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CALCULATING EDR FROM AIRCRAFT WIND DATA DURING FLIGHT IN AND OUT OFJUNEAU, AK: TECHNIQUES AND CHALLENGES ASSOCIATED WITH NON-STRAIGHT AND LEVEL FLIGHT PATTERNS

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1. INTRODUCTION

Juneau Alaska's airport sits in a basin surrounded by complex mountainous terrain, with nearby peaks rising from the ocean to over 1km in height. This complex terrain, coupled with both strong maritime and continental air masses converging in the basin, creates a region of high aviation due to both wind shear and turbulence. With a history of past aviation upsets and a desire to improve aviation safety in and out of Juneau, the project to develop a Juneau Wind Hazard Alert System (JHWAS) was initiated by NCAR with the support of the FAA. Over three field seasons, data were collected from a system of mountaintop anemometers, boundary layer wind profilers and instrumented aircraft. From these data, wind shear and turbulence estimates were derived and incorporated into the JHWAS system. Several companion papers in these proceedings cover further details of the site parameters, system set-up, alert warnings, and the performance of the final system (Barron, 2004; Braid, 2004; Cohn, 2004; Fowler, 2004; Morse, 2004; Mueller, 2004; Wilson, 2004). For the JHWAS system, aircraft data serves as a "truth" data set; turbulence and wind shear diagnostic algorithms rely on this data for calibration, thus a high-quality aircraft hazard data set was essential. This paper focuses specifically on the calculation of eddy dissipation rate (EDR), a turbulence parameter, from the aircraft data sets; included are discussions of the methods used to quality control the data, specifics on EDR calculations and problems with such calculations from flights through a complex flight region such as that surrounding Juneau.

Eddy dissipation rate is a well-established objective measure of atmospheric turbulence intensity in the atmospheric science community (Cornman, 1995; Smalikho, 1997), and has been used to quantify turbulence for aircraft (Lee, 1988; Poellot, 1991). However, the calculation of EDR from aircraft data has been primarily done for straight and level flight. Arrivals and departures from Juneau (Fig. 1) are anything but this and thus new challenges were presented for accurate estimation of atmospheric turbulence using EDR calculation methods. Because of the maneuvers and climbing/descending flight paths, analysis required special care to ensure quality data entered the calculations, including close attention to noise in the data created by the complex flight conditions.

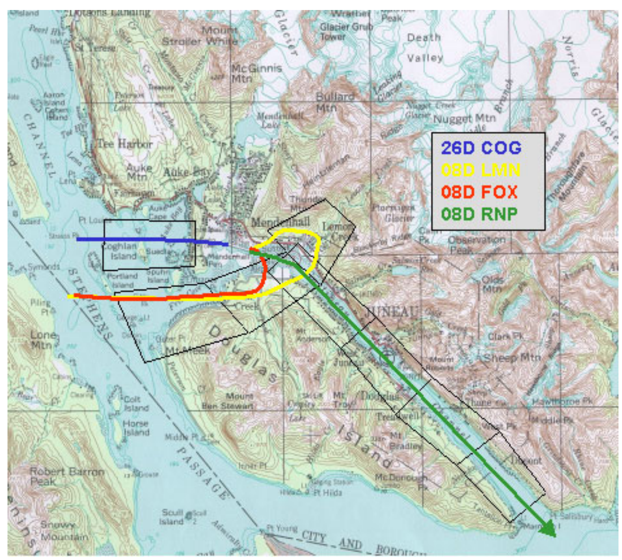

Figure 1. Juneau Alaska airport arrival and departure paths. COG is Coghlan arrival, LMN is Lemon Creek departure, FOX is Fox departure, RNP is arrival/departure (Gastineau Channel).

2. OVERVIEW OF AIRCRAFT DATA COLLECTION

Data were collected from three different aircraft, over three field seasons. Two of these were research aircraft equipped with an inertial

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navigation system (INS) and an analog data recording system. These two research planes recorded detailed environmental, physical, and geographical position information variables at a rate of 25Hz. The third aircraft was a contracted Boeing 737 equipped with a Quick Access Recorder (QAR), which recorded primary data at various update rates ranging from 8Hz to 1Hz.

The first of the two research aircraft, the University of North Dakota's Cessna Citation flew a total of 32 hours between February and April, 1998. The second, the University of Wyoming's King Air, flew for a total of 74 hours between December 1999 and March 2000. In 2003, the King Air again flew, along with the chartered B737-400 for a combined total of more than 60hrs. These two flew independently, as well as in dual aircraft flights, where one closely followed the other (for more details see Cohn et al. 2004). All raw aircraft data collected during the three field programs was then further processed to generate fields including three dimensional winds, of which the vertical wind was used for our EDR estimations.

3. EDDY DISSAPATION RATE (EDR) ESTIMATION

Winds derived from the recorded aircraft data are in an inertial coordinate system. In order to meet the assumptions of the turbulence theory applied here, it was necessary to calculate wind components that are parallel and perpendicular to a displacement vector. If one were to assume the aircraft center is a point in space, its' movement in space over time defines the displacement vector. The parallel and perpendicular wind components are then computed relative to the displacement vector. Hence, our final coordinate system is thus: the along-track wind forward along the flight track and the first of the cross track components is parallel to the ground at a right angle to the along-track component and second cross track component perpendicular to the plane of the first two. This conversion to a "track" relative coordinate system is important when the aircraft is not flying a straight and level path.

The vertical wind (z-wind) data were then divided into small, overlapping windows for which an EDR estimate is derived. Window sizes were selected for each aircraft dataset such that the window corresponded to approximately 1km distance. Our calculations assume that the aircraft is moving at a constant speed within the window, which is a reasonable assumption for these data, as shown in Figure 2. For the research aircraft data sets (at 25Hz) EDR estimates were calculated from a sliding window of 256 data points, overlapping by 25 pts (1 sec). For the 8Hz B737 wind data, we used smaller window sizes: 128 pts with an 8 pt overlap (1 sec).

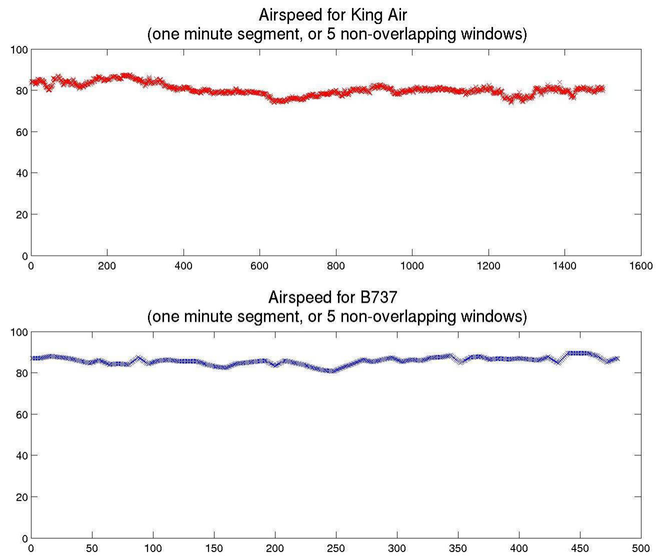

Figure 2. Airspeed (m/s) for King Air and B737 aircraft, sample from 1 minute segment of data, equivalent to 5 non-overlapping windows.

For each window, a power spectra is computed, from which an EDR estimate (EDR $^{2/3}$) is derived using a single parameter maximum likelihood model, assuming a –5/3 Komogorov power spectral form as described in Smalikho, 1997.

After examination of numerous spectra, we chose fixed cutoffs for each aircraft to avoid spectral points dominated by instrument noise at the highest frequencies, and where the spectra deviated from the assumed –5/3 slope at the lowest frequencies (Fig. 3).

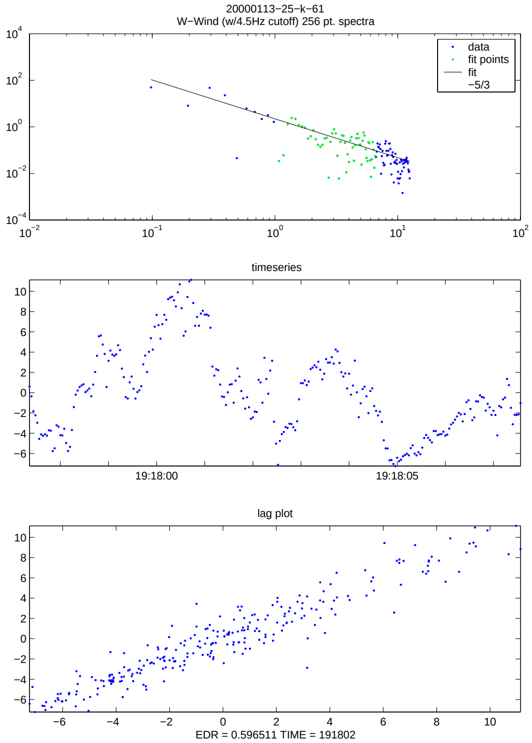

Figure 3. Sample of King Air flight segment: spectral plot (top), timeseries (middle), lag plot (bottom). Points in blue are excluded from the fit to calculate EDR estimate, those in green are included.

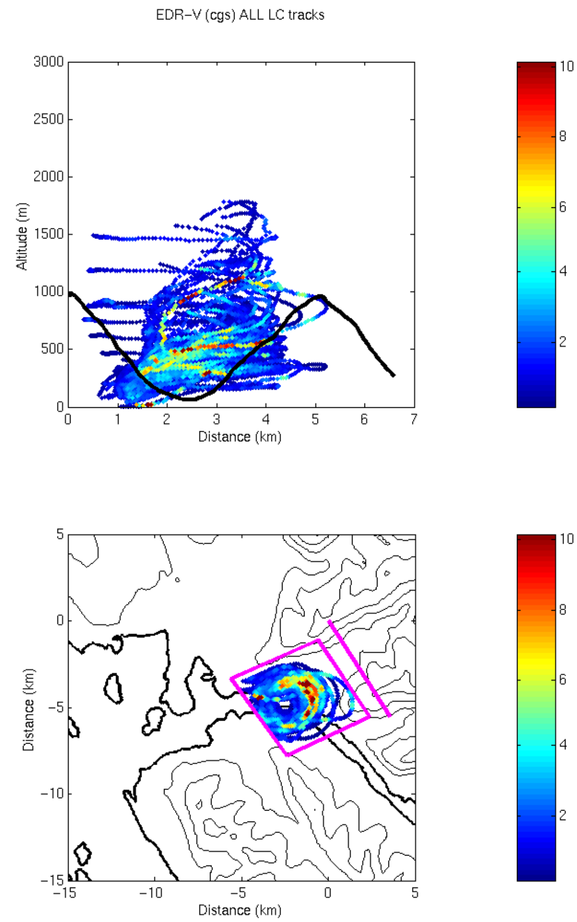

Figure 4. Spatial distribution of aircraft EDR (cgs units, all FY00 flights) estimates near Lemon Creek. Larger values are plotted over smaller values for clarity. Lower plot is a plan-view, upper plot is the projection of the same data onto a vertical plane going through the line shown in the lower plot.

4. TURBULENCE ON JUNEAU, ALASKA ARRIVAL/DEPARTURE PATHS

The largest turbulence events during aircraft departure and arrivals in Juneau are primarily in regions where the aircraft was turning near terrain. Our largest turbulence encounters recorded during the three field seasons were in the area known as Lemon Creek (Fig. 4). Pilot reports at the time confirm the occurrence of high turbulence corresponding with the calculated EDR peaks. Other large turbulence disturbances occur not in turns, but at previous predicted regions in the Gastineau Channel (Fig. 5) and Fox departures, where the airflow is tumultuous under certain wind regimes. These regions of increased hazard were persistent over multiple flight passes through the same regions, and were consistent in location during similar wind regimes over different flight days. This was to be expected given that much of the turbulence was induced mechanically via the surrounding terrain.

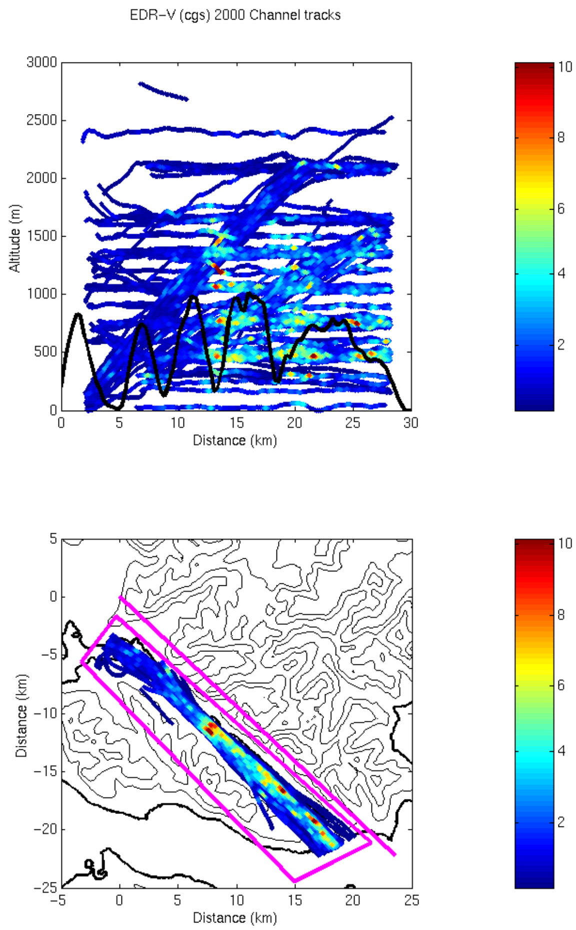

Figure 5. Spatial distribution of aircraft EDR (cgs units, all FY00 flights) estimates in the Gastineau Channel. Larger values are plotted over smaller values for clarity. Plots are of the same configuration as in figure 4.

5. PROBLEMS AND CHALLENGES IN CALCULATING EDR FROM AIRCRAFT MEASURED WINDS

Initial visual examination of the wind timeseries often revealed obvious outlier points. Closer examination of fields which enter into the wind calculations showed physically unreasonable fluctuations in fields such as altitude and airspeed (Fig. 6, altitude; Fig.7, airspeed outlier). As such, we chose to evaluate all of the aircraft wind data using an algorithm that looks for outlier points – a Least Squares Adaptive Polynomial (LSAP), also known as discounted least squares (Abraham and Ledolter, 1983). Any outliers detected by this algorithm were then physically examined to determine if they were indeed an egregious point or merely large but realistic fluctuations in the winds. Each data point was assigned a quality control value that determined whether it would be included in the final data set. Once the data was visually inspected, EDR values were calculated as previously described. These quality control efforts were time consuming but essential to developing a good clean “truth” data set.

As we examined the resulting values between the research aircraft from the first to second field season, we noticed significantly more variable and larger EDR values in the turns from the Citation aircraft data than in the King Air data, even under similar wind regimes. It was determined that there was an uncorrectable problem with the Citation data streams which allows for accurate wind calculations. The Citation INS system lacked this timestamp, and efforts to try and match the INS to the analog system for the Citation aircraft were laborious (and depended on many factors, such as length of turn, wind speeds, and aircraft speed). Thus, data in the turns were deemed unusable for our turbulence estimates.

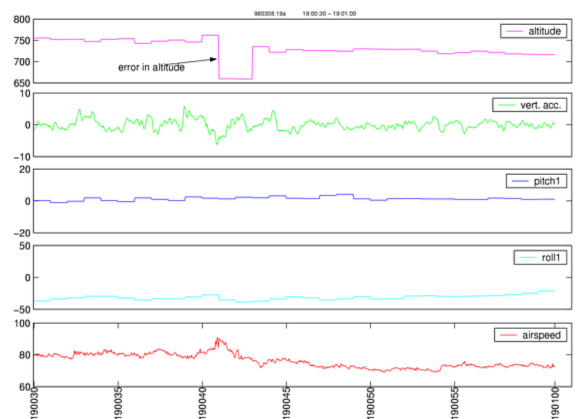

Figure 6. Example of an unrealistic change in altitude, detected during LSAP analysis and visual inspection.

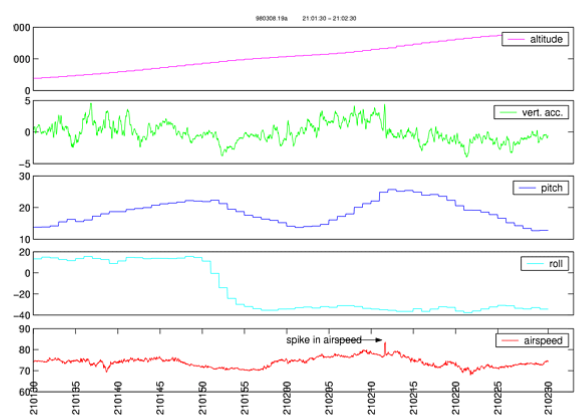

Figure 7. Example of error in airspeed field, detected by LSAP and visual inspection.

Working with the King Air data set, we identified EDR values that seemed erroneously high, based on pilot reports and winds recorded by the wind profiler and anemometer systems. As we looked closer at the underlying data for these EDR estimates, we found little that looked suspicious. It was only when we examined energy spectra from these data did we notice a high frequency contamination of the data (Fig. 8). This contamination was not consistently present in the spectra, nor seemingly predictable. After a through examination of the raw data input into the wind calculations we were able to identify two fields which contained the high frequency contamination. The two fields were unrelated physically, but the measurement systems on the aircraft shared a common desiccant trap and pitot pressure lines. Apparently, the right combination of aircraft speed, head wind and attack angle generated an oscillation in the desiccant trap, which then propagated through the calculations to contaminate our the wind measurements. This contamination was easily removed by a slight adjustment in the frequencies we used to calculate EDR from the power spectra estimates.

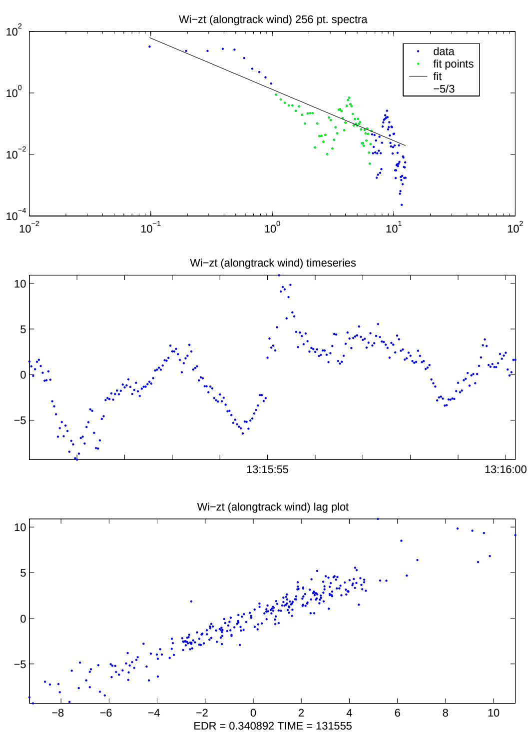

Figure 8. Segment of a King Air flight, showing spectral plot (top), timeseries (middle), and lag plot (bottom). Note the hump on the right side of the spectral plot (in blue, as compared to Figure 3.) – due to oscillation in desiccant trap. Green points are those included in the fit.

Initial comparisons of the FY 03 King Air turbulence estimates with the B737-400 showed reasonable agreement at times and poor agreement at others. Closer examination of dual flights down the Gastineau Channel revealed an error in the B737 wind calculations from the raw data. Once corrected, the two aircraft agreed more closely in the location and temporal placement of turbulence of similar magnitude. The B737 EDR data had a much greater variability than the King Air data, due to the lower resolution and quality of the data. Raw fields for the B737 were collected at different data rates, with the lowest used in the wind calculations at 4Hz. All fields going into the wind calculations were interpolated up to 8Hz, and then used in the wind calculations. Thus, the EDR estimates for this aircraft were less detailed and less reliable than the King Air data. However, they provided a useful means for comparison of the two aircrafts' response to turbulence. Pilot reports for the B737 were also useful for comparing the reactions of different aircraft to similar turbulent air regions.

In an effort to further check our turbulence estimates, we compared our calculated EDR (derived from the vertical winds) to the standard deviation of the measured vertical acceleration. Theoretically, $EDR^{1/3}$ should be linearly related to the standard deviation of the vertical acceleration. Point-wise comparisons of these two turbulence estimators showed some outliers we had previously missed in the winds. Overall, there was good agreement between these two turbulence indicators. The final values of EDR were then used, in comparison with anemometer and wind profiler data, to develop the turbulence warning system, forming the backbone of the JHWAS system (Morse, 2004).

6. CONCLUSIONS

Aircraft vertical wind data provide an excellent means of estimating atmospheric turbulence, even at non-cruising altitude, non-straight and level flight. However, data may require significant QC efforts to remove outlier points, and careful selection of spectral frequency cutoff values to ensure removal of any frequency specific contamination. In the Juneau project, if we had used the EDR values without careful QC work and careful selection of spectral cutoffs to eliminate noise, the truth data set would have contained a number of egregious EDR estimates. Without careful inspection of the data, we would not have realized many of the problems (such as the UND

INS system lag during maneuvers and the oscillation of the King Air desiccant trap) which would have resulted in erroneous EDR estimates entering the truth data set. At cruising altitudes, with straight and level flight, many of the problems we discovered with our data are not generally issues, but any research efforts using aircraft wind data during other phases of flight should use caution when calculating EDR estimates.

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