Garden Workshop 2015

01/07/2015

Mimicking the Albatross flight for long-range Mini-UAV applications

Vincent Bonnin

Institut Supérieur de l'Aéronautique et de l'Espace

Dpt Aérodynamique, Energétique et Propulsion (DAEP)

Jean-Marc Moschetta

Emmanuel Benard

University of the West of England

BRISTOL

Dpt Engineering Design and Mathematics

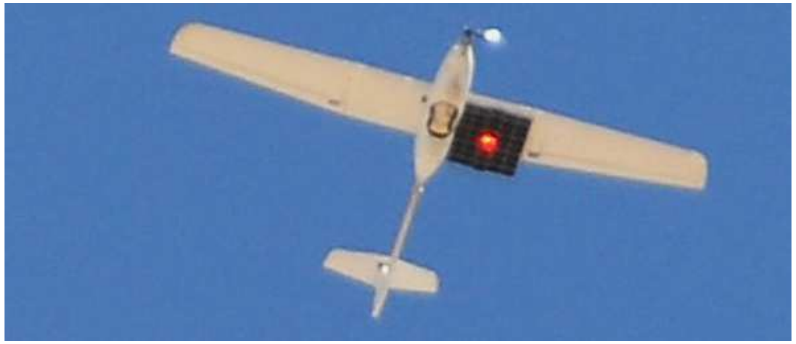
Chris Toomer

UK-French Joint - Supervised PhD

Long Endurance flight, a key factor of UAV utility

Ion Tiger

Energy Supply	Endurance
Fuel-Cell Powered	***48 h*** *(April 2013)*



LaserMotive (Lockheed Stalker)

Energy Supply	Endurance
Ground Beamed Laser	***48 h*** *(June 2012)*

Puma AE

Energy Supply	Endurance
Solar Powered	***9 h*** *(August 2013)*

Wandering Albatross

Mass	Wing span	*AR*	*Endurance*	*Energy Supply*
~ 9 kg	***~ 3 m***	***~ 15***	***days***	***?***

Late 19th century observations

Apparent Positive Energy Contribution:

Non-flapping flight

Late 1980s measurements

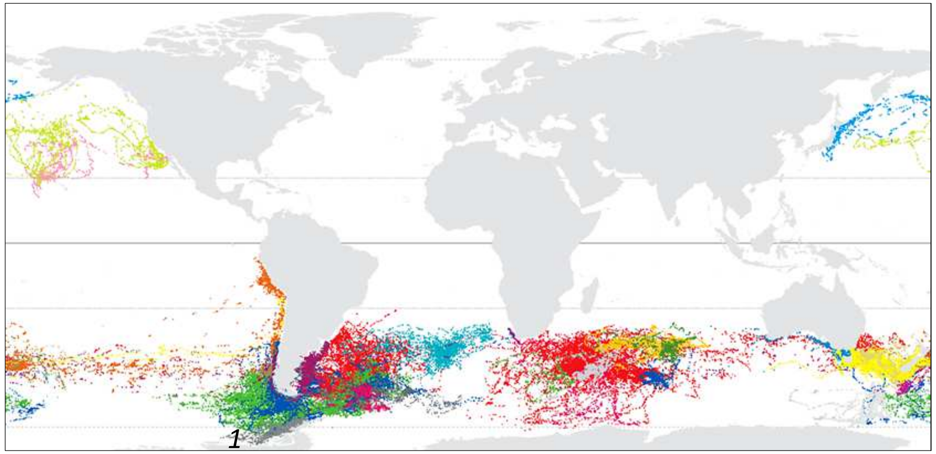
Significant Travel Performances:

Over 800 km a day on average

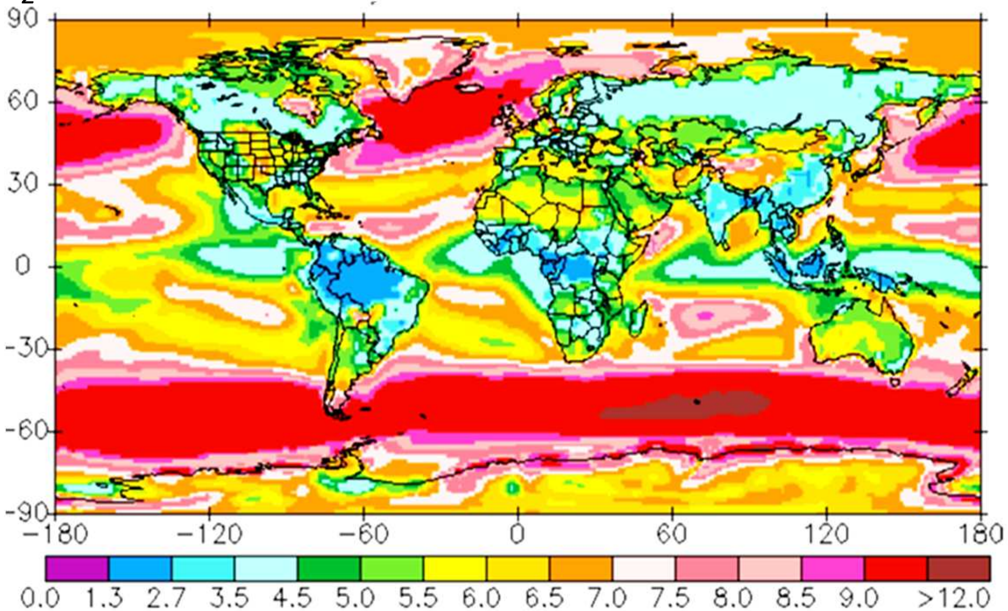
Research Topic

Albatross & Wind worldwide distribution

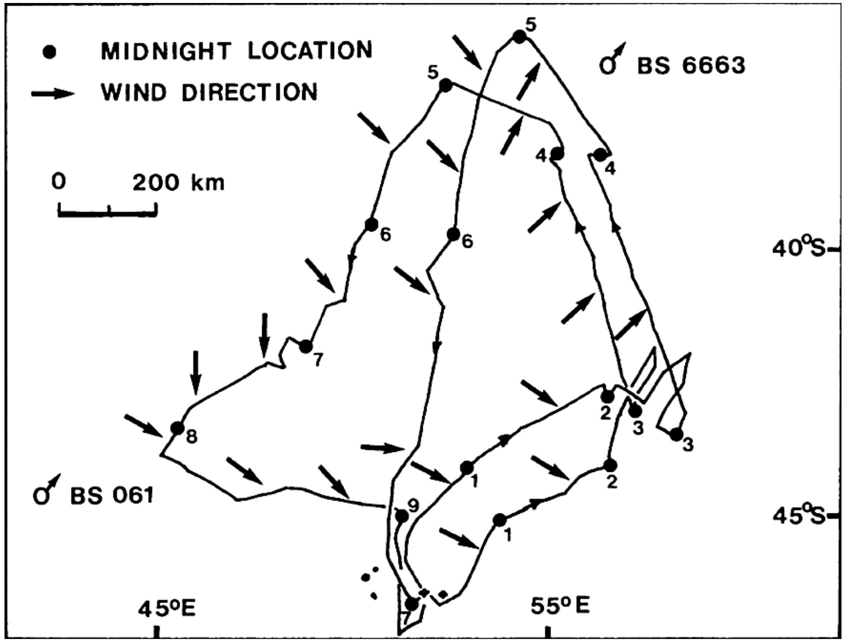
1



2



3



Simultaneous trips of two males from Crozet Islands

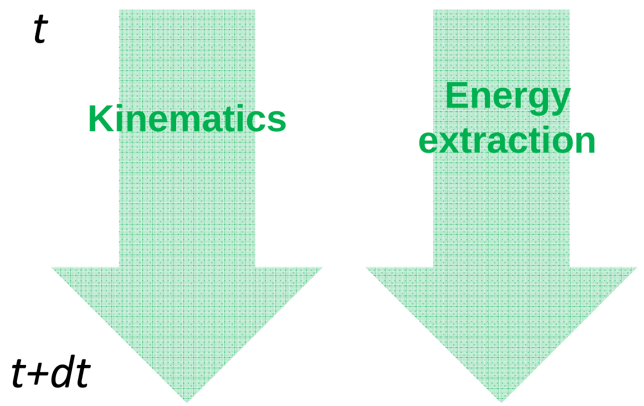
1_Birdlife International, "Tracking Ocean Wanderers", 2004

2_NASA, "Surface meteorology and solar energy: Methodology", 2004

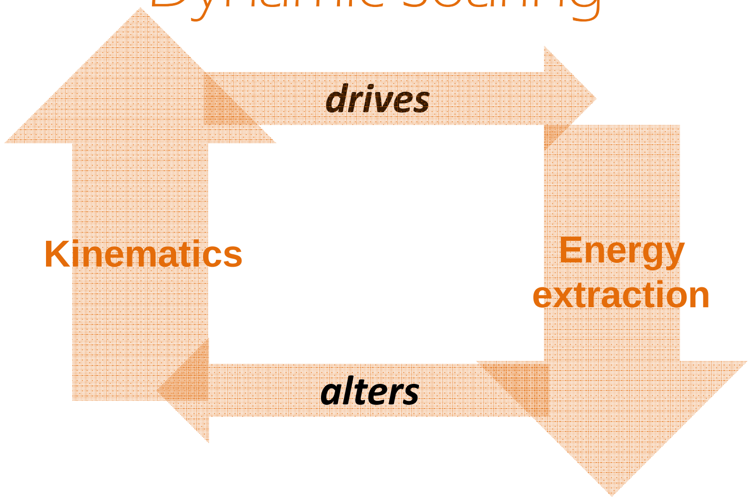
3_H. Weimerskirch et al. "Foraging Strategies of Wandering Albatrosses through the Breeding Season: A Study Using Satellite Telemetry",April 1993

Definition

Static Soaring



Dynamic Soaring

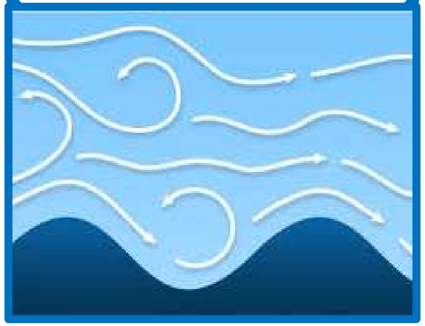


Vehicle model

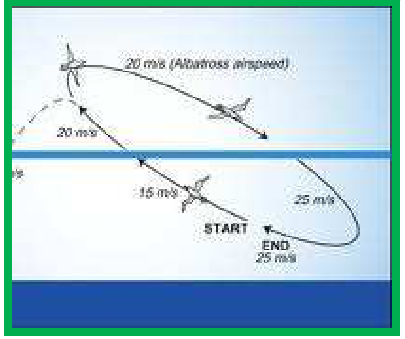
Which vehicle would be suitable for DS flight?

What are the environment condition required for DS?

Environment model



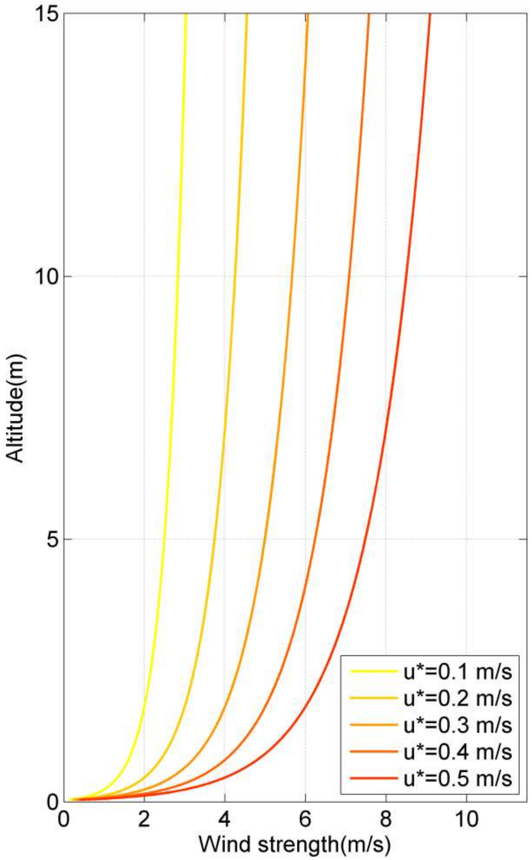
Flight Model

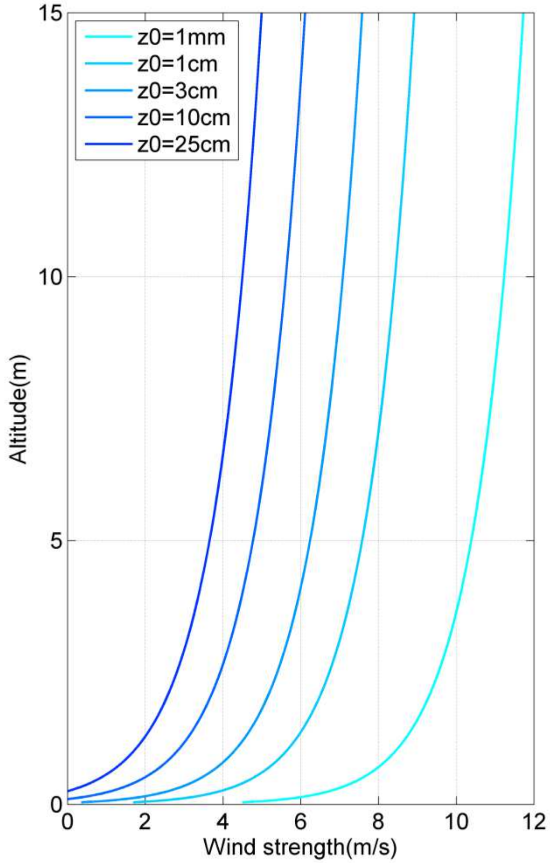


Which trajectories would optimize energy-extraction?

Rather flat surface, non-smooth

Mean velocity profile of a turbulent boundary layer $$\bar{u}(z) = \frac{u_*}{\chi} log\left(\frac{z}{z_0}\right)$$



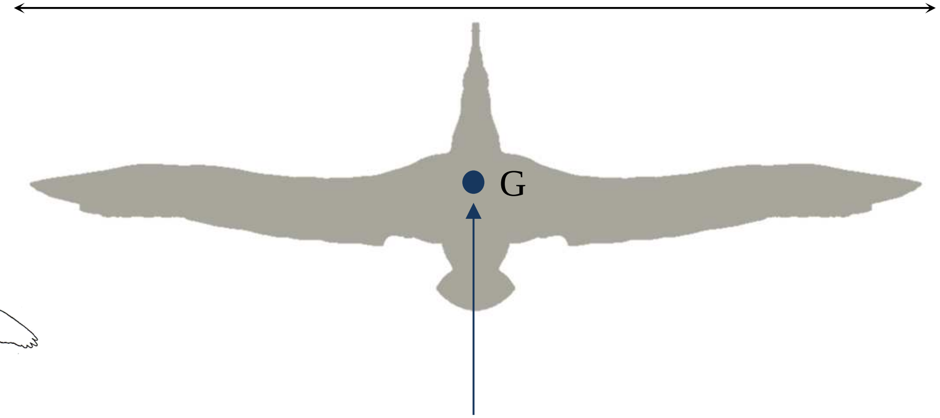


Point Mass Model

with Aerodynamic behaviour

Wandering Albatross

3.30 m



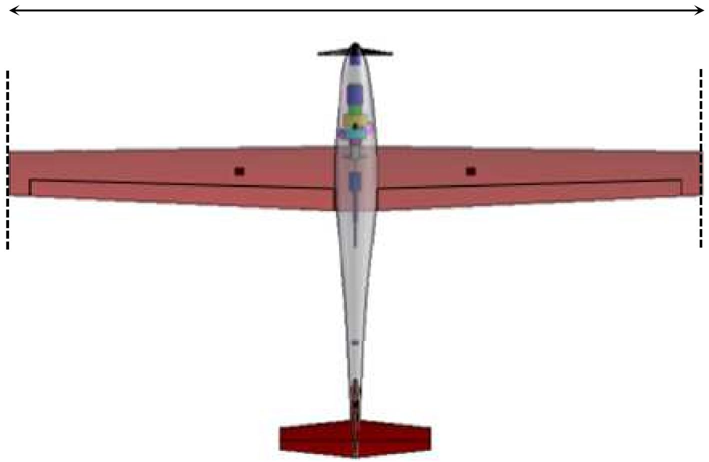
Pigeon

60 cm

$$L = \frac{1}{2}\rho . S . \boldsymbol{C_L} . V_{Air}{}^2 \qquad D = \frac{1}{2}\rho . S . \left(C_{D0} + C_{D2} . \boldsymbol{C_L}{}^2\right) . V_{Air}{}^2$$

UAV

2.5 m



	UAV	***Wandering Albatross***
Mass	***6.6 kg***	***8.5 kg***
Wing span	***2.49 m***	***3.3 m***
Wing Area	***0.485 m²***	***0.65 m²***
$(C_L/C_D)_{max}$	***20.5***	***20***

Bower, "Boundary Layer Dynamic Soaring for Autonomous Aircraft: Design and Validation. Ph.D. Dissertation",2011

Earth inertial reference frame
Point-Mass model

Equations of motion

Inertial speed $\mathrm{m}.\dot{\mathbf{V}} = \mathrm{L}.(\sin\varepsilon.\cos\delta.\cos\boldsymbol{\phi} + \sin\delta.\sin\boldsymbol{\phi}) - \mathrm{D}.\cos\varepsilon.\cos\delta + m.g.\sin\gamma$

Azimuth angle $\mathrm{m}.\dot{\boldsymbol{\psi}}.\mathrm{V}.\cos\gamma = \mathrm{L}.(\sin\varepsilon.\sin\delta.\cos\boldsymbol{\phi} - \cos\delta.\sin\boldsymbol{\phi}) - \mathrm{D}.\cos\varepsilon.\sin\delta$

Flight path angle $-\mathrm{m}.\dot{\boldsymbol{\gamma}}.\mathrm{V} = \mathrm{L}.\cos\varepsilon.\cos\boldsymbol{\phi} + \mathrm{D}.\sin\varepsilon - m.g.cos\,\gamma$

East position $\dot{\mathbf{x}} = \mathrm{V}.\cos\gamma.\cos\psi$

North position $\dot{\mathbf{y}} = \mathrm{V}.\cos\gamma.\sin\psi$

Height $\dot{\mathbf{z}} = -\mathrm{V}.\sin\gamma$

with Aerodynamic behaviour

$$\mathrm{L} = \frac{1}{2}\rho.\mathrm{S}.\boldsymbol{C_L}.{V_R}^2$$

$$D = \frac{1}{2}\rho.\mathrm{S}.\left(C_{D0} + C_{D1}.\boldsymbol{C_L} + C_{D2}.{\boldsymbol{C_L}}^2 + C_{D3}.{\boldsymbol{C_L}}^3 + C_{D4}.{\boldsymbol{C_L}}^4\right).{V_R}^2$$

$$X = \begin{pmatrix} \boldsymbol{V} \\ \boldsymbol{\psi} \\ \boldsymbol{\gamma} \\ \boldsymbol{x} \\ \boldsymbol{y} \\ \boldsymbol{z} \end{pmatrix} \qquad \dot{X} = \mathrm{G}(X, C_L, \phi)$$

Optimization Problem

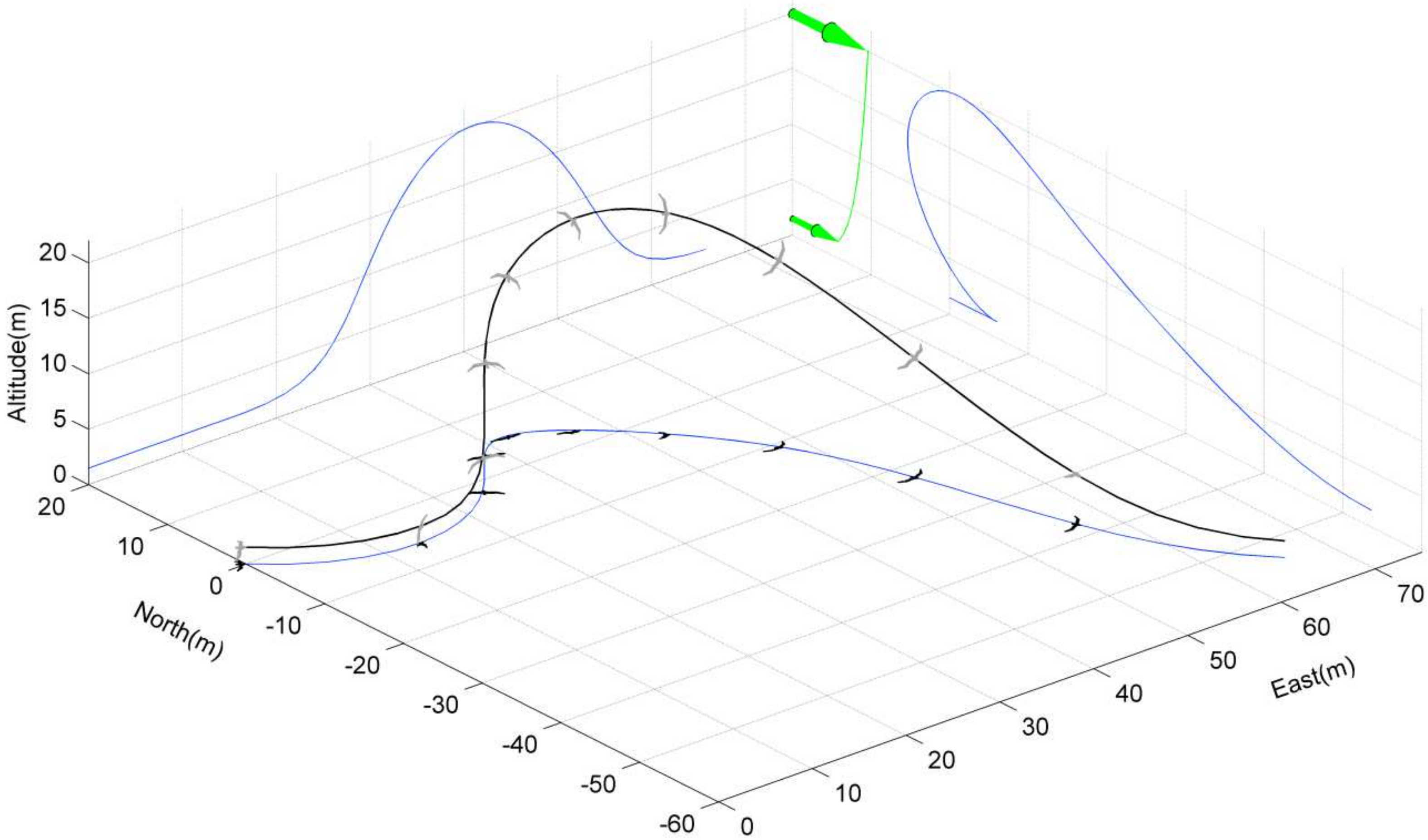
Minimize Nominal Wind: u_*

Subject to

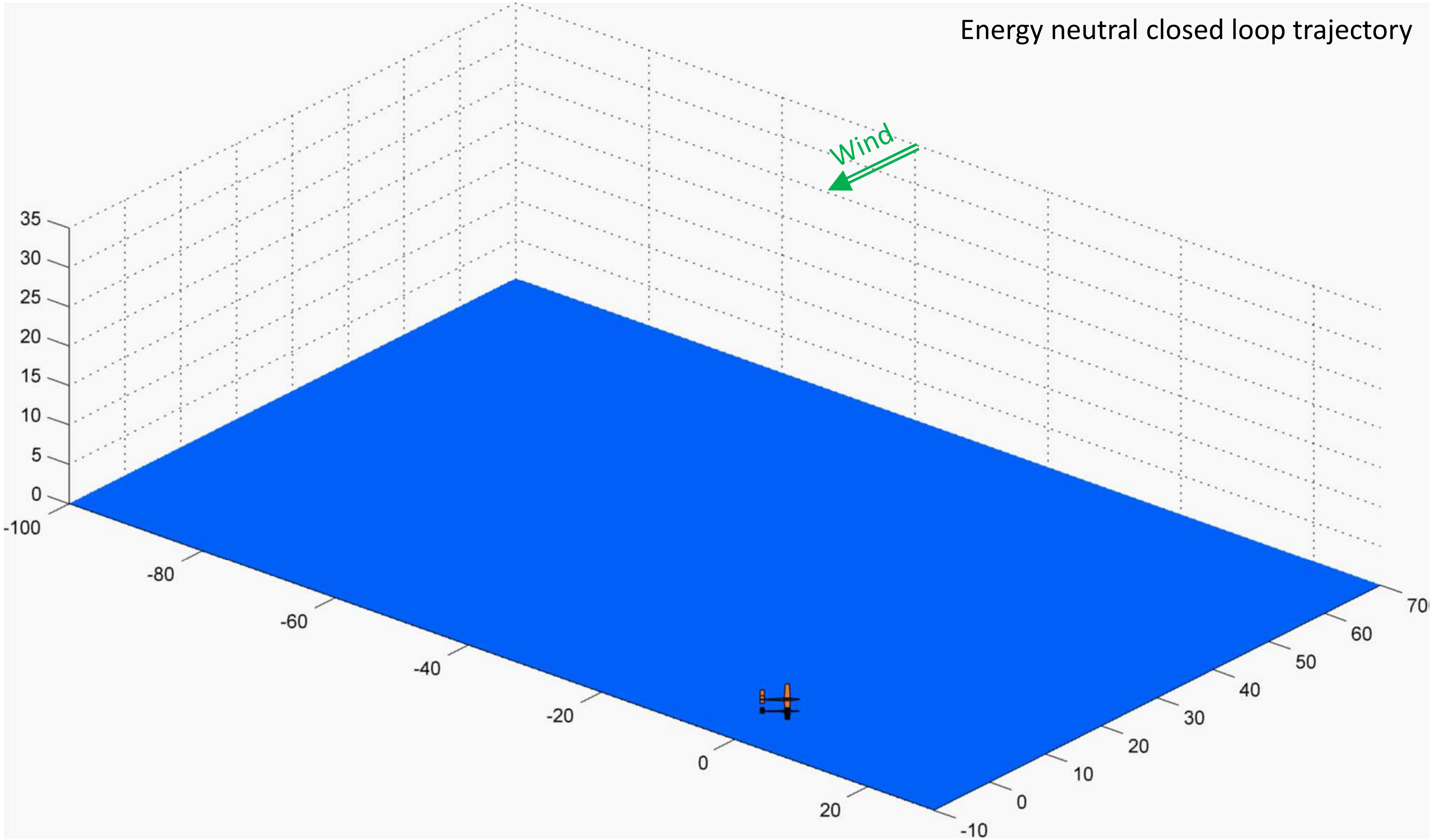
No stall	$C_L \leq 1.17$
Max. bank angle&rate	$-85^o \leq \phi \leq 85^o \quad \lvert\dot{\phi}\rvert \leq 90^o/s$
Max. flight path angle	$-75^o \leq \gamma \leq 75^o$
Wing tip clearance	50 cm
Equations of motion	$\dot{X} = G(X, C_L, \phi)$
Initial Conditions	$\{x_{initial}; y_{initial}\}$
Periodicity	$\begin{pmatrix} V \\ \psi \\ \gamma \\ x \\ y \\ z \end{pmatrix}_{\text{init}} = \begin{pmatrix} V \\ \psi \\ \gamma \\ x \\ y \\ z \end{pmatrix}_{\text{final}}$

Energy-Neutral Trajectory

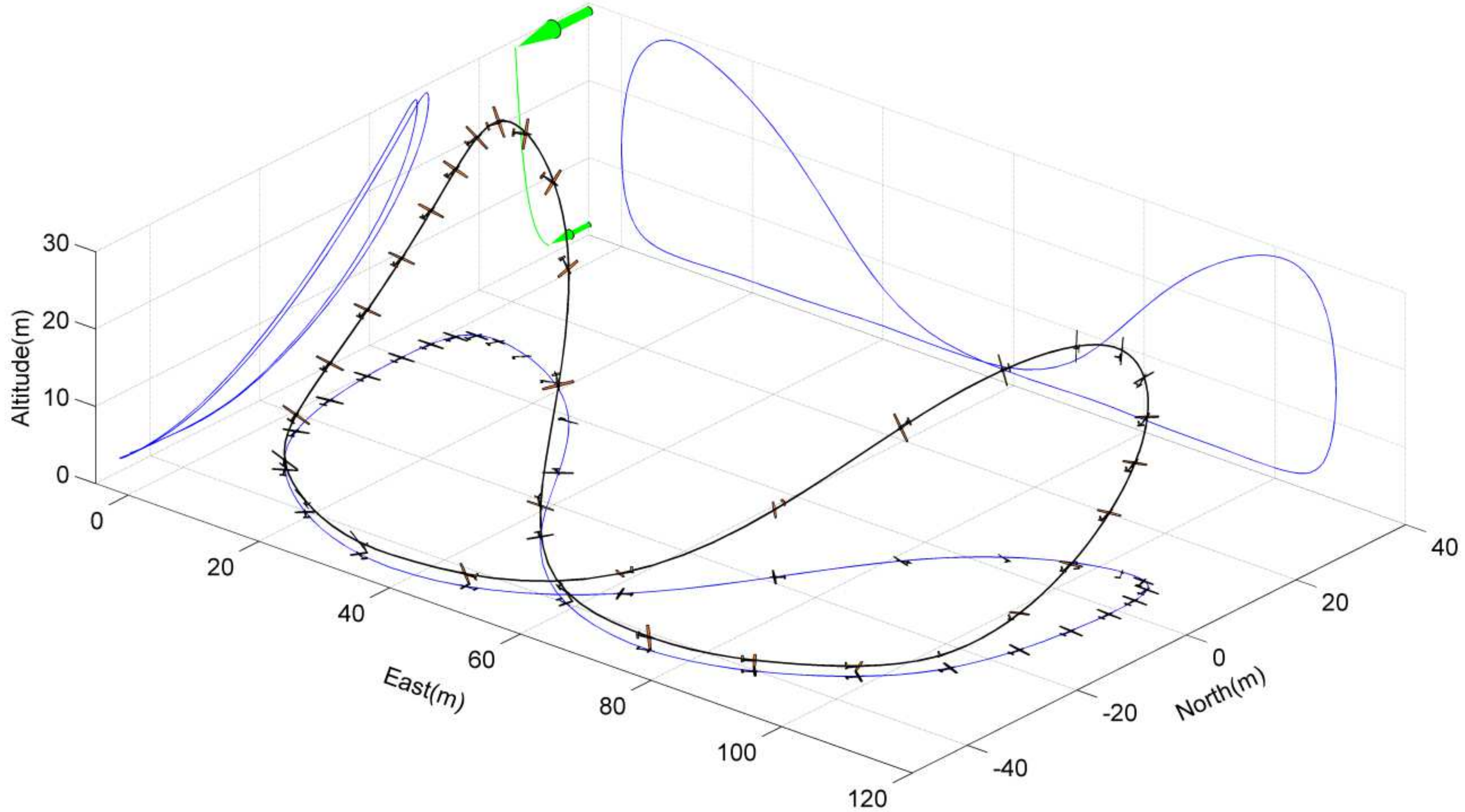
$$\boxed{E_{tot}(final) = E_{tot}(initial)}$$



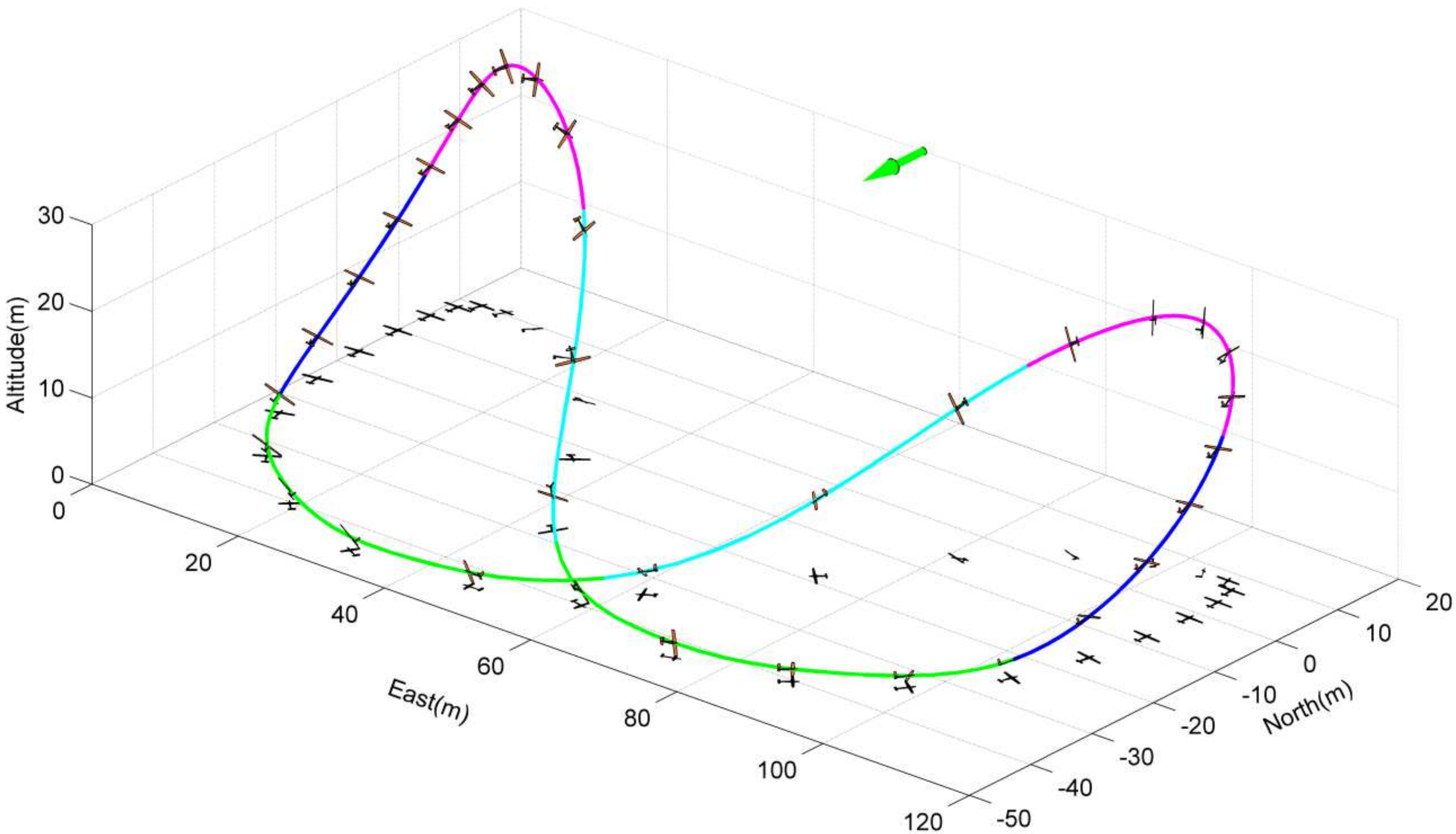
Optimized energy-neutral open trajectory


Energy neutral closed loop trajectory
Wind
35
30
25
20
15
10
5
0
-100
-80
-60
-40
-20
0
20
-10
0
10
20
30
40
50
60
70

Closed-Loop Trajectory



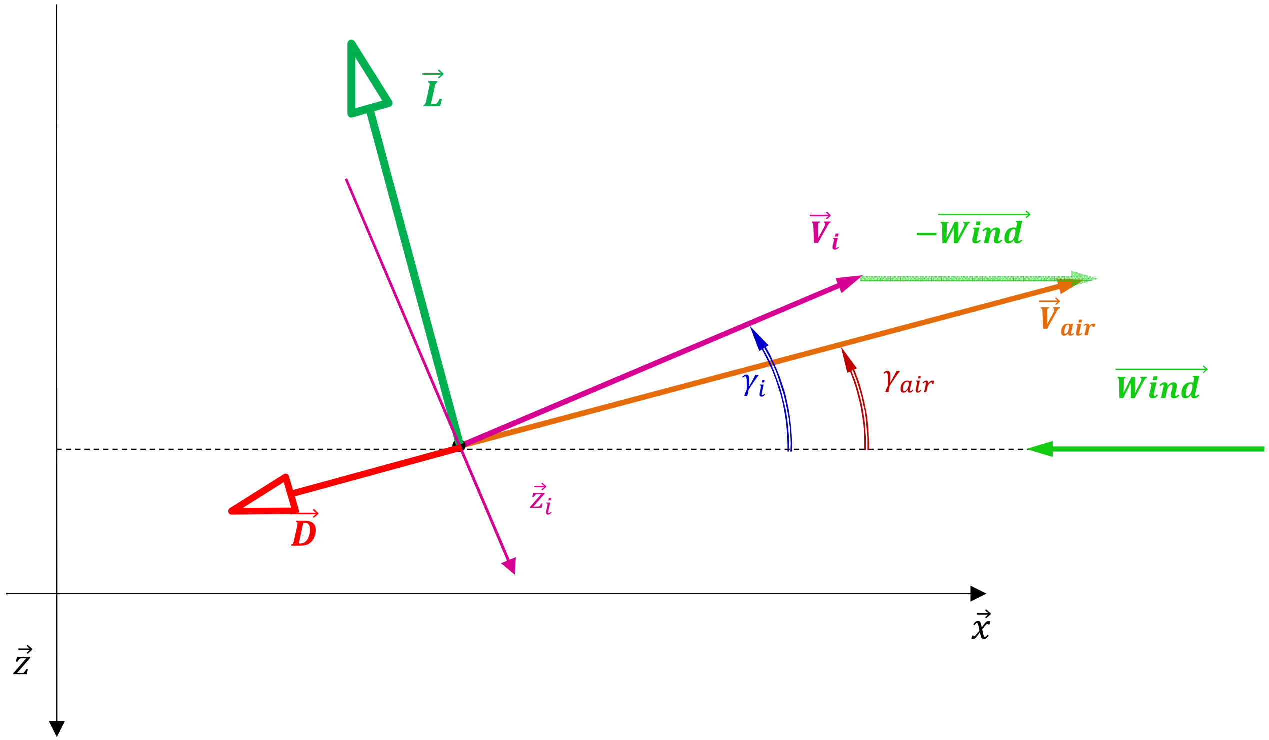
Optimized energy-neutral closed trajectory



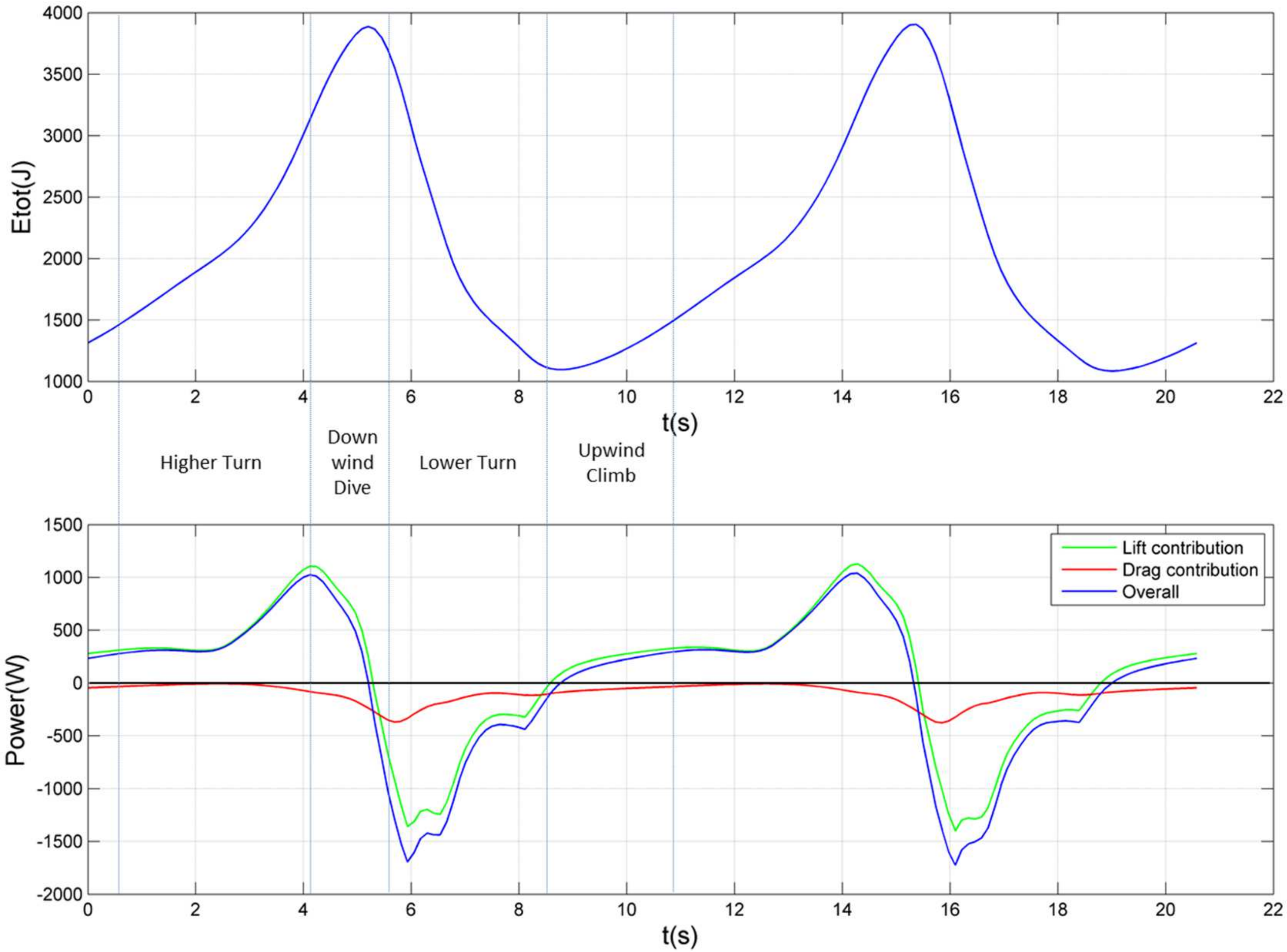
Optimized energy-neutral closed trajectory

Contributions from non-conservative forces

$$\frac{dE_{tot}}{dt} = \sum_{NCF} \vec{F}.\vec{V}_i = \left(\vec{L} + \vec{D}\right) \cdot (V_i.\vec{x}_i)$$



Overall Energy Cycle

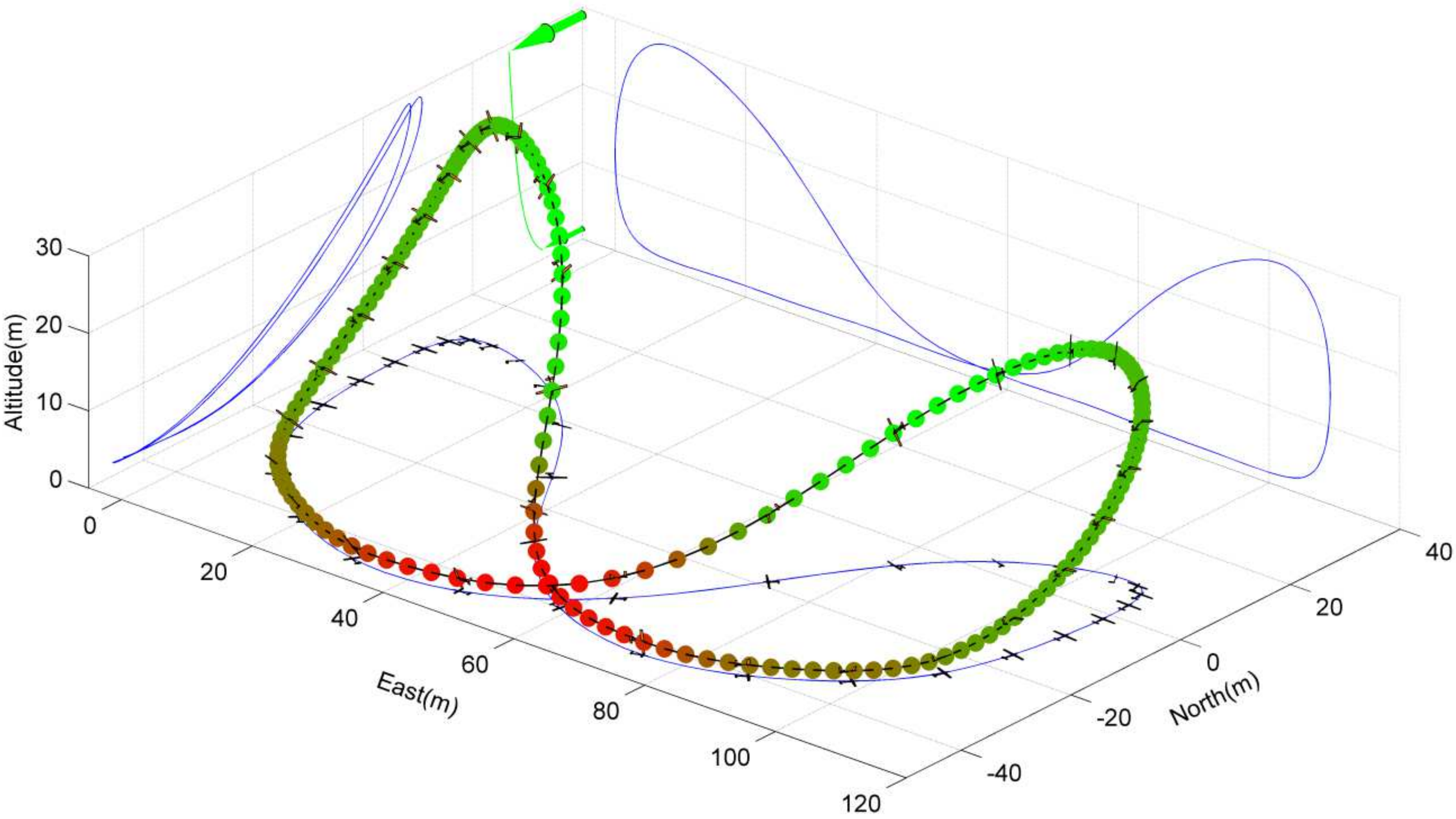


Variation in total energy with time

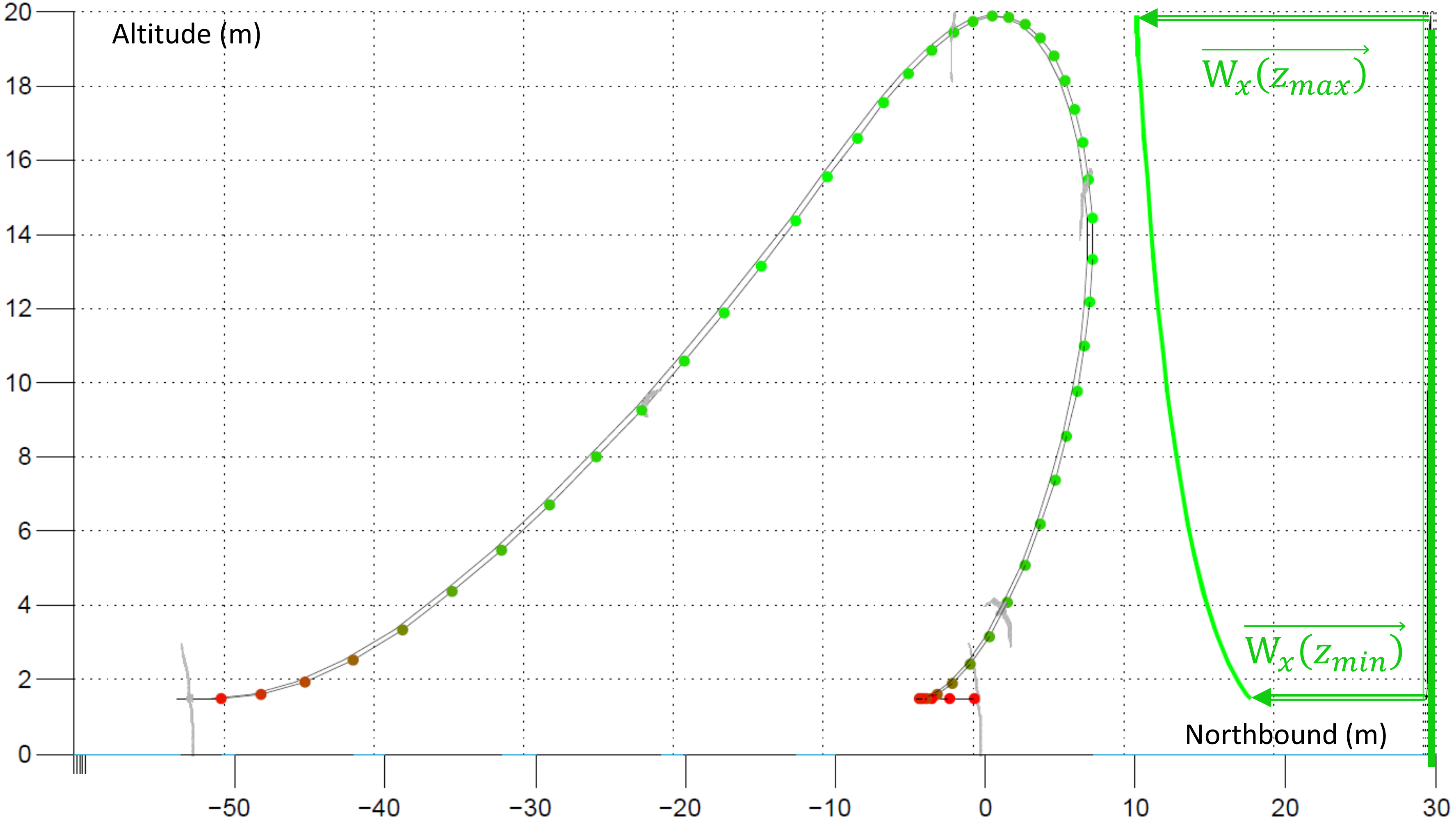
Periodic energy extraction

Variation in the components of energy rate with time

The Lift also provides a negative contribution at some parts of the trajectory

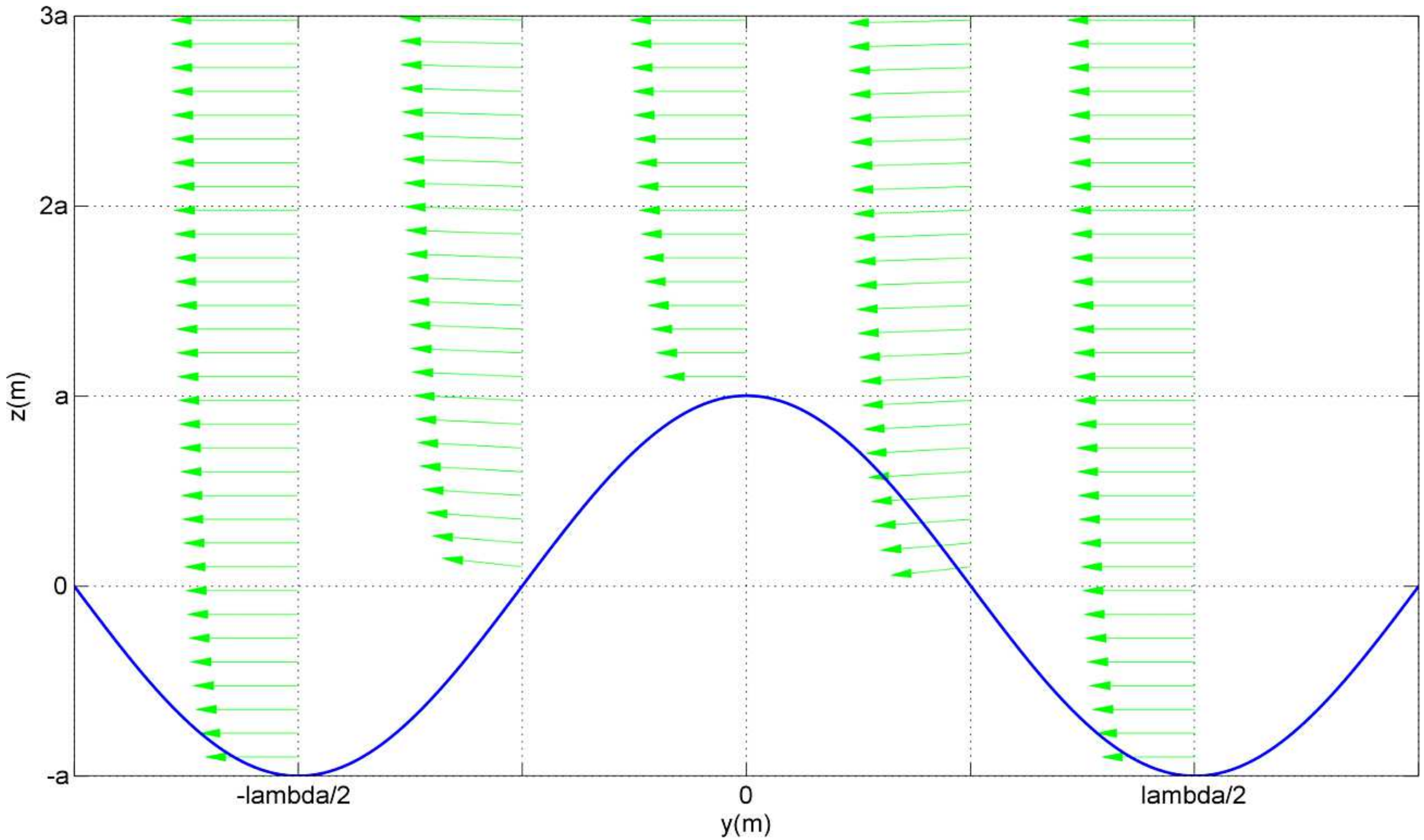


Energetic balance along an optimized energy-neutral closed trajectory



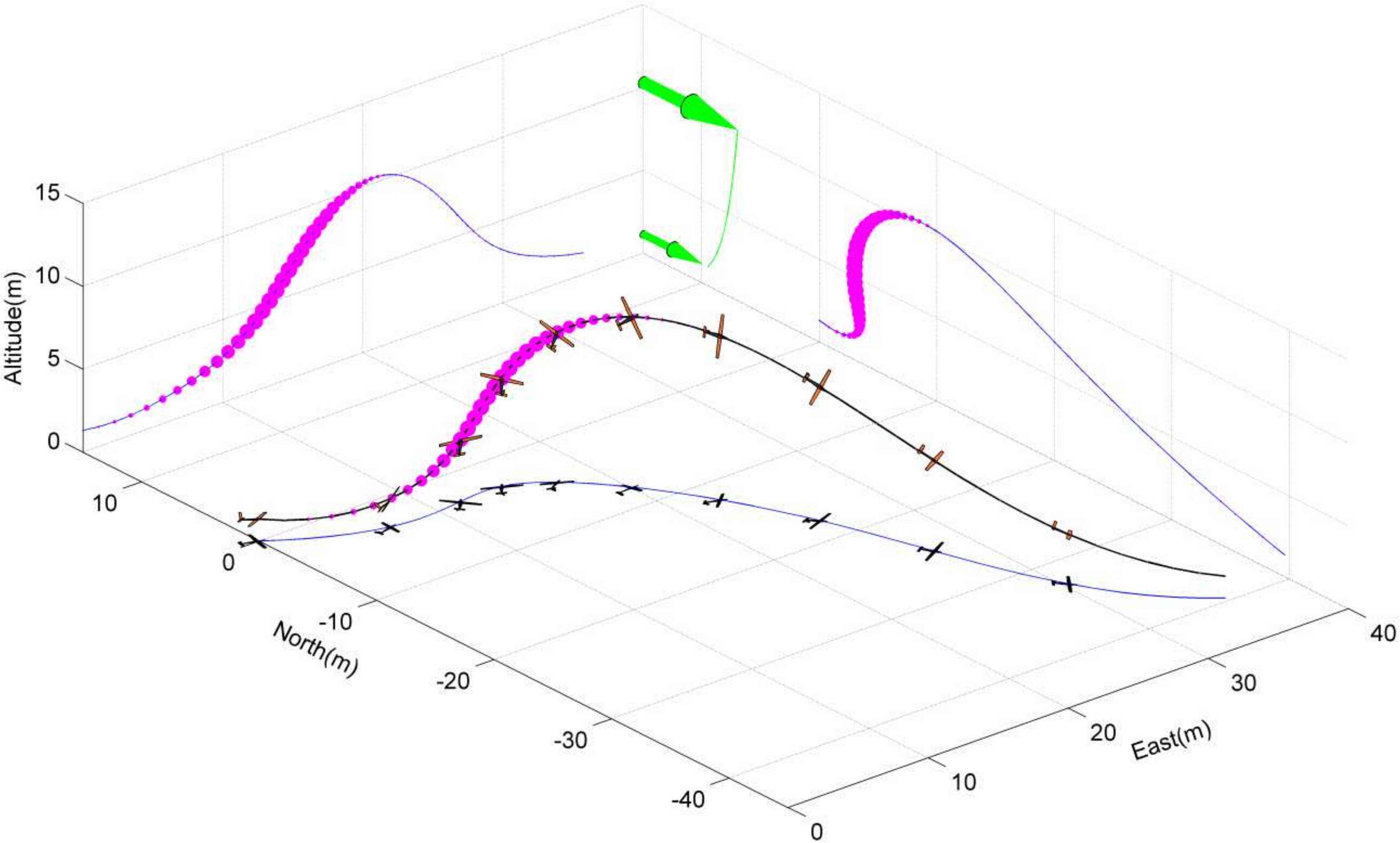
Vertical variation in horizontal wind enables repeatable energy-extraction cycle

Rather flat surface, non-smooth



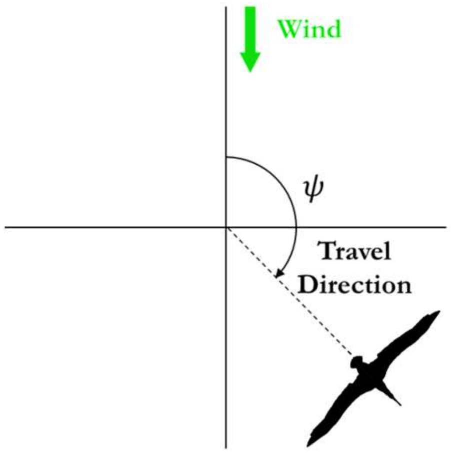
Velocity profiles of the wind established over a moving wavy surface

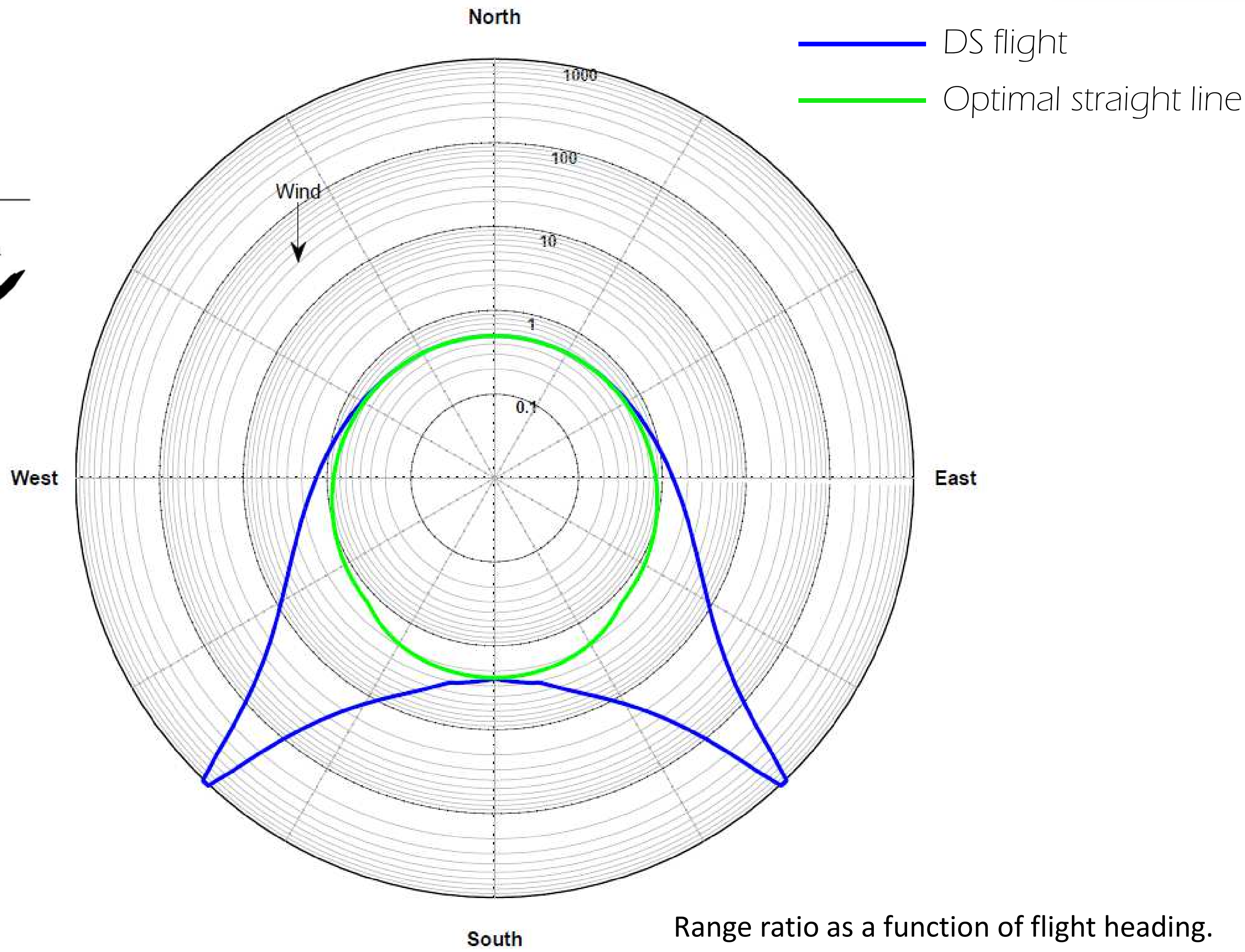
u_* decreased by 12%



Thrust-augmented-energy-neutral open loop

Range Performance by Dynamic Soaring

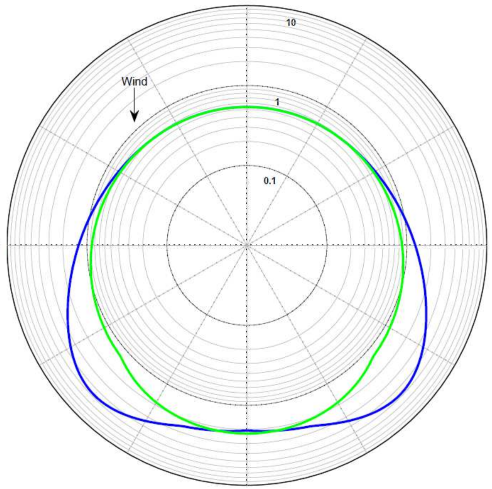




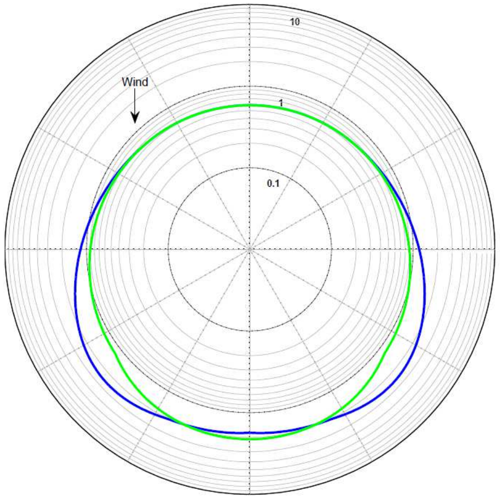
Range ratio as a function of flight heading.

Closing the loop

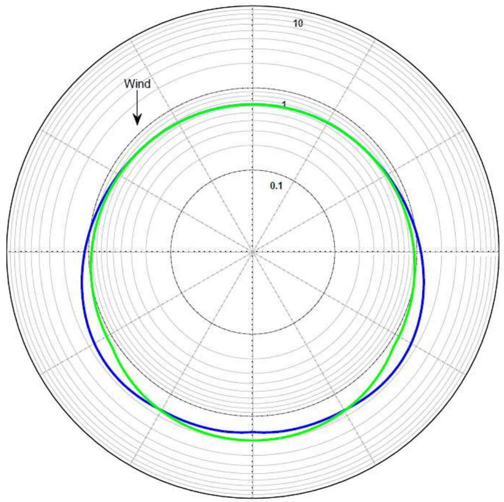
Variation in range performance with the wind strength at 10 m



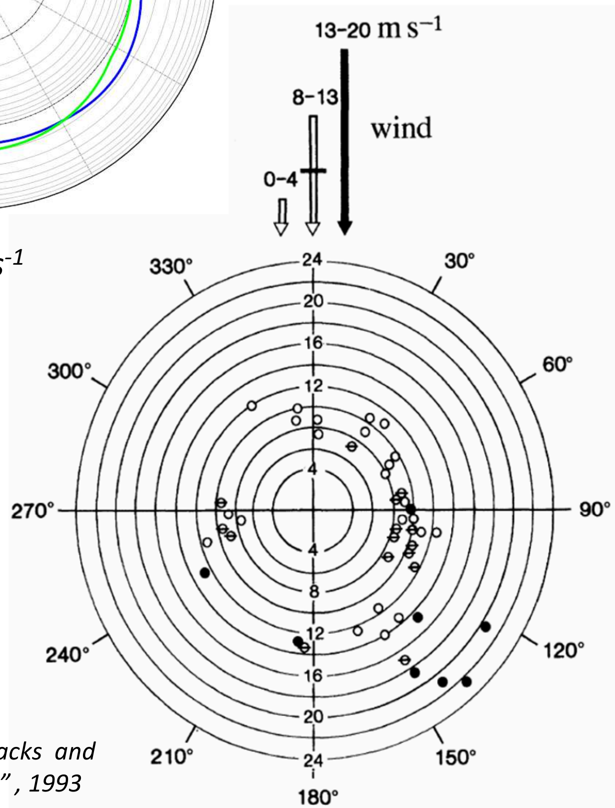
9 m.s^{-1}



8 m.s^{-1}



7 m.s^{-1}

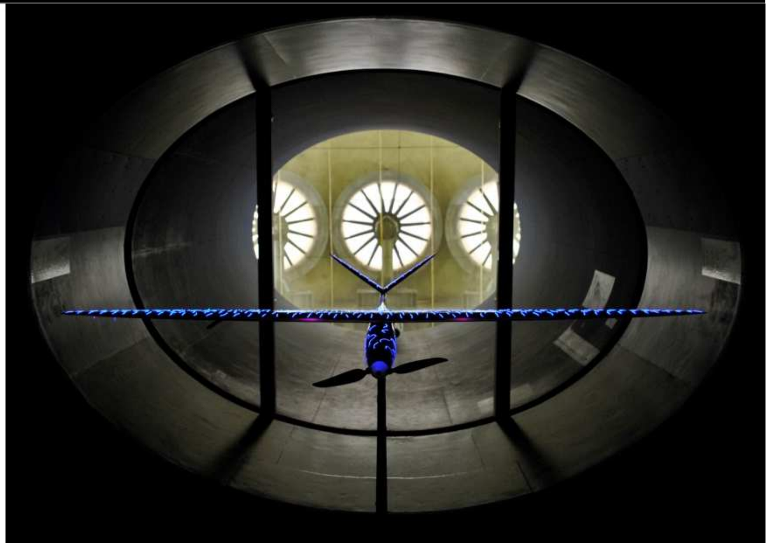


Variation in albatross's travel performances,
as a function of the wind strength and the flight heading

T. Alerstam, G. A. Gudmunsson and B. Larsson, "Flight Tracks and Speeds of Antartic Seabirds: Radar and Optical Measurements", 1993

Conclusions

- Simulation of DS flight
- Understanding of Energy-harvesting
- Variations in DS performances



Delair-Tech DT-18 in the ISAE S4 wind tunnel

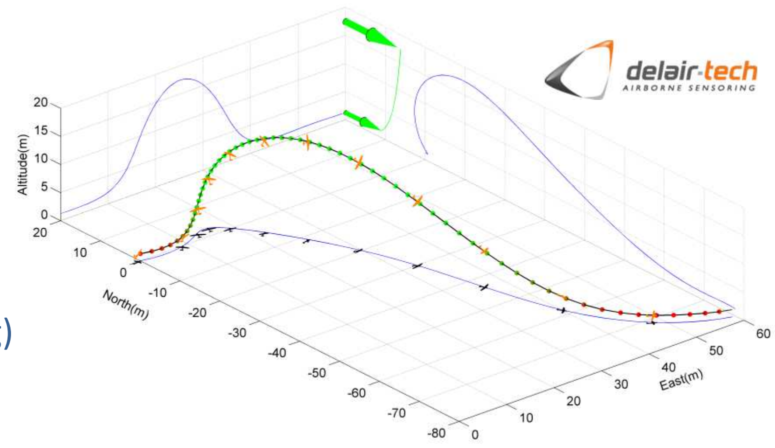
Perspectives

Get closer to practicability

- Turbulence disturbance
- Control-law strategy
- Experimental Validation

Enlarge the scope of DS

- Further control variables (flaps, regenerative soaring)
- Various environments: hill, jet stream
- Augment DS with gust soaring



DS simulation of Delair-Tech DT-18