Response to the Reviewers

Title: SAMURAI-S: Sonic Anemometer on a MUlti-Rotor drone for Atmospheric turbulence Investigation in a Sling load configuration

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Response To Reviewer #1

Overall Comments

> This paper presents very novel work in measuring turbulence from an UAV where the sonic anemometer is placed as a sling load from the UAV. This positioning overcomes difficulties from other solutions such as e.g. using a sideways facing boom. The study also presents methods on how to properly process the measurements data in order to get physically correct output.
>
> The new system opens up for detailed turbulence measurements in environments requiring a spatial resolution such as e.g. wakes from wind turbines.
>
> The authors must have put in a great effort in getting this system to work properly as shown with the comparative study from a recent field campaign. Some remaining issues with the overestimation of vertical wind fluctuations still needs to be investigated further. However, this study convincingly show that these type of measurements are possible and may yield results comparable to a fixed installation, a significant contribution to the field.
>
> The manuscript is well prepared and presents the applied method in a clear manner including relevant figures. I only have some minor comments and suggestions which you find below.

Response

We thank the reviewer for the positive and constructive feedback on the manuscripts. We acknowledge the remaining issues that have been pointed out, particularly regarding the overestimation of vertical wind fluctuations. All of the reviewer's comments and suggestions have been addressed in the revised manuscript.

General Comment

> I think it would be good to get some reflection on the practicalities/maneuverability of the system. How was take-off and landing prepared? Is it necessary with special training using this setup? Is there some danger with high gustiness that the system gets out of control? I could think of e.g. measuring in highly turbulent conditions such as close to forest edges. Also, did you fly it manually or with an autopilot?
>
> The larger values of σ_w from the UAV measurements seems to be systematic, in all samples. There is a risk that this might be some lingering effect from the downwash of the propellers. I think this needs to be further elaborated on in the discussion.

Response

We thank the reviewer for highlighting these points. Regarding the first part of the comment, we have included a new section in the text (Section 2.4: Flight Operation), which describes the practical aspects of deploying the SAMURAI-S UAS system. This addition also addresses the issues raised in Specific Comments 5 and 6 by outlining the step-by-step operational procedures followed during the validation

campaign, detailing strategies to mitigate technical challenges (such as vortex ring state during landing), and describing how the system performed in terms of flight stability.

The second part of the comment pertains to one of the issues highlighted in the "Overall Comments" section, specifically the systematic anomaly of higher σ_w values observed with the SAMURAI-S system compared to the tower-based setup. The cause of this anomaly remains unclear. While a PIF component generated by the drone may contribute to this effect to some extent, this hypothesis alone does not fully explain the observed trend.

As highlighted in previous studies cited in the text [1, 3, 4], a stronger free flow is expected to advect the downwash further downstream, thereby reducing its influence at the payload height (-18 m from the fuselage). The data, however, shows the opposite trend, suggesting that the primary driver of this overestimation lies elsewhere.

Specific Comments

1) Line 50, more clearly specify the novelty. Clearly establish the innovation and significance of the study.

- The text has been revised to highlight the novelty the study explicitly. The updated text now reads: "To the authors' knowledge, this represents the first attempt to deploy a research-grade sonic anemometer as a suspended payload under a UAV, in contrast to the conventional approach of mounting such instruments rigidly to the UAV structure at relatively short distances (typically on the order of decimeters to a meter), as in the studies above."

2) Line 89, specify that the weight is without payload.

- The text has been clarified to specify that the weight mentioned is without the payload. The text now reads: "In its default configuration, it is powered by two 6S lithium polymer (LiPo) batteries, each with a capacity of 22 A h, resulting in a take-off weight of roughly 15 kg excluding the sensor payload"

3) Section 2, placement of a sonic anemometer above the drone is not discussed, please add something here.

- In the second paragraph of Section 2.2, we acknowledge the placement of a sonic anemometer above the drone as an approach already explored in the research field, referencing several relevant studies. We believe this mention sufficiently indicates that this research area is active, and the presented work aims to provide an alternative approach to this existing method.

4) Section 2, Explaining why Foxtech was chosen over other potential UAVs would provide more context

- The choice of the Foxtech UAV was based on three main considerations. As mentioned in the text, the first is that it meets the specific requirements of weight, payload capacity, and flight time needed to perform this study. An additional factor, now explicitly stated in the revised text, is that the Foxtech D130 integrates an open-source flight controller in its default configuration. This provides great flexibility for development. Finally, the modular design of the Foxtech D130 allows for extensive customization and represents another important reason that has now been clarified in the updated text.

5) Section 2, Here some operational considerations could be included: e,g, operational procedures for deploying the UAV and sensor system in the field, details on pre and post flight checks necessary etc. This would be valuable for replicating the study.

- As anticipated in the response to the "General Comments", we have added an extra section in the manuscript (2.4 Flight Operation), expanding on the practical aspects of operating the system presented in the paper.

6) Also, potential limitations/challenges associated with the setup can be included here. It would provide a more balanced perspective. For example, addressing the potential impact of strong wind conditions on UAV performance would be useful.

- We thank the reviewer for this important comment. Flight stability is indeed a crucial factor when deploying any drone system, particularly in relation to operational safety. The SAMURAI-S system was field-tested in wind conditions of up to 15 m/s. Within this range, it demonstrated excellent stability. However, we cannot provide insights into its performance in wind conditions exceeding this range, as such scenarios were not tested during this study or its preparatory phases. The manuscript has been updated to include a statement clarifying that the SAMURAI-S system was flown in wind conditions of up to 15 m/s, where it consistently demonstrated excellent stability and operational safety.

7) Line 203, why was the 2% limit set (why not e.g. 1% or 3%)?

- We realized that the original wording may have led to confusion. The 2% mentioned is not a threshold or limit set for data exclusion; rather, it represents the proportion of missing or flagged data resulting from the data quality checks. To clarify this, the text now reads: "The combined amount of missing and flagged points, following this procedure, did not exceed 2 % in any flight data set."

8) Line 214, Please define how you determined TKE

- The manuscript has been updated. In Section 3.3 (Data Synchronization and Coordinate Transformation), Equation 3 now defines TKE as half the sum of the variances of the fluctuating velocity components.

9) Section 4.2, first paragraph: This section could benefit from some more description and motivation of the applied steps.

- We thank the reviewer for this suggestion. In Section 4.2 (now Section 4.4 in the updated manuscript), additional explanations have been provided to clarify both the necessity of controlling the time shift between the two datasets (specifically, to account for the fact that the drone and tower-based setup may measure different turbulent structures at slightly different times due to advection) and the method used to achieve this synchronization.

10) Line 283, Specify for the reader what you mean by misalignment in this context

- In this context, "misalignments" refer to small deviations between the assumed nominal orientation of the sonic anemometers and their actual physical alignment. These discrepancies can arise from slight mounting offset errors during the installation of the sonic anemometer on the tower or from inaccuracies in aligning the inertial navigation system (INS) with the sonic anemometer on the payload. Such misalignments, even if minor, can lead to systematic differences in the measured data. The text has been revised to clarify this for the reader (Section 4.4 in the updated manuscript).

11) Line 300, for completeness why don't you include also s2, s3 and s4 in the quadrant analysis? Could be interesting to see the results, but you could use different symbols to separate these.

- Following the reviewer's suggestions, we have included samples S2, S3, and S4 in the quadrant analysis (Fig. 15, in the current version of the manuscript). The figure now features an updated caption that reads: "Samples with a mean wind speed below 1 m s^{-1} are marked as grey triangles, as they are representative of intermittent turbulence, for which the assumption of local isotropy in the inertial subrange may not be well-defined."

  We would like to emphasize, however, that these samples exhibit non-stationary characteristics and do not adhere to the usual assumptions of stationary turbulence or frozen turbulence (as shown in the Figure 1, later in the text). Consequently, the interpretation of the spectral ratio S_w/S_u for these samples should be approached with caution, as their properties fall outside the framework required for studying local isotropy in the inertial subrange.
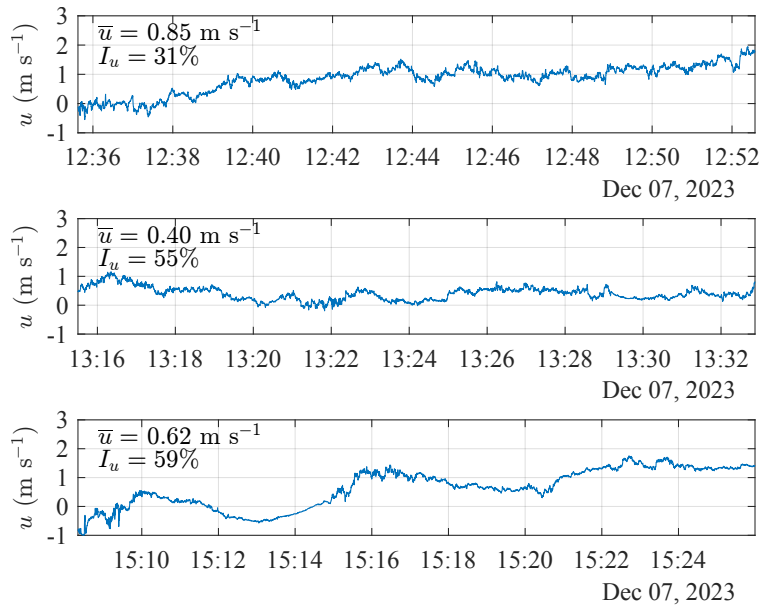
Figure 1: Time histories of the along-wind velocity component recorded by the sonic anemometer on the mast, for samples s_2 (top panel), s_3 (middle panel), and s_4 (bottom panel). The samples display non-stationary characteristics commonly observed in intermittent turbulence.

12) Section 5.1 Please provide some initial text motivating why these particular cases, s1 and s7 were chosen for the case study.

- The fourth paragraph of Section 5 introduces the key differences between the two samples. We believe this provides a smooth transition and context for the following sections of the text. Nevertheless, to make this more explicit, a reference to this paragraph has now been included within Section 5.1, as suggested by the reviewer.

13) Line 313, you previously introduced skewness and kurtosis, for consistency this could be repeated here. The sentence "Results related to temperature..." would be better placed after the sentence "Figure 8 presents time series of...".

- These comments have been implemented in the text exactly as per the reviewer's suggestions.

14) Figure 8, for completeness the figure caption should explain also the insert text in the figures e.g. "rot2" etc. This comment also goes for Figures 9, 10 and 11.

- We have followed the reviewer's suggestions and modified the captions of the cited figures to now include an explanation of all the relevant information shown in the figures.

15) Table 5, correct capital D in figure caption (on Data). Why not include also the u'w' and w't' terms in the table?

- We have implemented the suggestion exactly as indicated. The capital 'D' in the figure caption has been corrected, and the fluxes (momentum and buoyancy) have been added to table 5.

16) Line 334, can there be a risk that this is something induced by the UAV? Flight 1 was the one closest to the tower and the only one with unstable stratification and winds somewhat in the direction of the tower.

- We thank the reviewer for raising this important point. Based on the prevailing wind conditions observed during the first flight (S1), the risk of UAV-induced interference for the northwest sensor is minimal. Specifically, the mean wind direction during S1 was $97°$, with a standard deviation of $20°$, indicating a narrow dispersion. Furthermore, only a very small fraction of data points (less than 4%, corresponding to brief, random fluctuations) exceeded $135°$, which would be required for the mast to be downstream of the SAMURAI-S.

17) Line 340, which also is seen in the larger σ_w values in Table 5

- We thank the reviewer for this comment. This connection has been incorporated into the text by explicitly referencing the higher σ_w values in Table 5, further supporting the discussion.

18) Figures 12 and 13: please provide a table with comparative statistics, i.e. bias and RMSE of the UAV based measurements compared to the tower. This would improve the discussion in the paragraph starting on line 360. Additionally, these figures should be placed in section 5.2.

We thank the reviewer for this suggestion. However, we believe that bias and RMSE are not the most appropriate metrics for discrepancies between individual samples. The primary reason is that both bias and RMSE depend on the mean wind speed, meaning they inherently increase with higher wind speeds. If these metrics were normalised by the mean wind speed, they would yield relative differences and a normalised RMSE, which in turn would decrease with wind speed. However, these normalised metrics are also unsuitable, as they are inherently self-correlated with wind speed.

Moreover, even a theoretically perfect sensor would not yield a bias or RMSE of zero, as the two sensors are not colocated. While we assume homogeneous turbulence in our analysis, we cannot enforce it in real atmospheric conditions. The spatial separation between the drone-mounted and mast-mounted anemometers means that differences between their measurements are expected.

To address the reviewer's suggestion of including additional comparison metrics, we have chosen to analyse statistical uncertainties in the samples using the methodologies proposed by [2, 5, 6] (introduced in Section 4.2. in the updated manuscript). These methods are more appropriate for turbulence analysis as they do not assume that the mast-based measurements represent the true, unbiased reference. Additionally, these uncertainty metrics allow for a more informative pairwise comparison, as presented in Figures 12 and 13, highlighting that certain samples exhibit higher uncertainty than others.

Regarding the placement of Figures 12 and 13, we agree with the reviewer's suggestion and have now relocated them to Section 5.2.

19) Line 361: Why not use the same notation as in the previous sentence when it comes to the fluxes i.e. w't'?

- We have revised the notation for the fluxes to ensure consistency throughout the text.

20) Line 362-364: It is hard to determine whether L has low scatter, calculating some comparative statistics would improve this discussion. Additionally, I am not convinced about the explanation about the perceived low scatter for L, u* is to the third power in equation (7). Furthermore, it is not he w' itself which is important here, rather it's correlation with the other variable e.g. T'.

- The reviewer correctly highlights that the key issue lies in the correlation between w and other variables (such as T or u'). However, given the excellent agreement between the sonic temperature measurements from the drone and the mast, we infer that the primary source of uncertainties in the covariances $\overline{u'w'}$ and $\overline{\theta'w'}$ originates from the vertical velocity component (w'). In other words, the uncertainties in the covariance estimates are directly attributable to uncertainties in the w' component. This reinforces the need to address the vertical velocity component more thoroughly in future studies.

21) Paragraph starting at line 374 and figure 14: It appears only one sample is close to 1.33 for Sw/Su and that the deviation increases with increasing wind speed (as you also mention in the conclusions). Please rephrase the text here to better concur with the figure.

- The text has been revised to clarify that only one sample is near the theoretical ratio of 1.33 for $< S_w/S_u >$, and that this deviation increases at higher wind speeds, as reflected in Figure 12.

22) Could the overestimation of this ratio be related to the overestimation of σ_w? The underestimation of the tower could be due to problems with the setup? To short booms? This is something that can be commented in the text. Of course, it could be investigated since you have a larger dataset from the tower, but it might be out of the scope of this paper.

- We thank the reviewer for these observations. Indeed, the overestimation of S_w/S_u by the UAV could be influenced by its higher σ_w values. Similarly, the underestimation by the tower might result from setup-related factors (e.g., short booms, as noted by the reviewer), which could lead to potential flow distortion. Both possibilities have been mentioned in the revised text. However, a more detailed investigation of the tower dataset lies beyond the scope of this paper, which focuses primarily on the UAV system.

23) Conclusions section: This section could benfit from beeing more streamlined, excluding some summary focusing on the main results. Adding the comparative statistics I suggested above would further strengthen this section. Also, some tentative conclusions about the minimum sampling time could be added.

- The paper now includes additional statistical analyses, specifically turbulence uncertainties, as mentioned in response to Specific Comment 18. Furthermore, based on another reviewer's suggestion, we have incorporated a turbulence length scale analysis. The Conclusions section has been updated accordingly to reflect the contributions of these additional metrics. The second part of the comment is addressed through the turbulence uncertainty analysis, which is computed as a function of a given sampling time, as now introduced in Section 4.2 of the manuscript.

24) Appendix/supplementary material: It would be interesting to include the spectra from all flights and tower comparisons (e.g. like figure 9 and 11).

- The text has been revised to include, in the appendix, Figure B1, which presents the normalized power spectral densities of the three velocity components and the cross-spectral densities for samples S5, S6, S8, S9, and S10. Similarly, Figure B2 provides the corresponding analysis for temperature fluctuations.

Technical Corrections

1) The manuscript is mainly written in the present tense (with some deviations). Personally, I would prefer past tense for everything that you have done but I leave this to the editor. At least, check for inconsistencies which appear at some places.

- The manuscript has been revised to ensure consistency in tense usage. The present tense is now used when referring to established scientific knowledge, while the past tense is used to describe the work conducted in this study.

2) Line 14, reference from 2010 is not that recent (just a detail)

- We acknowledge that studies from 2010 may no longer be considered "recent." To address this, now the text reads "several", focusing on the quantity more than the timeframe of the works.

3) Figure 1, would benefit of a somewhat more detailed figure caption, e.g. here are batteries and logger mounted, dimensions of payload etc.

- The figure caption for Figure 1 has been expanded to include details about the UAV's dimensions (1.9 m × 0.7 m), the aluminum-frame geometry (including the longer arm for the GNSS antennas and the shorter arm for the anemometer and electronics), as well as the key payload components (IMU, GNSS antennas, data logger, and power source).

4) Figure 2, also this figure would benefit from a more detailed figure caption

- The caption for Figure 2 has been revised to explicitly describe the color scheme and label each component shown. This additional detail ensures that readers can interpret the figure more easily by clarifying what each color and label represents, with all relevant elements clearly identified.

5) Figure 4 is better located under section 3. 6)Table 4, Figures 12-13 should be placed in section 5.

- These comments will be taken into consideration during the editing and layout phase of the paper.

Response To Reviewer #2

Overall Comments

> The PIF phenomenon consisting in the presence of strong induced turbulence around a drone-type UAV leads to significant issues in direct measurements of atmospheric parameters. The manuscript proposes an original way to minimize the effect of the PIF phenomenon in direct measurements by hanging a sonic anemometer under the drone as a sling load. The study is interesting, urgent, and relevant to the topic of Atmospheric Measurement Techniques. The results reported by the authors can be of great interest to AMT readers. In my opinion, the below comments can help the authors to improve significantly the quality of the manuscript.

Response

We thank the reviewer for the positive feedback and thoughtful comments. We appreciate the recognition of the relevance and originality of our work and the suggestions provided to further improve the quality of the manuscript.

Reviewer Comment

> 1) Pages 1 and 2, Lines 7-9 and 57. The authors write that "This research aims to assess the accuracy and reliability of the developed measurement approach." In my opinion, the statement that 'The results demonstrate that SAMURAI-S matches the data quality of conventional setups for horizontal wind measurements while slightly overestimating vertical turbulence components. This overestimation increases as the wind speed increases" does not fully correspond to the purpose and results of the work. The authors should provide quantitative data on the discrepancy between Drone Data and Mast Data as a function of the increasing wind speed.

- We thank the reviewer for this comment. Quantitative data on the discrepancies between drone-based and mast-based measurements as a function of increasing wind speed were already provided in Figures 12 and 13 of the original draft. Nevertheless, we acknowledge the reviewer's suggestion to include more explicit metrics, and we have addressed this by adding two additional comparisons. First, we have incorporated the integral length scale, which is also relevant to the reviewer's third question, where its inclusion is explicitly requested.

  Second, we have introduced a calculation of the uncertainty in the flux measurements, following the methodology presented by [2, 5, 6]. This framework is now documented in Section 4.2 of the updated manuscript. Notably, wind speed plays a significant role in the calculation of these uncertainties, directly addressing the suggestion provided by the reviewer.

> 2) Page 13, Line 253, Eq. (6). This equation should be corrected as Sw into Suw.

- We have corrected the equation, replacing S_w with S_{uw}, as suggested by the reviewer.

3) Pages 17 and 20, Figures 8 and 10. The sonic anemometer allows measuring actual wind speed and actual ambient temperature with high spatial and temporal resolution. The analysis of the measurement series depicted in Figures 8 and 10 should be supplemented with the correlation coefficients, the turbulence scale data, and the distance between the sonic anemometers installed on the drone and the mast. In addition, histograms of the discrepancy between Drone Data and Mast Data, as well as the Cumulative Percent, which characterize the statistics of the discrepancy between the data, should be presented. It will be interesting to readers how the measurement data differ from each other at the actual wind speed and temperature.

We agree that a comparison of the integral length scales between the mast and drone data adds value to the study, and the manuscript now includes this as a new figure in the manuscript. Additionally, we have incorporated an uncertainty analysis to further enhance the discussion.

However, providing correlation coefficients and similar statistical metrics could be misleading. Readers might, for instance, expect a correlation coefficient of 1 if the drone-mounted anemometer were perfect. However, even with a theoretically perfect sensor, the correlation coefficient would be less than one because the two sensors are not located at the same position. Moreover, this correlation coefficient strongly depends on atmospheric conditions (e.g., wind speed and atmospheric stability) and would not accurately reflect the quality of the drone-mounted sensor due to the limited spatial coherence of turbulent eddies.

After discussions with our co-authors, we do not believe that including histograms of the discrepancies or cumulative percentage statistics is necessary. While such visualisations can facilitate qualitative analysis, we argue that these discrepancies are more effectively characterised using kurtosis, skewness, standard deviation estimates, and power spectral densities, which are already included in the analysis.

4) It is desirable to provide the estimated spatial resolution so that a reader could evaluate possible applications of the reported technique.

- We sincerely appreciate the reviewer's comment and the opportunity to provide further clarification. However, we find it difficult to precisely define "estimated spatial resolution" in this context. The spatial resolution of the sonic anemometer is primarily influenced by the open-path averaging process, which in turn depends on the geometry and specific model of the instrument used.

Reviewer Summary

The manuscript can be published in Atmospheric Measurement Techniques after revision with allowance made for the above comments. I believe that this will qualitatively improve both the clearness of the manuscript itself and the characteristics (accuracy, reliability, etc.) of the approach to monitoring atmospheric turbulence developed by the authors.

Response To Reviewer #3

Overall Comments

This manuscript outlines a novel atmospheric turbulence measurement via a sonic anemometer mounted to a multi-rotor uncrewed aerial system using a sling load. The authors outline the design of the system, operating parameters and analyze the performance of the method by comparing measurements to tower-based sonic anemometers. The manuscript is well-written, thorough and advances atmospheric measurement techniques. I recommend the paper for publication.

Response

We thank the reviewer for the positive and constructive feedback on the article. The reviewer's comments have been addressed. We believe that this has greatly improved the overall clarity of the manuscript.

Specific Comments

1) Line 89: Define GNSS

- The text has been updated and now features a definition of GNSS (Global Navigation Satellite System).

2) Table 1: p5. Define ESC

- The abbreviation "ESC" has been defined as "Electronic Speed Controller" in the table for better clarity, as suggested by the reviewer.

3) Line 142: It would be helpful to annotate the image (Figure 1) or diagram (Figure 2) with where the INS is located, the sensor coordinates, the crossbar and the GNSS antennas. This is just for clarity.

- We have addressed this comment by adding extra annotations to Figure 1. The figure now highlights the locations of the GNSS antennas, the IMU, and the Raspberry Pi. Additionally, Figure 2's caption has been updated to explicitly mention and explain the colour coding used, providing better guidance towards understanding the figure.

4) Line 147: It would also be helpful to have a diagram of the pitch, yaw, roll and balance of the sling load configuration attachment to the UAS. Connecting the theoretical diagram (Figure 3) to the logistical attachment strategies and pendulum physics (Figure 2) is a key understanding of the novelty of this approach and a visual connection may assist the reader in discerning the language in this paragraph.

- We thank the reviewer for this suggestion. Figure 3 has been revised to include an additional panel illustrating the sling load attachment of the payload to the UAV frame. The figure caption has been updated accordingly to explain how the drone's movements influence the payload reference frame (i.e., the body frame), thereby clarifying the relationship between the theoretical diagram in Figure 3 and the payload structure presented in Figure 2.

5) Line 186: Do you have any metric on the accuracy of the internal clock of the Raspberry pi? Is there drift or time compression?

- For this study, we did not actively evaluate or study potential drift in the internal clock of the Raspberry Pi. We acknowledge that the internal clock of the Raspberry Pi is not inherently reliable, as it is not synchronized to any GPS signal. For this reason, we did not use the timestamps generated by the Raspberry Pi in absolute terms, as specified in the text, but redefined them as relative time intervals (expected to be 1/32 s apart from each other) from a predefined starting point (namely the first timestamp given by the INS). It is important to note that every timestamp saved was effectively derived from the 32 Hz output of the Young 81000 sonic anemometer. Any potential drift in timing would, therefore, originate from the internal processing of the sonic anemometer itself. However, no discrepancies were observed between the expected number of data points and the actual data points collected over the overall measurement intervals. Therefore, we did not elaborate further on clock drift issues in the manuscript.

6) Line 188: I do not understand the time adjustment for the upside-down mounting orientation. If the measurements are instantaneous to an internal clock, why would time be a factor in transforming the phase space of the measurement. Please clarify.

- We thank the reviewer for bringing this to our attention. We understand that the statement may have caused confusion due to its placement. The mention of the "upside-down mounting orientation" was intended to explain the need for coordinate transformation of the sonic anemometer data, not a time adjustment. The revised text now appears in the section and clarifies this point.

7) Line 207: Explain the downsampling process from 50 Hz to 32 Hz. It would appear it would merely be a linear interpolation as the frequencies are too close for any averaging. If it is a smoothing function, please explain what that other smoothing function is.

- The downsampling process from 50 Hz to 32 Hz was indeed performed using linear interpolation. The manuscript has been updated to clarify this point.

8) Line 298 and Lines 402-405: If the flights s2, s3, and s4 have low mean flows and were not included in the quadrant analysis, please qualify the summative statements regarding the quadrant analysis for the assumptions required to apply it.

- Considering similar comments raised by other reviewers, we have decided to include flights s1, s2, and s3 in the quadrant analysis for completeness. The manuscript has been updated accordingly to reflect these changes (Figure 15).

References

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SAMURAI-S: Sonic Anemometer on a MUlti-Rotor drone for Atmospheric turbulence Investigation in a Sling load configuration

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Abstract. This study introduces the SAMURAI-S, a novel measurement system that incorporates a state-of-the-art sonic anemometer combined with a multi-rotor drone in a sling load configuration, designed to overcome the limitations of traditional mast-based observations in terms of spatial flexibility. This system enables the direct measurement of 3D wind vectors while hovering, providing a significant advantage in manoeuvrability and positional accuracy over fixed mast setups. The capabilities of the system ~~are~~ were quantified through a series of $10\,\mathrm{min}$ to $28\,\mathrm{min}$ flights, conducting close comparisons of turbulence measurements at altitudes of $30\,\mathrm{m}$ and $60\,\mathrm{m}$ against data from a 60-meter tower equipped with research-grade sonic anemometers. The results demonstrate that SAMURAI-S matches the data quality of conventional setups for horizontal wind measurements while slightly overestimating vertical turbulence components. This overestimation increases ~~as the wind speed increases~~ with wind speed.

1 Introduction

Since the 1960s, ~~mast~~ mast- and tower-based sonic anemometry ~~has~~ have been the standard for high-frequency turbulence measurements in atmospheric boundary layer (ABL) research (Foken, 2006; Mauder et al., 2021). With continuous technological development over the years, state-of-the-art sonic anemometers allow for ~~in-situ flux estimations~~ in situ flux estimation (e.g., Foken et al., 2012) and for the spectral characterization (e.g., Midjiyawa et al., 2021) of turbulence. However, ~~recent~~ several studies in ABL meteorology and wind energy, such as Fernando and Weil (2010), Mahrt (2014), or Veers et al. (2019), highlight the limitations of those traditional tower-based measurements, emphasizing the need for more flexible approaches to address a ~~wider~~ broader range of relevant ABL processes.

Some examples illustrating mast-based measurement limitations include the study of the coherence of turbulence (Cheynet et al., 2018), ~~which is a critical~~ a key design parameter for modern wind turbines. For such an investigation, ~~it would be required to erect~~ erecting multiple 300-meter masts close to each other would be required, which is impractical. The same holds for the detailed investigation of wind turbine wakes within a wind farm, as, e.g., explored by Porté-Agel et al. (2020), as variability in wind speed and direction make a proper positioning of masts in such dynamic conditions practically unfeasible. Other research topics that require alternative sensor carriers ~~are~~ include the investigation of the wave boundary layer (Wu and Qiao, 2022),

air-sea-exchange over the ocean (Taylor et al., 2018), and air-ice-sea interactions in polar regions, e.g., over open water areas within the sea ice (Marcq and Weiss, 2012).

Airborne platforms have been used to extend the range of turbulence-related measurements. Fixed-wing uncrewed aircraft systems (UASs), often employing multi-hole probes (Mansour et al., 2011; Wildmann et al., 2014a, b; Båserud et al., 2016; Witte et al., 2017; Calmer et al., 2018; Alaoui-Sosse et al., 2019; Rautenberg et al., 2019), have demonstrated their capability in turbulence sampling along the flight track across larger areas. However, the inability to hover or move very slowly restricts their ability to measure in situations requiring stationary point measurements or localized vertical profiling.

Conversely, tethersonde systems equipped with sonic anemometers can provide quasi-stationary measurements and are effective in vertical profiling (Ogawa and Ohara, 1982; Hobby, 2013; Canut et al., 2016). However, those systems require considerable logistical effort and have clear operational limits regarding wind speed and atmospheric turbulence, which strongly affect their controllability. Consequently, tethered systems cannot be easily deployed in remote areas and complex terrain or safely operated near structures and buildings, such as in urban areas or near wind turbines and wind farms.

Rotary-blade uncrewed aerial vehicles (UAVs) offer a more suitable sensor platform for localized and stationary measurements (Abichandani et al., 2020). Recent studies have explored the use of different methods of atmospheric flow measurements, using either the UAV's motion and attitude as a proxy for wind estimates (Segales et al., 2020; González-Rocha et al., 2020; Shelekhov et al., 2021; Wetz et al., 2021; Wildmann and Wetz, 2022), or by mounting miniaturized sonic anemometers (Palomaki et al., 2017; Li et al., 2023) on the vehicle. Both methods show limitations for turbulence investigations due to the limited sampling frequency and, for most small sonic anemometers, the inability to measure the full 3D flow. First attempts of flying research-grade sonic anemometers (Hofsäß et al., 2019; Thielicke et al., 2021) have shown promising results concerning the measurement of the mean wind speed, but full turbulence measurement capabilities are still unproven.

One main reason is that the propeller-induced flow (PIF) by the UAV can affect and disturb the on-board flow measurements. Mounting an extension arm to place the wind sensor either to the front (Hofsäß et al., 2019), to the side, or above the drone (Thielicke et al., 2021) is one obvious possibility to minimize the PIF effect. Any mass placed outside the centre of gravity of the UAV will inevitably compromise flight stability and complicate flight control. Thus, it is necessary to thoroughly investigate and characterize the PIF for appropriate sensor placement considerations (Ghirardelli et al., 2023; Jin et al., 2024; Flem et al., 2024). The second option, which mitigates the potential PIF influence on the measurements without significantly impacting flight control and stability, is to deploy the flow sensor as a sling load under the drone.

Based on the latter concept, this study introduces SAMURAI-S as a novel measurement system for airborne atmospheric research using drones. To the authors' knowledge, this represents the first attempt to deploy a research-grade sonic anemometer as a suspended payload under a UAV, in contrast to the conventional approach of mounting such instruments rigidly to the UAV structure at relatively short distances (typically on the order of decimeters to a meter), as in the studies above.

Carrying the turbulence sampling payload 18 m under a rotary-wing UAV, the sensor is located outside any measurable PIF effect (Flem et al., 2024). The payload consists of a sonic anemometer, an inertial navigation system (INS), a data acquisition unit, and a mounting frame. This design aims to overcome the limitations mentioned above, thus providing state-of-the-art sonic anemometry data with the added benefits of mobility, hover capability, and adaptable positioning. This will enable detailed turbulence analysis in various settings, including observations close to structures and in urban environments where other methods fail.

This research aims to assess the accuracy and reliability of the developed measurement approach. The methodology involves a comparative analysis between traditional mast-mounted 3D sonic anemometers and the one suspended under the drone. Another key aspect of this study is to evaluate the applicability of a dynamic tilt and motion compensation algorithm to account for the inevitable motion of the payload caused by wind drag and the drone's movements. This algorithm utilizes in situ velocity and attitude data linked to the movement and orientation of the anemometer recorded by the INS. It aims to convert sonic anemometer turbulence measurements obtained from a moving platform into a natural wind or streamline coordinate system, as commonly used in ABL research.

The manuscript is organized as follows: Section 2 details the design of the UAV-payload system. Section 3 introduces the algorithm developed to account for the payload motion. This section also outlines the data post-processing techniques employed in the experimental comparison. Section 4 describes the experimental design for system validation, including the measurement site and the setup of the mast instrumentation. Section 5 compares the integral and spectral flow characteristics derived from the mast- and drone-mounted sonic anemometers. Finally, Section 6 summarizes the main findings of the study and concludes that SAMURAI-S provides a novel airborne instrument platform with a large potential for effectively measuring ambient turbulent flow with unprecedented flexibility.

2 The SAMURAI-S system

2.1 Airframe

Several important design criteria guided the selection of an appropriate airframe. Turbulence measurement with a drone-mounted sonic anemometer requires lifting a payload of roughly 4 kg. This weight estimate results from the required components, i.e., a research-grade sonic anemometer, an inertial navigation system (INS), a battery, a data logger, and a mounting frame. A flight time of at least 15 min to 20 min is required to collect turbulent flow time series that allow robust turbulence statistics for variances and covariances, as well as spectral analysis (Van der Hoven, 1957; Kaimal and Finnigan, 1994). Finally, to comply with European regulations for drone operations in the open category, we wanted to limit the UAV's maximum take-off weight (MTOW) to 25 kg, which also aids the logistical aspects of deploying the system in the field. At the same time, we considered flight safety, stability, and precision in positioning design priorities since they are crucial in different real-world scenarios, such as operations near infrastructures, human presence, or complex environments.
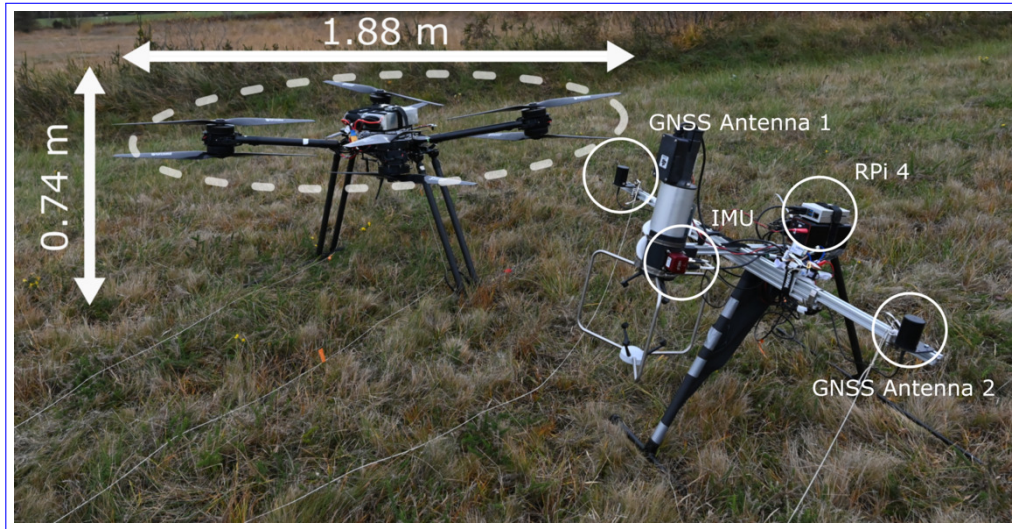
Figure 1. The SAMURAI-S UAS~~including~~, showing the Foxtech D130 octocopter (left) and the sampling payload (right). The D130 is an x8-configuration UAV measuring approximately 1.9m x 0.7m. The payload features a cross-shaped aluminium frame, with a longer arm (0.9 m) supporting two Here3 GNSS antennas and a shorter arm (0.6 m) holding an RM Young 81000 ultrasonic anemometer (mounted upside down) and a Raspberry Pi 4 powered by a dedicated power bank. An IMU is positioned on the side of the anemometer. Key components of the payload are highlighted in the figure.

To address these considerations, we opted for the Foxtech D 130 (Figure 1). This UAV has a nominal maximum payload of $20\,\mathrm{kg}$ and a maximum flight time in hovering mode of up to $45\,\mathrm{min}$ without payload, depending on the atmospheric conditions. It is equipped with eight coaxial contra-rotating propellers, where four pairs of propellers, each driven by brushless electric motors, share the same rotational axis and are mounted on arms extending from the main body (x8 configuration). The configuration of the propellers provides redundancy in case of a motor failure. The ~~UAV's frame~~ frame of the UAV weighs approximately $9\,\mathrm{kg}$. In its default configuration, it is powered by two 6S lithium polymer (LiPo) batteries, each with a capacity of $22\,\mathrm{A\,h}$, resulting in a take-off weight of roughly $15\,\mathrm{kg}$ excluding the sensor payload. The UAV ~~has an onboard autopilot unit (~~mounts a Cubepilot Cube Orange ~~) combined with 2 GNSS~~autopilot unit combined with two global navigation satellite system (GNSS) antennas (Here3). The inclusion of an open-source autopilot unit in the Foxtech D130's standard configuration, combined with its modular design that supports customization and easy rebuilding, ultimately led us to select this model over other alternatives available on the market.

The UAV's specifications are shown in Table 1.

2.2 Sensor placement

The placement of the sonic anemometer is critical for the quality of the turbulence observations, as it ~~is proven~~ has been shown that placing the sensor at a certain distance from the propellers effectively reduces the impact of the PIF (Prudden et al.,

Table 1. Specifications of Foxtech D130

Components	Characteristics
UAV diameter (m) × height (m)	1.88 × 0.74
UAV frame's weight (kg)	9
Propellers	Foxtech Supreme C/F 2880T
Propeller diameter (m) × pitch (m)	0.71 m × 0.20
Propeller's weight (g)	8 × 90
Battery	2 × 6S1P LiPo[*]
Battery's weight (kg)	2 × 2.4
Motors	T-Motor U10II[**]
~~ESC~~ Electronic speed controller (ESC)	T-Motor Flame 80A
Autopilot	Cubepilot Cube Orange[***]
GNNS	Here3 dual antenna
Flight Time (min)	40 to 45

[*] 22 A h; 22.2 V; 30 C

[**] 8.6 kg maximum thrust when paired to Foxtech Supreme C/F Propeller 2880T

[***] ArduCopter v4.3.6 in Aug and v4.4.3 in Dec

2016; Thielicke et al., 2021; Wilson et al., 2022). However, this approach requires ~~an estimation of~~ identifying the volume significantly affected by the PIF, which varies with the UAV's geometry (Guillermo et al., 2018; Lei and Cheng, 2020; Lei et al., 2020). Moreover, the angular momentum resulting from the additional weight mounted outside the UAV's centre of gravity could significantly compromise flight stability.

To limit the influence of the PIF on ~~the~~ velocity measurements, sensors mounted on a boom above the mean rotor plane of UAVs have been used in the past (Palomaki et al., 2017; Shimura et al., 2018; Natalie and Jacob, 2019; Thielicke et al., 2021; Wilson et al., 2022). This mounting configuration is designed to achieve an evenly balanced weight distribution around the drone by aligning the sensor's weight with the UAV's vertical axis and centre of mass. Nevertheless, this point is true primarily in low wind conditions. In scenarios with stronger winds, the drone must tilt further to counteract the increased drag, affecting the initial balance and tilt angle. Finding the right boom length that effectively reduces PIF while maintaining the drone's manoeuvrability and determining its best orientation remains a subject of ongoing research.

Previous studies (Ghirardelli et al., 2023; Jin et al., 2024), based on the Foxtech D130, suggest that the best trade-off between boom length and PIF reduction ~~,~~ while keeping the payload close to the UAV's fuselage ~~,~~ is achieved by positioning the boom upwind, with the sensor at the boom's end. This orientation avoids the areas significantly affected by the PIF as shown by Ghirardelli et al. (2023). However, to fully take advantage of this configuration, it is necessary to automatically align the sensor or UAV with the mean instantaneous wind direction, i.e. requiring an automatic flight control loop such as the "weathervaning"

algorithm recently implemented in ArduCopter v4.4.0 (see https://ardupilot.org/copter/docs/weathervaning.html) or through adjustments in forward flight. To the authors' knowledge, a reliable prototype of this design has yet to be developed.

125   In this study, we ~~adopt~~ present a novel approach, carrying the sonic payload platform as sling load $18\,\mathrm{m}$ under the drone, corresponding to about 26 rotor diameters (D). This setup places the payload in a stable equilibrium state instead of mounting it above the drone. When the payload is suspended beneath the drone, it creates a pendulum, swinging around the point of minimal potential energy. This natural stability allows the payload to stabilize itself through its oscillations, reducing the need for the drone to actively counteract these movements~~actively~~. The PIF features depend more on thrust rather than UAV's

130   geometry in the far field of the drone, i.e., in a distance of more than 5 D from the rotor plane, when the individual rotor downwash regions have merged to one, (Ghirardelli et al., 2023; Flem et al., 2024). This should extend the applicability of the payload set-up to a wider range of multi-copter platforms.

   Simulations and observations were used to estimate the required vertical displacement of the wind sensor below the UAV. As detailed in Ghirardelli et al. (2023), simulations within a domain extending $9.0\,\mathrm{m}$ below the drone ~~,~~ revealed that the ambient

135   wind effectively carries away the downdrafts. Notably, airflow closely resembled free-flow conditions at this domain's lower boundary, directly under the drone and ~~in conditions~~ where wind speeds surpassed $2.5\,\mathrm{m\,s^{-1}}$. This observation was further supported by Jin et al. (2024), which utilizes a configuration of three CW Doppler LIDARs to measure the PIF generated by Foxtech D130 in hover. ~~Measurements indicated~~ The measurements indicated a negligible PIF distortion at a distance of $4.5\,\mathrm{m}$ below the Foxtech D130, in an ambient flow of $4.0\,\mathrm{m\,s^{-1}}$. Finally, Flem et al. (2024) showed how, for the same drone model

140   and in the absence of a background flow, the downdraft drops by more than $40\,\%$ in the range between $1.5\,\mathrm{m}$ to $6\,\mathrm{m}$ under the plane of the rotors. An additional empirical confirmation can be derived from visual observations of a multi-rotor drone over the surface of a lake in low wind conditions (Flem et al., 2024), showing that the PIF of the drone does not reach the surface with the UAV hovering at a height of 15 D above the water. To add a margin of safety, we opted to double the distance identified in the CFD simulations.

145   ## 2.3   Payload Description

The payload consists of an RM Young 81000 sonic anemometer, an SBG Elipse-D inertial navigation system (INS) equipped with two GNSS antennas, and a Raspberry Pi 4 (RPi 4) microprocessor serving as a data logger (Figure 1 and Figure 2). The SBG Elipse-D is a compact INS featuring a dual-antenna GNSS receiver. It includes a MEMS-based ~~Inertial Measurement Unit~~ inertial measurement unit (IMU) and uses an ~~Extended Kalman Filter~~ extended Kalman filter (EKF) to fuse inertial and

150   GNSS data. Table 2 and Table 3 provide key specifications of the sonic anemometer and the INS, respectively.

   For the integration of the different sensors, the battery, and the data logger, we constructed a horizontal T-shaped aluminium frame with a $0.55\,\mathrm{m}$ long main bar and a $1.00\,\mathrm{m}$ long crossbar. In addition, we added a T-shaped support leg to better protect the sensors during landing, transport, and storage and a triangular wind vane to aid the sensor alignment with the mean wind direction and dampen lateral and rotational oscillations around the yaw axis.

155   The sonic anemometer was mounted upside down in the front of this frame, with the INS attached via a custom-fitted mounting plate to the side of its cylindrical support structure, assuring parallel alignment of both sensor coordinate systems.
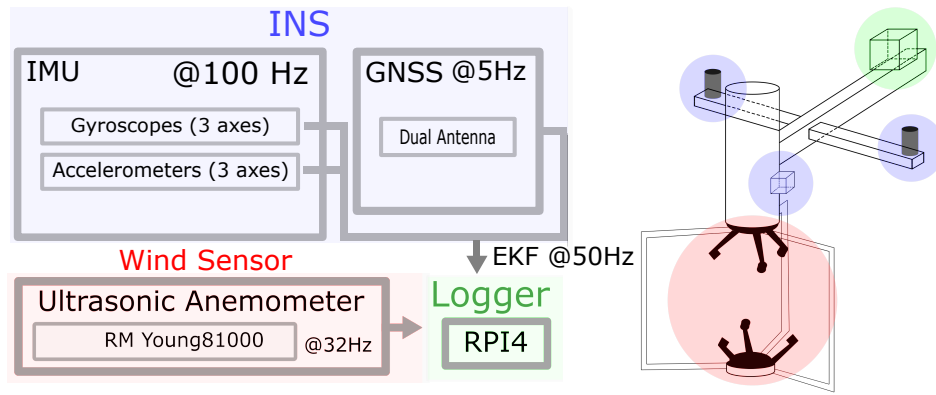
Figure 2. Diagram and blueprint of the measurement and acquisition system showing ~~the~~ how data flow from the sensors ~~to~~ into the logger. On the left, two main sensor outputs –INS (highlighted in blue) and the ultrasonic anemometer (highlighted in red)– are depicted as being stored and logged by the RPi 4 (highlighted in green). The diagram also indicates the sampling rates, namely 32 Hz for the ultrasonic anemometer and a 50 Hz extended Kalman filter (EKF) output from the INS, which fuses data from a 100 Hz IMU signal and 5 Hz GPS data. On the right, a schematic of the payload shows the physical placement of each component, colour-coded to match the diagram on the left.

Table 2. Specifications of RM Young 81000 sonic anemometer.

Specifications	RM Young 81000
Wind Speed Range ($\mathrm{m\,s^{-1}}$)	0 to 40
Wind Speed Resolution ($\mathrm{m\,s^{-1}}$)	0.01
Wind Speed Accuracy ($\mathrm{m\,s^{-1}}$, % RMSE)	±0.05 , ±1,
Wind Dir. Elevation Range (°)	±60.0
Wind Dir. Resolution (°)	0.1
Wind Dir. Accuracy[*](°)	±2
Sonic Temp. Range (°C)	-50 to 50
Sonic Temp. Resolution (K)	0.01
Sonic Temp. Accuracy[*](K)	±2
Air Sample Path (m)	0.15
Output Rate (Hz)	4 to 32
Weight (kg)	1.7

[*] $0\,\mathrm{m\,s^{-1}}$ to $30\,\mathrm{m\,s^{-1}}$ range

The crossbar of the frame served as an attachment point for two nylon ropes used to link the payload to the sides of the UAV and a $0.94\,\mathrm{m}$ long baseline for the two GNSS antennas mounted on the tips of the bar. The data logger and a battery were positioned at the tail of the frame.

Table 3. Specifications of the SBG Ellipse-D inertia navigation system with RTK aiding for airborne applications

Specifications	Ellipse-D*
Horizontal position accuracy	$0.01\,\mathrm{m}$
Vertical position accuracy	$0.02\,\mathrm{m}$
Horizontal velocity accuracy	$0.03\,\mathrm{m\,s}^{-1}$
Vertical velocity accuracy	$0.03\,\mathrm{m\,s}^{-1}$
Pitch and Roll accuracy	$0.05°$
Heading accuracy	$0.4°$
Weight INS (including GNSS antennas)	$0.3\,\mathrm{kg}$

* data were logged using the sbgBasicLogger program (sbgECom library v3.2.4011, https://github.com/SBG-Systems/sbgECom)

160   The attachment points for the ropes ~~are~~ were aligned with the pitch axis of both the UAV and the sling load (SL) frame. The entire payload system was balanced for the sonic anemometer's pitch by shifting the position of the crossbar~~as well as the battery~~~~and~~ , the battery, and the data logger. ~~The~~ According to this payload design and placement, the roll motion is directly transferred to the sonic anemometer from the drone~~in contrast to~~ , whereas the yaw motion ~~, while~~ results from a combination of the drone's dynamics and aerodynamic drag, and the pitch depends ~~solely on the balance of the payload~~ mainly on the

165 payload balance. Although the drone-payload setup behaves like a compound pendulum due to the two suspension ropes attached to the same weight (the payload), it has been treated as a simple pendulum for simplicity. The natural oscillation period (T) is estimated using the formula $T = 2\pi\sqrt{\frac{l}{g}}$, where l is the length of the ropes, and $g = 9.81\,\mathrm{m\,s}^{-2}$ is the gravitational acceleration. This calculation yields an oscillation period of approximately $8.5\,\mathrm{s}$, corresponding to a frequency of $0.12\,\mathrm{Hz}$. Preliminary analysis of the sonic data, conducted before performing the motion compensation, consistently ~~reveals~~ revealed a

170 distinct peak at this frequency across all flights.

2.4   Flight Operation

The operation of the SAMURAI-S UAS requires a team of three: a radio control (RC) pilot, a ground control station (GCS) operator, and a payload operator. Before each flight, the UAV and the payload are positioned approximately $10\,\mathrm{m}$ apart. The UAV batteries are securely connected, and a telemetry and an RC link are established. The two ropes are attached to two

175 release servos on the UAV, ensuring that they are free of entanglement with the landing gear or ground obstacles. The payload is powered on and held steady to allow proper IMU initialization and gyro calibration. Finally, the operator connects to the RPi 4 hotspot to verify data streams from the sonic anemometer and the INS, checking for stable GNSS signal and EKF solutions.

During take-off, the payload operator holds the payload steady while the RC pilot executes a vertical ascent to an altitude of approximately 10 m, ensuring that the ropes lift freely without entanglement. Once the ropes are taut, the payload operator releases the payload, and the RC pilot increases the ascent speed. From this point onward, the flight typically continues in auto-mode, following a predefined flight plan, including an algorithm to actively adjust the UAV's heading to face the wind (weathervaning).

Throughout the flight, the GCS operator monitors the system's performance and payload data as long as the WiFi connection to the RPi 4 is maintained. After completing the programmed flight plan, the RC pilot can manually or automatically trigger a return-to-launch (RTL) command. In addition, other fail-safe mechanisms, including low battery, are set to trigger an automatic RTL command based on preset conditions.

During landing, the RC pilot takes control as the UAV approaches the landing area, while the payload operator prepares to catch the payload. During the initial fast descent phase, the UAS is flown diagonally to avoid potential stability issues, such as the vortex ring state (Chenglong et al., 2015; Talaeizadeh et al., 2020). The UAV then descends slowly, with the pilot counteracting any swaying of the payload to ensure a smooth catch. Once the payload is secured, the GCS operator releases the ropes via the servos. The RC pilot then increases the distance between the UAV and the payload before initiating the final landing phase. When the UAV is landed, the payload is placed on the ground, and the data acquisition is stopped. After each flight, the data from the payload and flight controller are downloaded and quickly checked, the UAV and payload are powered off, and the batteries are recharged for future flights.

The system consistently performs excellently, showing no stability issues during the flight, take-off, or landing phases, even under strong wind conditions of up to $15\,\mathrm{m\,s^{-1}}$.

3 Payload data processing workflow

This section outlines the methodological approach to convert the raw flow data sampled by the payload into the natural wind vector expressed in the standard meteorological coordinate system. One primary challenge is ~~the handling of~~ handling asynchronous raw sensor ~~outputs~~ output expressed in different coordinate frames. In addition, it is necessary to compensate ~~the measurements~~ for the motion of the payload. The workflow herein presented addresses both points through a three-stage process~~: first~~. First, the sonic and INS outputs ~~are~~ were filtered to remove faulty data and outliers~~, enhancing their quality and reliability~~. Next, ~~INS and sonic output are~~ these outputs were synchronized, creating a unified temporal framework. Finally, dynamic rotational and translatory transformations ~~are~~ were applied to account for changes in the orientation of the payload and its movements, which primarily come from swinging motions during hovering. For clarity, we first introduce the reference systems~~that~~, which describe the coordinates in which the data are collected and the rotations performed.

3.1 Wind vector, coordinate frames and transformation

We here define two right-handed coordinate systems to describe the motion of the payload: the inertial frame and the body frame, denoted by the indices $\mathbf{i}_n$ and $\mathbf{b}_n$ ($n = 1, 2, 3$), respectively. The inertial (or NED) frame is Earth-fixed, and its axes
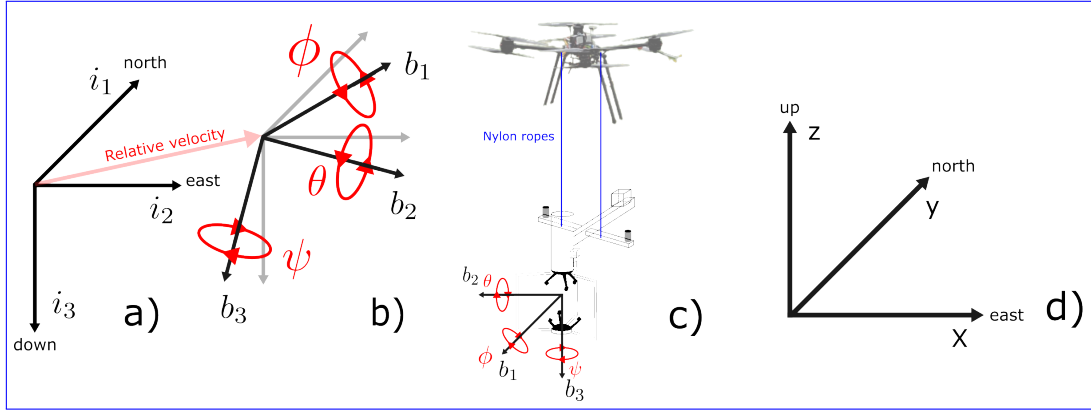
Figure 3. Panel (a) illustrates the inertial frame (NED), where the axes i_1, i_2, and i_3 point northward, eastward, and downward, respectively. Panel (b) depicts the body frame centred at the sonic anemometer's sampling volume, with axes b_1, b_2, and b_3 pointing forward, to the right, and downward. This panel also includes the Euler angles ϕ, θ, and ψ depicting the orientation of the body frame relative to the inertial frame, along with the relative velocity vector $\mathbf{V}_i^b$. Panel (c) illustrates how the payload is attached to the drone by two nylon ropes so that the drone's motion influences the payload's body frame. This configuration causes the payload to inherit the drone's yaw (ψ) and roll (θ) motions while allowing it to pitch freely. Finally, panel (d) shows the meteorological frame ~~used to represent~~ that represents the wind vector $\mathbf{U}$, with ~~axes oriented~~ eastward, northward, and upward axes.

210   (i_1, i_2, i_3) are oriented northward, eastward, and downward, respectively (Figure 3a). The body frame is centred at the sonic anemometer's sampling volume and moves along with the payload. Its axes are defined based on the geometry of the payload, with b_1 pointing forward, b_2 to the right side, and b_3 downward (e.g., Palomaki et al. 2017). Its orientation (attitude) and movements relative to the inertial frame can be described by the Euler angles and the velocity vector measured by the INS, respectively (Figure 3b).

215   To transform the raw flow measurements from body frame coordinates ($\mathbf{V_b}$) to inertial frame coordinates ($\mathbf{V_i}$), a rotation matrix $R(\phi, \theta, \psi)$ is applied (Beard and McLain, 2012; Wetz et al., 2021). This matrix, defined by the roll, pitch, and yaw angles (ϕ, θ, and ψ), adjusts the raw wind vector to reflect the orientation of the payload relative to the inertial frame ~~,~~ and is fully detailed in Appendix A. By subtracting the relative velocity vector $\mathbf{V}_i^b$, accounting for the movement of the body frame relative to the inertial frame, it is ~~in addition~~ possible to eliminate any component of the velocity due to the motion

220 of the payload, isolating the natural wind vector in the inertial frame. The equation that accounts for both of these dynamic corrections is expressed as:

$$\mathbf{V_i} = R(\phi, \theta, \psi)\mathbf{V_b} - \mathbf{V}_i^b. \tag{1}$$

A final orthogonal rotation by right angles is ~~performed~~ needed to retrieve the wind vector (**U**) in the standard meteorological coordinate frame, the natural wind coordinate system, with x, y, and z pointing east, north, and up, respectively (Figure 3c).

$$\mathbf{U} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \mathbf{V}_i \tag{2}$$

3.2 Data filtering

The sonic anemometer, providing the three wind velocity components and the sonic temperature, was set to a sampling frequency of $32\,\mathrm{Hz}$. Each data instance ~~is~~ was timestamped according to the ~~Raspberry Pi~~ RPi 4 internal clock. Since the ~~Raspberry Pi~~ RPi 4 does not have a GNSS signal, the internal clock does not necessarily correspond to the exact UTC. Therefore, these time stamps ~~are~~ were converted to µs from the start of the logging interval, using the first recorded timestamp as an offset. ~~In addition, the time series were adjusted to account for the upside-down mounting orientation of the sonic anemometer, ensuring that the measured vectors were appropriately rotated in the body frame coordinates before processing.~~

The raw INS output consists of $100\,\mathrm{Hz}$ IMU data and $5\,\mathrm{Hz}$ GNSS data. The IMU provides angular rates (gyroscope data) and accelerations (accelerometer data), while the GNSS supplies the local velocity, latitude, longitude, altitude, and roll and yaw angles. Furthermore, the INS outputs ~~Kalman-filtered (EKF)~~ EKF data at $50\,\mathrm{Hz}$, fusing inputs from both GNSS and IMU. It consists of 3D velocity data and Euler angles, both given in the NED inertial frame, as well as latitude, longitude and altitude data. Given the prototype nature of the developed system, the data processing was exclusively based on the EKF output (Table 3).

Moreover, the SBG Ellipse-D INS allows ~~to output~~ the output of position, velocity and attitude data at a geometrically specified location relative to the sensor. For convenience, we thus configured the INS to output data in the body frame centred on the sonic anemometer measurement volume. Each data point from the INS ~~is~~ was timestamped with the INS internal time in ns from the start of the data log and in UTC post-GNSS signal acquisition. Figure 2 shows a schematic representation of the payload system.

Before any steps in the filtering workflow, the raw time series were adjusted to account for the sonic anemometer's upside-down mounting orientation. This ensured the measured vectors were appropriately rotated in the body frame coordinates.

As an initial filter, we removed all data collected before establishing a valid and stable GNSS time. Following this, data points exceeding the measurement range of the instruments were discarded from further analysis. The filtering thresholds were determined based on the sensor specifications provided by the manufacturers. Additionally, following a despiking method adopted from Mauder et al. (2013), outliers were removed using a moving absolute deviation (MAD) filter relying on a sliding window of $10\,\mathrm{s}$ and a distance of ± 7 MAD from the median. ~~Missing or flagged data accounted for less than $2\,\%$ of all the collected data for each individual flight~~ The combined amount of missing and flagged points, following this procedure, did not exceed $2\,\%$ in any flight data set. Thus, they were filled using linear interpolation. The third and final step of the filtering process consisted of identifying the time windows corresponding to the hovering state of the drone. This involved a two-step filtering approach. Initially, a filter was applied based on the median altitude $\pm\,3\,\mathrm{m}$, followed by a $\pm\,4\,\mathrm{m}$ median filter on
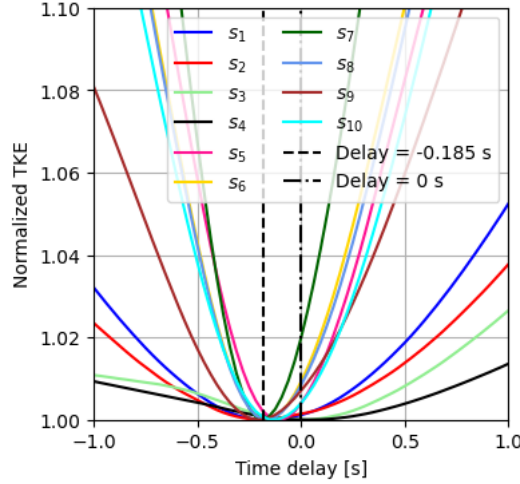
Figure 4. Normalized ~~Turbulent Kinetic Energy~~ turbulent kinetic energy (TKE) curves across validation flights (named s_1 to s_{10}) plotted as a function of time delay (in seconds) of the sonic anemometer output relative to the INS output. Each TKE profile is normalized by its minimum value to facilitate direct comparisons. Vertical lines at $-0.185\,\mathrm{s}$ (dashed line) and $0\,\mathrm{s}$ (dash-dot line) indicate the time window where all minimum values are located. The axes limits are set to -1 to 1 for the x-axis and 1 to 1.1 on the y-axis to highlight subtle differences among the profiles.

255 horizontal movements to address horizontal swinging. Finally, the EKF output ~~is then~~ was downsampled to $32\,\mathrm{Hz}$ to match the sampling frequency of the sonic anemometer via linear interpolation.

3.3 Data synchronization and coordinates transformation

Ensuring accurate synchronization between the INS and the sonic anemometer outputs is crucial for correctly applying Equation (1), designed to compensate for payload motion during flight. To address potential synchronization discrepancies, we
260 implemented an iterative process that involves progressively changing the time lag of the sonic anemometer relative to the INS within a range of $\pm\,2\,\mathrm{s}$, with each step corresponding to $1/32\,\mathrm{s}$. At each adjustment step, Equation (1) ~~is~~ was applied to the sonic data, and we ~~calculate~~ calculated the mean turbulent kinetic energy (TKE) from the resulting time series~~.~~, defined as

$$TKE = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right). \tag{3}$$

Notably, the TKE as a function of the time lag consistently shows a reverse bell shape with the minimum located between
265 $-0.185\,\mathrm{s}$ to $0\,\mathrm{s}$, as shown in Figure 4. Apart from the location of the time lag, this figure also indicates that potential errors associated with an imperfect time-lag correction, e.g. by a few time increments, would result in small relative errors in the computed TKE.

The time series adjusted using the time lag that minimizes the TKE were selected for further analysis. This selection was based on the assumption that the payload movement is most effectively compensated at this optimal lag. Finally, these time series were transformed into natural wind coordinates using Equation (2).

4 Data and methods for the validation experiment

The validation study was conducted at the Plateforme Pyrénéenne d'Observations Atmosphériques (P2OA) in Lannemezan, southwestern France, during two special observation periods in August and December 2023, as part of the Model and Observation for Surface Atmosphere Interactions (MOSAI) campaign. During these periods, the SAMURAI-S, reusable radiosondes, multiple eddy-covariance stations, meteorological masts, and various remotely piloted aircraft systems were used to study the effects of surface heterogeneities on the local wind conditions. Additionally, a tethered balloon equipped with a sonic anemometer (Canut et al., 2016) provided a complementary method for assessing atmospheric turbulence. While this constitutes an important experimental dataset, the current work focuses solely on validating the SAMURAI-S system. Detailed analysis of the scientific data from the experimental campaign is reserved for future publications.

The P2OA observatory is located in a rural and heterogeneous area, characterized primarily by agricultural fields and forests, with a typical length scale of $500\,\mathrm{m}$ (e.g., BLLAST Lothon et al., 2014). The site has a 60-meter meteorological tower with a triangular lattice structure (Figure 5). The terrain around the tower is predominantly flat and is characterized by a heterogeneous mix of grazing land, grasslands, crop fields, and forest. Within $1\,\mathrm{km}$ of the 60-meter tower, grasslands are more prevalent. The tower is equipped with slow-response sensors for temperature, humidity, wind speed, and direction at five levels ($2\,\mathrm{m}$, $15\,\mathrm{m}$, $30\,\mathrm{m}$, $45\,\mathrm{m}$ and $60\,\mathrm{m}$) and eddy-covariance systems at three levels ($30\,\mathrm{m}$, $45\,\mathrm{m}$ and $60\,\mathrm{m}$), of which only the lower- and uppermost system were operational during our validation period. Two Campbell Scientific CSAT3 sonic anemometers are mounted on horizontal booms on the tower at heights of $30\,\mathrm{m}$ and $60\,\mathrm{m}$ meters above the ground ($633\,\mathrm{m}$ and $663\,\mathrm{m}$ above mean sea level), with an azimuth of 218.0° and 230.5°, respectively. These anemometers operated with a sampling frequency of $10\,\mathrm{Hz}$, recording the three velocity components and the sonic temperature. The validation study described herein comprises several hovering flights of SAMURAI-S at target altitudes of $30\,\mathrm{m}$ and $60\,\mathrm{m}$ near the mast.

4.1 Tower validation study: theoretical framework

For this validation study, we express the wind vector $\mathbf{U}$ in a coordinate system that is aligned with the mean flow streamlines (Kaimal and Finnigan, 1994). In this coordinate system, the three velocity components (u, v, and w) correspond to the along-wind, cross-wind, and vertical (upward) directions, respectively. We apply Reynold decomposition, splitting each component $i = u, v, w$ into a mean, $\bar{i}$, and a fluctuating part, i'. The fluctuating component with a zero mean is treated as a stationary, homogeneous, ergodic, and Gaussian random process. The standard deviations of the u, v, and w components
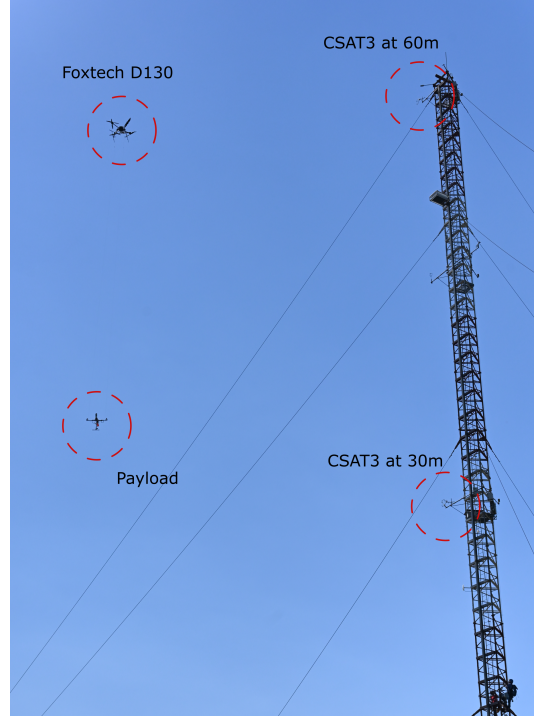
Figure 5. SAMURAI-S hovering side-by-side with the reference mast. The two CSAT sonic anemometers are mounted at $30\,\mathrm{m}$ and $60\,\mathrm{m}$ agl, oriented towards $218.0°$ and $230.5°$, respectively.

are represented by σ_u, σ_v, and σ_w. Additionally, the skewness and kurtosis of these components, which quantify the deviation from the assumption of Gaussian fluctuations, are denoted by γ_i and κ_i.

This study utilizes the blunt and pointed spectral models (Olesen et al., 1984; Tieleman, 1995) to examine whether the velocity spectra conform to the $-5/3$ power law in the inertial subrange. The models are ~~expressed dimensionless as follows:~~ a good approximation of the turbulence spectra in the atmospheric surface layer. In this study, they are expressed in their dimensionless form as

$$\frac{f S_u(f)}{u_*^2} = \frac{a_u f_r}{(1 + b_u f_r)^{5/3}} \tag{4}$$

$$\frac{f S_v(f)}{u_*^2} = \frac{a_v f_r}{(1 + b_v f_r)^{5/3}} \tag{5}$$

$$\frac{f S_w(f)}{u_*^2} = \frac{a_w f_r}{1 + b_w f_r^{5/3}} \tag{6}$$

$$\frac{f\,\mathrm{Re}\,(S_w(f))}{u_*^2}\frac{f\,\mathrm{Re}\,(S_{uw}(f))}{u_*^2} = \frac{a_{uw} f_r}{(1 + b_{uw} f_r)^{7/3}} \tag{7}$$

310 ~~where $f_r = \frac{fz}{\overline{u}}$ represents the reduced frequency, while~~ where a_i and b_i, with $i = \{u, v, w, uw\}$, are coefficients empirically determined ~~,~~ and f_r is a reduced frequency defined as

$$f_r = \frac{fz}{\overline{u}}. \tag{8}$$

The Obukhov length ~~(Foken, 2006)~~ (Monin and Obukhov, 1954) can be calculated as

$$L = -\frac{u_*^3 \overline{\theta}_v}{g\kappa(\overline{w'\theta_v'})} \tag{9}$$

315 where $\overline{\theta}_v$ is the mean virtual potential temperature approximated by the sonic temperature, $\kappa = 0.40$ is the von Kármán constant, and $\overline{w'\theta_v'}$ is the ~~vertical kinematic fluxof virtual potential temperature~~buoyancy flux. The nondimensional stability parameter ζ is defined as $\zeta = z/L$, where z is the height above the surface.

Following Kolmogorov's hypothesis of local isotropy in the inertial subrange, the spectral ratios S_w/S_u and S_v/S_u should converge toward $4/3$ as the frequency increases (Busch and Panofsky, 1968; Kaimal et al., 1972). To compare the effectiveness

320 of the mast-mounted and drone-mounted sonic anemometers in resolving turbulence with minimal flow distortion, we apply a quadrant analysis based on the comparison of the ratio S_w/S_u between the two sensor configurations (Figure 6). In the ideal scenario, data points in this figure would cluster around the centre of the plot, as the $4/3$ ratio is reached by both the drone and mast-based data. Deviations from this ratio could indicate flow distortion caused by the supporting structure, the sensor head, or both (Cheynet et al., 2019; Peña et al., 2019). A spectral ratio approaching but not reaching $4/3$ may suggest that isotropy in

325 the inertial subrange is not achieved within the investigated frequency range (Chamecki and Dias, 2004). A spectral ratio that plateaus without reaching the $4/3$ law may reflect flow distortion, typically manifesting as an underestimation of the vertical velocity component. It should be noted that Kolmogorov's hypothesis of local isotropy in the inertial subrange may not apply under non-stationary conditions, e.g., in very stable atmospheric conditions with intermittent turbulence. Thus, the quadrant analysis was conducted only for samples with a mean wind speed above $2\,\mathrm{m\,s^{-1}}$, which was sufficient in this study to eliminate

330 samples that did not exhibit characteristics consistent with the framework adopted here to describe turbulence.

In this study, the spectral ratios are studied using a limited frequency range of interest, which is computed using the reduced frequency ~~$f_r = fz/\overline{u}$~~f_r (Eq. (8)), and $f_r > 2$ following Kaimal et al. (1972). An upper boundary $f_r < 10$ is also applied to ensure a fairer comparison between the drone and mast data.

4.2 ~~Data processingThe processed data from the payload and those from mast-mounted anemometersare initially~~

335 ~~synchronized using the cross-correlation function between the horizontal~~ Satistical uncertainties

The uncertainties associated with turbulent flux measurements are analysed using the methodology described by Wyngaard (1973); Forrer a[...]. This approach quantifies the random error arising from a fixed averaging period (τ) and the mean wind speed ($\overline{u}$). Within this framework, the uncertainties in the momentum fluxes (a_{uw}, a_{vw}), the buoyancy flux ($a_{w\theta_v}$), and those associated with any
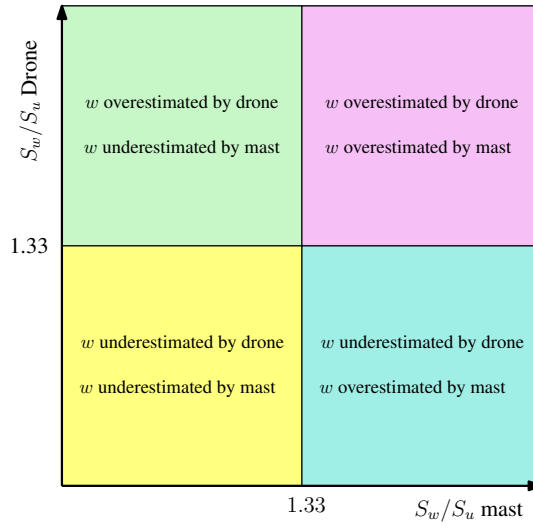
Figure 6. Quadrant analysis of the spectral ratios S_w/S_u to identify which sensor configuration may overestimate or underestimate the vertical velocity component. For brevity, "drone" refers to the drone-mounted sonic anemometer in this figure, and "mast" refers to the mast-mounted sonic anemometer.

turbulent variable ξ are expressed as the following non-dimensional quantities:

$$a_{uw}^2 = \frac{z}{\tau \overline{u}} \left(\frac{\overline{(u'w')^2}}{u_*^4} - 1 \right), \tag{10}$$

$$a_{vw}^2 = \frac{z}{\tau \overline{u}} \left(\frac{\overline{(v'w')^2}}{u_*^4} - 1 \right), \tag{11}$$

$$a_{\theta_v w}^2 = \frac{z}{\tau \overline{u}} \left(\frac{\overline{(w'\theta_v')^2}}{(\overline{w'\theta_v'})^2} - 1 \right), \tag{12}$$

$$a_{\xi^2}^2 = \frac{4z}{\tau \overline{u}} \left(\frac{\overline{\xi'^4}}{(\overline{\xi'^2})^2} - 1 \right). \tag{13}$$

These uncertainties reflect the assumption of ergodicity, which states that the time average converges towards the ensemble average given a sufficiently long averaging period. This assumption is at the core of the turbulence analysis with ultrasonic anemometers. Consequently, these uncertainties are inversely proportional to both the averaging time and the wind speed. Equations (10) to (12) are typically associated with greater uncertainties than Eq. (13), as the estimation of covariance requires a longer averaging period than variance estimates (Kaimal and Finnigan, 1994). The relative magnitude of uncertainties also depends on terrain roughness and stability conditions. Following the recommendations of Stiperski and Rotach (2016); Cheynet et al. (2019), uncertainties below 0.5 indicate high-quality measurements.

4.3 Integral length scales

The integral length scales of turbulence are one-point statistics that quantify the spatial structure of turbulent eddies. These length scales are used both in micrometeorolgy and wind engineering for structural design. One integral length scale can be defined per velocity component. In this study, the integral length scales were estimated in two steps. First, the integral time scale was determined by fitting an exponential function to the autocovariance function of the velocity fluctuations. ~~This aligns the time series of horizontal velocity, correcting any time lags up to 6 s through linear interpolation~~ The autocovariance function for a given velocity component, ξ, is defined as:

$$R_{\xi\xi}(\tau) = \overline{\xi'(t)\xi'(t+\tau)}, \tag{14}$$

where $R_{\xi\xi}(\tau)$ is the autocovariance function at lag τ. The integral time scale, T_ξ, was then obtained by a least-square fit of an exponential function to Eq. (14)

$$R_{\xi\xi}(\tau) \approx R_{\xi\xi}(0) \exp\left(\frac{-\tau}{T_\xi}\right). \tag{15}$$

In the second step, Taylor's frozen turbulence hypothesis was applied to convert the integral time scale into the integral length scale. Taylor's hypothesis is generally valid for moderate and low turbulence intensities. Hereinafter, we define turbulence as "frozen" when the following conditions are satisfied:

$$I_u = \frac{\sigma_u}{\overline{u}} < 0.5 \quad \text{and} \quad \overline{u} > 1 \text{ m s}^{-1}. \tag{16}$$

Under these conditions, the integral length scale, L_ξ, is given by:

$$L_\xi = \overline{u}T_\xi, \tag{17}$$

4.4 Data processing

Data from the payload and the mast-mounted anemometers are collected at different locations. Therefore, the same turbulent structures may be detected at slightly different times due to flow advection. To address this, the two datasets are initially synchronized by an automated procedure that iteratively identifies and applies the optimal time shift (up to a maximum of 6 s) that maximizes the cross-correlation of the horizontal velocity fluctuations. The procedure then uses linear interpolation to align the time series and ensure both datasets capture the same turbulent features. Subsequently, the data are decimated by a factor of 4, and an anti-aliasing finite impulse response (FIR) filter of order 4 is applied. This leads to a sampling frequency of 8 Hz, which was adequate for properly comparing the two datasets.

Misalignments ~~could occur when mounting the sonic anemometer~~ due to small errors in estimating the orientation of the sonic anemometers mounted on the tower or the relative positioning between the INS and the sonic anemometer on the payload can occur. To detect such discrepancies, the datasets from both the payload and the mast (set as the reference) are compared after retrieving the velocity components—namely u, v, and w—using single, double, or triple rotation methods

Table 4. Summary of the ten samples assessed in this study.

Sample ID	Starting Time (UTC)	Duration (min)	Mean wind Direction (°)*	Payload height (m)**	Wind Speed (m s^{-1})*	Stability parameter ζ (–)*
s_1	21-Aug-2023 14:05:32	28.0	97	28	3.1	-0.46
s_2	07-Dec-2023 12:33:52	18.7	277	27	0.8	0.38
s_3	07-Dec-2023 13:15:26	17.6	265	50	0.4	0.32
s_4	07-Dec-2023 15:08:09	17.8	277	57	0.6	1.25
s_5	08-Dec-2023 15:09:53	10.6	282	56	7.4	0.07
s_6	13-Dec-2023 07:27:17	18.3	300	48	8.2	0.2
s_7	13-Dec-2023 07:53:37	15.3	304	49	10.4	0.1
s_8	13-Dec-2023 08:37:11	15.3	310	23	7.1	0.20
s_9	13-Dec-2023 09:54:21	16.5	298	26	6.5	0.01
s_{10}	13-Dec-2023 10:19:58	20.2	296	49	7.1	0.05

[*] Value estimated by the mast-mounted sonic anemometer closest to the payload height during the hovering window

[**] Average height of the drone during the hovering window.

(McMillen, 1988). While the single rotation aligns u with the mean wind direction, the double-rotation method involves an additional pitch rotation, ensuring $\overline{w} = 0$. In contrast, the triple rotation includes a third rotation around the roll axis to ensure the crosswind component of the kinematic momentum flux $(\overline{v'w'})$ becomes zero. A preliminary comparison involving these three rotations showed limited differences, demonstrating the suitability of the measurement setup. ~~Therefore~~For simplicity, the double-rotation method was chosen for both the mast-mounted and the drone-mounted anemometers for further analysis.

Integral and spectral turbulence characteristics are studied using linearly detrended data. Auto ~~(PSD~~power spectral densities (PSDs) and cross-power spectral densities (~~CPSD~~CPSDs) of the velocity and temperature fluctuations are estimated using Welch's method (Welch, 1967). ~~This involves segmenting~~ We divided the data into three ~~parts~~ segments with 50% overlap. An additional step includes smoothing the PSDs by bin-averaging them over 100 logarithmically-spaced bins (Kaimal and Finnigan, 1994).

5 Results and discussion

In this study, we examine a data set comprising ten samples, labelled s_1 to s_{10} in Table 4, to assess turbulence measurements obtained via the drone-mounted sonic anemometer.

These samples were chosen from 17 initial flights, with the selection criteria based on at least $10\,\text{min}$ of continuous, high-quality EKF output corresponding to hovering flight. Notably, s_2, s_3, and s_4 have mean flows of less than $2\,\text{m s}^{-1}$. The assumptions of turbulence being stationary, homogeneous, ergodic, and modelled as a Gaussian random process might not hold for these flights~~. For this reason, they are not subjects of~~, making them unsuitable for the quadrant analysis ~~, the framework~~
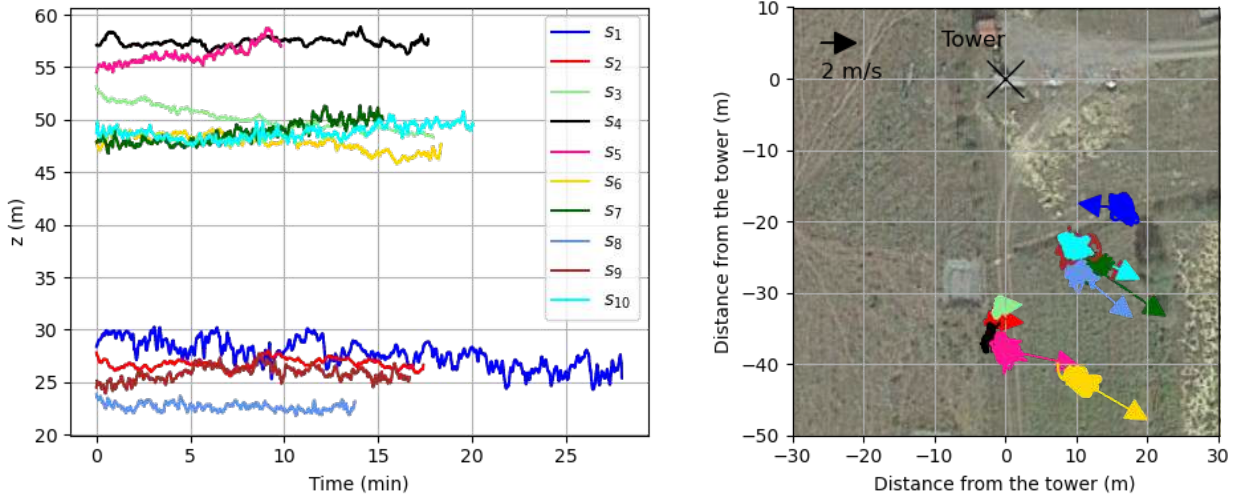
Figure 7. Drone altitude (left panel) and horizontal position relative to the tower (right panel) during the measurement periods of the ten validation flights. The sonic anemometers on the mast are mounted at heights of $30\,\mathrm{m}$ and $60\,\mathrm{m}$, oriented at $218°$ and $230.5°$, respectively. Wind directions for each flight are shown as coloured arrows, originating from the average horizontal positions. The arrow lengths correspond to a reference vector of $2\,\mathrm{m\,s^{-1}}$. Imagery ©2024 Maxar Technologies, Map data ©2024 Google

~~of which is presented~~ framework proposed in Section 4.1. Nevertheless, they ~~are~~ were included in the ~~rest of the analysis for completeness.~~ analysis for the sake of completeness.

Figure 7 shows the associated altitude of the payload above the ground (left panel) and the hovering distance from the tower
400 during the measurement periods (right panel).

Although all flights were analyzed, for brevity, Section 5.1 features a detailed comparison of the exemplary cases from sample s_1 and s_7 as they exhibit markedly different characteristics. Sample s_1 targeted a height of $30\,\mathrm{m}$ and features convective conditions ($\zeta = -0.46$) with rather weak wind of $3.1\,\mathrm{m\,s^{-1}}$. Conversely, sample s_7, which targeted $60\,\mathrm{m}$, is characterized by stable stratification conditions ($\zeta = 0.1$) and the highest wind speed in the series ($10.4\,\mathrm{m\,s^{-1}}$). It will be shown that while
405 s_1 exhibits an excellent correlation between the drone-mounted anemometer and its mast-mounted counterpart, s_7 presents some discrepancies in the vertical component when comparing the two anemometers. Following these detailed examinations, we systematically compare all samples ~~based on their integral flow characteristics~~ in Section 5.2. Finally, we conclude the comparison by presenting flux uncertainties between the drone and mast-based datasets in Section 5.3

5.1 Cases of samples s_1 and s_7

410 This section focuses first on the second-order structure of turbulence (i.e., variances and covariances) of s_1 and s_7, ~~though the~~ as these samples show strongly contrasting characteristics, as pointed out in the previous section. The third and fourth statistical moments (i.e., skewness and kurtosis) are also briefly discussed for completeness. ~~Results related to temperature are presented~~
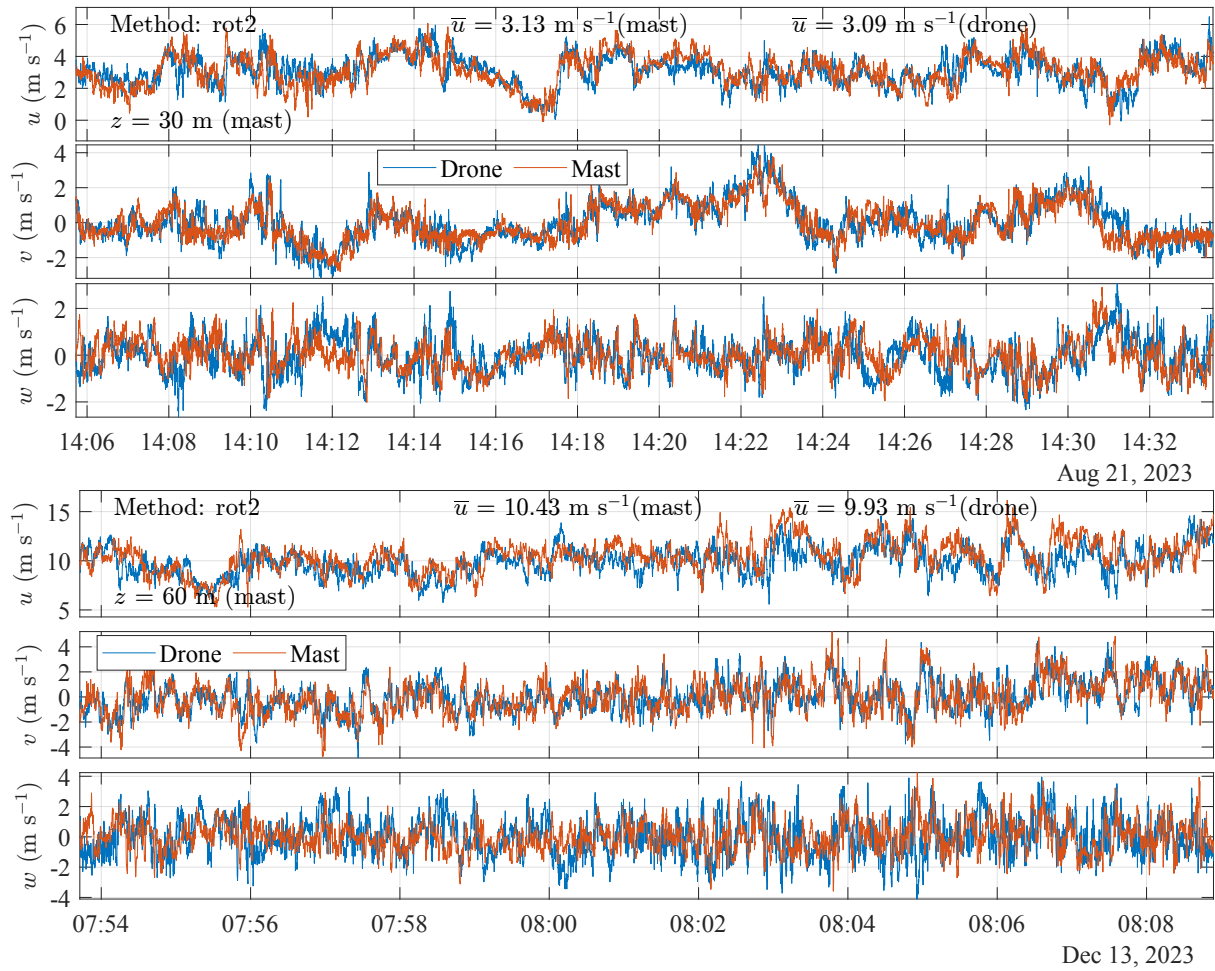
Figure 8. Velocity time series ~~from~~ of the wind components: streamwise (u), crosswind (v), and vertical (w), from drone and mast-based set-ups during flights s_1 (upper panel) and s_7 (lower panel)~~where the SAMURAI-S anemometer is located near~~. The time series from the ~~sonic~~ drone and tower-based setup are coloured blue and orange, respectively. The double rotation (~~samples s_1~~Method: rot2) was applied to both the drone and tower data. The variable z corresponds to the height of the sonic ~~(sample s_7)~~anemometer mounted on the tower, which was the one closest to the drone-mounted sonic anemometer hovering altitude. At the same time, $\overline{u}$ denotes the average streamwise wind component calculated over the sampling period.

~~separately later in the section.~~ Figure 8 presents time series of the velocity components u, v, and w for samples s_1 and s_7. Results related to temperature are presented separately later in the section.

415   Table 5 expands ~~further~~ on this comparison by showing the statistical moments for the three velocity components between the reference mast data and the SAMURAI-S data.

~~The data exhibit a clear similarity, with no noticeable deviations~~ Flow statistics from the drone and mast-mounted sensors are in good agreement, except for the vertical velocity component w of sample s_7, where the drone-mounted sonic anemometer

Table 5. ~~Statistical moments~~ Mean and turbulent flow statistics for samples s_1 and s_7 for drone and mast ~~Data~~ data. Samples s_1 and s_7 refer to the samples described in Table 4. σ_i, γ_i, and κ_i, where $i = u, v, w$, refer to the standard deviation, skewness, and kurtosis estimates, respectively. The table also includes the momentum flux values ($\overline{u'w'}$) and buoyancy flux ($\overline{w'\theta_v'}$, respectively) values.

Statistic	Sample s_1		Sample s_7	
	Drone Data	**Mast Data**	**Drone Data**	**Mast Data**
$\overline{u}$ (~~m s^{-1}~~ m s^{-1})	3.1	3.1	9.9	10.4
σ_u (~~m s^{-1}~~ m s^{-1})	0.9	1.0	1.4	1.5
σ_v (~~m s^{-1}~~ m s^{-1})	1.1	1.0	1.2	1.3
σ_w (~~m s^{-1}~~ m s^{-1})	0.8	0.7	1.3	1.0
γ_u	-0.2	-0.2	0.0	-0.1
γ_v	0.4	0.4	0.1	0.0
γ_w	0.0	0.3	0.2	0.3
κ_u	3.0	2.7	2.8	3.0
κ_v	3.4	2.8	3.2	3.3
κ_w	2.8	3.4	2.8	3.4
$\overline{u'w'}$ (m^2 s^{-2})	-0.2	-0.1	-0.7	-0.5
$\overline{w'\theta_v'}$ (K m s^{-1})	0.1	0.1	-0.1	0.0

shows slightly larger fluctuations ($\sigma_w = 1.3\,\mathrm{m\,s^{-1}}$) than those from the mast-mounted sensor ($\sigma_w = 1\,\mathrm{m\,s^{-1}}$). All three velocity components in the mast and the payload data exhibit skewness and kurtosis values close to zero and three, respectively. These measurements indicate Gaussian fluctuations, typically observed ~~in~~ under stationary conditions within the ABL. Despite a 11 m altitude discrepancy between the sensors (see Figure 7), the drone-mounted sensor accurately tracks short-term horizontal velocity fluctuations. The altitude difference is primarily due to the UAV's altitude control being based on pressure rather than GNSS. Unfortunately, this discrepancy was only noticed during the post-processing phase and was not corrected in the field.

Figure 9 presents the auto power spectral density (PSD) for each velocity component and the real part of the cross-spectrum between u and w for samples s_1 and s_7, plotted on a log-log scale and multiplied by the frequency f to highlight spectral features. The smooth PSD is computed using ~~Equations (4) to (7)~~ Eqs. (4) to (7) that is fitted to the data recorded by the payload sensor. This least-square fit is useful to assess whether the estimated PSD follows the $-5/3$ power law associated with the inertial subrange for the S_u, S_v, and S_w spectra, and the $-7/3$ power law for the co-spectrum $\mathrm{Re}(S_{uw})$. A slightly steeper roll-off is observed for the mast data.

Both sensors consistently capture the along-wind (u) and across-wind (v) velocity components for the selected samples s_1 and s_7. In sample s_1, the S_v spectrum reveals a small peak at approximately $0.20\,\mathrm{Hz}$. This peak cannot be attributed to the oscillation frequencies of the payload, which are established around $0.11\,\mathrm{Hz}$. Thus, it is more likely related to ~~a real flow feature~~ random fluctuations. The co-spectrum between u and w for sample s_1 features unusual positive values in the mast-
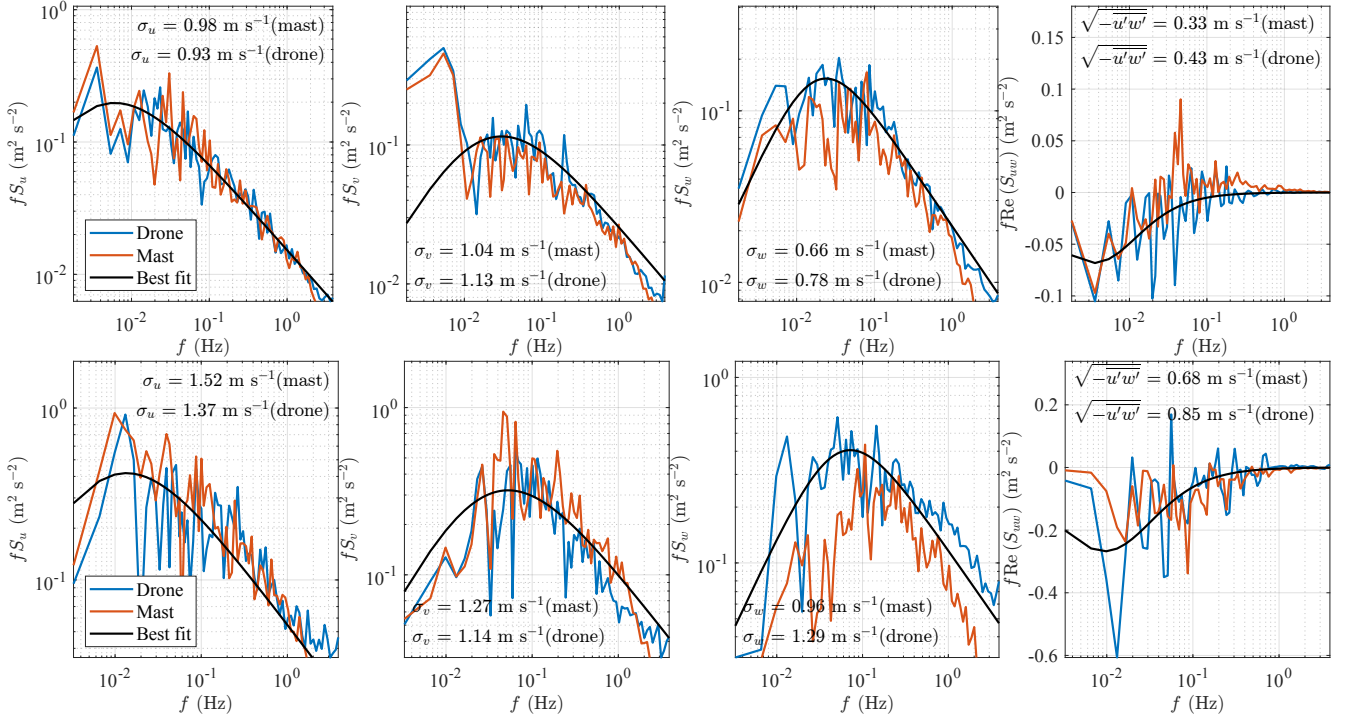
Figure 9. Power spectral density ~~(PSD)~~ estimates of the velocity components~~for both the flying sonic anemometer~~: streamwise (u), crosswind (v), and vertical (w), as well as the ~~one mounted on the mast at a height of 30 m above the ground for samples~~ co-spectrum ($Re(S_uw)$), from drone and mast-based set-ups during flight s_1 (~~top~~upper panels) and ~~the one mounted at 60 m for~~ s_7 (~~bottom~~lower panels). The solid black line refers to the blunt model (for S_u, S_v, and ~~S_{uw}~~$Re(S_{uw})$) or pointed model (for S_w) fitted to the data from the drone-mounted anemometer. The variances of the velocity components (σ_u, σ_v and σ_w) and the Reynold stress element $\overline{u'w'}$ are indicated within each corresponding plot.

435   mounted data between $0.03\,\mathrm{Hz}$ to $1\,\mathrm{Hz}$, with a distinctive positive peak at $0.04\,\mathrm{Hz}$. These features are not present in the SAMURAI-S data, indicating differences in the flow between those captured by the tower-mounted instrument. This peak is unlikely related to a shadow effect of the tower, given that the wind direction was $97°$ and the tower-mounted sonic sensor is oriented towards $218°$ for s_1.

    For flight s_7, the power spectral density of the vertical component clearly shows a higher energy content at all frequencies
440   recorded by the drone-based sonic anemometer compared to those from the tower (Figure 9). This is consistent with the higher σ_w values from the drone data shown in Table 5. This feature is present in nearly all flights (see Section 5.2), although it is particularly pronounced in s_7.

    The comparative analysis of the sonic temperature time series reveals a good agreement across sample s_1 and s_7, with minor deviations for the mean temperature likely attributable to different calibration values between the sonic anemometers
445   (Figure 10). Further insights are provided by Figure 11, which displays the PSD estimates of the sonic temperature and the
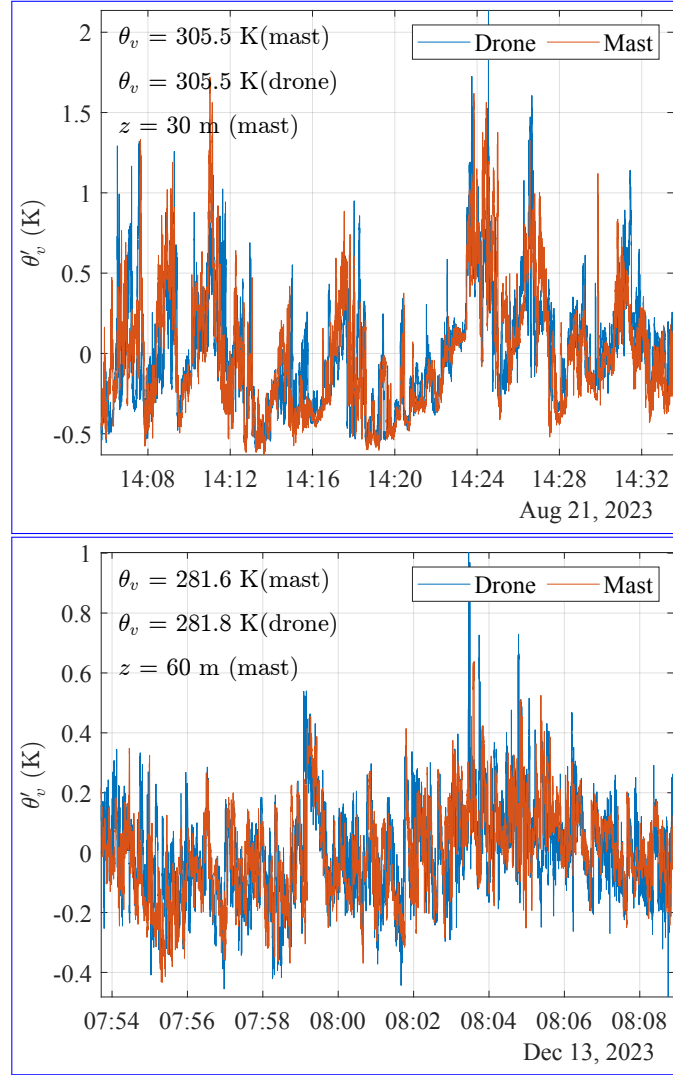
Figure 10. Time series of the fluctuations of the sonic temperature (θ'_w) for samples s_1 (left panel) and s_7 (right panel) measured by the drone-mounted anemometer (blue line) and the mast-mounted sonic (orange line) at a height of $30\,\mathrm{m}$ and $60\,\mathrm{m}$ above the ground, respectively. The mean sonic temperature (θ_v) is also indicated in each panel for both the drone and the mast measurements.

CPSD between the vertical and the along wind component with the virtual potential temperature. Notably, the PSD for sample s_1 demonstrates an excellent agreement between the sonic temperature from the mast-mounted sensor and SAMURAI-S. However, for sample s_7, the PSD of the drone-based anemometer deviates from the expected $-5/3$ power law at frequencies greater than $1\,\mathrm{Hz}$. This deviation scales with frequency f, suggesting the influence of white noise on the measurement data. For the mast-mounted anemometer, the PSD estimates of the temperature exhibit slight discrepancies from this $-5/3$ power
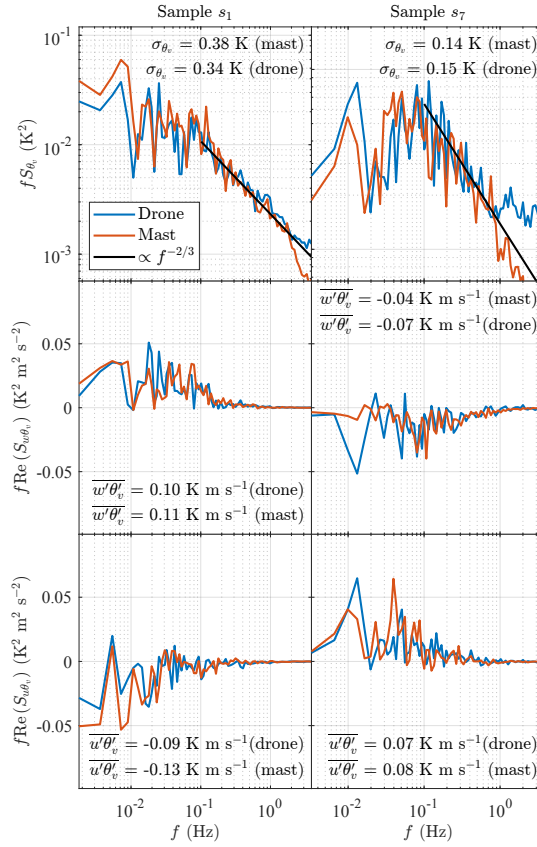
Figure 11. PSD estimates of the sonic temperature ~~fluctuations~~ (θ_v) and associated ~~CPSD with~~ CPSDs, including the vertical $(Re(S_{w\theta_v}))$ and ~~the along-wind~~ along-wind $(Re(S_{u\theta_v}))$ component for both the flying sonic anemometer (blue line) and the one mounted on the mast (orange line) $30\,\text{m}$ above the ground for samples s_1 (left panels) and at $60\,\text{m}$ above ground for samples s_7 (right panels).

law in samples s_1 and s_7. Additional plots showing PSD spectra for samples s_5, s_6, s_8, s_9 and s_{10} are provided in Appendix B.

5.2 ~~Comprehensive~~ Mean and turbulence statistics comparison

~~A comprehensive~~ This section presents a detailed analysis of the sensor performance~~is conducted in this section~~, focusing on
455   integral mean flow and turbulence characteristics for all three velocity components u, v, and w (Figure 12 ~~) for all ten samples.~~ ~~Figure 13 compares the covariance-based kinematic momentum, heat fluxes, and stability estimated from the SAMURAI-S and the mast-mounted anemometer.~~
and Figure 13). The drone-mounted anemometer slightly underestimates the mean wind speed $\overline{u}$ (Figure 12a), but the data scatter is low. ~~This underestimation is possibly due to differences in height, since, as it is shown in Table 4~~ The height difference
460   between the two sensors may explain this underestimation (Table 4). More specifically, the payload height was on average $4\,\text{m}$
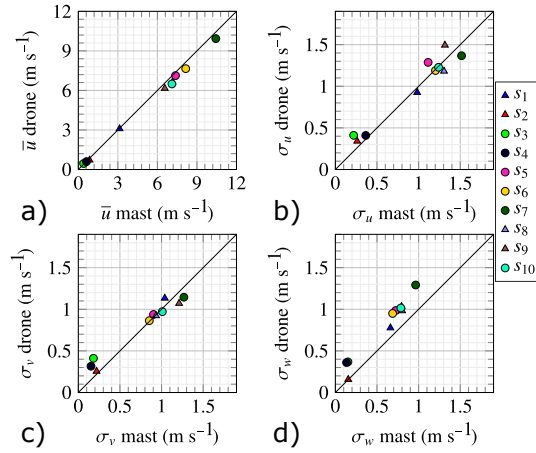
Figure 12. Mean wind speed and standard deviation of the three velocity components for the mast- and the drone-mounted sonic ~~anemometer~~ anemometers across the ten validation samples. Circle markers indicate measurements from the mast at $30\,\mathrm{m}$ above the surface, while triangle markers correspond to measurements at $60\,\mathrm{m}$.
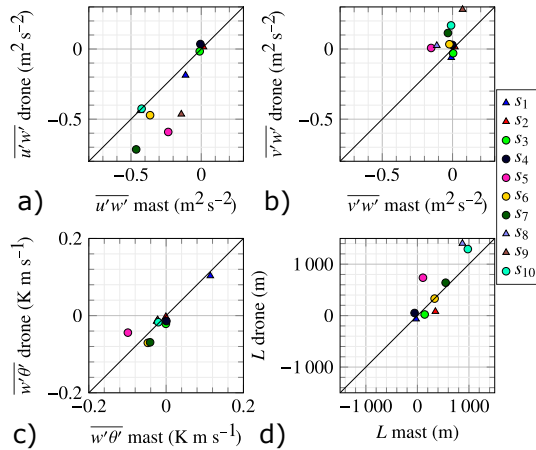
Figure 13. Turbulence covariance and Obukhov length for the ten validation samples, as measured by the mast- and the drone-mounted sonic ~~anemometer~~anemometers. Circle markers represent measurements from the mast at $30\,\mathrm{m}$ above the surface, whereas triangle markers signify measurements at $60\,\mathrm{m}$.

lower than the target altitude for the sonic at $30\,\mathrm{m}$ and $8.5\,\mathrm{m}$ for the sonic at $60\,\mathrm{m}$. The standard deviations of the along-wind and across-wind velocity components denoted σ_u (Figure 12b) and σ_v (Figure 12c), respectively, show excellent agreement. The drone-mounted anemometer slightly overestimates the standard deviation σ_w of the vertical component (Figure 12d), and this overestimation increases nearly linearly with the mean wind speed in absolute terms.

465   The covariance estimates $\overline{u'w'}$ (Figure 13a) exhibit a larger scatter than $\overline{v'w'}$ (Figure 13b). ~~The covariance between sonic temperature θ' and the fluctuating vertical component w'~~ At the same time, the covariance estimate of $\overline{\theta'w'}$ (Figure 13c), and
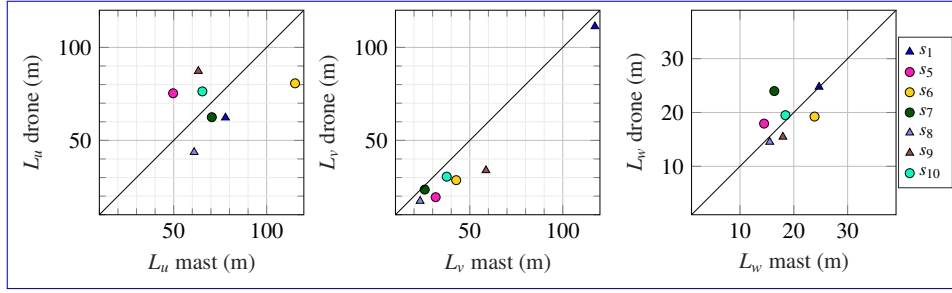
Figure 14. Integral turbulence length scale of the three velocity components for the mast- and the drone-mounted sonic anemometers across the ten validation samples. Circle markers indicate measurements from the mast at $30\,\mathrm{m}$ above the surface, while triangle markers correspond to measurements at $60\,\mathrm{m}$. Only samples associated with $I_u < 0.5$ and $\overline{u} > 1\,\mathrm{m\,s^{-1}}$ are used to satisfy the conditions required for applying Taylor's hypothesis of frozen turbulence.

the Obukhov length L (Figure 13d) demonstrate good correlation and small scatter. The vertical velocity component is used in the numerator and denominator when calculating L. Thus, the lower scatter may be attributed to the larger uncertainties associated with component w cancelling each other to some degree. Sample s_5, depicted in pink, consistently exhibits the
470   highest scatter. This sample has the shortest duration, lasting only $10\,\mathrm{min}$, which is at least $4.7\,\mathrm{min}$ shorter than all other samples. Thus, sample s_5 may be more prone to errors associated with insufficient sampling of the largest turbulent eddies.

Figure 14 compares the integral length scales for each velocity component, estimated following the procedure presented in Section 4.3. Samples s_2, s_3, and s_4 did not satisfy the conditions required to apply Taylor's hypothesis of frozen turbulence, which were defined as a turbulence intensity of $I_u = \sigma_u/\overline{u} < 0.5$ and a mean wind speed of $\overline{u} > 1\,\mathrm{m\,s^{-1}}$. All other samples
475   met these conditions, with I_u ranging from 0.15 to 0.31 and a mean wind speed exceeding $3\,\mathrm{m\,s^{-1}}$.

The streamwise length scale L_u (Fig. 14, left panel) shows a rather large scatter around the 1:1 line. However, there is no systematic deviation between mast and drone measurements. In contrast, the middle panel suggests that the drone-mounted anemometer systematically underestimates the lateral length scale L_v. However, it is unclear whether this discrepancy arises from sensor characteristics or the specific position of the drone. The best agreement is observed in the right panel for the
480   vertical length scale L_w, which exhibits low scatter and no clear bias, despite the overestimation of σ_w by the drone-mounted sonic anemometer (Fig. 12d).

The discrepancies between the vertical velocity spectral densities estimated by the mast-mounted sonic anemometers and by the drone are explored in more detail through the ratios S_w/S_u and S_v/S_u, following the method presented in Section 4.1. Chamecki and Dias (2004) states that if the spectral ratio trends towards 4/3 without actually reaching it, this could indicate
485   that isotropy in the inertial subrange has not been achieved within the examined frequency range, a situation typically occurring ~~in stable stratification flow~~ under stable atmospheric conditions. In this study, the spectral ratios reached a plateau for all ten samples, albeit not always with a value of 4/3. This suggests that the atmospheric conditions were ~~favorable to the observation of local isotropy ,~~ favourable to observing local isotropy but that flow distortion may have been present. The results for all the samples are shown in Figure 15. Values corresponding to s_2, s_3, and s_4 are displayed with grey triangle markers to highlight
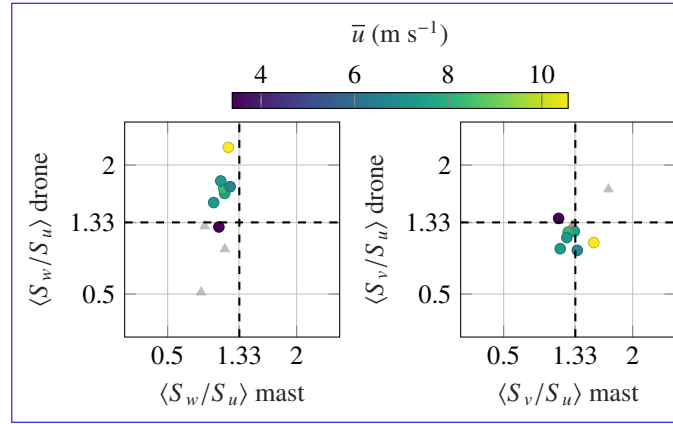
Figure 15. Quadrant analysis for the frequency-averaged spectral ratios $< S_w/S_u >$ (left panel) and $< S_v/S_u >$ (right panel) with $fr > 2$ and $fr < 10$ between the mast and drone-based measurements for different mean wind speeds. The notation $< >$ denotes an average over frequency bins. ~~Only samples~~ Samples with a mean wind speed ~~above $2\,\mathrm{m\,s^{-1}}$~~ below $1\,\mathrm{m\,s^{-1}}$ are ~~included~~ marked as grey triangles, as they are representative of intermittent turbulence, for which the assumption of local isotropy in the inertial subrange may not be defined.

490   their non-stationary nature, which does not fit within the analysis framework. The following discussion and comments exclude these three samples unless explicitly stated otherwise.

Figure 15 shows that ~~at lower wind speeds, SAMURAI-S may provide accurate estimations of the vertical velocity components as $< S_w/S_u >$ is fairly close to~~ only one sample from the drone-based dataset is close to the theoretical ratio of 1.33 for ~~$\overline{u} < 6\,\mathrm{m\,s^{-1}}$. As an opposite trend, SAMURAI-S overestimates this ratio as~~ $< S_w/S_u >$. As wind speed increases, the ratio
495   measured by SAMURAI-S diverges further from 1.33, whereas the mast data ~~display ratios~~ fluctuates between 1.0 and 1.25. ~~While these mast data may be~~ This could be related to the bigger σ_w values measured by the drone setup.

Although the mast data appear closer to the expected ratio of 1.33 compared to the SAMURAI-S, they could still represent an underestimation of up to 20% of the vertical fluctuating component. As discussed above, not achieving the 4/3 ratio may hint at the presence of flow distortion caused by the mast or the sonic anemometer itself, contributing to this underestimation.
500   Similar observations apply for the ratios $< S_v/S_u >$. For $\overline{u} > 6\,\mathrm{m\,s^{-1}}$, the ratio $< S_w/S_u >$ exceeds the expected value of 1.33 in drone measurements.

The ~~recorded data~~ data recorded in this study mainly represent stable or near-neutral atmospheric conditions~~, as ζ was positive for most flights~~. An exception is found in s_1, collected under unstable atmospheric conditions ($\zeta = -0.46$) and ~~features the closest agreement~~ shows one of the closest agreements between the drone and mast-mounted sensors. It should also be noted
505   that for all flights except s_1, the wind consistently came from the $280°$ to $310°$ sector. The limited number of samples and the variability in stability and wind direction prevent determining whether the improved agreement under unstable conditions is a systematic effect or influenced by differences in wind direction over heterogeneous topography. Further research is necessary to determine whether convective conditions consistently enhance the performance of the drone-based setup described in this

paper~~or if these observations can be generalized across different turbulence intensities and atmospheric conditions. In addition,~~
~~it is necessary to point out that except for s_1,.~~

5.3 Uncertainties analysis

Figure 16 presents the uncertainty metrics associated with the calculation of $\sigma_u^2, \sigma_v^2, \sigma_w^2, \overline{u'w'}, \overline{v'w'}$, and $\overline{\theta_v'w'}$. Most samples exhibit reasonably low uncertainties, as indicated by the green patch in Fig. 16, which corresponds to a normalised value of 0.5, consistent with that used in Stiperski and Rotach (2016); Cheynet et al. (2019). However, samples s_2, s_3, and s_4 systematically fall outside this green area due to the low wind speed at the time of recording. Consequently, they should not be included in the analysis of turbulence statistics, at least within the framework of stationary homogeneous turbulence. These samples exhibit characteristics of intermittent turbulence, the study of which is beyond the scope of this work.

In Fig. 16, the uncertainty metric $a_{\theta_v w}^2$ shows higher-than-expected uncertainties for samples s_5 and s_9. The relatively high uncertainty for sample s_5 is partly attributable to the short duration of the record—less than $10\,\text{min}$, which results in large uncertainties for covariance estimates. Sample s_9 has a record duration of approximately $17\,\text{min}$, so the high uncertainty value remains unclear, notably since it is only visible in the covariance between the sonic temperature and the vertical velocity component of the ~~wind originates from a sector of 280° to 310° for all other flights. The limited number of samples and the range of stability and wind directions prevent drawing broader conclusions concerning systematic effects~~drone-mounted anemometer. It should be noted that the uncertainty metrics are generally comparable between the drone-based and mast-based measurements, supporting the potential of this mobile platform for turbulence analysis.

6 Conclusions

This study presents a pioneering effort in atmospheric research, focusing on using a research-grade 3D sonic anemometer mounted $18\,\text{m}$ under a drone to observe turbulence. The goal was to assess the effectiveness of drone-mounted sonic anemometers as a versatile tool for turbulence measurement, challenging traditional methods that mount the same sensor on masts or towers. A notable aspect of this research was the application of a dynamic motion compensation algorithm that accounts for the motion and tilt of the sonic anemometer~~while~~. At the same time, the drone hovered above the location of interest. ~~This study also employed the double-rotation method for static tilt correction.~~

Data collection took place during the Models and Observations for Surface Atmosphere Interactions (MOSAI) campaign in France. The methodology included a comparative analysis between conventional mast-mounted 3D sonic anemometers at $30\,\text{m}$ and $60\,\text{m}$ above ground and the drone-mounted anemometer. This comparison focused on mean flow and turbulence ~~characteristics, cross-covariance~~statistics, including the integral length scales, covariance, and auto- and cross-spectral densities of velocity fluctuations. Our findings indicate that the drone-mounted anemometer effectively captures detailed turbulence measurements. Although there is good agreement regarding the along-wind and cross-wind flow when comparing the drone and mast data, ~~the~~ drone-based observations consistently overestimate ~~the fluctuations of the vertical wind~~ vertical wind fluctuations across all flights~~performed~~. This overestimation increases as the wind speed increases, calling for further analysis under a
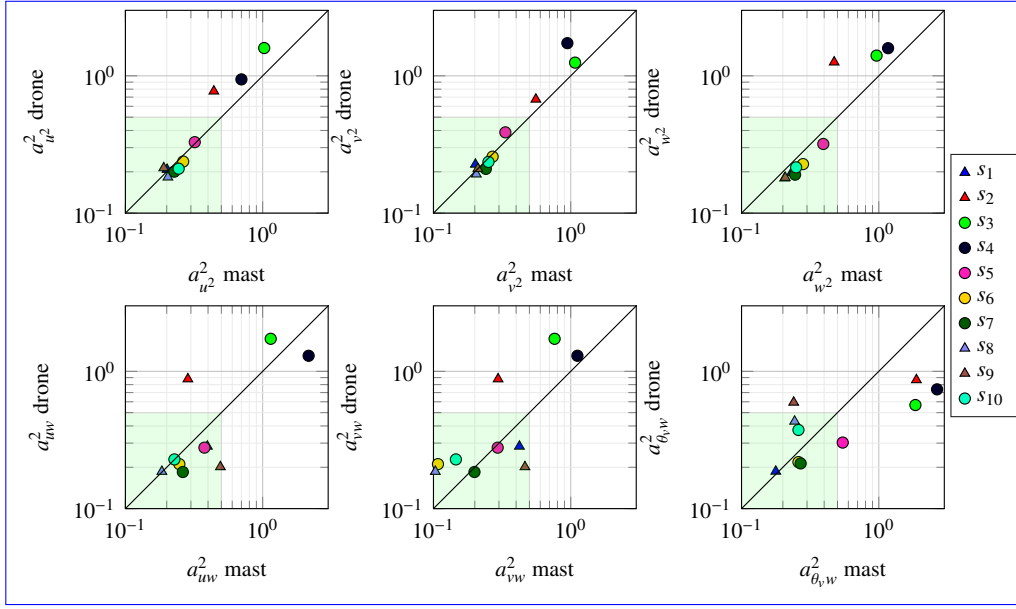
Figure 16. Uncertainty metrics (Eqs. (10) to (13)) estimated for the drone-mounted sensor (y-axis) and the mast-mounted sensor (x-axis). The green patch represents the region with low statistical uncertainties.

broader range of wind conditions. Also, our findings show that the drone-mounted sensor and mast-mounted sonic anemometers provide turbulence statistics with similar levels of uncertainty.

For the drone-mounted anemometer, the spectral ratio S_w/S_u was up to 63% larger than the local isotropy hypothesis predicted in the inertial subrange. However, it was also observed that the mast-mounted anemometer could significantly under-
545 estimate the vertical turbulence component, with a spectral ratio S_w/S_u that was up to 22% lower than predicted by the local isotropy hypothesis in the inertial subrange.

The sonic temperature and the Obukhov length estimated by both sensors were also investigated. The comparison provides a positive and encouraging overall picture, with good agreement between the mast and drone measurements. The only excep-tion is the shortest sample ($10\,\mathrm{min}$ compared to at least $15\,\mathrm{min}$ for all others), which exhibits markedly divergent behaviour
550 compared to its mast-measured counterpart.

Overall, the findings underscore the ~~reliability of the drone-mounted anemometer in recording the along-wind velocity component and its potential~~ potential of the SAMURAI-S system, especially its complementarity with mast-mounted sonic anemometers and Scanning Doppler wind lidar for ~~the study of atmospheric~~ studying three-dimensional turbulence in the atmosphere.

555 *Data availability.* Data underlying the results presented in this paper can be obtained from the authors upon reasonable request.

Appendix A: Trasformation Matrix

The transformation matrix $R(\phi, \theta, \psi)$ is defined as

$$R(\phi, \theta, \psi) = [R_3(\phi) R_2(\theta) R_1(\psi)]^T$$

where

$$R_1(\psi) = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$R_2(\theta) = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix},$$

$$R_3(\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}.$$

Appendix B: Power spectral density estimates for other samples

Figure B1 presents the power spectral densities of the three velocity components, as well as the cross-spectral densities between u and w, for samples s_5, s_6, s_8, s_9, and s_{10}, where the concept of spectral density is well-defined. For clarity, these spectral densities are normalised by the variance or covariance of the corresponding variable. Similarly, Fig. B2 displays the normalised power spectral densities of the sonic temperature, along with the normalised co-spectral densities. These figures exhibit trends similar to those observed for samples s_1 and s_7, which were analysed in detail in this study.

Author contributions. Conceptualization was done by EC, JR, MG, and STK. The methodology was developed by EC, JR, MG, and STK. Project management was handled by JR. The experiment was conducted by JR, MG, and STK. Data analysis was performed by EC, MG, and STK. The original draft was prepared by EC, JR, MG, and STK, and the review and editing were done by EC, JR, MG, and STK.

Competing interests. The authors declare no conflict of interest.

Disclaimer. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
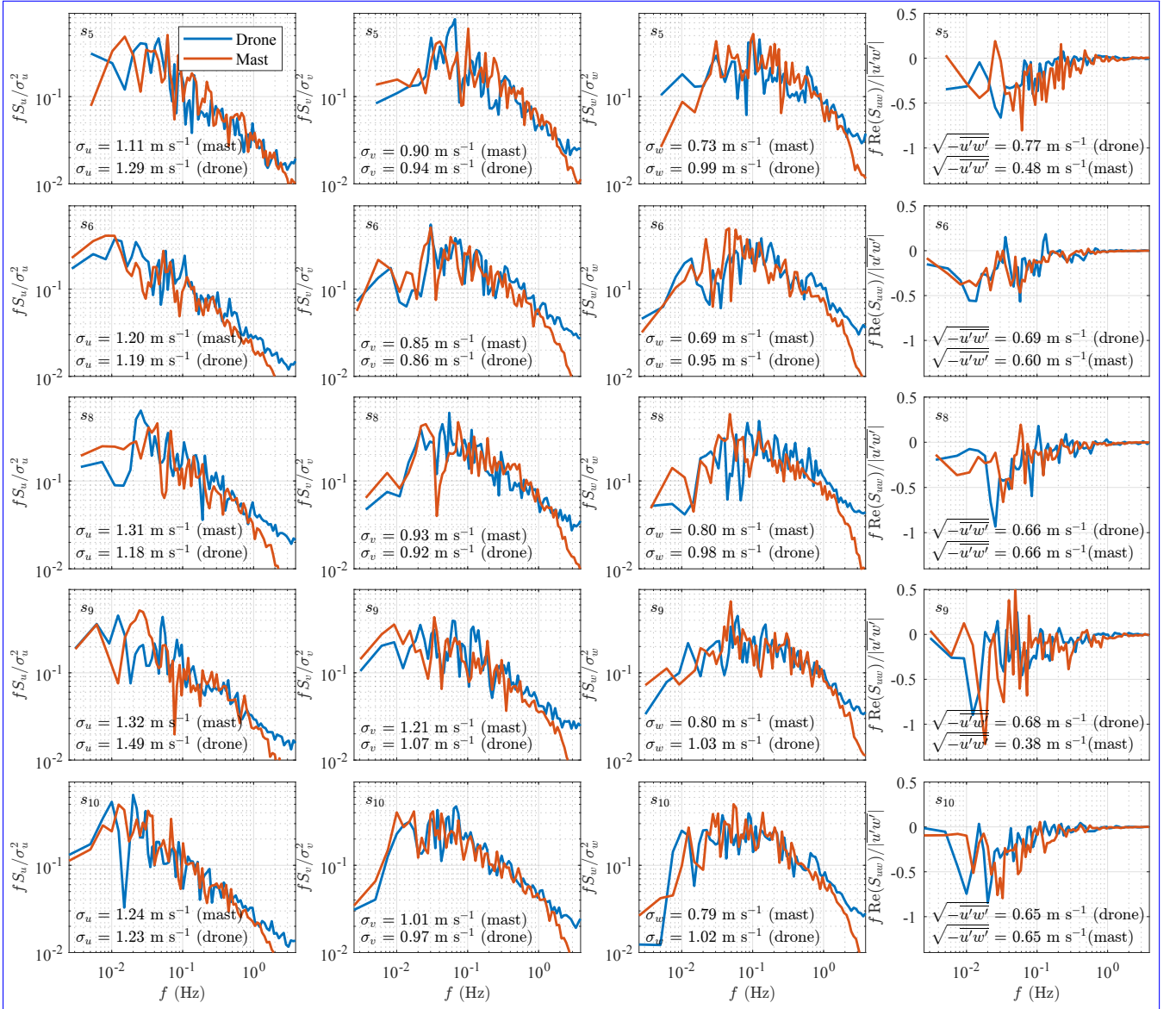
Figure B1. Normalised power spectral densities of the three velocity components and co-spectral densities for samples s_5, s_6, s_8, s_9, and s_{10}.

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580 Observation System) instrumented sites. AERIS data ~~center~~ centre is in charge of ~~the~~ data distribution and ~~of the website of MOSAI project~~ the MOSAI project website. (https://mosai.aeris-data.fr). We want to thank Tor Olav Kristensen for supporting the initial phase of this project.
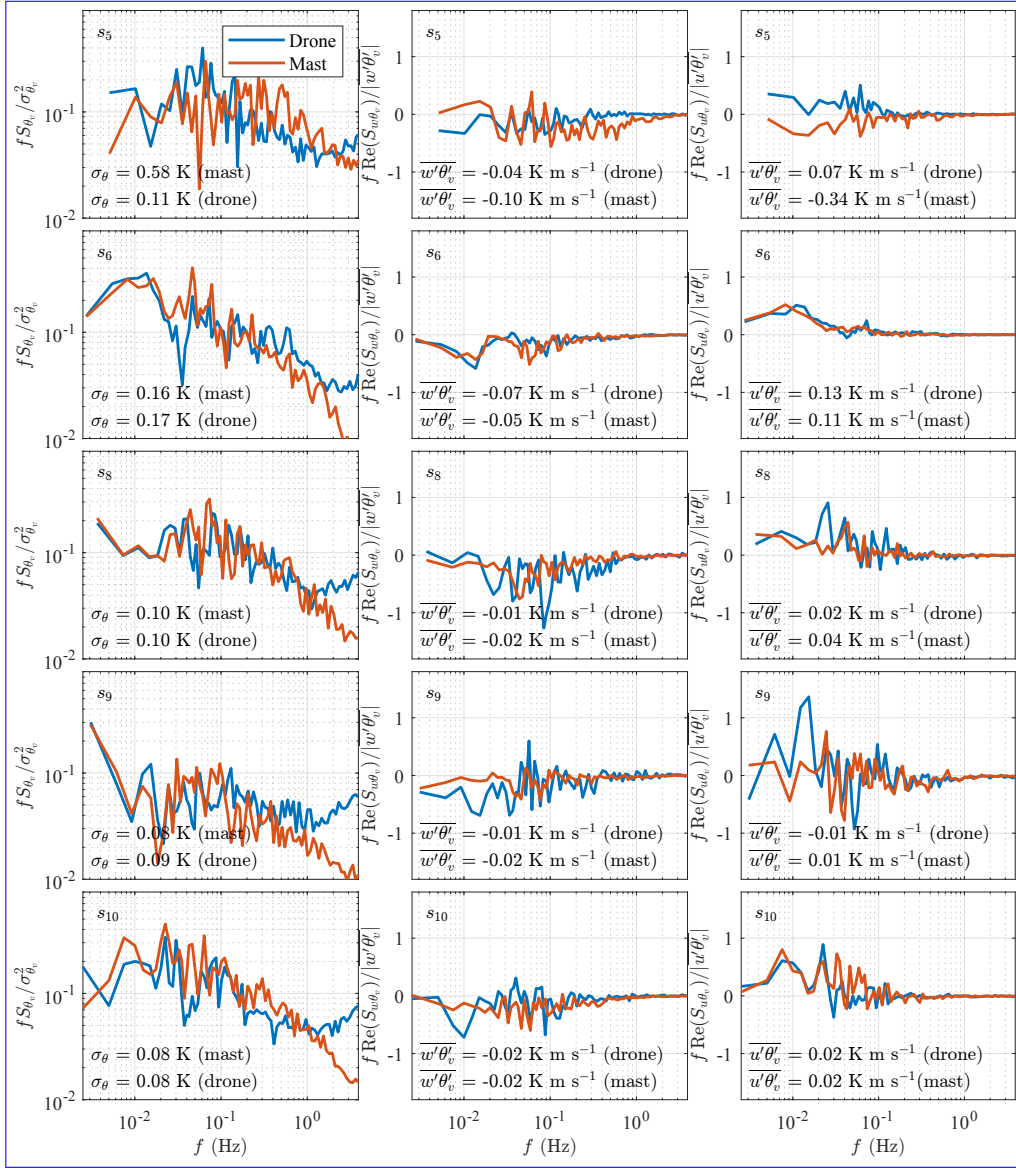
Figure B2. Normalised power spectral densities of the sonic temperature and associated co-spectral densities for samples s_5, s_6, s_8, s_9, and s_{10}.

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