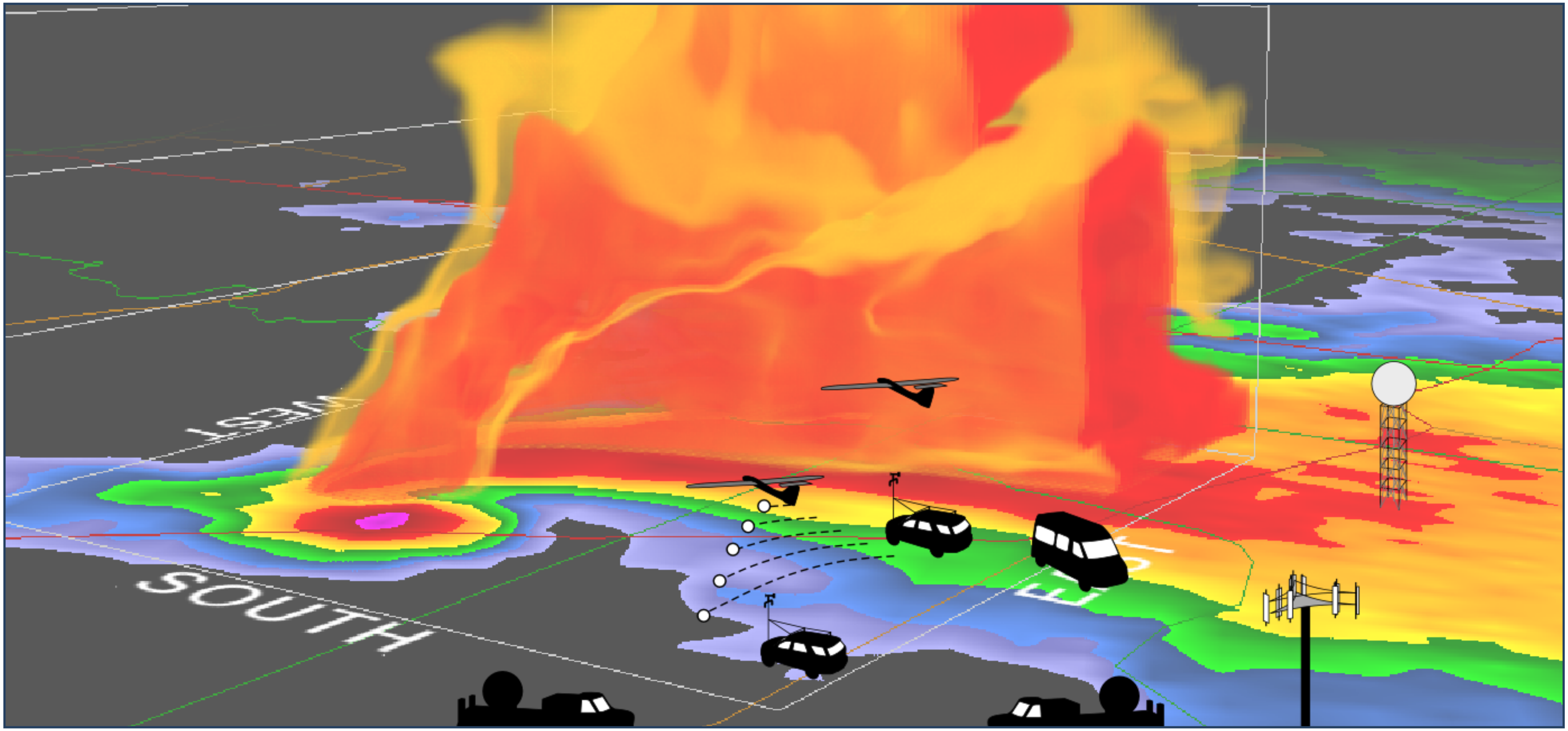
Targeted Observation of Severe Local Storms Using Aerial Robots



Roger Laurence, University of Colorado

Eric Frew and Brian Argrow, University of Colorado

Adam Houston, University of Nebraska

Chris Weiss, Texas Tech University

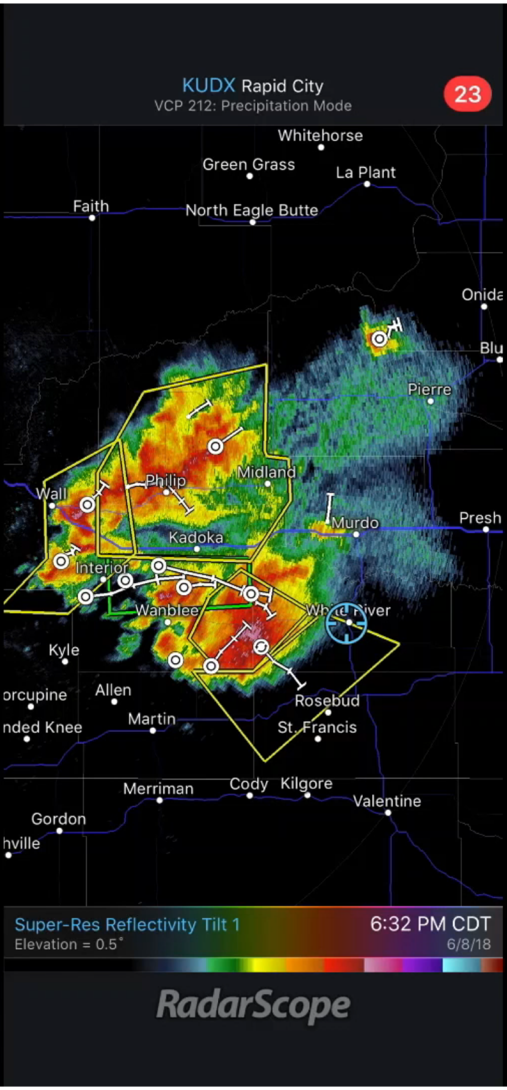
Volkan Isler, University of Minnesota

Dezhen Song, Texas A&M University

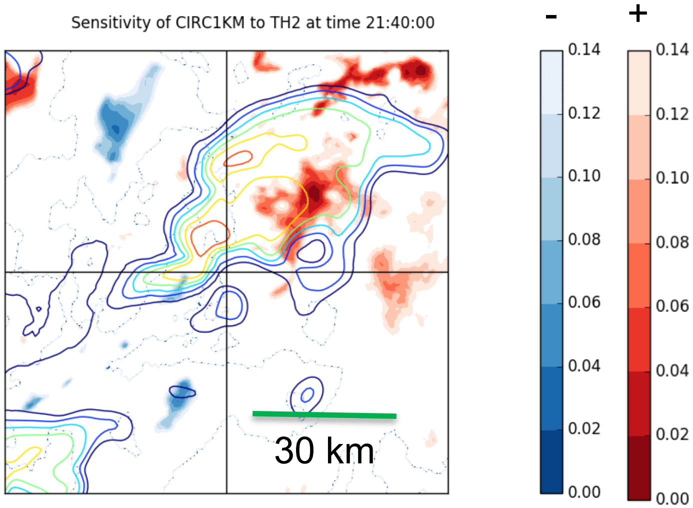
Be Boulder.

University of Colorado **Boulder**

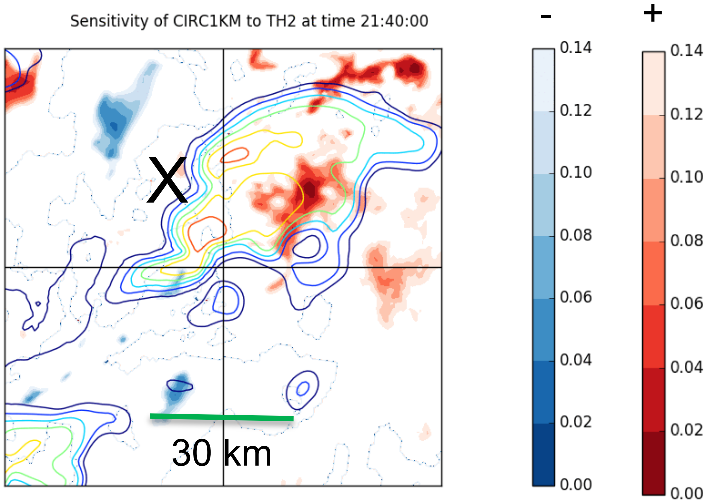
Severe Local Storm Intercepts



Targeting with Numerical Ensemble Sensitivity Analysis

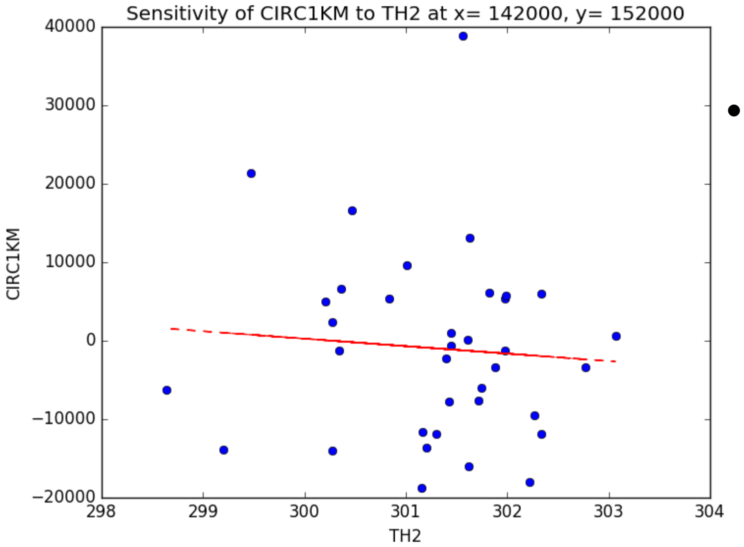


P-value of d/dt (~700 m AGL circulation) / virtual potential temperature regression (masked for $\alpha > 0.14$) at individual output times. Lead time = 20 min.



Running composite sensitivity

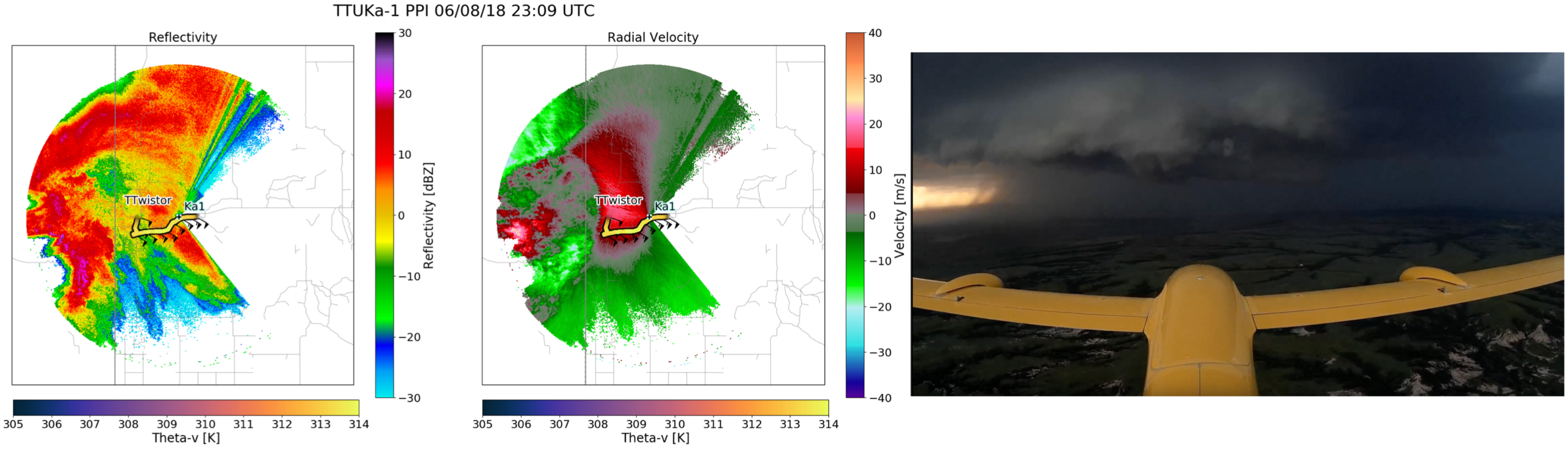
d/dt (C_{700m})



Scatterplot of composite regression relationship at position “X”

- High-resolution numerical weather model forecasts of past events used to identify key locations for UAS to sample to improve forecasts of tornadoes

Coordinated Severe Storm Intercepts with UAS and TTUKa Mobile Doppler Radar

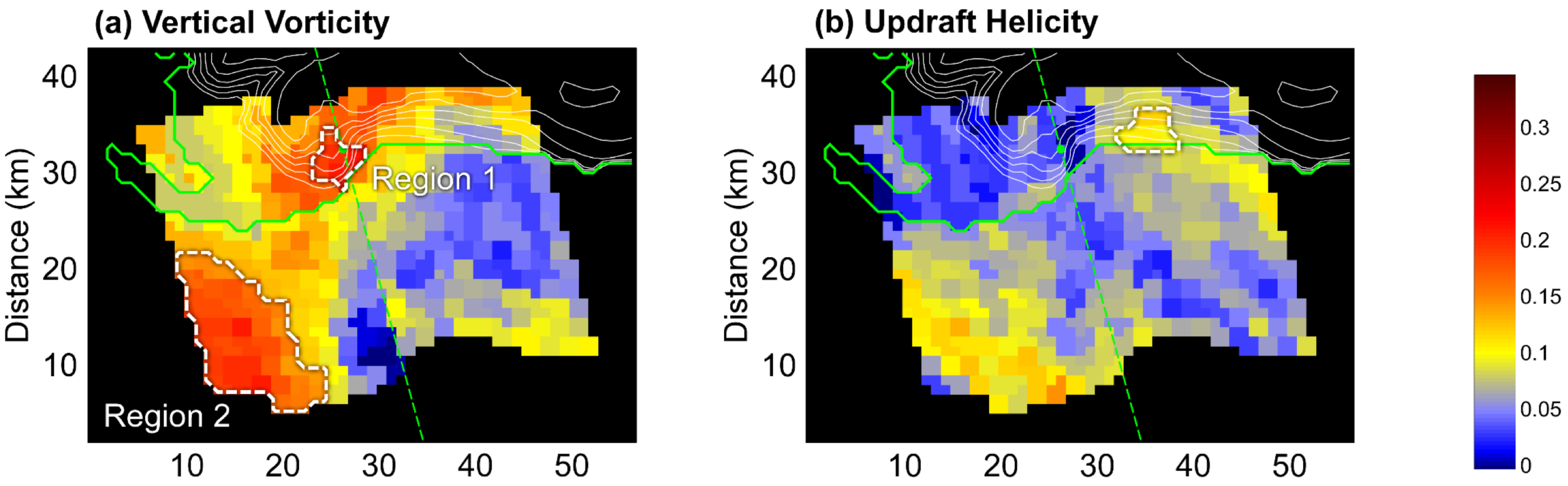


TTUKa 0.5 deg radar (left) reflectivity (dBZ) and (center) radial velocity (m s^{-1}), valid at 2309 UTC on 8 Jun 2018. Track of TTwistor is overlaid with flight-level winds and virtual potential temperature (shaded, K, scale at bottom); (right) Photo from the TTwistor aircraft during the deployment.

- Successful intercept of a supercell thunderstorm in South Dakota on 8 Jun 2018
- UAS flight paths guided by targeting information gleaned from (offline) numerical model analysis
- TTwistor gathers data on key 3-D gradients in air density relevant to developing tornadoes

Storm-Scale Ensemble Sensitivity Analysis

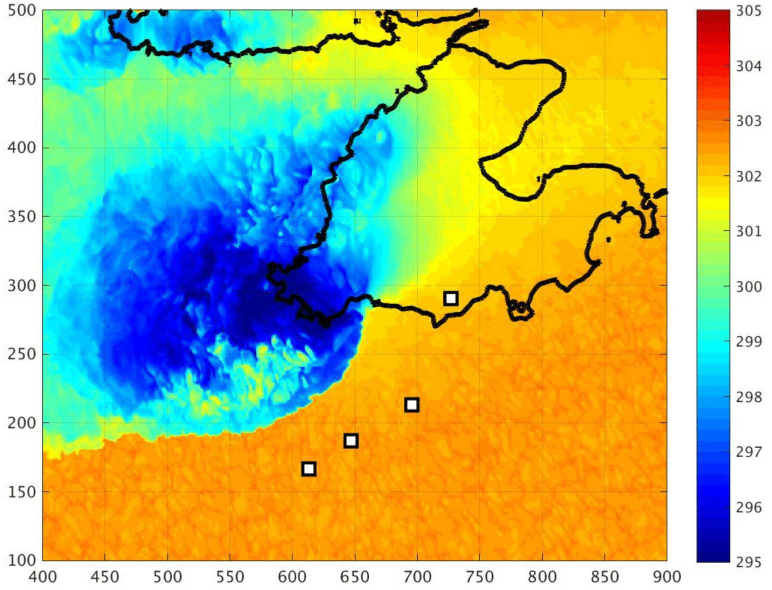
- Storm-scale ESA experiments have been completed (**Limpert and Houston 2018**)
- This work features the following innovations:
  - No prior work has implemented ESA on the storm scale
  - Sensitivity is evaluated based on multivariate and not single-variate statistics
- Coherent regions of sensitivity highlight areas where targeted observations may have value
- Inherent non-linearity and auto-correlation produce large uncertainties



Severe-storm Targeted Observation and Robotic Monitoring (STORM)

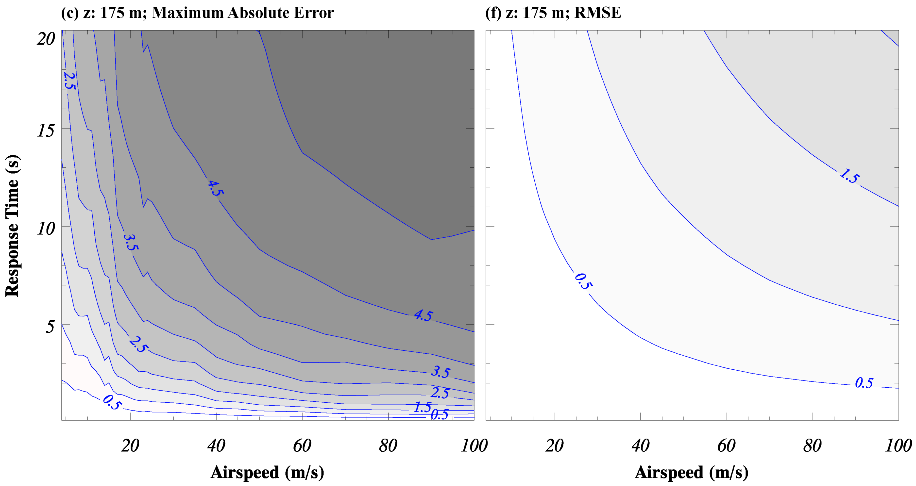
Observing System Simulation Experiments

- The nature run (from which synthetic observations will be derived) has been completed.
- The aircraft model (for use in the nature run) has been developed and tested.
- The data assimilation component will capitalize on a nascent collaboration with the NOAA National Severe Storms Laboratory.



UAS Airspeed and Sensor Response Effect on Sampled Data

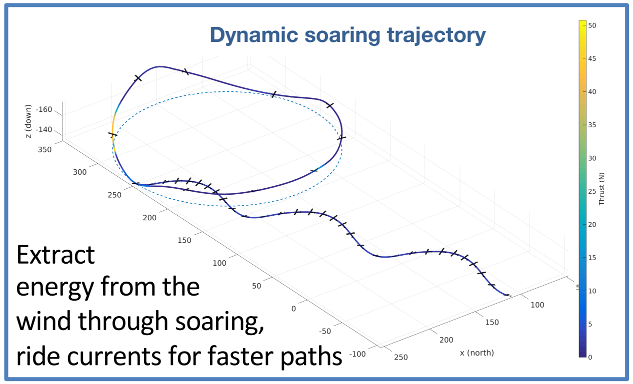
- In this work we investigated the relationship between sensor response, airspeed, and the time scales over which atmospheric boundary layer phenomena (i.e., thermals and density currents) evolve (**Houston and Keeler 2018**).
- The results offer specific guidance for UAS users who aim to observe common phenomena in the PBL.
- This grant supported the development of atmospheric simulations utilized in this study.



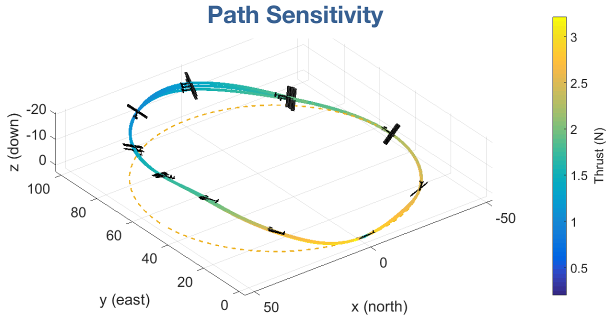
Co-Optimization of Energy, Sensing, and Communication for Targeted Observation

Energy: Autonomous Soaring in Wind Shear and Wind Flow

$$\overbrace{\dot{e}_a}^{\text{Energy rate}} = \underbrace{-V_a\frac{D}{m}}_{\text{Drag}} + \underbrace{V_a\frac{T}{m}}_{\text{Thrust}} - \underbrace{gw_z}_{\text{Static Soaring}} - \underbrace{\begin{pmatrix}\cos\gamma_a\cos\chi_a\\ \cos\gamma_a\sin\chi_a\\ -\sin\gamma_a\end{pmatrix}\begin{bmatrix}\frac{\partial w_x}{\partial x} & \frac{\partial w_x}{\partial y} & \frac{\partial w_x}{\partial z}\\ \frac{\partial w_y}{\partial x} & \frac{\partial w_y}{\partial y} & \frac{\partial w_y}{\partial z}\\ \frac{\partial w_z}{\partial x} & \frac{\partial w_z}{\partial y} & \frac{\partial w_z}{\partial z}\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix}}_{\text{Dynamic Soaring}}$$

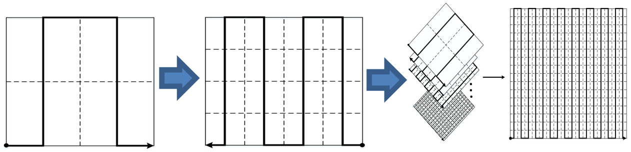


Extract energy from the wind through soaring, ride currents for faster paths



Characterizing robustness of dynamic soaring to aircraft drag polar, assessing limits of feedback to recover performance

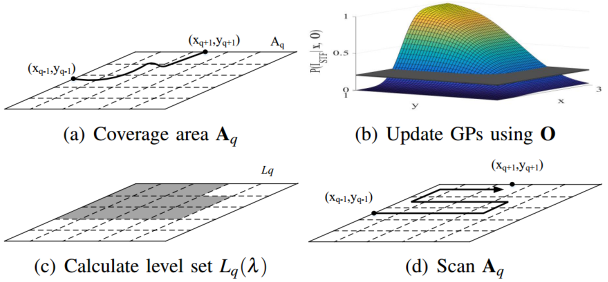
Sensing: Probabilistic Search and Coverage for Sparse Target Fields



Lemma 1 (**Global Search**): The expected search trajectory length $E(L_G)$ has the following upper bound

$$E(L_G) = \frac{(4A+10B)(A-B)}{3B},$$

where $A = (1-\alpha)a$, $B = L_{xmin} + 2d_s$ and α is the missing probability to detect the target field.



(a) Coverage area $\mathbf{A}_q$

(b) Update GPs using $\mathbf{O}$

(c) Calculate level set $L_q(\lambda)$

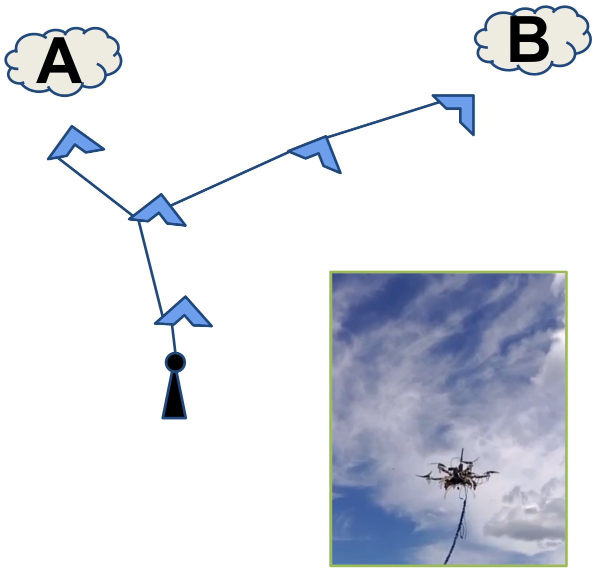
(d) Scan $\mathbf{A}_q$

Lemma 2 (**Local Coverage**): with $1-\tau$ probability, $\mathbf{P(I_{STF})}$ which is the unconditional probability that a lattice point in A_q belongs to STF has the following lower bound $\mathbf{B}_q^-$

$$P(I_{STF}) \geq B_q^-$$
$$= \inf_{\eta>0}\left\{E\left(P(I_{STF}|\mathbf{x},\mathbf{O}_L)\right) - \frac{\eta}{2} - \frac{1}{l_{\max}\eta}\log\frac{1}{\tau}\right\},$$

Where $\tau \in (0,1)$ is a chosen small number.

Communication: Connectivity Aware Tracking and Routing

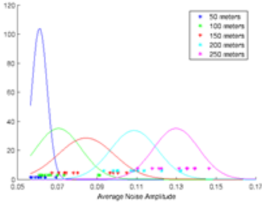


Received Signal Characteristics

Yellow stars denote the locations of the bear collar. 10 measurements were taken from each location. Each measurement take 30 sec.

Significant overlaps between these distributions

Hard to classify range given a measurement



Signal values for all the measurements taken from varying distances along with Gaussian distributions fitted to the six varying ranges.

Improved Trajectory Optimization Performance for Dynamic Soaring

Differential flatness

+

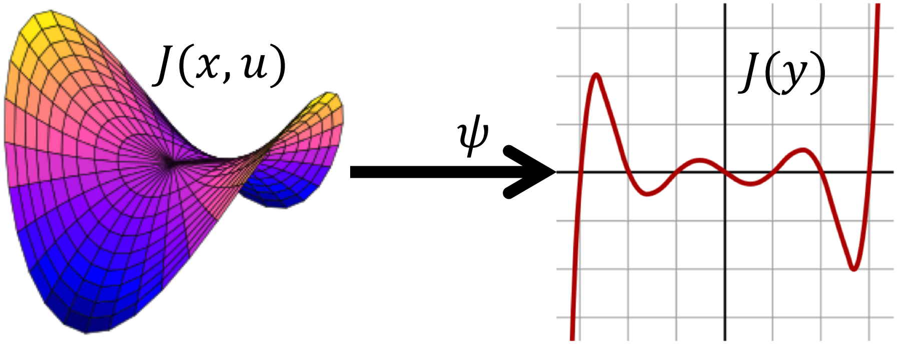
Given a nonlinear system

$$\dot{x}(t) = f(x(t), u(t)), x(t_0) = x_0, x(t) \in \mathbb{R}^n, u(t) \in \mathbb{R}^m$$

There may exist a **flat output** $y(t) \in \mathbb{R}^m$ where

$$y(t) = \psi\left(x(t), u(t), \dot{u}(t), \ddot{u}(t), \dots, u^{(\alpha)}(t)\right)$$

$$\left(x(t), u(t)\right) = \varphi\left(y(t), \dot{y}(t), \ddot{y}(t), \dots, y^{(\beta)}(t)\right)$$



Andrew B. Mills, Daniel Kim, and Eric W. Frew. “Energy-Aware Aircraft Trajectory Generation Using Pseudospectral Methods with Differential Flatness”. *1st IEEE Conference on Control Technology and Applications*. Kohala Coast, Hawaii, Aug. 27-30, 2017.

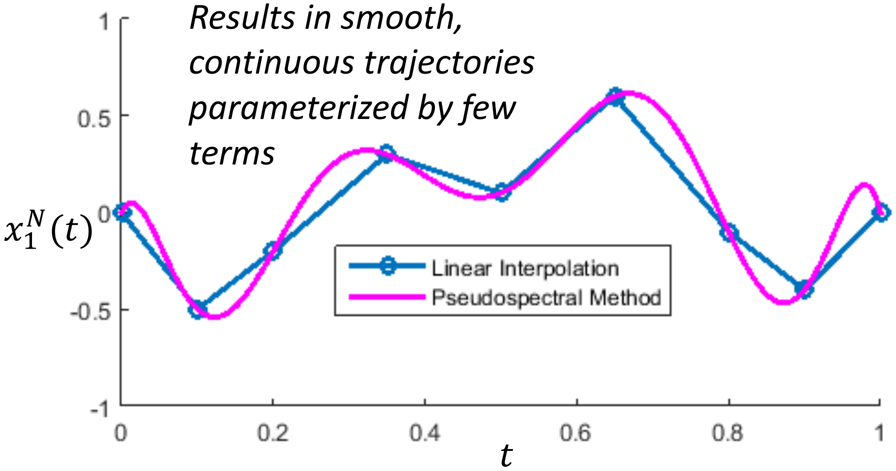
Pseudospectral methods

Discretize x(t) and u(t) using a **polynomial discretization**:

$$x(t) \approx x^N(t) = \sum_{i=0}^{N} x_i \phi_i(t)$$

$$u(t) \approx u^N(t) = \sum_{i=0}^{N} u_i \phi_i(t)$$

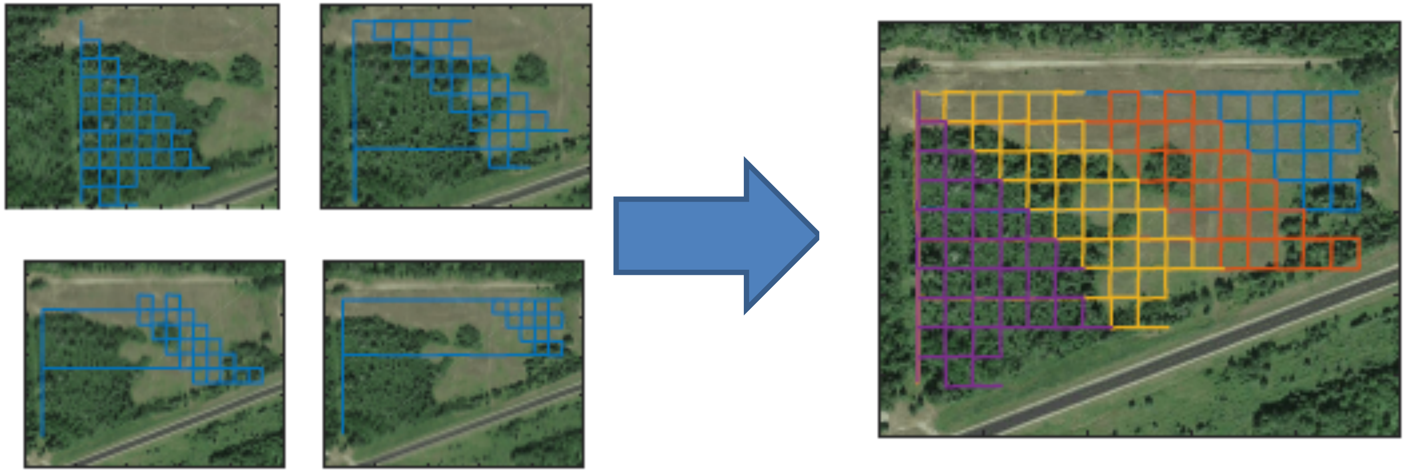
where $\phi_i(t)$ is the i^{th} Lagrange interpolating polynomial of order N.



Results in smooth, continuous trajectories parameterized by few terms

Energy Aware Planning

Given a (large) coverage area
with a charging station, and
a bound on maximum distance
traveled,
what is the quickest way to cover
the area
(including recharging stops)?



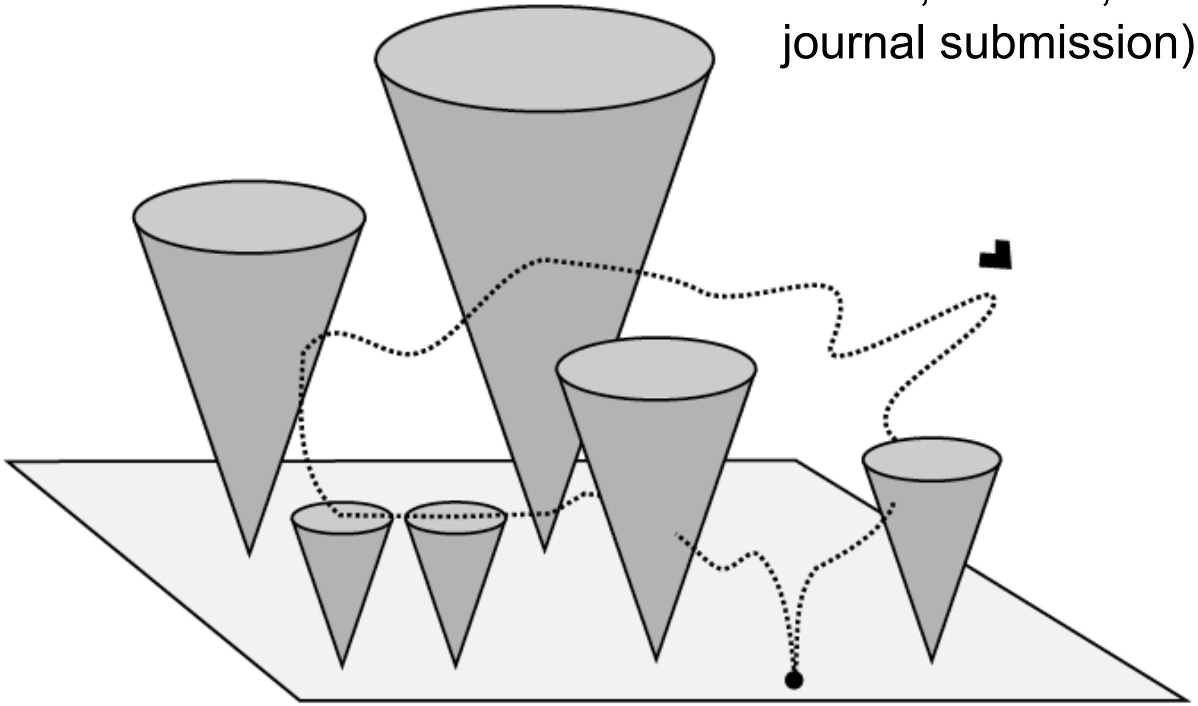
Actual UAV paths,
Total area:
58800m2

Wei, Isler, ICRA’18, ICAPS’28, IJRR submission

Sensing Aware Planning

Cone height ➡ desired resolution
Cone angle ➡ camera FOV
What is the optimal path to visit a given set of cones?

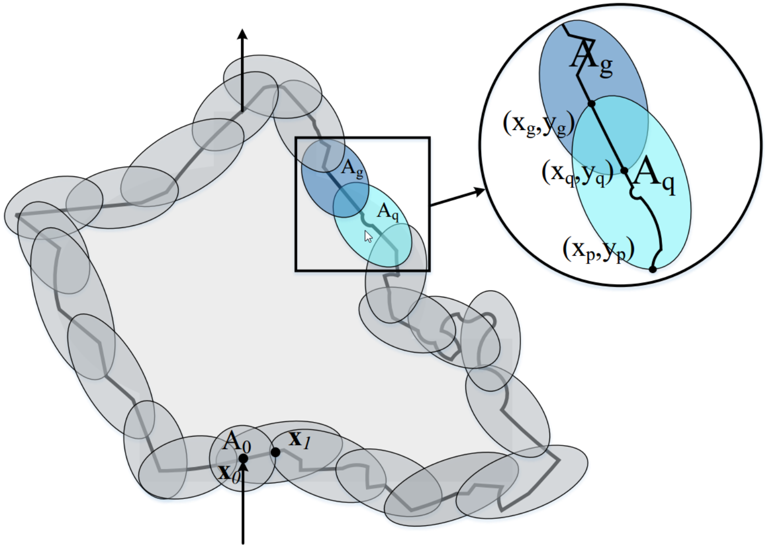
Plonski, Isler (WAFR 2016, IJRR)
Stefas, Plonski, Isler (ICRA 2018, journal submission)



Boundary Traversing for Storm Fields as Unknown Target Fields

Challenges

- Unknown field dispersion function
- Large perception uncertainties
- Limited sensing range
- Moving fields



Problem definition

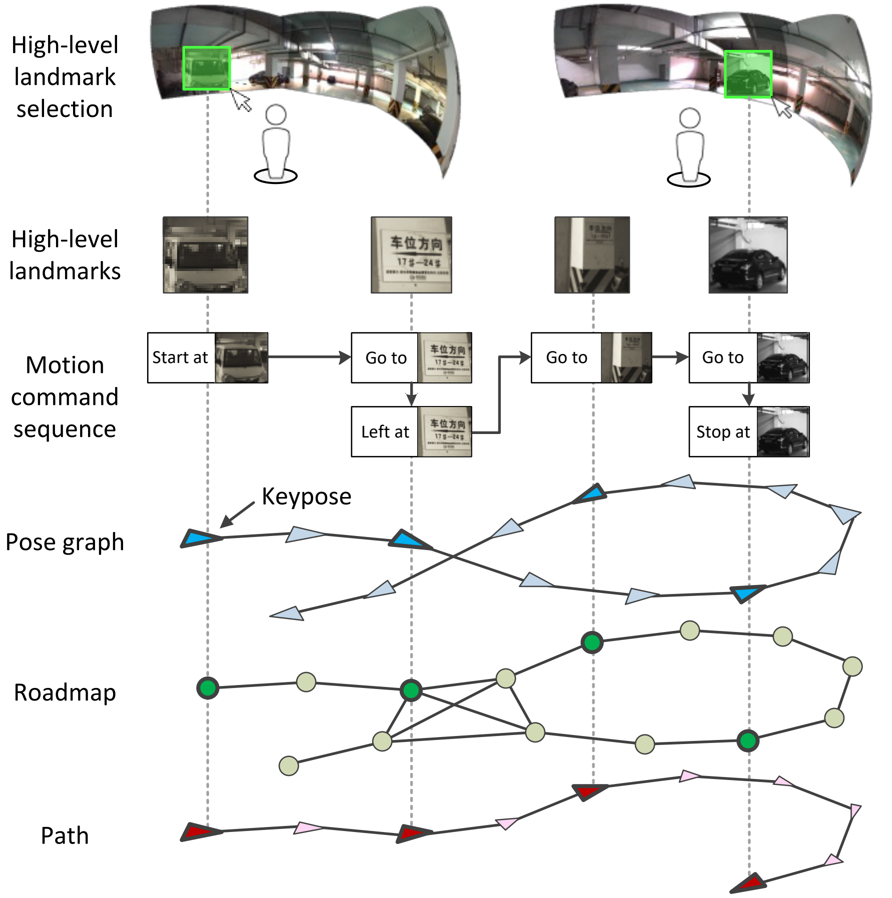
- Given the observation set, plan trajectory to guide robot to generate ellipses to cover the UTF’s boundary with the quality metric satisfied.

Binbin Li and Dezhen Song, *Probabilistic Boundary Coverage for Unknown Target Fields with Large Perception Uncertainty and Limited Sensing Range,* International Symposium on Robotics Research (ISRR), Puerto Varas, Chile, Dec. 11-14, 2017

Co-Robot Navigation in Unknown Target Fields

Problem definition

- Input:
    - Human inputs using high-level landmarks including semantic commands (e.g. avoid object 1, or patrol between object 2 and object 3).
    - Low level landmarks from SLAM
- Output:
    - A trajectory in SE(3) for robot to execute.



Joseph Lee, Yan Lu, Yiliang Xu, Dezhen Song, *Visual Programming for Mobile Robot Navigation Using High-level Landmarks*, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, Korea, Oct. 9-14, 2016

Air-Launched Drifter System

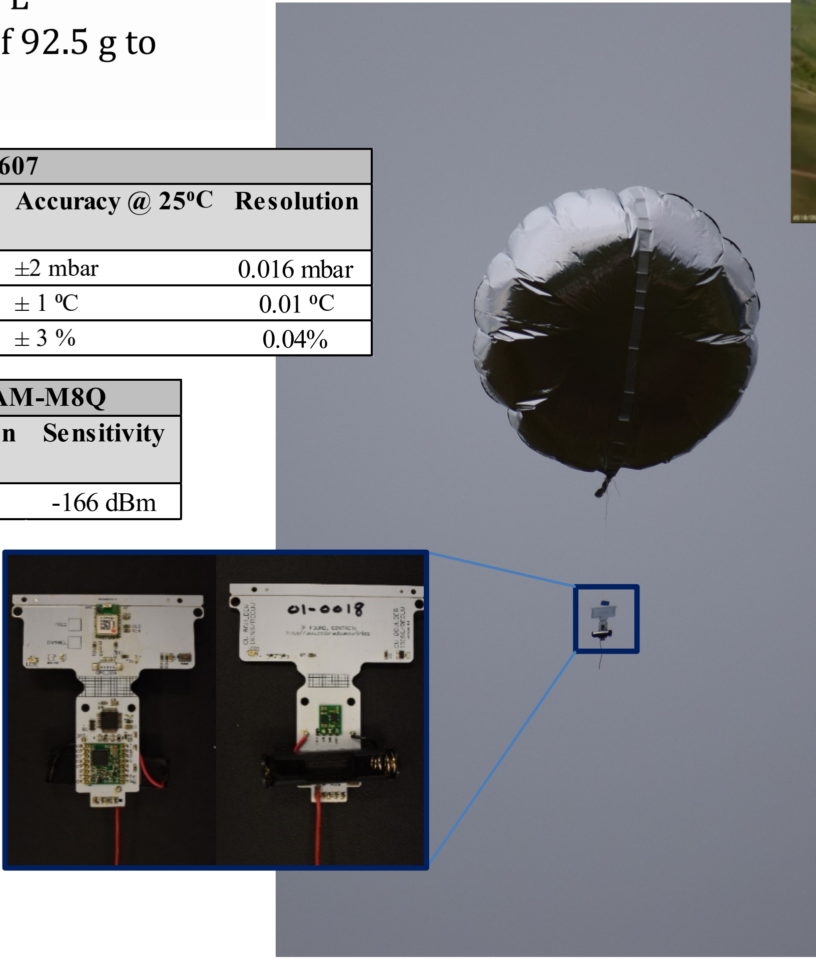
Super-pressure Balloon

- Material: 30 μm Polyethylene Foil
- Helium Capacity: 125 L
- Can carry a payload of 92.5 g to 10,000ft

PTH Sensor: MS8607			
	Max. Operating Range	**Accuracy @ 25°C**	**Resolution**
Pressure	10-2000 mbar	±2 mbar	0.016 mbar
Temperature	-40 - 80 °C	± 1 °C	0.01 °C
Relative Humidity	0 - 100 %	± 3 %	0.04%

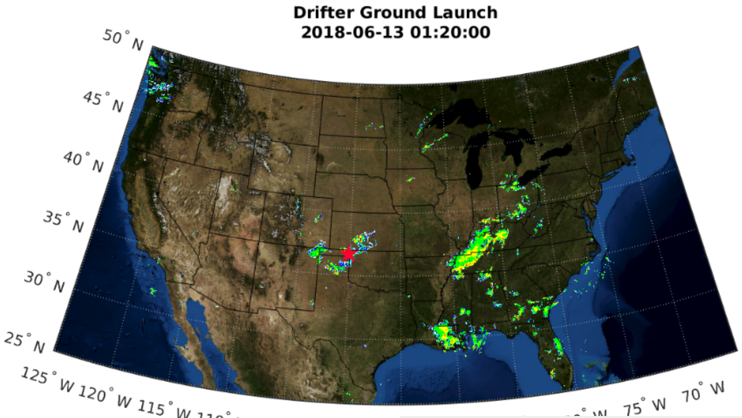
GPS Module: ublox CAM-M8Q		
Horizontal Position Accuracy	**Max. Navigation Update Rate**	**Sensitivity**
2.5 m	10 Hz	-166 dBm

Component	Mass (g)
1.5V Battery and Holder	10.5
PCB	6
Radio	2
GPS Module	0.5
Microcontroller	0.01
PTH Sensor	0.01
Miscellaneous Parts	1
Total:	**~ 20**



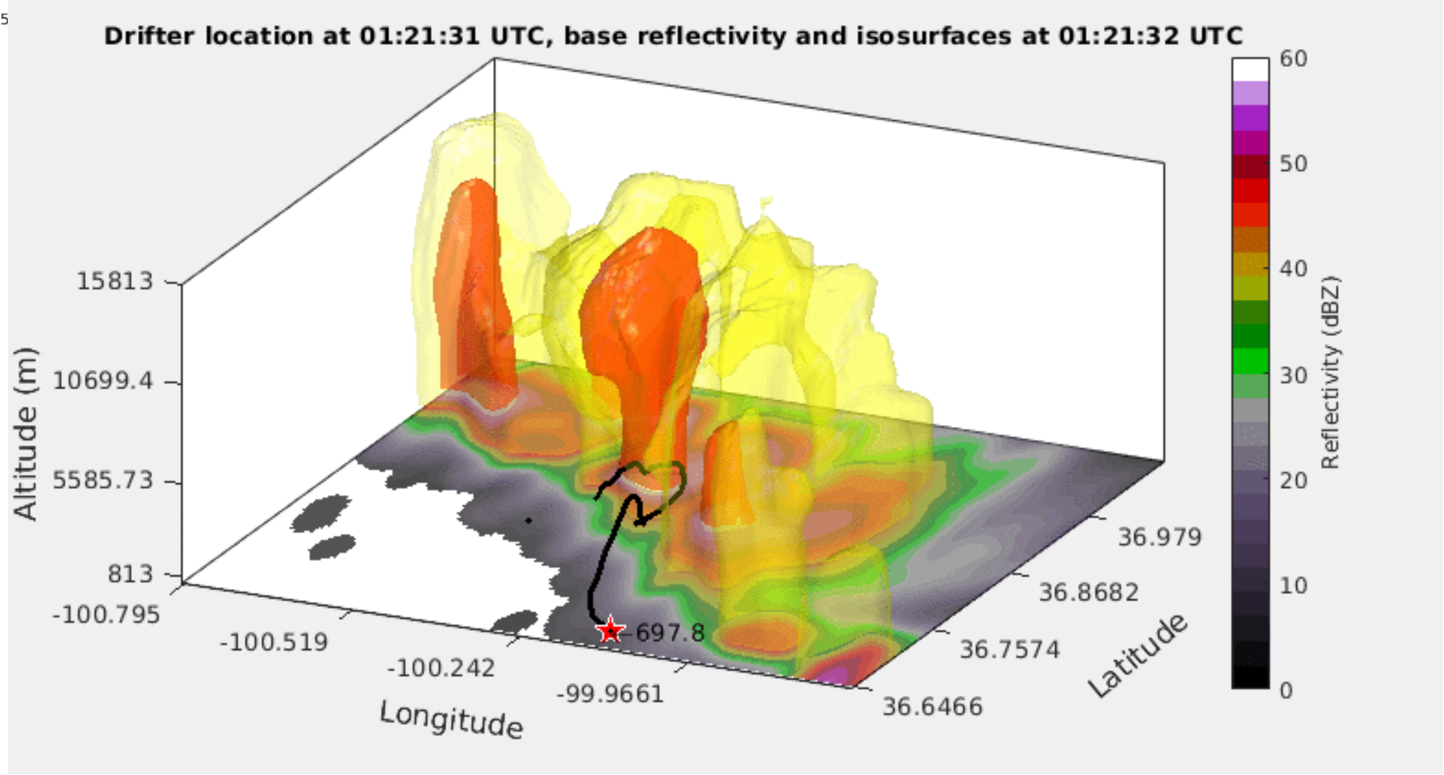
Aspect	Value
Empty Weight	18 lb
Max. Payload Capacity	15 lb
Wingspan	16 ft
Autopilot	Pixhawk
Max. Speed	90kts (~ 104 mph 46 m/s)
Loiter Speed	38 kts (~ 44 mph 20 m/s)
Endurance*	2-6 hrs

Supercell Verification



Drifter Ground Launch
2018-06-13 01:20:00

- June 12, 2018
- Storm located in Oklahoma panhandle
- Nexrad data from Dodge City, KS



Drifter location at 01:21:31 UTC, base reflectivity and isosurfaces at 01:21:32 UTC

Field Experiments

Successful storm intercept,
June 8, 2018, South Central SD

New Mobile UAS Research Collaboratory (MURC)
and CU Mistral aircraft for extended endurance

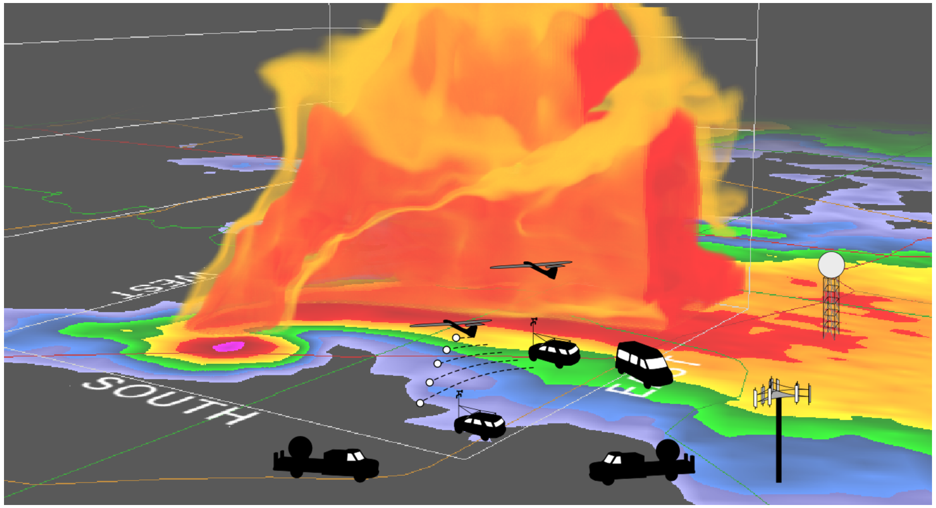
UMN Team

- Volkan Isler (UMN PI)
- Two partially supported PhD Students:
  - Nikolaos Stefas (sensing-aware planning; UAV Navigation)
  - Minghan Wei (energy-aware planning)
- Post-doc: Haluk Bayram (partial support)
- Undergraduate Student
  - Alan Koval (optimal paths for turning a corner with a Dubins car – ICRA submission!)

NRI: Collaborative Research: Targeted Observation of Severe Local Storms Using Aerial Robots

Texas A&M Team

- Dezhen Song (TAMU PI)
- 4 PhD Students:
    - Binbin Li (Algorithm Development – Storm field Tracking)
    - Joseph Lee (Algorithm and system development - Co-Robot navigation)
    - Chieh Zhou (Algorithm Development – Sparse method for fast optimization in graph)
    - Jasmine Zheng (Algorithm Development - Sensing)
- 1 MS Student:
    - Di Wang (experiment assistant)
- Undergraduate Student
    - Ankit Ramchandani (experiment assistant)



TTUKa Specs

Transmitter Frequency: ~34,860 MHz (λ=8.6 mm)
Transmit Power: 200 W peak, 100 W average
Transmitter Type: TWTA
Duty Cycle: up to 50%
Antenna Gain: 50 dB
Antenna Type: Cassegrain feed, epoxy reflector
Antenna Beamwidth: 0.33 deg
Polarization: Linear, horizontal
Waveguide: WR-28, pressurized
PRF: Variable, up to 20 KHz
Gate Spacing: 15 m
Receiver: MDS: -118 dBm
IF Frequency: 60 MHz
Pedestal: Orbit AL-4016
DSP: Vaisala/Sigmet RVP-9
Vehicle: Chevy C5500 Crewcab
Moments: Reflectivity, radial velocity, spectrum width

Severe-storm Targeted Observation and Robotic Monitoring (STORM)

Objectives and Description

- Autonomous **self-deploying aerial robotic systems (SDARS)** will enable new in-situ atmospheric science applications through targeted observation.
- SDARS is comprised of:
  - multiple fixed-wing unmanned aircraft,
  - deployable Lagrangian drifters,
  - mobile Doppler radar,
  - distributed computation nodes in the field and in the lab,
  - a net-centric middleware connecting the dispersed elements
  - autonomous decision-making that closes the loop between sensing in the field and online numerical weather prediction

Status and Approach

- Subsystem development and testing, including field deployments
- New effort focusing on atmospheric science application => add science goals into planning framework
- Deployable sensors to drift with wind to provide additional data along streamlines

Merit and Impact

Intellectual Merit	Broader Impact
In-situ wind measurement Onboard and cloud-based autonomy Deployable sensors Wind energy extraction Online trajectory optimization	Atmos. science, wind turbines, beyond PBL Safe, robust operation of UAS in the NAS Application-specific flight plan optimization