USING THE ATTITUDE RESPONSE OF AEROSTABLE SPACECRAFT TO DETERMINE THERMOSPHERIC WIND

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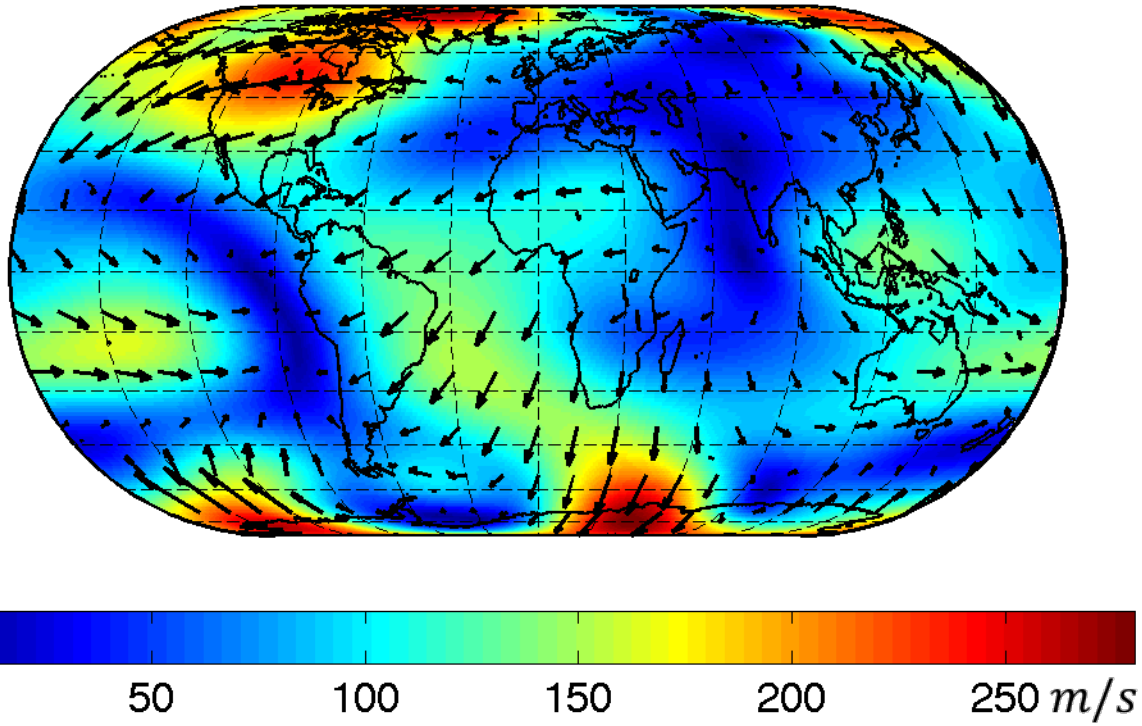
Outline

- Existing methods
- Concept
- Iterative approach
- Frequency approach
- Ideal performance
- Estimated performance

Thermospheric wind overview



Thermospheric wind at 250 km according to the HWM93 model

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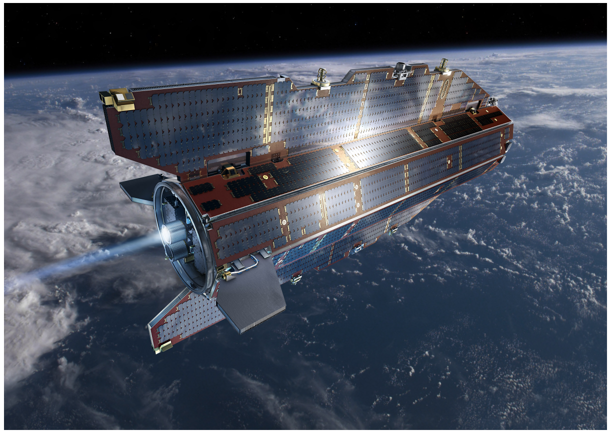
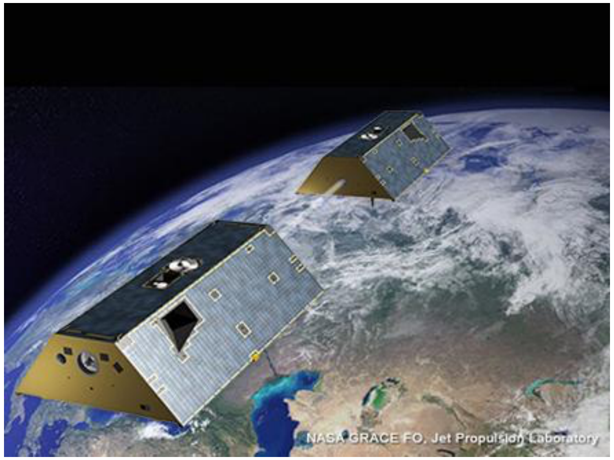
Existing methods:

- Remote sensing:
  - Interferometer
  - Incoherent Scatter Radar
- In-situ:
  - Chemical tracer
  - Accelerometer based (Doornbos 2010)



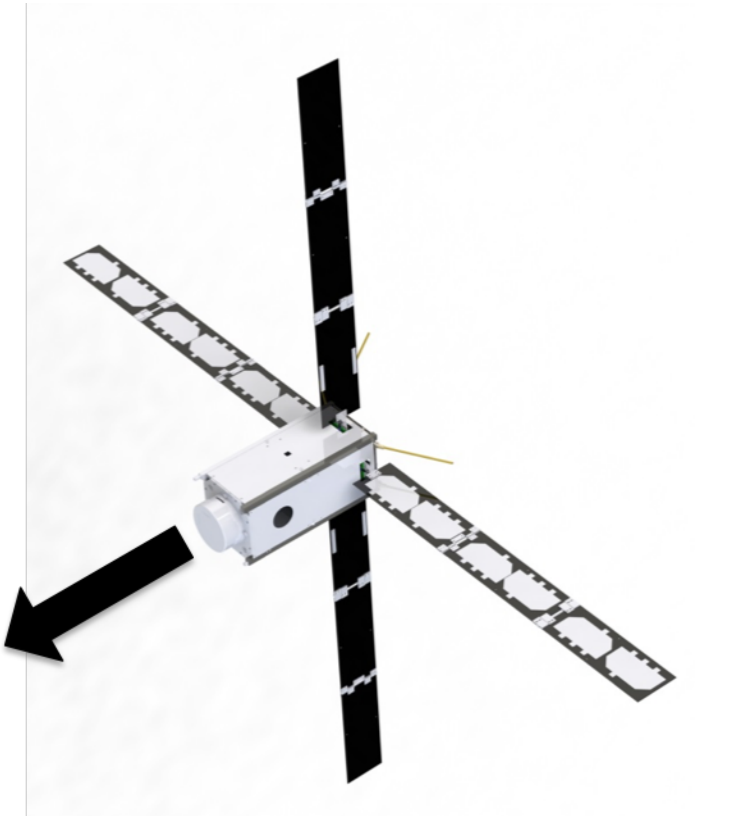
GOCE (ESA)



GRACE (NASA)

Concept:

- Estimate the thermospheric wind by observing the attitude evolution.
- Aerostable spacecraft, which exhibit a restoring torque are used as their attitude oscillates around the equilibrium point.
- Knowledge on the aerodynamic properties and the atmospheric density is required.



Prototype of a highly aerostable CubeSat that could be used to measure thermospheric wind

Aerodynamic Torques:

Atmospheric density

Reference Area and Length

$$\tau_{\text{aero}} = \frac{1}{2}\rho V_{\text{f}}^2 A_{ref} l_{ref} C_T$$

Aerodynamic torque

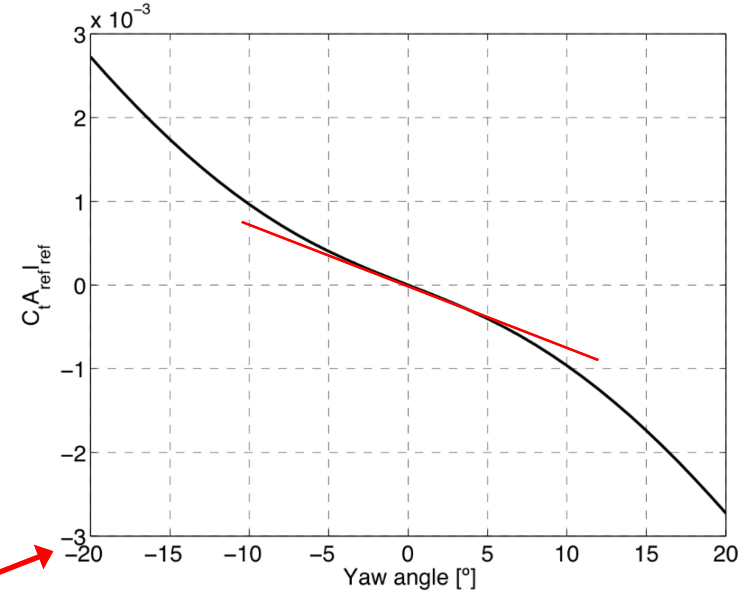
Relative flow velocity

Torque Coefficient

Aerostable spacecraft:

$$\tau_{aero} = -q f\left(\theta_{\text{sf}}\right)$$

Generic aerostable behavior



Linear simplification

$$\tau_{\text{aero}} = -qk\theta_{\text{sf}}$$

One rotational degree-of-freedom simplification:

$$I\ddot{\theta} = -qk\theta_{\text{sf}}$$

- Aerostable spacecraft behave as harmonic oscillators.
- k is the **aerodynamic stiffness**.
- Natural frequency:

$$\omega = \sqrt{\frac{qk}{I}}$$

- In-track and cross-track wind components

$$w^2 = w_i^2 + w_c^2 \longrightarrow V_i \gg w_i$$

Iterative approach (cross-track):

- Iterate to measure cross-track wind.
- In-track wind must be known
  - Set it to 0?
- How to minimize the error due to unknown w_i?

$$\hat{q} = \frac{1}{2}\rho\left((V_i + \hat{w}_i)^2 + \hat{w}_c^2\right)$$

$$\hat{\omega} = \sqrt{\frac{\hat{q}k}{I}}$$

$$\hat{\theta}_{flow} = \frac{\ddot{\theta}}{\hat{\omega}^2} + \theta$$

$$\hat{w}_c = (V_i + \hat{w}_i)\tan\left(\hat{\theta}_{flow}\right)$$

$$\frac{\partial w_c}{\partial w_i} = \frac{w_c}{V_i + w_i} - \frac{2\ddot{\theta}}{\omega^2}$$

$$\ddot{\theta} = \frac{\omega^2 w_c}{2\,(V_i + w_i)} \approx \frac{\omega^2 w_c}{2V_i}$$

Two measurement opportunities per oscillation

Iterative approach (in-track):

- Iterate to measure in-track wind.
- Cross-track wind must be known
- How to minimize the error due to unknown w_c?

$$\hat{\theta}_{\text{flow}} = \arctan\left(\frac{\hat{w}_c}{V_i + \hat{w}_i}\right)$$

$$\hat{\omega}^2 = \frac{\ddot{\theta}}{\hat{\theta}_{\text{flow}} - \theta}$$

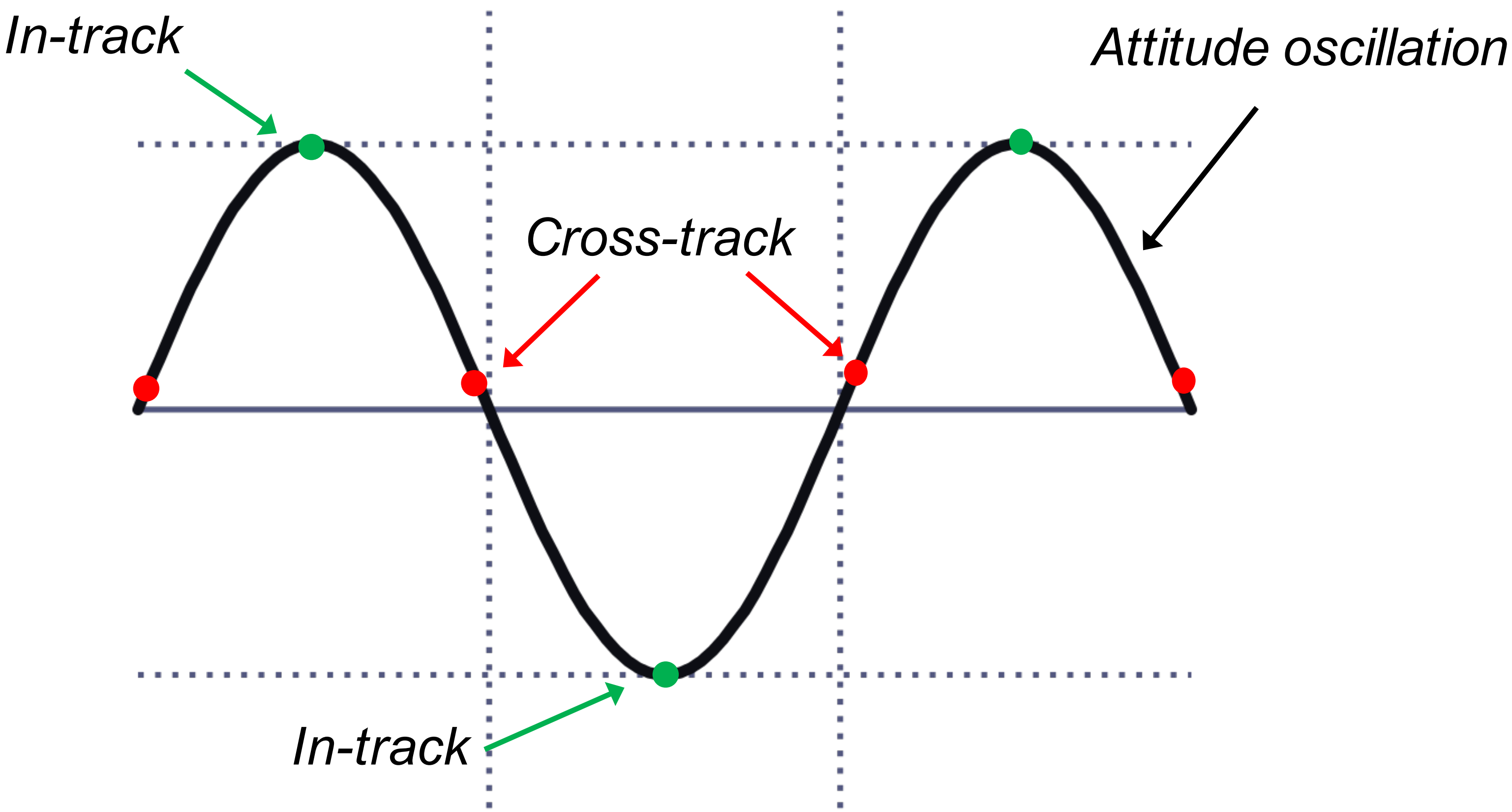
$$\hat{q} = \frac{\hat{\omega}^2 I}{k}$$

$$\hat{w}_i = \sqrt{\frac{2\hat{q}}{\rho} - \hat{w}_c^2} - V_i$$

Maximum $\left\|\ddot{\theta}\right\|$

Two measurement opportunities per oscillation

Iterative approach:



Iterative Approach IV

Summary of iterative approach:

- Both iterative procedures are executed in parallel interpolating the in-track and cross track wind results.
- The procedure is then **iteratively repeated** until it converges (processed offline).
- Two measurements per cycle of cross-track and in-track wind.
- Angular acceleration and atmospheric density are required.

Frequency approach:

- Assumes that wind is constant during oscillation.
- Measure oscillation period τ.
- Measure attitude θ during maximum angular rate $\dot{\theta}_{\mathrm{max}}$.

$$\bar{w}_c = \sin\left(\theta_{\dot{\theta}\mathrm{max}}\right) \frac{2\pi}{\tau} \sqrt{\frac{2I}{\rho k}}$$

$$\bar{w}_i = \cos\left(\theta_{\dot{\theta}\mathrm{max}}\right) \frac{2\pi}{\tau} \sqrt{\frac{2I}{\rho k}} - V_i$$

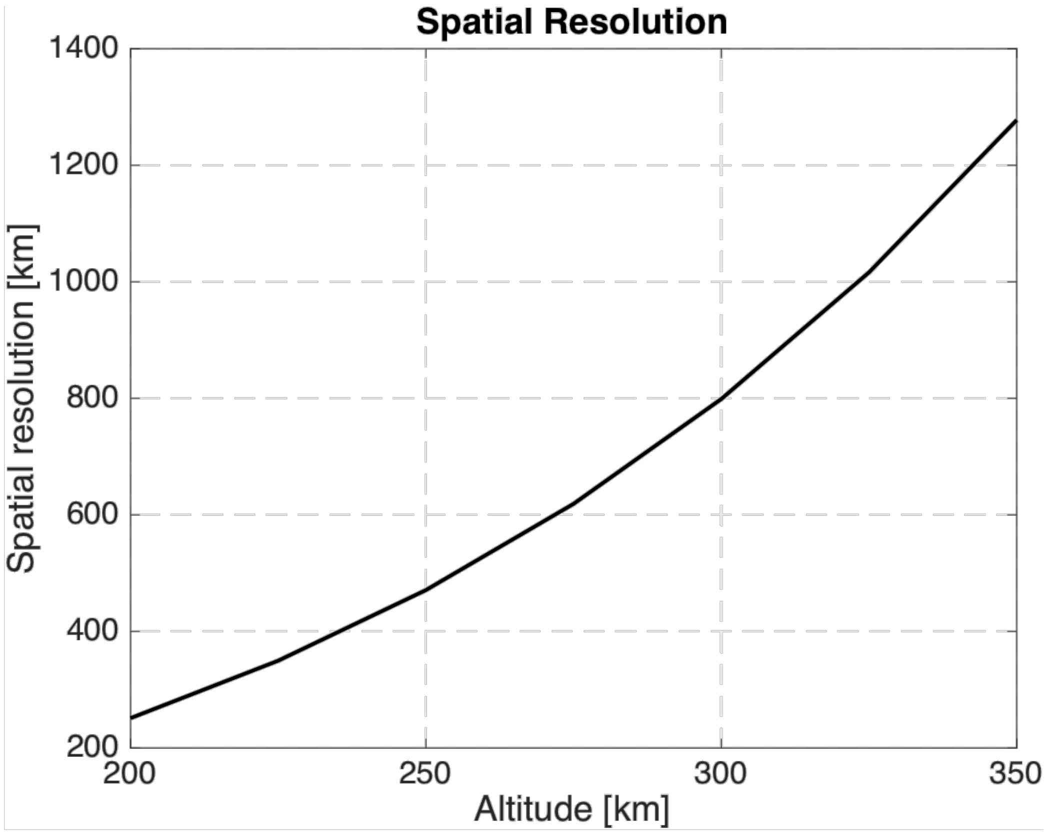
- Simpler but more sensitive to timing → lower performance.

Spatial Resolution:

- Measurement frequency sets the spatial resolution.

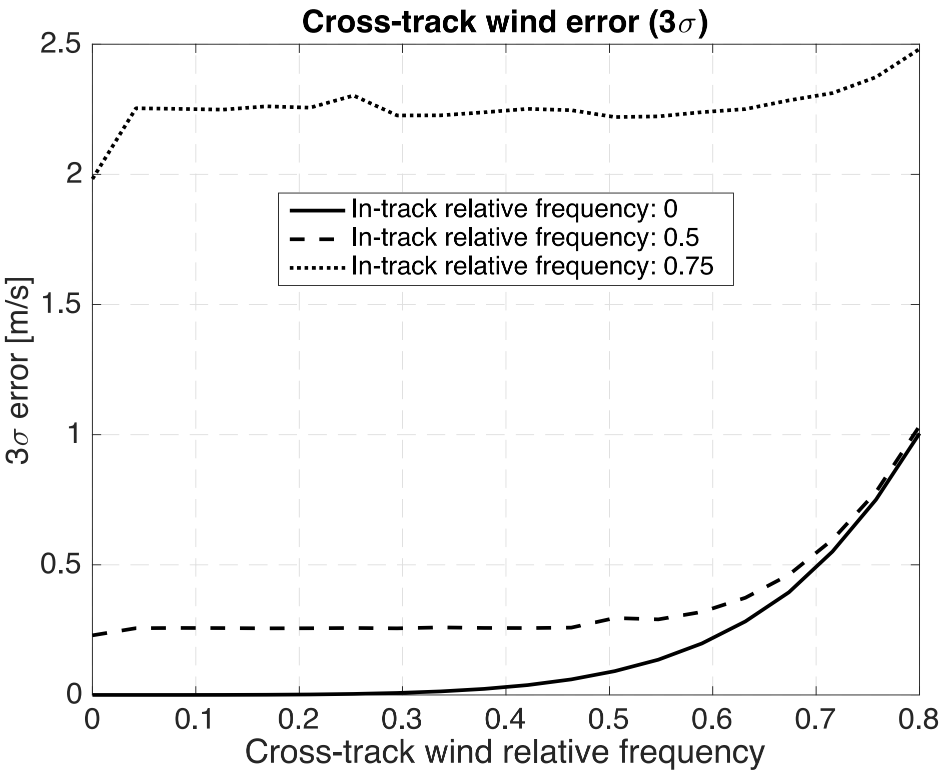
$$d = \frac{2\pi V_i}{\omega} \approx 2\pi\sqrt{\frac{2I}{\rho k}}$$

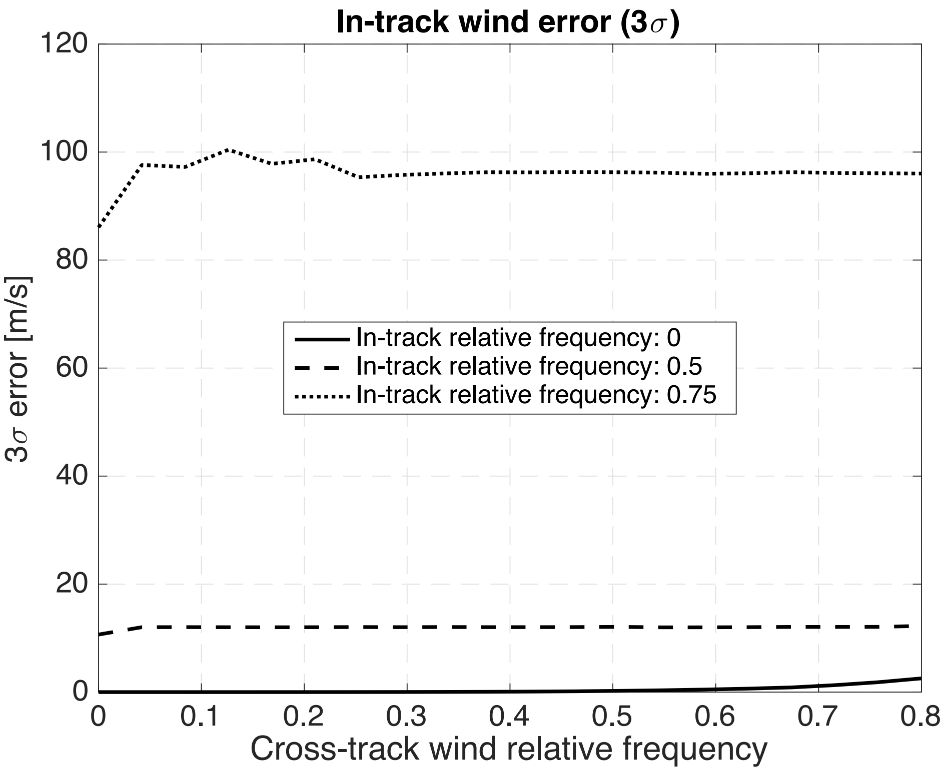
- Wind variability should be below spacecraft natural frequency.



Spatial Resolution for the proposed CubeSat design.

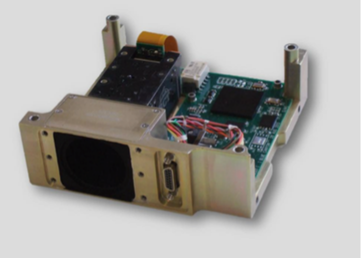
Ideal performance of iterative approach 1 Hz measurement (no uncertainties):





Multidimensional case:

- Use full Euler rotational equation.
- Requires aerodynamic model $\tau_{\text{aero}} = -qf(\theta_{sf})$
- Needs a function that finds attitude with respect to the flow based on model $\theta_{\text{sf}} = f^{-1}(-\tau_{aero}/q)$



- Example using proposed CubeSat with:
  - 10% 3σ ρ
  - 5% 3σ on aerodynamic properties
  - $k = 0.17 \text{ Nm/rad}$
  - $\sigma_{\theta_{inertial}} = 40 \text{ arcsec } (1\sigma)$ ← BCT Star tracker CubeSat (5Hz)
  - $\sigma_{\alpha} = 2 \text{ arcsec/s}^2 \ (1\sigma)$ ← TVDiff (Chartrand 2011)

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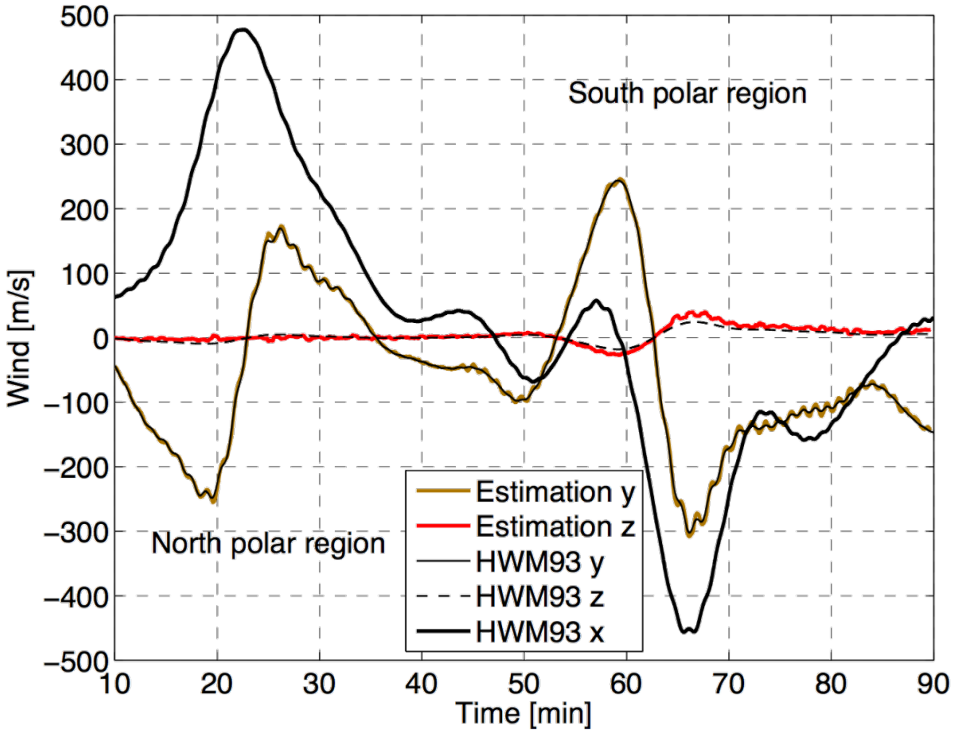
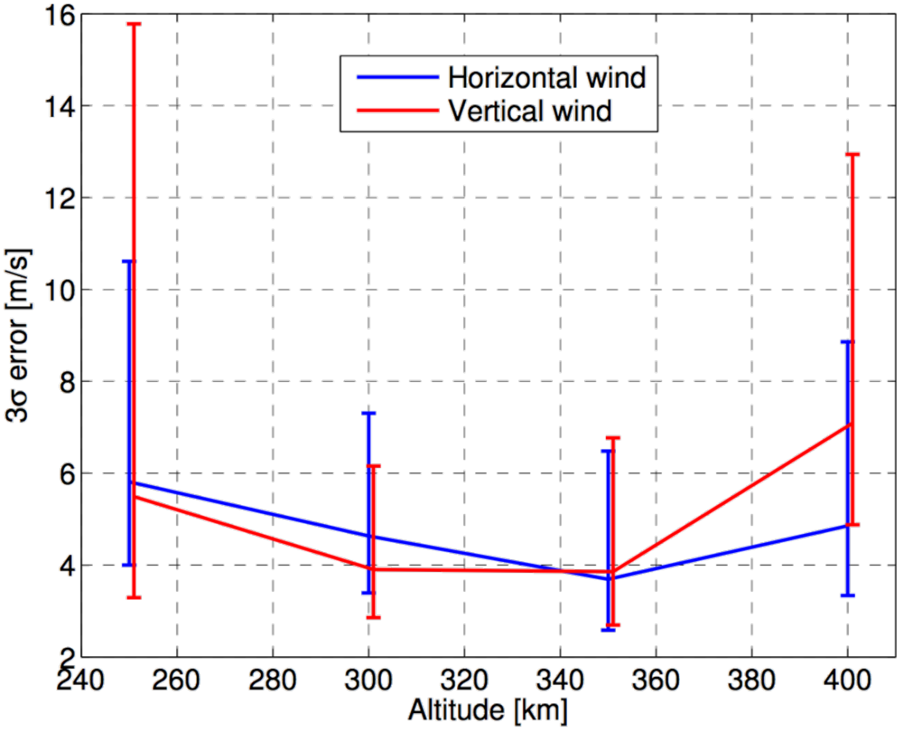
Estimated performance (with proposed CubeSat):





Dominated by accuracy on the density.

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Conclusions:

- Observing the attitude evolution of aerostable spacecraft can yield wind measurements.
- High aerodynamic stiffness increases spatial resolution and the overall method accuracy.
- A separate source of atmospheric density is required.
- In-track wind is less observable.
- Can be used as a complement of other wind measurement techniques.

Thank you for your attention.

Questions?

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