Response to review of the manuscript Retrieving clear-air turbulence information from regular commercial aircraft using Mode-S and ADS-B broadcast by Anonymous Reviever #1

Dear Anonymous Reviewer #1,

thank you for your valuable comments and the time you have taken for evaluating our manuscript. Below are you will find responses to your comments.

On behalf of the authors,
Jacek Kopeć

Introduction

The response to the review is structured as follows: the reviewer comments are first reproduced in **bold font** followed by authors' responses and indication of appropriate changes in the manuscript.

Review #1 response

This paper provides some initial feasibility studies of the use of Mode-S and ADS-B data streams to infer turbulence experienced by commercial aircraft transmitting those messages. Unfortunately the data available for verification was very limited, and robust results could not be obtained. Still, the paper provides a basis for which future, more detailed studies could be performed to better assess the reliability of the techniques. I recommend therefore that the paper be accepted for final publication, subject to addressing some minor comments listed below.

Minor comments
1. Title: First, the proposed techniques to infer turbulence is not limited to clear-air sources, and in fact they cannot distinguish between encounters in clear air vs in cloud or turbulence due to mountain waves. So the "clear-air" qualifier could be removed. Second, "ADS-B" is an acronym for "Automatic Dependent Surveillance – Broadcast", thus the last word in the title "broadcast" is redundant and could be removed.

Title has been changed accordingly.

Manuscript change

Previous: (Title) Retrieving clear-air turbulence information from regular commercial aircraft using Mode-S and ADS-B broadcast

Current: (Title) Retrieving atmospheric turbulence information from regular commercial aircraft using Mode-S and ADS-B

2.Similarly in the abstract and introduction it is implied that the turbulence inference techniques would be useful for identifying region of turbulence in the "upper troposphere", but many commercial flights, especially in winter, would cruise in the lower stratosphere, so the techniques could be applied to turbulence encounters in the upper troposphere-lower stratosphere (i.e., the UTLS).

Abstract and introduction changed accordingly (i.e. by replacing 'upper troposphere' with 'upper troposphere and lower stratosphere).

3. Abstract: "can be considered a new and valid source". It is not clear from this study that "valid" is an appropriate descriptor. And the technique, if proved feasible, does not

really "measure" turbulence, it can only infer its presence.

Both are good points. Changed abstract formulation accordingly.

Manuscript change

Previous: (Abstract) Navigational information broadcast by commercial aircraft in the form of Mode-S and ADS-B messages can be considered a new and valid source of upper air turbulence measurements. A set of three processing methods is proposed and analysed using a quality record of turbulence encounters made by a research aircraft.

Current: (Abstract) Navigational information broadcast by commercial aircraft in the form of Mode-S and ADS-B messages can be considered a new source of upper troposphere and lower stratosphere turbulence estimates. A set of three processing methods is proposed and analysed using a quality record of turbulence encounters made by a research aircraft.

4. Introduction, lines 27-28. It is stated that "EDR is still not an industry standard". In fact, EDR is the atmospheric turbulence metric required by the International Civil Aviation Organization (ICAO 2001) for routine turbulence reporting, and will likely become the Aircraft Meteorological Data Relay (AMDAR) standard for turbulence reporting as well.

This is of course a mistake in formulation. Thank you for pointing this out. It is a fact that EDR is an industry standard metric when it comes to reporting turbulence (Annex 3 to the ICAO convention). However, the transmission schedule and software requirements for the aircraft are, to our best knowledge, not an international standard. We have rephrased the sentence to be more accurate (according to suggestions of Reviever #2).

Manuscript change

Previous: The only drawback of the EDR data is that it still is not an industry standard, hence its availability is an effect of negotiations with the individual airlines.

Current: The only drawback of the EDR data is that it still is not in widespread use, and its availability is by negotiation with individual airlines.

Introduction, p. 11820 lines 15-16. The proposed technique would have a "spatial resolution of approximately 25 km which is comparable to the in situ EDR data." Current implementations of in situ EDR data provide reports over one-minute of cruise, which for typical airspeeds amounts to about 12-13 km, twice the resolution of the suggested techniques.

Yes, indeed. Looks like we have used way too large airspeed estimate (the calculations indicated 20 km for in-situ EDR which, of course is not reasonable). The error has been corrected and both resolutions have been recalculated for theoretical aircraft velocity 250 ms^{-1}. They are now 25 km and 15 km for Mode-S derived EDR and in situ EDR respectively.

Section 2.1 lists the flights used for calibration of the proposed techniques. These were all summertime cases, and may not be "CAT" at all, but may be related to convection. Calibration for CAT cases may in fact not be included in these data sets.

This may be correct. However, the research aircraft was equipped with forward looking lidar and hence we know the turbulence instances we analyzed were encountered in clear air (despite the presence of clouds nearby). However as available satellite images for the time flights do not serve to totally exclude any potential convective events in the vicinity of the flight tracks we might in fact deal with NCT according to classification from (Sharman et al., 2012). Added explanation in the text.

Manuscript change

Previous: Flight FL9 was selected because of multiple CAT encounters of light to borderline moderate (peak vertical acceleration 0.4 g) intensity as shown in Figs. 1 and 2. Therefore the analysis will be based on three very different flights: turbulent flight (FL9) for validity check, calm flight for (FL6) sanity check and calm flight with turbulence reported in vicinity (FL8) for detection precision check.

Current: Flight FL9 was selected because of multiple turbulence encounters of light to borderline moderate (peak vertical acceleration 0.4 g) intensity as shown in Figs. 1 and 2. The data from the forward looking lidar served to confirm that the investigated encounters were in clear air. However, it is not clear whether the encounters were CAT or near cloud turbulence (NCT) according to classification introduced by Sharman et al. (2012). This choice of flights allows the analysis to be based on three different cases: turbulent flight (FL9) for validity check, calm flight for (FL6) sanity check and calm flight with turbulence reported in vicinity (FL8) for detection precision check.

Section 2.2 describes the processing of the data. Here actual Mode-S data was missing and the data from the DELICAT flights had to be processed to mimic what the Mode-S data transmissions would have provided. This may or may not be satisfactory and leaves some question about the integrity of the results.

We agree that this is not a perfect solution. However due to the early stage of the research and lengthy data access procedures (or data collection times in case one has a receiver available) we have decided to use this method to demonstrate feasibility of this kind of processing. That is why we have taken special care to show as clearly as possible the processing methods and results and demonstrate that in fact the processed data have appropriate structure, time resolution, quantization rules, etc.

8. Section 3 describes methods to infer turbulence from three different techniques. The first and third methods produce estimates of the vertical component of EDR, while the second provides an estimate of the longitudinal component of EDR. In the stably stratified shear flow environment of the UTLS it is not clear the horizontal and vertical component should be the same. Indeed there is ample evidence that they are not the same from field campaigns (e.g., Schumann et al. JGR 1995; Kennedy and Shapiro MWR 1975; Lilly et al. JAM 1974; Sharman and Frehlich AIAA paper 2003-194 2003).

In fact only the first method estimates the vertical component of EDR whilst second and third methods both estimate horizontal component of the EDR. It is a fact that the UTLS turbulence is strongly stratified thus vertical and horizontal components of EDR may differ significantly. We are not trying to imply that the magnitude of EDR estimates should be the same (note that the estimates using method 1 are known up to a constant). The anisotropy may be problematic in another respect. The aircraft is mainly susceptible to vertical velocity variations (hence vertical acceleration as a reference) while methods 2 and 3 use horizontal components of EDR for locating areas of turbulence. The important question here is whether the vertical motion is decoupled from the horizontal motion at kilometer scales which would lead to strong inconsistencies? The mentioned papers neither support nor deny the hypothesis that vertical and horizontal motions are coupled at such scales. (Schumann et al. JGR 1995) might deny such hypothesis but the measurements were conducted in very calm air. Authors indicate the measured ϵ was almost an order of magnitude smaller than climatological values. Another example that could be an issue for such hypothesis is (Sharman and Frehlich AIAA paper 2003-194 2003, Figs. 7 and 8). However, the presented results were achieved using RUC runs with resolution 10km. It is also evident from observations of (Kennedy and Saphiro, MWR 1975) that strong vertical acceleration is related to regions of increased horizontal wind velocity variability at smaller scales. This kind of coupling of the vertical structure in stratified turbulence has been suggested by Lilly (1983) and further observed by e.g. Fincham et. al (1995) and Cho et al. (JGR, 2003). There seems to be a general consensus that in the stably stratified atmosphere the vertical structure is decoupled for scales greater than 10 km and is well coupled for scales O(1 km) and smaller. Somewhere in this range the decoupling begins. Since we are collectively investigating scales 3 - 10 km for horizontal motions where the spectra of horizontal turbulence behave similarly to isotropic turbulence (see e.g., Lindborg, 2006) it is reasonable to assume the horizontal energy cascade to smaller scales where the vertical structure is well coupled.

Aside from all the above considerations, from purely scientific point of view, using commercial aircraft to estimate even only horizontal EDR in UTLS is quite an interesting source of measurements that could help in estimating various transport processes between the troposphere and the stratosphere.

9. The results section 4 discusses the findings relative to an estimated moderate turbulence threshold for small business jets provided in Sharman et al. 2014. However when I look at Fig. 6 in that paper there is a lot of scatter in the data used to de- fine thresholds, so too much emphasis should not be placed on deviations from this number.

Yes that is right. (Sharman et al. 2014) is the only paper we found actually mentioning the number for small business jet. We have changed the text in order to put a slightly smaller emphasis on the discrepancies.

Manuscript change

Previous: The threshold crossing EDR estimate displays values much smaller than those measured by the standard on-board sensors. 0.05 $\mathrm{m}^{\frac{2}{3}}\mathrm{s}^{-1}$ for our estimate vs. 0.18 $\mathrm{m}^{\frac{2}{3}}\mathrm{s}^{-1}$ for small business jet aircraft as reported in (Sharman et al., 2014). This can have various underlying causes. One of the most likely causes is the fundamental difference between the form and properties of canopy turbulence considered in (Poggi and Katul, 2010) and the upper tropospheric/lower stratospheric turbulence investigated in the current analysis.

Current: The threshold crossing EDR estimate displays values much smaller than those measured by the standard on-board sensors. 0.05 $\mathrm{m}^{\frac{2}{3}}\mathrm{s}^{-1}$ for our estimate vs. 0.18 $\mathrm{m}^{\frac{2}{3}}\mathrm{s}^{-1}$ for small business jet aircraft as reported in (Sharman et al., 2014). Due to very significant scatter of the reference results this may be not a very serious issue. However, it is worth pointing out that our analysis is based on a theory developed for canopy turbulence considered in (Poggi and Katul, 2010) and not for the upper tropospheric/lower stratospheric turbulence investigated in the current analysis.

10. I think the conclusions as stated are fair, and that probably much more work needs to be done using more data in all seasons to better assess the feasibility and reliability of the proposed approaches. Another approach besides using methods independently is perhaps to use a synthesis of Mode-S and ADS-B inferences in some sort of ensemble-like or fuzzy-logic framework to provide more robust results. Operationally it is important to provide high reliability at the larger EDR vales. Inconsistency at low values, e.g. 0.08 vs 0.12, is probably less operationally significant, at least for commercial aircraft. In this regard the approach used by Krozel and Sharman ("Remote detection of turbulence via ADS-B", AIAA Guidance, Navigation, and Control Conf., Kissimmee, FL, Jan., 2015) where only significant ADS-B altitude deviations were used to infer turbulence might be operationally more reliable. One problem in that study was the lack of aircraft that were actually outfitted with ADS-B. Full implementation is not expected until 2020. Also the authors should be aware that there is a proposal to incorporate a field for in situ edr measurements in the ADS-B data stream (see RTCA DO-260B, Appendix V). However manufacturers of ADS-B have not yet implemented this, and it would likely be some years before it would happen.

Thank you for this comment and for the reference. We were not aware of the paper by Krozel and Sharman. The reference has been mentioned in the paper now. Ensemble like approach probably is the next logical step but applied on a much larger dataset and depending on the relative performance of the individual methods. We agree that investigating more intense turbulence is necessary and it would be a very interesting exercise to compare our methods against those proposed by Krozel and Sharman and against in situ EDR measurements on a much bigger dataset than used in the present study. We are also aware that even presently there are possibilities to broadcast EDR directly via Mode-S (MRAR messages) . Such broadcast requires ANSPs to actively query the transponders for such data. However, MRAR messages have two problems: the number of aircraft thar are capable of broadcasting such data is very limited and ANSPs we have contacted are generally not willing to enable routine MRAR queries due to bandwidth considerations. The planned ADS-B EDR incorporation is a very valuable and interesting initiative in this context. We consider in situ data always preferable to remote estimates proposed in our manuscript. However, as long as the exchange of meteorological data with aircraft will be as heavily constrained as it is now our idea is to use whatever data available to enable research that would be otherwise very hard with low resolution datasets such as AMDAR. Regarding ADS-B data they are available in Europe in ample quantities (we are currently maintaining a set of receivers in Poznań, Poland). However, in situ EDR coverage is very sparse in comparison with the United States.

MANUSCRIPT CHANGE

Added a sentence in the introduction: We know of one other alternative approach to ADS-B being investigated simultaneously (Krozel and Sharman, 2015).
Added a reference (Kozel and Sharman, 2015).

11. The English needs some reworking here and there, but for the most part is understandable.

We have made an effort to improve the quality of English in the whole manuscript resulting in a number of minor corrections.