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AUTOMATED CLASSIFICATION OF NON-KOLMOGOROV TURBULENCE USING A HIGH-ORDER SURROGATE FUNCTION

Kevin Lieb, et al.

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AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
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14. ABSTRACT
When using sonic anemometry to determine the temperature structure function parameter, there are multiple times in the data collection process where averaging occurs. In particular, this work considers the impact on the temperature structure function from spatial averaging of temperature between the piezoelectric transducer heads. It is found that the impact is nearly constant for separations greater than twice the transducer spacing. is found that the impact is

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Automated Classification of Non-Kolmogorov Turbulence Using a Higher-Order Surrogate Function

[1]**Kevin Lieb,** [2]**Melissa Beason,** [3]**Benjamin Wilson**
[1]*Department of Aerospace Engineering, Texas A&M University, College Station TX 77843*
[2]*AFRL 3550 Aberdeen Dr. SE, Kirtland Air Force Base NM 87117*
[3]*AFIT ENP 2950 Hobson Way, Wright Patterson Air Force Base OH 45433*
kevin.lieb@tamu.edu

Abstract: A method of automated turbulence characterization has been developed for sonic anemometer data. We found that the structure function slope followed an exponential curve and used that observation to incorporate a surrogate function to simplify finding slopes and ranges of turbulence. © 2022 The Author(s)

Virtual temperature data derived from the speed of flight of an ultrasonic pulse has been used for many years to determine the temperature structure function parameter and from this derive the refractive index parameter. Typically, the temperature data is used to generate a power spectrum from which the temperature parameter is found. However, in this effort, we sought to work with the structure function to see if it was possible to identify various ranges of turbulence based on an expected inertial range, buoyancy range, and eventually loss of correlation shown in Eqs. (1)-(3).

$$\text{Inertial Range: } D_T(R) = C_T^2 R^{\frac{2}{3}} \tag{1}$$

$$\text{Buoyancy Range: } D_T(R) = \tilde{C}_T^2 R^{\frac{2}{5}} \tag{2}$$

$$\text{Loss of Correlation: } D_T(R) = C R^0 \tag{3}$$

An example of Kolmogorov turbulence and two power-law fits is shown in Fig. 1. Modeling the entire range as following the 2/3 power law results in an over-prediction of the structure function constant at larger scales, while modeling the entire range as following the 2/5 power law results in over-prediction of small-scale phenomena.

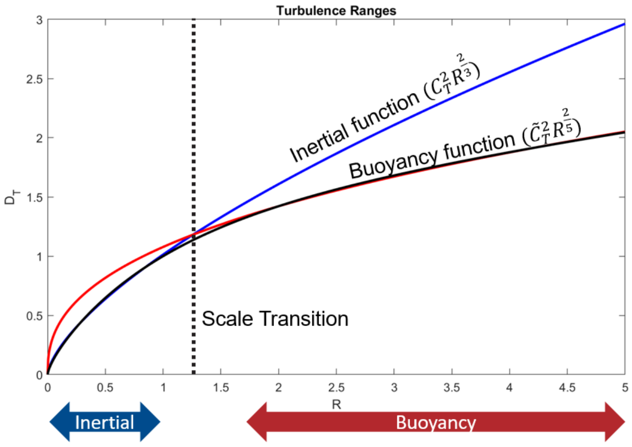

Fig. 1. Example turbulence ranges with sample structure function shown in black.

Using Taylor's frozen flow hypothesis, we can convert temporal data into spatial data by multiplying the time separation between points, Δt, by the mean wind speed, $\bar{u}$. From this we calculate the structure function for a given temperature time series by taking the ensemble average shown in equation 4.

$$D_T(R) = D_T(\bar{u}\,\Delta t) = \langle [T(R_1) - T(R_1 + R)]^2 \rangle \tag{4}$$

To accurately model this turbulence, we must find regions where each structure function slope is valid prior to the curve fit. Locating this region is difficult when working directly with the sampled points and inherent variations in measured data may lead to incorrect curve fitting, resulting in poor turbulence range identification. In our attempt to determine the slopes and isolate the ranges over which they occurred, we discovered that the logarithmic slope of the structure function followed an exponential form, $A + Be^{-CR}$ with the structure function being well represented by equation 5.

$$D_T(R) = I_T^2 R^{A+Be^{-CR}} \tag{5}$$

Fig. 2 demonstrates a typical exponent of the structure function as a function of radius, found by taking the slope of the logarithm of the structure function. As shown in equation 6, for power-law turbulence, this logarithmic slope represents the current exponent, presuming a constant C_T^2 term. The exponent itself is observed to decay exponentially.

$$\log D_T = 2\log C_T + m\log R \tag{6}$$

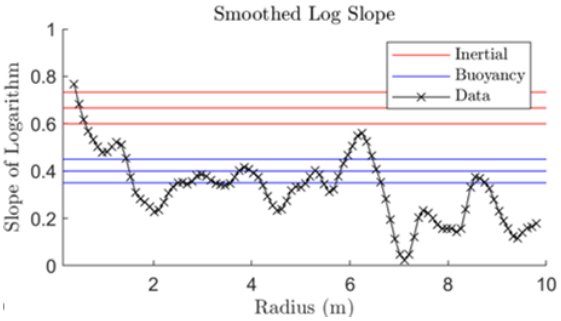

Fig. 2. Example exponent of structure function from log-slope.

As typical data can be imperfect and difficult to fit to multiple turbulence ranges simultaneously, we found we could fit a higher-order “surrogate function” (Eq. 5) to our measured structure function and then use it in place of the original. This surrogate function has 4 degrees of freedom and follows a power law with an exponential term.

The surrogate function demonstrated remarkably good fit to many turbulence data samples, whether Kolmogorov or not. Using this curve, regions of power law validity such as inertial or buoyancy are identified and then freeform power laws are fit to the underlying data. If these final power laws are acceptably close to theory, the sample is classified as Kolmogorov, and if power laws are not close to theory, the sample is flagged as non-Kolmogorov. Examples of using the surrogate function to find turbulence ranges are shown in Figs. 3 and 4. This data was collected at 5 m height using an ATI SATI 3-D sonic anemometer reporting at 200 Hz.

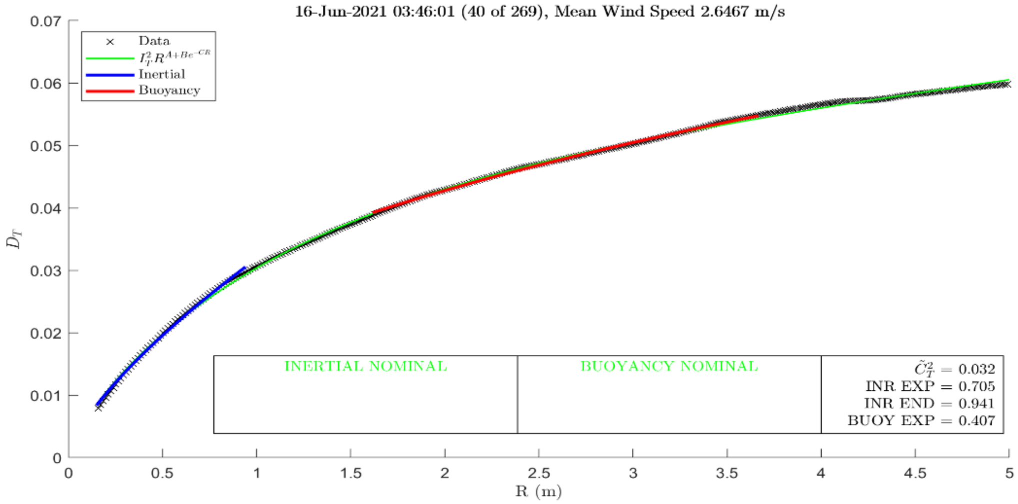

Fig. 3. Surrogate function fit to structure function data (green) with inertial range (blue) and buoyancy range (red). Note that in this data, the inertial range was considered satisfactory. Time shown in UTC.

The classification system has been successfully demonstrated on sonic anemometer data, correctly identifying both Kolmogorov and non-Kolmogorov turbulence. Future work will include tuning selection parameters, testing against Shack-Hartmann turbulence sensors, and classifying data from other locations and times.

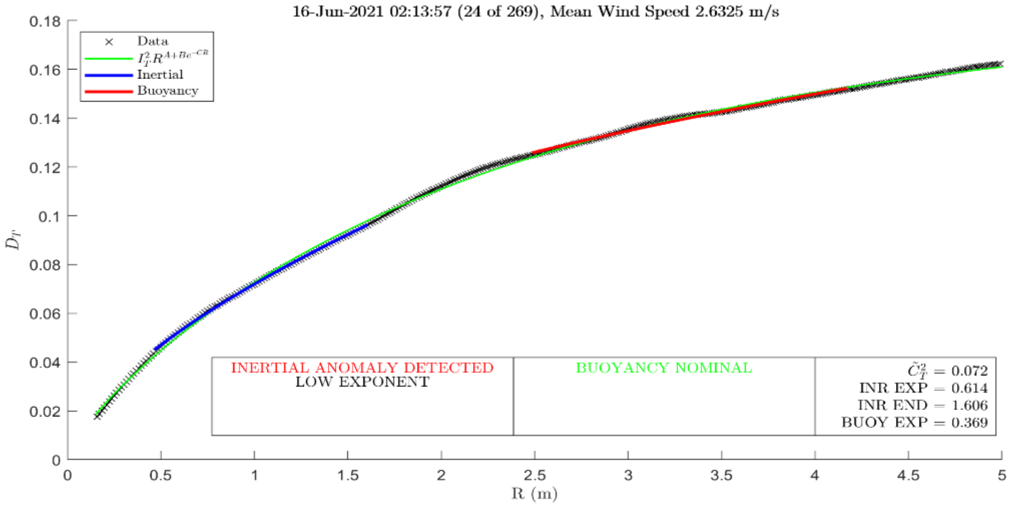

Fig. 4. Surrogate function fit to structure function data (green) with inertial range (blue) and buoyancy range (red). Note that in this data, the inertial range was flagged as having a low exponent. Time shown in UTC.