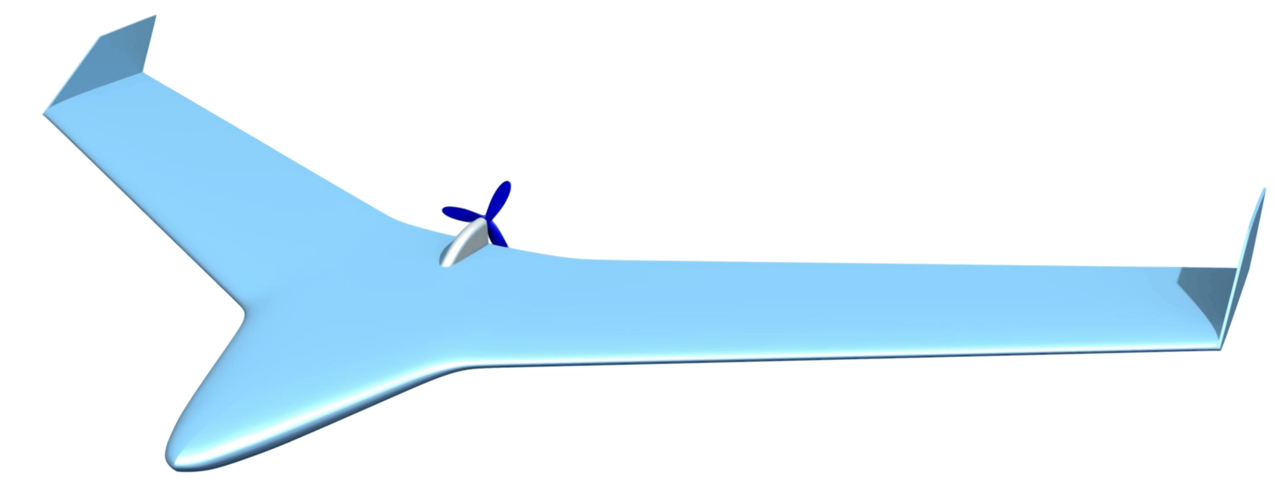
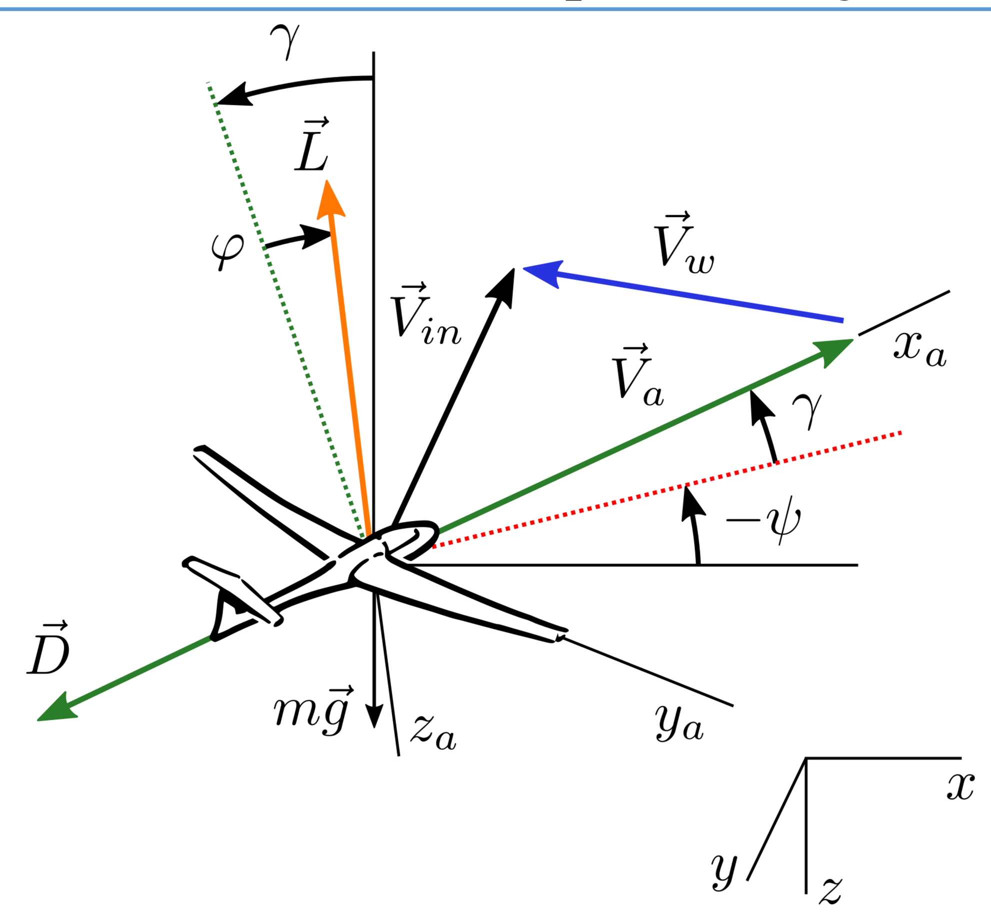
Atmospheric Flight Mechanics on Other Planets

Adrien Bouskela and Sergey Shkarayev



The successful deployment of sailplanes on other planets of the solar system can provide a high volume of scientific data at a relatively low cost by exploiting atmospheric wind gradients and shear layers for dynamic soaring. In the present work comparative studies of such trajectories are conducted based on a three degree of freedom sailplane model. Establishing the necessary conditions for energy positive soaring on Mars, Venus and Titan.

Method: 3Dof Model & optimal trajectory



- Three degree of freedom sailplane model with parameters($C_{L_{max}} = 0.8, C_{D_0}, C_L/C_D|_{max}$) and scaling $V = \sqrt{\frac{mg}{0.5\rho S}}$, $Z = \frac{m}{0.5\rho S}$, $T = \sqrt{\frac{m}{0.5\rho S g}}$, on velocity, length and time allows for the governing equations :

$$\vec{V}_{in}' = \vec{V}_a' + \vec{V}_w' = \begin{bmatrix}\dot{x}'\\ \dot{y}'\\ \dot{z}'\end{bmatrix} = V_a'\begin{bmatrix}\cos(\psi)\cos(\gamma)\\ \cos(\gamma)\sin(\psi)\\ -\sin(\gamma)\end{bmatrix} + \begin{bmatrix}V_{wx}'\\ V_{wy}'\\ V_{wz}'\end{bmatrix}$$

$$\dot{V}_a' = -D^* - \sin(\gamma) + \dot{V}_{wz}'\sin(\gamma) - \dot{V}_{wy}'\sin(\psi)\cos(\gamma) - \dot{V}_{wx}'\cos(\gamma)\cos(\psi)$$
$$V_a'\,\dot{\gamma}' = L^*\cos(\varphi) - \cos(\gamma) + \dot{V}_{wy}'\sin(\gamma)\sin(\psi) + \dot{V}_{wx}'\sin(\gamma)\cos(\psi) + \dot{V}_{wz}'\cos(\gamma)$$
$$V_a'\cos(\gamma)\,\dot{\psi}' = L^*\sin(\varphi) + \dot{V}_{wx}'\sin(\psi) - \dot{V}_{wy}'\cos(\psi)$$

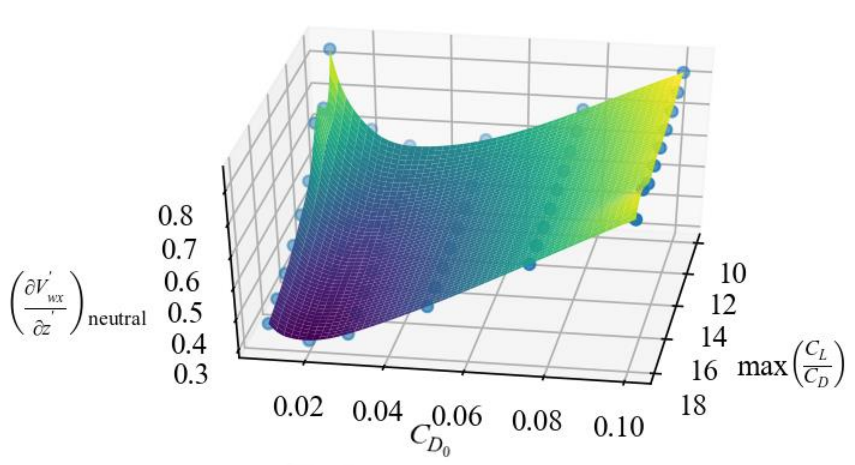
$$L^* = V_a'^2\, C_L; \qquad D^* = V_a'^2\left(C_{D_0} + kC_L^2\right)$$

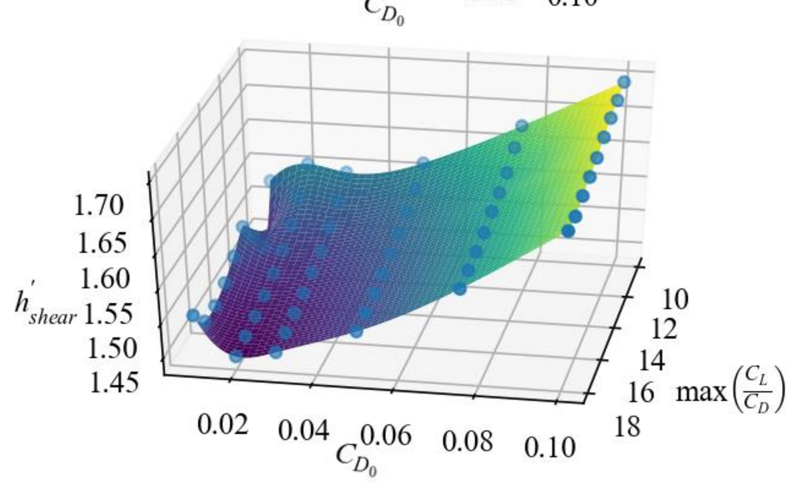
Optimal solution is sought with objective function subjected to constraints

$$\max_{C_L,\varphi}\left\{\frac{d}{dt'}(0.5V_a'^2)\colon \forall t'\right\}; \quad z' < 0; \quad V_{stall}' < V_a'; \quad z_{t'=0}' = z_{tf'}'; \quad \psi_{t'=0}' = \psi_{tf}'$$

Comparative study approach

- Assuming linear and unidirectional wind function $V_{wx}' = z'\frac{\partial V_{wx}'}{\partial z'} + V_{wx0}'$
- Solving optimal trajectory problem for $C_{L_{max}} = 0.8$; $C_{D_0} = [0.01, 0.02, \ldots, 0.1]$; $C_L/C_D|_{max} = [10, 11, \ldots, 20]$
- And finding $\partial V_{wx}'/\partial z'\,(C_{D_0}, C_L/C_D|_{max})$ for the energy neutral cycle, such that total energy at initial and final time is equal





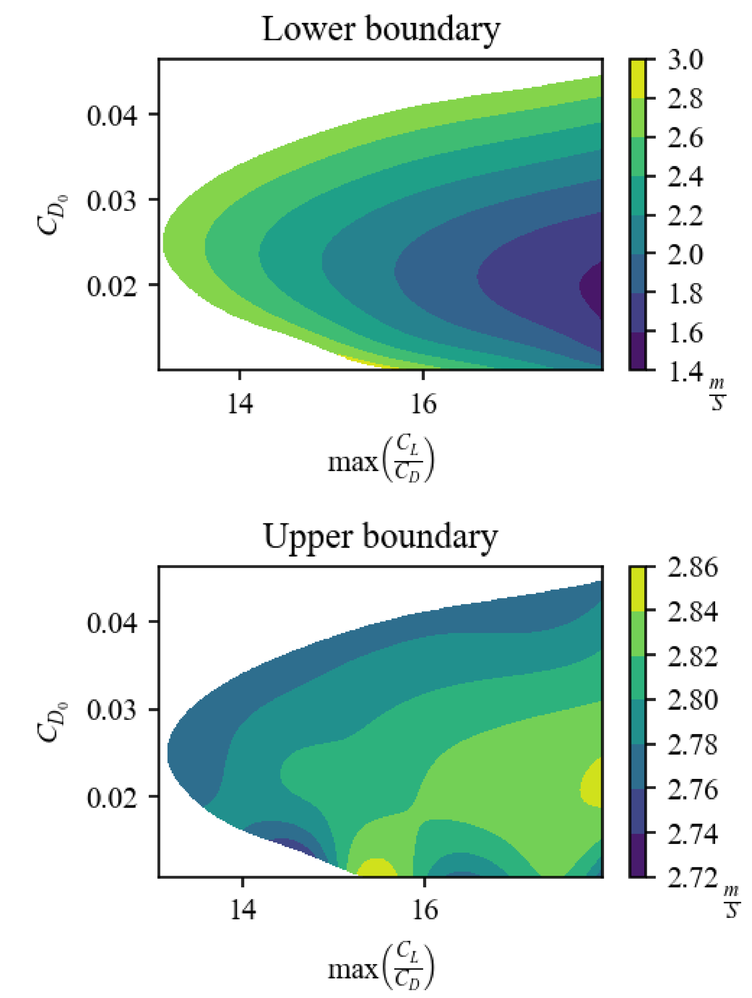
Based on the results for $\left(\partial V_{wx}'/\partial z'\right)_{neutral}$, and corresponding $h_{neutral}'$ sufficient conditions on the neutral energy cycle can be found

$$\frac{\left(\partial V_{wx}'/\partial z'\right)_{neutral}^2 0.5\rho g}{\left(\partial V_{wx}/\partial z\right)_{shear}^2} \le \frac{m}{S} \le \frac{h_{shear}0.5\rho}{h_{neutral}'}$$

Dynamic Soaring in Atmosphere of Mars, Titan, Venus

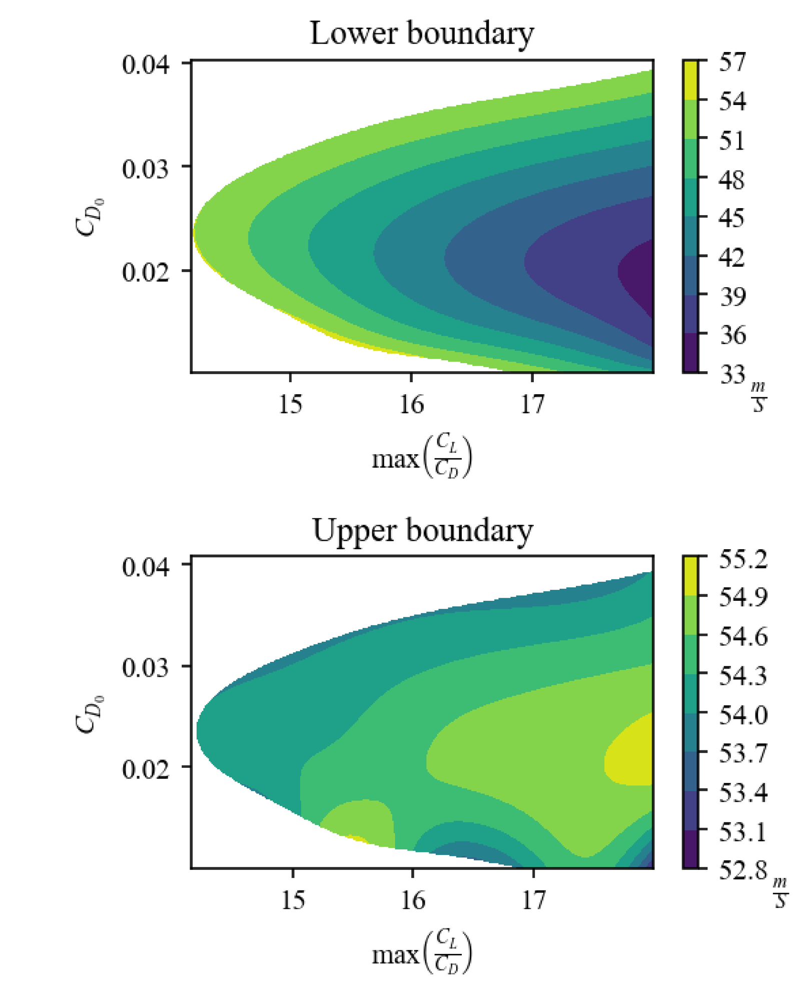
Mars at ground level: $\rho = 0.0137\ kg/m^3$ $g = 3.711\ m/s^2$ $\partial V_{wx}/\partial z \approx 40\ m/s\ /km$

boundaries on m/S for energy positive dynamic soaring, $h_{shear} = 600$ m



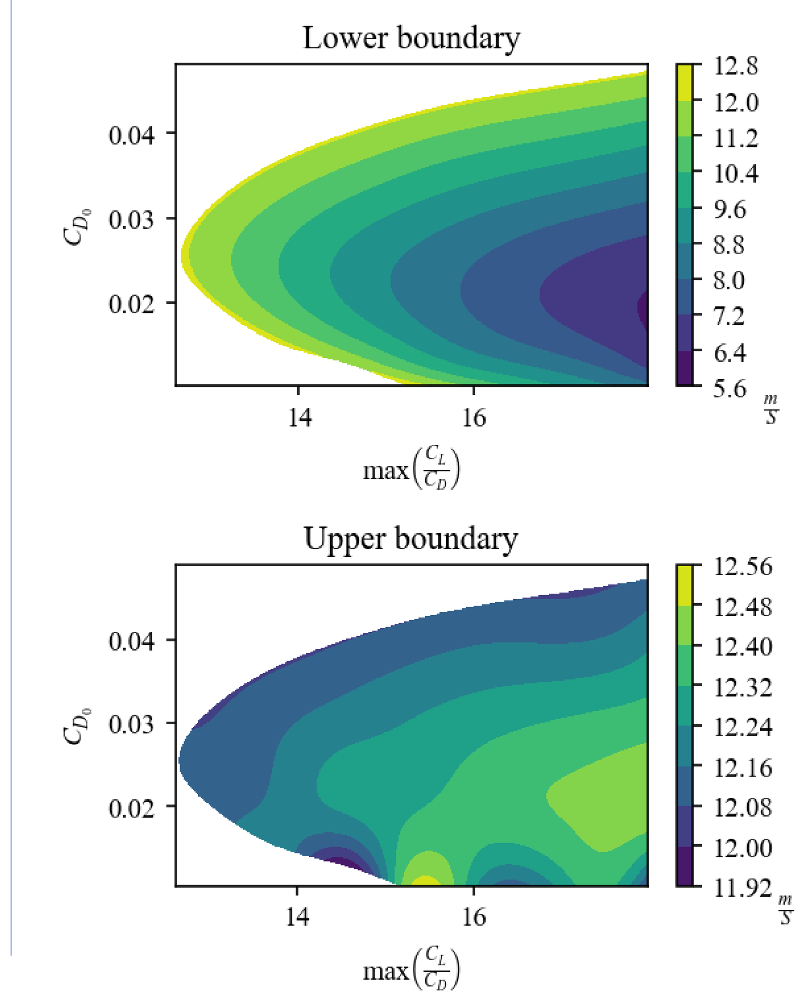
Titan at ground level: $\rho = 5.3\ kg/m^3$ $g = 1.35\ m/s^2$

boundaries on m/S for energy positive dynamic soaring, $h_{shear} = 30$ m, $\partial V_{wx}/\partial z = 100\ m/s\ /km$



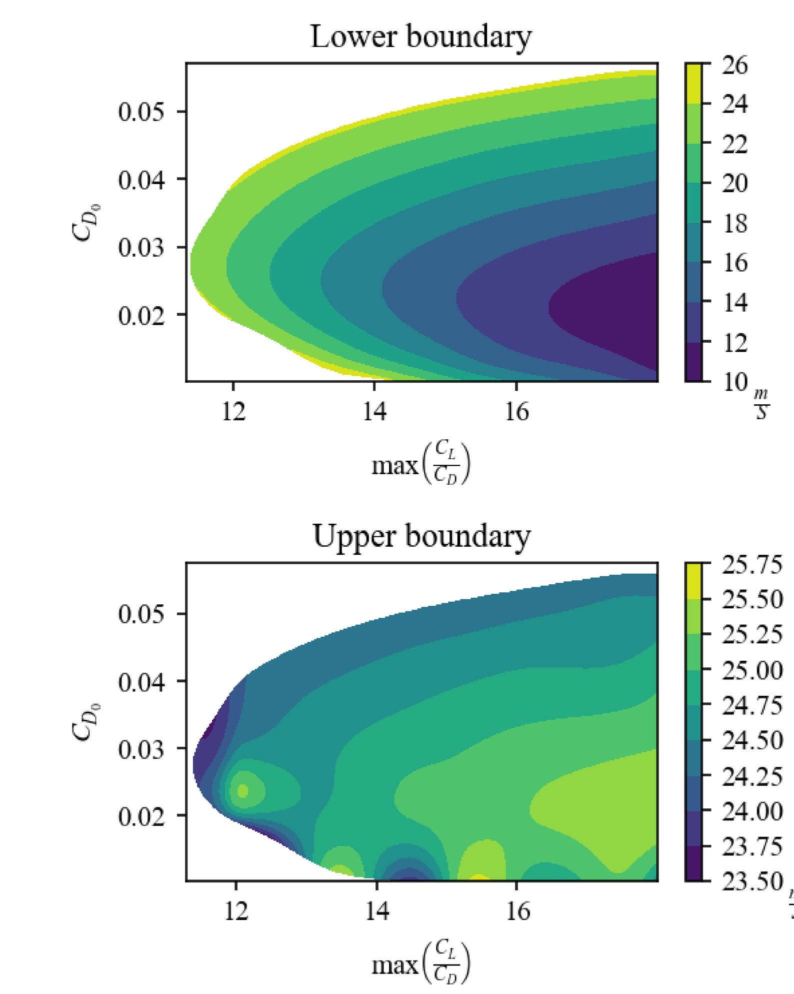
Titan in shear layer (80km): $\rho = 0.06\ kg/m^3$ $g = 1.35\ m/s^2$

boundaries on m/S for energy positive dynamic soaring, $h_{shear} = 600$ m, $\partial V_{wx}/\partial z = 25\ m/s\ /km$



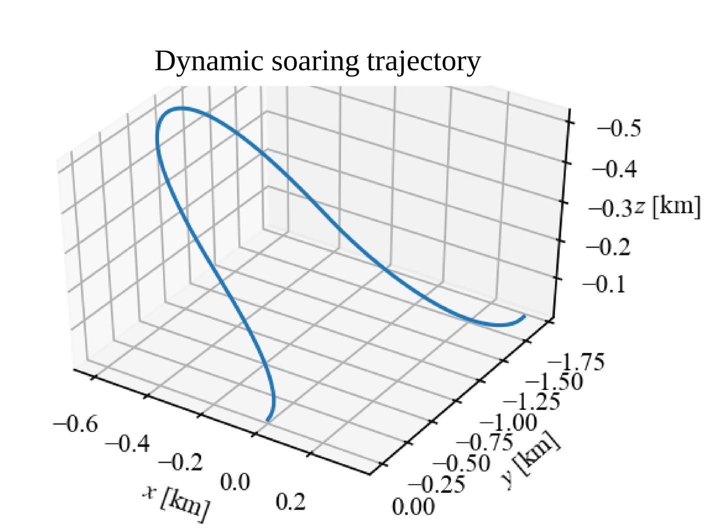
Venus in shear layer (50km): $\rho = 1.46\ kg/m^3$ $g = 8.87\ m/s^2$

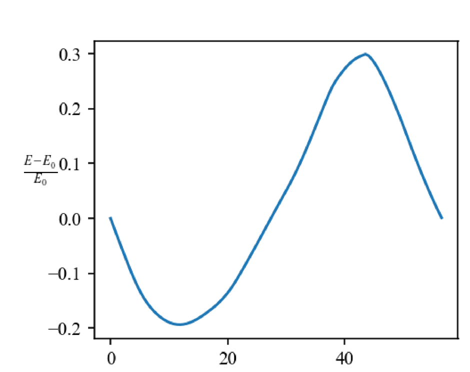
boundaries on m/S for energy positive dynamic soaring, $h_{shear} = 50$ m, $\partial V_{wx}/\partial z = 250\ m/s\ /km$



Sailplane Designs

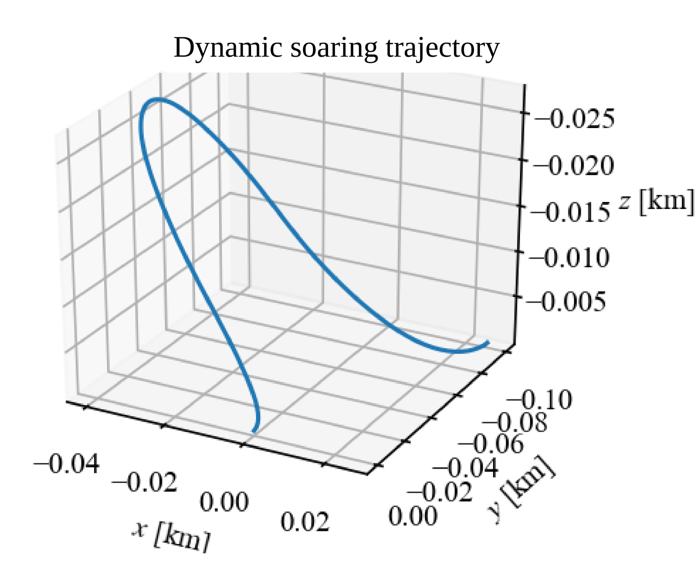
$S = 4.46\ m^2$ $m = 5\ kg$ $C_L/C_D|_{max} = 14.4$
$C_{D_0} = 0.027$ Wingspan = 5 m $\partial V_{wx}/\partial z = 40\ m/s\ /km$

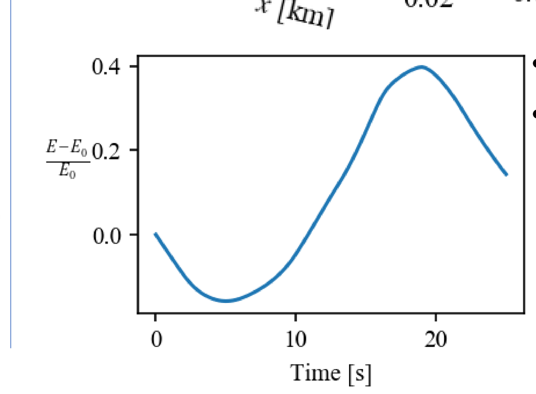




- excess power 43 W
- Narrow solution range
- Low Reynolds number range number (10^4 to 10^5)

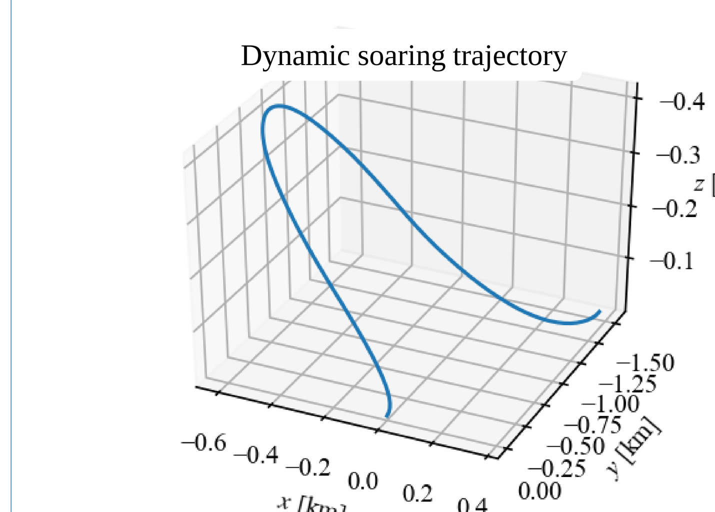
$S = 0.125\ m^2$; $m = 5\ kg$; $C_L/C_D|_{max} = 20$
$C_{D_0} = 0.015$; Wingspan = 1.0 m; $\partial V_{wx}/\partial z = 100\ m/s\ /km$

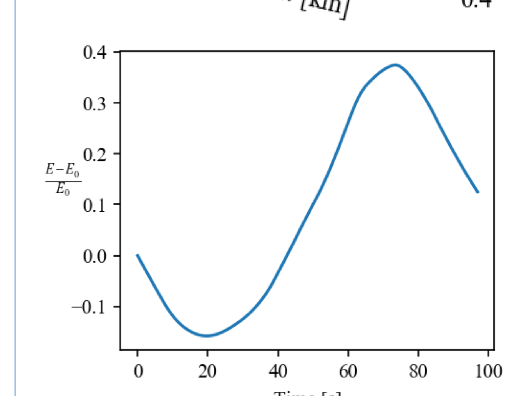




- excess power 42 W
- Efficient High Reynolds number flight with low speeds

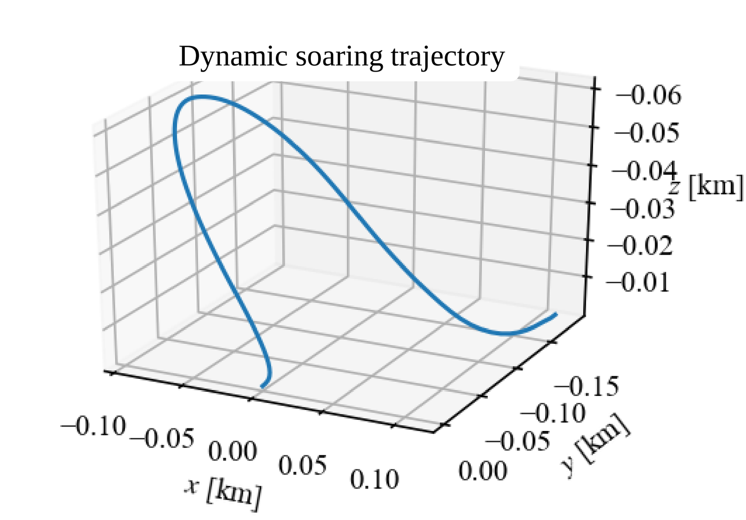
$S = 0.5\ m^2$; $m = 3.5\ kg$; $C_L/C_D|_{max} = 19.25$
$C_{D_0} = 0.015$; Wingspan = 1.7 m; $\partial V_{wx}/\partial z = 25\ m/s\ /km$

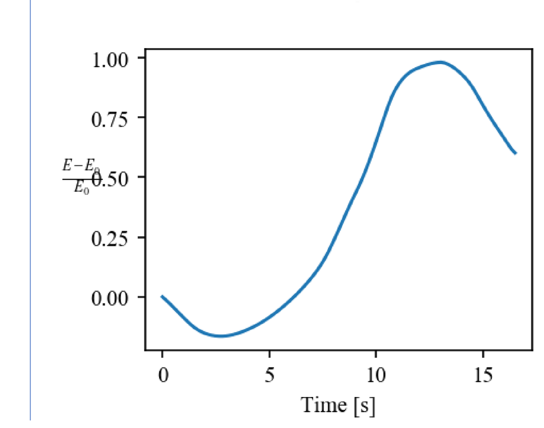




- excess power 496 W
- Most efficient dynamic soaring: high gain for low wind gradients

$S = 0.4\ m^2$; $m = 5\ kg$; $C_L/C_D|_{max} = 20$
$C_{D_0} = 0.015$; Wingspan = 1.5 m; $\partial V_{wx}/\partial z = 250\ m/s\ /km$





- excess power 434 W
- Near earth results: efficient soaring with large gradients over a small height

Conclusions

- The algorithm for comparative dynamic soaring cycles studies has been developed based on three degrees of freedom and linear unidirectional wind models. Allowing the expression of energy positive trajectories in various atmospheres.
- Sufficient conditions for the energy positive dynamic soaring are established providing wind shear gradients and altitude range. Higher density atmosphere requiring greater values over smaller heights for designs with wing loading ranging from 1 to 60.
- Dynamic soaring is feasible on Mars with a narrow wing loading range and requires a larger sailplane than for Titan or Venus, where it is easier to achieve within the given conditions in high altitude shear layers. Future studies are needed involving higher fidelity wind data.

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