Atmospheric Flight Mechanics on Other Planets

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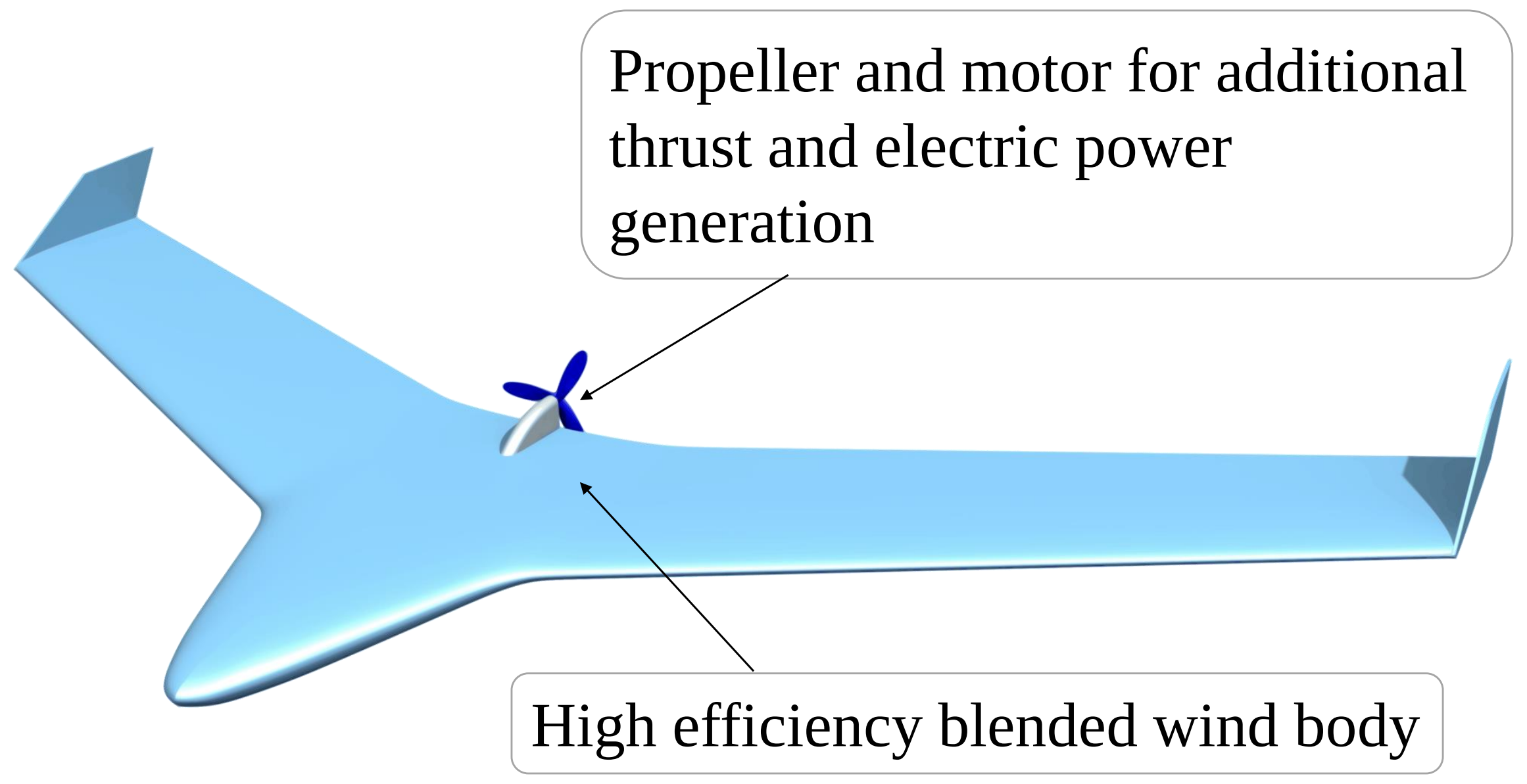
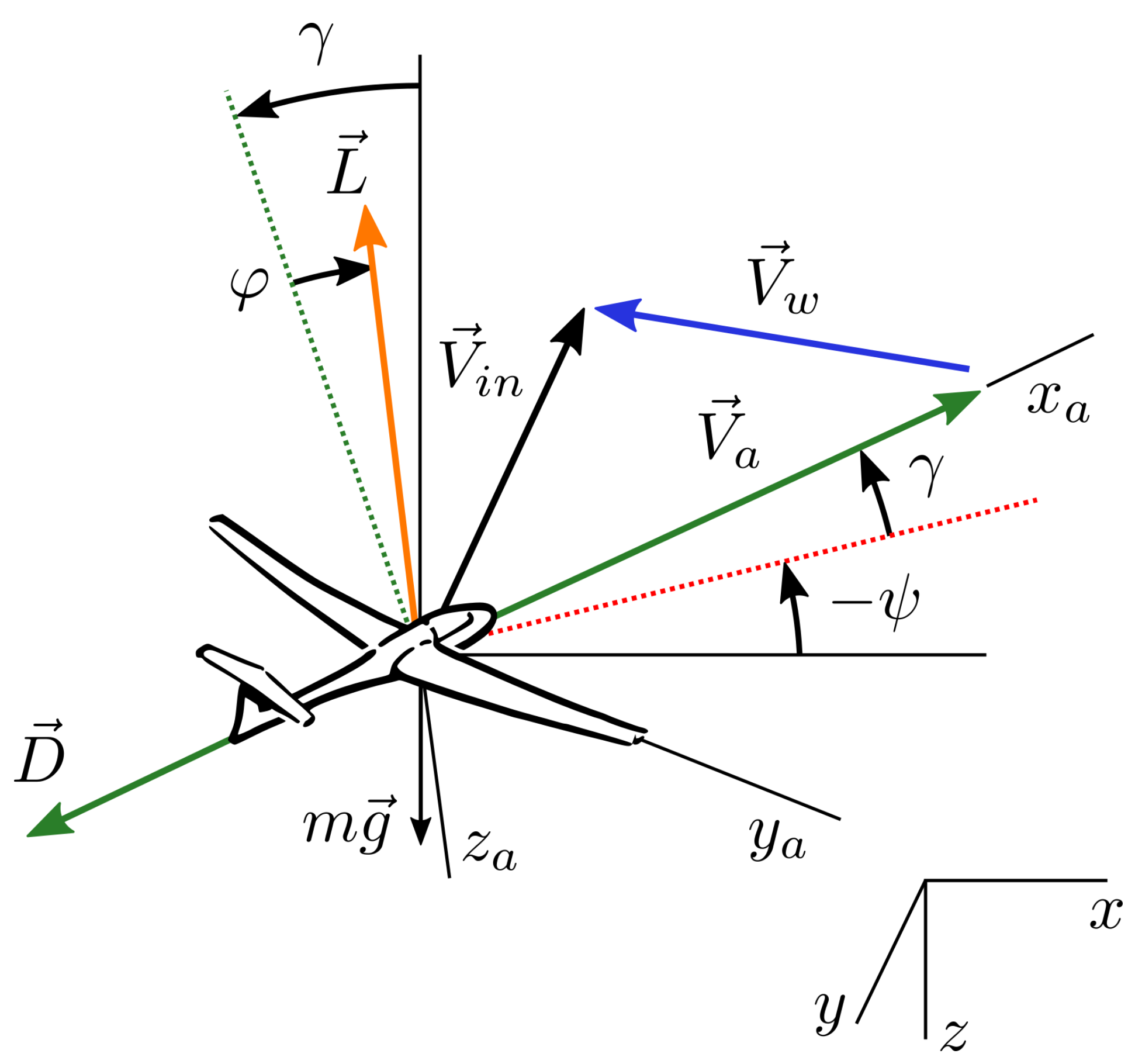
The successful deployment of sailplanes on other planets of the solar system can provide a high volume of scientific data at a relatively low cost. Sailplanes can fly without power limitations by exploiting atmospheric wind gradients and shear layers for dynamic soaring, as well as slope and thermal updrafts for static soaring. In the present work, aerodynamic studies have been conducted identifying general principles of sailplane design and flight maneuvers in different atmospheric conditions, exploring the feasibility of extended missions via the use of atmospheric energy. The proposed high efficiency sailplane presents a blended wing body and propeller for extended range and recharging batteries



Propeller and motor for additional thrust and electric power generation

High efficiency blended wind body

Method: 3Dof Model



A sailplane is modeled as a three degree of freedom point mass, m, to which lift L, drag D, and gravitational forces are applied following the convention described above. It's motion while preforming dynamic soaring maneuvers is described by the system of normalized equations

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

$$\dot{V}_a' = -{V_a'}^2\left(C_{D_0} + kC_L^2\right) - \sin(\gamma) + \dot{V}_{wz}' \sin(\gamma) - \dot{V}_{wy}' \sin(\psi)\cos(\gamma) - \dot{V}_{wx}' \cos(\gamma)\cos(\psi)$$
$$V_a'\,\dot{\gamma}' = {V_a'}^2\, C_L \cos(\varphi) - \cos(\gamma) + \dot{V}_{wy}' \sin(\gamma)\sin(\psi) + \dot{V}_{wx}' \sin(\gamma)\cos(\psi) + \dot{V}_{wz}' \cos(\gamma)$$
$$V_a' \cos(\gamma)\ \dot{\psi}' = {V_a'}^2 C_L \sin(\varphi) + \dot{V}_{wx}' \sin(\psi) - \dot{V}_{wy}' \cos(\psi)$$

$$L = {}^1\!/_2\, \rho V_a^2 S C_L; \qquad D = {}^1\!/_2\, \rho V_a^2 S (C_{D_0} + kC_L^2)$$

$$k = \left(4\, C_{D_0} \left(\frac{C_L}{C_D}\Big|_{max}\right)^2\right)^{-1}$$

$$\max_{C_L,\varphi}\left\{\frac{d}{dt'}(0.5{V_a'}^2)\colon\ \forall t'\right\}; \qquad \mathrm{z}' < 0; \quad \mathrm{V}_{\mathrm{stall}}' < \mathrm{V}_{\mathrm{a}}'$$

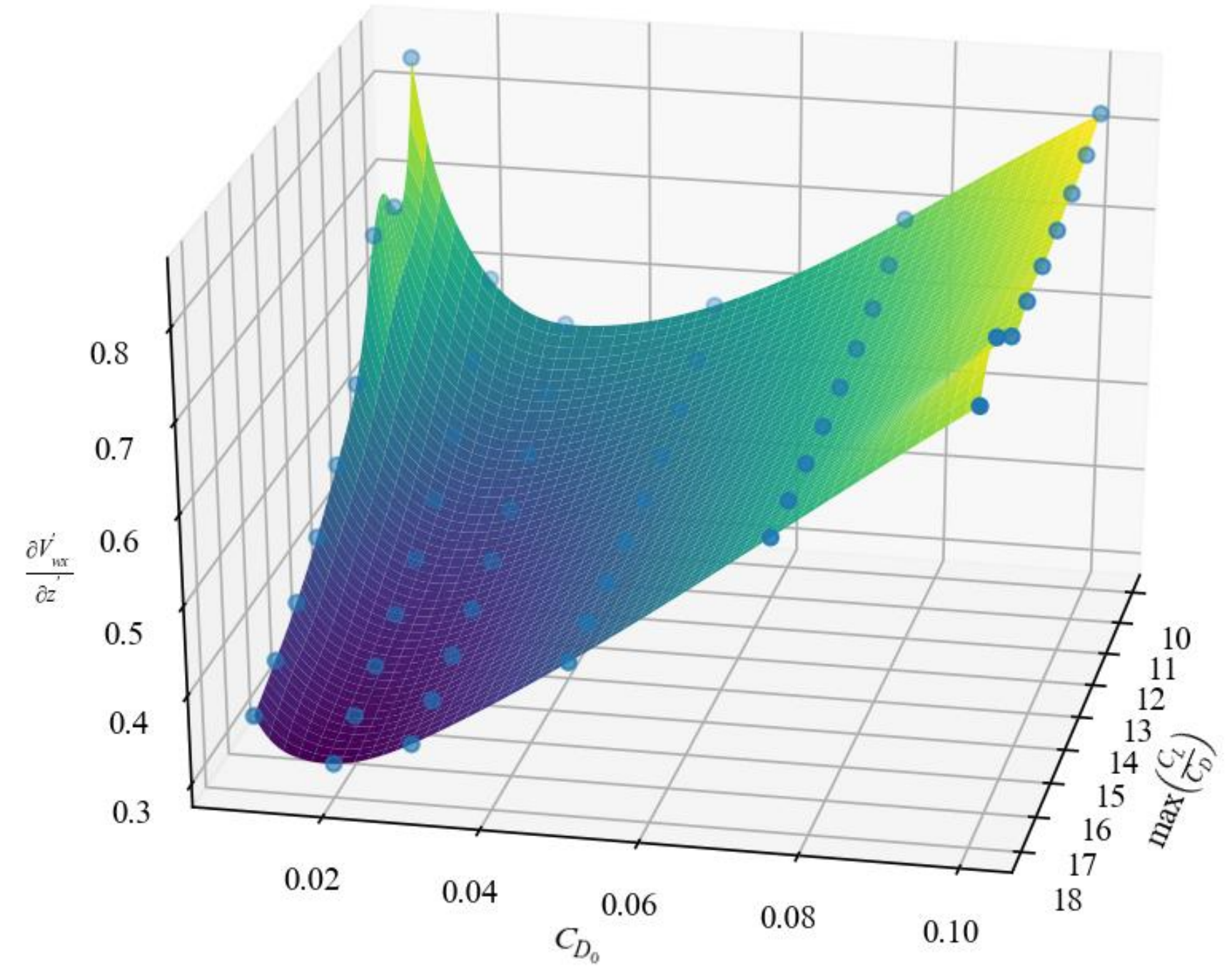
With the scaling factors on velocity, length and time

$$V = \sqrt{\frac{mg}{0.5\rho S}}; \qquad Z = \frac{m}{0.5\rho S}; \qquad T = \sqrt{\frac{m}{0.5\rho S g}}$$

Then conditions on environment and sailplane parameters are found from numerical results of the normalized problem for an energy neutral cycle, where the sailplane is represented by $(C_{L_{max}} = 0.8, C_{D_0}, C_L/C_D|_{max})$, and wind is unidirectional and varies linearly with altitude h.

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

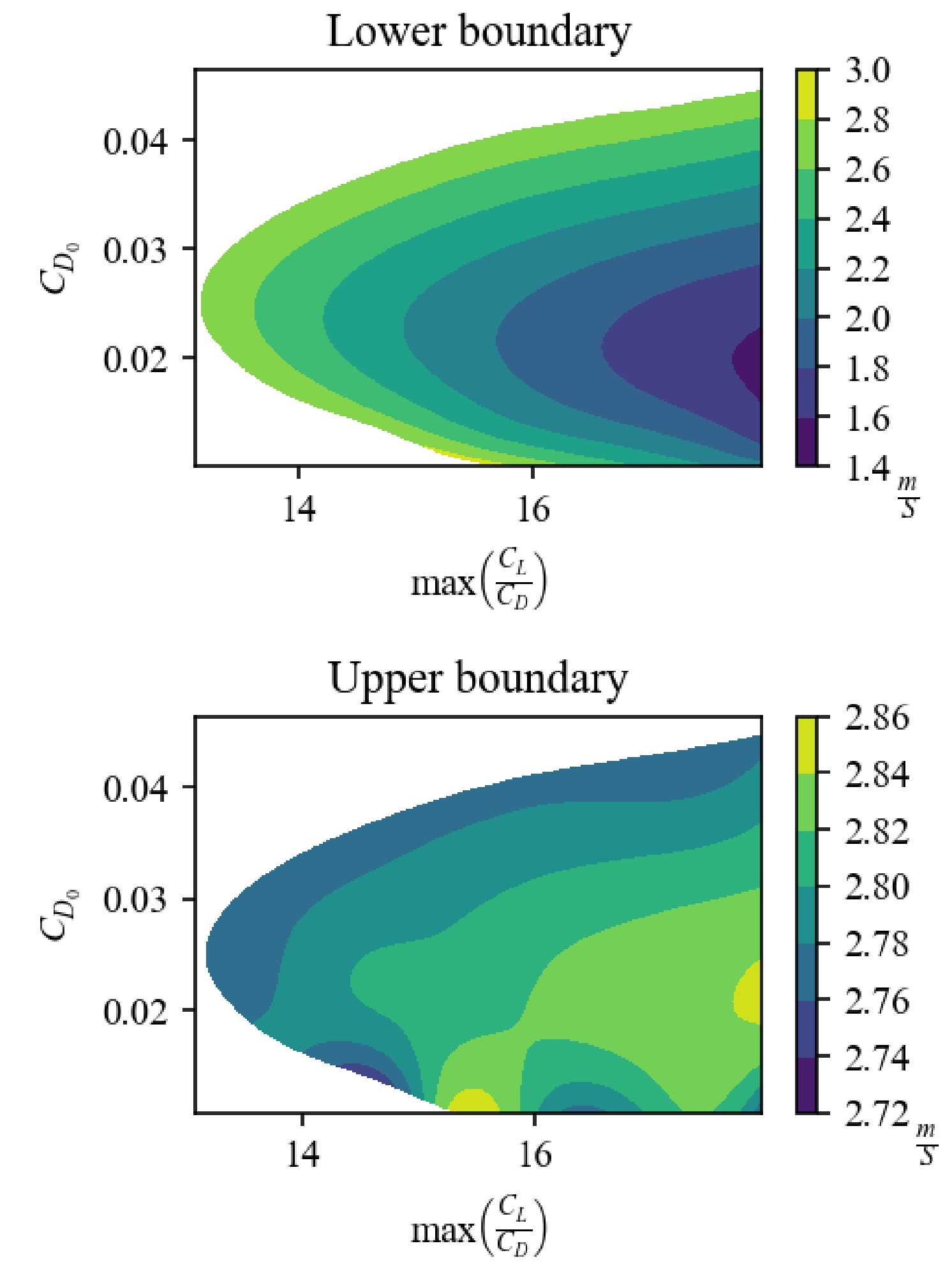
Surface for the normalized wind gradient of energy neutral dynamic soaring cycles



Atmospheric environments and dynamic soaring

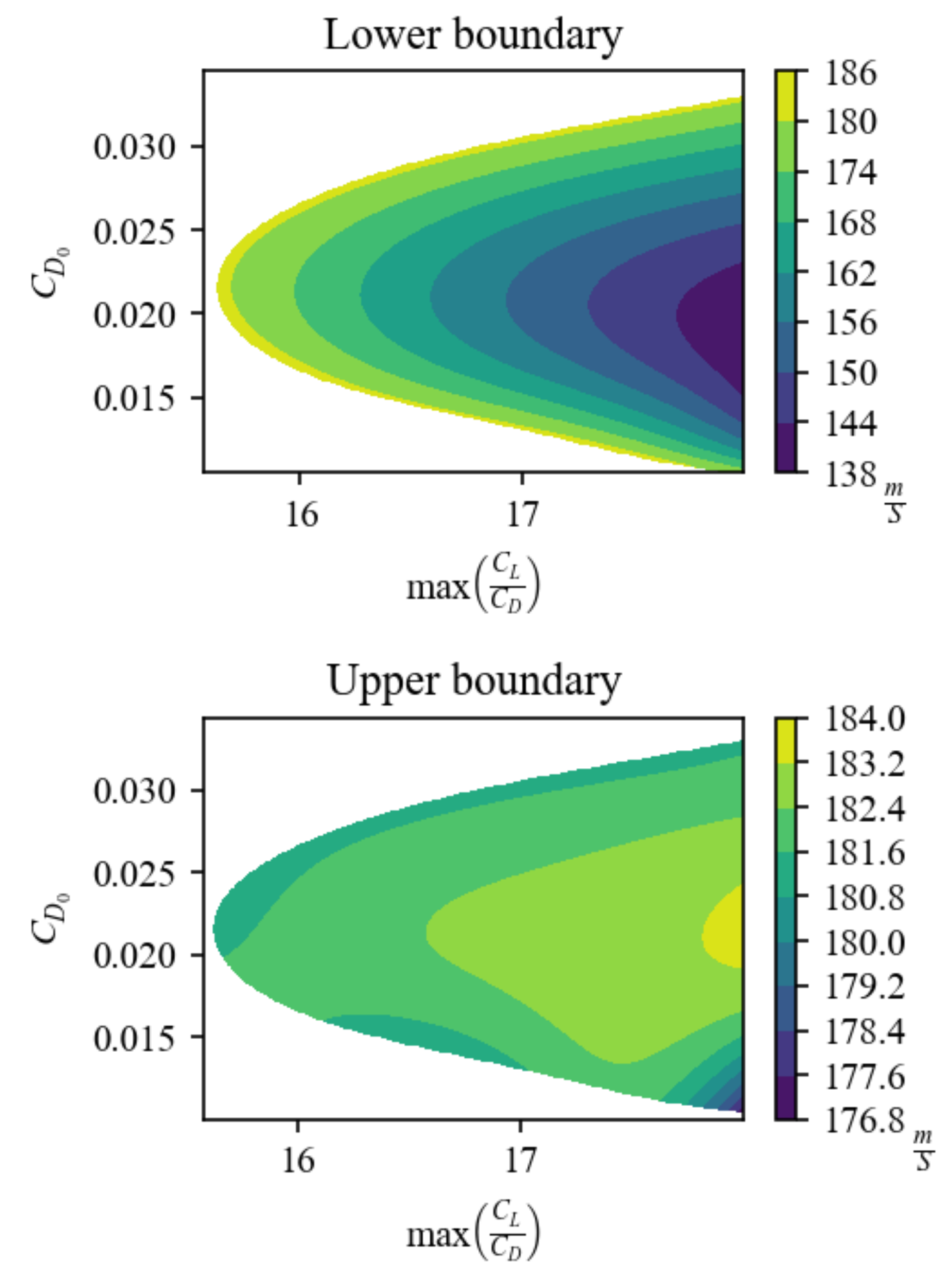
Mars ground level: $\rho = 0.0137\ kg/m^3$
$g = 3.711\ m/s^2$ ${}^{\partial V_{wx}}\!/_{\partial z} \approx 40\ m/s\ /km$

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



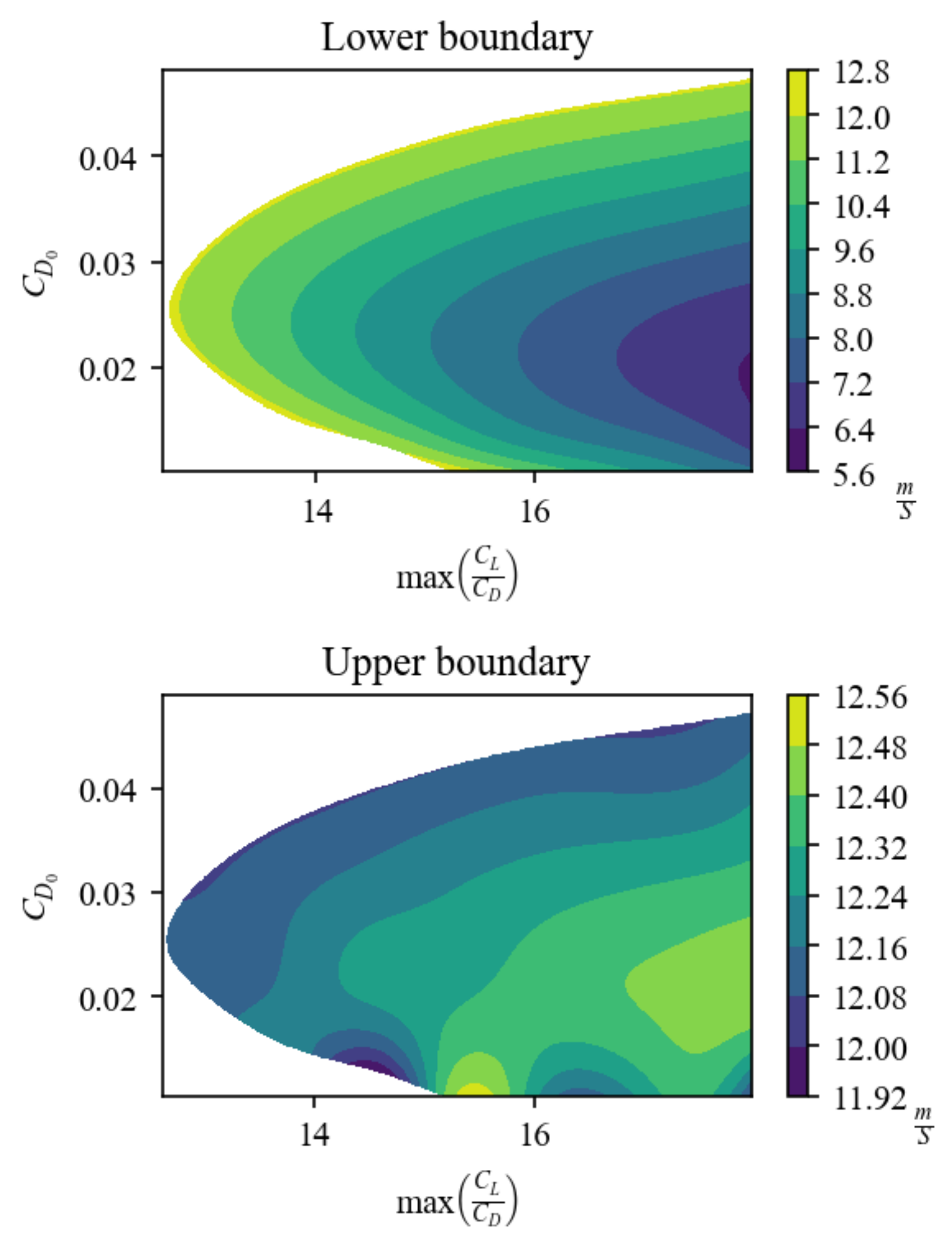
Titan ground level: $\rho = 5.3\ kg/m^3$
$g = 1.35\ m/s^2$

boundaries on m/S for energy positive dynamic soaring, $h_{shear} = 100$ m, ${}^{\partial V_{wx}}\!/_{\partial z} = 50\ m/s\ /km$



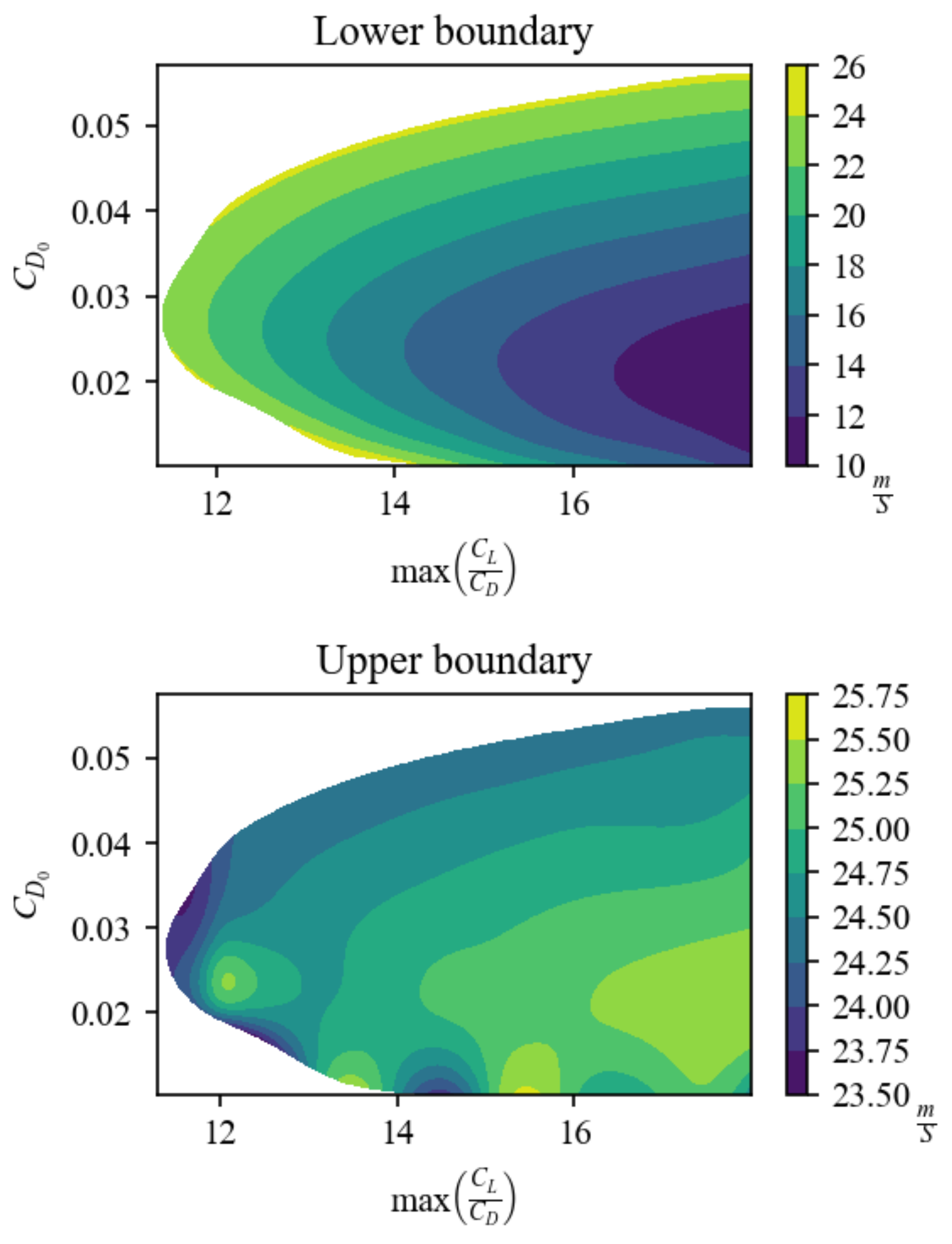
Titan shear layer (80km): $\rho = 0.06\ kg/m^3$
$g = 1.35\ m/s^2$

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



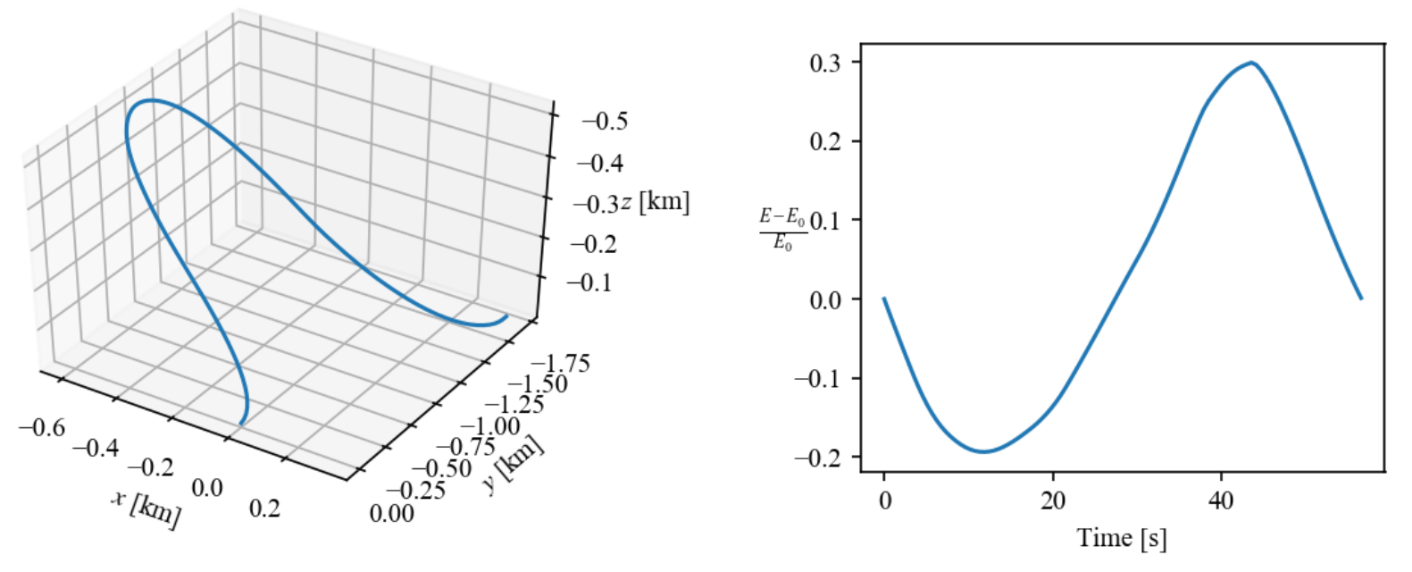
Venus shear layer (50km): $\rho = 1.46\ kg/m^3$
$g = 8.87\ m/s^2$

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



Sailplane design results

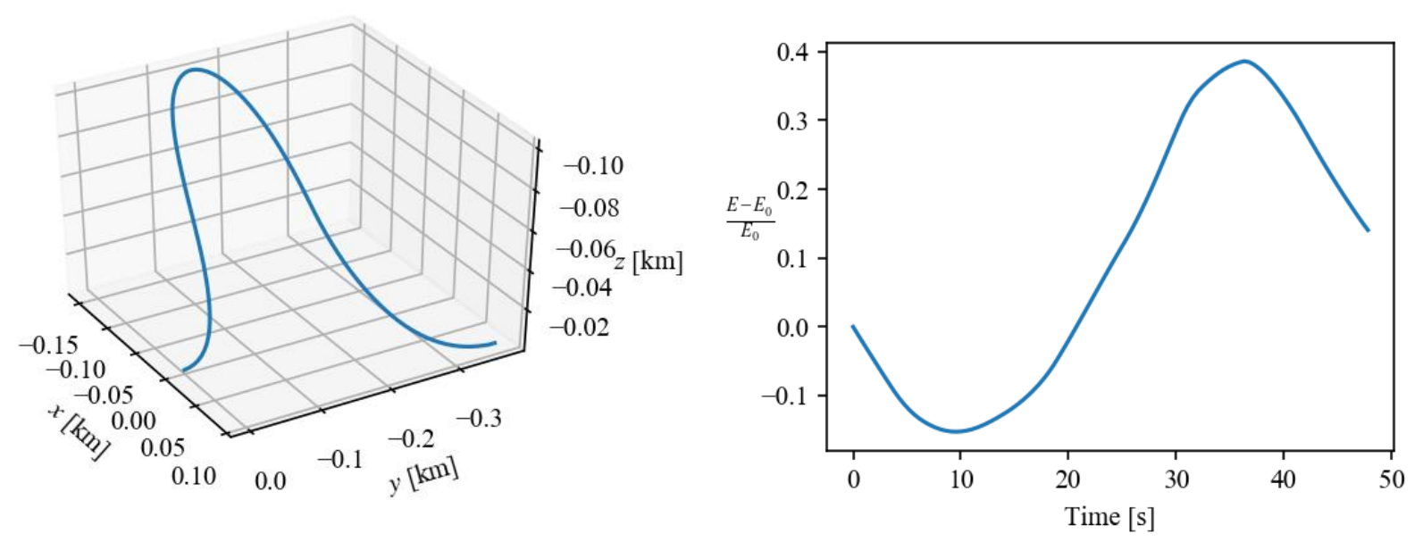
$S = 4.46\ m^2$ $m = 5\ kg$ ${}^{C_L}\!/_{C_D}|_{max} = 14.4$ $C_{D_0} = 0.027$
Wingspan = 5 m $P_{motor}(cruise) = 59.8$ W



Dynamic soaring trajectory and Energy ratio over time, ${}^{\partial V_{wx}}\!/_{\partial z} = 40$ m/s /km, excess power 43 W

On mars dynamic soaring is possible in the atmospheric boundary layer, although the low density and moderate gravity are additional constraints to aerodynamics with Reynolds numbers in the order of 10^4 and 10^5. Reducing efficiency and the overall excess power, as well as narrowing the solution range

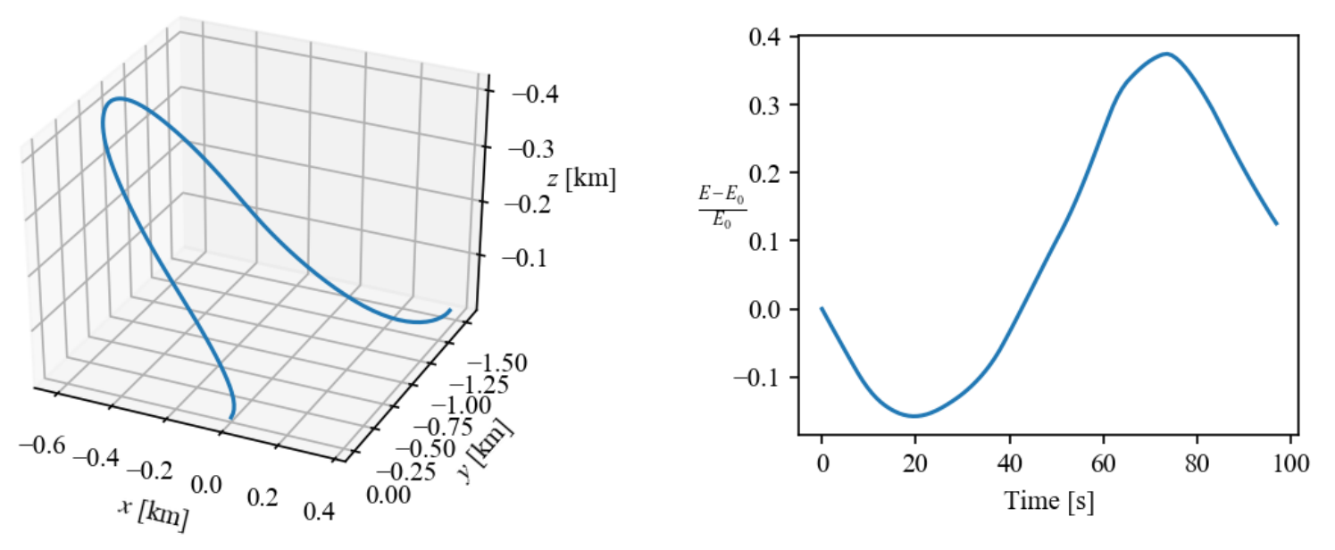
$S = 0.05\ m^2$ $m = 7.5\ kg$ ${}^{C_L}\!/_{C_D}|_{max} = 20$ $C_{D_0} = 0.015$
Wingspan = 0.6 m $P_{motor}(cruise) = 7.8$ W



Dynamic soaring trajectory and Energy ratio over time, ${}^{\partial V_{wx}}\!/_{\partial z} = 50$ m/s /km, excess power 142 W

Titan presents a unique environment with high density and low gravity, because of which the solution range presents high ratios of mas over lifting area. To mitigate this the wind gradient must be high with values in the order of 10^2 m/s/km over a small altitude range, such values have not been found close to the surface of Titan by the Huygens probe or numerical simulations. The present work, and available wind data, then disproves dynamic soaring in Titan's near surface atmospheric boundary layer

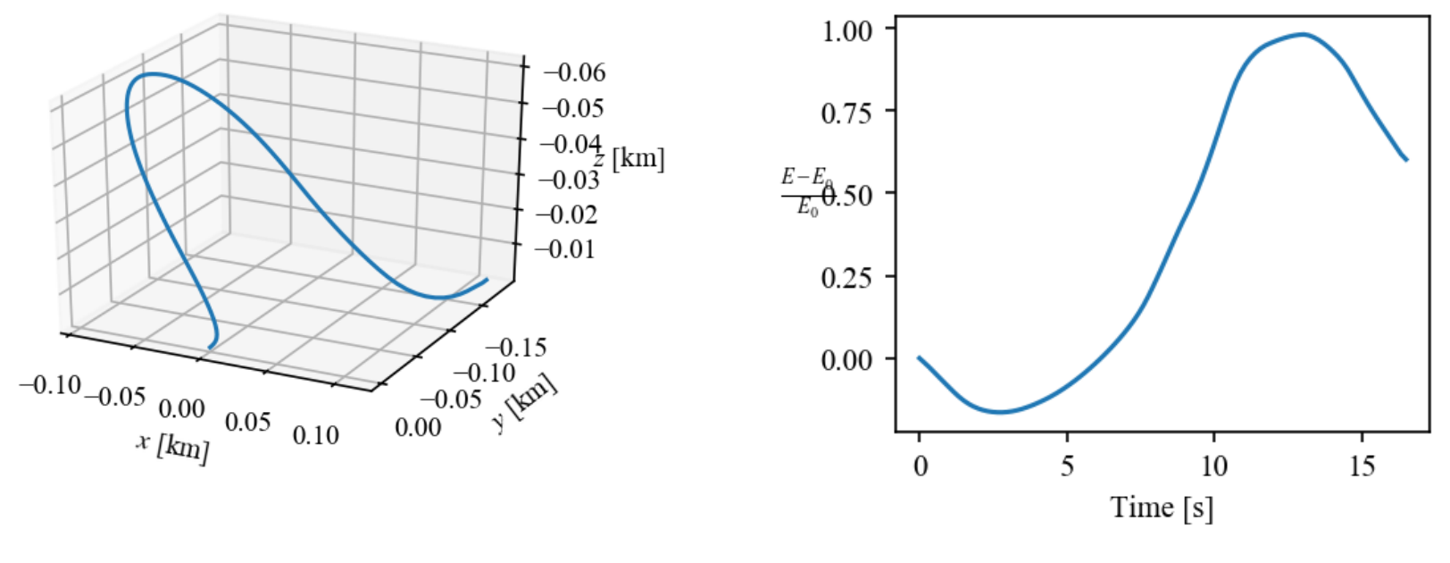
$S = 0.5\ m^2$ $m = 3.5\ kg$ ${}^{C_L}\!/_{C_D}|_{max} = 19.25$ $C_{D_0} = 0.015$
Wingspan = 1.7 m $P_{motor}(cruise) = 26.5$ W



Dynamic soaring trajectory and Energy ratio over time, ${}^{\partial V_{wx}}\!/_{\partial z} = 25$ m/s /km, excess power 496 W

In contrast to the near surface region, there exists large convection features in Titan's upper atmosphere which create shear layers as observed by Huygens. With moderate vertical gradient from these layers, dynamic soaring is feasible in this potion of the atmosphere with significant amounts of excess energy available, assuring sustained flight.

$S = 0.4\ m^2$ $m = 5\ kg$ ${}^{C_L}\!/_{C_D}|_{max} = 20$ $C_{D_0} = 0.015$
Wingspan = 1.5 m $P_{motor}(cruise) = 161$ W



Dynamic soaring trajectory and Energy ratio over time, ${}^{\partial V_{wx}}\!/_{\partial z} = 250$ m/s /km, excess power 434 W

Venus's upper atmosphere is said to be similar in properties to earth's sea level environment, thus it is expected that sustained flight through dynamic soaring would also be possible. Numerical results using the three degree of freedom model confirms this point if high magnitude gradients in the vertical winds exist at an altitude of 50km, an area corresponding to the lower part of the planet's cloud layer. Remote and local measurements have confirmed the existance of high wind magnitudes and flow direction reversals in this region, leading to believe that dynamic soaring is feasible in the lower cloud layers.

Conclusions

The feasibility of extended flight via harvesting of energy available in vertical gradients of horizontal winds has been studied through dynamic soaring optimization models for a set of planetary bodies with an atmosphere and a high science value. Quantifying the range of design solutions for a long range exploration sailplane. The differences if physical properties between the planets and moon lead to narrowing of the solution region of the atmosphere and in some cases render near ground flight impractical. Mars presents the highest fidelity solutions thanks to the availability of wind measurements and detailed models, but is also the one with the narrowest solution space and smallest excess energy due to low Reynolds numbers. Higher energy gain can be made on Venus and Titan if the theorized gradients are available, making these last two prime candidates for this high risk, and high reward soaring based exploration.

References

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