Inflight Wind Velocity and Aerodynamic Coefficient Estimation for fixed Wing UAVs and Applications to Icing Detection

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Outline

I. Inflight Wind Velocity and Aerodynamic Coefficient Estimation

   1. Motivation
   2. Modelling
   3. Estimation Setup
   4. Moving Horizon Estimation

II. Flight Tests

III. Conclusions

IV. Drag Estimation

Motivation

Why do we need Wind velocity estimation?

- Allows Angle of Attack, Airspeed and Sideslip calculation
- Useful for path planning and following as well as landing

→ Problems:

- Small UAVs have no sensors to measure angle of attack
- Aerodynamic coefficients often unknown

Wind Velocity Estimation

Kinematic Model
(Pitot-static Tube)

Aerodynamic Model
(Accelerometer)

non parametric

parametric

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Kinematic Model

- Wind triangle

$$\boldsymbol{v}_r^b = \boldsymbol{v}^b - \boldsymbol{R}_n^b \boldsymbol{v}_w^n$$

- Angle of Attack

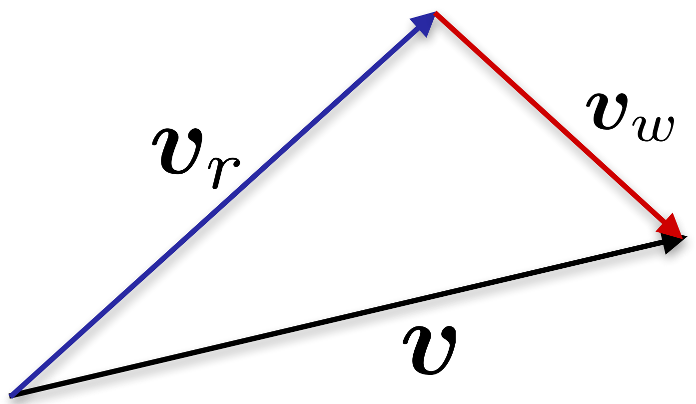
$$\alpha = \tan^{-1}\left(\frac{w_r^b}{u_r^b}\right)$$

- Sideslipangle

$$\beta = \sin^{-1}\left(\frac{v_r^b}{\|\boldsymbol{v}_r\|}\right)$$

- Airspeed

$$V_a = \|\boldsymbol{v}_r\|$$



Kinematic Model

- Pitot-static tube measures $\tilde{V}_a^m$ if tube wide enough and airspeed small

$$\tilde{V}_a^m = \frac{V_a}{\gamma} + \eta$$

- The relative airspeed vector:

$$\boldsymbol{v}_r^b = V_a \begin{bmatrix} \cos\alpha\cos\beta \\ \sin\beta \\ \sin\alpha\cos\beta \end{bmatrix}$$

if $\cos(\beta) \approx 1$

$$\begin{bmatrix} u^b \\ w^b \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \boldsymbol{R}_n^b \boldsymbol{v}_w^n + V_a \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix}$$

Aerodynamic Model

- General model for specific force in z-direction

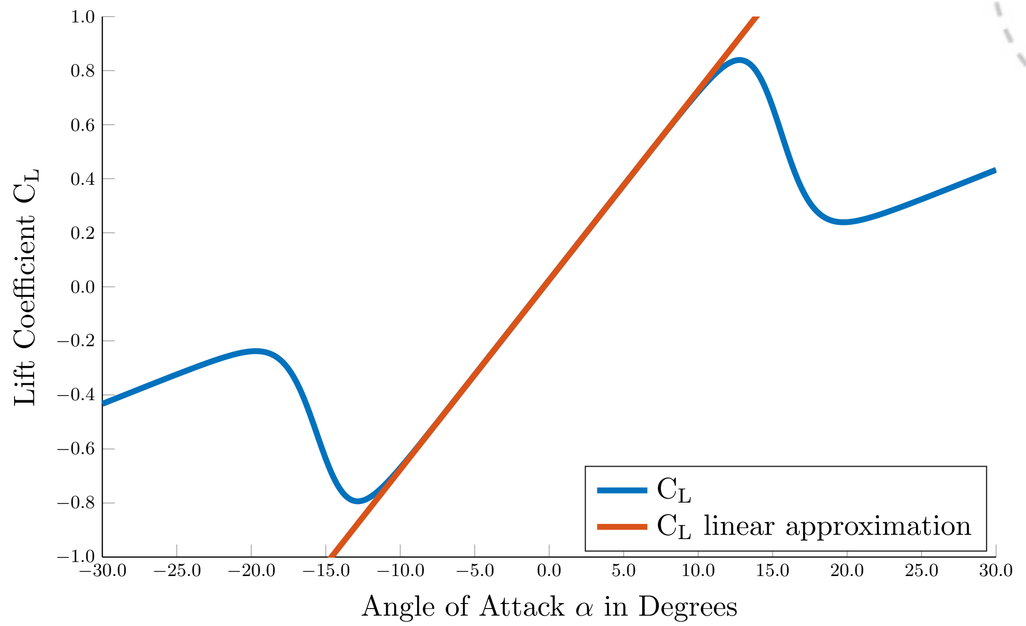
$$f_z = \frac{\rho S}{2m} V_a^2 \left(-C_L(\alpha) cos(\alpha) - C_D(\alpha) sin(\alpha)\right)$$

- Coefficients

$$C_L(\alpha) = C_{L,0} + \alpha C_{L,\alpha}$$
$$C_D(\alpha) = C_{D,0} + \alpha C_{D,\alpha}$$

- Since α is small in normal flying conditions:

$$\boxed{f_z = -K V_a^2 \left(C_{L,0} + \alpha C_{L,\alpha}\right)}$$



Wind Model

- Frequency separation in steady and turbulent wind velocity components

$$\boldsymbol{v}_{w,k}^n = \boldsymbol{v}_{s,k}^n + \boldsymbol{v}_{t,k}^n$$

  - Steady wind velocity model

$$\Delta \boldsymbol{v}_{s,k}^n \approx 0$$

  - Turbulent wind velocity model

  Dryden model [5]:

$$\Delta \boldsymbol{v}_{t,k}^n = -\Delta T V_{a,k} \left. \begin{pmatrix} \frac{u_t^n}{L_u} \\ \frac{v_t^n}{L_v} \\ \frac{w_t^n}{L_w} \end{pmatrix} \right|_k + \left. \begin{pmatrix} \sigma_u \sqrt{2 \Delta T \frac{V_a}{L_u}} \eta_u \\ \sigma_v \sqrt{2 \Delta T \frac{V_a}{L_v}} \eta_v \\ \sigma_w \sqrt{2 \Delta T \frac{V_a}{L_w}} \eta_w \end{pmatrix} \right|_k$$

State-Space Model

- States

$$\boldsymbol{x} = \begin{bmatrix} u_t^n & v_t^n & w_t^n \end{bmatrix}^T$$

- Parameters

$$\boldsymbol{p} = \begin{bmatrix} u_s^n & v_s^n & w_s^n & KC_{L_0} & KC_{L_\alpha} & \gamma \end{bmatrix}^T$$

- Inputs

$$\tilde{\boldsymbol{u}} = \begin{bmatrix} \tilde{u}^b & \tilde{v}^b & \tilde{w}^b & \boldsymbol{R}_n^b & h \end{bmatrix}^T$$

- Outputs

$$\boldsymbol{z} = \begin{bmatrix} \tilde{f}_z & \tilde{V_a^m} & \tilde{u}^b & \tilde{w}^b \end{bmatrix}$$

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State-Space Model

- State transition function

$$\boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) = -\bar{V}_a \left. \begin{pmatrix} \frac{u_t}{L_u} \\ \frac{v_t}{L_v} \\ \frac{w_t}{L_w} \end{pmatrix} \right|_{\substack{\boldsymbol{u} \\ \boldsymbol{x} \\ p}}$$

- Noise transition function

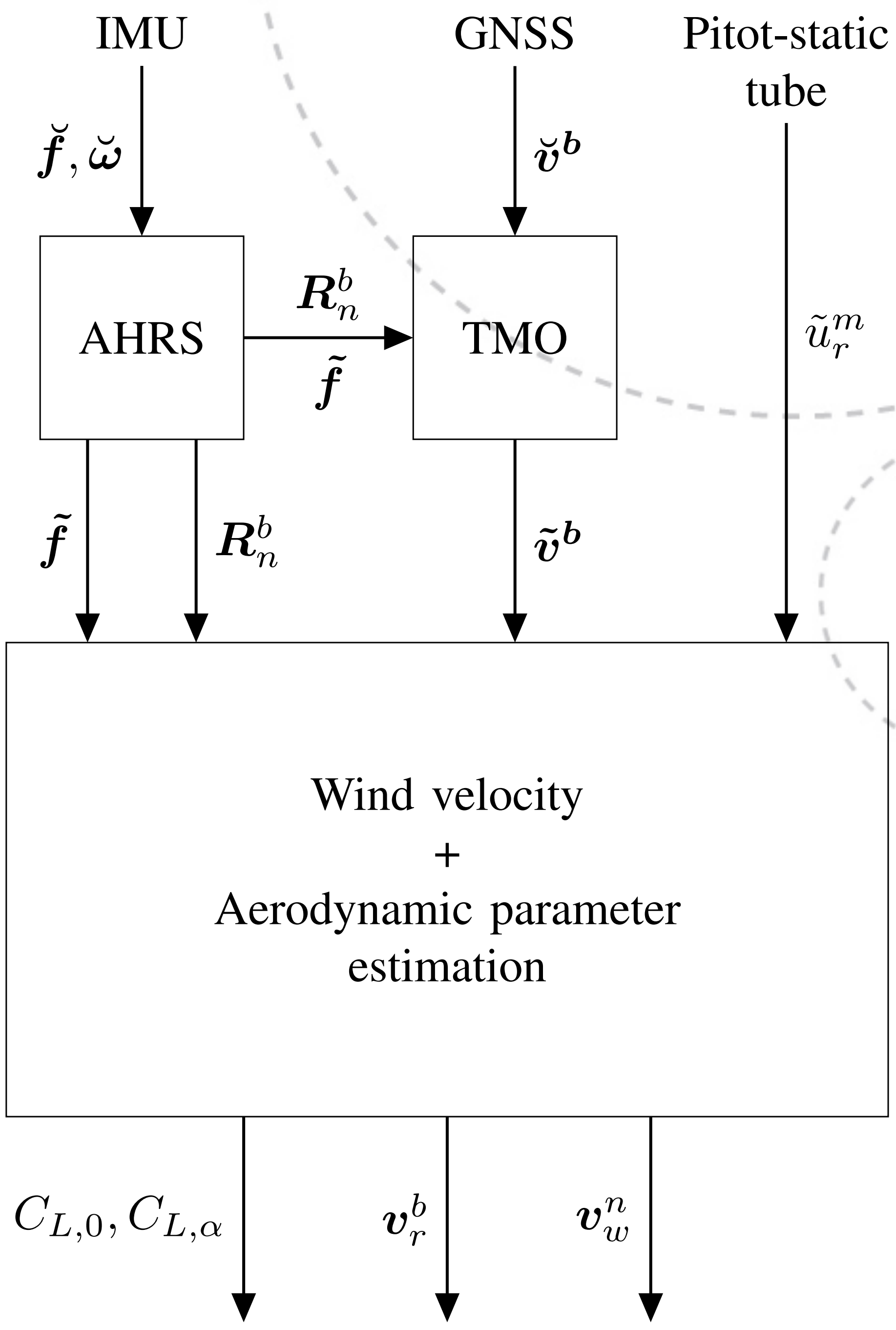
$$\boldsymbol{w}(\boldsymbol{x}_k,\boldsymbol{u}_k,\boldsymbol{\eta}_{\boldsymbol{v}_t,k},\boldsymbol{p}) = \left. \begin{pmatrix} \sigma_u \sqrt{2\Delta T \frac{\bar{V}_a}{L_u}} \eta_{u_t} \\ \sigma_v \sqrt{2\Delta T \frac{\bar{V}_a}{L_v}} \eta_{v_t} \\ \sigma_w \sqrt{2\Delta T \frac{\bar{V}_a}{L_w}} \eta_{w_t} \end{pmatrix} \right|_k$$

- Measurement function

$$\boldsymbol{h}(\boldsymbol{x_k},\boldsymbol{u_k},\boldsymbol{p}) = \begin{bmatrix} -KV_a^2(C_{L_0} + C_{L_\alpha}\alpha) \\ V_a/\gamma \\ \boldsymbol{d}_1 \boldsymbol{R}_n^b(\boldsymbol{v}_s^n + \boldsymbol{v}_t^n) + V_a\cos(\alpha) \\ \boldsymbol{d}_3 \boldsymbol{R}_n^b(\boldsymbol{v}_s^n + \boldsymbol{v}_t^n) + V_a\sin(\alpha) \end{bmatrix}$$

Estimation Setup

- Sensors:
  - GNSS
  - IMU
  - Pitot-static tube
- AHRS for orientation matrix estimation
- TMO for ground velocity estimation
- Wind velocity and coefficient estimator:
  - Moving Horizon Estimator
  - Direct Collocation Method
  - UKF for arrival cost approximation
- Implementation in Matlab + Casadi



Moving Horizon Estimation

- Objective Function

Arrival Cost — Measurement Error — Noise

$$\min_{\substack{\boldsymbol{x}_{k-L},\ldots,\boldsymbol{x}_k \\ \boldsymbol{w}_{k-L},\ldots,\boldsymbol{w}_k \\ \boldsymbol{\theta}_{k-L,0},\ldots,\boldsymbol{\theta}_{k,d} \\ \boldsymbol{p}}} \left(\left\| \begin{matrix} \boldsymbol{x}_{k-L} - \hat{\boldsymbol{x}}_{k-L} \\ \boldsymbol{p} - \hat{\boldsymbol{p}}_{k-L} \end{matrix} \right\|^2_{\hat{\boldsymbol{P}}^{-1}_{k-L}} c + \sum_{j=k-L}^{k} \left\| \boldsymbol{y}_j - \boldsymbol{h}(\boldsymbol{x}_j, \boldsymbol{u}_j, \boldsymbol{p}) \right\|^2_{\boldsymbol{R}(q)^{-1}} + \sum_{j=k-L}^{k-1} \|\boldsymbol{\eta}_j\|^2_{\boldsymbol{W}^{-1}} \right)$$

$$\boldsymbol{\eta}_j = \begin{bmatrix} \boldsymbol{\eta}_{\boldsymbol{v}_t,j} & \boldsymbol{\eta}_{\boldsymbol{u},j} & \boldsymbol{\eta}_{\boldsymbol{z}_j} \end{bmatrix}$$

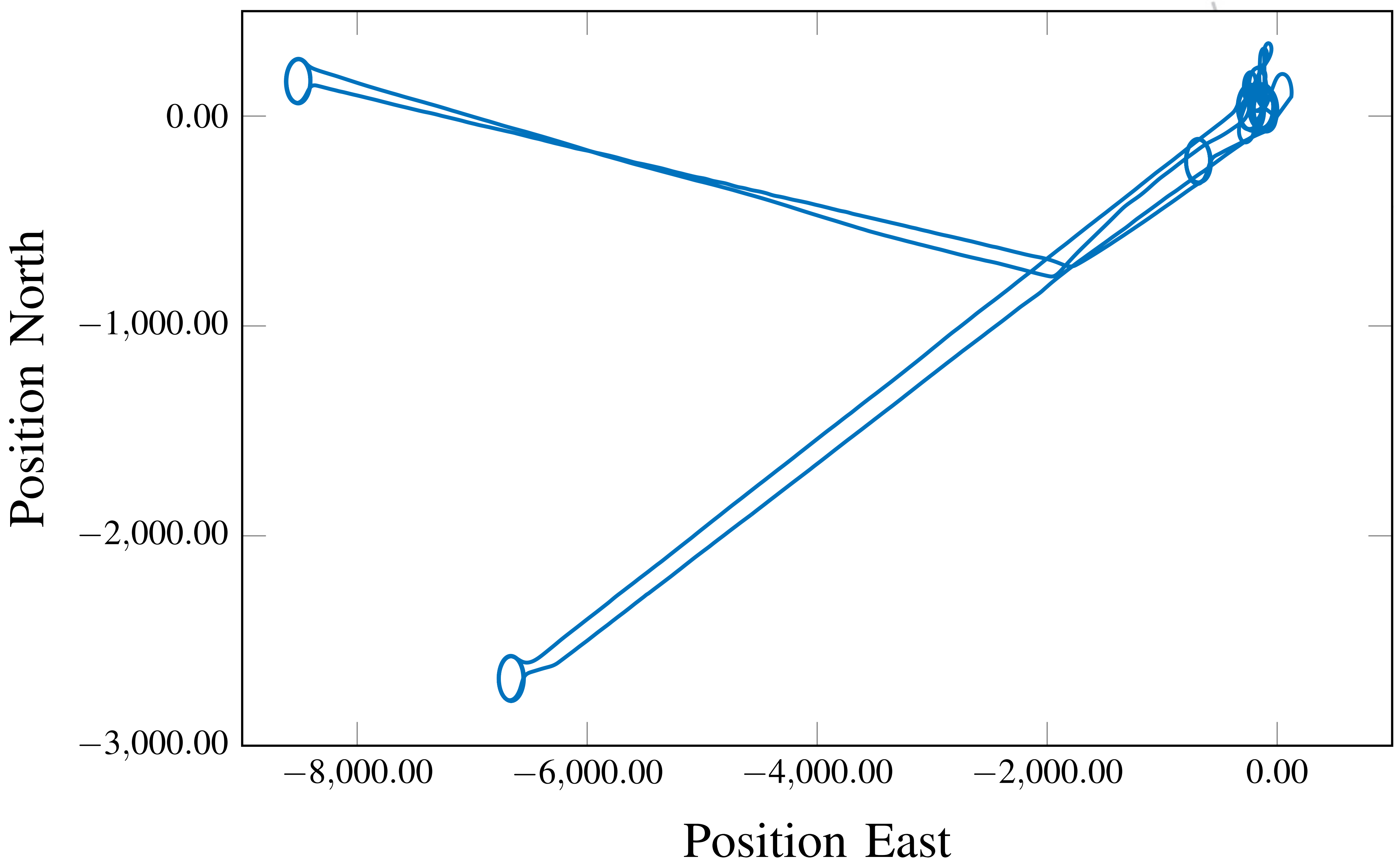
- Arrival Cost:
  - Summarises the information before the current window
  - Tuning factor c
  - Approximation necessary:

→ Unscented Kalman Filter:

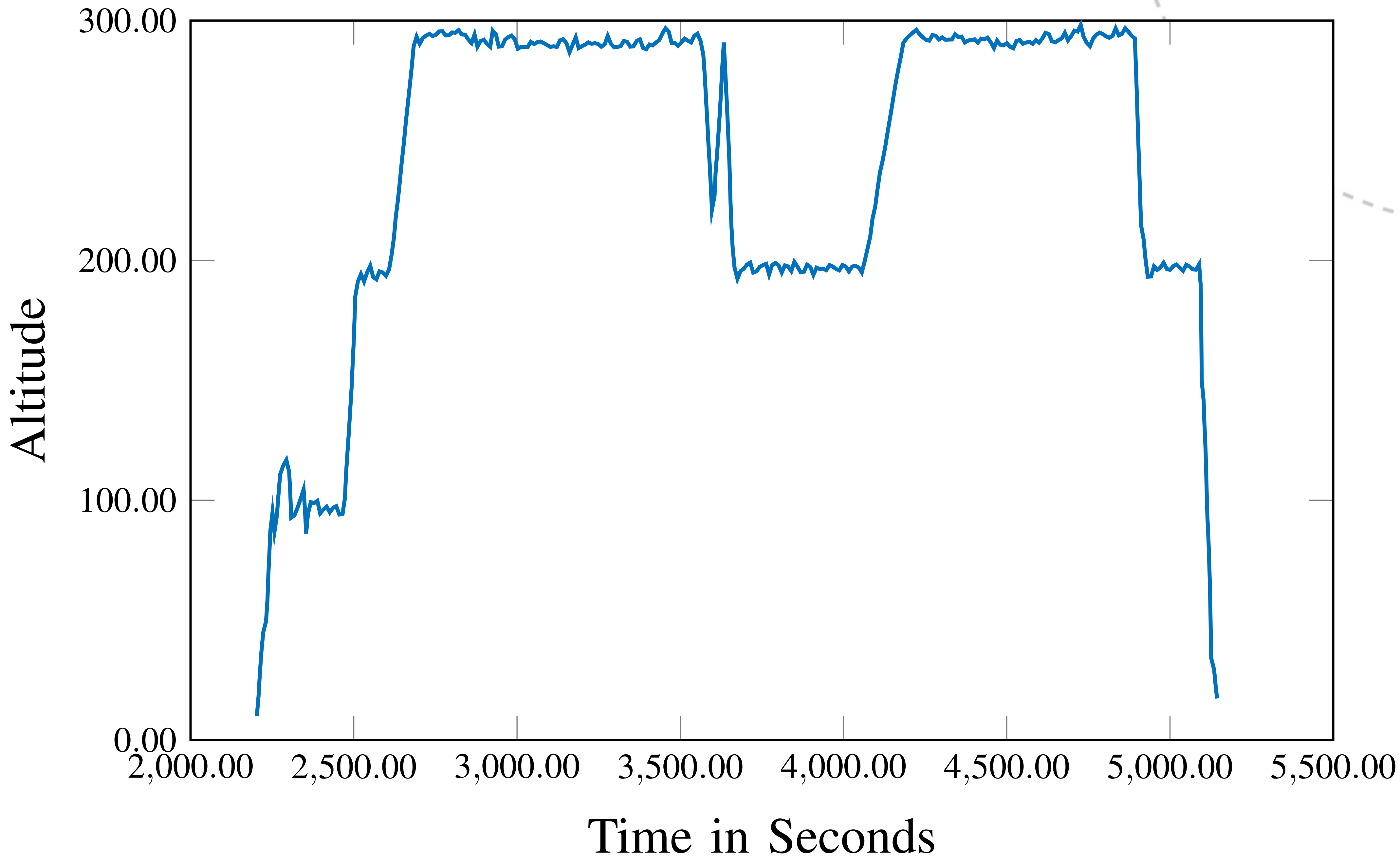
  - Avoids linearisation
  - Allows representation of input noise
  - Easy to implement

Flight Tests

Flight Profile



Flight Profile



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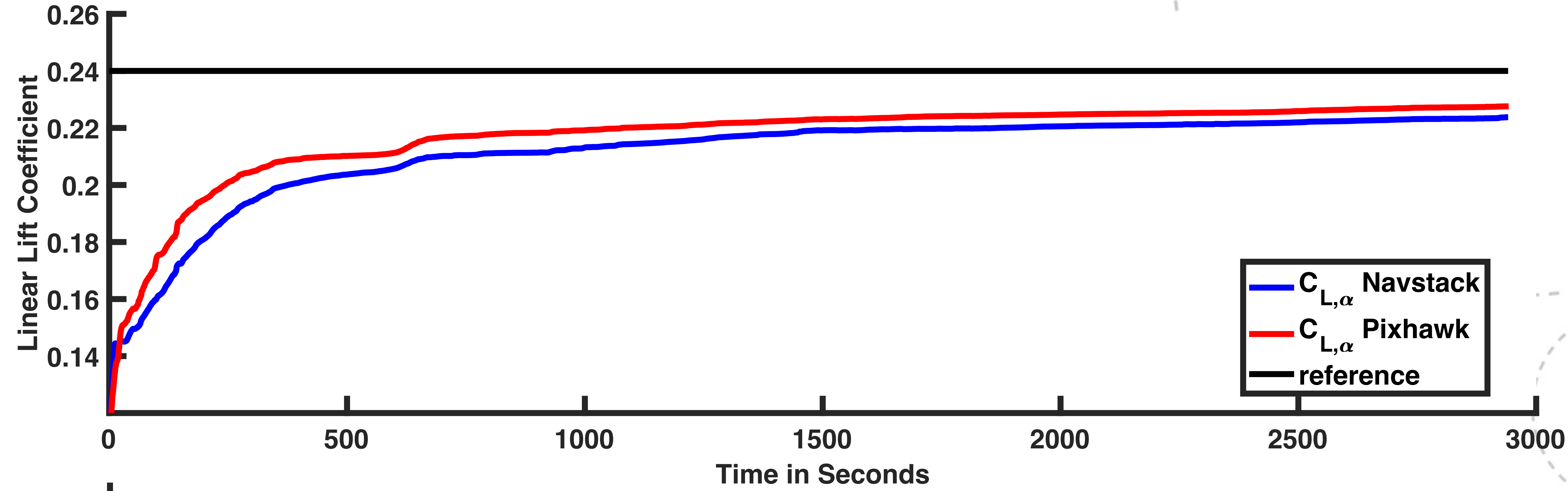
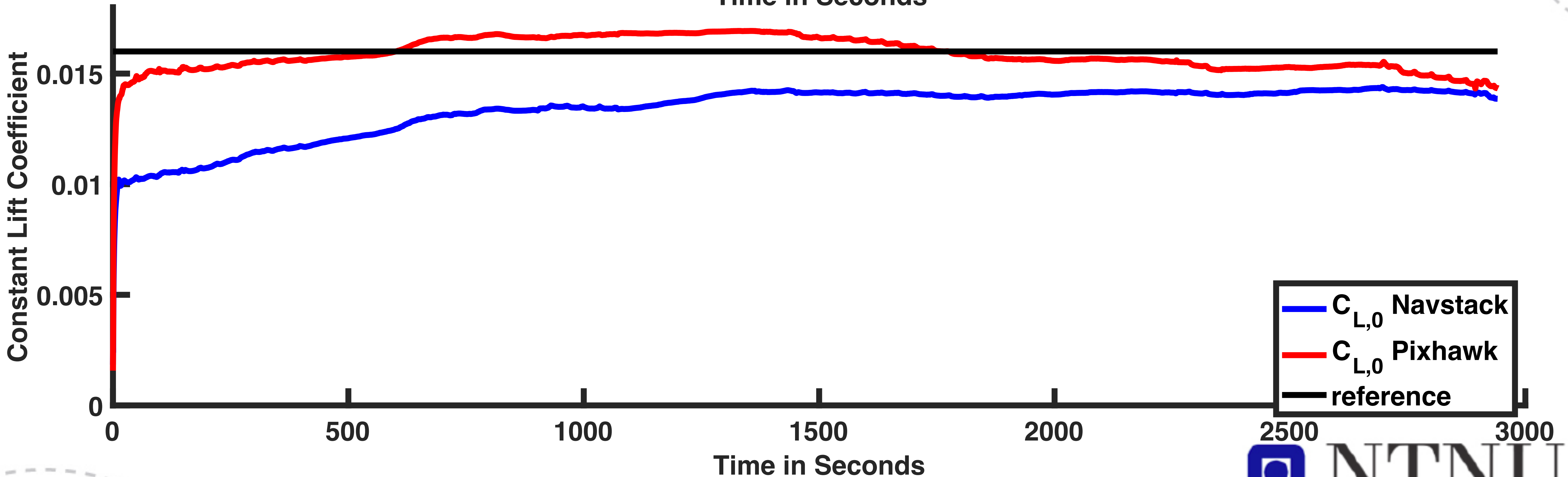
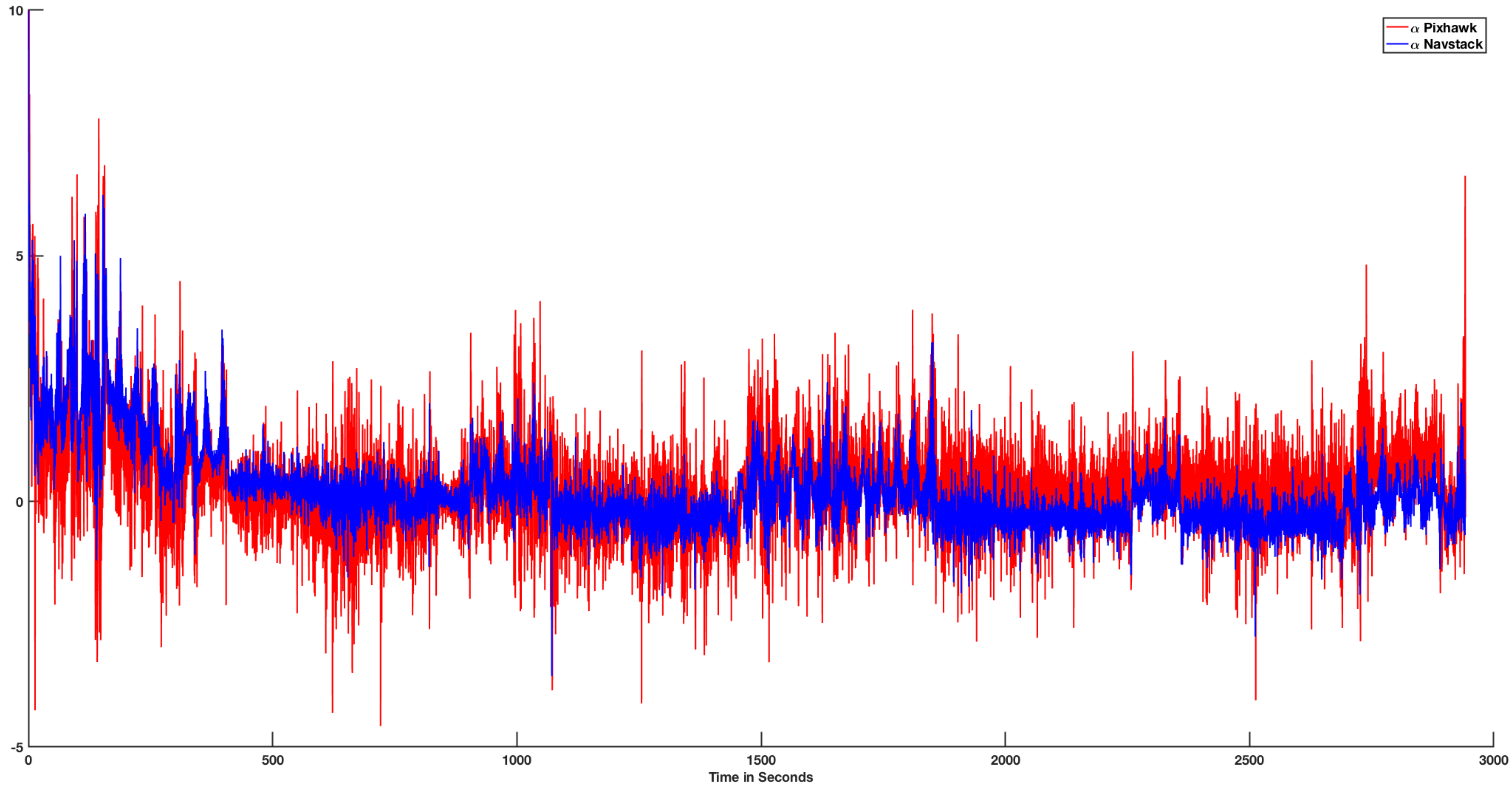
Coefficient Estimates





Angle of Attack Estimation Error



$$RMSE_{pixhawk} = 0.96^{\circ}, RMSE_{navstack} = 0.81^{\circ}$$

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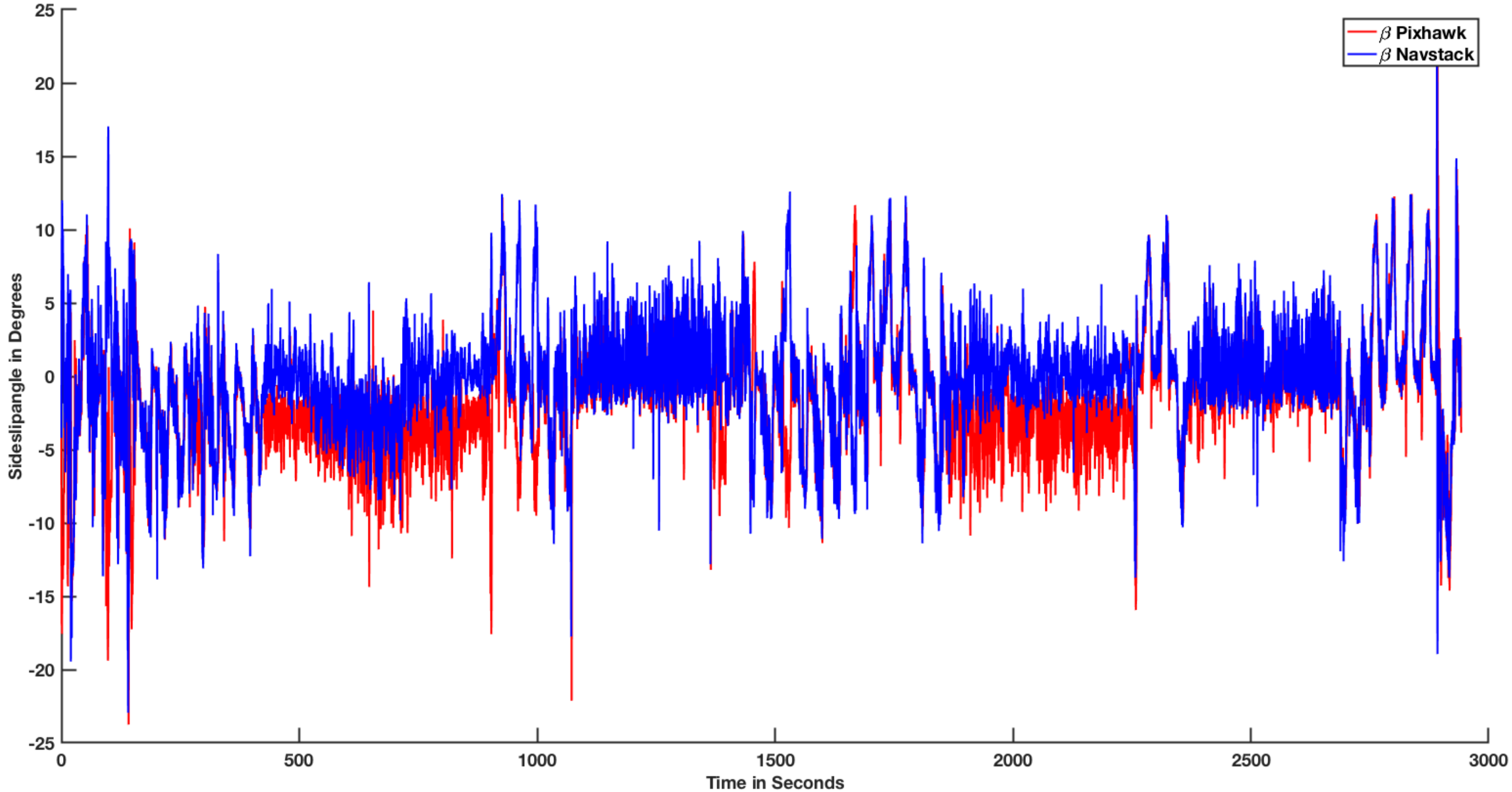
Sideslip Angle Estimation Error



$$RMSE_{pixhawk} = 4.25°, RMSE_{navstack} = 3.85°$$

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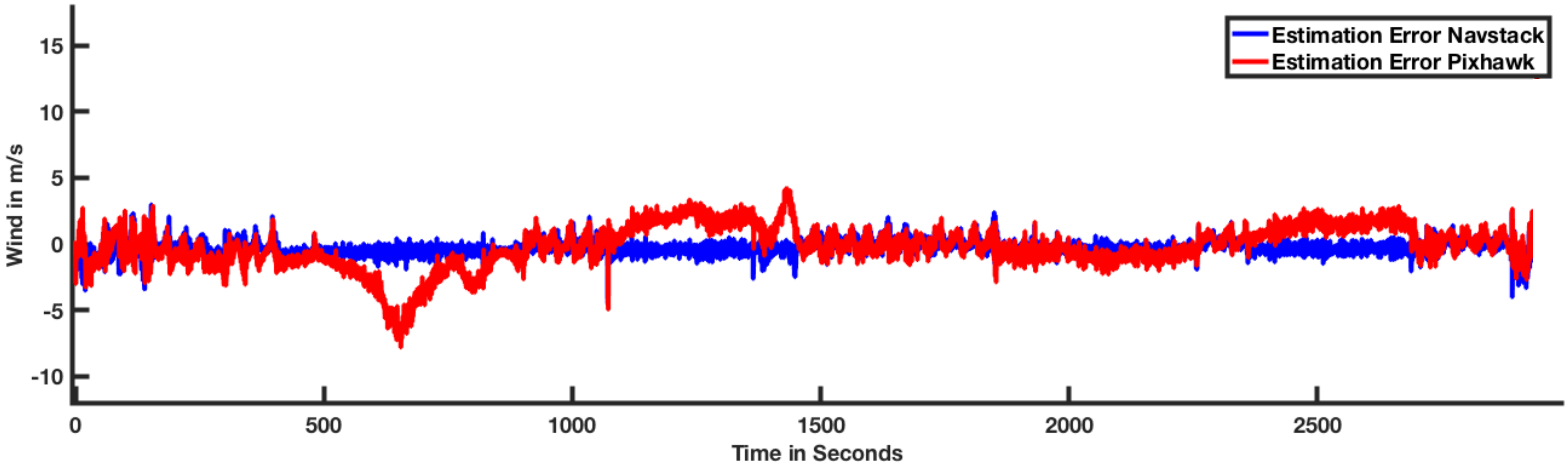
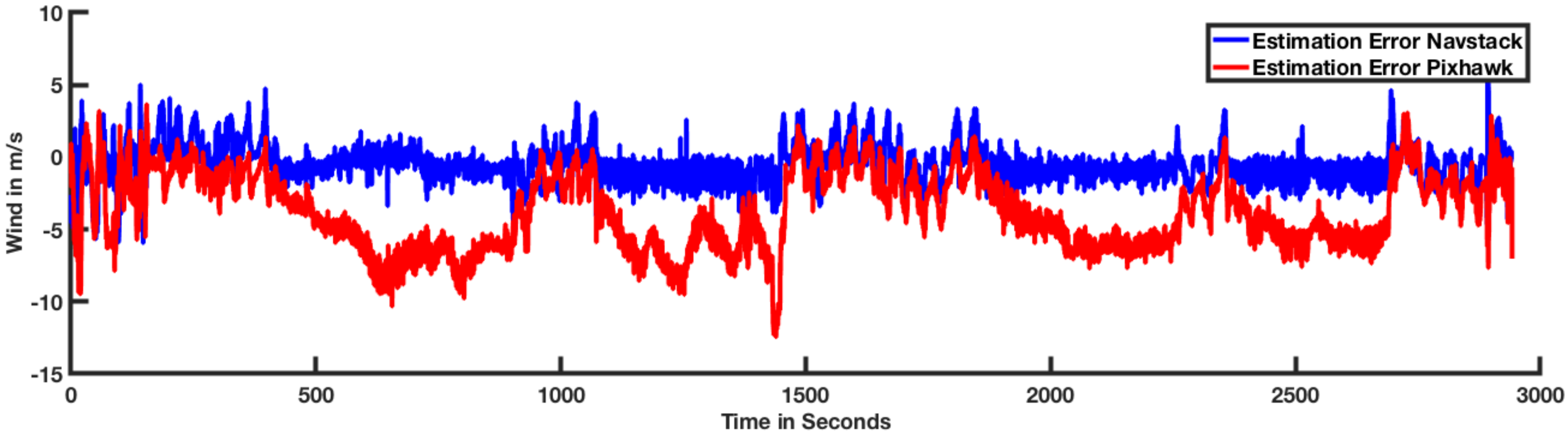
Wind Estimation Error



x-direction



y-direction

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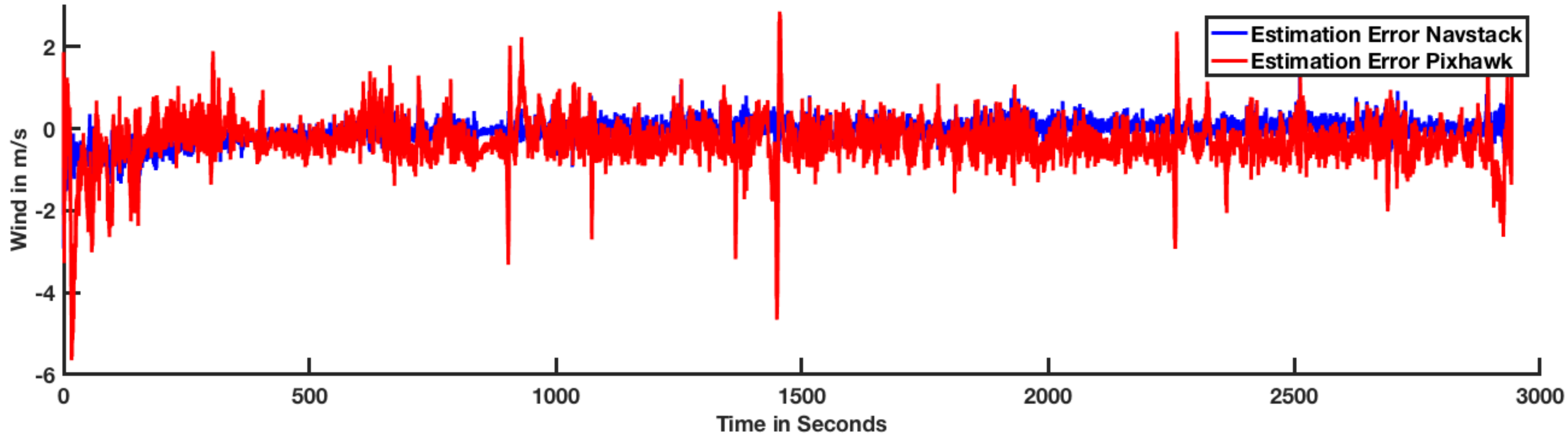
Wind Estimation Error



z-direction

Conclusions

- MHE provides accurate estimation of AoA, Coefficients and Wind velocities
- Attitude changes during take off sufficient for persistence of excitation
- No prior knowledge about the UAV needed
- Realtime capable (0.072 s/sample < 0.2 s)

<u>Future / Current Work:</u>

- Wind adaptive path planning/ following
- Icing detection

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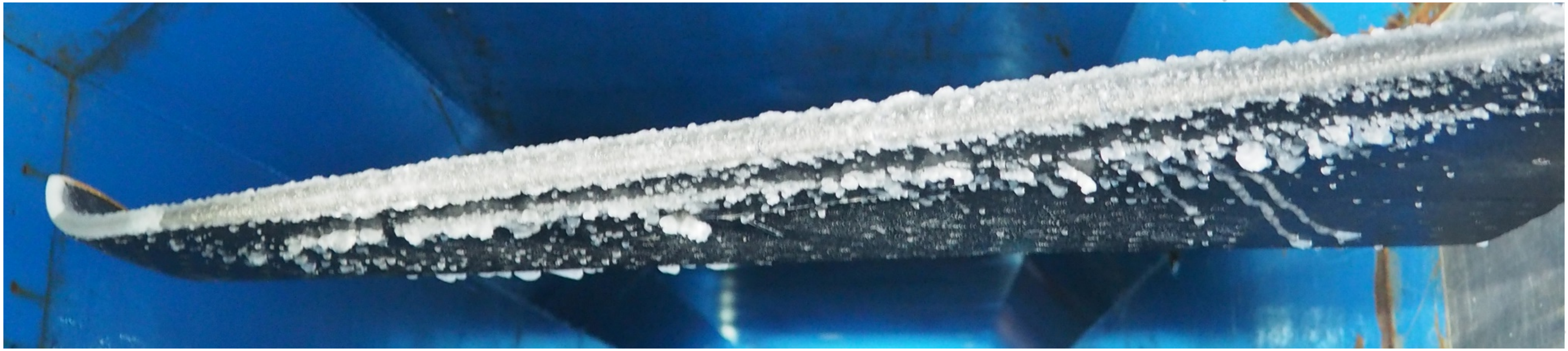
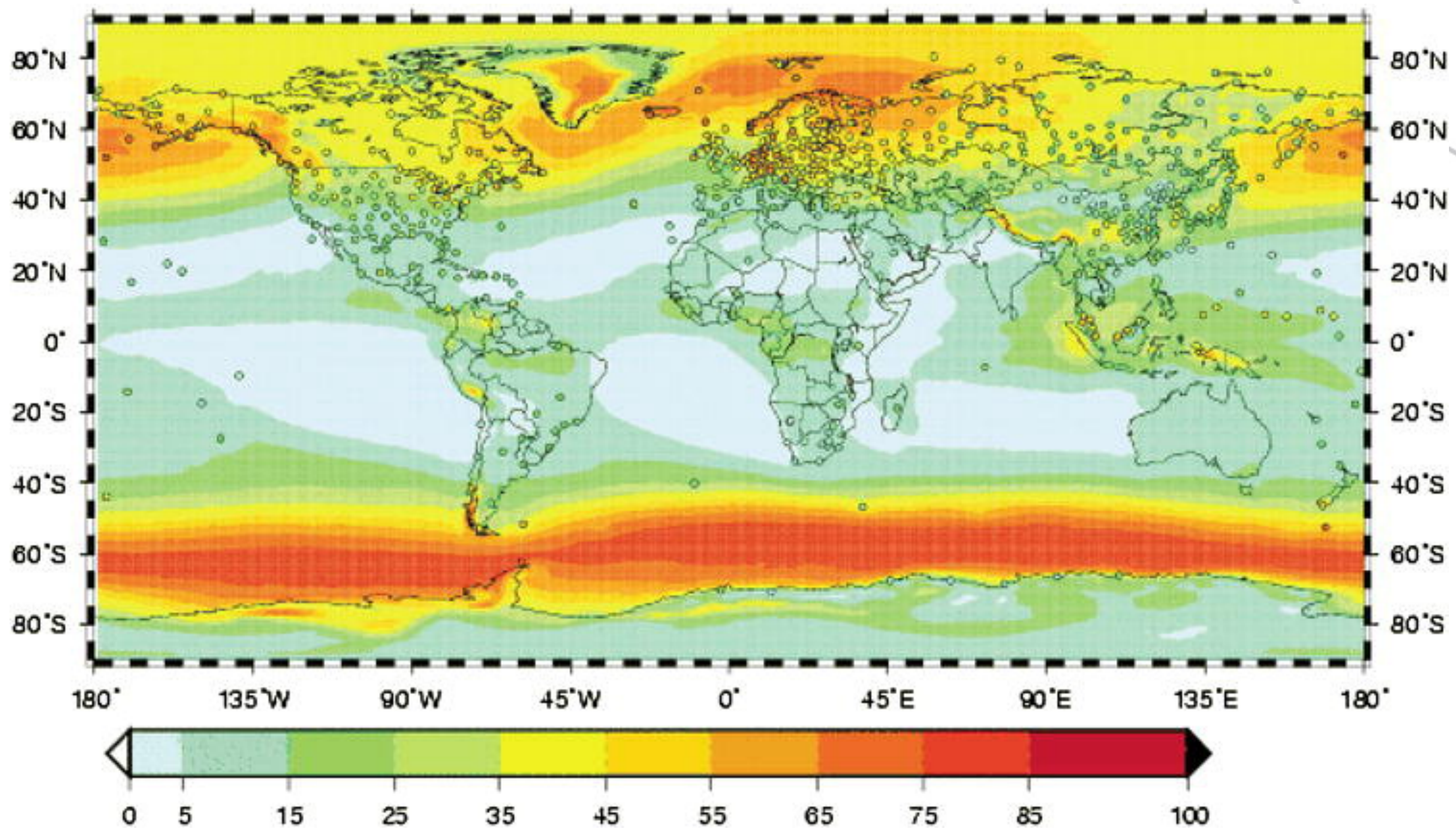


Icing Detection

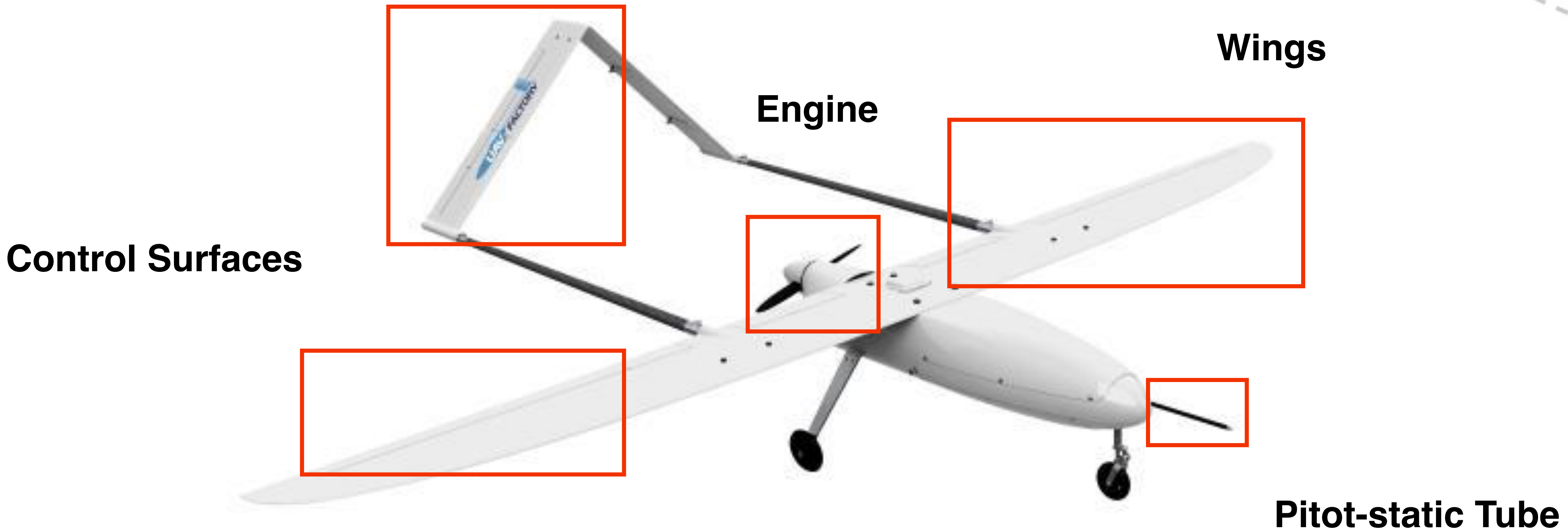
Motivation

Inflight icing is a global phenomenon

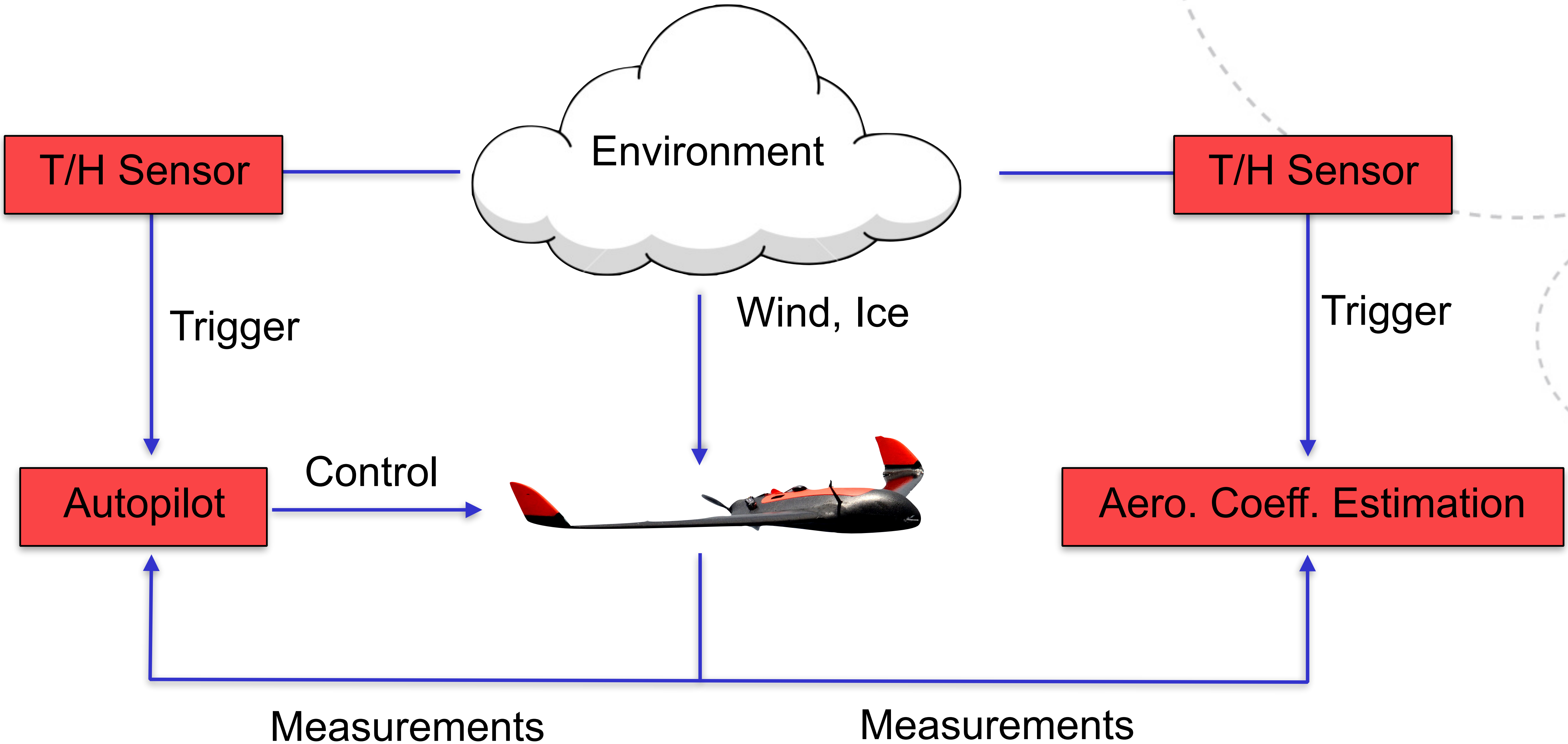


Bernstein, B. C. et.al. (2009). An inferred climatology of icing conditions aloft, including supercooled large drops. Part II: Europe, Asia, and the Globe. Journal of Applied Meteorology and Climatology, 48(8), 1503–1526.

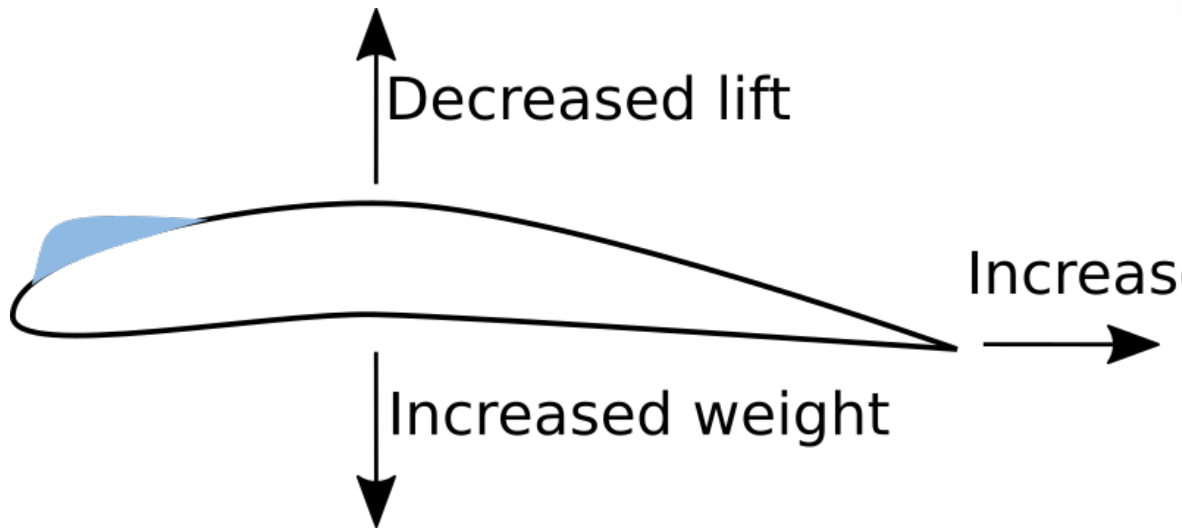
Effects of Inflight Icing on UAVs

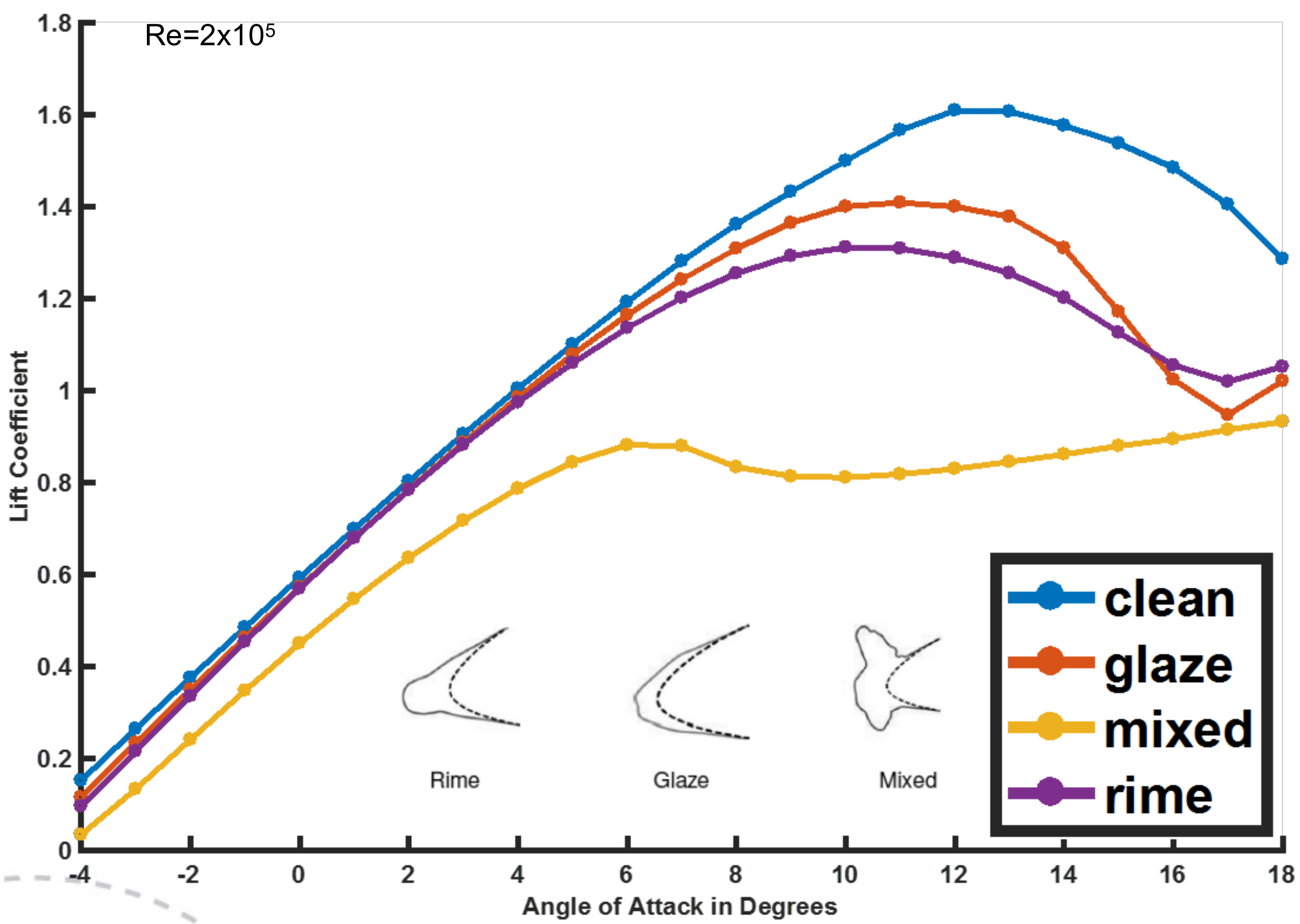


Icing Detection Architecture



Effects of Airfoil Icing

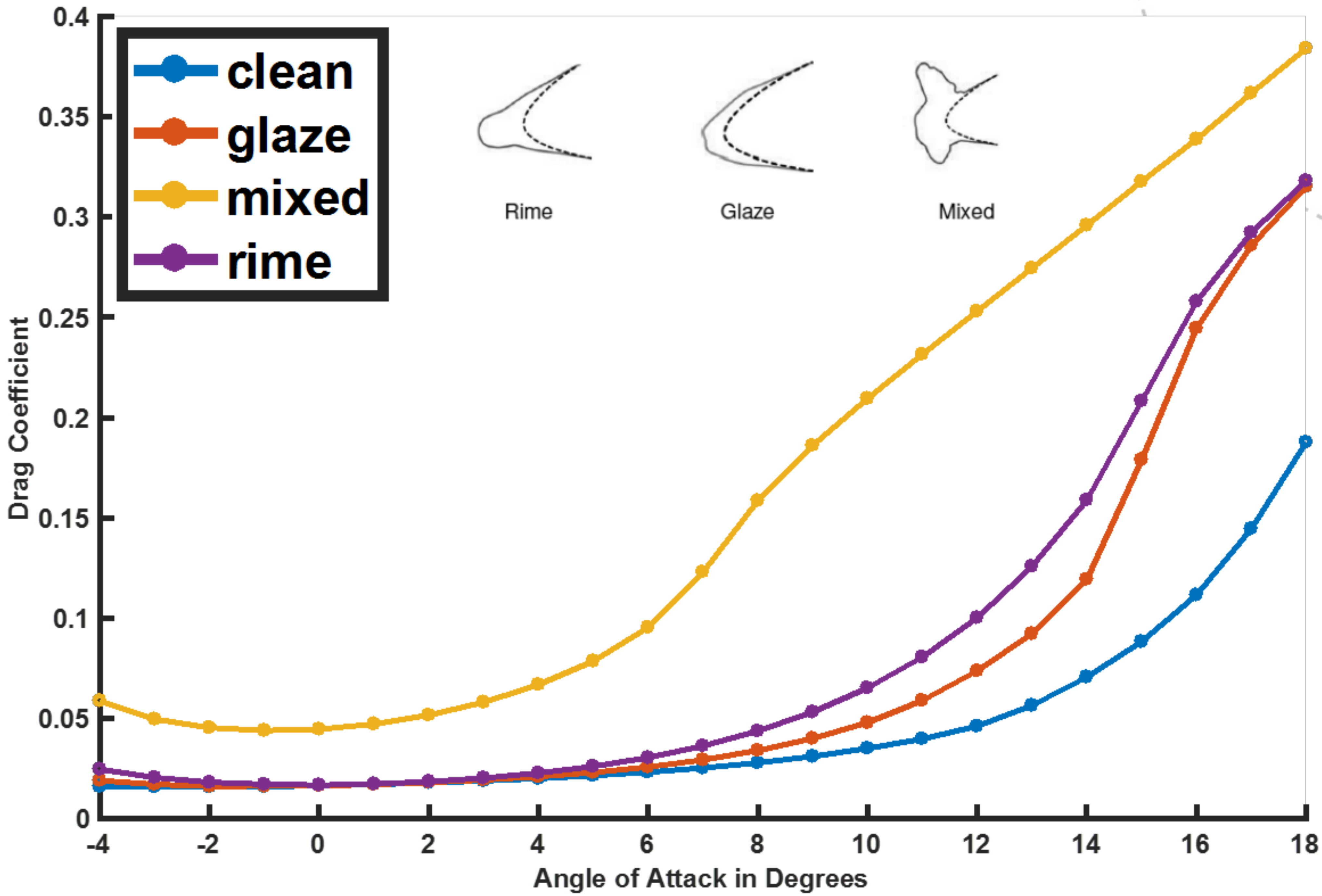




Effects on Lift Coefficient:

- Lower stall angle
- Lower maximal lift force
- Flatter rise in lift coefficient

Drag coefficients in Icing



Future Work: Drag Estimation

Benefits

- More accurate icing detection
- Allows pitot-tube and engine fault detection

Challenges

- More parameters to estimate => Lack of excitation source of errors
- Thrust estimation needed => RPM sensor or RPM estimation

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References

(1) Estimation of Wind Velocities and Aerodynamic Coefficients for UAVs using standard Autopilot Sensors and a Moving Horizon Estimator, Wenz et.a., ICUAS 2017

(2) Combining model-free and model-based Angle of Attack estimation for small fixed-wing UAVs using a standard sensor suite, Wenz et.al., ICUAS 2016, Arlington

(3) On estimation of wind velocity , angle-of-attack and sideslip angle of small UAVs using standard sensors, Johansen et.al., ICUAS 2015, Denver

(4) Wenz, A., & Johansen, T. A. (2016). Icing detection for small fixed wing UAVs using inflight aerodynamic coefficient estimation. In *Multiconference on Systems and Control*. Buenos Aires, Argentina.

(5) Hann, R., Wenz, A., Gryte, K., & Johansen, T. A. (2017). Impact of Atmospheric Icing on UAV Aerodynamic Performance. In *RED-UAS*. Linköping, Sweden.

(6) Small Unmanned Aircraft: Theory and Practice, Beard and McLain 2012

(7) MIL-STD-1797A: Flying Qualities of Piloted Aircraft

(8) A General Purpose Software Framework for Dynamic Optimization, Andersson, J. (2013). KU Leuven.

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Questions?