WHITE PAPER

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En-route turbulence detection using Aireon space-based ADS-B

Severe turbulence encounters can force airlines to ground and inspect affected aircraft upon arrival, thereby losing operational capability and decreasing the efficiency of their fleet operations; in the worst cases, severe turbulence can also lead to passenger and crew injuries. Often, airlines do not have access to severe turbulence encounter information until after the aircraft lands, which causes delays in the inspection operations and lengthens the grounding of the aircraft. This paper presents a novel method that exploits Aireon space-based Automatic Dependent Surveillance Broadcast (ADS-B) data to detect in near-real-time severe turbulence encounters at a global scale, which can be implemented to provide additional awareness to air traffic stakeholders, allowing for rapid response both in terms of airborne and on-ground operations.

I. Introduction

Climate change has caused an increase in aviation turbulence encounters globally, augmenting the stress on an already saturated network [1, 2]. In the U.S., around 65,000 moderate turbulence Pilot Reports (PIREP) and 5,500 severe turbulence PIREPs are issued every year [3]; in the period between 2009 and 2018, 123 people were seriously injured following a turbulence encounter by Regularly Scheduled Air Carriers (Part 121), 78.9% of which were flight attendants and 21.1% were passengers [4]. Even in cases where no injuries occur, turbulence encounters cause economic burden for the airlines and discomfort for passengers, with delays due to grounding aircraft for inspection and maintenance.

Awareness of ongoing turbulence phenomena is currently limited for both crews and ground operators. With the widespread adoption of ADS-B data from aircraft, partially thanks to mandates in many countries across the globe, the telemetry information included within these messages can be analyzed to identify severe turbulence encounters and make this information available in real-time. Stakeholders can use this information for route optimization, and ground operation planning, and to corroborate the severity of a turbulence encounter with subjective PIREP information.

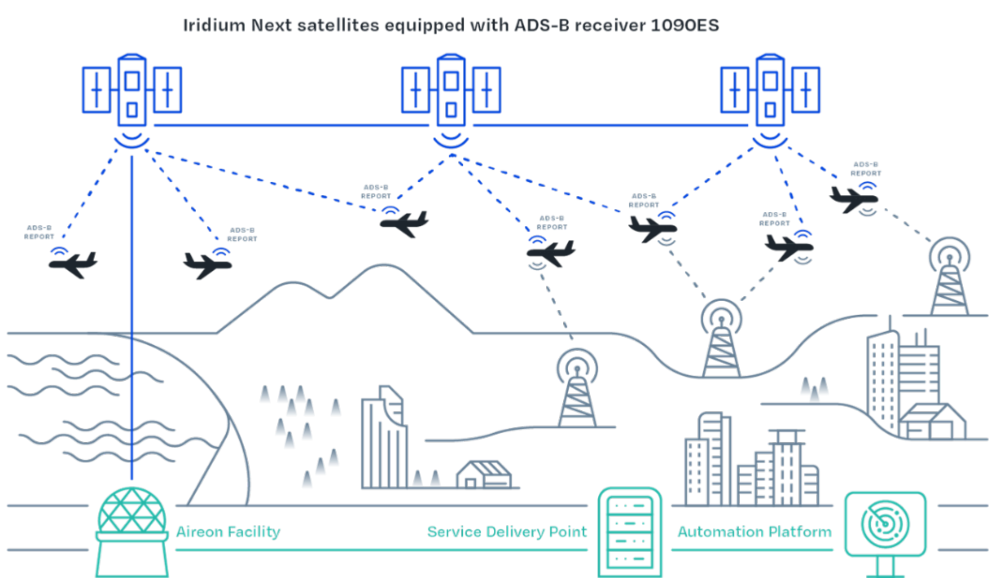
In this paper, the authors present a novel approach that uses the aircraft position, altitude, and velocity reports from Aireon space-based ADS-B data to infer the encounter with turbulence phenomena. The main parameters used are the geometric and barometric altitude, the geometric and barometric vertical rate, and the airborne ground vector information, all of which are readily available in ADS-B reports. An analysis of the variance of these parameters, compared to expected trends for the different flight phases allows the detection of turbulence. The use of surveillance data, and specifically ADS-B, for the detection of turbulence encounters has been addressed in previous research [5], which, given their high update rate, constitute a strong dataset to understand the behavior of the aircraft; in [6, 7], the use of this concept is expanded by means of combining ADS-B with Enhanced Mode S (EHS) data. The approach presented in this paper differentiates from previous research by using only information available in ADS-B messages, which does not include EHS data, with no other data sources. Additionally, the analysis is extended to a global scale, via Aireon space-based ADS-B, overcoming the limitation of being tied to areas where ground secondary surveillance radars are available. This paper focuses on the detection of turbulence encounters during level flight phases.

Section II of the paper provides an overview of the Aireon system and its performance; the proposed methodology for the detection of turbulence is described in Section A of this paper. Finally, in Section III results are presented where the proposed approach was applied to data for known events across different regions and to randomly selected regions in different point in time to assess the sensitivity.

II. Aireon System

In April of 2019, the Aireon space-based Automatic Dependent Surveillance Broadcast (ADS-B) system went operational and began providing service to air navigation service providers around the world. The Aireon system leverages the Iridium constellation of satellites. Iridium’s low-latency, 66 cross-linked LEO satellites – plus 14 orbiting spares – orbit approximately 485 miles above the earth, with each satellite linked to up to four others, creating a dynamic mesh network to ensure continuous availability, everywhere on the planet. The Iridium satellites host the Aireon ADS-B receivers that relay signals from ADS-B equipped aircraft to the ground in real-time [8].

FIGURE 1
Aireon’s space-based ADS-B system



The latency of Aireon system amounts to less than 400ms when delivering ADS-B messages from reception at the satellite to the downstream user [9], providing a high rate of detection in many environments around the world. Although generally the system is targeting meeting an 8s or less update interval 96% of the time, a median update rate of 2 seconds is observed in areas with low traffic density and low interference in the 1090MHz spectrum [10].

A. Methodology

The approach presented in this section, exploits time series analysis techniques to identify outliers in the behavior of the aircraft that can be related to turbulence encounters, using only fields available in ADS-B reports (e.g., barometric, and geometric altitude, barometric and geometric vertical rates, ground speed and track angle). Aireon stores and shares ADS-B messages using the standard ASTERIX CAT021 format [11], which are constructed from the ADS-B squitters following the EUROCAE ED-129B specification [12].

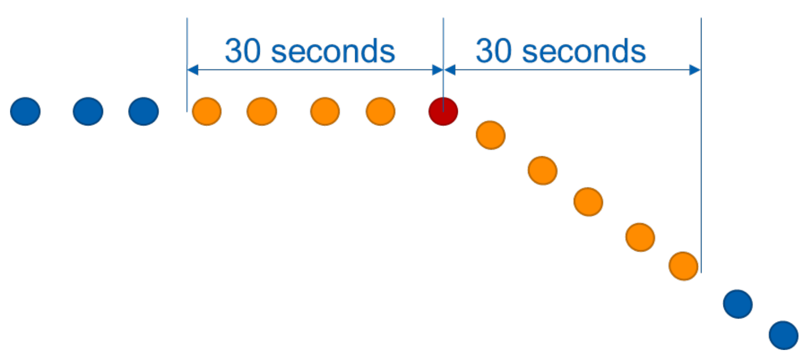
B. Level-flight Phase Identification

Maneuvers, both at low and high altitude, cause rapid changes in the vertical rate that could mislead the detection algorithm. In this paper, the turbulence detection algorithm is applied only to level-flight phases. To ensure a timely and precise identification of a flight phase transition, a pivot-based approach was developed, based on the analysis of the trend of data on defined time windows prior and after a given candidate position (pivot-point). A rolling average of the derived Vertical Rate, V_D, based on changes in the reported altitude over the previous $30\ seconds$ is computed. The use of altitude to derive V_D reduces delay and steadies flight phase transitions versus using the noisier vertical rate reported from the aircraft.

An absolute comparison of reported altitude, A, to pilot selected altitude, S, is also used to identify when the aircraft transitions in and out of the cruise phase. This comparison is done on a message by message and not on a window.

Consider a candidate transition point (highlighted in red in Figure 2) v_D, the rolling average of Vertical Rate values in a window of $30\ seconds$ prior to the pivot point V_D^-, and the rolling average Vertical Rate values in a window of $30\ seconds$ after the pivot point V_D^+. The union of the two sets is denoted as V_D and contains all the smoothed values across the entire $1\ minute$ horizon.

FIGURE 2
Representation (altitude vs time) of pivot-base flight phase transition logic



Transitions are then identified using the following algorithms, where $\bar{X}$ is used to identify the average value and $||X||$ represents the absolute value:

Any Phase — Cruise Transition:

$$||\bar{V}_D^-|| > 150\ fpm\ \ AND\ \ ||\bar{V}_D^+|| \leq 150\ fpm\ AND\ ||A - S||\ \leq 400\ ft$$

Cruise-Climb Transition:

$$||\bar{V}_D^-|| \leq 150\ fpm\ \ AND\ \ \bar{V}_D^+ > 900\ fpm\ OR\ ||V_D|| \geq 800\ fpm$$

Cruise-Descent Transition:

$$||\bar{V}_D^-|| \leq 150\ fpm\ \ AND\ \ \bar{V}_D^+ < -600\ fpm$$

Descent-Climb Transition:

$$\bar{V}_D^- \leq -600\ fpm\ \ AND\ \ \bar{V}_D^+ \geq 900\ fpm$$

Climb-Descent Transition:

$$\bar{V}_D^- \geq 500\ fpm\ \ AND\ \ \bar{V}_D^+ \leq -1500\ fpm$$

Each new flight starts from an UNKNOWN state, from which a transition into the one of the phases is detected using the following logics:

UNKNOWN-Climb:

$$\overline{V_D} \geq 1500$$

UNKNOWN-Descent:

$$\overline{V_D} \leq -1500$$

UNKNOWN-Cruise

$$||\overline{V_D}|| \leq 150$$

The flight phase will return to UNKNOWN state if at any time during a Cruise phase the following holds true:

Cruise-Unknown Transition:

$$||A - S|| \geq 400\ ft$$

Considering that gaps in the data could lead the algorithm to miss flight phase transitions, thereby applying the turbulence detection logic to the phase, the flight phase is reset to UNKNOWN if fewer than 3 reports are seen within $30\ seconds$.

C. Data Preparation

Due to the nature of the ASTERIX CAT021 format and the different transponders and systems installed onboard the aircraft, fields might not be always populated. There are instances where the aircraft might switch from barometric to geometric altitude or report only one of the two (the same applies to the vertical rate information); in other cases, the ADS-B message might report the altitude but not the relative vertical rate. Prior to applying the turbulence detection logic, the above-mentioned issues need to be addressed.

Data is first resampled to one message per second, then the altitude values are coalesced into the $\hat{h}$ value. To compensate for the difference in resolution between barometric and geometric altitude and to overcome value jumps due to data binning and resolution, a smoothing approach is applied, resulting in a smoothed altitude $\tilde{h}$. The smoothed vertical rated $\widetilde{v_h}$ is then computed as follows:

$$\widetilde{v_h} = \frac{\Delta\tilde{h}}{\Delta t} = \frac{\tilde{h}_i - \tilde{h}_{i-1}}{t_i - t_{i-1}} \;\forall\, i = 1, \dots, N$$

with t being the Time of Message Received (TOMR) for the ADS-B position squitter message. Similarly, the acceleration related to the ground speed v_g is computed using the equation below:

$$a_g = \frac{\Delta v_g}{\Delta t} = \frac{v_{g,i} - v_{g,i-1}}{t_i - t_{i-1}} \;\forall\, i = 1, \dots, N$$

D. Turbulence Detection

When analyzing data related to known encounters (flight HAL35 on 2022-12-18 [13] and flight ARG1133 on 2022-10-18 [14]), a common trend of high dispersion of the data around the time of these encounters was identified (see Fig. 3 and Fig. 4); another characteristic of this phenomenon is the short period in which it manifests, generally amounting up to few minutes. To explore anomalies in the vertical rate and acceleration, the variance on a sliding window of 60 seconds was computed ($\sigma_v^2(60)$ and $\sigma_{a,}^2(60)$ respectively). All the Figures below report the smoothed vertical rate $\widetilde{v_h}$.

FIGURE 3

Example of turbulence encounter - Flight HAL35 on 2022-12-18

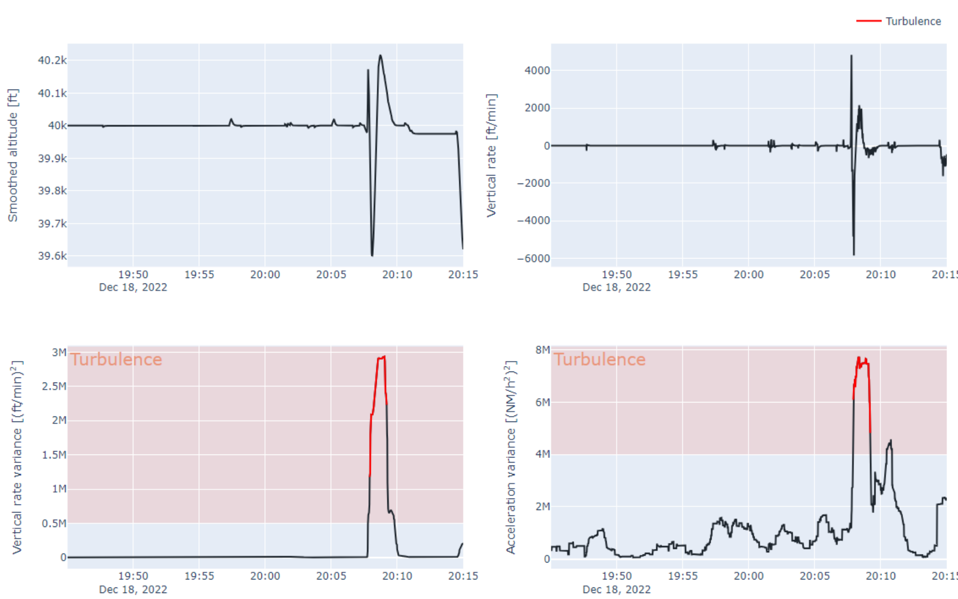
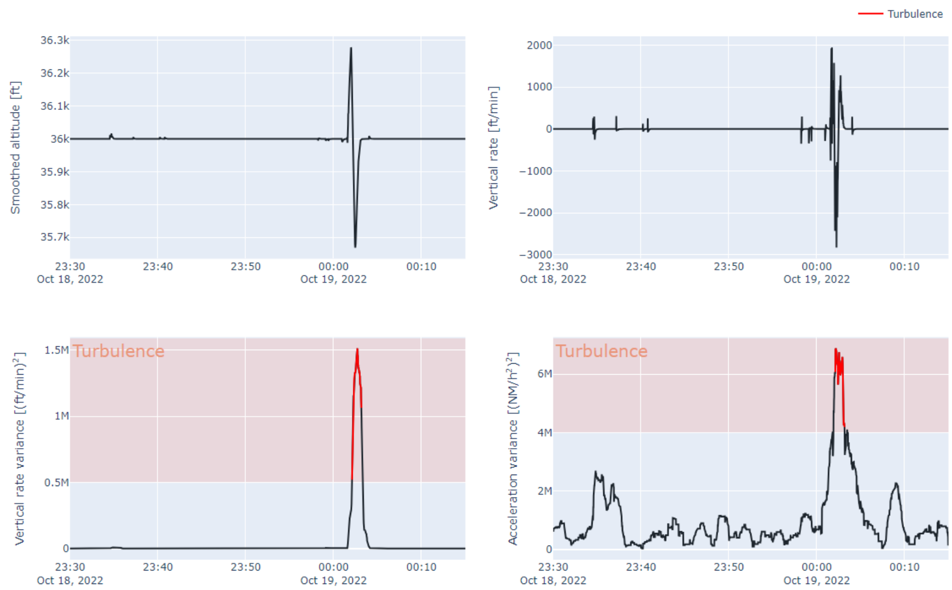


FIGURE 4
Example of turbulence encounter - Flight ARG1133 on 2022-10-18



The analysis shows that spikes in the variance can be identified both in the vertical rate and the acceleration timeseries at the time of the turbulence encounter for both test cases. Thresholds of $\sigma_v^2(60) = 0.5 \times 10^6$ and $\sigma_a^2(60) = 4 \times 10^6$ were set to identify when turbulence was encountered; the extent of the portion of flight identified as being affected by turbulence encounter will depend on the severity of the turbulence event. In the case of flight HAL35, these thresholds successfully captured the turbulence encounter, but did not indicate turbulence during the descent, shown around 20:15Z in

Figure 3, where altitude and vertical rate are expected to change.

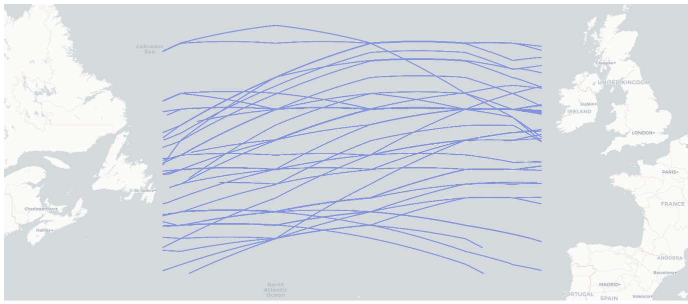
III. Results

A. Datasets Used

In the recent years, several cases of severe turbulence encounters occurred causing several injuries across passengers and crew members [15-20]. These flights were used to verify the effectiveness of the proposed methodology. In addition, a dataset of 50 randomly selected flights across the North Atlantic routes on 2024-06-01 (

Figure 5), for which no turbulence encounter was reported, was used to verify the false positive rate when applying the algorithm to an unknown dataset.

FIGURE 5
50 flights over the North Atlantic on 2024-06-01



B. Test Case Results
Figure 6 to

Figure 10 depict cases for which the algorithm was able to correctly detect a severe turbulence encounter; it can be observed how the turbulence affects the aircraft in very different ways for each flight and the algorithm is able to properly address all these different cases. Furthermore, when analyzing the data for flight TSC123, MLT1975, and QTR017, a persistent level of noise in the vertical rate and speed could be identified, which can be caused by the accuracy of the onboard sensors or by the quantization of the ADS-B data; however, the algorithm proved to be robust to the noise in the data, triggering only at the time of the reported turbulence encounter.

FIGURE 6
Flight HAL451 on 2023-06-30

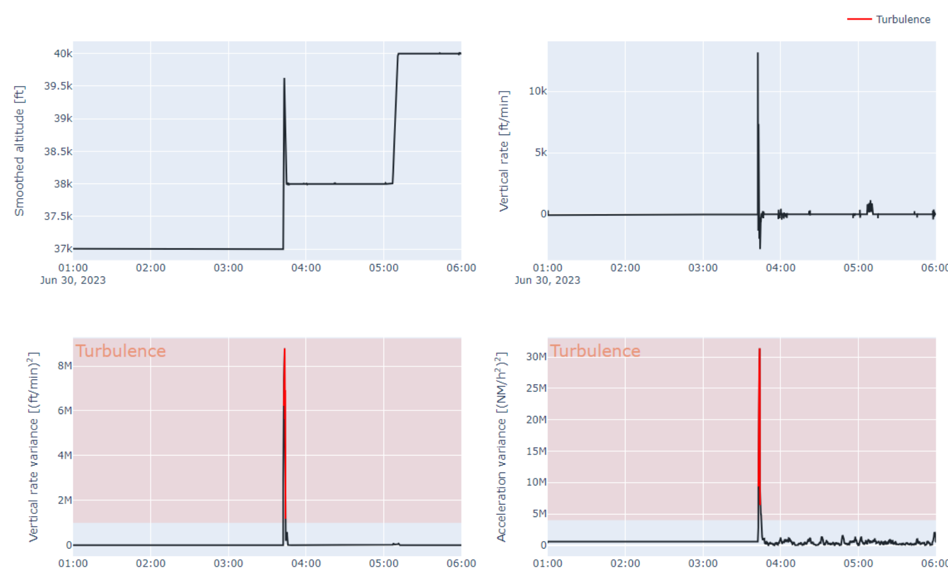


FIGURE 7

Flight SIA321 on 2024-05-21

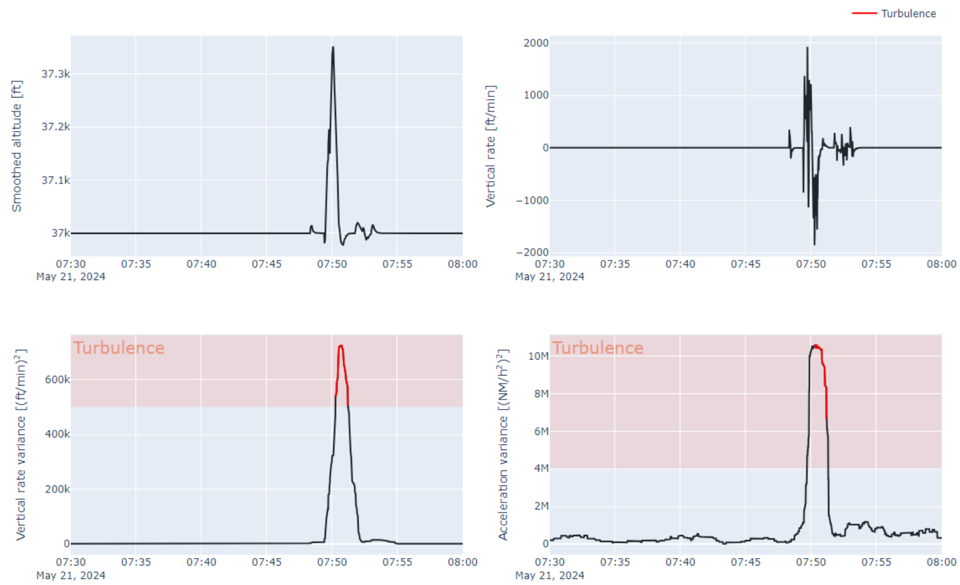


FIGURE 8

Flight TSC123 on 2023-11-07

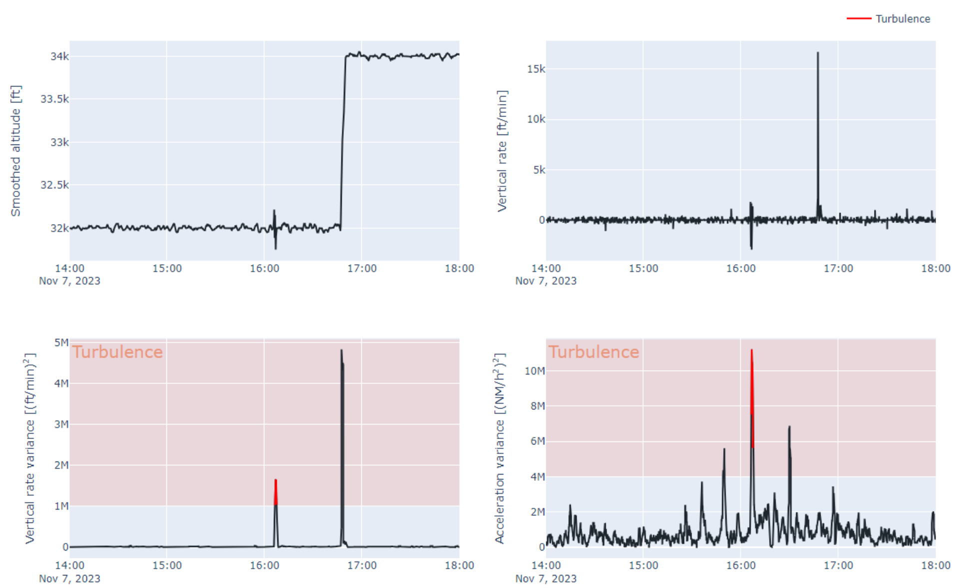


FIGURE 9
Flight MLT1975 on 2023-12-24

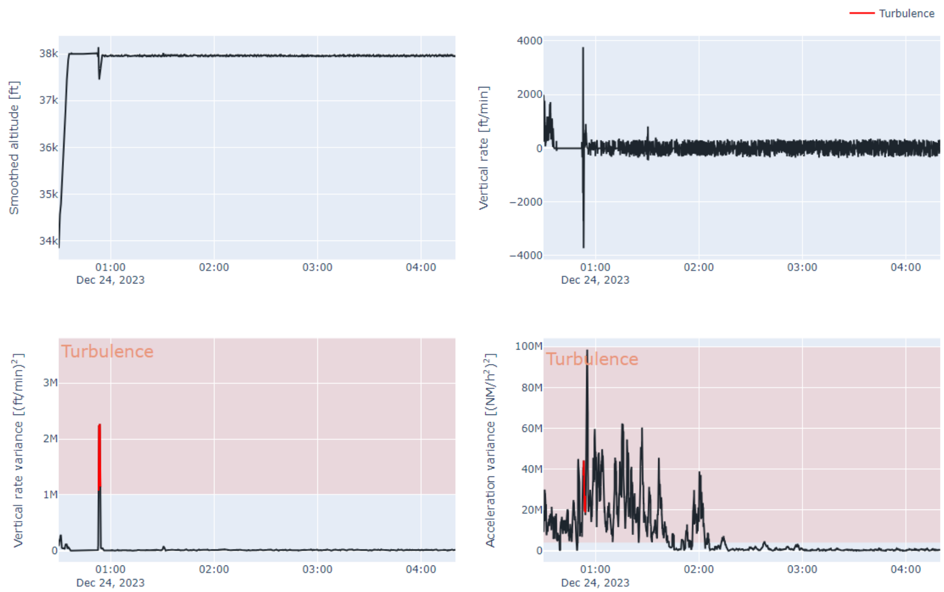
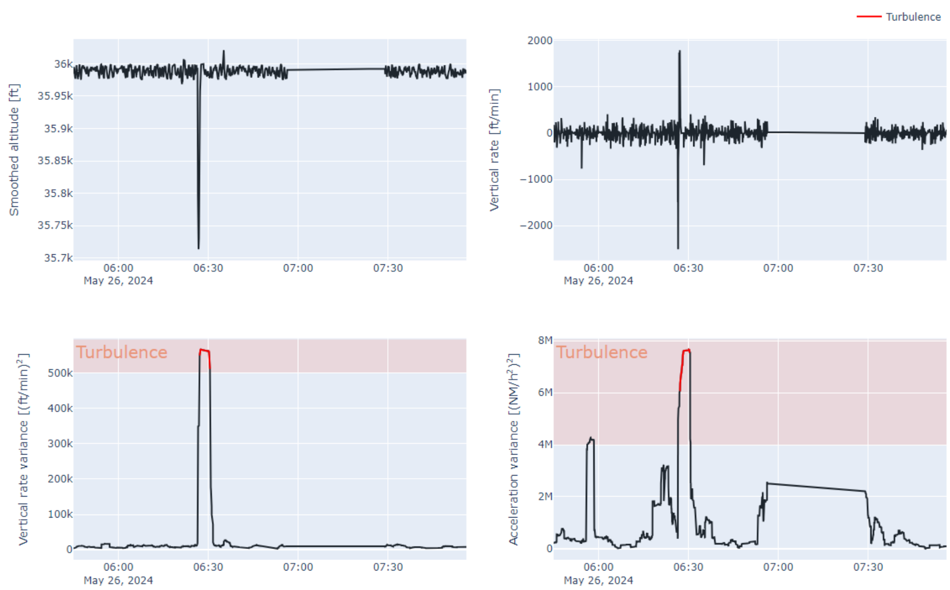


FIGURE 10
Flight QTR017 on 2024-05-26



When investigating the cases of Flight UAE421 in

Figure 11 and ANZ65 in

Figure 12, the algorithm did not detect any encounter; by examining the underlying data, it can be found that the turbulence was not reflected in the ADS-B reports in the form of sudden variations in altitude and/or vertical rate. A variation in the vertical rate can be observed for flight UAE421 around 21:05Z but its magnitude is not comparable with the other cases analyzed.

FIGURE 11
Flight UAE421 on 2023-12-04

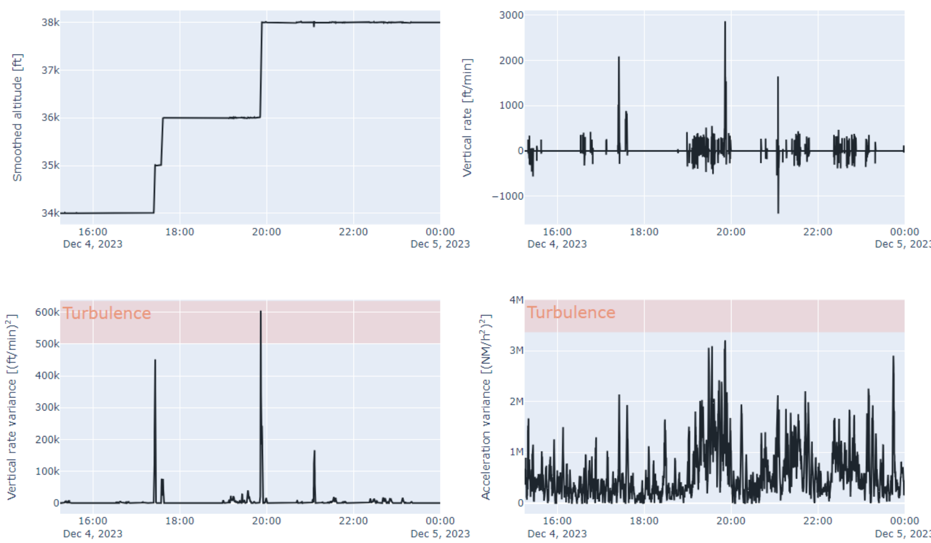
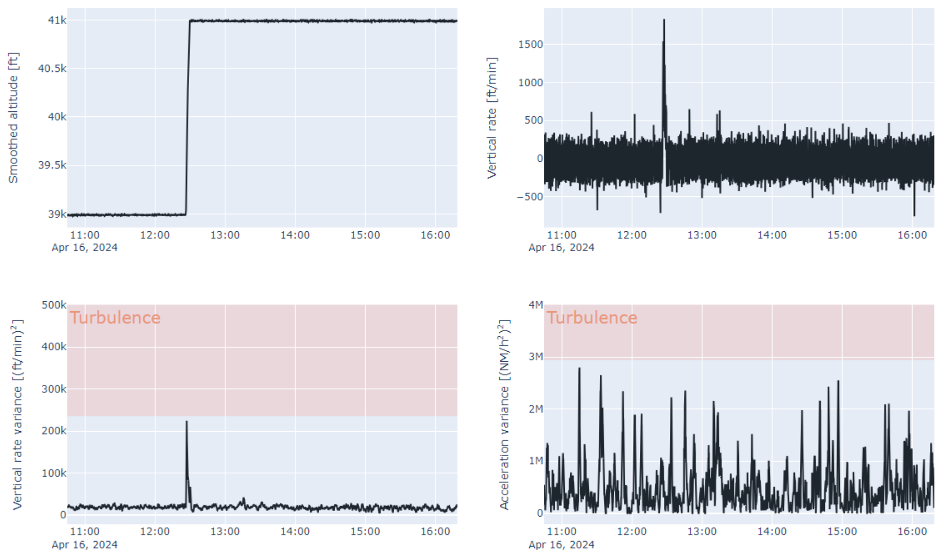


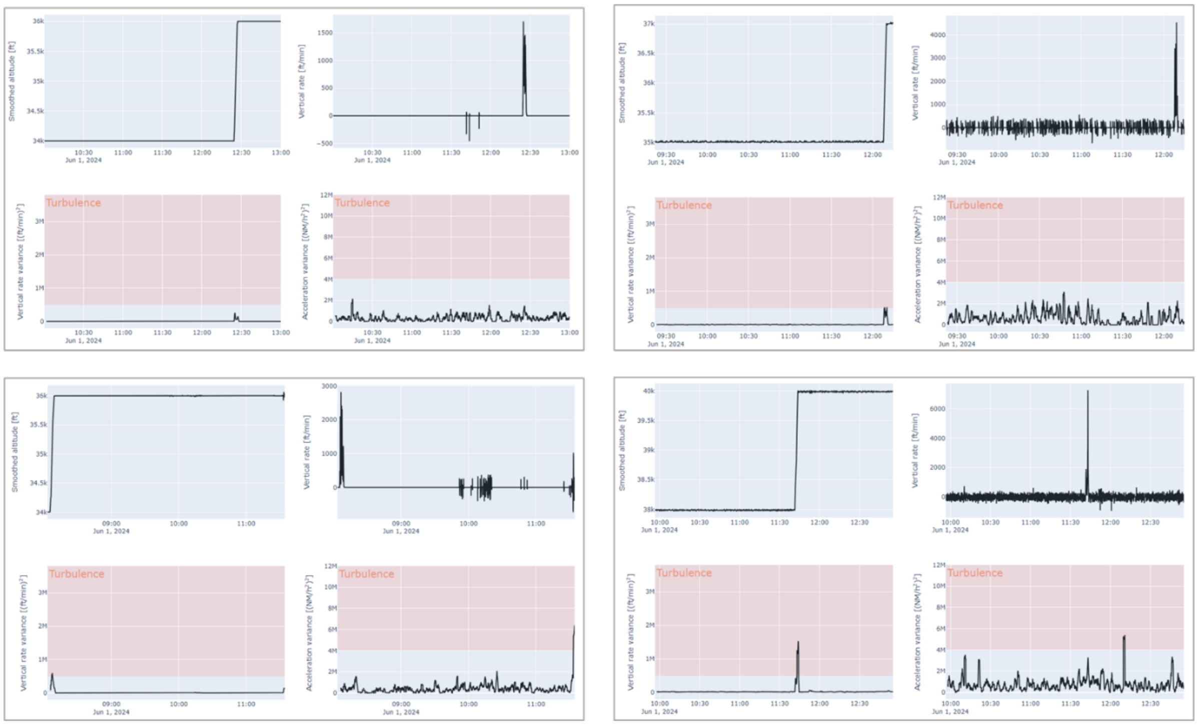
FIGURE 12
Flight ANZ65 on 2024-04-16



1. *False Positive Assessment*

Figure 13 reports the analysis of a sample of these flights showing smooth timeseries and no sudden variations in the vertical rate or acceleration, other than the ones due to climb and descent maneuvers when changing cruising altitude. These results demonstrate the algorithm could be applied to different scenarios while maintaining a low number of false positives.

FIGURE 13
Sample result for flights over the North Atlantic on 2024-06-01



IV.Conclusion

With the ongoing increase in severe turbulence encounters by aircraft across the globe, a tool that can identify in near real-time these encounters at a global scale becomes extremely valuable as it can be used to broadcast such information to nearby aircraft and can inform airline operators about possible damage to their aircraft, leading to more efficient organization of the ground operations and inspections after the aircraft lands.

In this paper, the authors propose a methodology that leverages only Aireon space-based ADS-B data to detect said encounters globally. The current approach showed encouraging results but is limited to level-flight applications; the authors aim at extending the model to work in all flight phases in the next future. Future work will also focus on the identification of precursors for these events in flights that flew in the proximity of the aircraft that encountered turbulence in the minutes preceding the event.

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