ETNZ training for the next America Cup (October 2024, Barcelona)

Faster than the wind…

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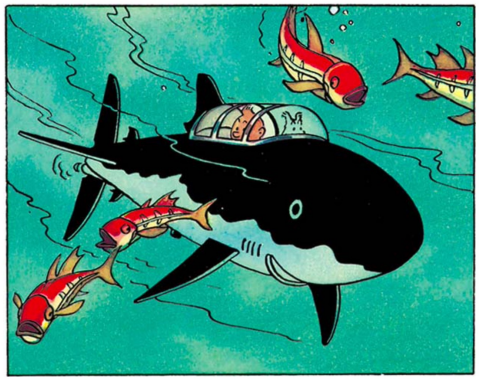
DPhP-CEA, 30 janvier 2023

What is a sailing boat?

Air

Water



What qualities do you look for in a sailboat?

1) Do not sink!
2) Don't turn over!
Transport of goods...
Comfort ...
Sea resistance ...
3) Speed ...

1) Do not sink... (vertical balance of forces)

Static floating
(Archimedean mode)

Pogo 12.50

Dynamic floating
(planing or flying mode)

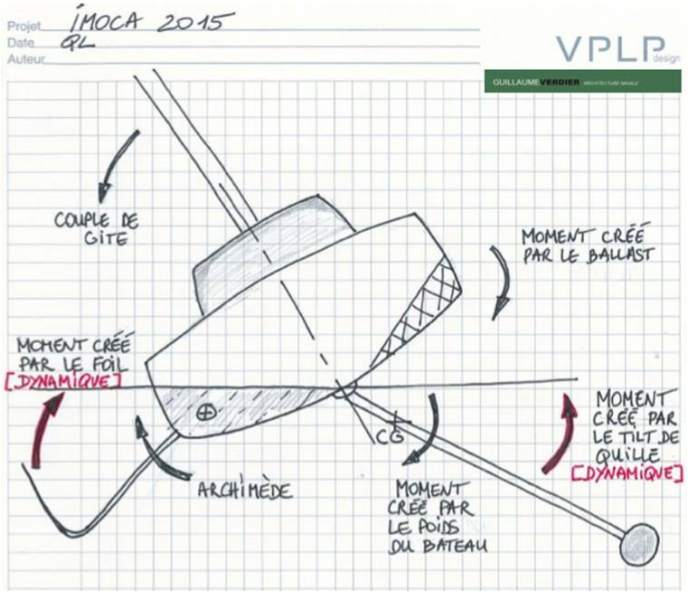
Gitana 17

2) Don't turn around... (balance of moments)
Centre of Gravity versus Centre of Thrust

Weight stability

Importance of ballast (80 % of boat weight!)

Shape stability



Importance of hull shape

Do not turn around...

Dynamic stability => moving the CG

49er (JO)

Moth International

Propulsion: Pushed by the wind

Running (detached flow)

Trois-mâts Belem

Detached and turbulent flow

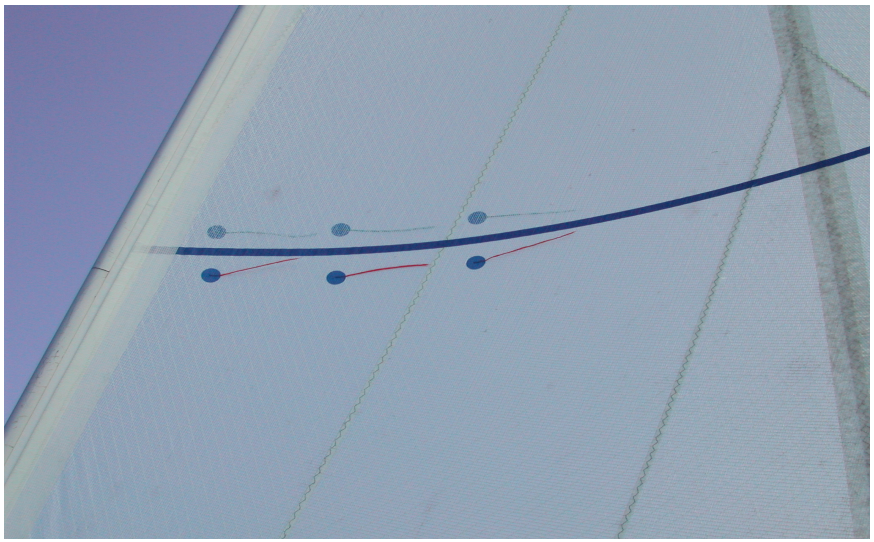
The propulsive force is mainly due to the drag force

Sailing into the wind?

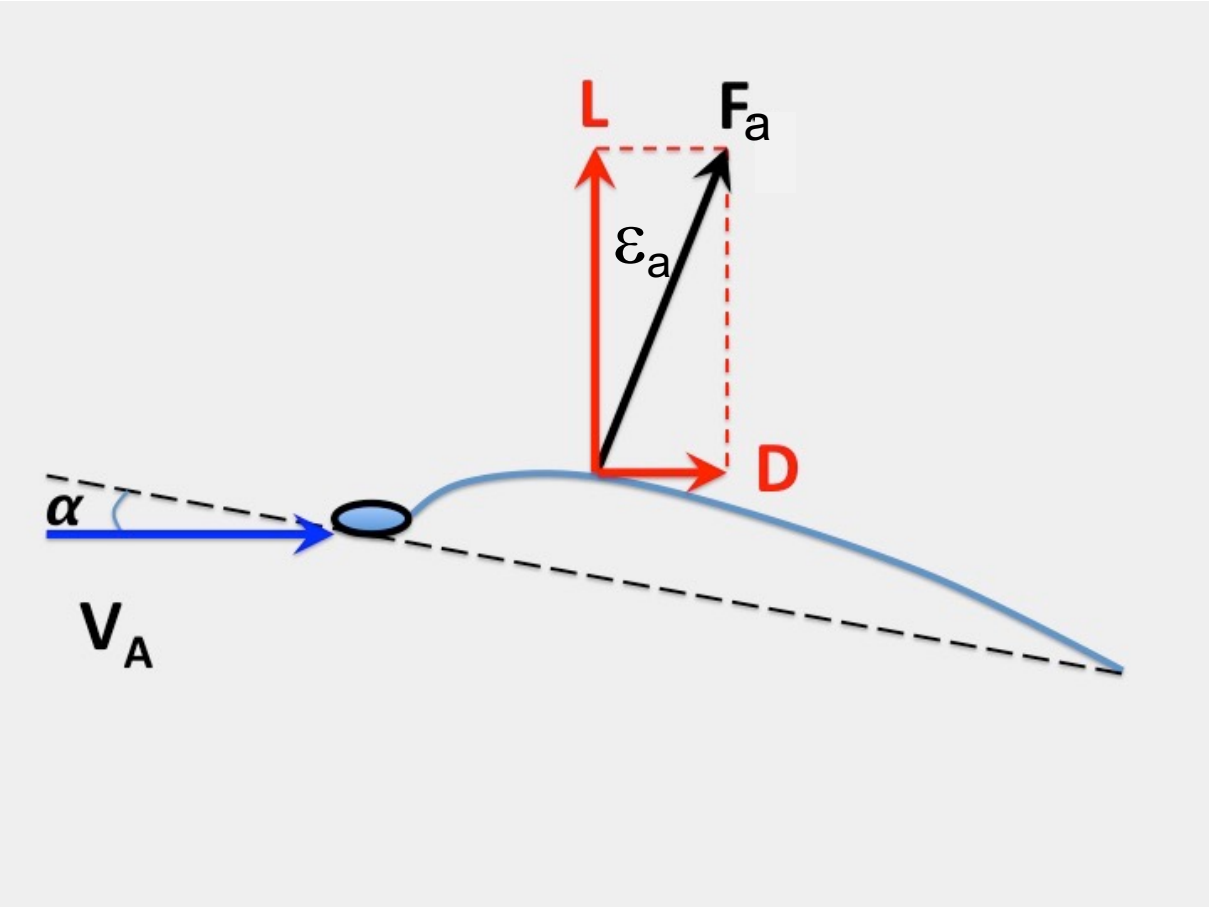
« Navigation en finesse »
(laminar flow)

Pen Duick

The propulsive force is
essentially a lift force



sailing « en finesse »

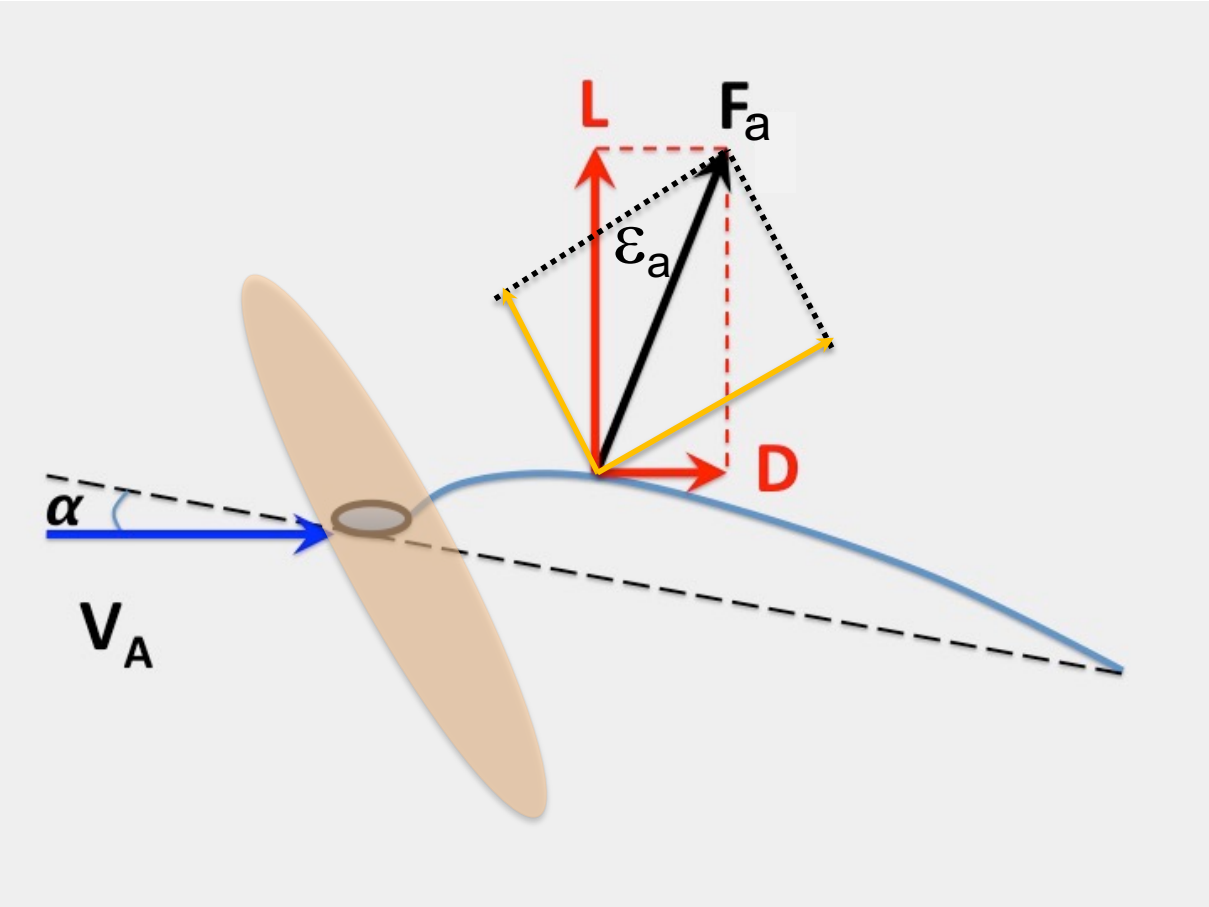


$$L = \tfrac{1}{2}\rho V^2 S C_L$$

$$D = \tfrac{1}{2}\rho V^2 S C_D$$

Finesse = lift-to-drag ratio = L / D = 1 / tan(ε_a)

sailing « en finesse »



$$L = \tfrac{1}{2}\rho V^2 S C_L$$

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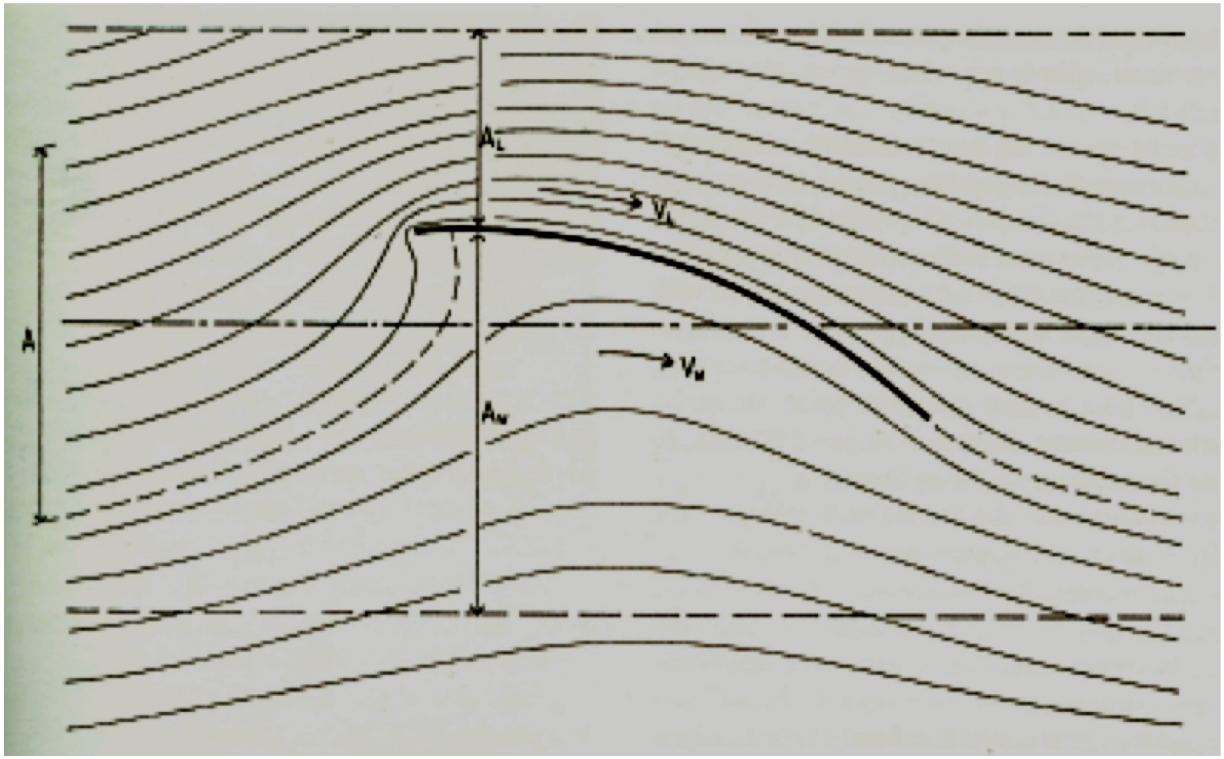
Finesse = lift-to-drag ratio = L / D = 1 / tan(ε_a)

Origine of lift

$$P + \tfrac{1}{2}\rho V^2 = \text{Constante}$$

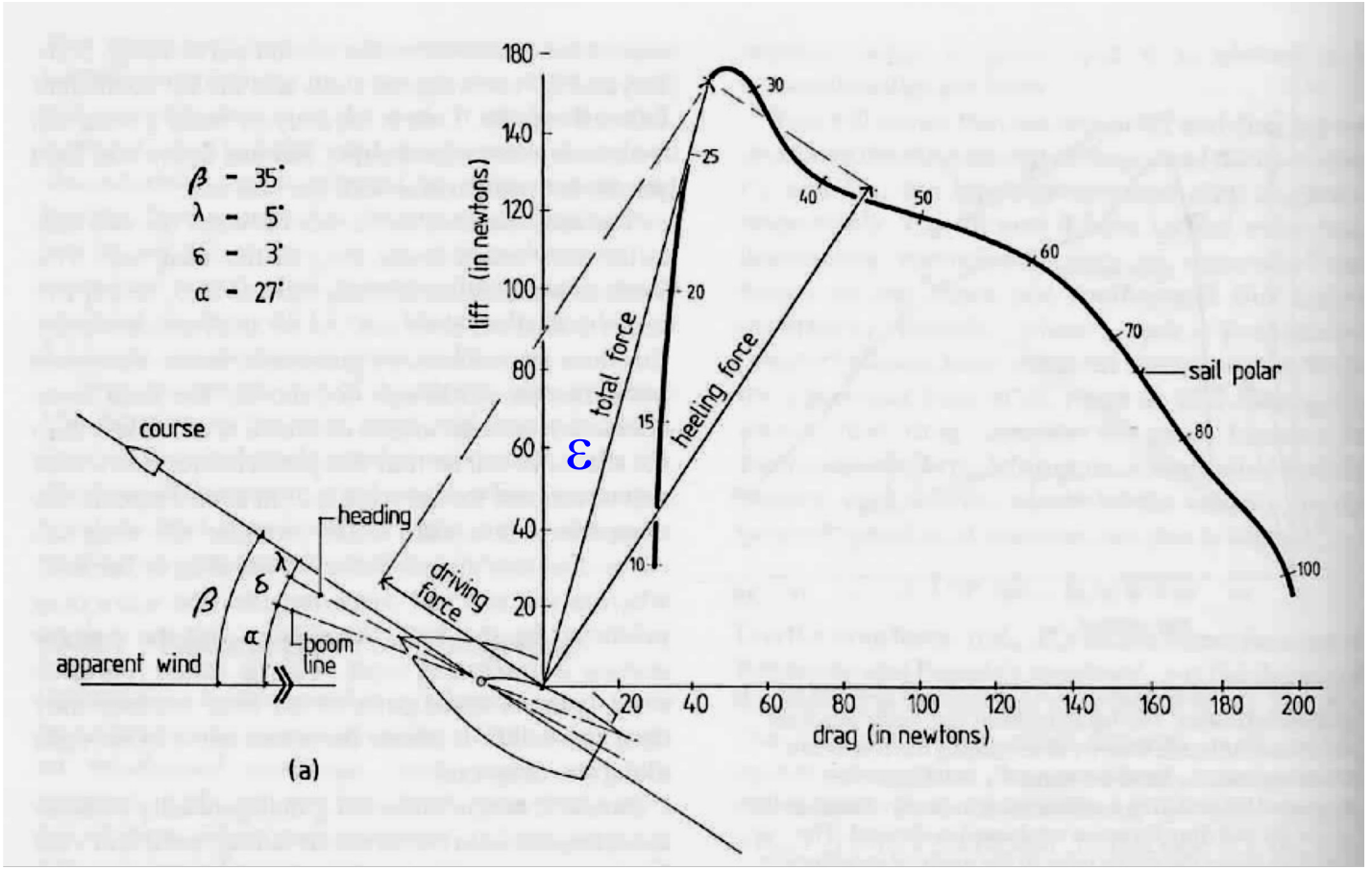
Daniel Bernoulli (1700-1782)



Simulation of a potential flow around a thin sail

Use of the « Eiffel » polar curve: L = f(D)

Gustave Eiffel
(1832-1923)



- Upwing sailing: $\text{finesse} = \frac{L}{D} = 1/\tan\epsilon$

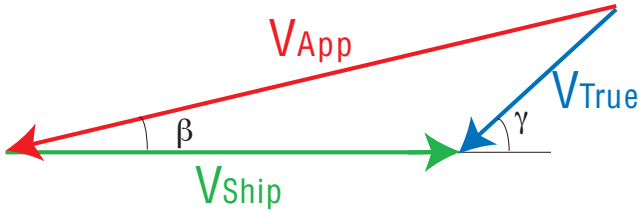
Keels and sails having good lift/drag ratio

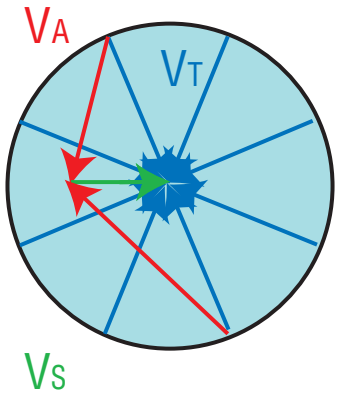
Imoca

Performance glider

Real or apparent wind?

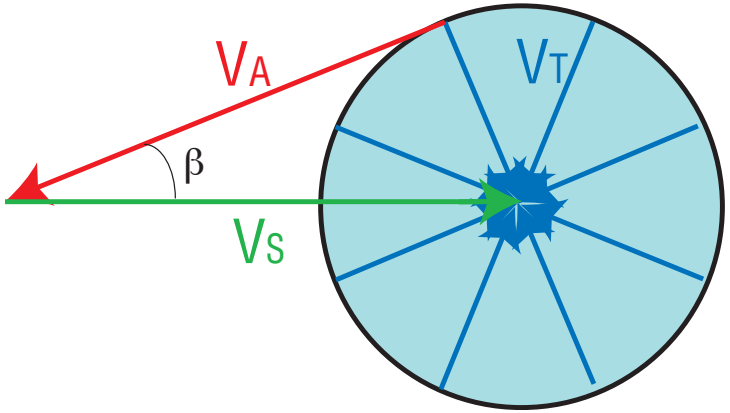
Real or apparent wind?





« Slow » boat

$$R = \frac{V_S}{V_T} < 1$$



« Fast » boat

$$R = \frac{V_S}{V_T} > 1$$

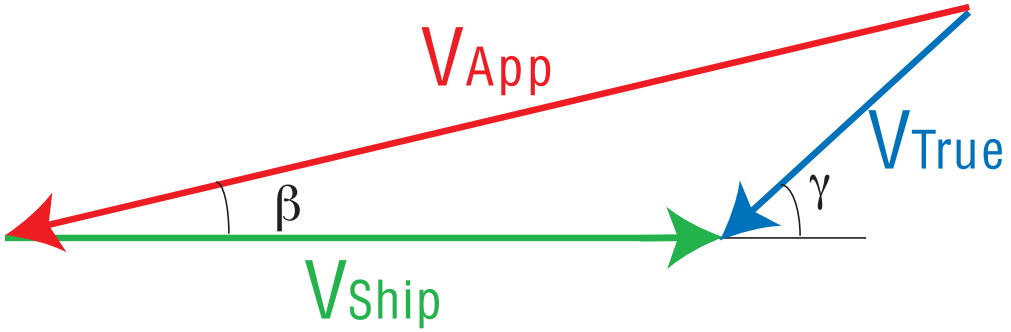
$$\sin(\beta_{max}) = \frac{1}{R}$$

⇒ *A fast sailing boat always sails close to the (apparent) wind.*

⇒ *If R >> 1 then β becomes quite small!*

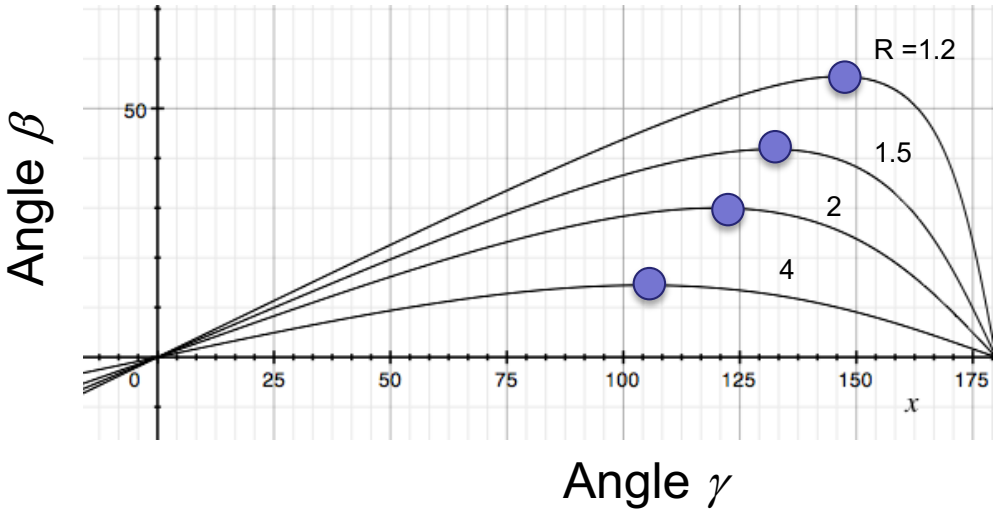
Real or apparent wind?

$$R = \frac{V_S}{V_T}$$



$$V_A^2 = V_T^2 + V_S^2 + 2V_T V_S \cos\gamma$$

$$\tan\beta = \frac{V_T \sin\gamma}{V_T \cos\gamma + V_S} = \frac{\sin\gamma}{\cos\gamma + X}$$



$$\sin\left(\beta_{\max}\right) = \frac{1}{X}$$

⇒ *A fast sailing boat always sails close to the (apparent) wind.*

⇒ *If R >> 1 then β becomes quite small!*

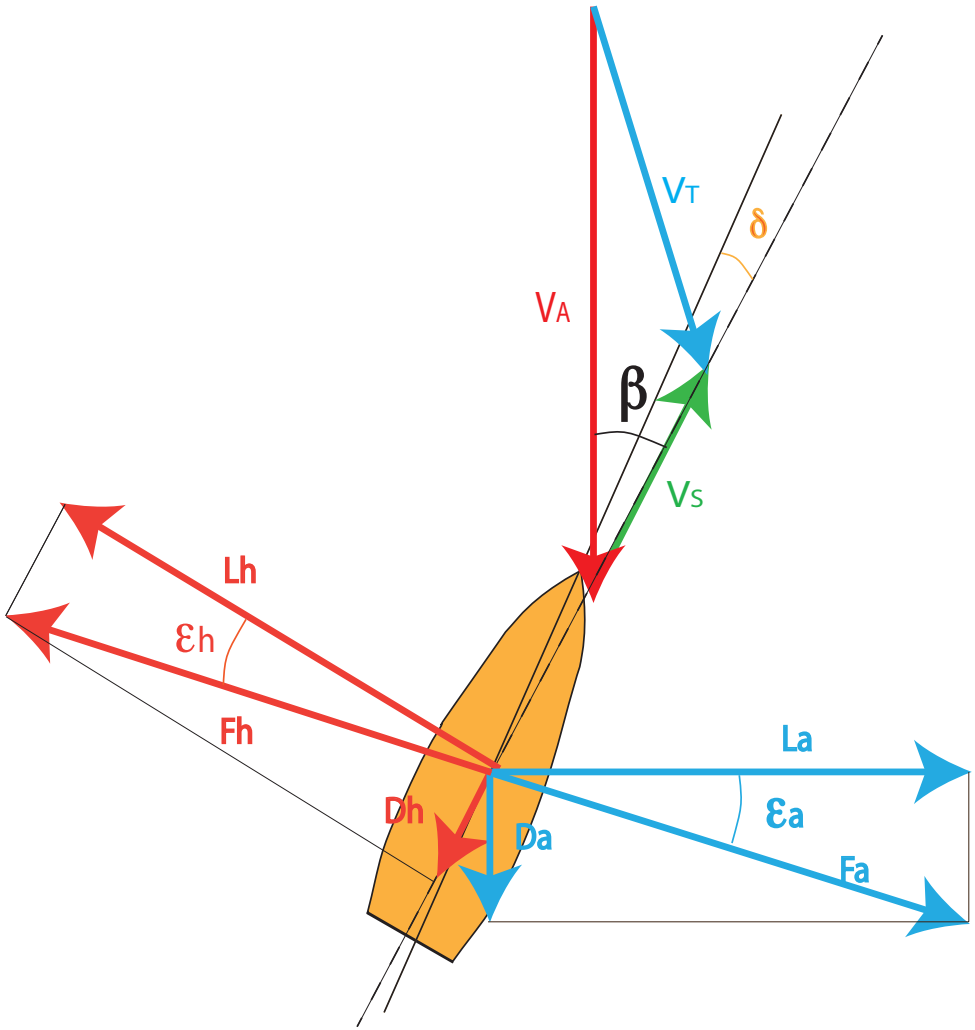
$$R = \frac{Boat\ speed}{True\ wind\ speed}$$

1492 : Caravelle
25 m, 270 m^2, 100 tonnes
R ≈ 0,25 ?

2007 : AC32
24 m, 200 m^2, 24 tonnes
R ≈ 1

2020 : Imoca
18 m, 600 m^2, 7 tonnes
R ≈ 1,5

Why is it necessary to increase the lift/drag ratio?



Aero/hydro equilibrium
(here in 2D)

Lanchester theorem (1907)

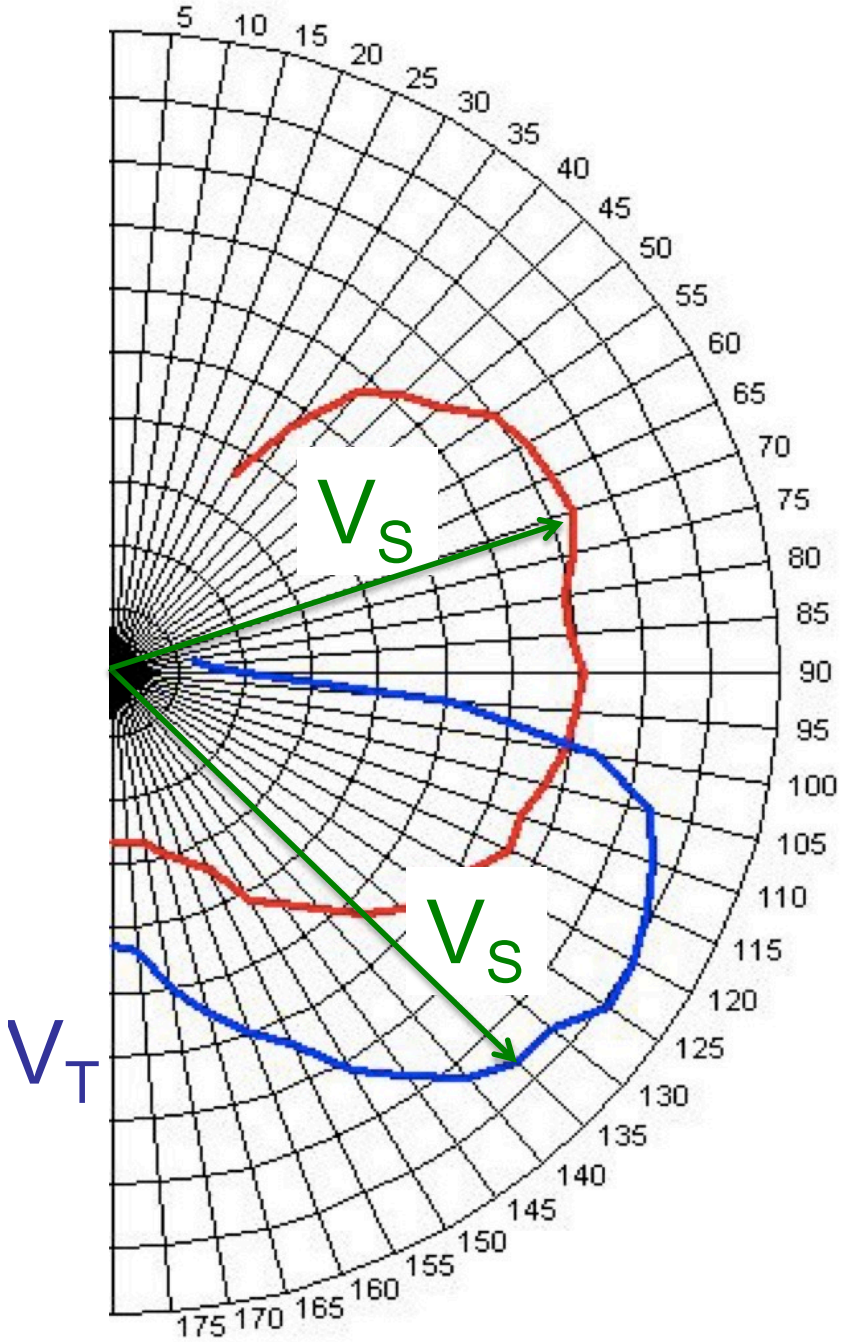
The apparent upwind angle is equal to the sum of the aerodynamic and hydrodynamic glide angles:

$$\beta = \varepsilon_a + \varepsilon_h$$

$$R = 3 => \beta_{min} = \epsilon_a + \epsilon_h \approx 20^o, f \sim 6$$

$$R = 5 => \beta_{min} = \epsilon_a + \epsilon_h \approx 11^o, f \sim 10$$

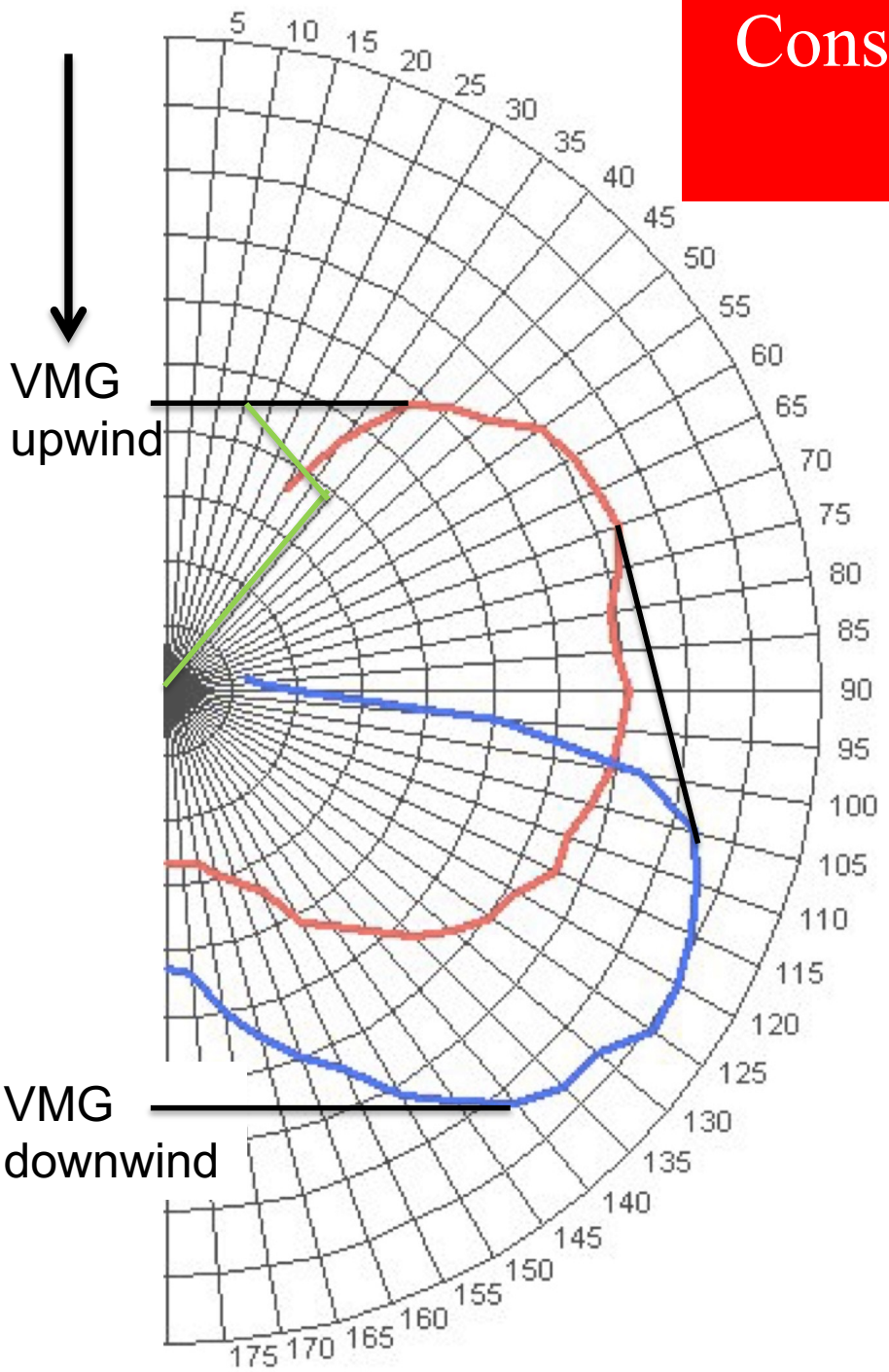
Sailboat speed polar curve



$V_S(\theta)$ *:* curve of target speeds as a function of heading versus true wind.

- depends on the sail set,
- the wind strength
- the state of the sea

Construction of the convex envelope: V(θ)



- The flat areas correspond to the tackable positions (VMG).
- Similar to Wulff's construction in crystals growth

How to go faster

- Increasing the sail surfaces?

Shamrock IV
(sir Lipton)

- Decreasing the hydrodynamic drag ? (wave drag)

Club Méd. (A. Colas)

- Decreasing the immersed volume (lightening and foils)

Flying boats and speed records

They all learn to fly!

Windfoil

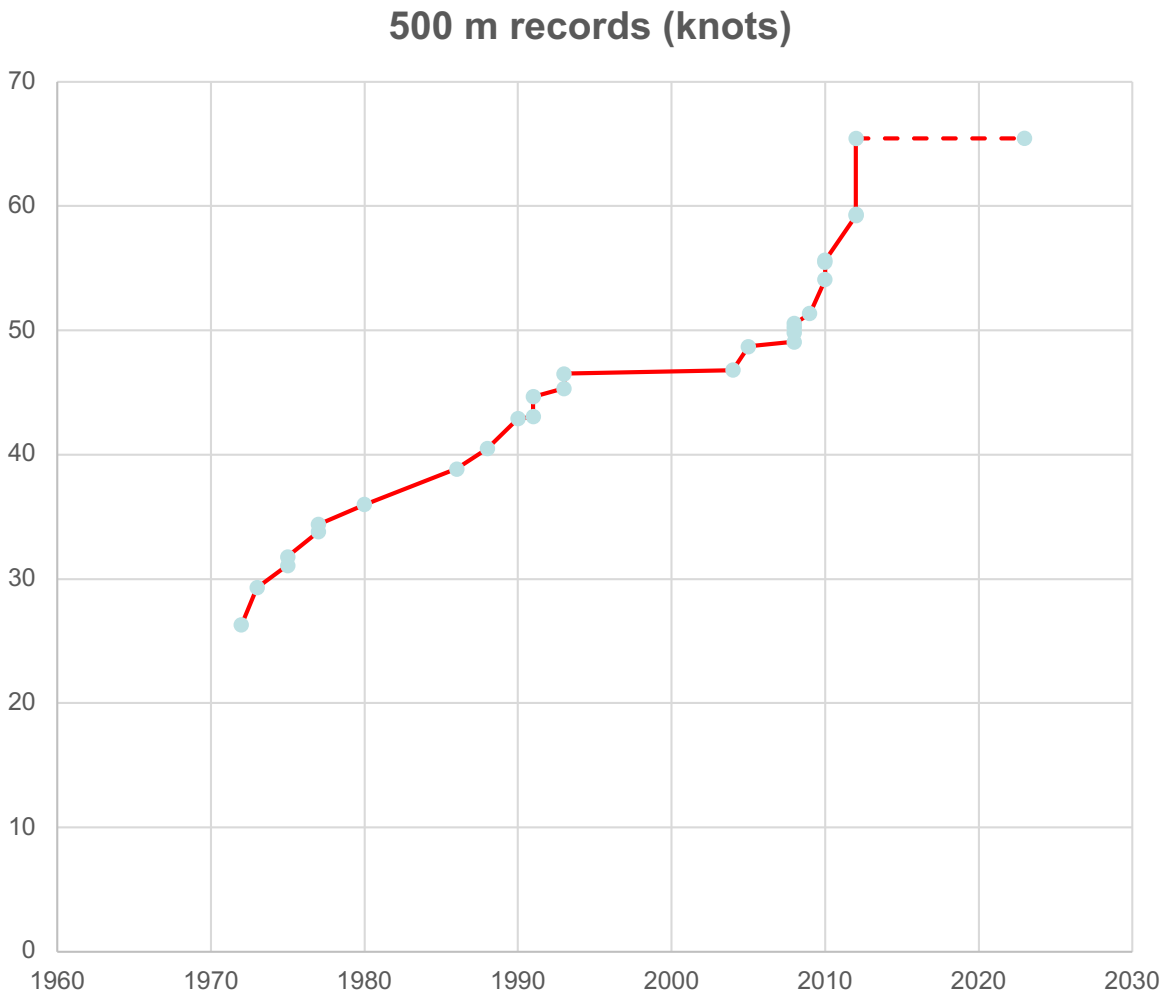
Kitefoil

Nacra 17

← Mini 6.50

AC 45 -->

What is the speed limit for a sailing boat?



Evolution of speed records (over 500 m)

1 knot = 1 nautical mille/hour
=1,852 km/h

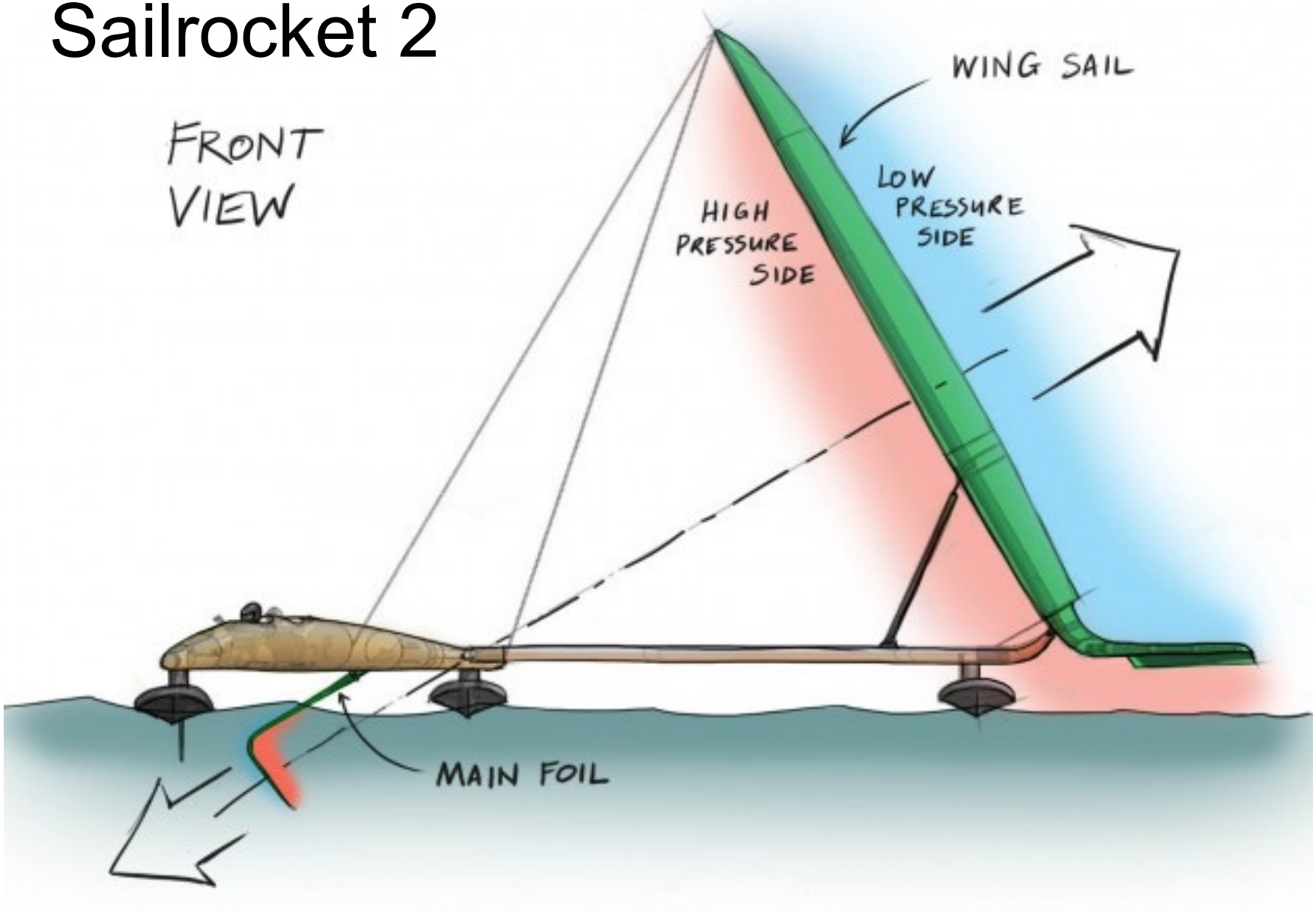
Cavitation or ventilation speed

At 50 knots, $\frac{1}{2}\rho_w V_S^2 \approx 3P_{atm}$

Supercavitating foils

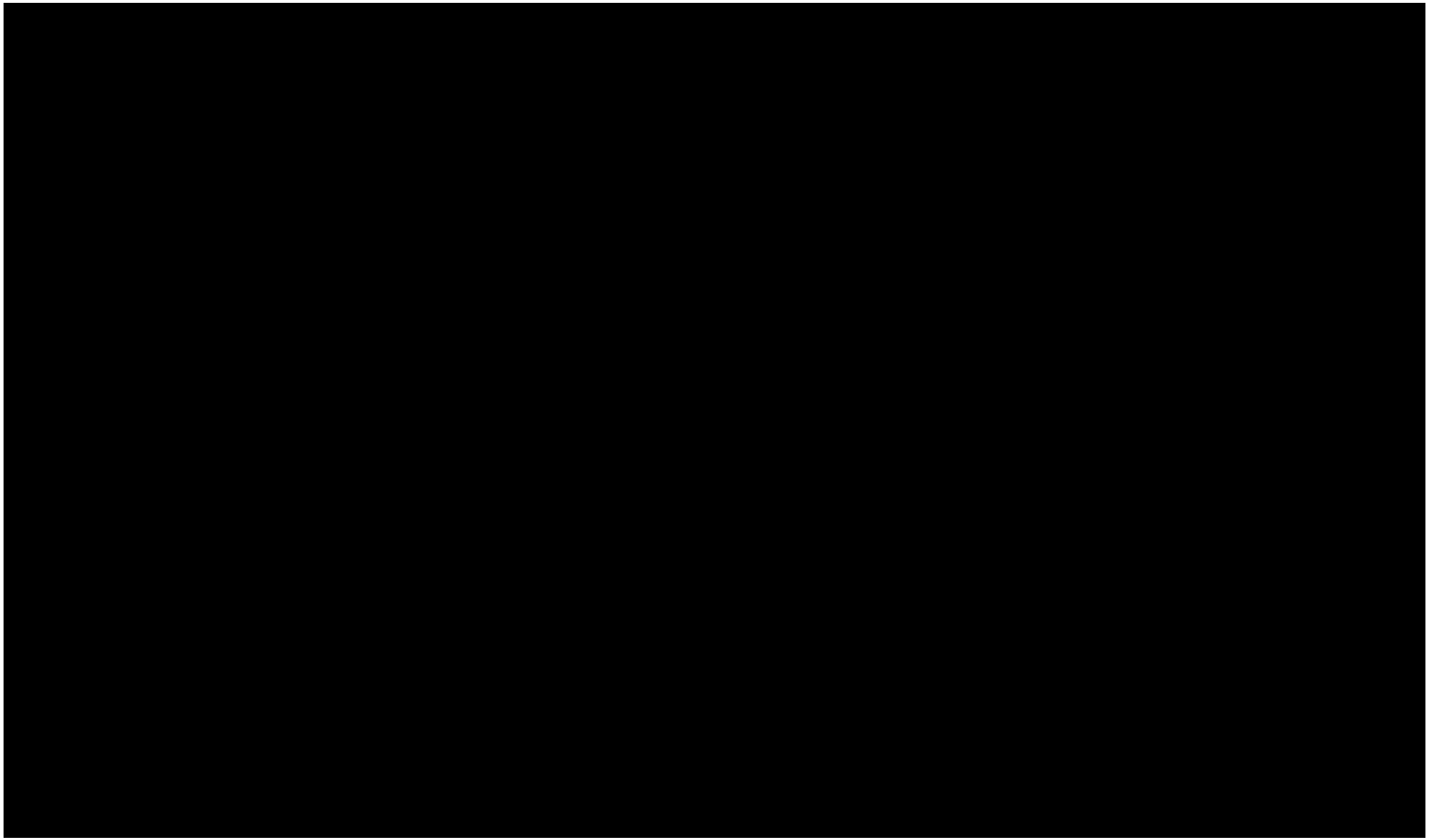
Ventilation on a kitefoil 'mast'.

Sailrocket 2



(World record at 121 km/h in 2012)

World sailing speed record! 121 km/h!



Faster than the wind?

- Is there a maximum value for R_{max}?

- Is the Lanchester theorem really a limit?

Can we sail directly into the wind?

Sailing into the wind... is it possible?

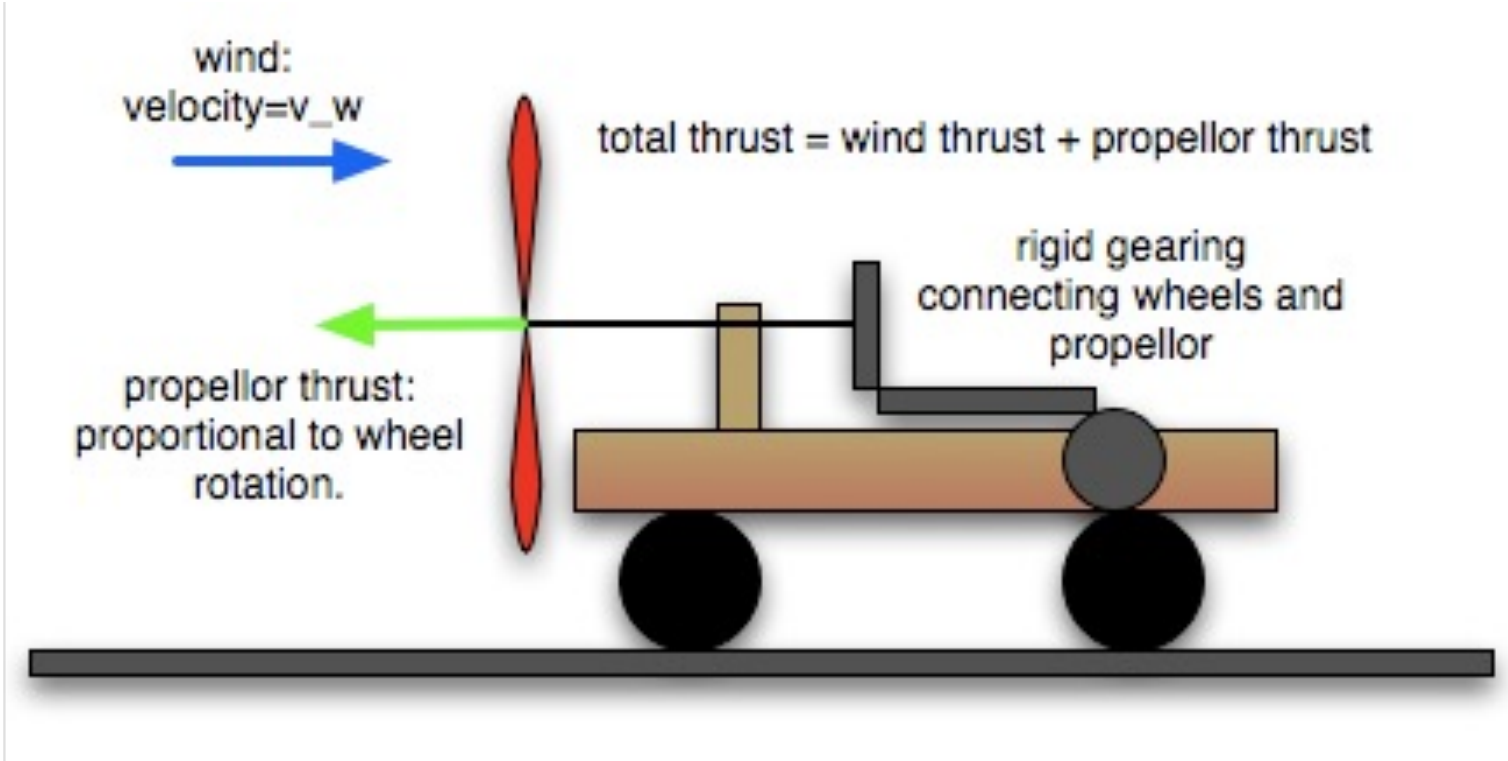
1920 – Constantin (on the river Seine)

1933 – Lord Brabazon

1980 – Jim Bates

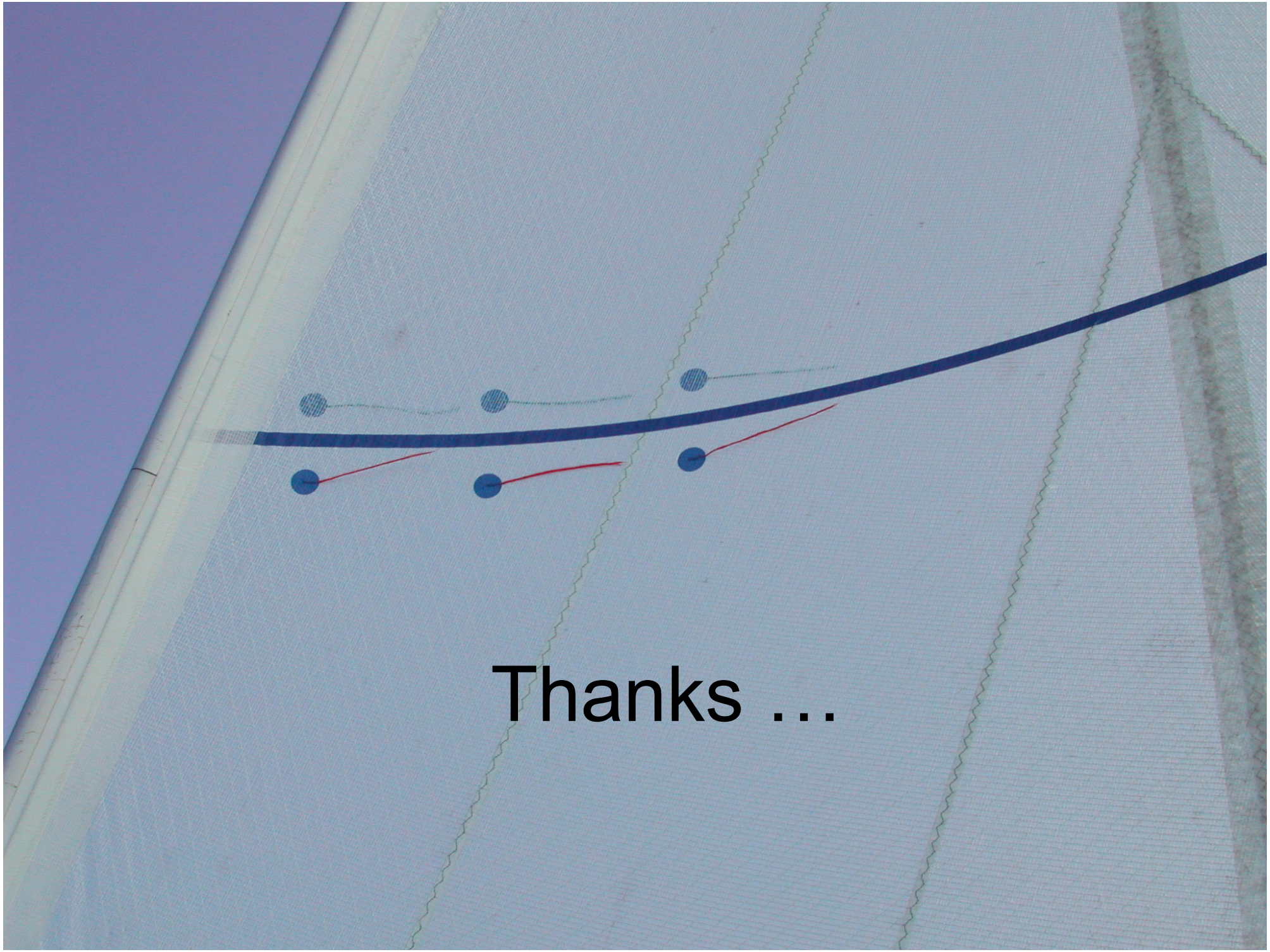
Autogiro, gyrovoile, Archinaute …

Peter Worsley, 2008


wind:
velocity=v_w
total thrust = wind thrust + propellor thrust
rigid gearing
connecting wheels and
propellor
propellor thrust:
proportional to wheel
rotation.

Directly downwind, faster than the wind (DDWFTTW)

Blackbird, July 2010, record at 2.8 times the wind velocity.


Thanks …