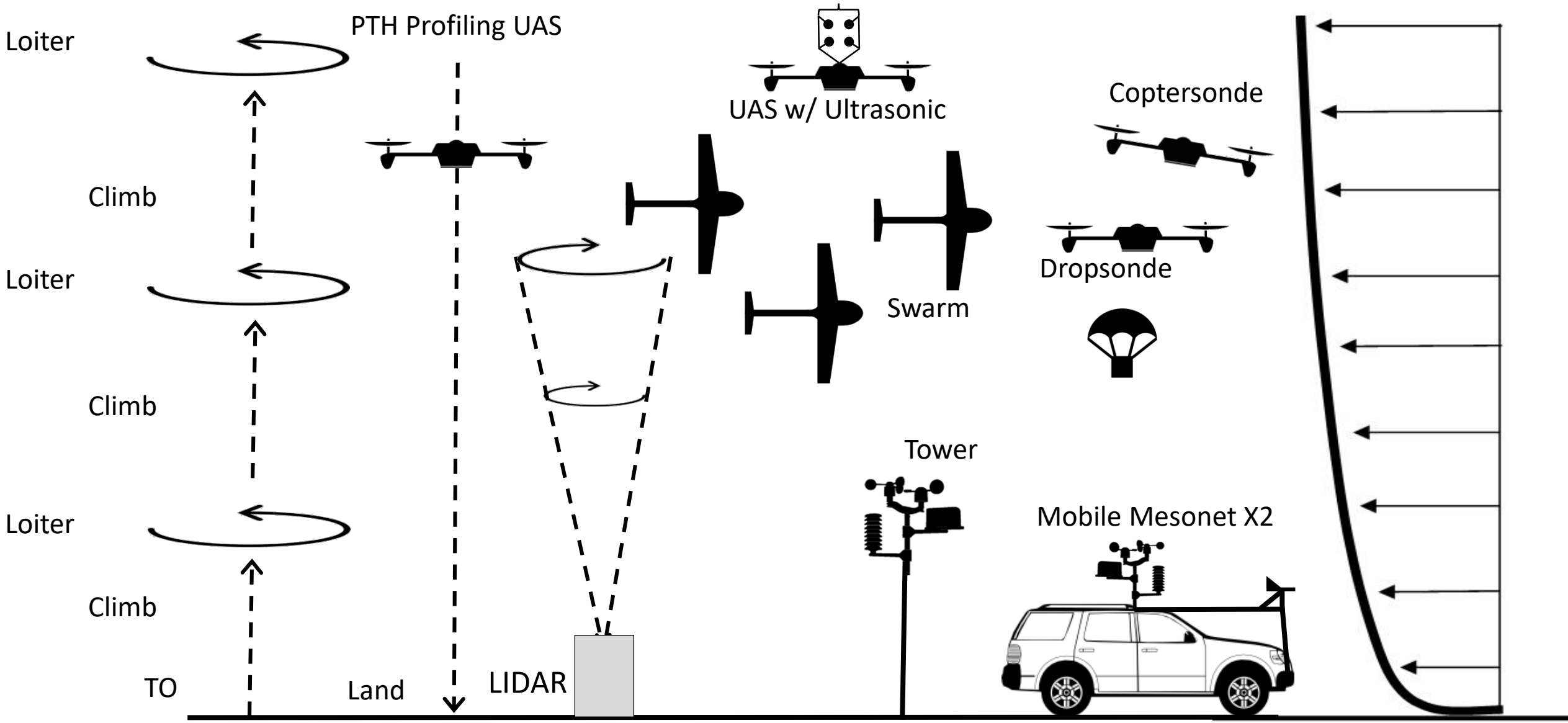
Car

- Medium to heavy
- Requires road
- Subject to crosswinds

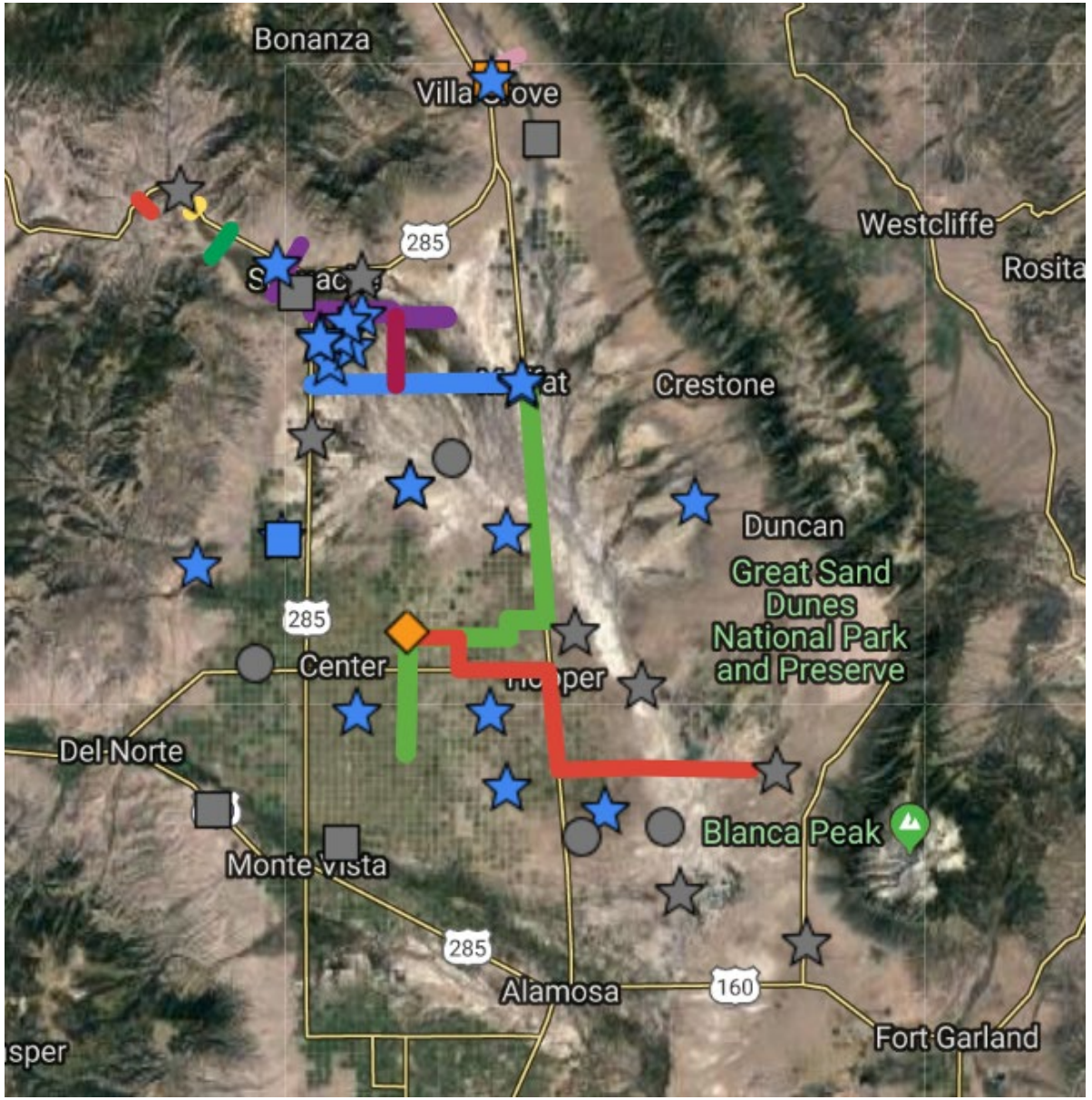
FW Launching – Hand/Bungee

FW Launching – Car

2018 LAPSE-RATE/CLOUD-MAP Field Campaign

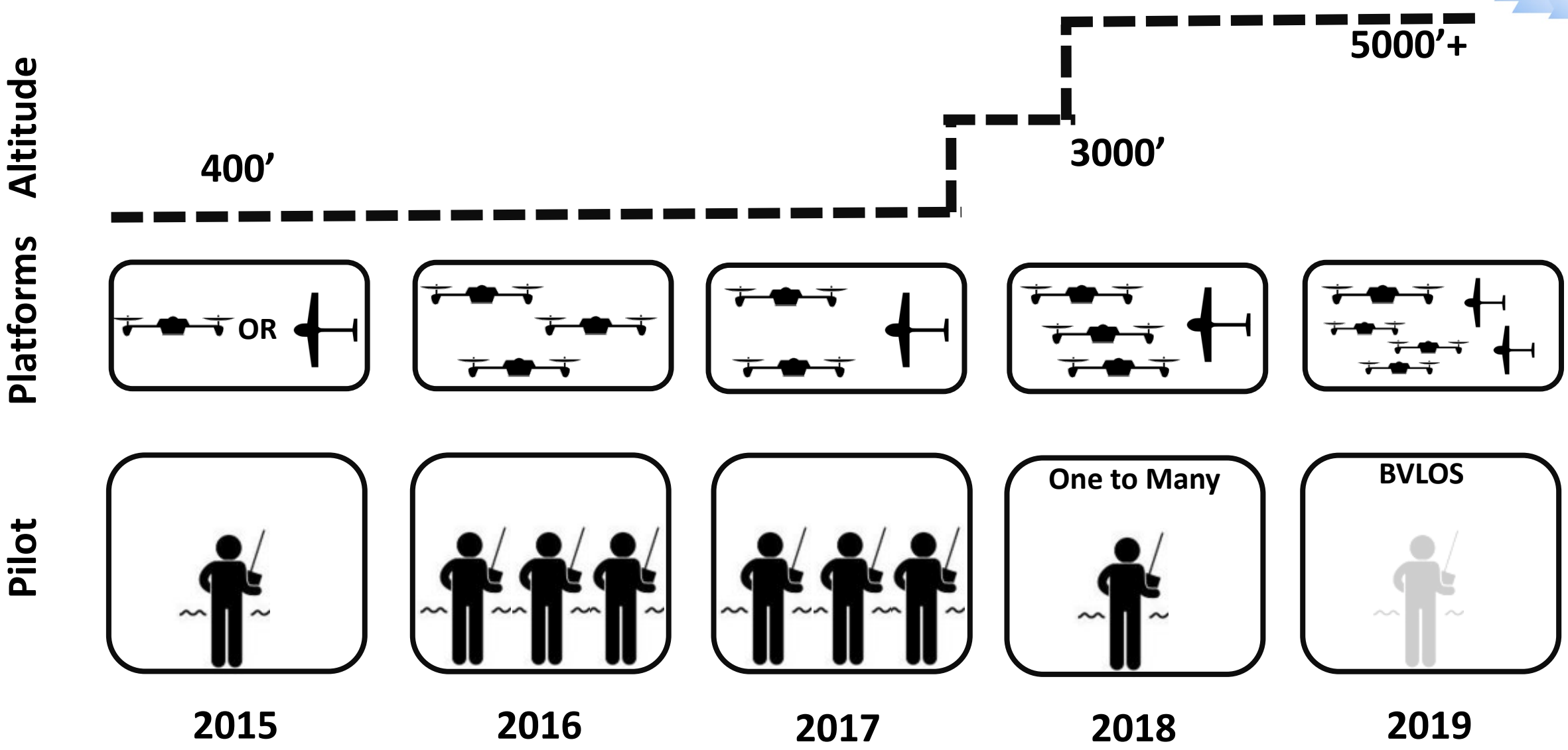


LAPSE-RATE

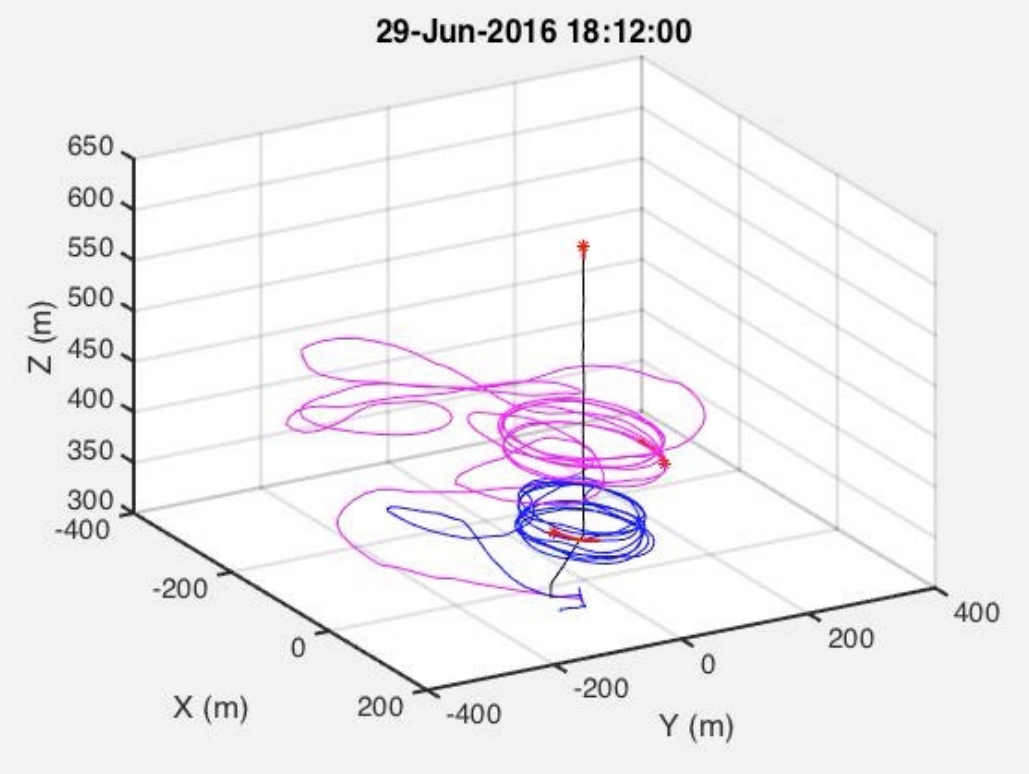


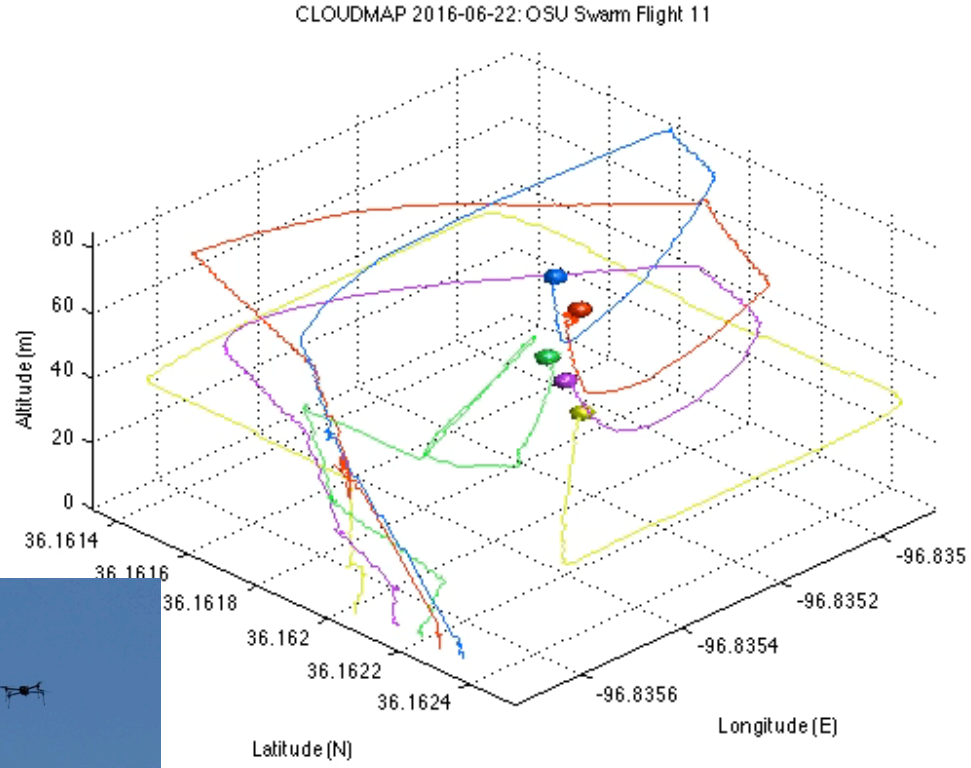
- Organized by Gijs de Boer as part of ISARRA 2018
- 8 Universities + US & Int. Agencies
- 96 Participants
- 50 UAS Platforms
- 1287 Flights
- 262.38 Hours of Data
- FAA Authorizations for Flight to 3,000’
- **3 Weather Questions**: Convection Initiation, Boundary-Layer Evolution, and Cold Air Drainage
- Sensor Cross Comparison and Calibration Studies
- Comparison to Forecast Models
- Data Processing (Still) Underway

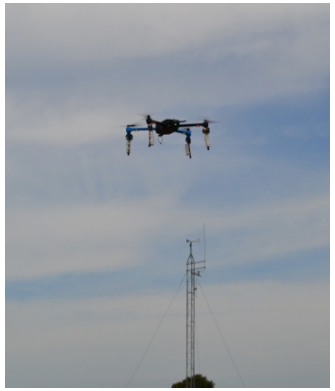
SWARM TIMELINE



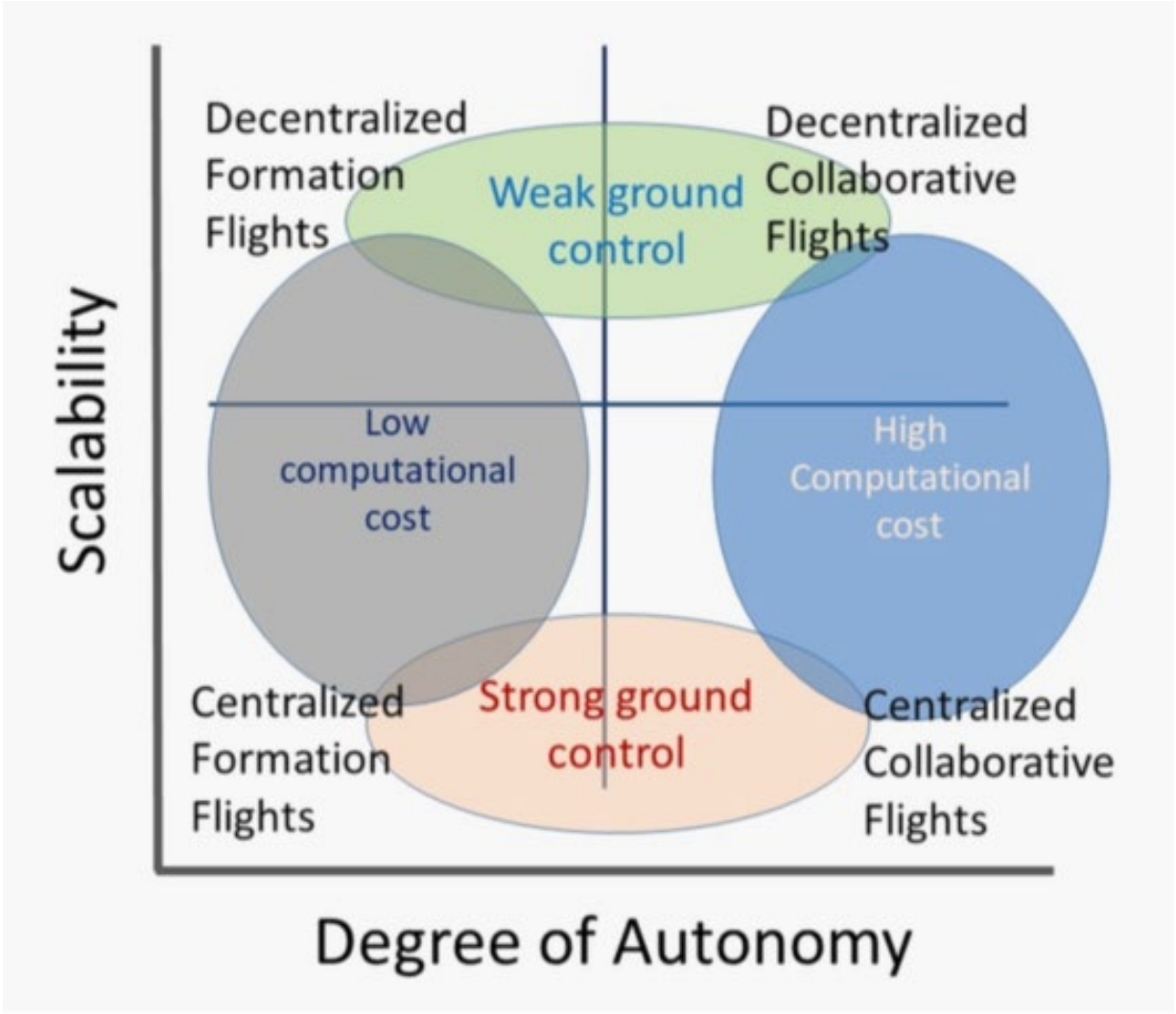
2016 Campaign Field Trials

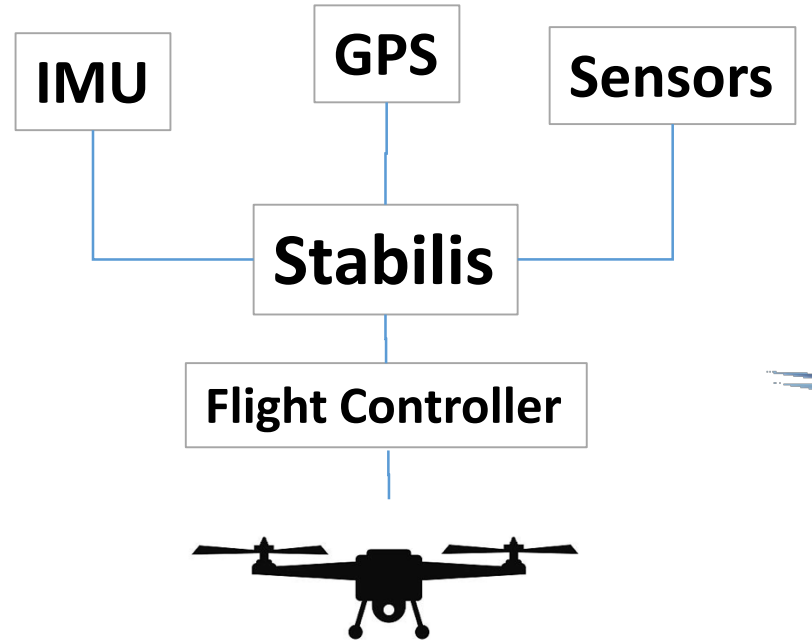


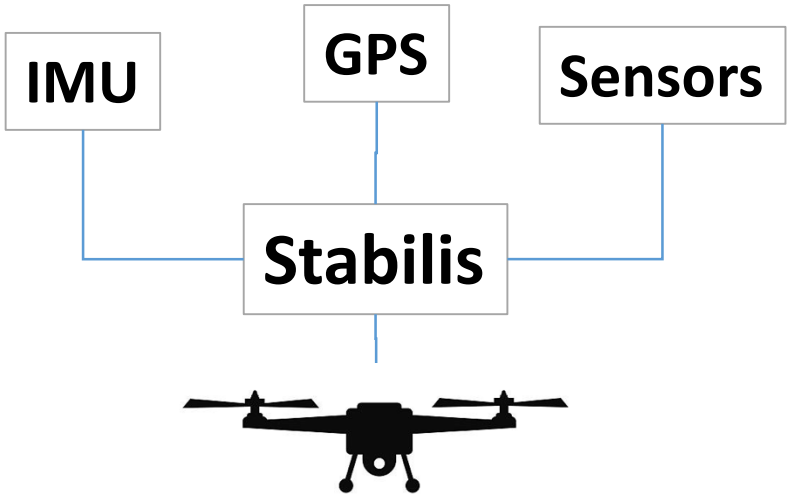




Autonomy Approaches

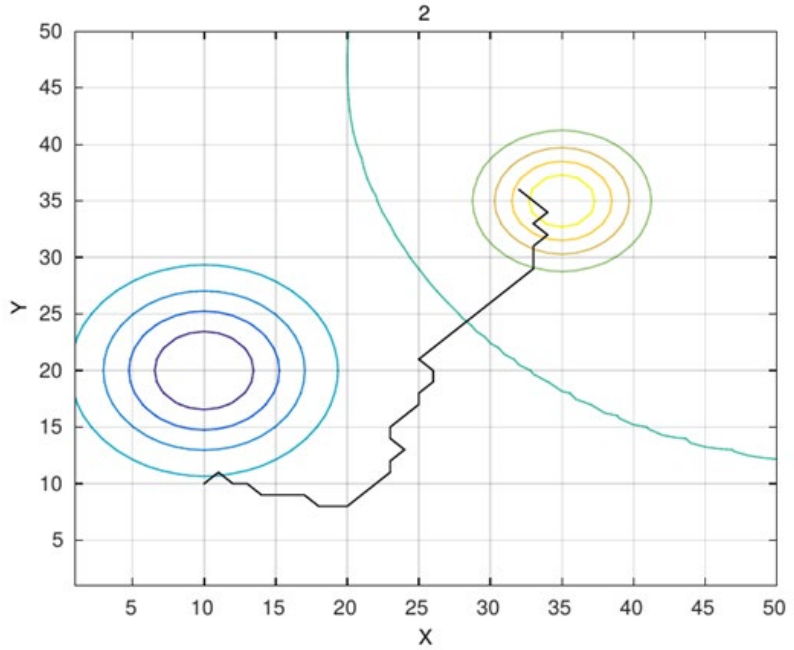






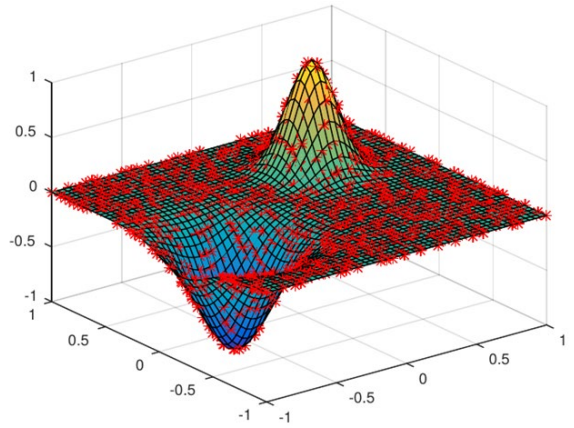
Measurement Driven Autonomy

- Derive path based upon sensor data and mission goals (e.g., scalar concentration)
- GPS and/or data driven navigation and control, with onboard real-time path planning for optimal mission execution.
- Optimal path generated by data from sensor input
- Data driven navigation available in GPS-denied applications
- Planner is formulated as a Markov Decision Process(MDP), which generates actions (e.g., turn, ascend, loiter) from a particular state

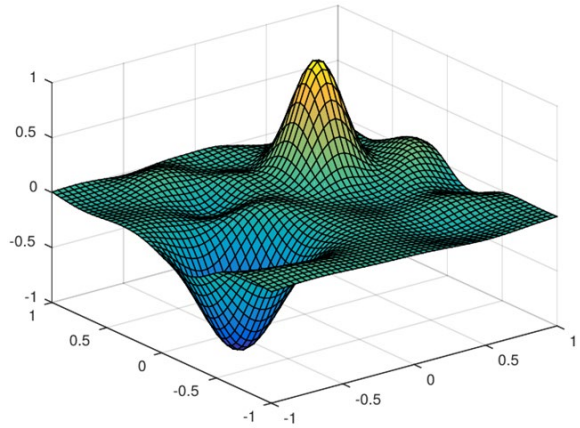


Optimal path generated from data

Raw Sensor Data

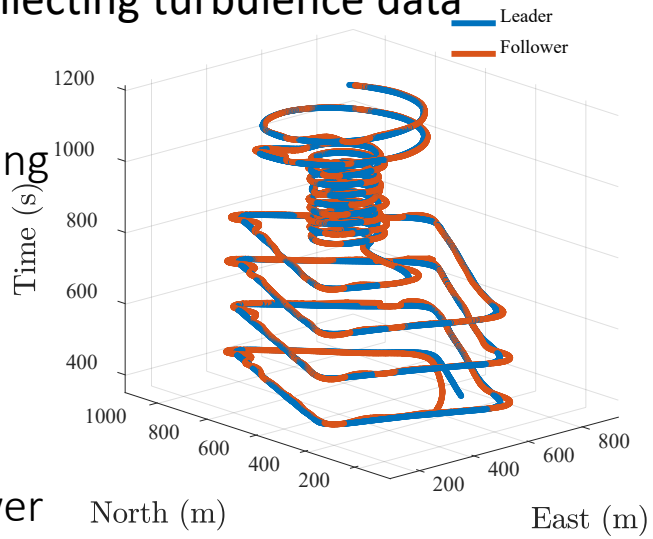


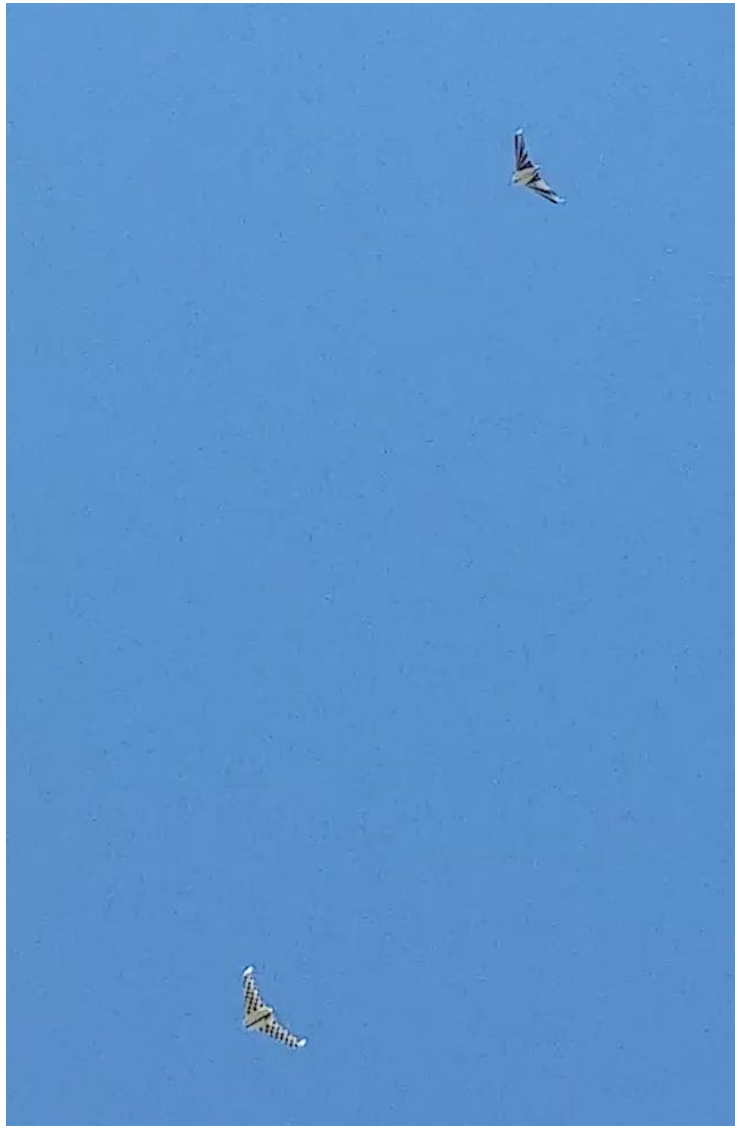
Estimated Distribution



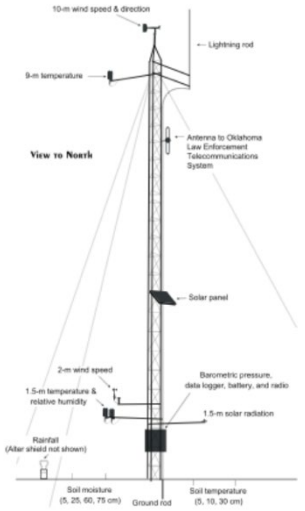
Fixed Wing Swarm Control

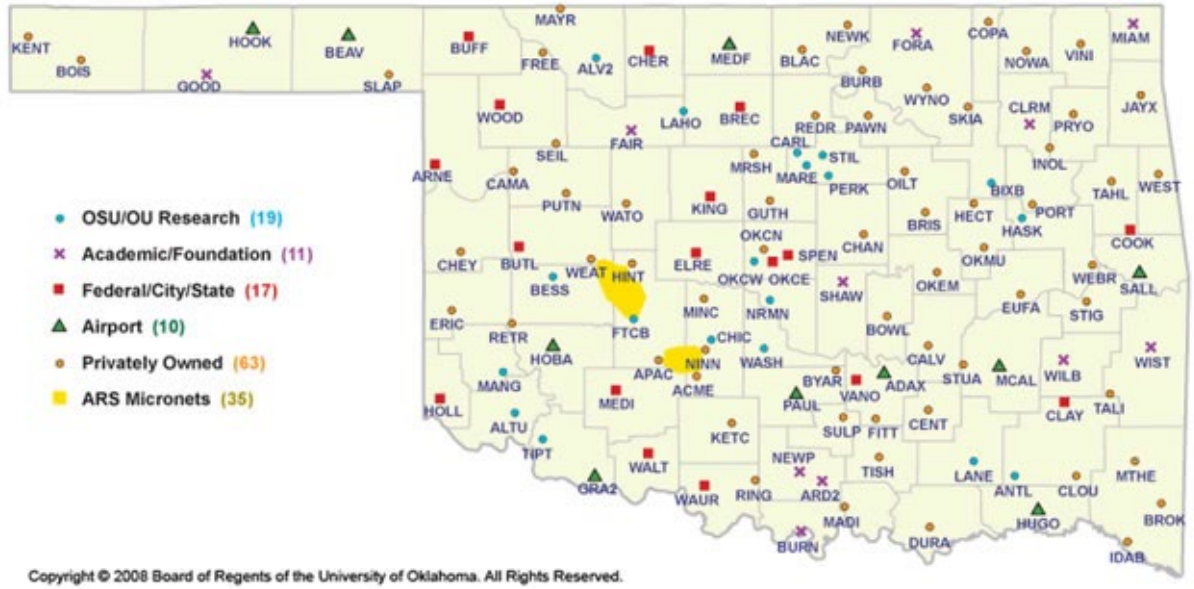
- **Goal:** Design and implement fixed-wing UAV leader-follower formation control algorithms, which are suitable for collecting turbulence data
- **Implementation:**
  - Pixhawk autopilot in FBWA communicating with Raspberry Pi 3
  - Wireless network over secure ad-hoc WiFi
- **Major Accomplishments:**
  - Successfully demonstrated leader-follower formation control with fixed-wing UAVs
  - Designed control algorithm for *n* agents
- **Ongoing Work:**
  - Controller tuning (e.g., improved heading control)
  - Experiments with more than 2 UAVs
  - Streamline for field operations





CERC Testbed Goal – 3D Mesonet





V. Natalie

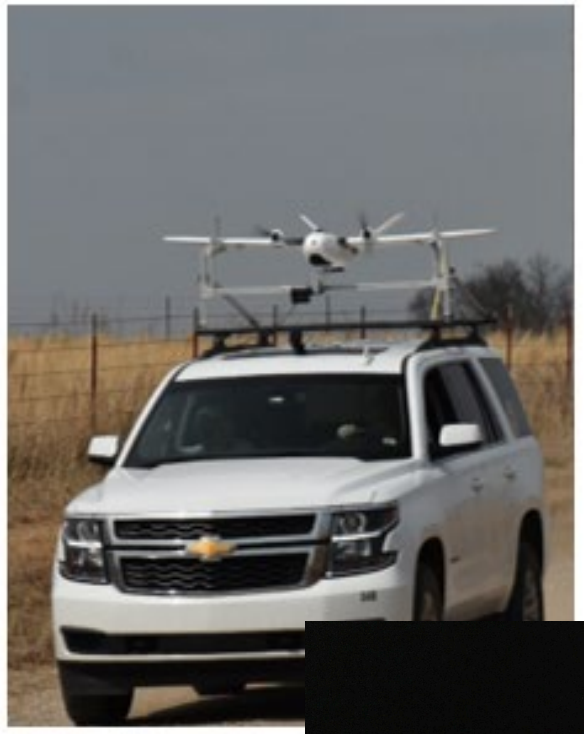
CLOUD-MAP.org

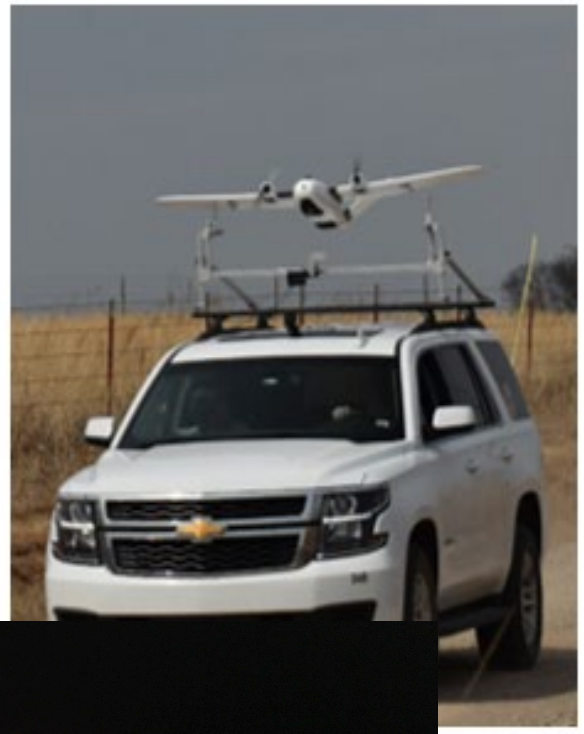
Data sharing site for the CLOUD-MAP community; **cloud-map.org**

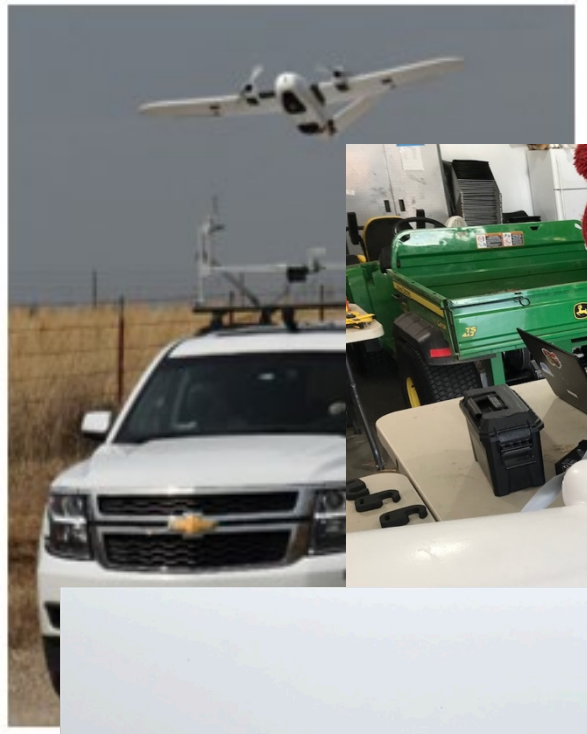
NSF reports and Presentations from the 2019 CLOUD-MAP Symposium

Regular updates at www.facebook.com/uasweather/ and @uasweather

Benefits of COTS







The Perils of COTS


Pro-Tronik

CERC – Center for Precision Meteorology

University of Nebraska Lincoln

The University of Oklahoma

Oklahoma State University

University of Kentucky

University of Colorado

Prairie View A&M