Characterizing the Atmospheric Boundary Layer: A Comparison of Uncrewed Aircraft Systems and Tower Observations

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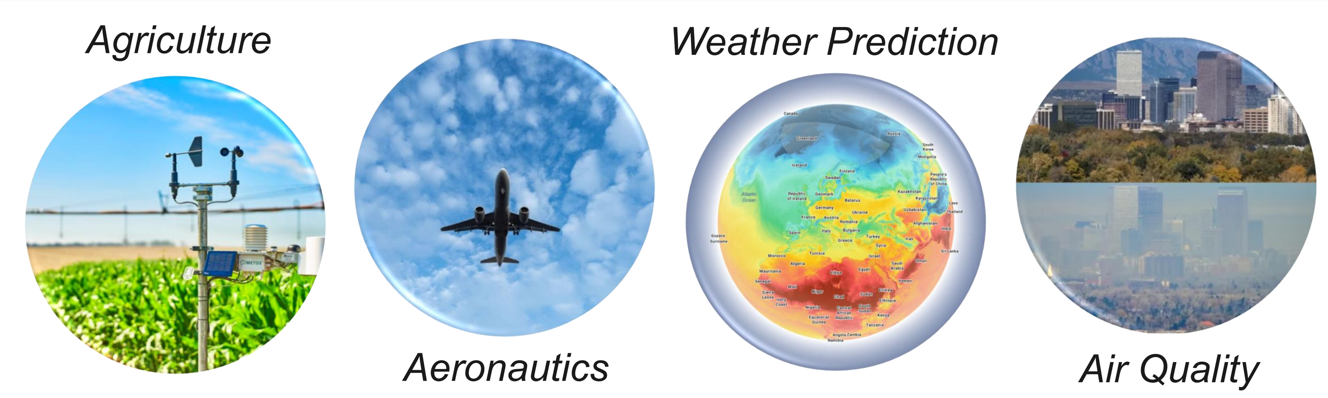
Introduction

The *atmospheric boundary layer* (**ABL**) is the lowest portion of the troposphere, shaped directly **by Earth's surface**, the layer in which **humans live and experience weather.**

✓ The *ABL* is shaped by a range of **complex dynamics**, including the characteristics of the *surface*, *wind*, and both **smooth and irregular** (turbulent) **air flow** and movement at different times and **heights** (Garratt, 1994; Stull, 2006)

✓ No single system can capture this full structure; some **measure continuously but only at fixed points**, while others **move through the atmosphere** but only briefly. Characterizing the *ABL* requires comparing what different systems can capture

How does the RAAVEN (Uncrewed Aircraft System) sampling capture atmospheric boundary layer structure compared to collocated meteorological tower observations?



Methods

Data Collection

RAAVEN
0-100 m AGL
Single flight
15:41 - 16:56 UTC

NCAR's ISFS
3 · 7 · 12 · 32 m AGL
7 hourly files
12:00 - 18:00 UTC

Standardization

Quality Control
Filtering & Conversion

Time Alignment & Matching
UTC-synced; height & flight-phase matched

NetCDF

Analysis

Statistical Metrics
Bias, variance ratio, correlation

Temperature, Pressure, Relative Humidity, Wind

MATLAB

Flight Segmentation

Flight-Phase Detection

- Based on **vertical rate**
- Must last ≥5s to qualify as **Ascent/Descent**
- Must **change altitude** by ≥15m to qualify

Horizontal Classification

- Based on **geographic** position
- Categories: **straight, turn, near-tower**
- Feeds Time Series

Vertical Profile
RAAVEN profile vs 4 Tower heights

- *Matched:* RAAVEN points within ±2 m of each tower height, then **averaged**
- Only 4 comparison points, **qualitative characterization**, not statistical validation

Time Series
RAAVEN vs Tower measurements (32m)

- **60-second continuous bins** (*de Boer et al. 2024 method*)
- Measures average difference (**bias**) and variability match (**variance ratio**)
- **Filtered** by flight time and steady altitude

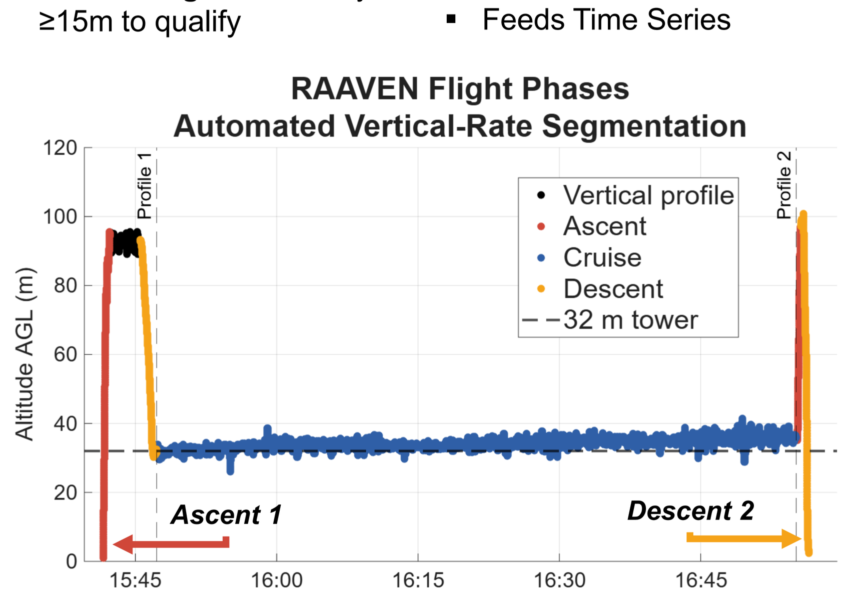


Figure 1. RAAVEN flight phases: Ascent 1 (94.2 m in 45 s), Descent 2 (94.9 m in 50 s); cruise altitude tracks the tower's 32 m sensor

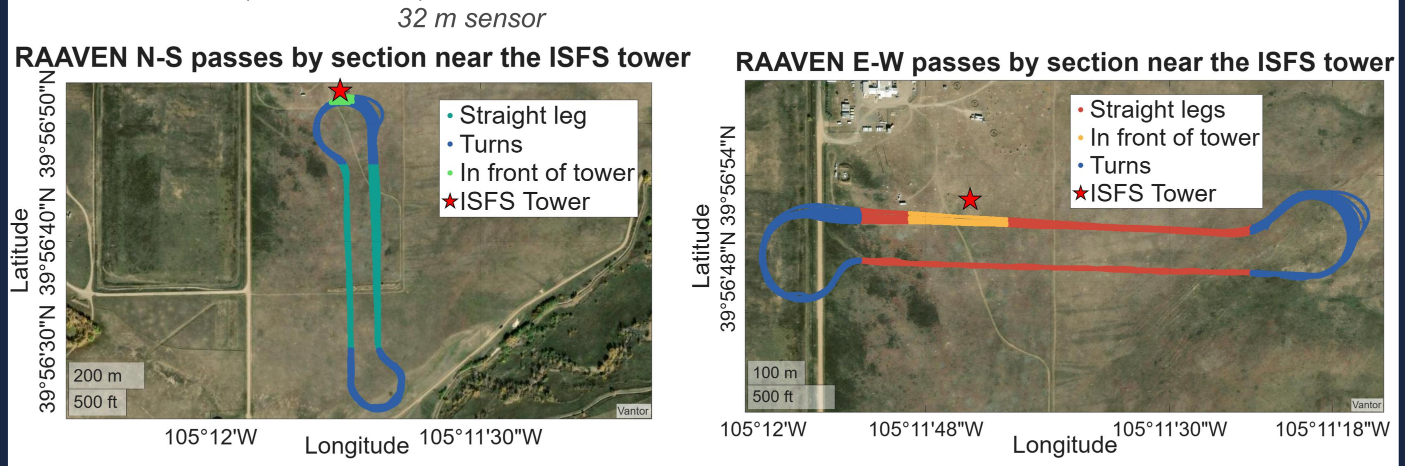


Figure 2. RAAVEN horizontal flight passes near the ISFS tower, classified by geometric position, for the E-W (right) and N-S (left) flight legs

2026-03-25 Marshall Field Site, Boulder, CO

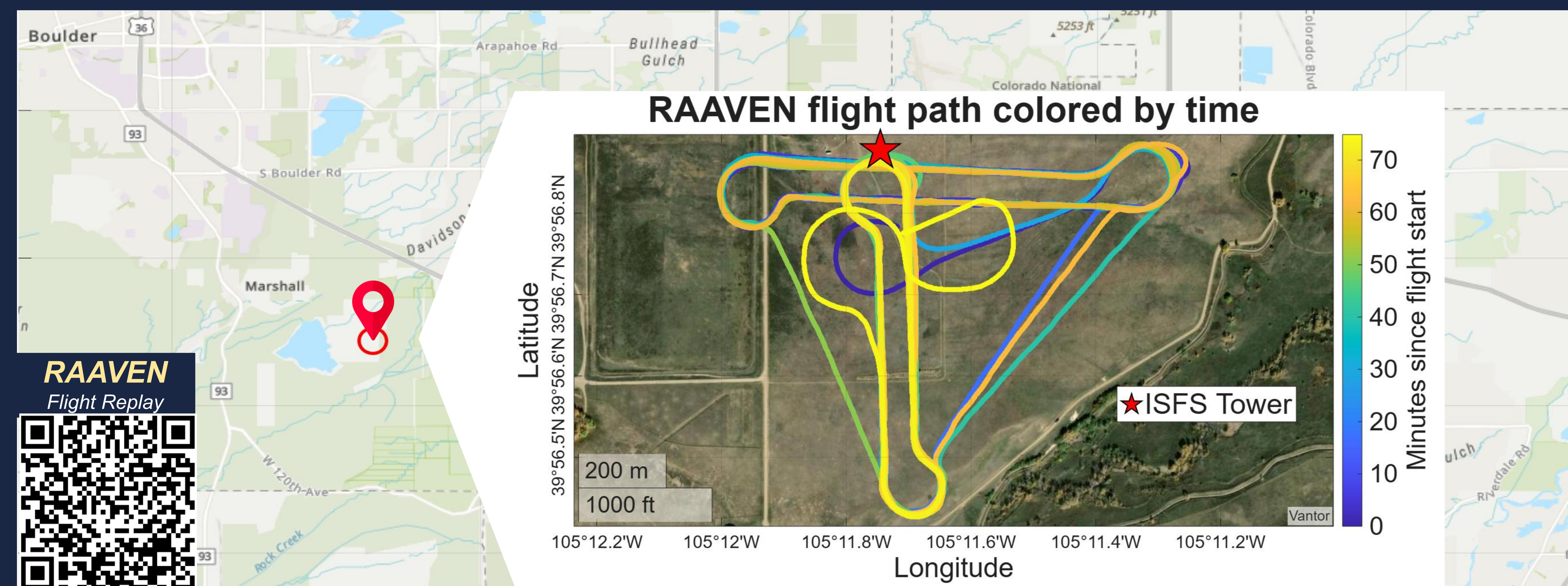


Figure 3. RAAVEN ground track for the full flight, illustrating both the spatial extent of the flight pattern and its temporal progression (color denotes elapsed time since takeoff). Red star: ISFS tower (39.948°N, 105.196°W)

RAAVEN
Robust Autonomous Aerial Vehicle - Endurant Nimble

Figure 4. The RAAVEN fixed-wing UAS, used to collect in-situ measurements

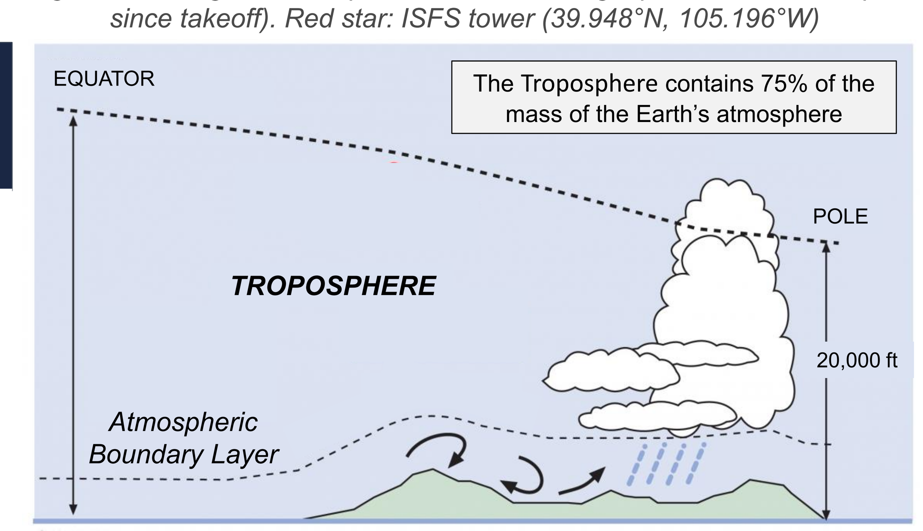


Figure 5. ABL is where air properties become directly influenced by proximity to the surface of the Earth

ISFS
Integrated Surface Flux System

Figure 6. The ISFS tower, operated by the National Center for Atmospheric Research

Results

Vertical Profile

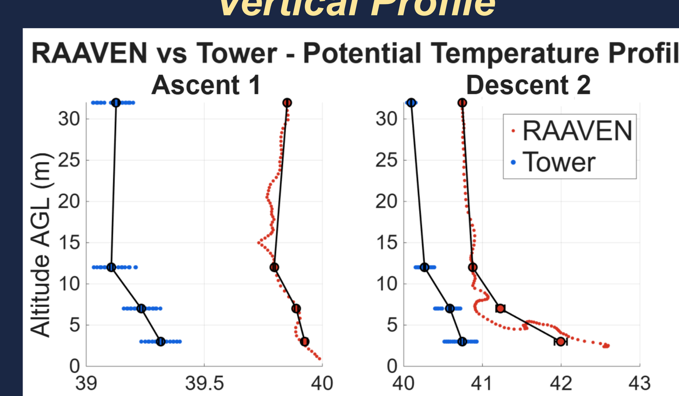


Figure 7. Captures the boundary layer's morning transition from neutral to unstable in real time

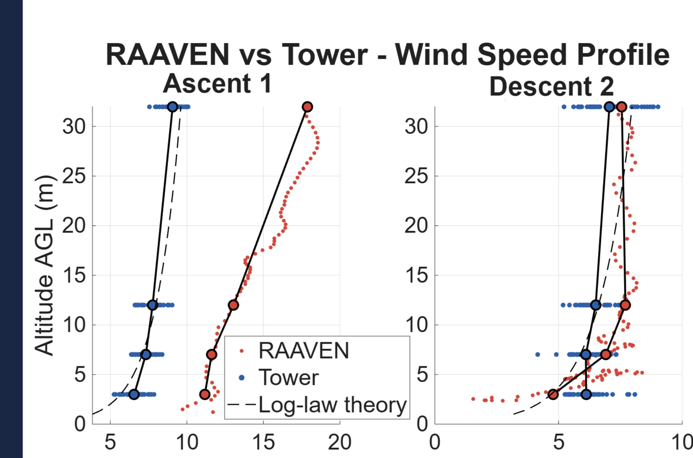


Figure 8. Log-law reflects surface friction slowing wind near the ground

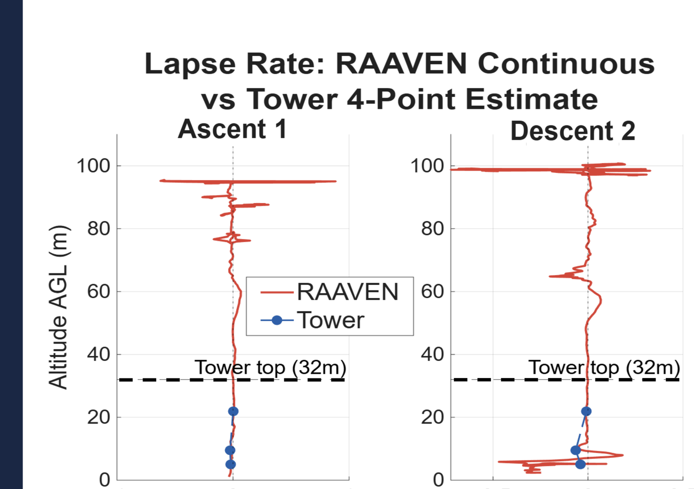


Figure 9. Lapse rate = temperature change with height: 0 = neutral, + = stable, − = unstable

Time Series

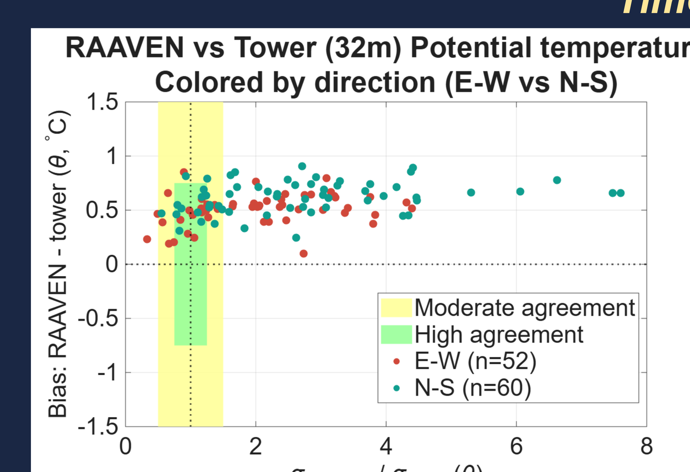


Figure 10. Variance ratio: E-W: 2.05, N-S: 2.74; reflects real temperature heterogeneity RAAVEN detects that the tower cannot

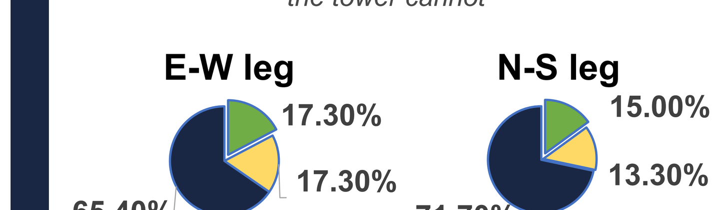


Figure 11. Percentage of bins in each agreement category, by direction

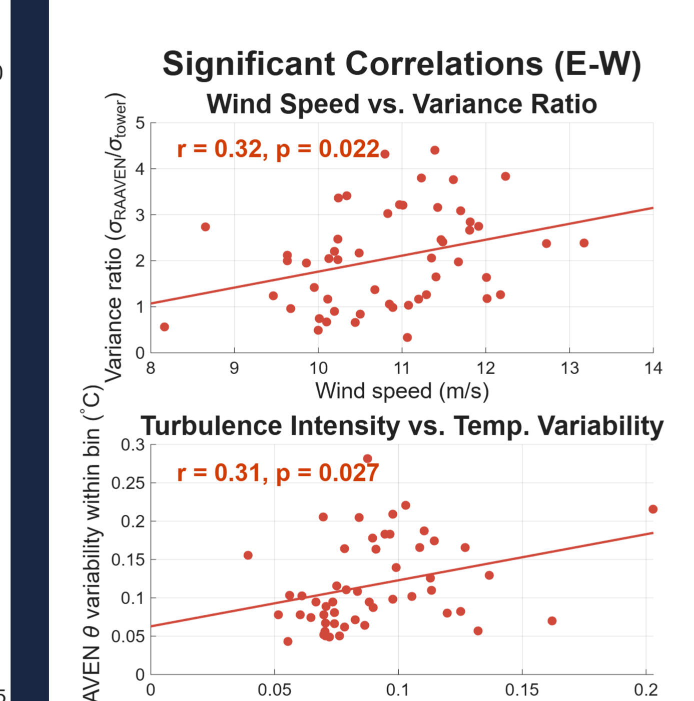


Figure 12. Both correlations (p<0.05) point to real atmospheric turbulence, not sensor noise

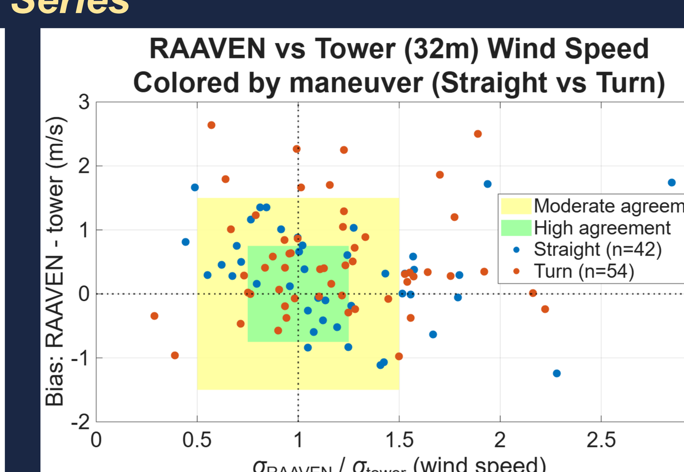


Figure 13. Bias: S: +0.28 T: +0.51 m/s; reflects known banking-induced probe distortion

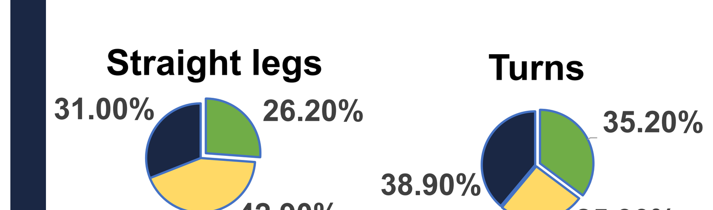


Figure 14. Percentage of bins in each agreement category, by maneuver

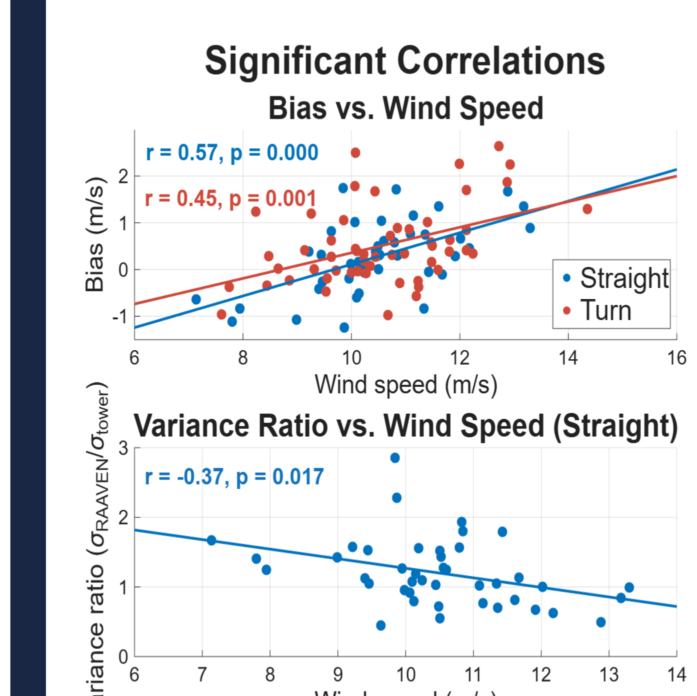


Figure 15. Bias grows with wind speed (both maneuvers), a probe calibration effect

Vertical Profile

- The evolution from near-neutral *Ascent 1* to a much warmer near-surface layer during *Descent 2* **matches typical morning ABL growth**, as the sun heats the surface (Stull, 1988)
- RAAVEN's **wind-speed readings near the ground scattered more during Descent 2** than *Ascent 1* (Figure 8). The log-law (calm, near-neutral conditions) fits *Ascent 1* better, earlier in time
- RAAVEN resolves **unstable oscillations near the surface** in *Descent 2* that the tower's 4-point estimate cannot resolve (Figure 9)
- **Qualitative only**, 4 tower points, not enough data for a meaningful statistical correlation

Time Series

+0.50°C E-W
+0.62°C N-S
Temperature bias (Cruise)

69.1% / 61.1%
Wind agreement, straight legs and turns

✓ The wind speed grouping (*Straight vs Turn*) reflects a known instrument limitation: **banking distorts the aircraft's wind-probe measurement**

✓ Temperature was grouped by direction (*E-W vs N-S*) instead, after **Straight/Turn showed no effect** (ruling out the same artifact), and **direction was found to carry a real atmospheric signal**

- Temperature bias is small in both directions, but **variance ratio is elevated** (Figure 10). Higher variance on the **E-W track correlates with wind speed and turbulence intensity** (Figure 12, $p<0.05$), indicating real atmospheric turbulence. **N-S shows no such relationship** despite testing flight timing, wind geometry (crosswind angle, wind direction), distance to tower, and ground-speed (all $p>0.05$), leaving the **N-S asymmetry as an open characterization question**
- **Wind bias grows with wind speed in both maneuvers** (Figure 15, $p<0.001$), a probe calibration effect, confirmed by temperature showing no equivalent relationship. Variance ratio stays near 1, unlike temperature's elevated ratio, though it decreases further with wind speed in Straight legs. **Straight legs show better overall agreement** than turns, driven by Turn's larger bias (Figure 14, **banking-induced probe distortion**), not by variance ratio, which is nearly identical between maneuvers

Conclusions

- The vertical profile revealed **near-surface warming that intensified over the flight**, with an increasingly unstable zone during descent, consistent with morning *ABL* growth (Stull, (1988)
- Temperature's small bias but elevated variance ratio reflects real **atmospheric heterogeneity that RAAVEN's spatial sampling captures** and the tower cannot, confirmed by significant turbulence correlations (*E-W*); wind's bias, in contrast, grew with wind speed regardless of maneuver
- RAAVEN's agreement with the tower varied depending on **both the variable measured and how the platform sampled it**, reflecting **overall relatively good agreement with the tower**

Limitations & Future Work

- **Single flight**, one day, no test of different times/seasons
- Vertical profile limited to only 4 tower heights (**small sample**)
- Future work would benefit from **coordinating with NCAR** to better understand sensor calibration and offsets with additional comparisons
- **Conduct additional flights** to better understand the influence of flight patterns and examine other variables (*e.g., pressure, relative humidity*)
- Explore additional **sensing opportunities and sampling configurations**, and formally quantify calibration differences between the RAAVEN and tower

References & Acknowledgements

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