Quasi-Steady Model of a Pumping Kite Power System

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Challenge the
future

Introduction

Kiteboarding to Kitepower

Introduction

KitePower from the TU Delft

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- Fundamental Theory: gravity excluded
- Extend to include gravitational force
- Tether
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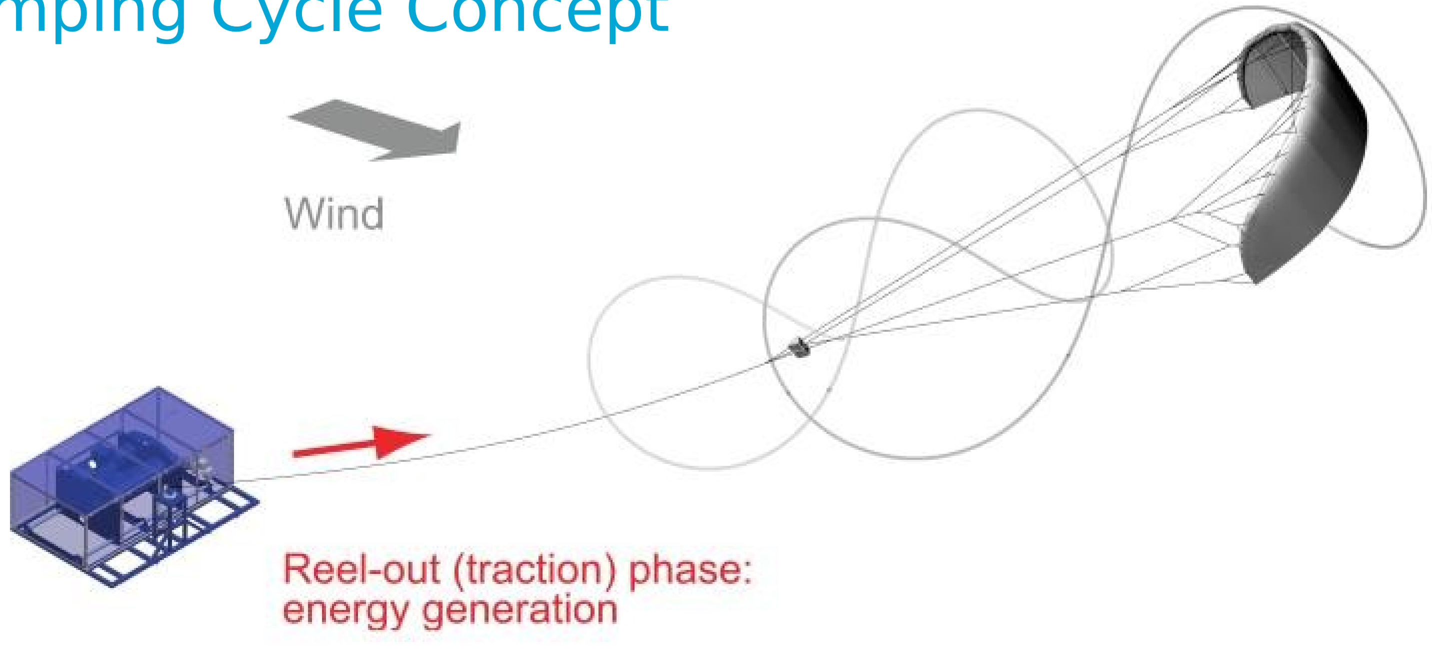
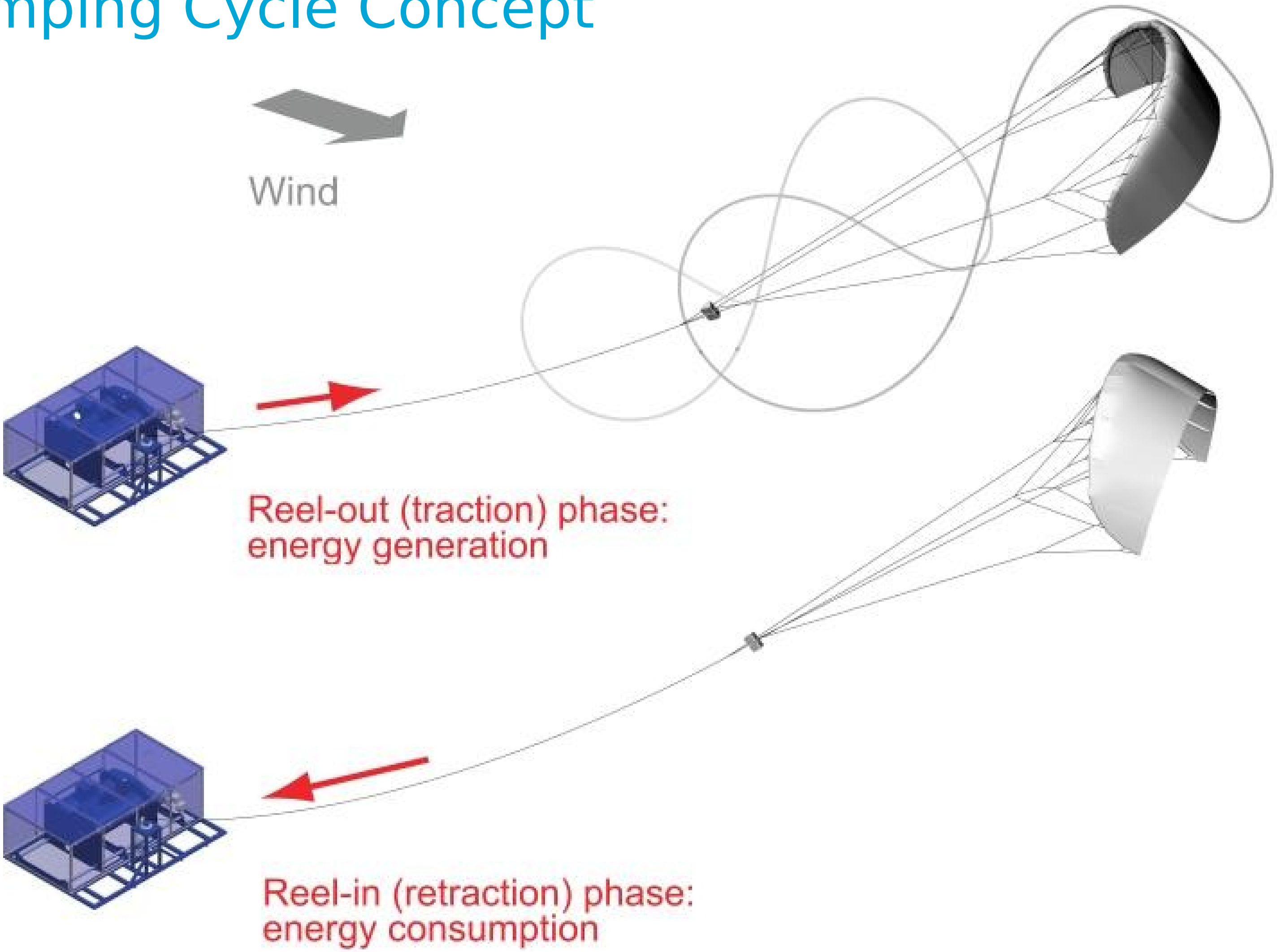
Introduction

Pumping Cycle Concept



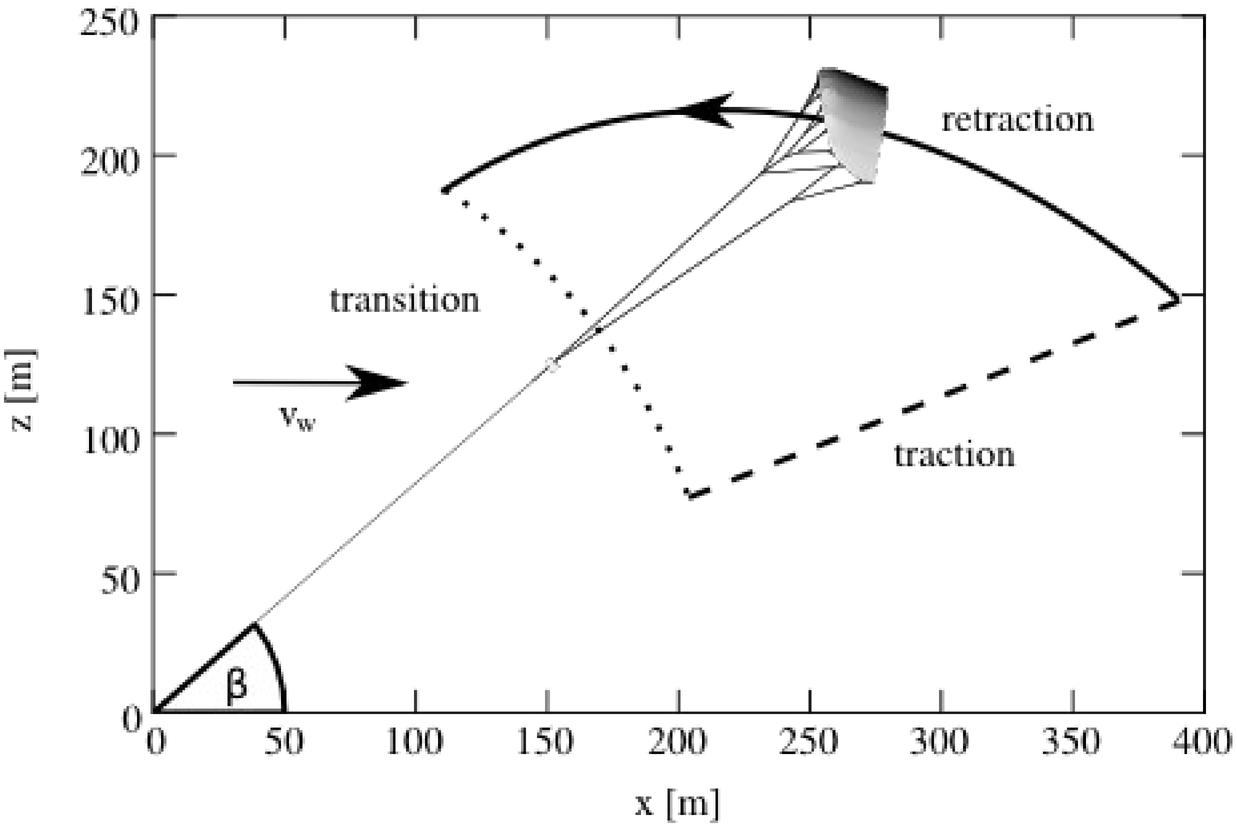
Introduction

Pumping Cycle Concept



Introduction

Pumping Cycle Concept



(Source: Fechner and Schmehl, 2013)

Introduction

Motivation for Analysis

- Model to predict power produced over complete cycle

- Can be used for economical analysis, optimization and preliminary design

- Easy to implement

- Dynamic modeling too heavy on computation and too complex to implement in smaller projects

- Models found in literature focus on traction phase

- Missing validation of applying models on a complete cycle

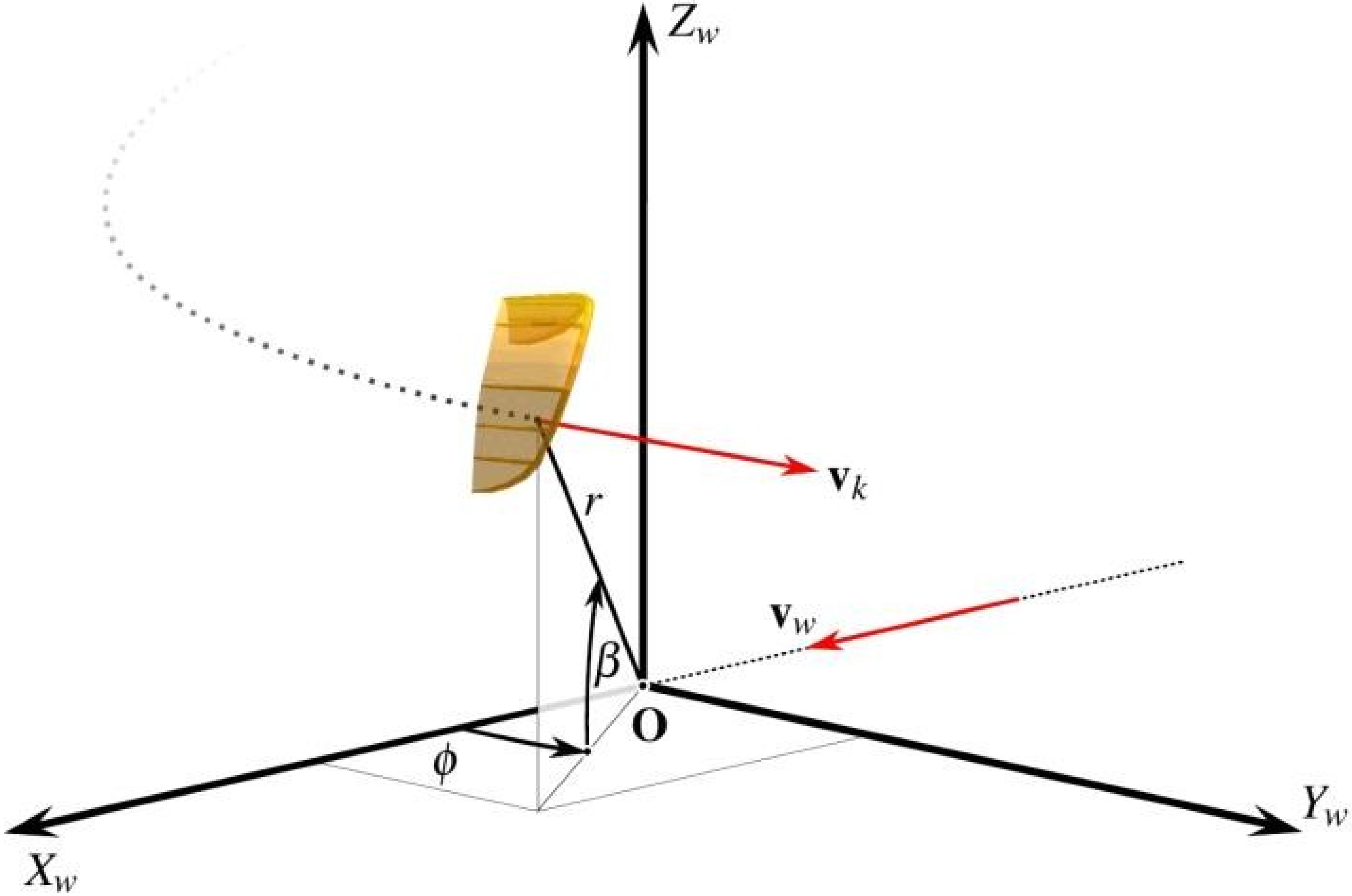
Fundamental Theory

Assumptions

- Quasi-Steady behavior
- Fixed aerodynamic properties during each phase
- Straight and non-flexible tether
- Atmosphere: Velocity and density gradient
- Influence of kite mass
- Tether mass and aerodynamic tether drag

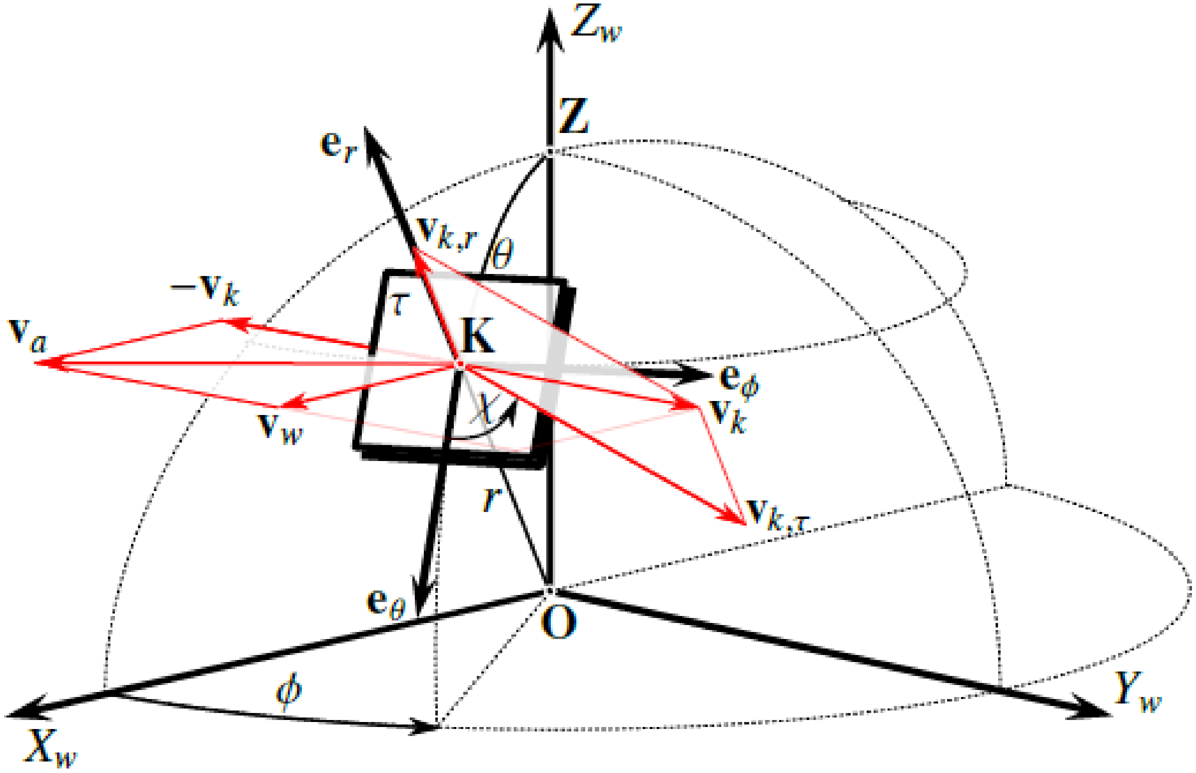
Fundamental Theory

Definitions



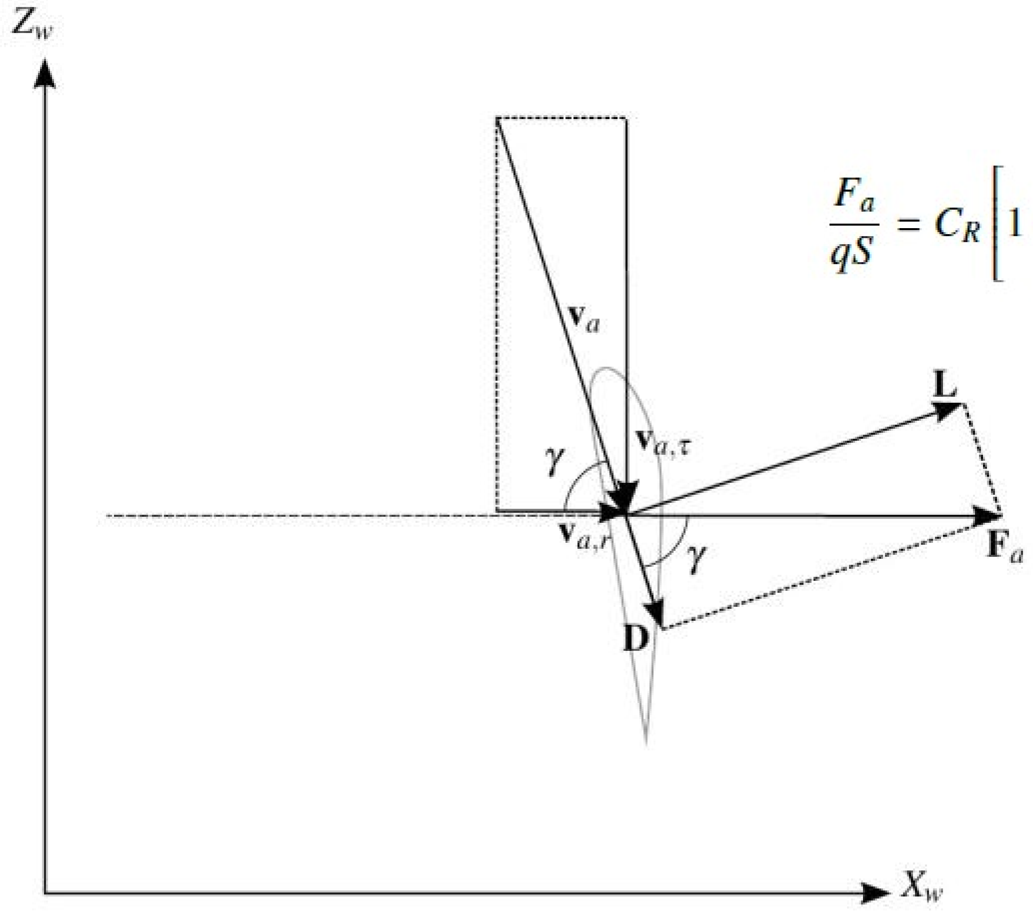
Fundamental Theory

Definitions



Fundamental Theory

Flight State Approximation



$$\frac{v_{a,\tau}}{v_{a,r}} = \frac{L}{D}$$

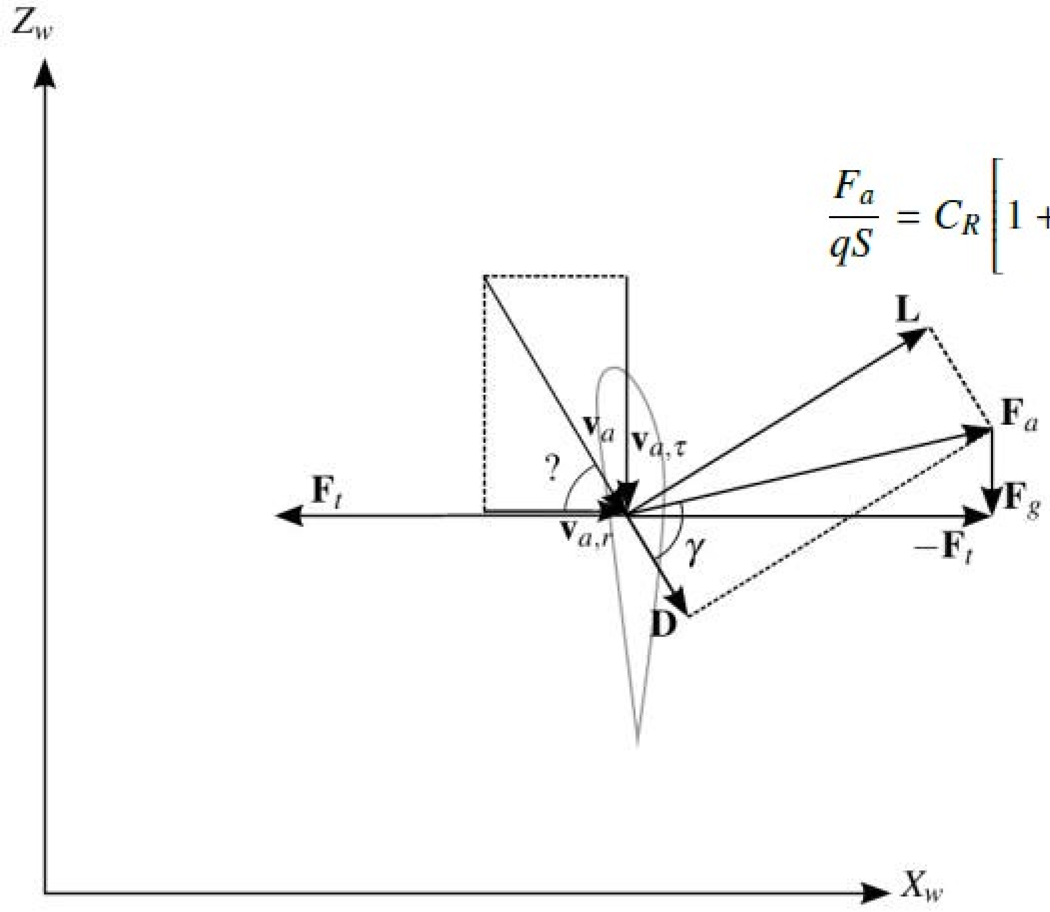
$$\frac{F_a}{qS} = C_R\left[1 + \left(\frac{v_{a,\tau}}{v_{a,r}}\right)^2\right](\sin\theta\cos\phi - f)^2.$$

Include Gravity

Flight State Approximation

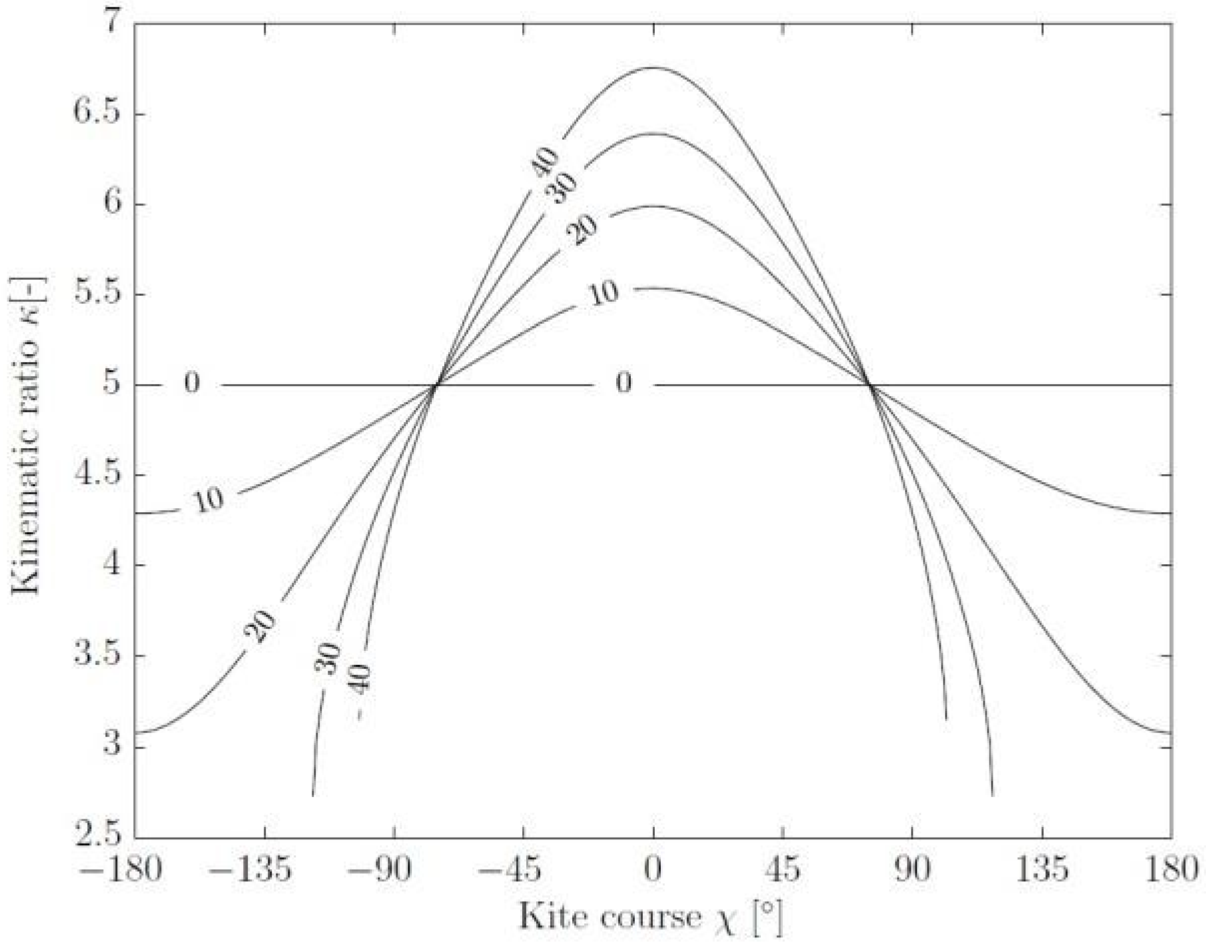
$$\frac{v_{a,\tau}}{v_{a,r}} \neq \frac{L}{D}$$

$$\frac{F_a}{qS} = C_R \left[1 + \left(\frac{v_{a,\tau}}{v_{a,r}} \right)^2 \right] (\sin\theta \cos\phi - f)^2.$$



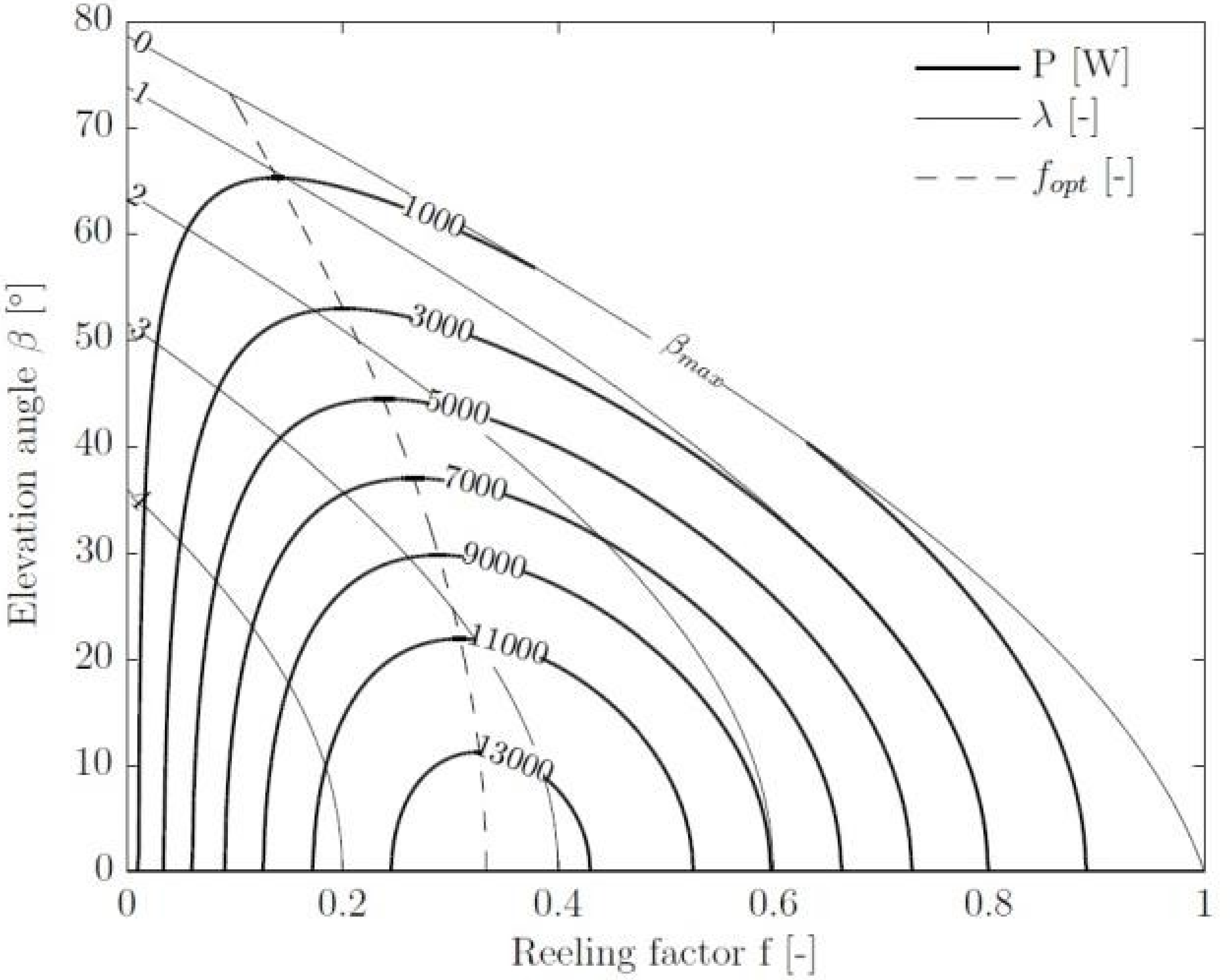
Include Gravity

Kinematic Ratio



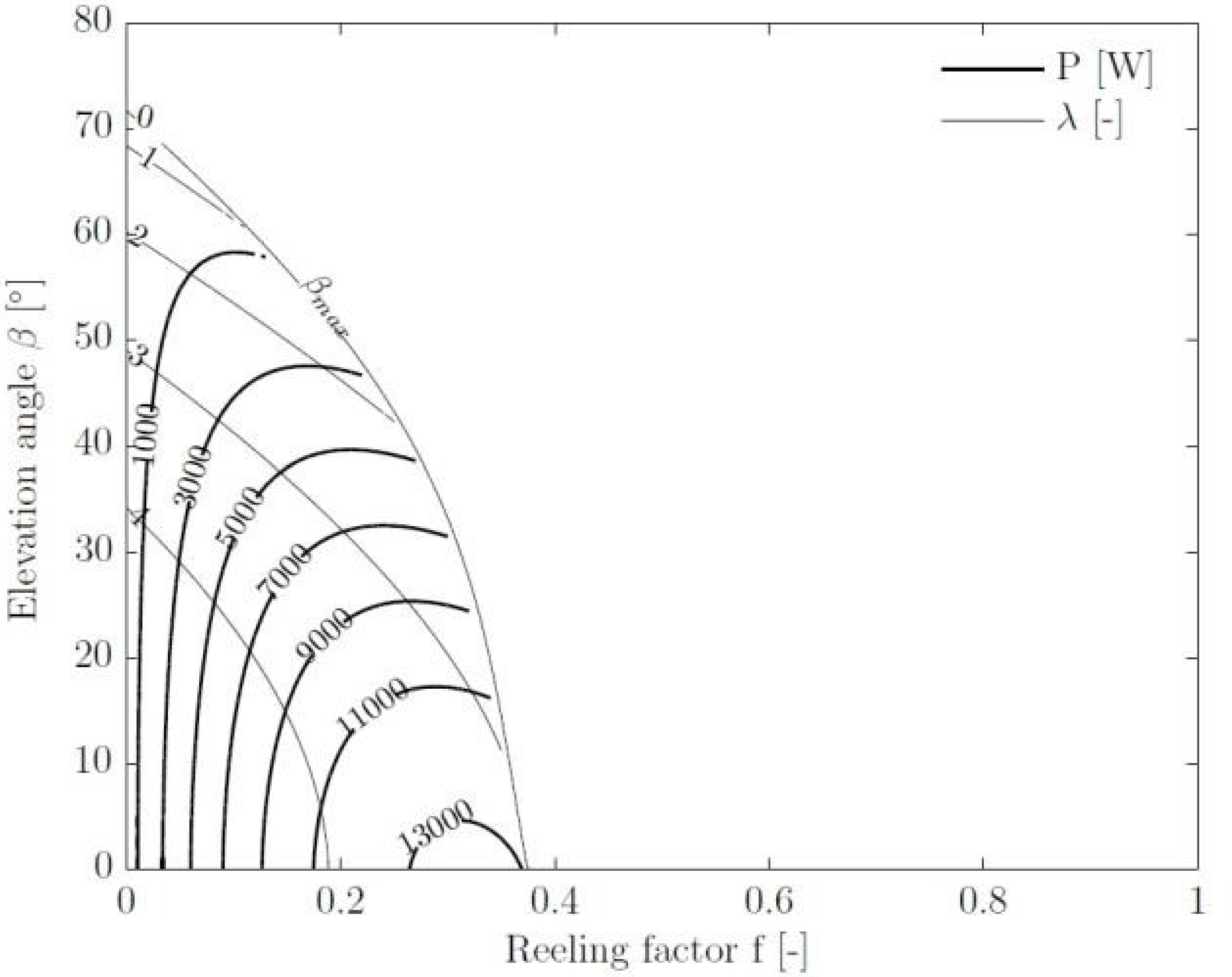
Include Gravity

Power Plot



Include Gravity

Power Plot



Tether

Problem description

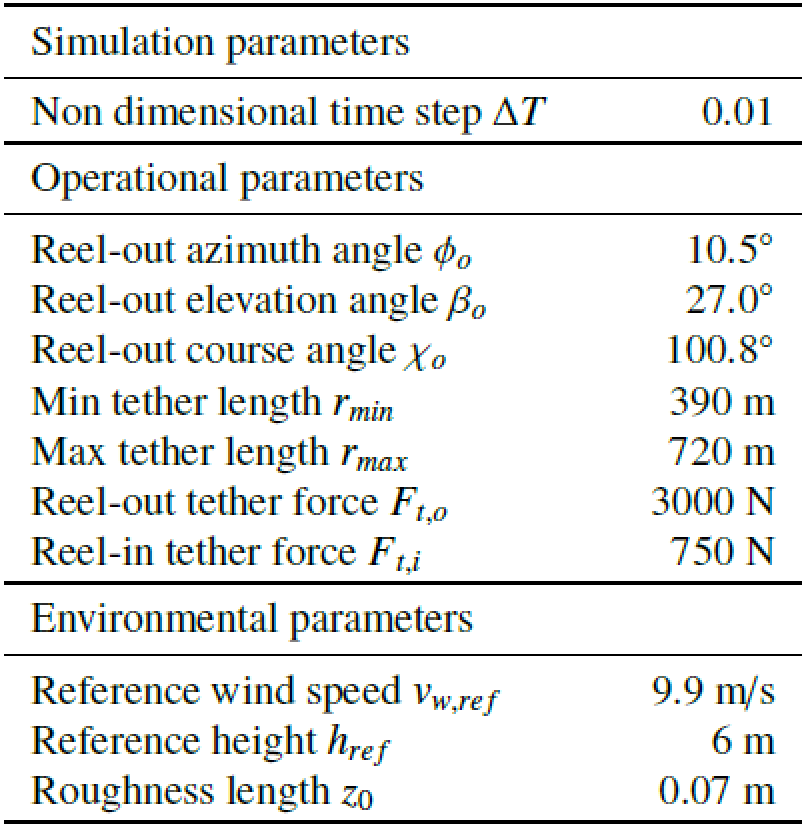
$$D = D_k + D_t,$$

$$D_t = \frac{1}{8}\rho\, d\, r\, C_{D,c}\, v_a^2,$$

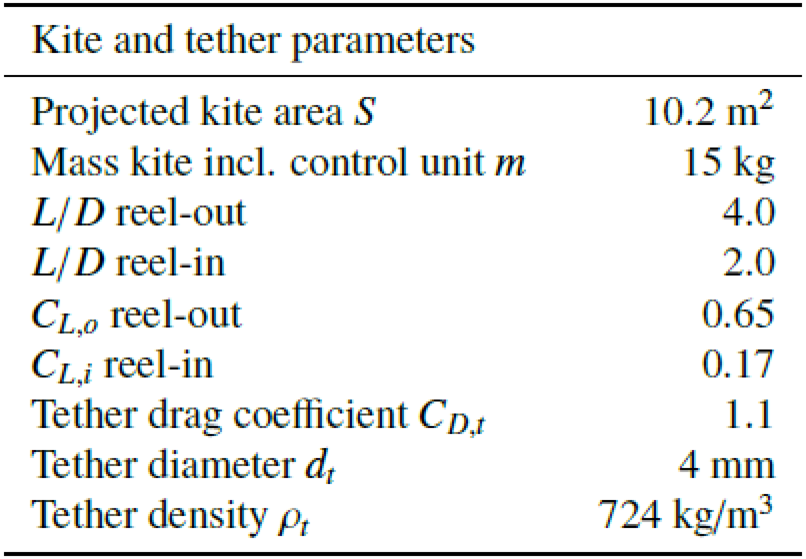
$$\mathbf{F}_g = \begin{bmatrix} -\cos\theta \\ \sin\theta \\ 0 \end{bmatrix} mg + \begin{bmatrix} -\cos\theta \\ \frac{1}{2}\sin\theta \\ 0 \end{bmatrix} m_t g,$$

Model

Characterization



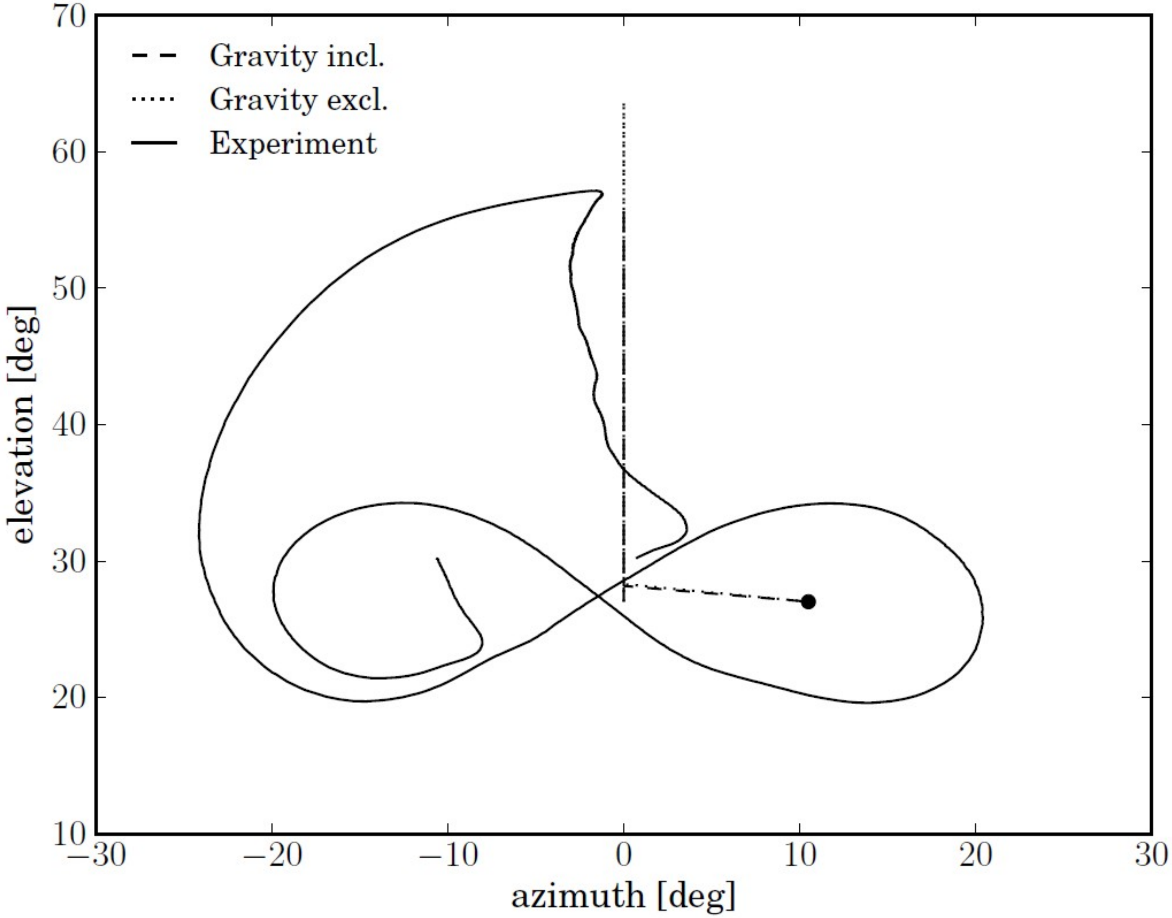
Simulation parameters	
Non dimensional time step ΔT	0.01
Operational parameters	
Reel-out azimuth angle ϕ_o	10.5°
Reel-out elevation angle β_o	27.0°
Reel-out course angle χ_o	100.8°
Min tether length r_{min}	390 m
Max tether length r_{max}	720 m
Reel-out tether force $F_{t,o}$	3000 N
Reel-in tether force $F_{t,i}$	750 N
Environmental parameters	
Reference wind speed $v_{w,ref}$	9.9 m/s
Reference height h_{ref}	6 m
Roughness length z_0	0.07 m



Kite and tether parameters	
Projected kite area S	10.2 m^2
Mass kite incl. control unit m	15 kg
L/D reel-out	4.0
L/D reel-in	2.0
$C_{L,o}$ reel-out	0.65
$C_{L,i}$ reel-in	0.17
Tether drag coefficient $C_{D,t}$	1.1
Tether diameter d_t	4 mm
Tether density ρ_t	724 kg/m^3

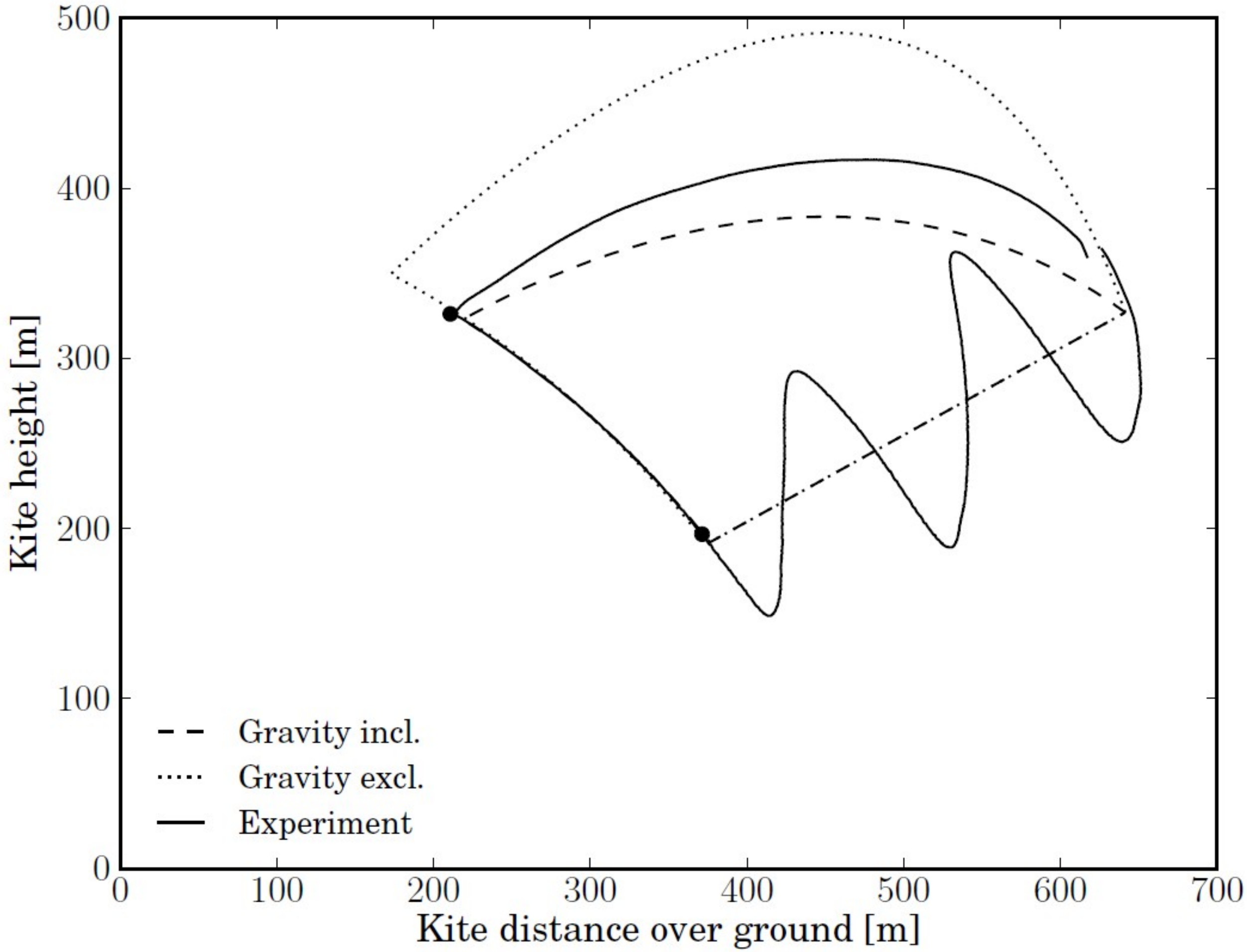
Results

Position



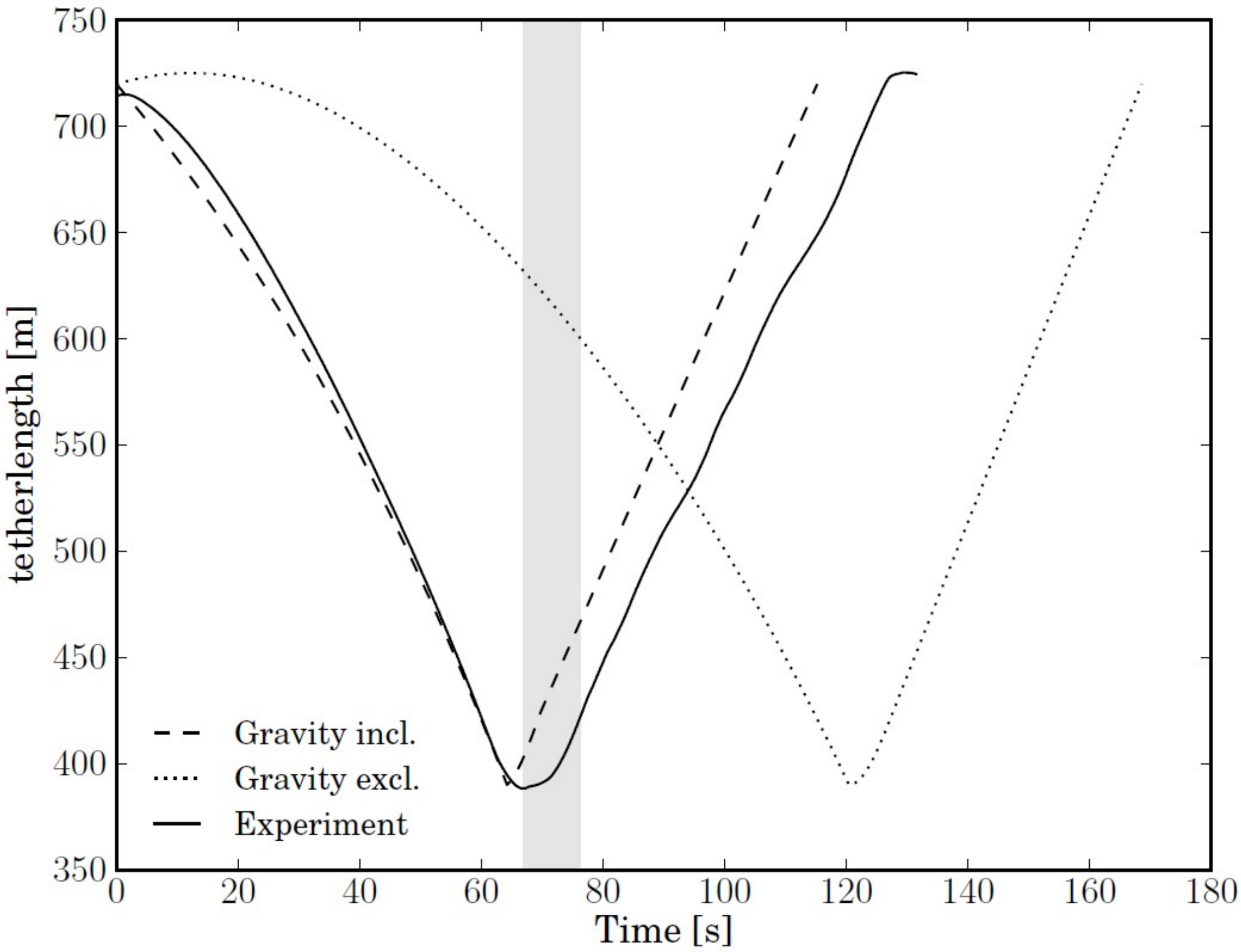
Results

Position



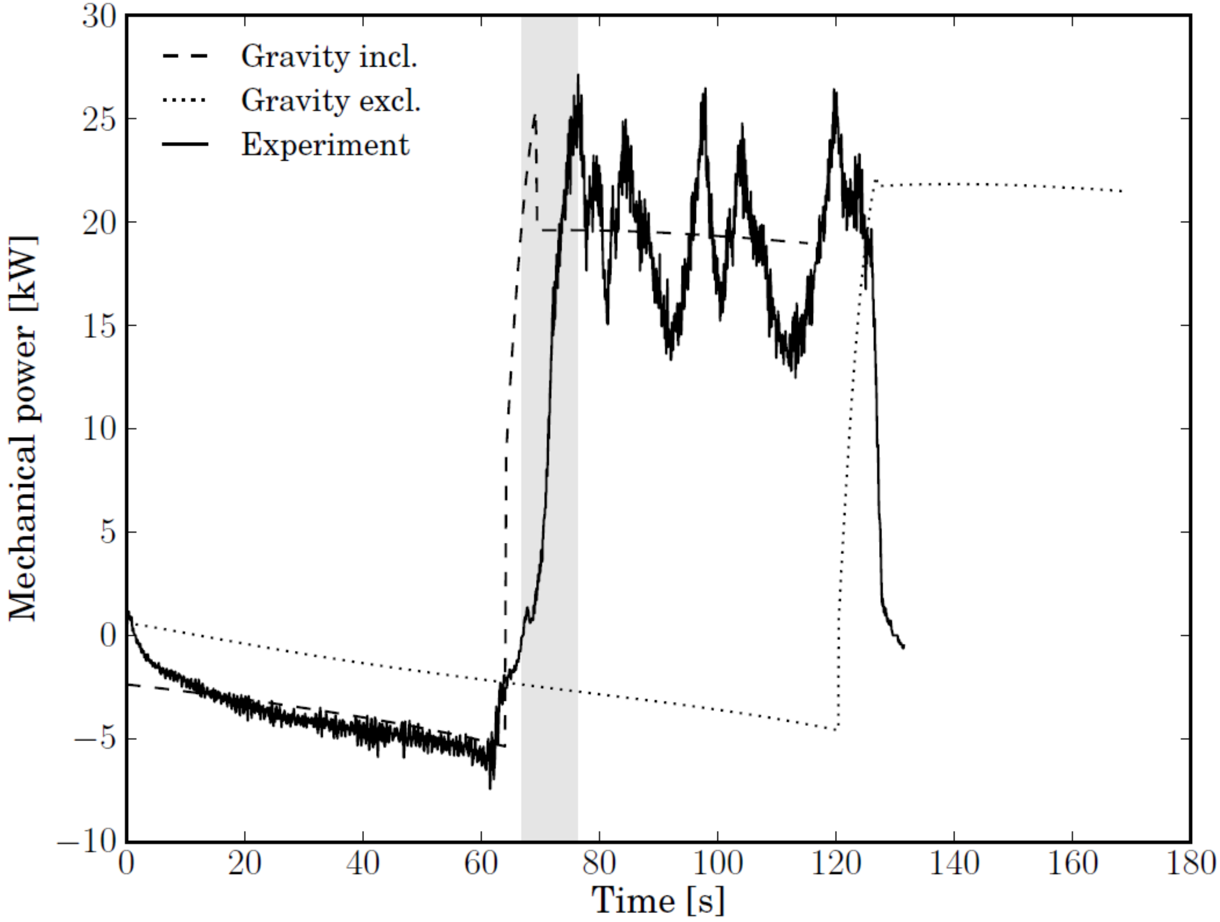
Results

Tether Length



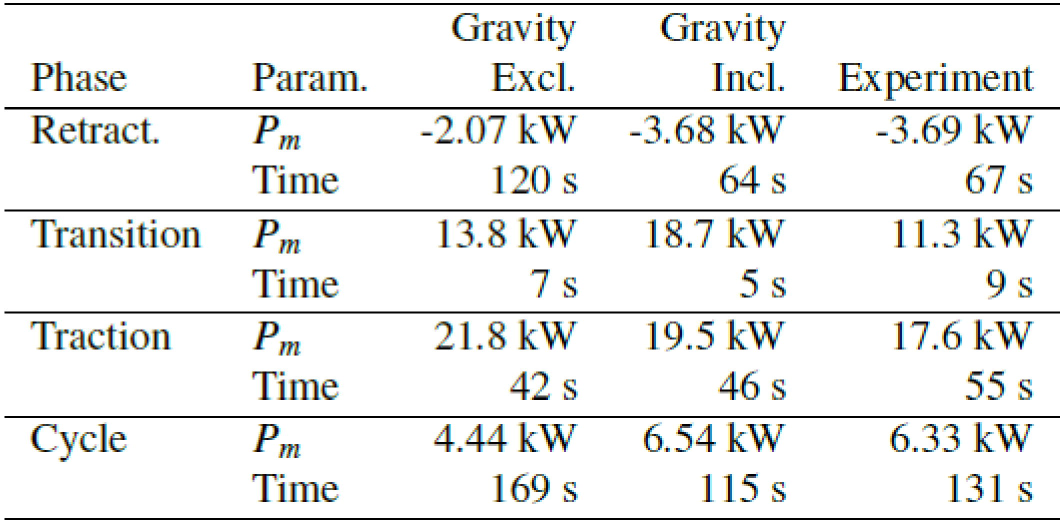
Results

Mechanical Power



Results

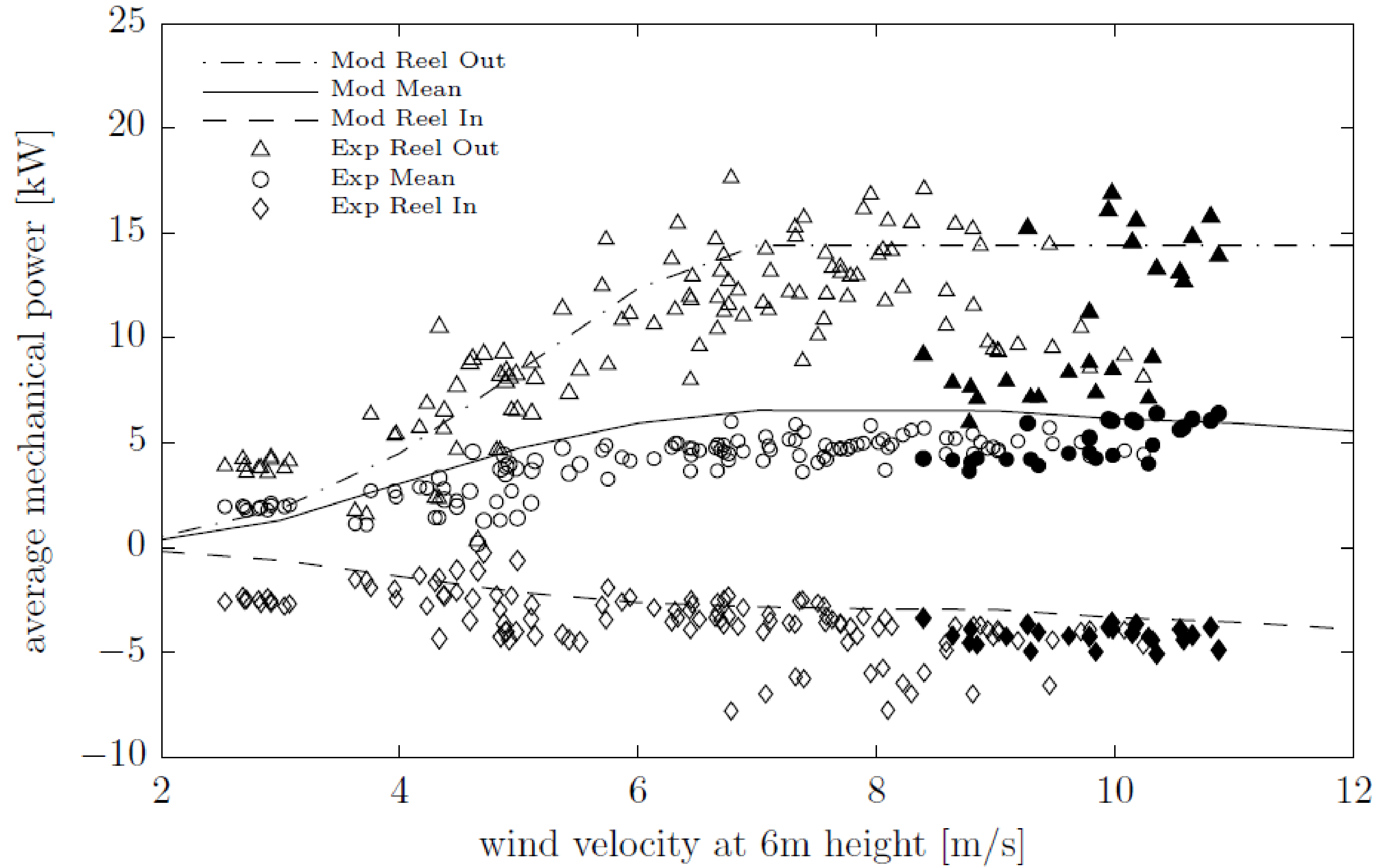
Mechanical Power



Phase	Param.	Gravity Excl.	Gravity Incl.	Experiment
Retract.	P_m	-2.07 kW	-3.68 kW	-3.69 kW
	Time	120 s	64 s	67 s
Transition	P_m	13.8 kW	18.7 kW	11.3 kW
	Time	7 s	5 s	9 s
Traction	P_m	21.8 kW	19.5 kW	17.6 kW
	Time	42 s	46 s	55 s
Cycle	P_m	4.44 kW	6.54 kW	6.33 kW
	Time	169 s	115 s	131 s

Results

Mechanical Power

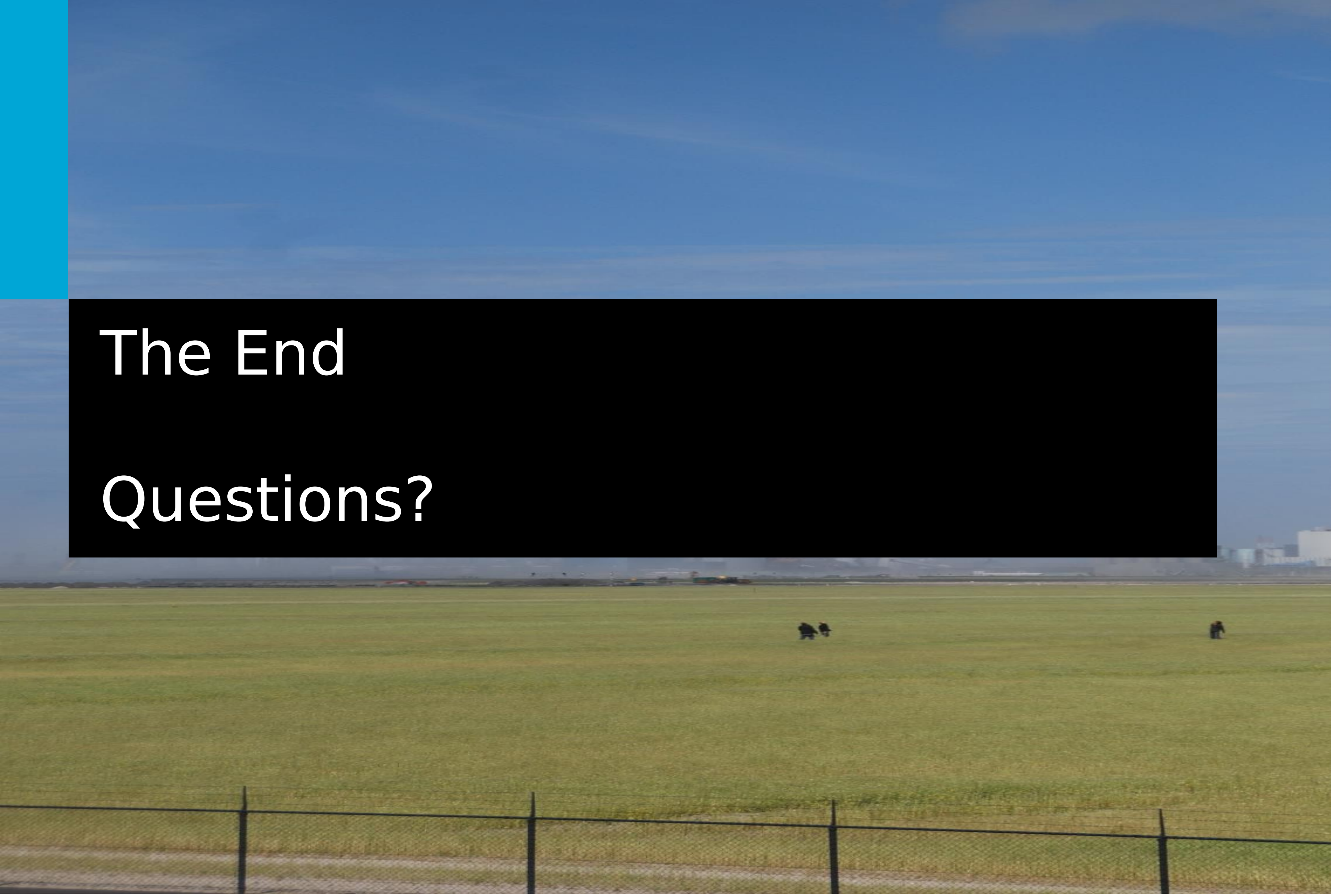


Conclusion

- Fundamental relationships established
- Effect of kite mass on the system
- Effect of a tether on the system
- Mechanical power delivered to the groundstation can accurately be predicted.
- Mass should not be neglected when modeling a full cycle

Future Work

- Extend the model to include:
    - Conversion mechanical to electrical energy
    - Annual power production
    - Lifetime and cost model
    - Cost of energy estimation
    - Optimization algorithms
- Use dynamic model as comparison to further improve system characterization



The End

Questions?