Atmospheric energy harvesting for autonomous in-flight path planning of a UAV instrumented with Doppler Wind Lidar.

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Working Group on Space-based Lidar Winds

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Objectives of SBIR project AEORA

- Extend the mission time of UAVs by autonomously utilizing (harvesting) atmospheric motions, particularly vertical motions.
- Provide mission planning tools to estimate the probability and locations of advantageous atmospheric motions as well as deleterious motions to be avoided.
- Develop algorithms that use “all available information”, especially an on board DWL, to make in-flight path decisions to optimally use the atmospheric energy opportunities consistent with the mission constraints.

Atmospheric Energy Opportunity and Ranking Algorithm (AEORA)

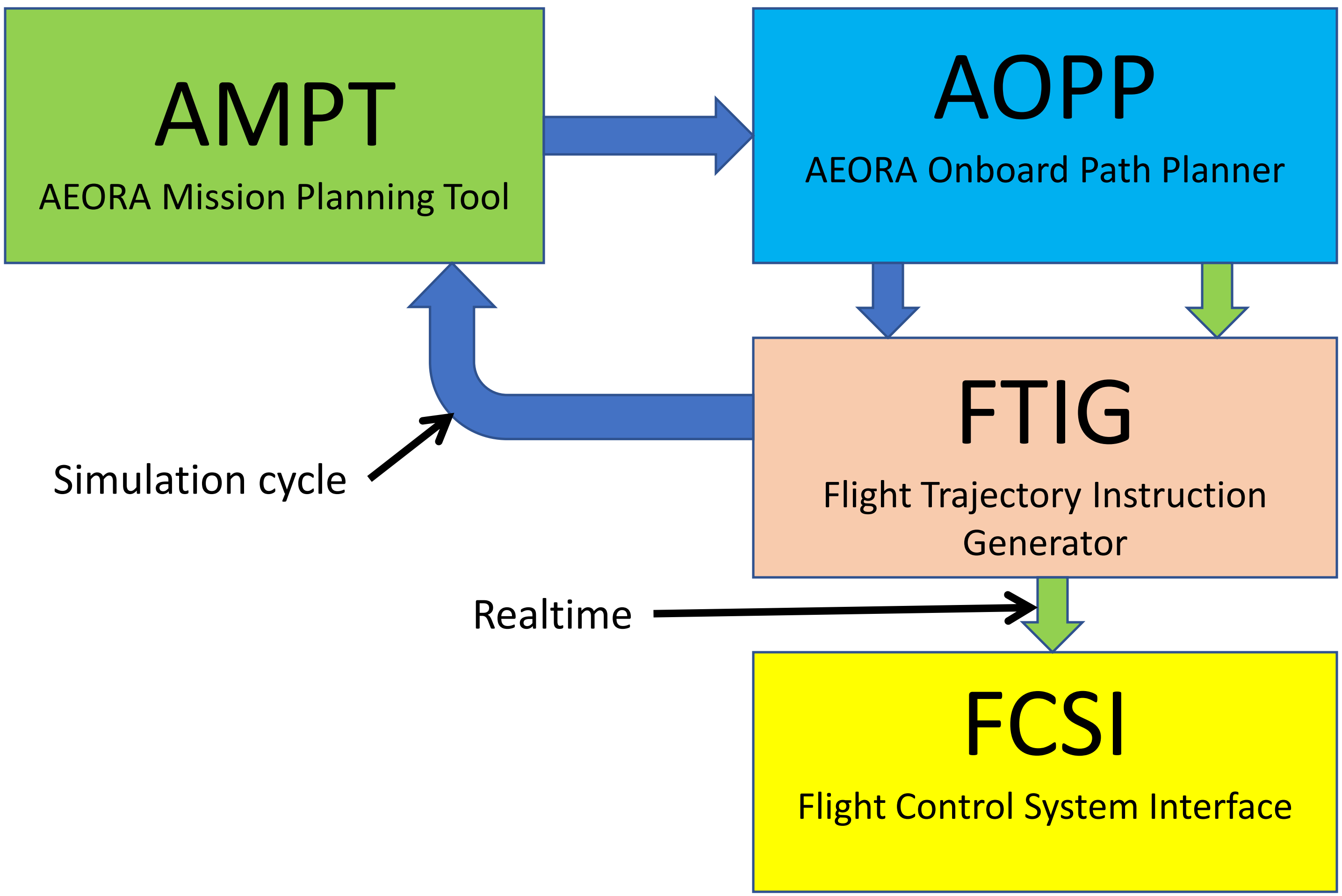
Potential atmospheric energy sources

Phenomenology	Description (dimensions)	Nominal Magnitudes	Lifecycle Metrics	Remote Sensing Signatures
Thermals (non-orographic); triggered by differential surface heating	Few 100 meters in diameter; vertical extent controlled by environmental structure	1- 5 m/s	May last for large fraction of an hour; daytime features only	Convergence Optical depth Temperature Refractive turbulence
Thermals (slopes); driven by differential heating of sloped surfaces during direct solar illumination	100's meter diameter; vertical extent limited by environmental structure	1 -5 m/s	May last for hours during the daytime.	Convergence Optical depth Temperature Refractive turbulence
Organized Large Eddies (OLEs); upward branch of a semi-closed vertical circulation within the PBL	A few 100 meters in diameter; vertical extent defined by depth of PBL; organized in lines allowing "next AA" to be more easily predicted than thermals	1 – 3 m/s	May last for hours but with much variation in strength; Not much known about night-time characteristics	Convergence Optical depth Refractive turbulence
Obstacle flow; Strong horizontal flow deflected upward by orography and airmass collisions; (ridge soaring; frontal soaring)	Many miles in horizontal extent; vertical extent usually a few 100 meters above ridge line	1 – 10 m/s	May last for many hours and vary as the horizontal flow varies; Occurs at all hours of the day.	The obstacle Convergence Optical depth Refractive turbulence
Cloud updrafts; main targets are cloud base updrafts of non- or lightly precipitating cumuli.	Dimensions similar to thermals (a few 100's of meters); vertical extent can be 1000's of meters	1 – 5 m/s depending upon atmospheric stability.	A few minutes, maximum duration ~ 10 minutes.	The cloud Convergence Temperature Precipitation
Mountain Waves	Horizontal extent of many km; Vertical extent of 10's of km possible	Up to 10 m/s vertical velocities distributed in bands downwind of ridge line.	May last for hours throughout entire diurnal cycle	Vertical motions; visual wave clouds on occasion.
Gravity waves on density interface	Horizontal extent of many kms (50 – 500); Vertical extent of 5 – 10 km	1 – 3 m/s	1 – 3 hours	Vertical motions Inversions
Shear layers	Horizontal extent of many kms defined by surface topography and atmospheric structures; vertical extent a few 100 meters	10 – 25m/s with a maximum near 100 - 300 meters.	May persist for several days lasting through the nighttime	Horizontal wind speed; Optical depths

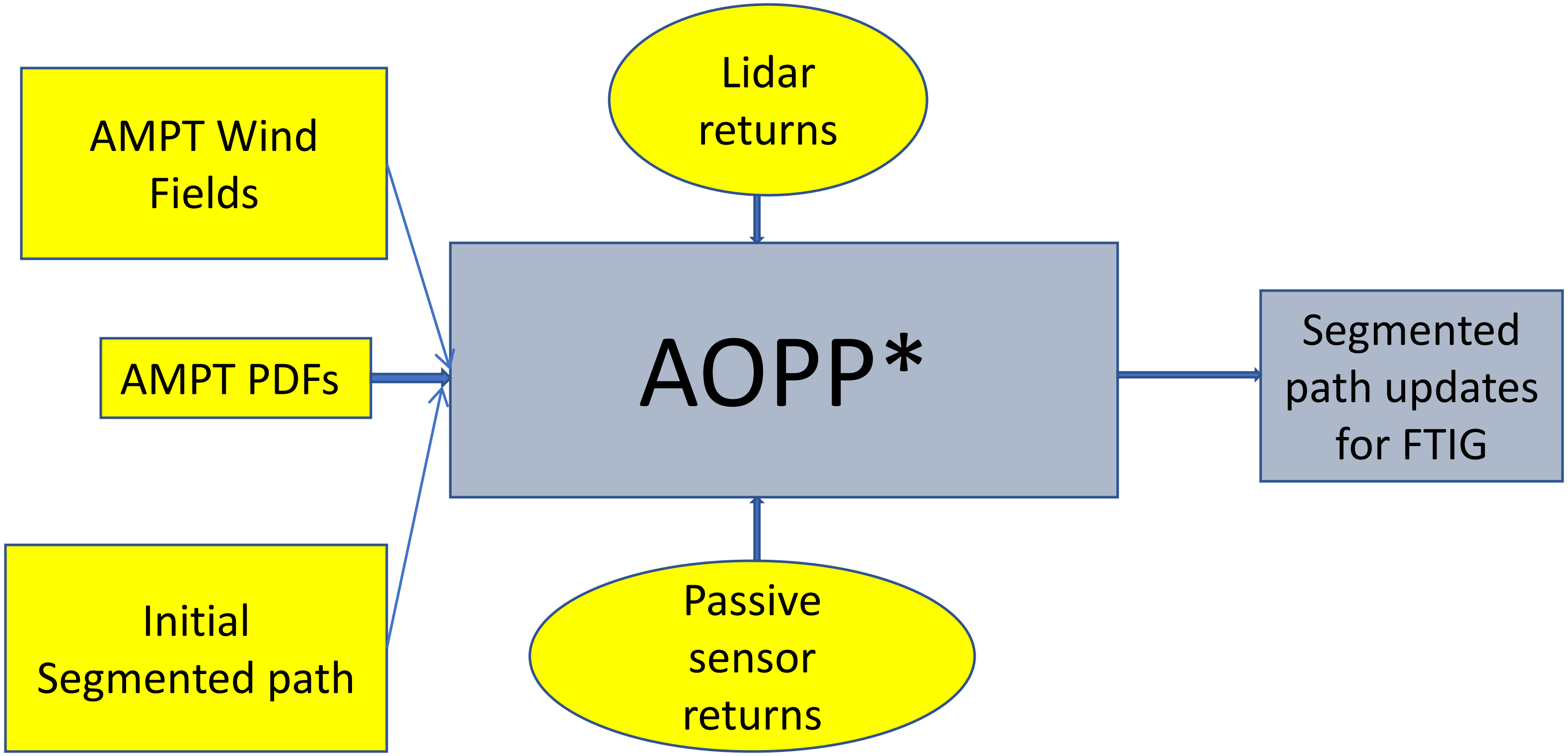
= features studied with airborne Doppler wind lidar

Source: SWA (Emmitt)

AEORA Software Package



AOPP
(AEORA Onboard Path Planner)

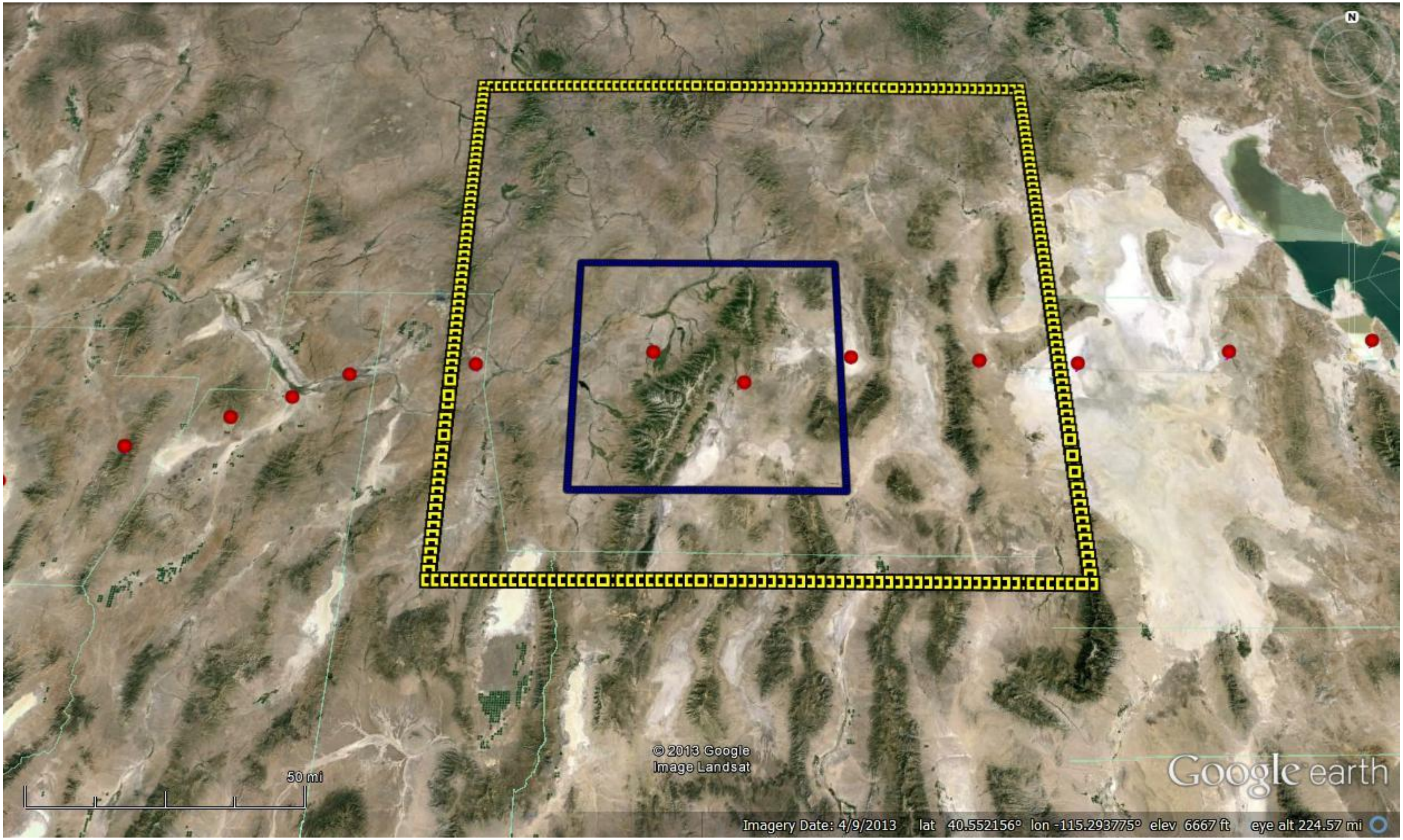


* AOPP is the "heart and soul" of AEORA and resides on the UAS. Continuously processing the lidar and instrument data, running the feature detection software and ranking the energy features. The segmented path for the top ranked feature is passed along to the FTIG.

Weather Research Forecast (WRF) Model

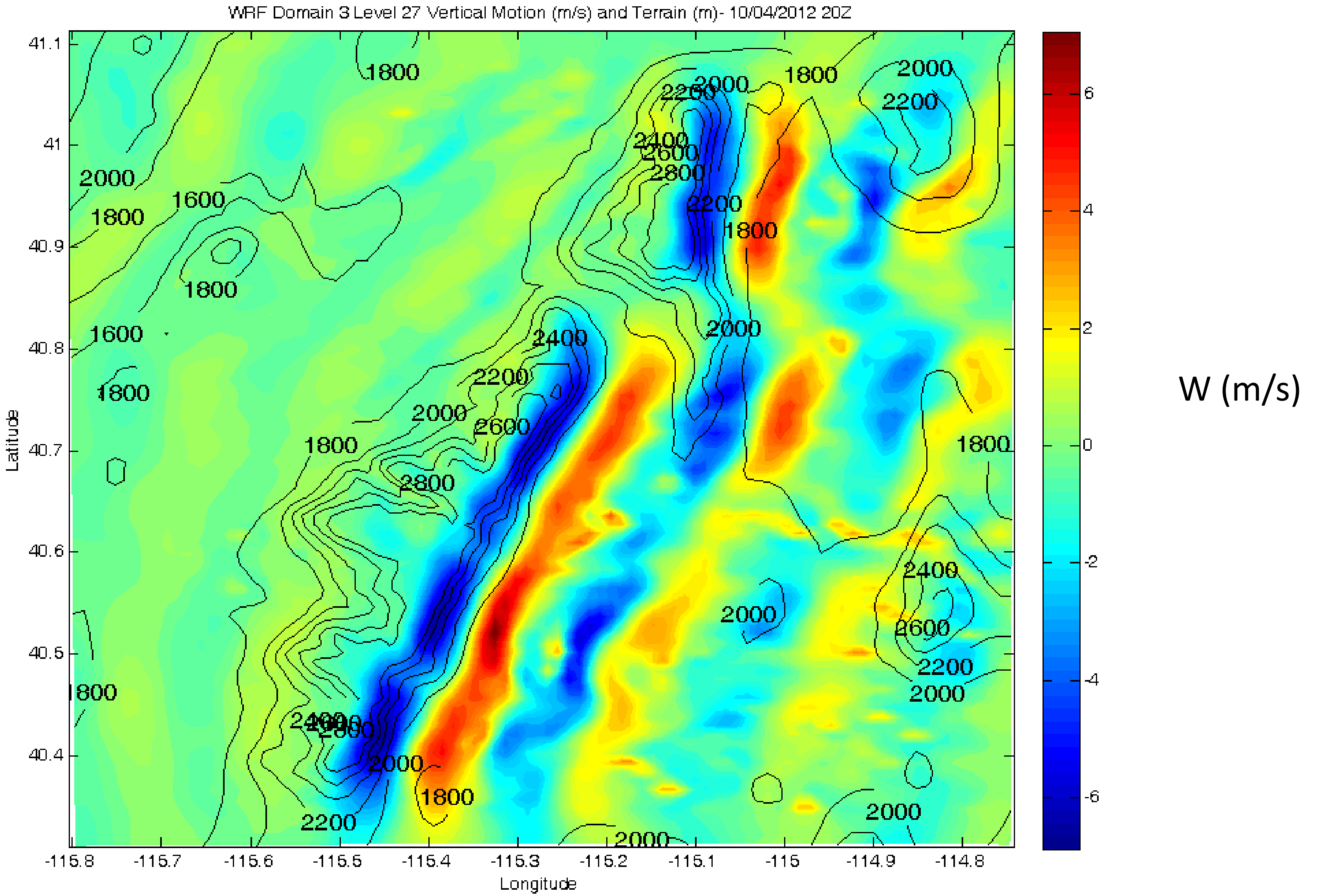
- WRF V3.4
- LES options
- Lin Microphysics
- Surface layer physics based on M-O
- Surface physics – Noah Land Surface Model
- Mellor-Yamada Janjic scheme for BL Physics
- Betts-Miller Cum. Parameterization Scheme
- W-damping turned on

WRF Domains 2 (3 km res.) and 3 (1 km res) for 10/04/2012 20Z

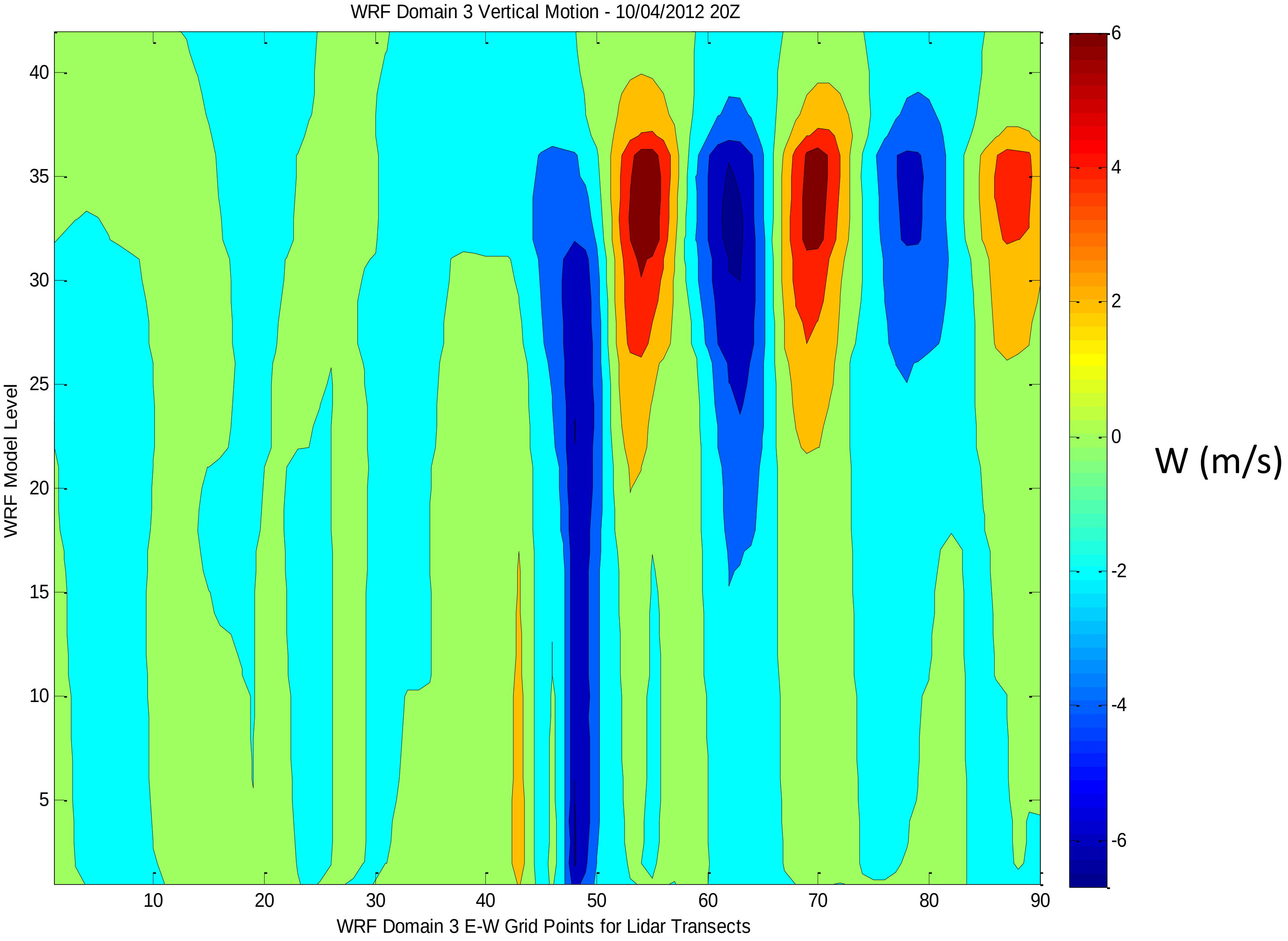


Waves and Vertical Motion

WRF Domain 3 Level 27 Vertical Motion and Terrain

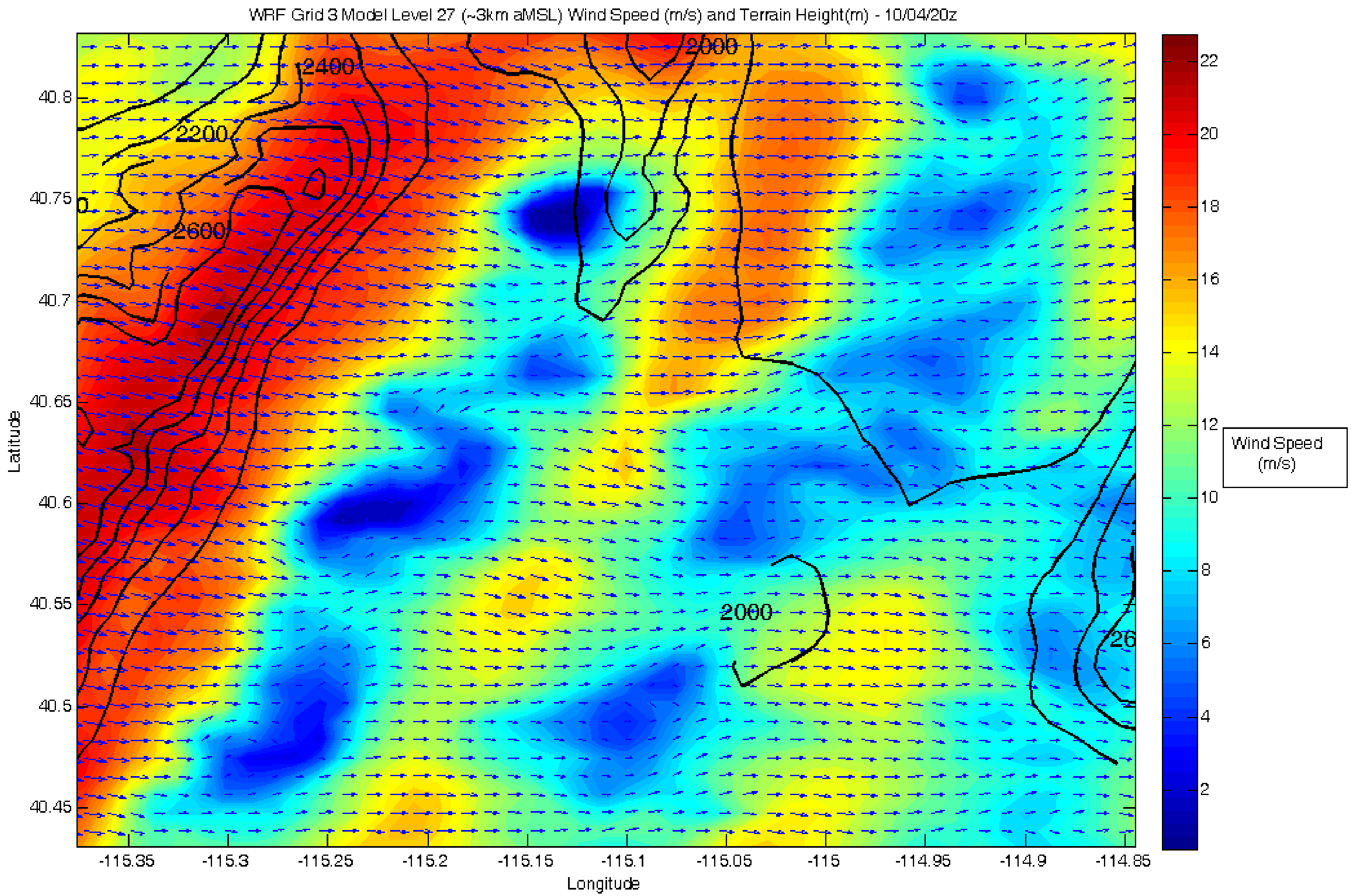


WRF Domain 3 Level 27 Z-X Vertical Motion Along Lidar Transect

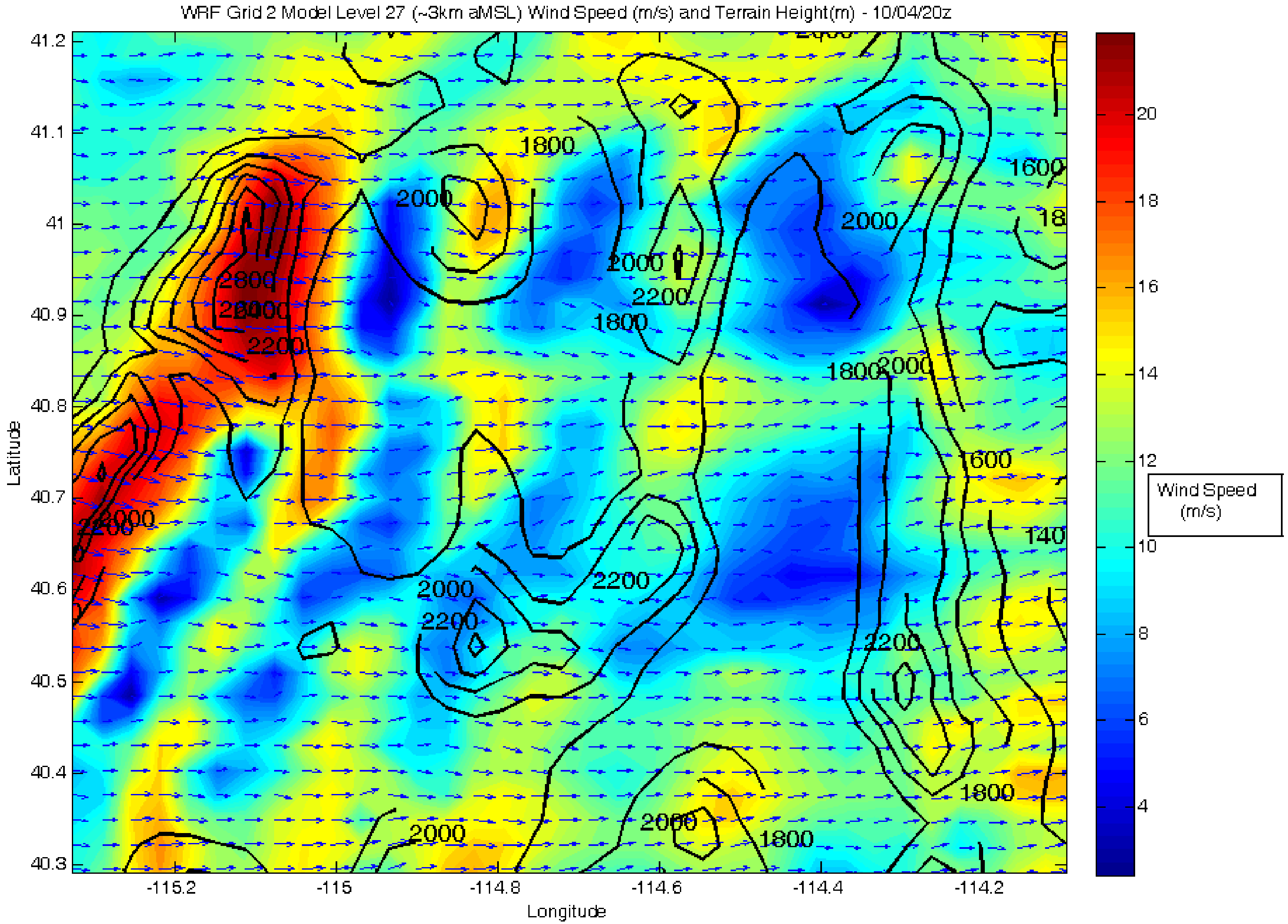


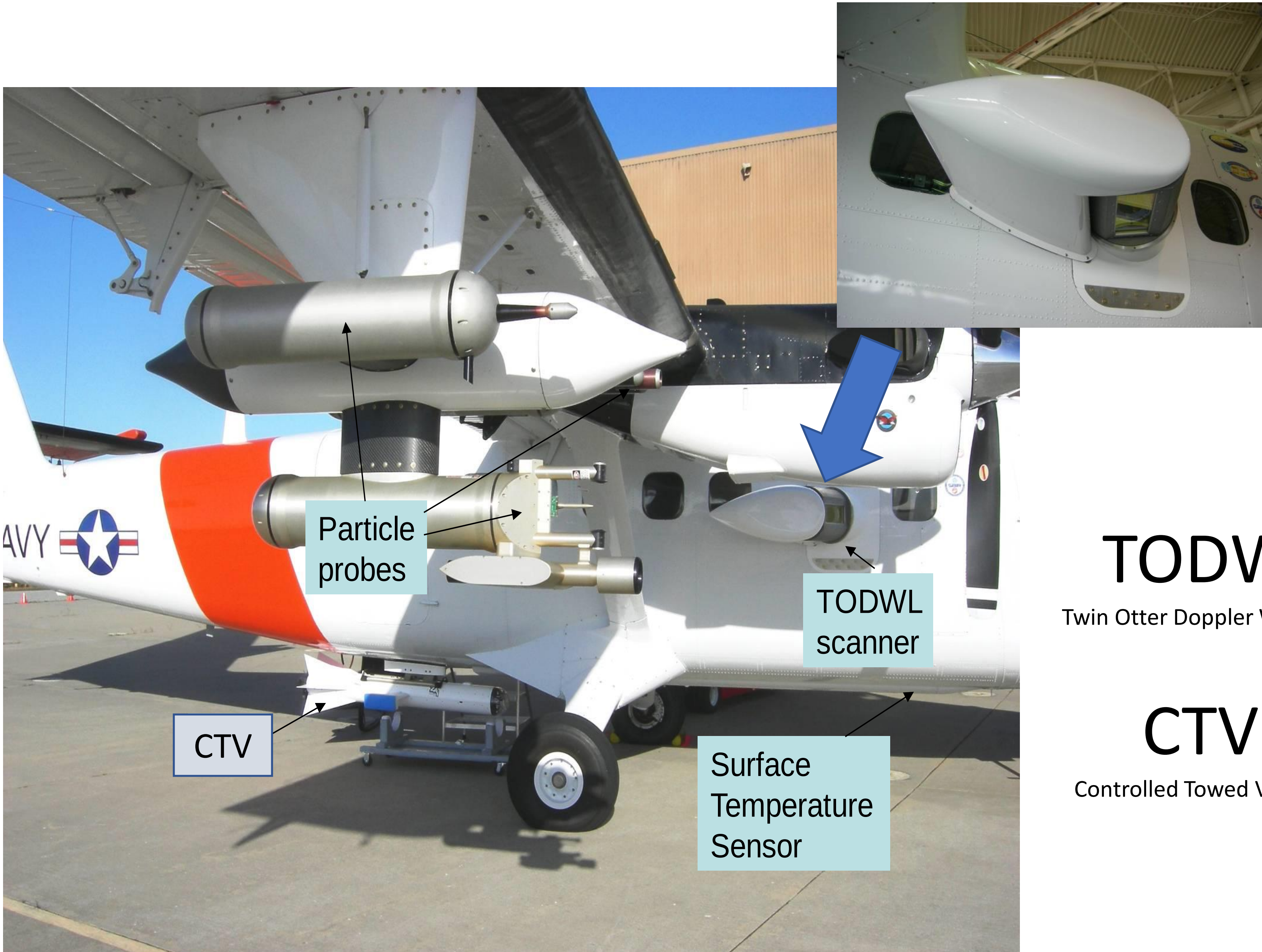
Waves and Horizontal Motion

WRF Domain 3 Level 27 Wind Speed and Terrain - Zoom



WRF Domain 2 Level 27 Wind Speed and Terrain - Zoom





TODWL

Twin Otter Doppler Wind Lidar

CTV

Controlled Towed Vehicle

SWA

N41.9°
N41.7°
N41.5°
N41.3°
N41.1°
N40.9°
Elko
W116.25°
W115.75°
W115.25°
N40.7°
W114.75°
N40.5°
N40.3°
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Image Landsat
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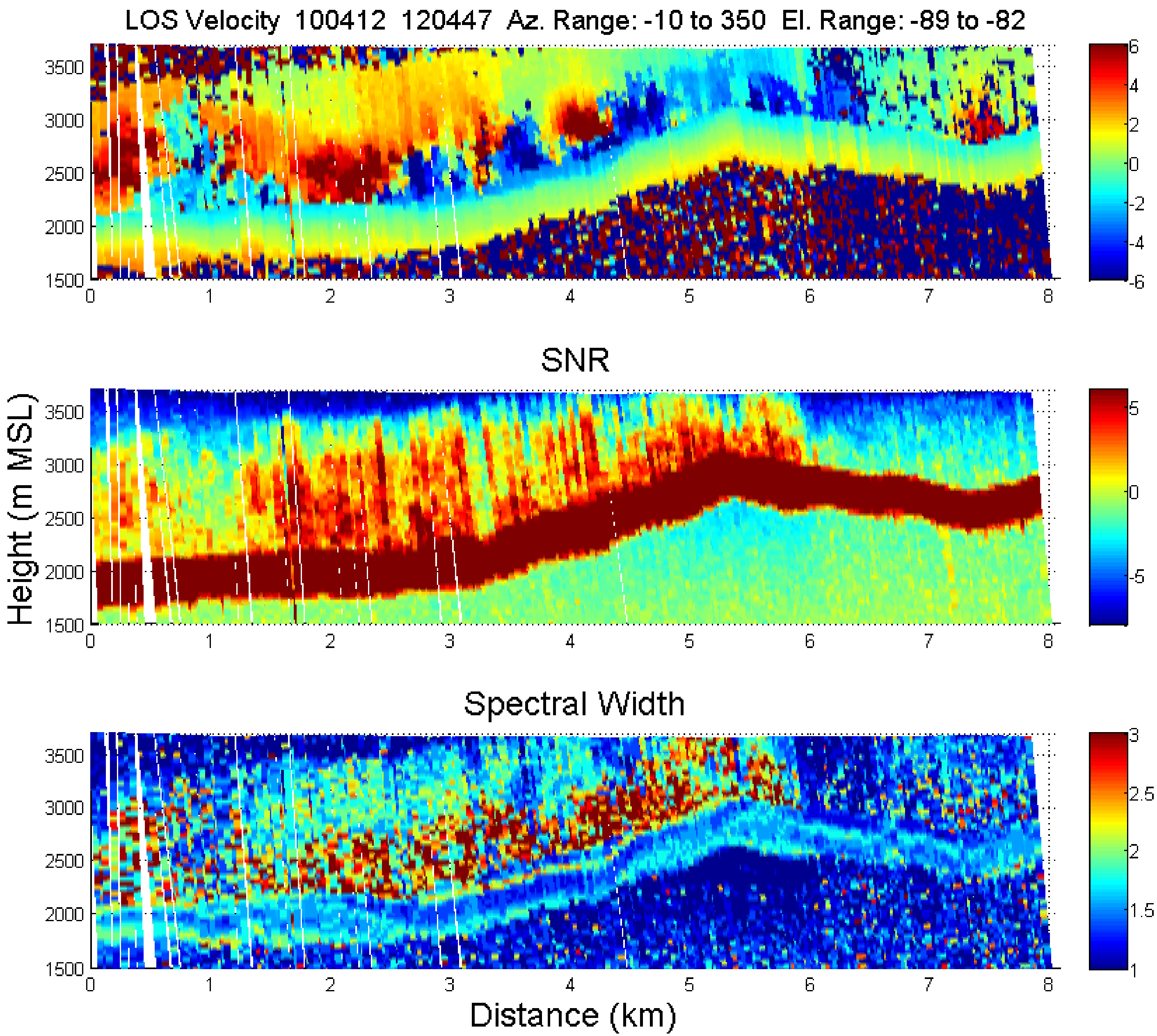
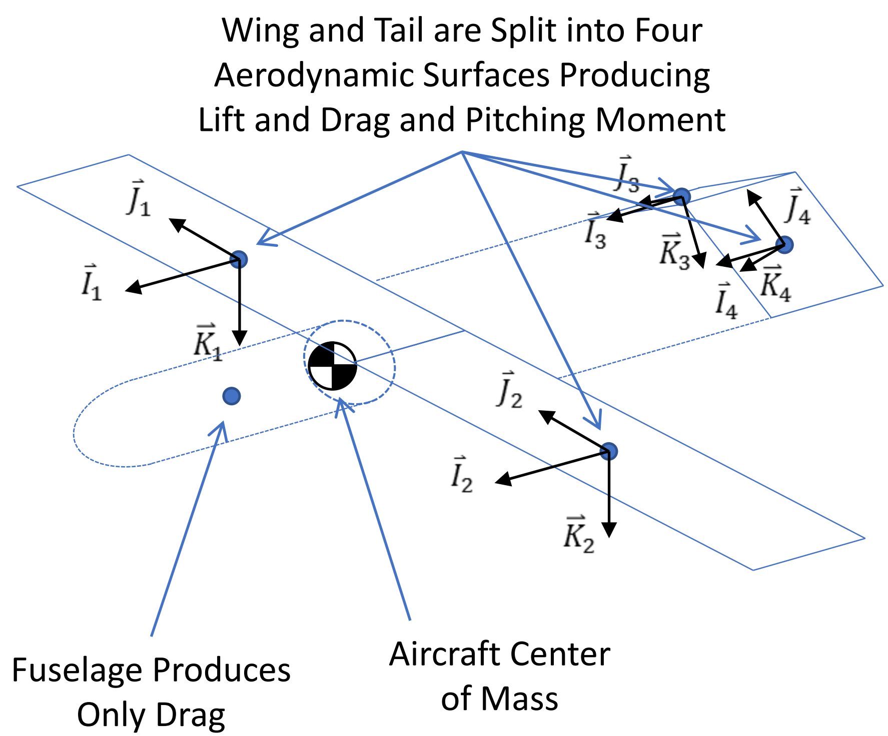

LOS Velocity 100412 120447 Az. Range: -10 to 350 El. Range: -89 to -82
SNR
Spectral Width
Height (m MSL)
Distance (km)
3500
3000
2500
2000
1500
0
1
2
3
4
5
6
7
8
6
4
2
0
-2
-4
-6
5
-5
3
2.5
1.5
1

Energy utilization strategies

Simulation Model

- Aircraft is modeled as a rigid body with 6 degrees of freedom
- Wings and tail are modeled as separated aerodynamic surfaces
- There are 4 control surfaces, one for each aerodynamic element, which can modify the lift and drag forces on that element
- Parameters set to match RQ7B Shadow



Atmospheric Energy Extraction

- We are assuming that information is provided about the type and the approximate shape, location, and strength of an atmospheric feature (DWL, numerical models, imagers..)
- The goal is develop robust control algorithms which can not only fly the feature in an optimal way, but also be robust to uncertainties in the shape and location of the feature
- Currently, three areas are being pursued
  - Thermal Centering
  - Lift Lines (Ridge lift, mountain waves)
  - Small scale gust energy extraction
- The development of control logic for the robust flight of wind shear (dynamic soaring) and other more complex features is being pursued.

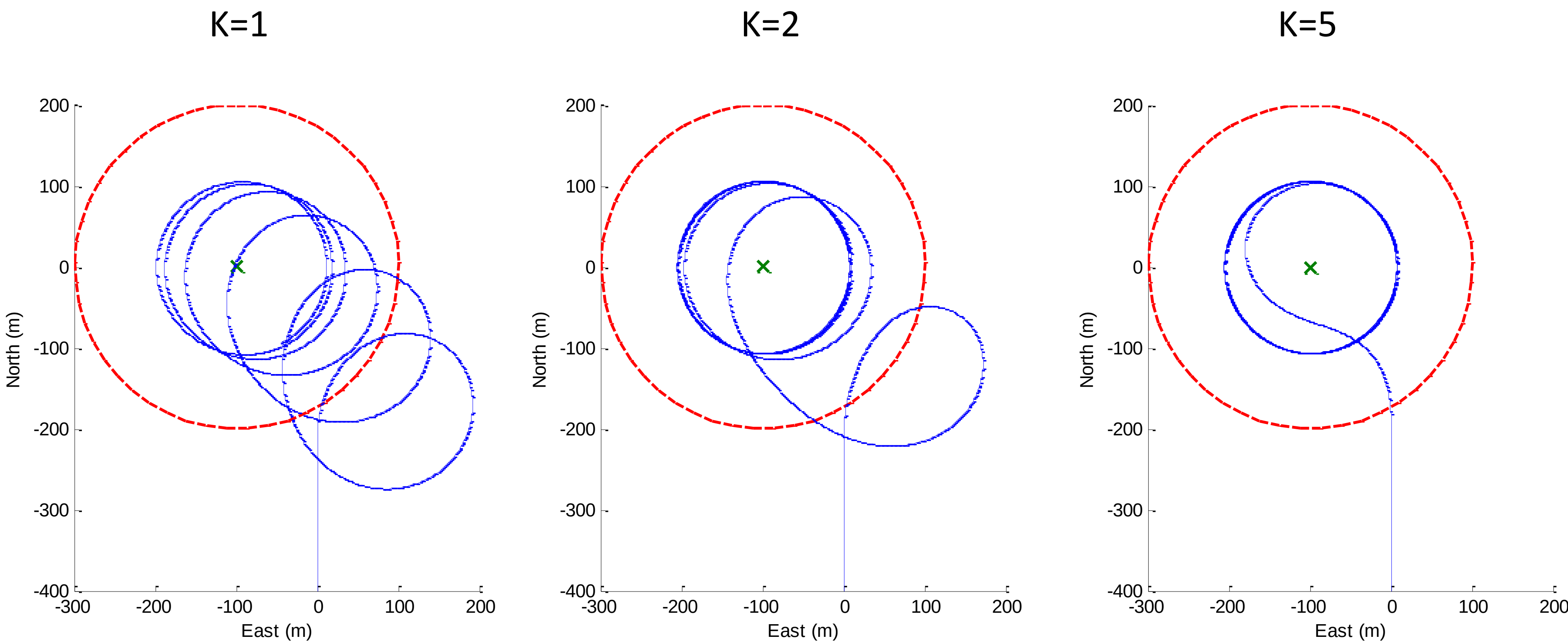
Thermal Centering

- The implementation is a very basic, robust centering controller flight tested by Naval Post Graduate School
  (Andersson, Kaminer, Dobrokhodov, Cichella, "Thermal Centering Control for Autonomous Soaring: Stability Analysis and Flight Test Results," *Journal of Guidance Control and Dynamics*, 2012)
- The goal is a circular flight path around the core of a thermal
- A desired final bank angle is specified and perturbations are made to center the flight path on the core
  - If lift is increasing, the bank angle is decreased, straightening the flight path and bringing the aircraft closer to the core
  - Conversely, if the lift is decreasing, bank angle is increased, bringing the aircraft back around to the stronger lift

$$\underbrace{\phi}_{\text{Commanded Bank Angle}} = \underbrace{\phi_{nom}}_{\text{Nominal Thermalling Bank Angle}} + \underbrace{k}_{\text{Control Gain}}\,\underbrace{\ddot{h}}_{\text{Rate of Change of Climb Rate}}$$

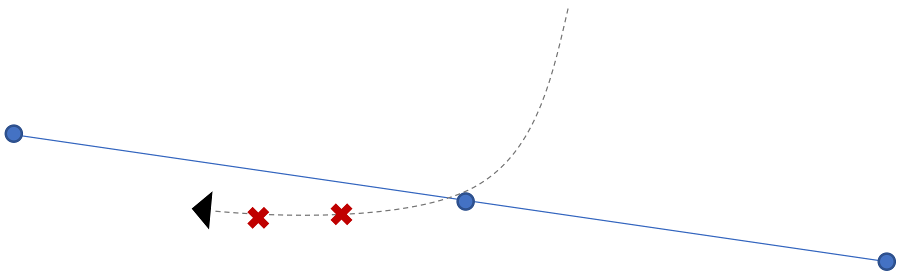
Thermal Centering

- The effect of varying control gain (nominal bank angle set to 20 degrees)



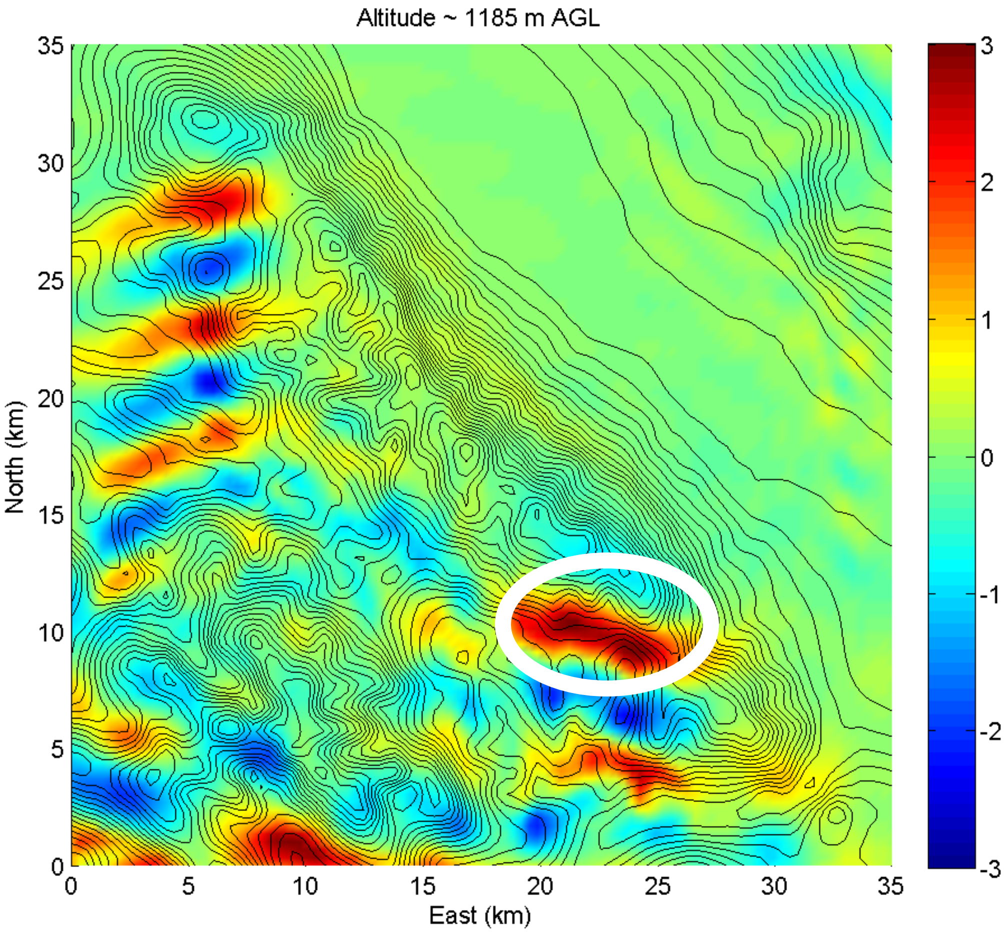
Lift Line Controller

- Assume there is a known area of lift with a roughly linear shape
- This is represented by a line with waypoints at the ends and middle
- As the aircraft flies the waypoints, points of strong lift are recorded



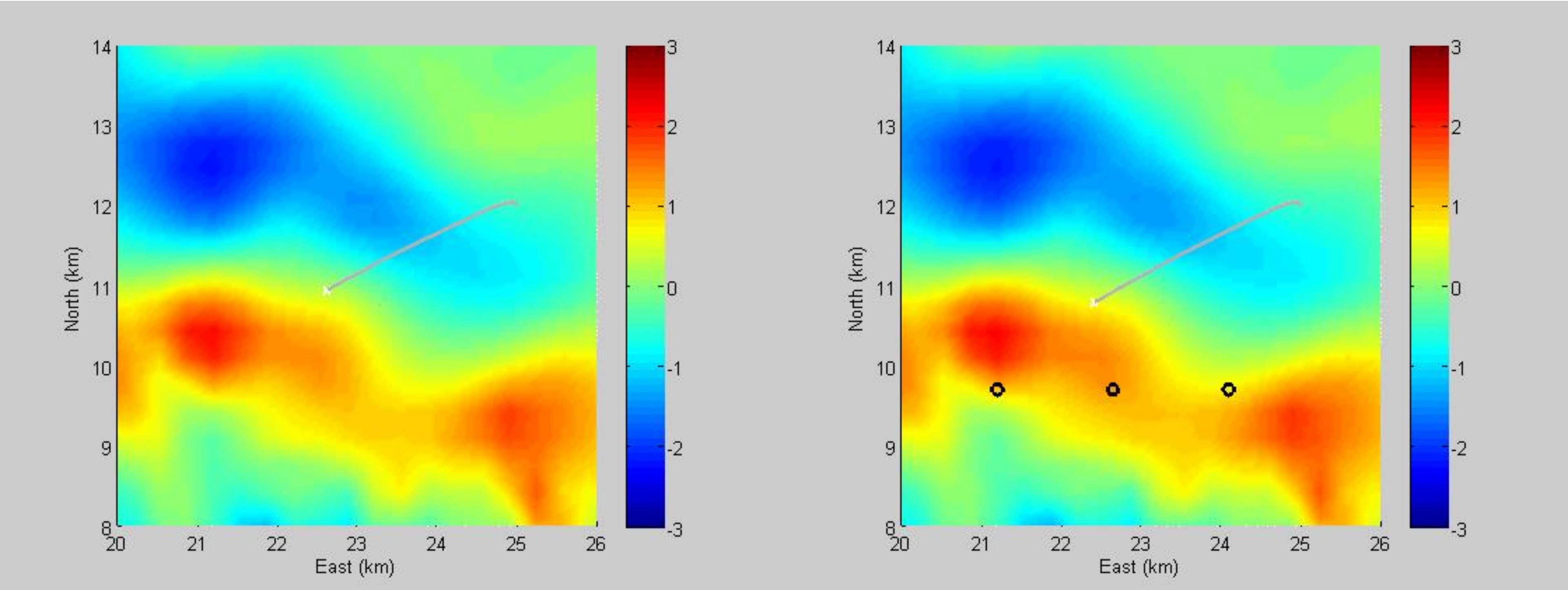
WRF Wind Field

- WRF data from a single instant in simulation time of a 35km x 35km grid was provided by Simpson Weather
- Simulation results presented here focus on the mountain wave circled below

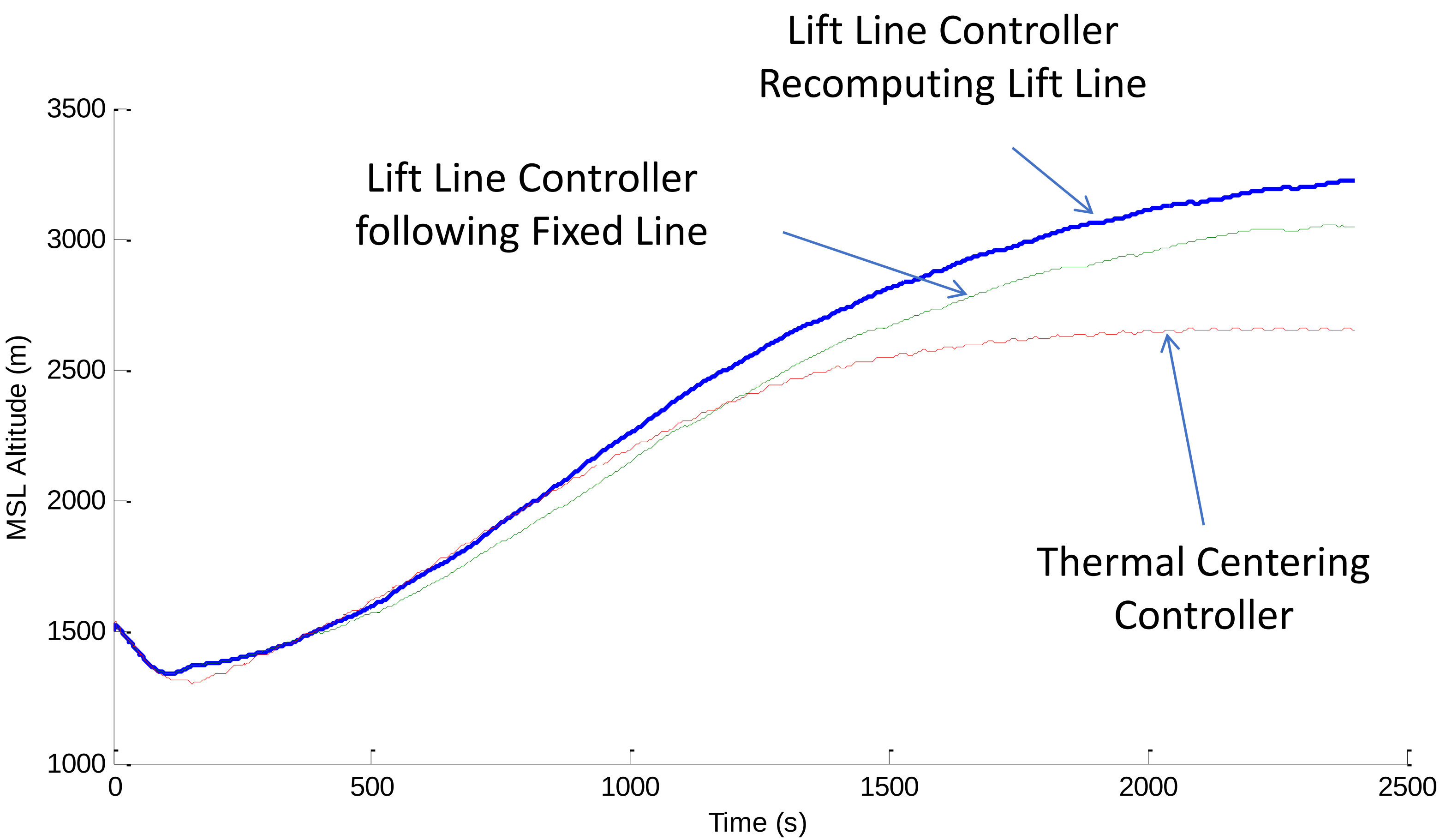


Thermal centering & lift line controller comparisons for mountain waves

- Comparing Trajectories using Thermal Centering and Lift Line Controller flying Mountain Wave in WRF simulated wind field



Net advantage comparisons



Small Scale Energy Extraction

- Employ control logic to extract energy from wind gusts to enhance efficiency in transit between waypoints
- Some work has been done optimizing simple control laws to enhance gliding efficiency in the presence of random vertical gusts
  - Patel, Lee, Kroo, "Extracting Energy from Atmospheric Turbulence," OSTIV, 2008.
  - Langelaan, "Gust Energy Extraction for Mini and Micro Uninhabited Aerial Vehicles," Journal of Guidance Control and Dynamics, 2009.

$$\delta_e = K_1 w_g + K_2 V_a + K_3$$

δ_e = elevator, w_g = vertical gust, V_a = airspeed

$$\delta_e = K_1 w_g + K_2 V_a + K_3 + K_4 w_{g,x+50m} + K_5 u_{g,x+50m} + \cdots$$

- This work can be incorporated and also extended by using information from an onboard, forward-looking LIDAR

Mission Planning Tool for AEORA

Mission Planning Tool for AEORA