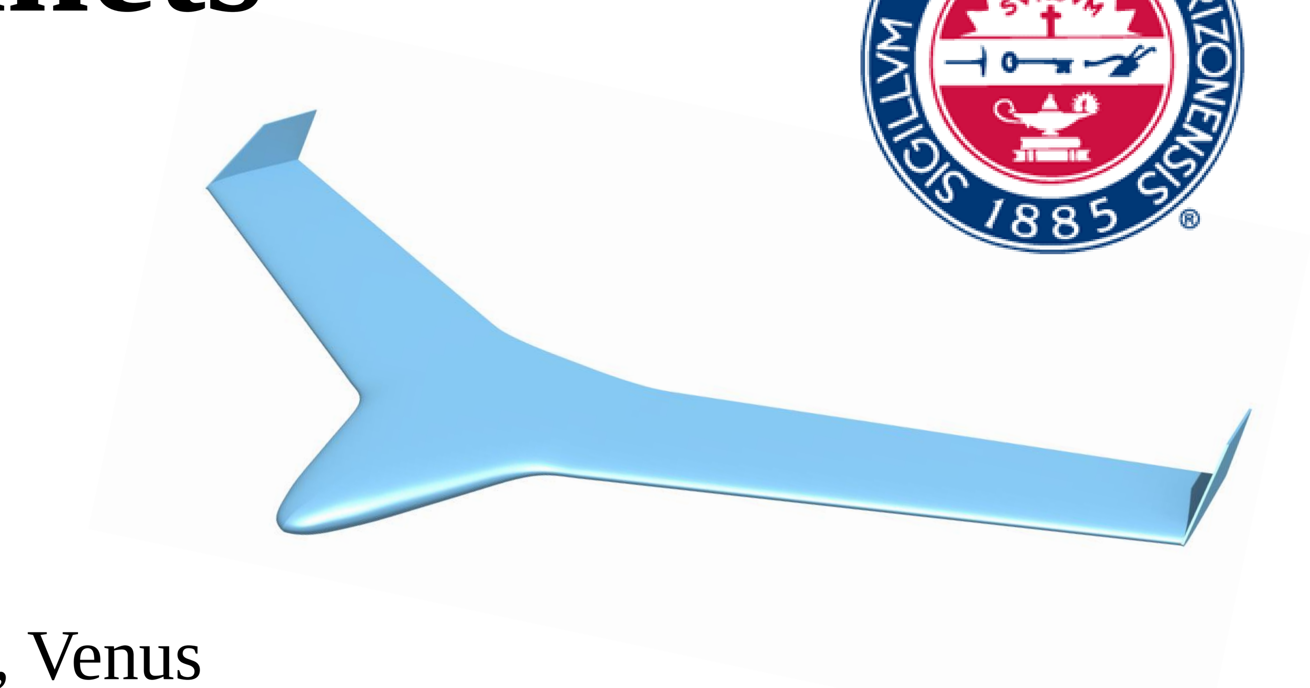
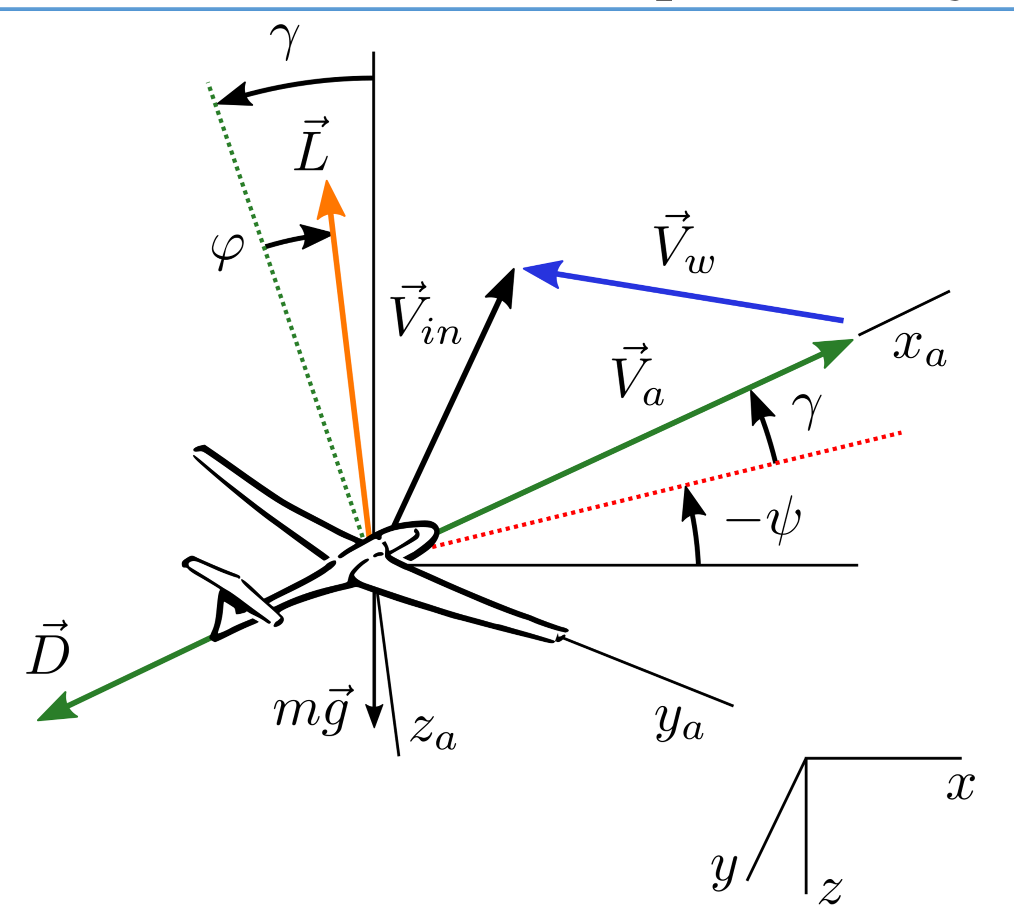
Atmospheric Flight Mechanics on Other Planets

Adrien Bouskela and Sergey Shkarayev
University of Arizona



The 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 flight trajectories are conducted based on a three degree of freedom sailplane model. Necessary and sufficient conditions are established for energy positive dynamic soaring on Mars, Venus and Titan.

Equations of Motion and Optimal Trajectories



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

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

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

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

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

Optimal trajectory is sought with objective function

$$\max_{C_L,\varphi}\left\{\frac{d}{dt'}(0.5{V'_a}^2):\ \forall t'\right\}$$

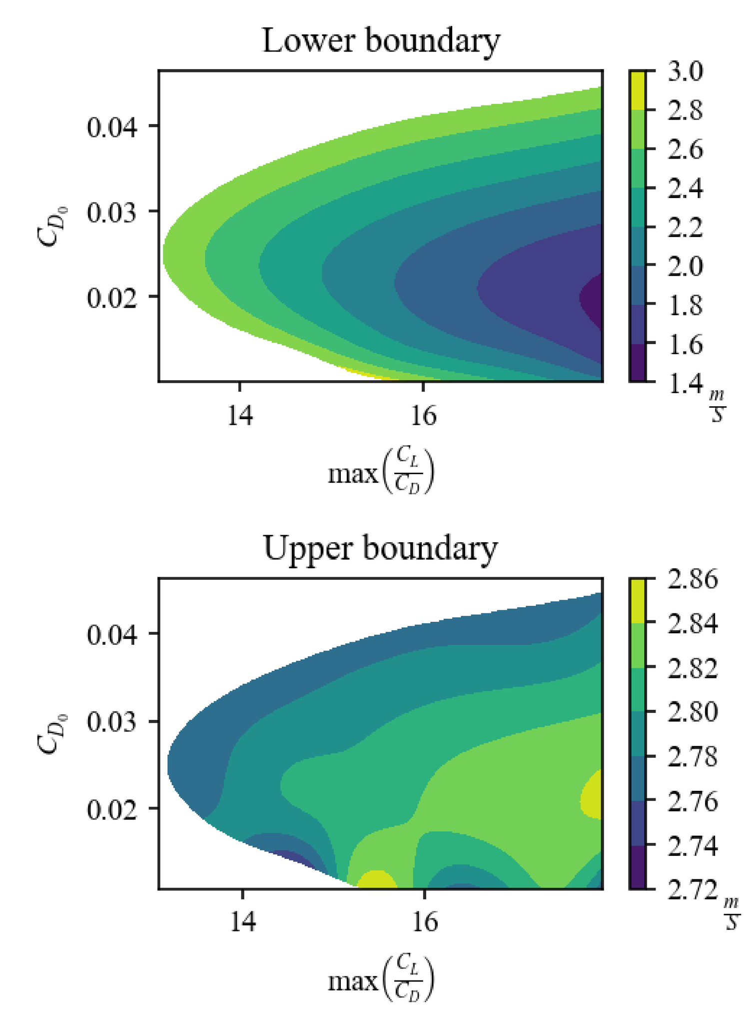
subjected to constraints

$$z' < 0; \quad V'_{stall} < V'_a; \quad z'_{t'=0} = z'_{tf'}; \quad \psi'_{t'=0} = \psi'_{tf}$$

Dynamic Soaring in Atmosphere of Mars, Titan, Venus

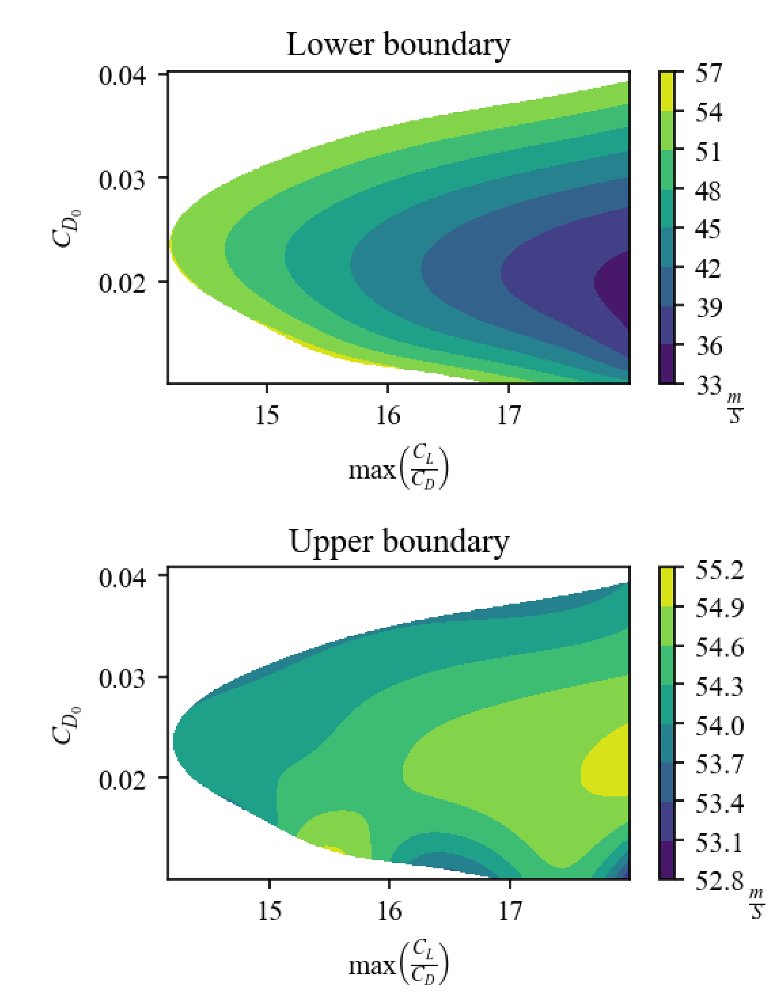
Mars at ground level: $\rho = 0.0137\ kg/m^3$ $g = 3.711\ m/s^2$ $\partial V_{wx}/\partial z \approx 40\ m/s\ /km$

m/S contours for energy positive dynamic soaring $h_{shear} = 600$ m



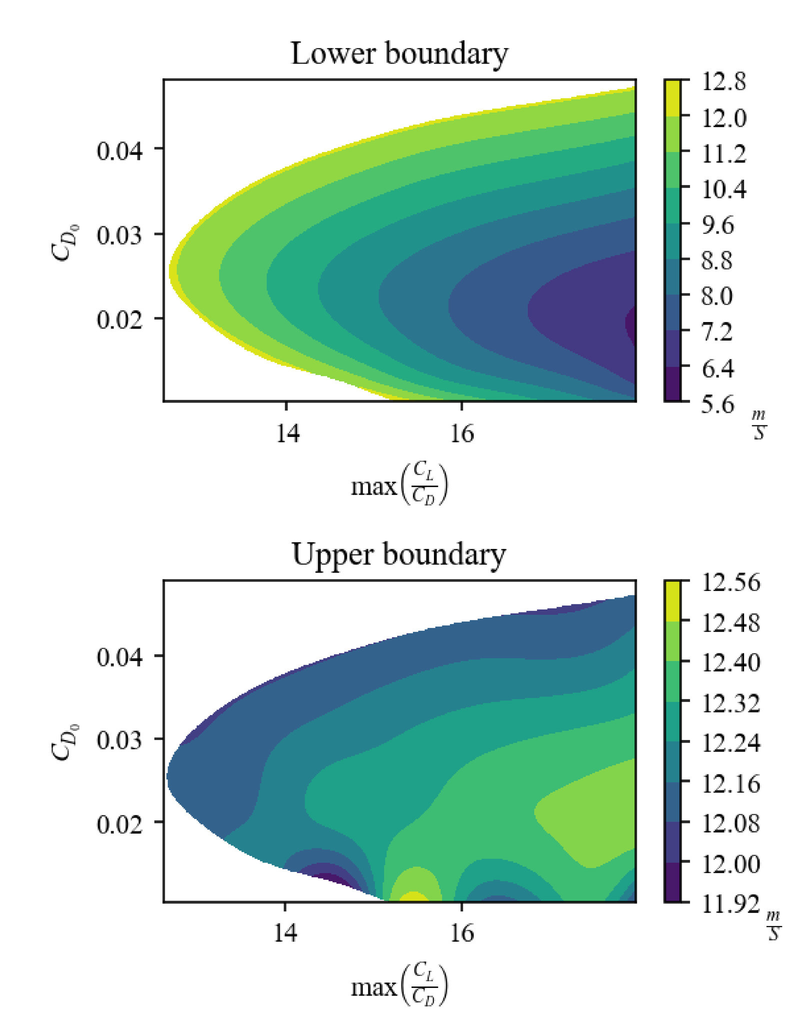
Titan at ground level: $\rho = 5.3\ kg/m^3$ $g = 1.35\ m/s^2$

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



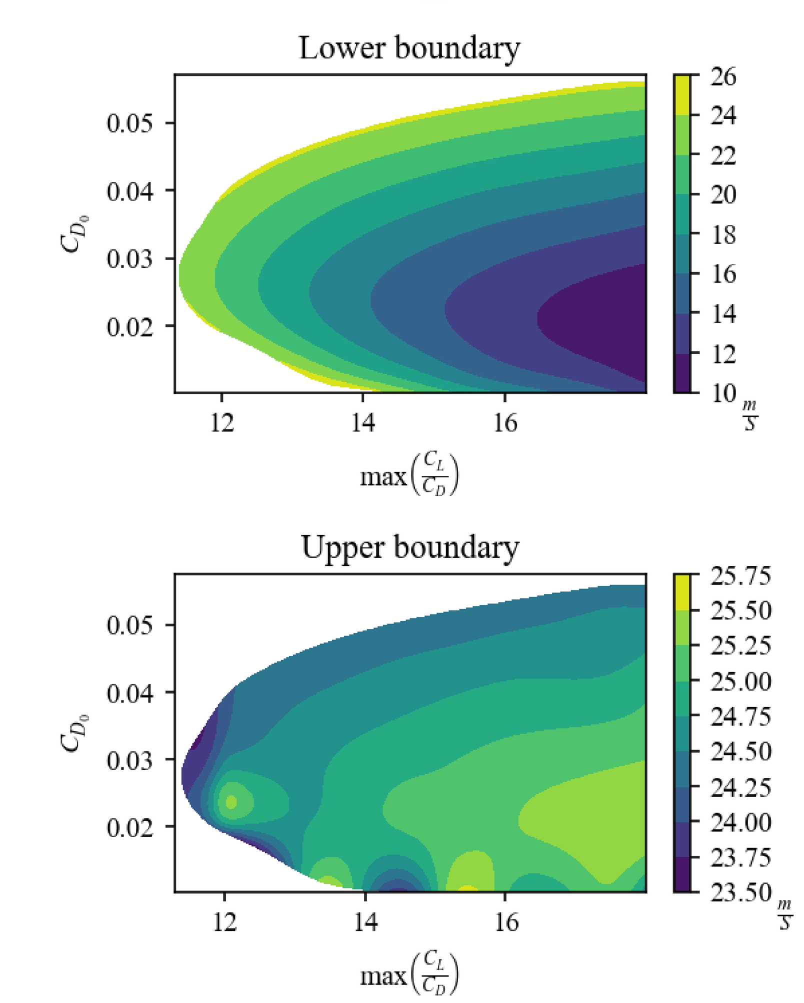
Titan in shear layer (80km): $\rho = 0.06\ kg/m^3$ $g = 1.35\ m/s^2$

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



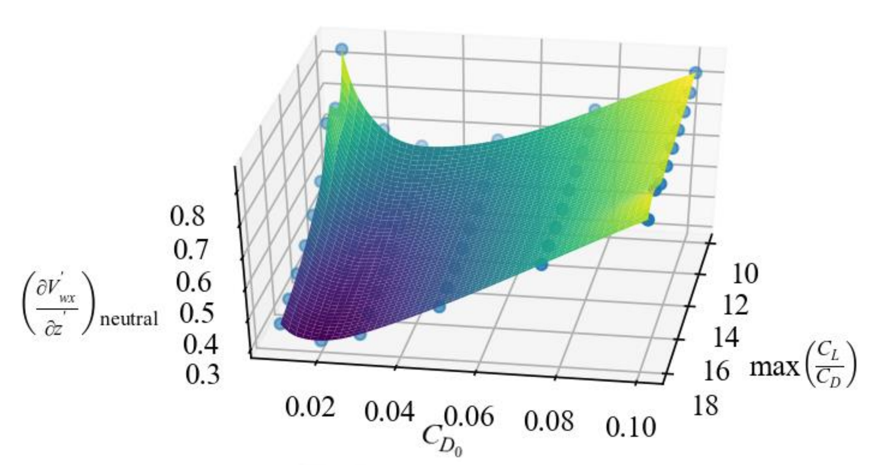
Venus in shear layer (50km): $\rho = 1.46\ kg/m^3$ $g = 8.87\ m/s^2$

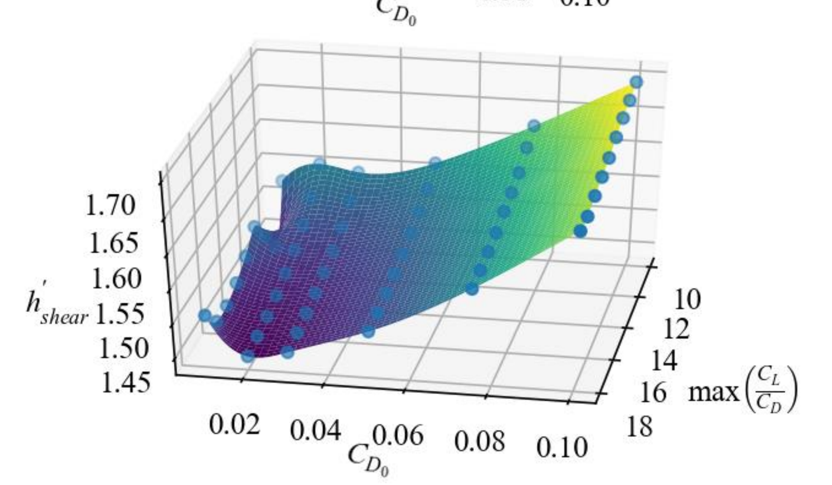
m/S contours for energy positive dynamic soaring $h_{shear} = 50$ m, $\partial V_{wx}/\partial z = 250\ m/s\ /km$



Comparative study approach

- Assuming linear and unidirectional wind function $V'_{wx} = z'\frac{\partial V'_{wx}}{\partial z'} + V'_{wx\,0}$
- Solving optimal trajectory problem for $C_{L_{max}} = 0.8$; $C_{D_0} = [0.01, 0.02, \ldots, 0.1]$; $C_L/C_D|_{max} = [10, 11, \ldots, 20]$
- To find $\partial V'_{wx}/\partial z'\,(C_{D_0}, C_L/C_D|_{max})$ for the energy neutral cycle, such that total energy at initial and final time instants stay the same



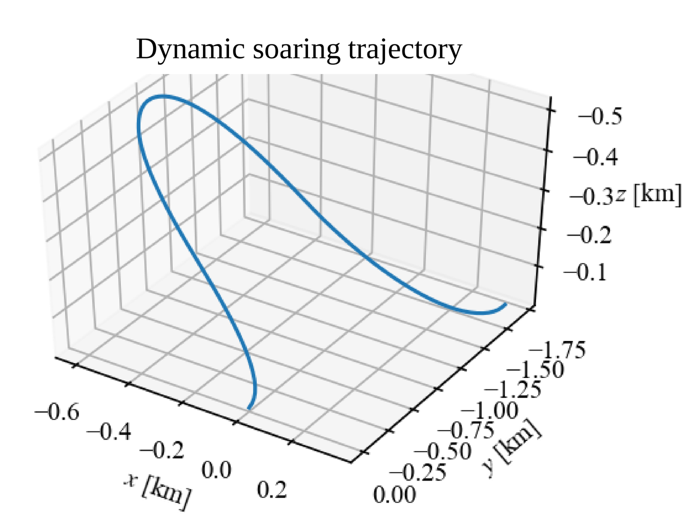


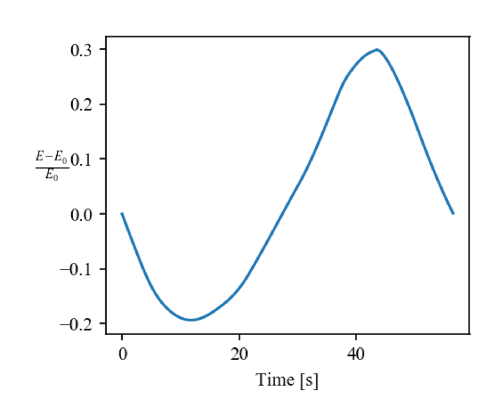
Based on the results for $\left(\partial V'_{wx}/\partial z'\right)_{neutral}$, and corresponding $h'_{neutral}$, sufficient conditions on the neutral energy cycle are found

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

Sailplane Designs

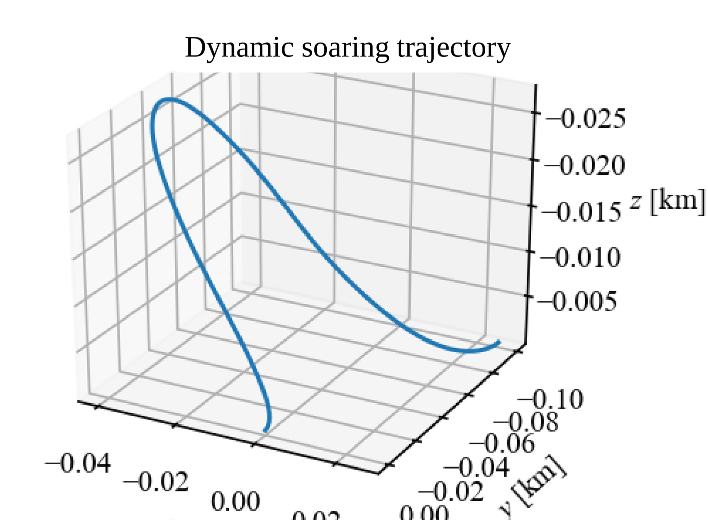
$S = 4.46\ m^2$ $m = 5\ kg$ $C_L/C_D|_{max} = 14.4$ $C_{D_0} = 0.027$ Wingspan = 5 m $\partial V_{wx}/\partial z = 40\ m/s\ /km$

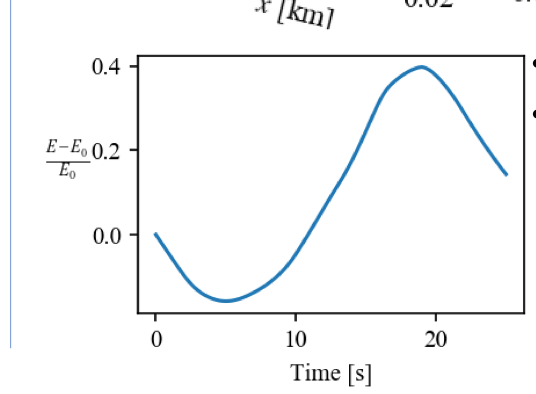




- excess power 43 W
- Narrow solution range
- Low Reynolds number range number (10^4 to 10^5)

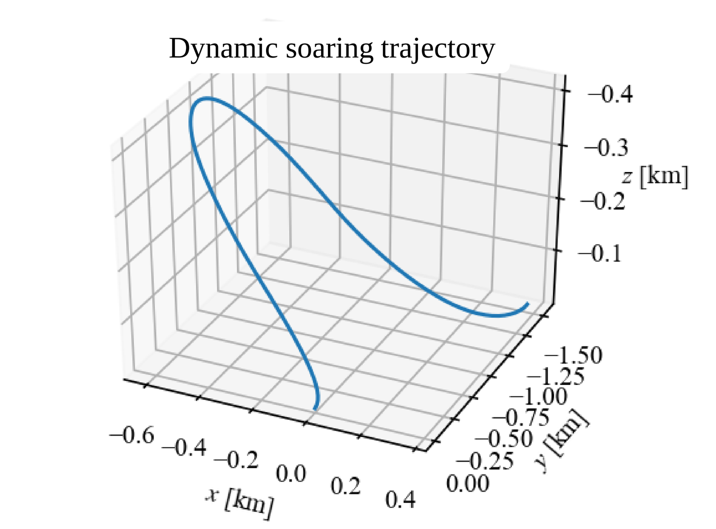
$S = 0.125\ m^2$; $m = 5\ kg$; $C_L/C_D|_{max} = 20$ $C_{D_0} = 0.015$; Wingspan = 1.0 m; $\partial V_{wx}/\partial z = 100\ m/s\ /km$

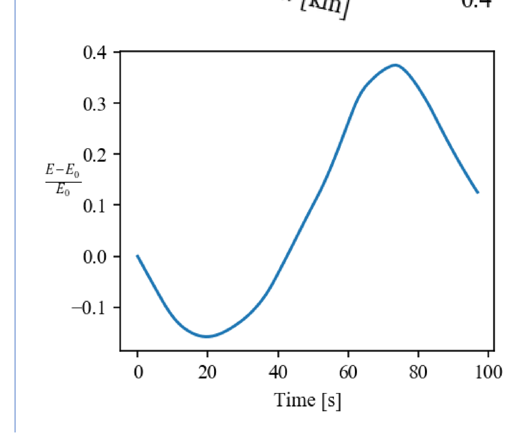




- excess power 42 W
- Efficient High Reynolds number flight with low speeds

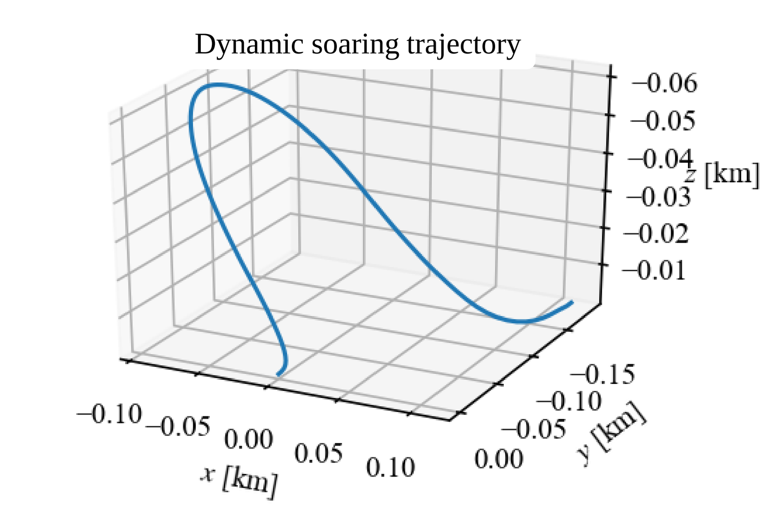
$S = 0.5\ m^2$; $m = 3.5\ kg$; $C_L/C_D|_{max} = 19.25$ $C_{D_0} = 0.015$; Wingspan = 1.7 m; $\partial V_{wx}/\partial z = 25\ m/s\ /km$

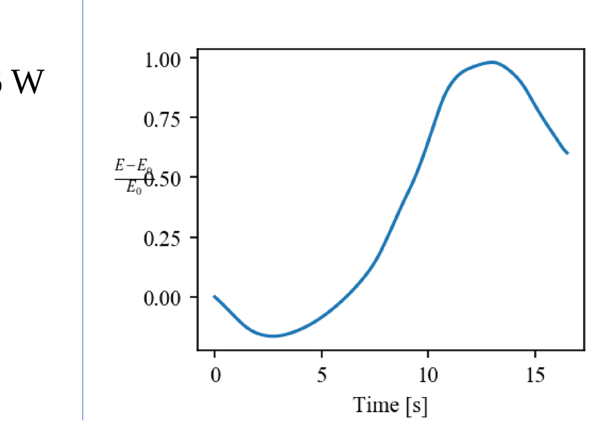




- excess power 496 W
- Most efficient dynamic soaring: high gain for low wind gradients

$S = 0.4\ m^2$; $m = 5\ kg$; $C_L/C_D|_{max} = 20$ $C_{D_0} = 0.015$; 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. It allows 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 requires greater wind gradients over smaller heights for sailplane designs with wing loading ranging from 1 to 60.
- Dynamic soaring is feasible on Mars with a narrow wing loading range. It 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.

References

- Bencatel, R., Kabamba, P. and Girard, A., 2014. Perpetual dynamic soaring in linear wind shear. *Journal of Guidance, Control, and Dynamics*, *37*(5), pp.1712-1716.
- Tokano, T., 2007. Near-surface winds at the Huygens site on Titan: interpretation by means of a general circulation model. *Planetary and Space Science*, *55*(13), pp.1990-2009.
- Lorenz, R.D., 2007. Titan atmosphere profiles from Huygens engineering (temperature and acceleration) sensors. *Planetary and Space Science*, *55*(13), pp.1949-1958.
- Petropoulos, B., 1988. Physical parameters of the atmosphere of Venus. *Earth, Moon, and Planets*, *42*(1), pp.29-40.
- Sánchez-Lavega, A., Lebonnois, S., Imamura, T., Read, P. and Luz, D., 2017. The atmospheric dynamics of Venus. *Space Science Reviews*, *212*(3-4), pp.1541-1616.
- Sachs, G., Traugott, J., Nesterova, A.P., Dell'Omo, G., Kümmeth, F., Heidrich, W., Vyssotski, A.L. and Bonadonna, F., 2012. Flying at no mechanical energy cost: disclosing the secret of wandering albatrosses. *PloS one*, *7*(9). Petrosyan, A., Galperin, B., Larsen, S.E., Lewis, S.R., Määttänen, A., Read, P.L., Renno, N., Rogberg, L.P.H.T., Savijärvi, H., Siili, T. and Spiga, A., 2011. The Martian atmospheric boundary layer. *Reviews of Geophysics*, *49*(3).