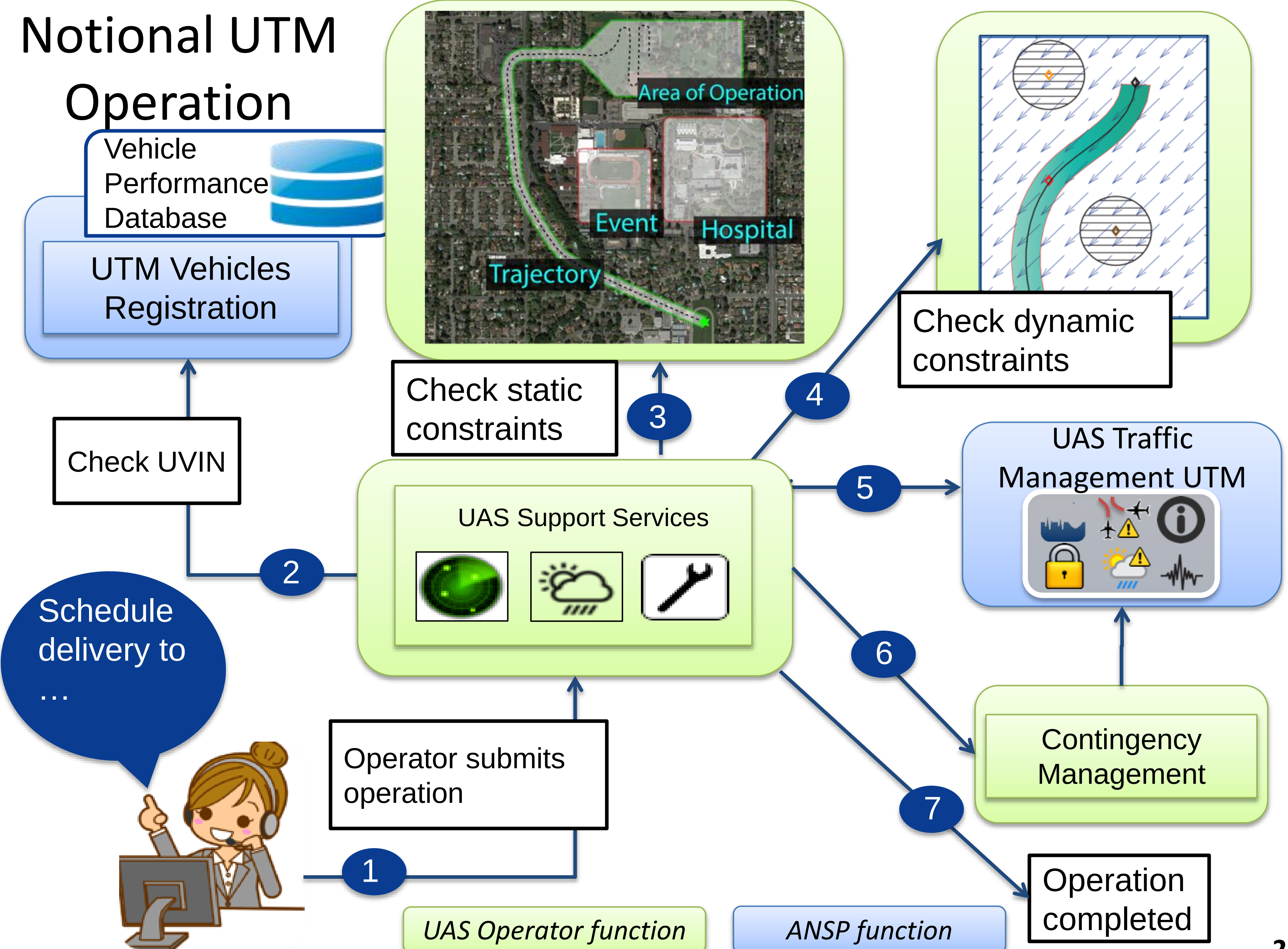
UTM Constraint Checking with Vehicle Trajectory

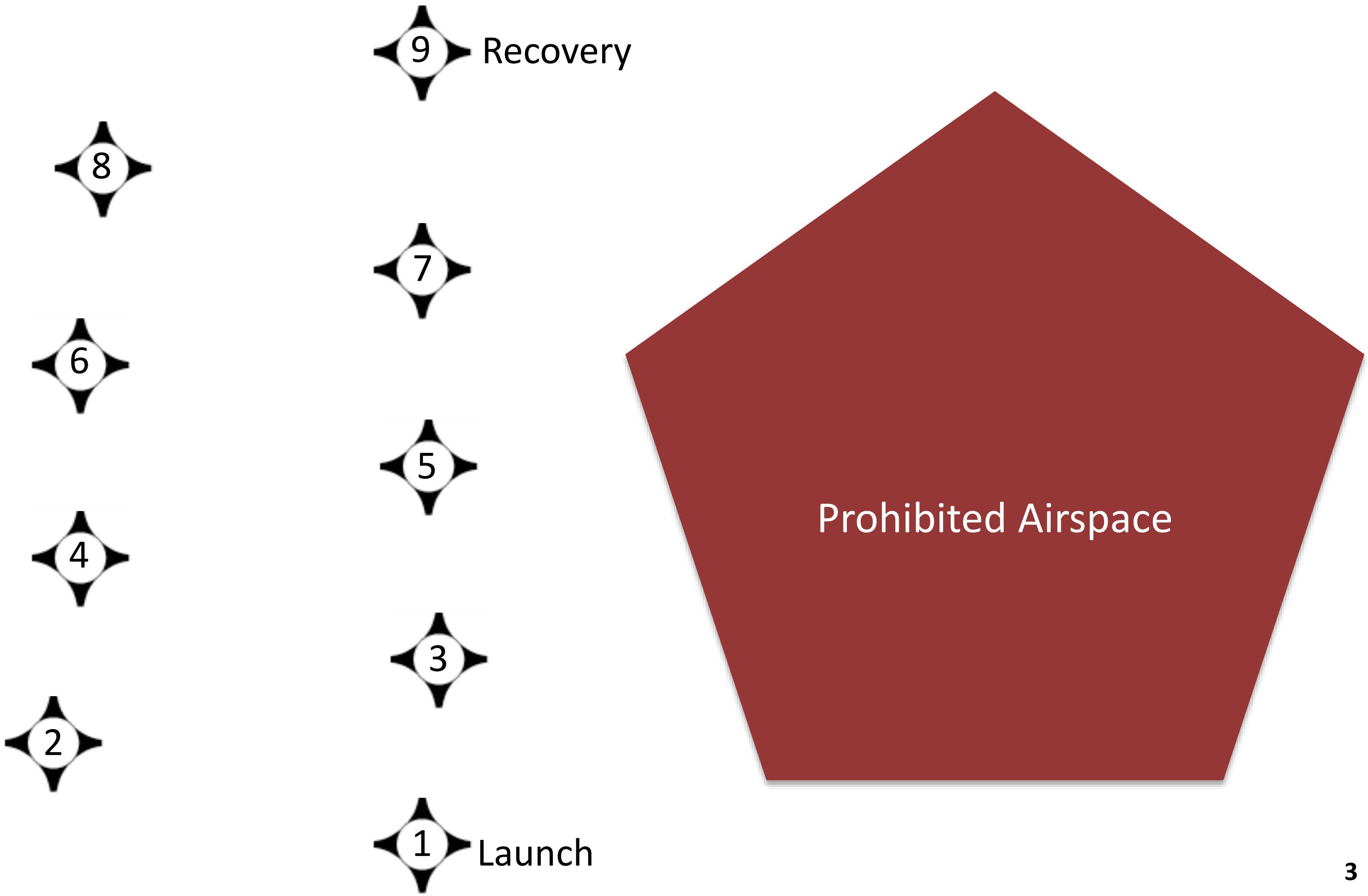
Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Weather Workshop, July 2016

Notional UTM Operation

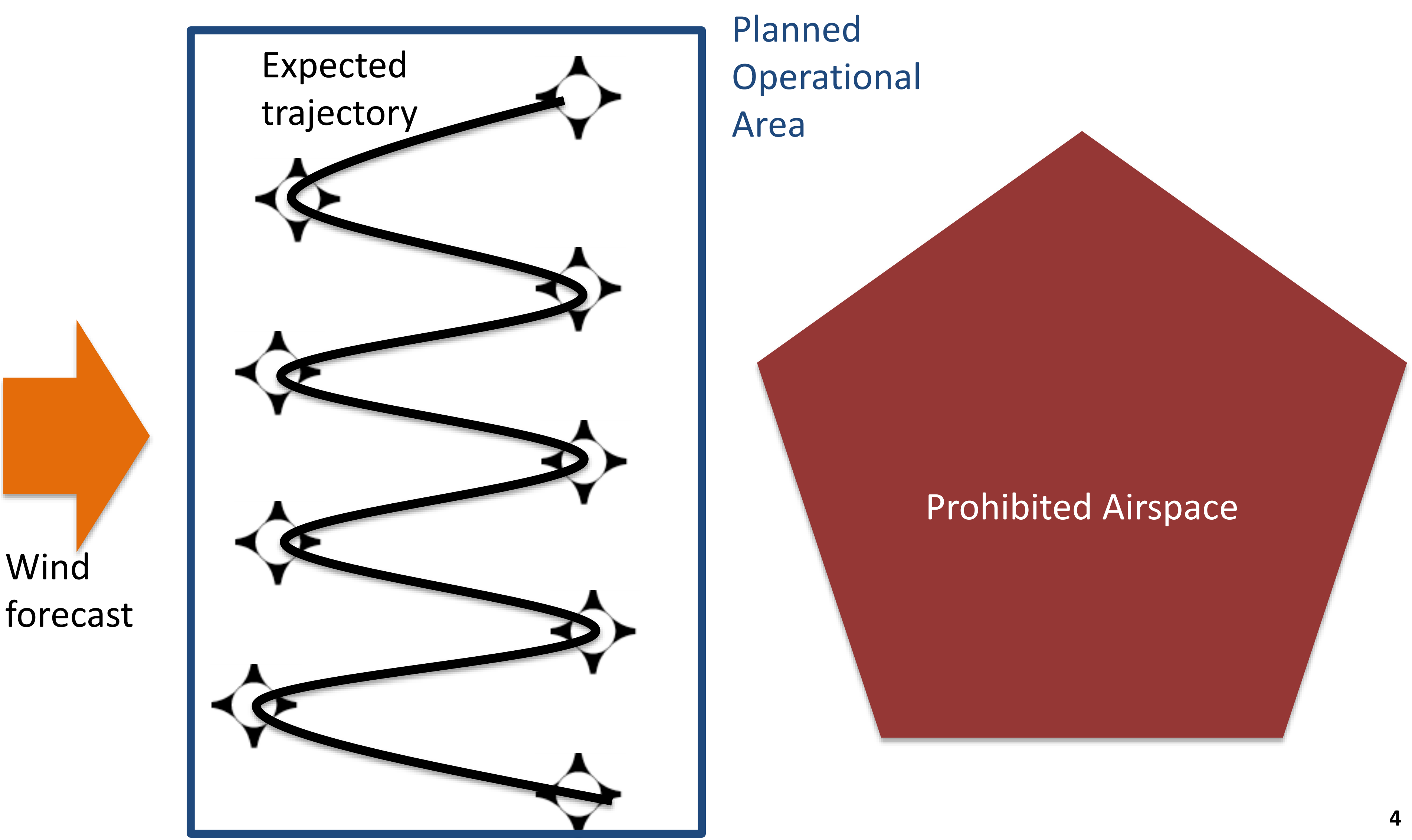


Constraint Check with Vehicle Performance

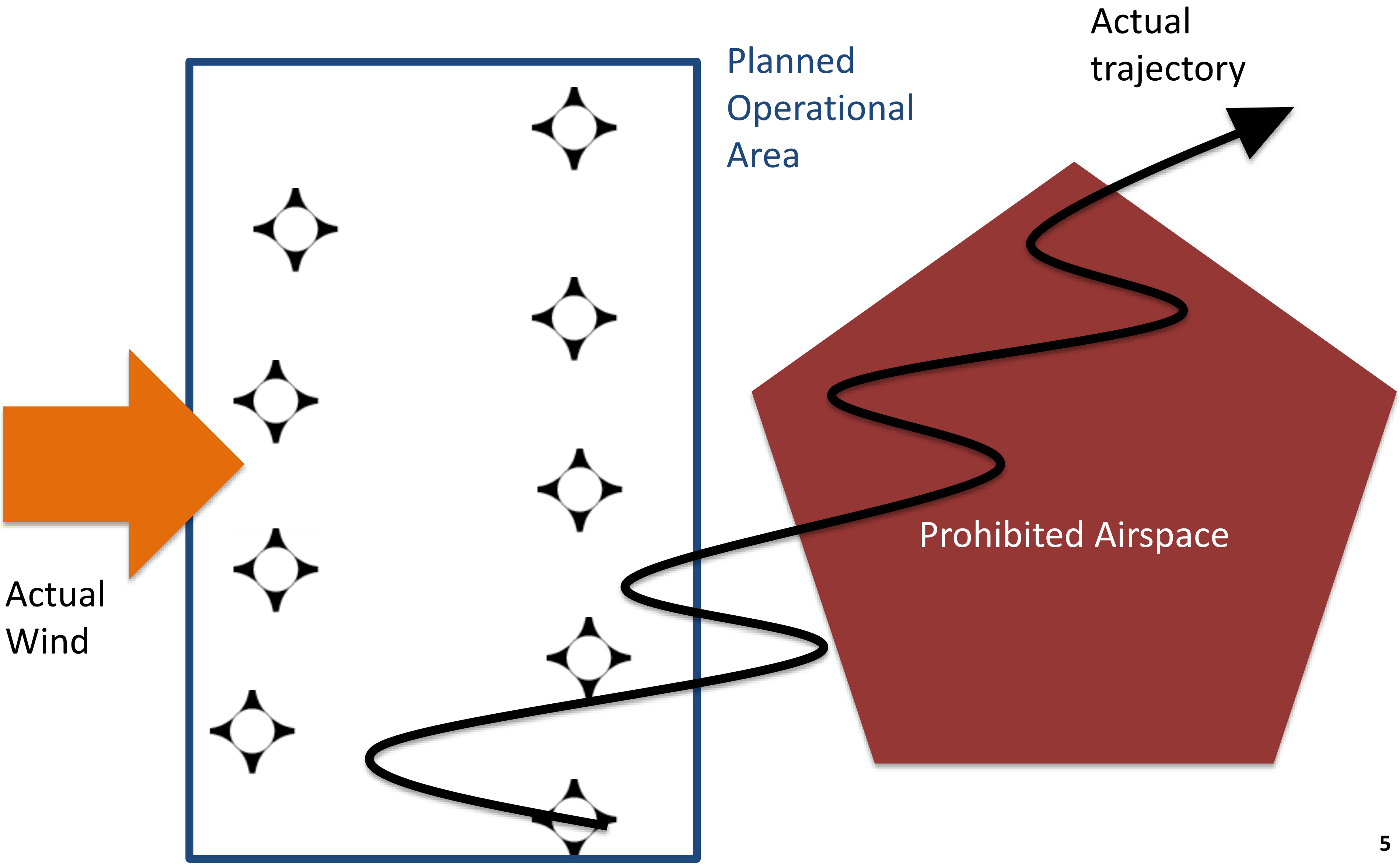
Example operation plan: Fly from waypoint 1 to waypoint 9 in sequence



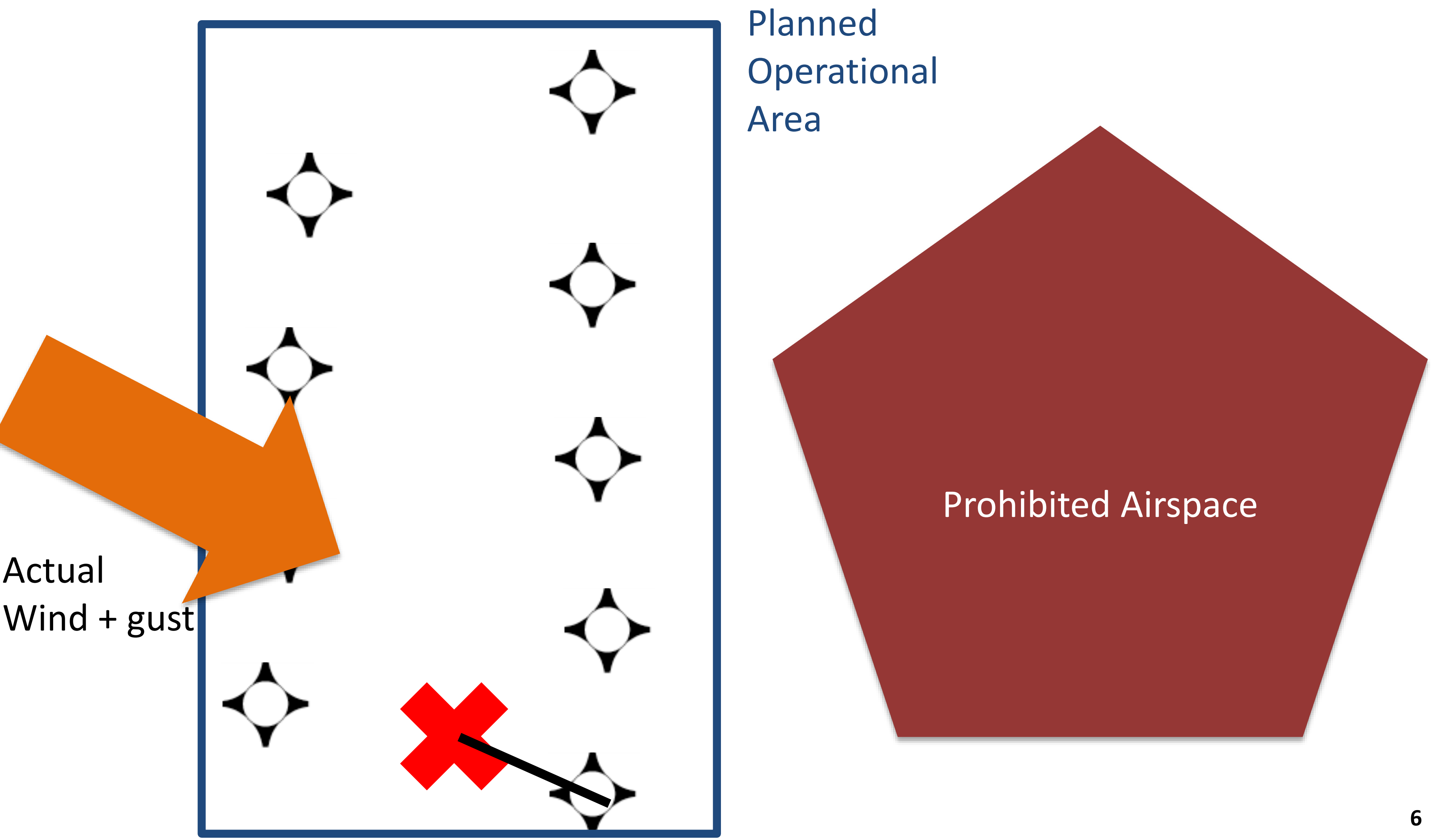
Expected Outcome



Potential Actual Outcome



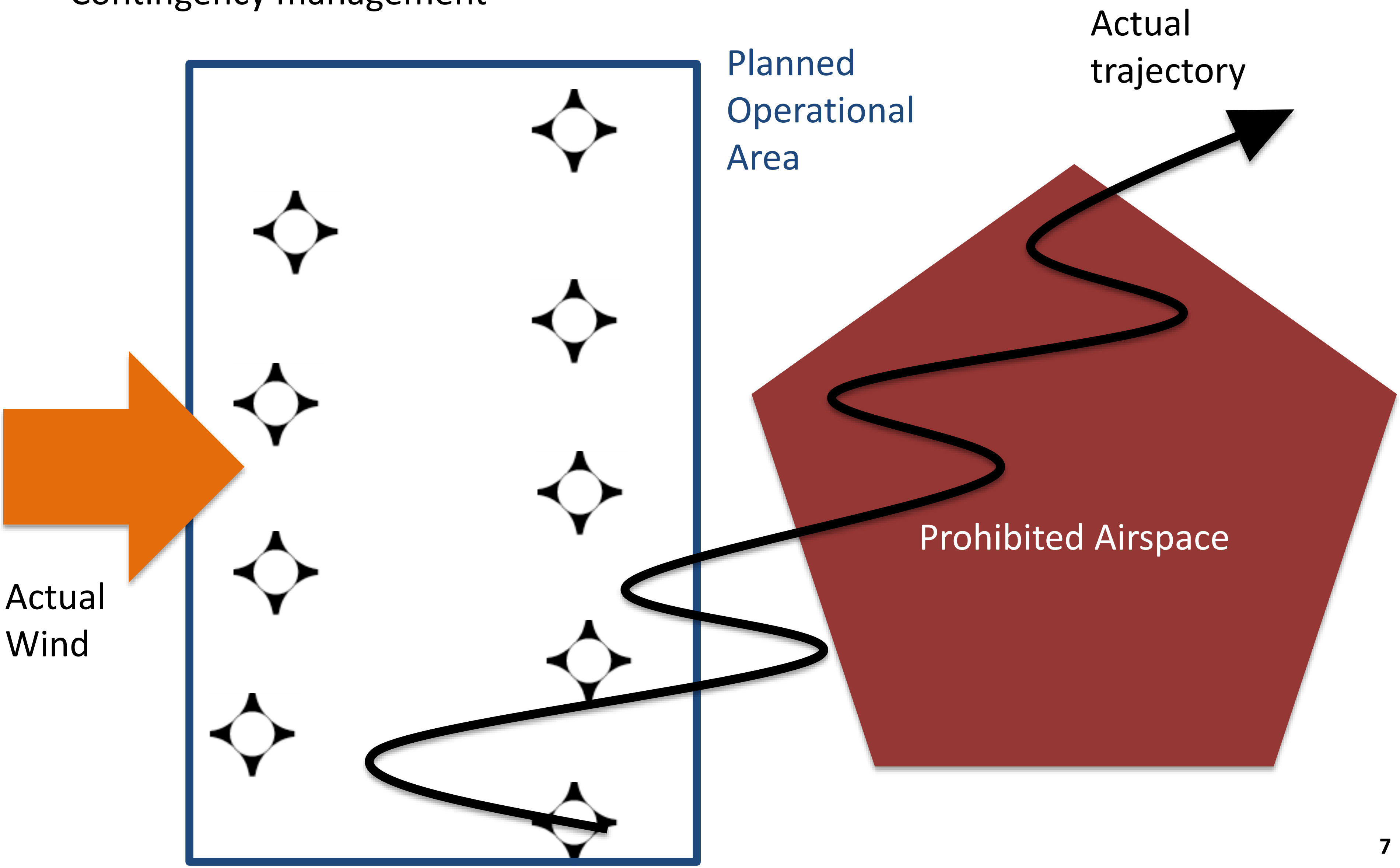
Potential Actual Outcome



Multiple ways to address these problems

- Increase in operational area size
- Improve wind forecast & trajectory model
- Contingency management

NASA UTM Vehicles and Surveillance Focus group



Vehicles and Surveillance Focus Group is working on trajectory modeling improvement

- Trajectory conformance depends on:
  - Aerodynamic characteristics (e.g., coefficient of drag)
  - Vehicle performance (e.g., thrust)
  - Vehicle structural limit (e.g., load factor)
  - Automatic flight control (e.g., linear control)

- Ongoing efforts:
  - Vehicle modeling with available data
  - Model test with Computational Fluid Dynamics wind field
  - Model validation with field tests
  - Wind tunnel tests and system identification
  - Weather product requirements development

Vehicle Modeling with Available Data

- Existing data gathered from the internet and partners
- Available data not enough for high fidelity modeling
- Models developed with simplifying assumptions
  - Wind-generated lift negligible for quad-rotor type
  - Constant $C_D A_{ref}$

$$D = C_D \frac{1}{2} \rho A_{ref} \left(V - V_{wind}\right)^2 s_V$$

$$\text{where } s_V = -sign\left(V - V_{wind}\right)$$

From VIPER Team: Systems Analysis Office (AA) report

Vehicle Modeling with Available Data

Rotational Motion

$$\ddot{\boldsymbol{\phi}} = \frac{(\boldsymbol{F_L} - \boldsymbol{F_R})\boldsymbol{l}}{\boldsymbol{J_x}}$$

$$\ddot{\boldsymbol{\theta}} = \frac{(\boldsymbol{F_F} - \boldsymbol{F_B})\boldsymbol{l}}{\boldsymbol{J_y}}$$

$$\ddot{\boldsymbol{\psi}} = \frac{\boldsymbol{k_\psi}\left(-\boldsymbol{\omega}_F^2 + \boldsymbol{\omega}_R^2 - \boldsymbol{\omega}_B^2 + \boldsymbol{\omega}_L^2\right)}{\boldsymbol{J_z}}$$

Translational Motion

$$\boldsymbol{m\ddot{x}} = -\cos(\boldsymbol{\phi})\sin(\boldsymbol{\theta})\,\boldsymbol{F} + \boldsymbol{D_x}$$

$$\boldsymbol{m\ddot{y}} = \sin(\boldsymbol{\phi})\,\boldsymbol{F} + \boldsymbol{D_y}$$

$$\boldsymbol{m\ddot{z}} = \cos(\boldsymbol{\phi})\cos(\boldsymbol{\theta})\,\boldsymbol{F} - \boldsymbol{F_g} + \boldsymbol{D_z}$$

State Variables

x,y,z denote position in the *body frame*

ϕ = Roll Angle
θ = Pitch Angle
ψ = Yaw Angle

Vehicle Specific Parameters

D **=** Drag
J = Moment of Inertia
l = Arm length

Control Parameters

ω = Motor RPM
$\mathbf{k}_\psi$ = Yaw Constant
F = Total UAV Thrust
PID Controllers Employed

From VIPER Team: Systems Analysis Office (AA) report

Vehicle Modeling with Available Data

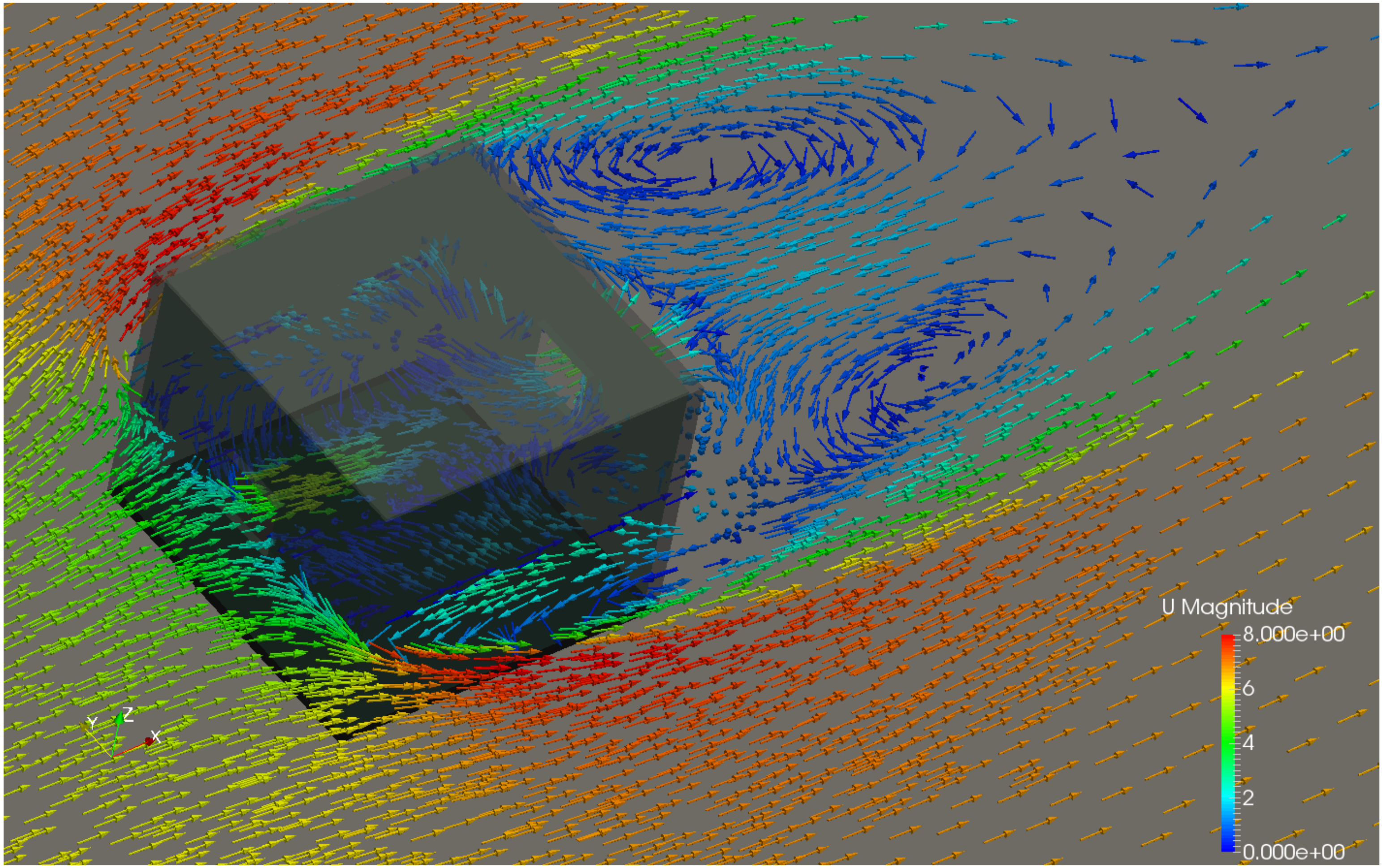
Examples of information that are essential for high fidelity quad rotor kinetic modeling

Mass	**UAV Structure**	**UAV Rotors**	**UAV Power Systems**	**UAV Motor**	**Other**
Total Structure Mass	Arm Lengths	Number of Rotors	Battery Type	Motor Response Latency	Gains
Motor Mass	Mass Moments of Inertia	Rotor Diameter	Battery Capacity	Maximum RPM	Manufactu
Rotor Mass	Body Dimension	Rotor Pitch	Max Voltage	Torque vs. Power	PWM Value
Payload mass		Rotor Chord	Max Current	Motor Moment of Inertia	
Other Component Mass		Gear Ratio		Motor Resistance	
		Thrust vs. RPM		Motor Inductance	
		Motor Torque vs. RPM		Electromotive force constant	
		Prop Efficiency vs. Advanced Ratio		Mechanical System Damping	
		Blade Flapping Inertia*			
		Blade Stiffness*			
		Blade Natural Frequency*			
		Blade Lift curve slope			

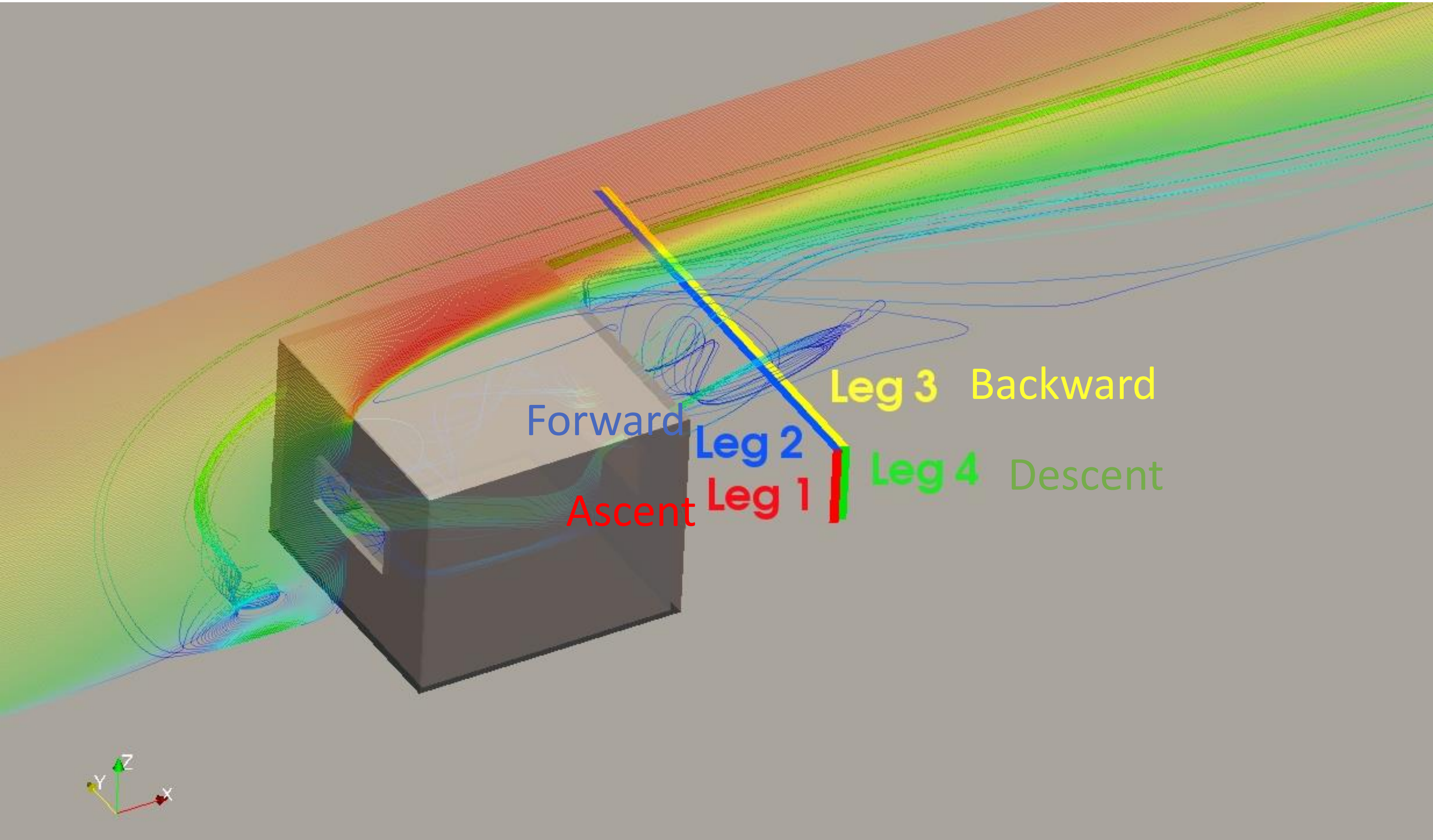
*Required for future models where blade flapping will be incorporated

From VIPER Team: Systems Analysis Office (AA) report

Model Test with Computational Fluid Dynamics
Wind Field



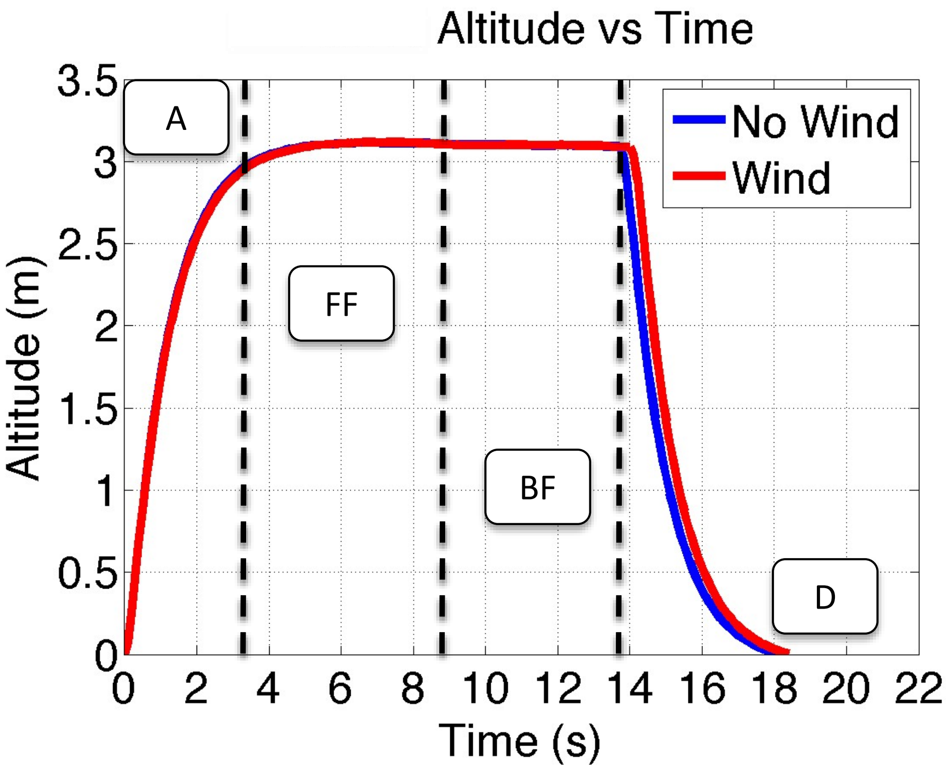
Test Example

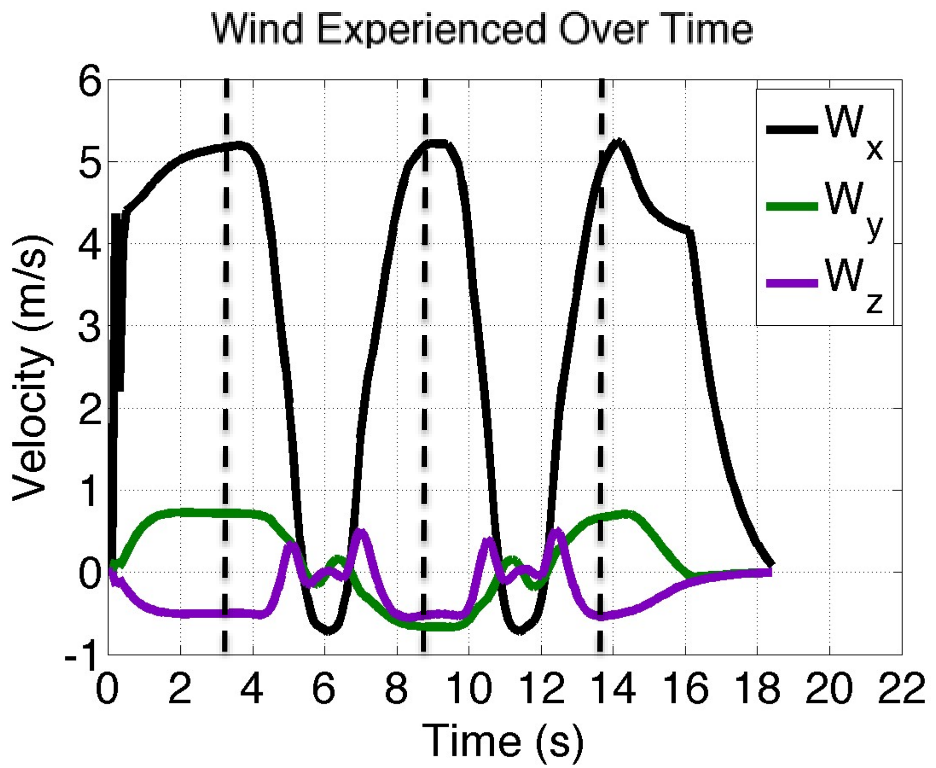


Generated by Ben E. Nikaido, ARC-AA/STC

Ref:8

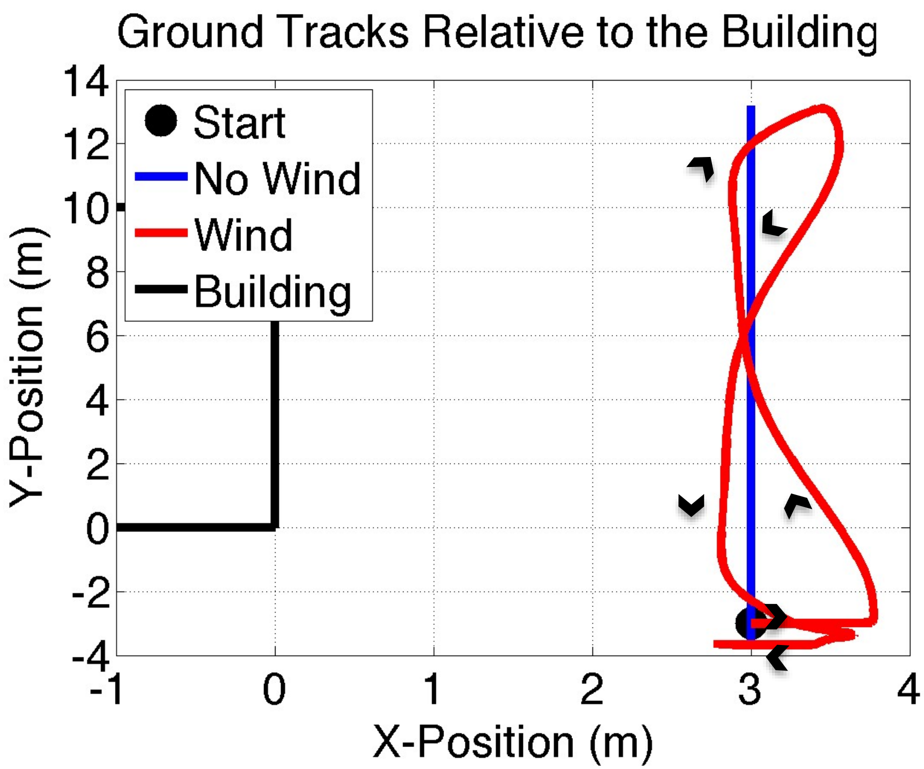
Test Example: Altitude & Wind

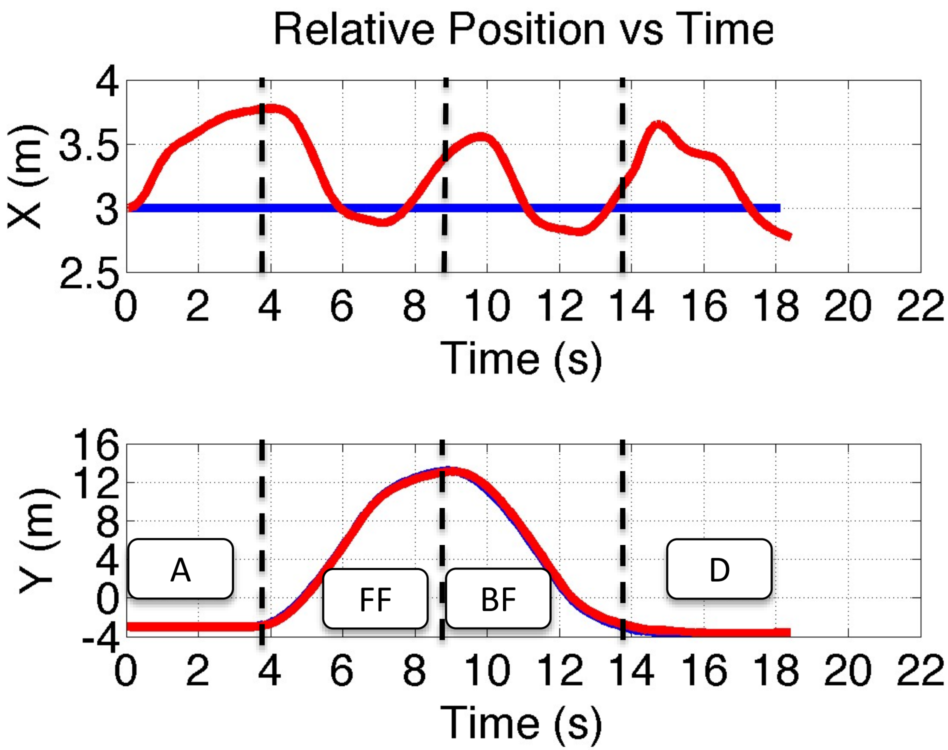




Ascent = “A”, Forward Flight = “FF”, Backward Flight = “BF”, Descent = “D”

Test Example: Ground Tracks





Ascent = “A”, Forward Flight = “FF”, Backward Flight = “BF”, Descent = “D”

Model Validation with Field Tests

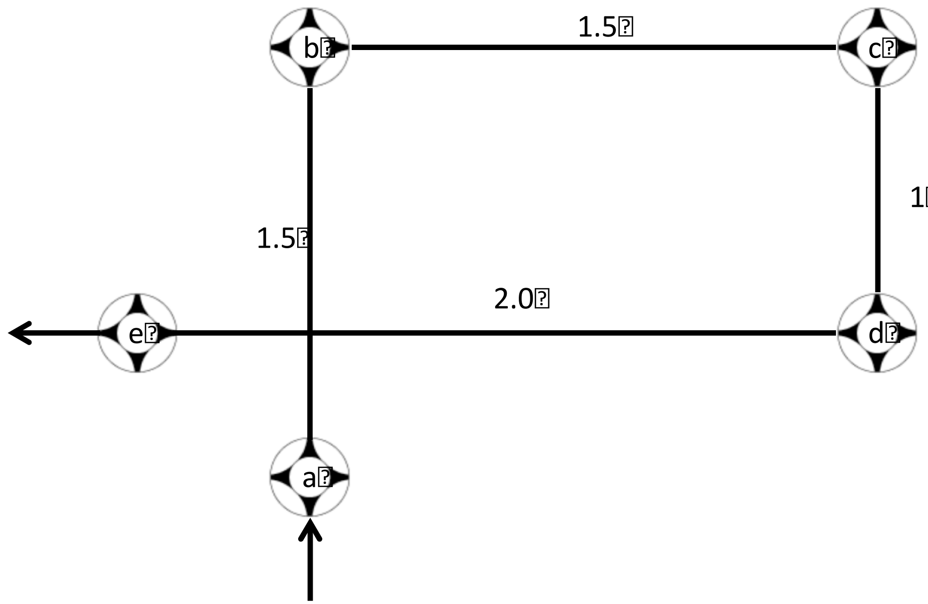
- At the upcoming field test, following are planned
  - Record airfield environmental data
    - 10 m weather tower
    - SODAR
  - Fly a set of Lateral Routes and Vertical Maneuvers
    - NASA UAS
    - Partner UAS

- Model validation
  - "Fly" trajectory models with the recorded wind data
  - Compare model's trajectory with the actual trajectory

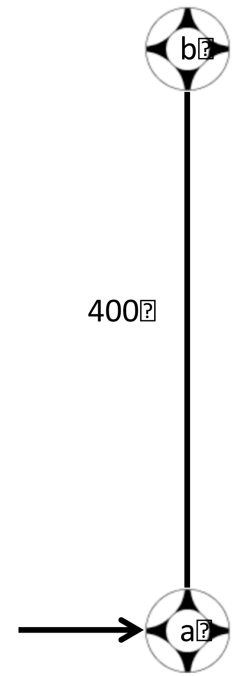
Model Validation with Field Tests

Weather tower

Example Lateral Route

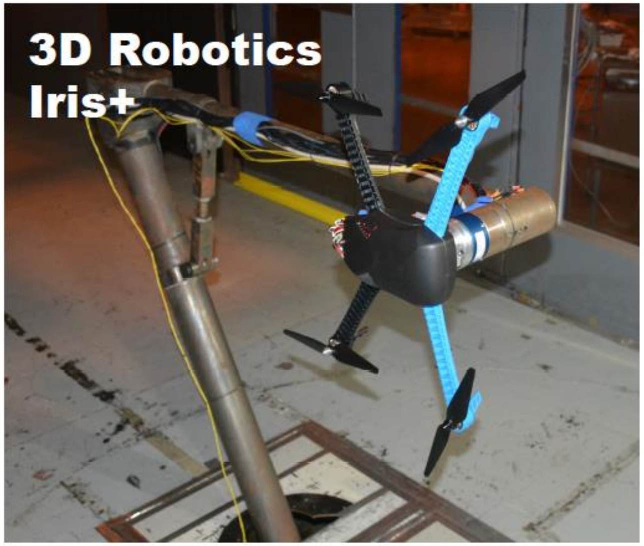


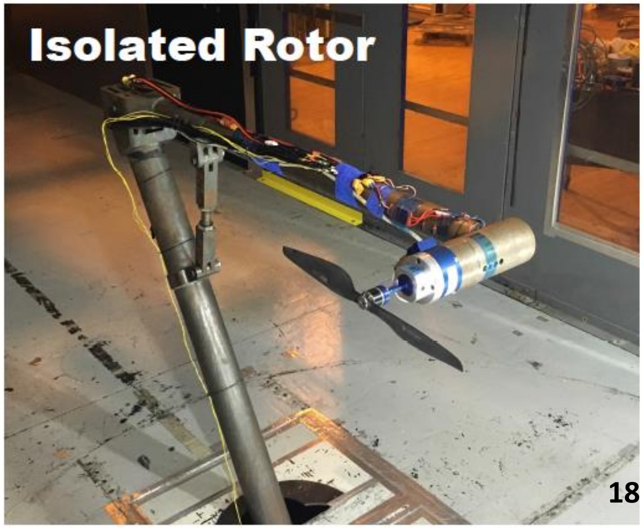
Example Vertical Maneuver



Wind Tunnel Test: Mounted Type

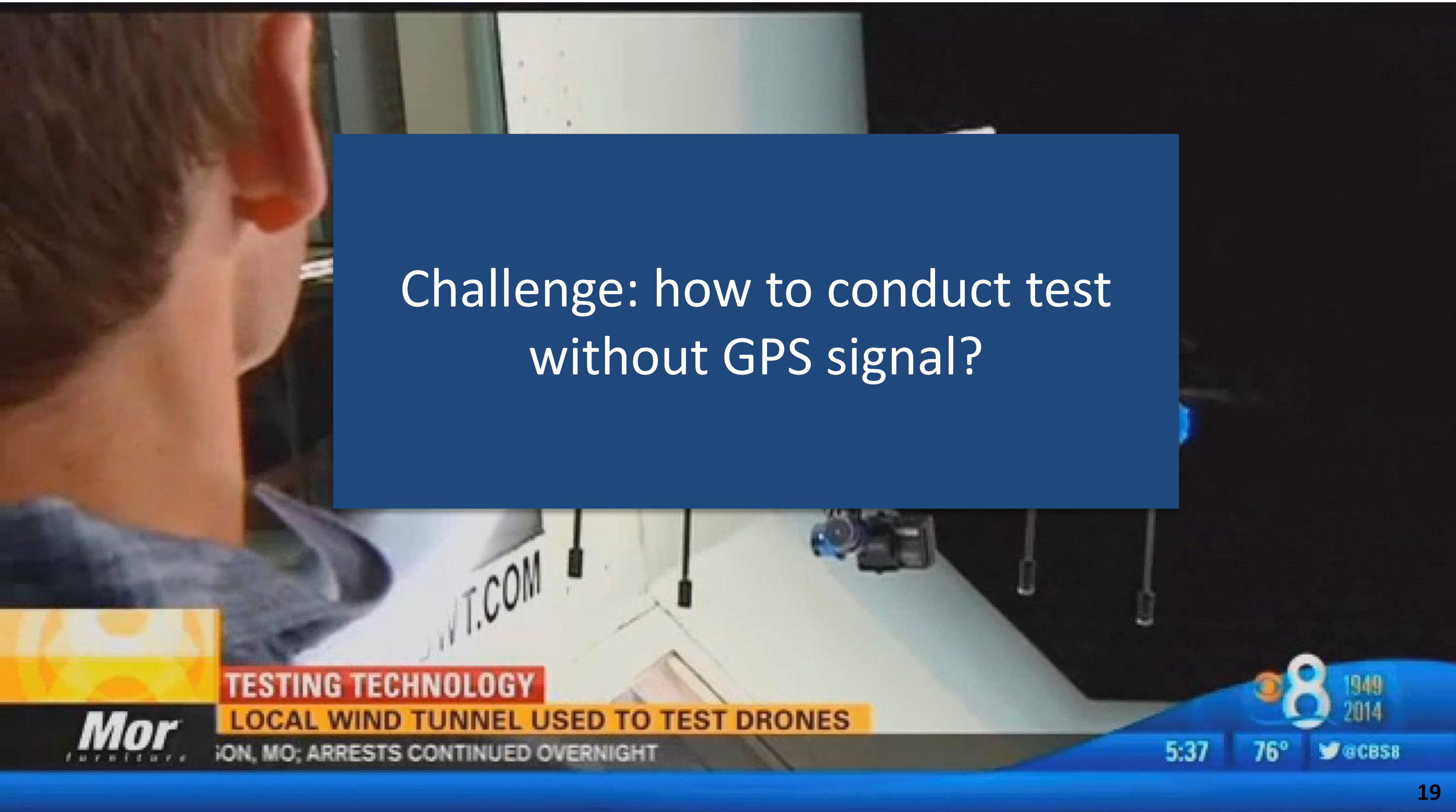
- Measure force (airframe and propulsion) and associated electric current, voltage, battery stat
- Five multi rotor UAS tested in the US Army 7- by 10-ft wind tunnel at NASA Ames





Wind Tunnel Test: Free-flight type

- Perform position holding at different wind speed
- Capability of automatic flight control can be assessed
- Wind-gust can be simulated (not currently available 7x10 wind tunnel feature)



Challenge: how to conduct test without GPS signal?

System Identification

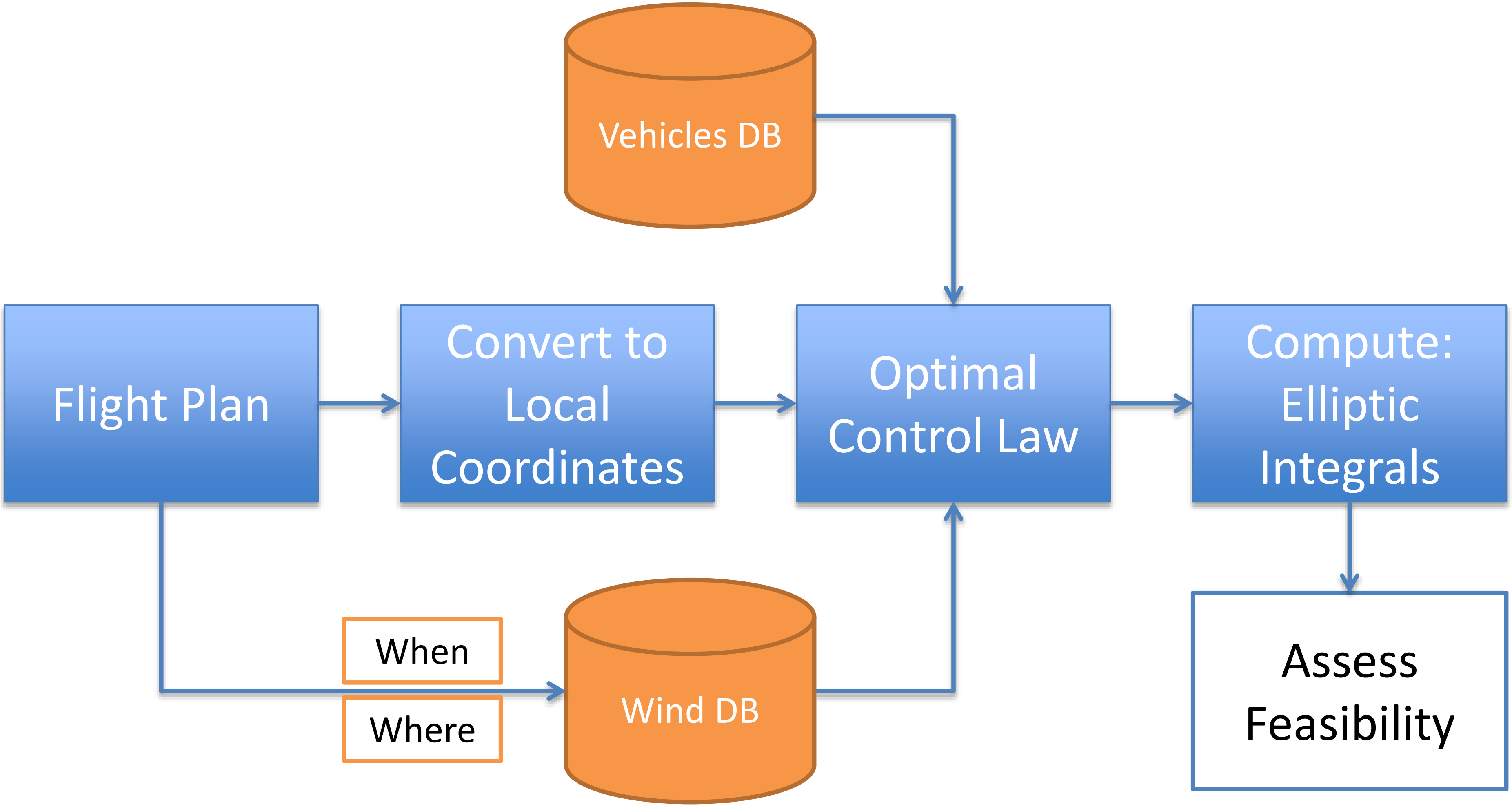
- Initiated discussion with system identification experts
  - Necessary setup
  - What can and can not be identified

Weather Product Requirements Development

Wind Model

- NOAA HRRR (High Resolution Rapid Refresh)
  - Highest granularity of all current products
  - Temporal resolution – 15 min
  - Spatial resolution – 3 km
  - 15hr – Forecast; Hourly update
  - Low altitude data

Procedure

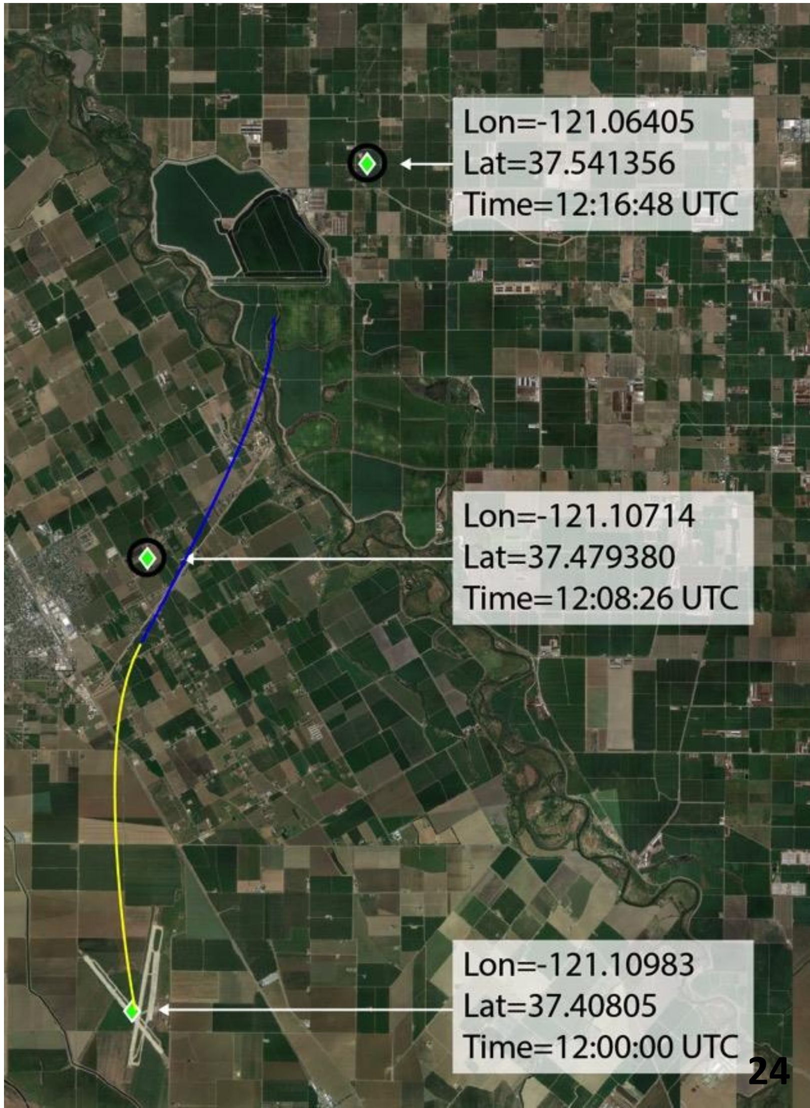


Vehicles DB
Flight Plan
Convert to Local Coordinates
Optimal Control Law
Compute: Elliptic Integrals
When
Where
Wind DB
Assess Feasibility

Test Case: Crows Landing, CA

Dragon Eye
Max Vel: 20.11 m/s
Min Vel: 8.9 m/s
Cruise: 15.64 m/s
Max Turn Rate: 0.28 rad/s

Way-Point	Client Arrival Time	Nominal Vel	Optimal Vel	Feasible ?
1	12:08:26 UTC	15.64	?	?
2	12:16:48 UTC	15.64	?	?



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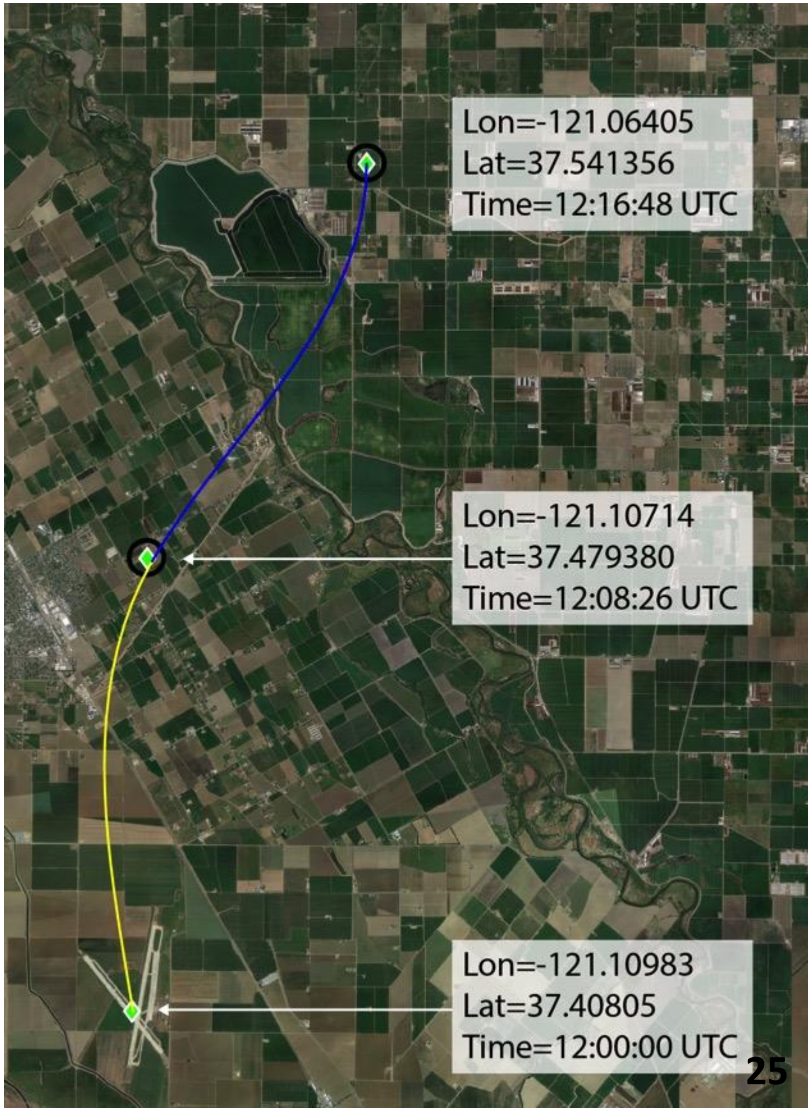
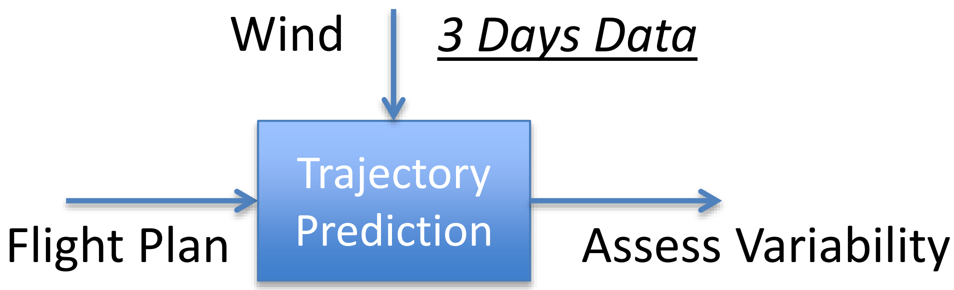
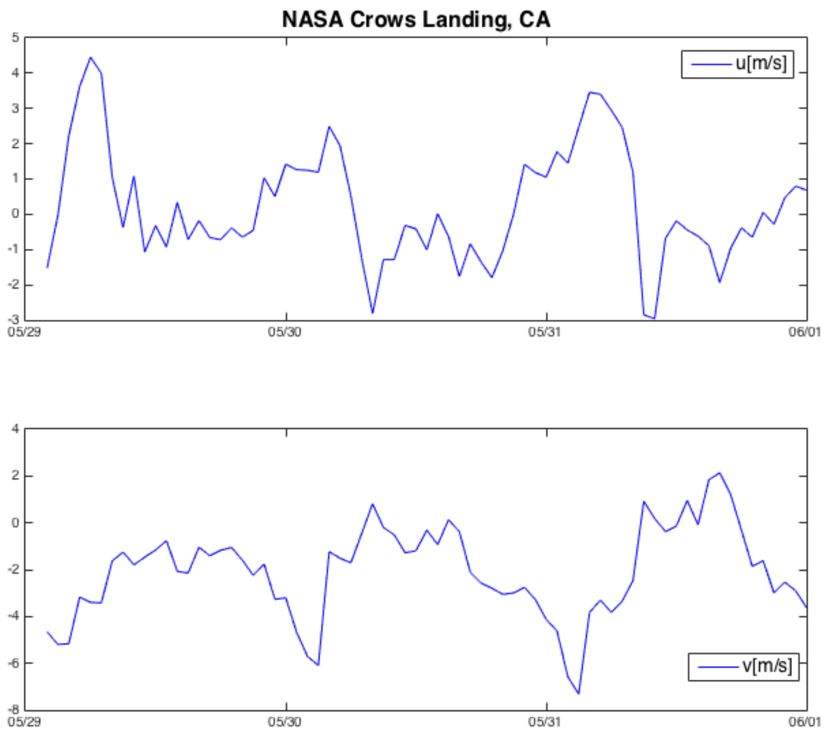
Max Turn Rate: 0.28 rad/s

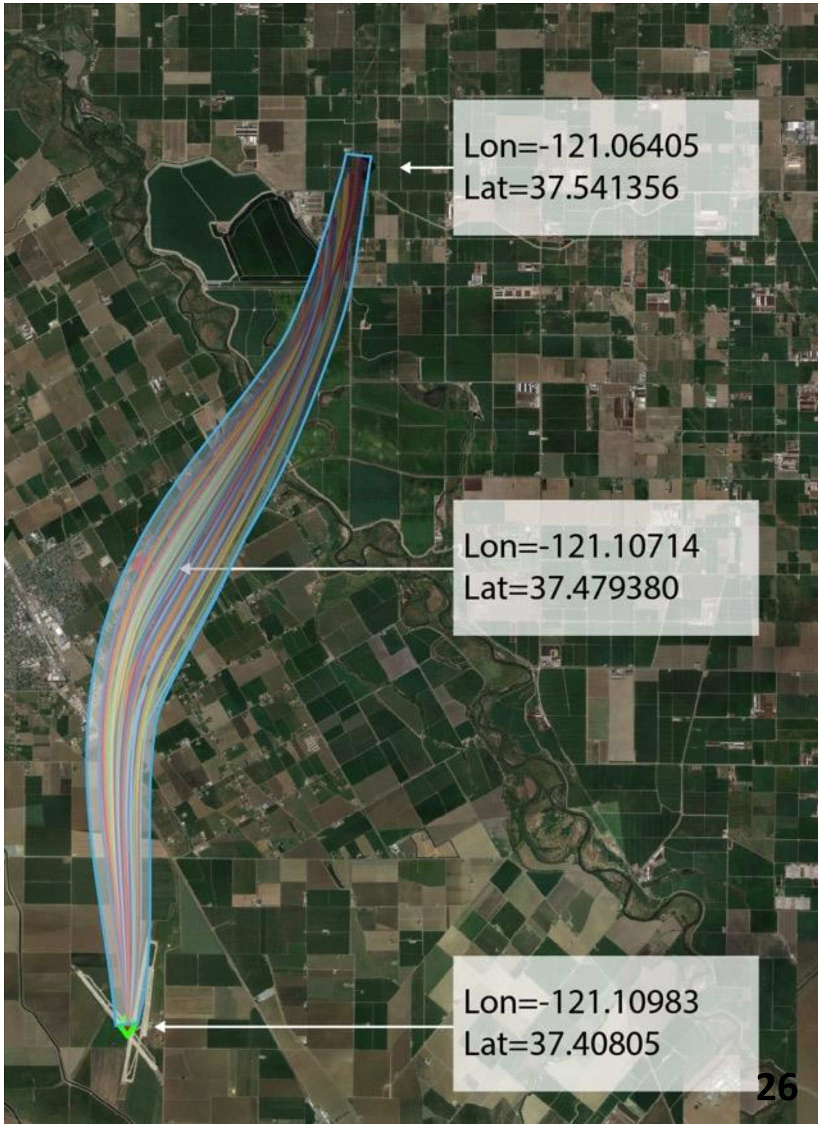
Way-Point	Client Arrival Time	Nominal Vel	Optimal Vel	Feasible ?
1	12:08:26 UTC	15.64	18.62	yes
2	12:16:48 UTC	15.64	19.1689	yes



Impact due to Wind Variation







Summary

- UTM constraint check with vehicle performance
- Vehicle modeling
  - Test
  - Refinement
- Weather product requirements
  - Lower altitude data
  - Uncertainty