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
Existing methods:

- Remote sensing:
  - Interferometer
  - Incoherent Scatter Radar

- In-situ:
  - Chemical tracer
  - Accelerometer based (Doornbos 2010)
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.
Aerostable Spacecraft

Aerodynamic Torques:

\[ \tau_{\text{aero}} = \frac{1}{2} \rho V_f^2 A_{\text{ref}} l_{\text{ref}} C_T \]

- Aerodynamic torque
- Atmospheric density
- Relative flow velocity
- Reference Area and Length
- Torque Coefficient

Aerostable spacecraft:

\[ \tau_{\text{aero}} = -q f (\theta_{sf}) \]

Generic aerostable behavior

Linear simplification

\[ \tau_{\text{aero}} = -q k \theta_{sf} \]
One rotational degree-of-freedom simplification:

\[ I \ddot{\theta} = -qk\theta_{sf} \]

- 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
  \[ \omega^2 = \omega_i^2 + \omega_c^2 \rightarrow V_i \gg \omega_i \]
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 $w_i$?

\[
\dot{\theta} = \frac{\omega^2 w_c}{2(V_i + w_i)} \approx \frac{\omega^2 w_c}{2V_i}
\]

\[
\dot{\omega} = \sqrt{\frac{\dot{q} k}{I}}
\]

\[
\hat{\omega} = \sqrt{\frac{\dot{q} k}{I}}
\]

\[
\hat{\omega}_c = (V_i + \hat{w}_i) \tan (\hat{\theta}_{flow})
\]

\[
\hat{q} = \frac{1}{2} \rho \left( (V_i + \hat{w}_i)^2 + \hat{w}_c^2 \right)
\]
Iterative approach (in-track):

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

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

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

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

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

Two measurement opportunities per oscillation.
Iterative approach:

- *In-track*
- *Cross-track*
- *Attitude oscillation*
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 \( \tau \).
- Measure attitude \( \theta \) during maximum angular rate \( \dot{\theta}_{\text{max}} \).

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

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

- Simpler but more sensitive to timing \( \rightarrow \) 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):

Cross-track wind error (3σ)

In-track wind error (3σ)

In-track relative frequency: 0
In-track relative frequency: 0.5
In-track relative frequency: 0.75
Multidimensional case:

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

Example using proposed CubeSat with:
- 10% 3\( \sigma \) \( \rho \)
- 5% 3\( \sigma \) on aerodynamic properties
- \( k = 0.17 \) Nm/rad
- \( \sigma_{\theta_{\text{inertial}}} = 40 \) arcsec (1\( \sigma \))
- \( \sigma_\alpha = 2 \) arcsec/s\(^2\) (1\( \sigma \))
Estimated performance (with proposed CubeSat):

Dominated by accuracy on the density.
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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