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DEVELOPMENT AND FLIGHT DEMONSTRATION OF A NEW LIDAR-BASED ONBOARD TURBULENCE INFORMATION SYSTEM

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Abstract

Atmospheric turbulence has been the major cause of in-flight injuries of commercial airliners during the past 20 years. The Japan Aerospace Exploration Agency (JAXA) has developed the airborne turbulence information system using the airborne Doppler lidar. The system is designed to inform pilots of preceding turbulence or windshear in clear sky condition, in which the existing airborne Doppler radar does not work. The JAXA installed the system on a small jet aircraft and successfully flight-demonstrated its turbulence and windshear detection capability. In addition, the JAXA and the University of Tokyo jointly developed a novel airspeed advisory system that shows lidar-predicted airspeed change for pilots to help airspeed maintenance in turbulent or windshear conditions.

1 Introduction

Atmospheric turbulence has been the major cause of in-flight injuries of commercial airliners during the past 20 years. More than half of the commercial airliner's accidents in Japan are caused by turbulences (Fig. 1). The number of accidents due to turbulence also increases in the United States of America [1]. Considering that air traffic steadily increases in the world, the number of accidents due to turbulence will further increase without effective countermeasures. Currently, most of such turbulence related accidents are caused by clear air turbulences (CATs) which are not detected by the existing airborne Doppler radar. We need a new airborne sensor that detects CATs to prevent accidents. The lidar, laser radar, can detect CATs by detecting the movement of small particles (aerosols) in the air or air molecules themselves. Although several studies of the airborne lidar for CAT detection have conducted mainly in Europe [2], there is no practical CAT detection system yet.

The Japan Aerospace Exploration Agency (JAXA) and the Mitsubishi Electric Corporation (MELCO) have jointly developed the new Doppler lidar whose laser power is powerful enough to detect CAT in over 10 km ahead. In addition, the lidar is small enough to be installed on even small aircraft [3]. Using this Doppler lidar, the JAXA has developed the airborne turbulence information system, named 'SafeAvio', to inform pilots of preceding turbulence or windshear in clear sky condition, in which the existing airborne Doppler radar does not work. The SafeAvio system also has airspeed advisory function that informs pilots of predicted airspeed change in several ten seconds by exploiting the lidar-measured headwind information. This function was jointly developed by the JAXA and the University of Tokyo [4]. The JAXA installed the SafeAvio system on a business jet airplane and conducted the flight test to evaluate its performance. A piloted flight simulation using full flight simulator was also conducted to evaluate the SafeAvio airspeed advisory function. This paper describes the SafeAvio system including its design and evaluation results.

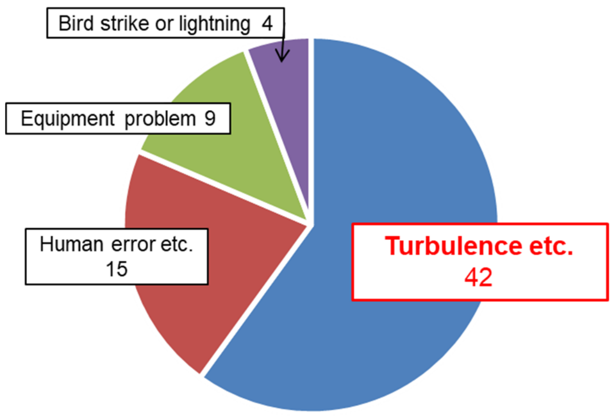


Fig. 1. Numbers and causes of commercial airliner's accidents in Japan during 1990-2014. (Based on the accident reports of the Japan Transport Safety Board)

2 SafeAvio System

2.1 Concept of Operation

Figure 2 shows the concept of operation of the SafeAvio system. In the cruise phase, the SafeAvio system provides CAT information to pilots. Based on the information, pilots can prepare for turbulence penetration including encouraging passengers to fasten seatbelts and decreasing airspeed down to turbulence penetration speed. While, in the approach phase, the SafeAvio system provides windshear information to pilots. Based on the information, pilots can conduct a go-around maneuver to avoid windshear. As airspeed advisory, the SafeAvio system provides the predicted airspeed and the target airspeed information to pilots, considering headwind change observed by the lidar. Based on the information, pilots can conduct corresponding operation to airspeed change in a timely manner, resulting in preventing overspeed or stall in windshear.

2.2 Performance Requirement

To realize the concept of operation, we defined the turbulence/windshear detection requirement of the SafeAvio system as shown in table 1. The requirements are based on the existing performance requirements for airborne Doppler radar [5], which are also shown in table 1 for reference. Although the requirements for turbulence detection range in the cruise phase and detection area are relaxed compared to the those for radar systems, it should be clear that the lidar would be an addition to and not a replacement for the radar system. At the same

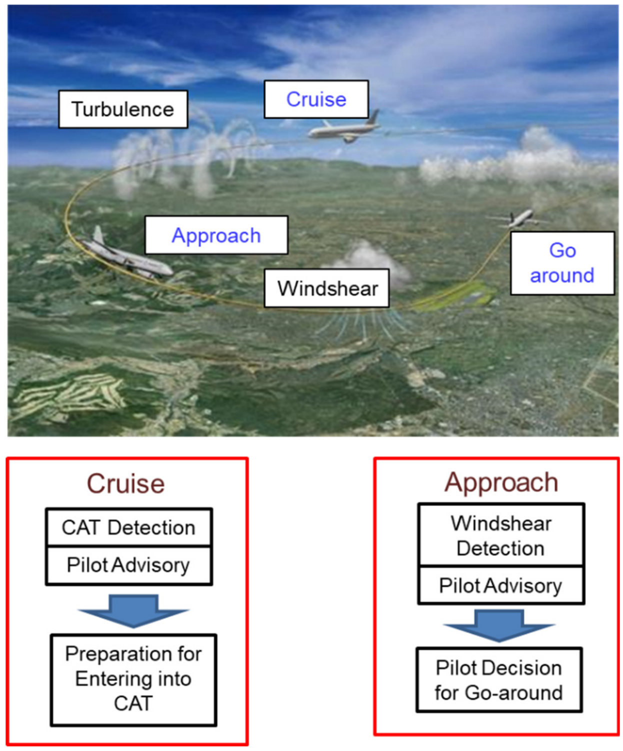


Fig. 2. Concept of operation of SafeAvio.

Table 1. Turbulence/windshear detection requirement of SafeAvio system.

(a) Turbulence detection (cruise phase)

Sensor	Detection threshold	Detection range	Detection area
SafeAvio (Lidar)	0.3 g*	14 km	Forward only
Radar	0.3 g*	74 km	Forward ±60 deg.

* running 5-second windowed root mean square of the aircraft vertical acceleration

(b) Windshear detection (approach phase)

Sensor	Detection threshold	Detection range	Detection area
SafeAvio (Lidar)	2.5 kt/sec.*	5.6 km	Forward only
Radar	2.5 kt/sec.*	5.6 km	Forward ±30 deg.

* corresponding to F-factor = 0.13

time, the radar system would not be able to detect anything in clear air (0km range, 0deg area), basically making any detection range and area a valuable addition.

In general, lidar's measurement range is shorter than radar because back scattered laser signals from small particles or molecules are much weaker than back scattered radio signals from precipitations. In addition, the density of small particles decreases at high altitudes where aircraft cruise, resulting in further weaker back scattered signal. Therefore, we defined the required turbulence detection range in cruise phase as 14 km that corresponds to 60 seconds advance detection considering aircraft cruise speed. The 60 seconds advance warning is not long enough for turbulence avoidance, but enough to prepare for turbulence penetration such as fastening seatbelt. The relaxation of detection area requirement is stemmed from lidar's hi-speed scanning difficulty due to its low data output rate. The SafeAvio's lidar outputs airflow data at 0.25 – 1 Hz. The lidar needs signal integration time of 1 – 4 seconds to retrieve airflow information from back scattered signal. This integration is necessary to suppress random noise in the signal. Such integration is also conducted in radar signal process. However, lidar's integration time is much longer than radar due to weaker back scattered signal. In scanning, low data output rate results in low angular resolution in azimuth. We therefore abandon scanning and only requires forward looking capability for lidar.

As to the airspeed advisory, we require two functions: the lidar-based predictive airspeed indication (L-PSPD) and the lidar-based target airspeed indication (L-TSPD). The L-PSPD provides the predicted airspeed in 5/10/20 seconds. The L-TSPD provides target airspeed, which dynamically changes according to the predicted airspeed, to minimize airspeed deviation from the reference airspeed. Both the L-PSPD and the L-TSPD help pilots to maintain airspeed in windshear conditions.

2.3 System Design

Figure 3 shows the block diagram of SafeAvio system. Airflow information ahead of aircraft is measured by the onboard Doppler lidar jointly developed by the JAXA and the MELCO (Fig. 4, Table 2). This lidar is all-fiber based Doppler lidar and its weight is about one-tenth of the existing lidar of the same laser power class thanks to its advanced optical lased amplifier and signal processing for noise suppression [3]. The SafeAvio system estimates headwind component at every 300 m up to about 30 km ahead of aircraft by subtracting aircraft motion from lidar-

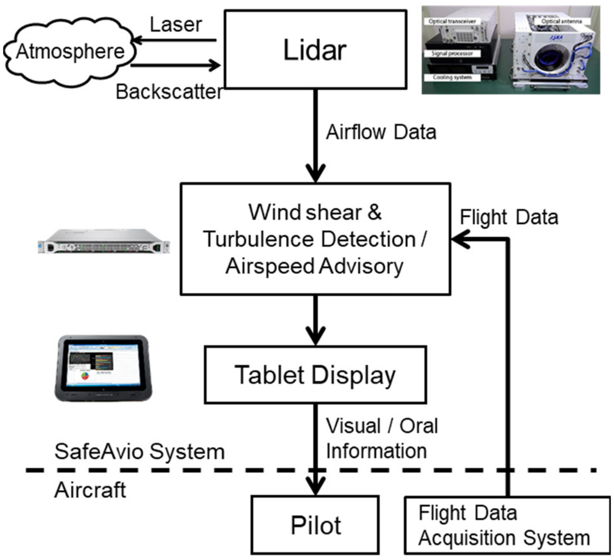


Fig. 3. Block diagram of SafeAvio system.

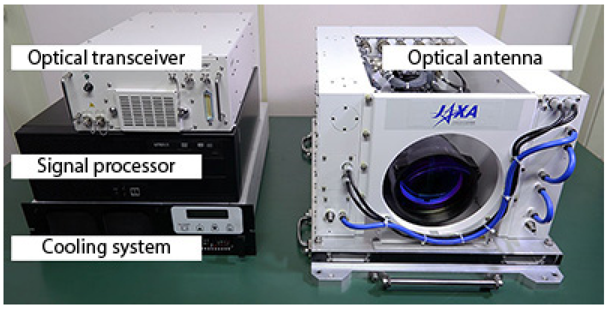


Fig. 4. Airborne Doppler lidar.

Table 2. Major specifications of airborne Doppler lidar.

Laser wave length	1.5 µm
Laser power	3.3 W
Beam diameter	150mm
Weight	83.7 kg
Power consumption	936 W

measured airflow data. Please note that lidar measurement range depends on the density of aerosols whose size is micro-meter order. 30 km is almost the maximum range typically achieved at low altitudes. The estimated wind data output rate is 0.25 – 1 Hz. All functions of the SafeAvio system, including turbulence/windshear detection and airspeed advisory, are conducted using this headwind information. The tablet PC is used to show the outputs of the SafeAvio system: detected turbulence/windshear, the L-PSPD and the L-TSPD. The outputs are displayed on the primary flight display (PFD) and the navigation display (ND) simulated in the tablet PC.

2.3.1 Windshear Detection

The SafeAvio system detects windshear using the 'F-factor' that indicates aircraft energy change due to headwind change and vertical wind. The conventional Doppler radar also uses the F-factor for windshear detection [5]. The SafeAvio system calculates the F-factor by equation (1), smooths it by the moving average of the average section of 1 km, and detects windshear if the F-factor exceeds the predefined threshold value.

$$F_i = -\frac{u_i - u_{i-1}}{\Delta r}\left(\frac{v_g}{g} + \frac{2h}{v_a}\right) \quad (1)$$

where, i : lidar's range bin number, F_i : F-factor at i^{th} range bin, u_i : headwind at i^{th} range bin, Δr : lidar's range bin interval, v_g : aircraft ground speed, v_a : aircraft airspeed, h : aircraft height above ground, g : gravitational acceleration.

The performance requirements for airborne Doppler radar requires detecting an F factor of 0.13 or more as windshear and not detecting less than 0.085 as windshear. To satisfy this requirement, we set the F-factor threshold for windshear detection as 0.096 based on windshear encounter simulations. In addition, we incorporate Boolean operations (AND/OR) on the multiple windshear detection results acquired at adjacent ranges or line of sights in order to improve detection rate and nuisance alarm rate of windshear detection.

2.3.2 Turbulence Detection

The SafeAvio system detects turbulence using the 'Fh-factor' that indicates headwind change (Eq. 2). Turbulence detection by the Fh-factor assumes the isotropic turbulence. In the past flight test of JAXA, a correlation has been confirmed between the Fh-factor calculated from the lidar data and the actual shake (vertical acceleration) of the aircraft [3].

$$Fh_i = \frac{u_i - u_{i-1}}{\Delta r} \cdot \frac{v_g}{g} \quad (2)$$

where, i : lidar's range bin number, Fh_i : Fh-factor at i^{th} range bin, u_i : headwind at i^{th} range bin, Δr : lidar's range bin interval, v_g : aircraft ground speed, g : gravitational acceleration.

The performance requirements for airborne Doppler radar requires detecting an $\sigma_{\Delta n}$ of 0.3 or more as turbulence and not detecting less than 0.1 as turbulence, where $\sigma_{\Delta n}$ is a running 5-second windowed root mean square of the aircraft vertical acceleration. To satisfy this requirement, we set the Fh-factor threshold for turbulence detection as 0.14 based on turbulence encounter simulations. However, since the Fh-factor is not corrected by the wing load factor nor flight speed of the aircraft, the threshold value may change depending on the size of the aircraft and the flight condition. The threshold of 0.14 assumes a business jet used in the flight test. Same as windshear detection, the Boolean operations (AND/OR) are applied on the multiple turbulence detection results acquired at adjacent ranges or line of sights in order to improve detection rate and nuisance alarm rate of windshear detection.

2.3.3 Airspeed Advisory

Equation (3) shows the airspeed prediction logic of the L-PSPD. The L-PSPD predicts airspeed in 5/10/20 seconds by extrapolating current aircraft longitudinal acceleration like the conventional speed trend vector. In addition, the L-PSPD uses lidar's headwind information to consider headwind change between the current aircraft position and the locations where the aircraft would be in 5/10/20 seconds, assuming the aircraft flies straight. By considering headwind changes, the L-PSPD gives better airspeed prediction compared to the conventional speed trend vector, especially in windshear condition.

$$v_a(t+\Delta t_i) = v_a(t) + a \cdot \min(\Delta t_i, 10) + (u_j - u_1),\ j = \max\left(\mathrm{round}\left(\frac{v_g(t)\cdot\Delta t_i}{\Delta r}\right), 1\right) \quad (3)$$

where, v_a : aircraft airspeed, t : time, Δt_i : i^{th} prediction time, a : aircraft longitudinal acceleration, j : lidar's range bin number, u_j : headwind at j^{th} range bin, Δr : lidar's range bin interval, v_g : aircraft ground speed.

Equation (4) shows the target airspeed calculation logic of the L-TSPD. To minimize airspeed deviation from the reference airspeed, the L-TSPD calculates the target airspeed by feedbacking the airspeed change predicted by the L-PSPD. The L-TSPD is activated only when the predicted airspeed would exceed the predefined airspeed limits.

$$v_{tgt}(t) = v_{ref} - \Sigma_i\left[k_i * \left\{\Delta v_{ai}(t) + \frac{\Delta v_{ai}(t)}{|\Delta v_{ai}(t)|} \cdot k_{sig} \cdot \sigma v_a(t+\Delta t_i)\right\}\right], \Delta v_{ai}(t) = v_a(t+\Delta t_i) - v_a(t) \quad (4)$$

where, v_{tgt} : aircraft target airspeed, v_{ref} : aircraft reference airspeed, v_a : aircraft airspeed, σv_a : aircraft airspeed variation, t : time, i : identifier of prediction time, Δt_i : i^{th} prediction time, k_i : i^{th} feedback gain for airspeed change, k_{sig} : feedback gain for airspeed variation.

2.3.4 Display for Pilots

The detected turbulence/windshear information is displayed on the PFD and the ND simulated in the SafeAvio tablet display (Fig. 5). The location of the turbulence/windshear relative to the aircraft is shown on the ND. If the windshear is detected within 2.8km ahead of aircraft, windshear warning is issued on the PFD and oral warning is also given. These display formats are based on the existing performance requirements for airborne Doppler radar [5], aiming to accelerate authorization process of the SafeAvio system and to shorten the pilot training time.

The L-PSPD and the L-TSPD are displayed on the speed tape in the PFD (Fig. 6). Three ellipse shaped symbols show the predicted airspeed in 5/10/20 seconds. The center of the ellipse indicates the predicted airspeed and the

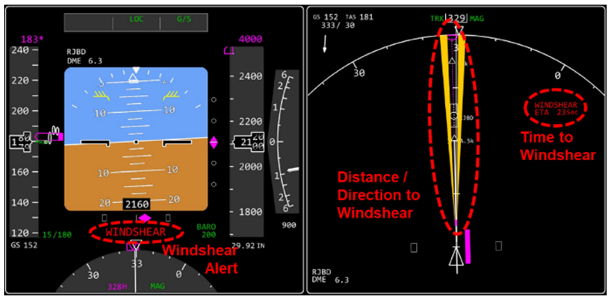


Fig. 5. Turbulence/windshear display.

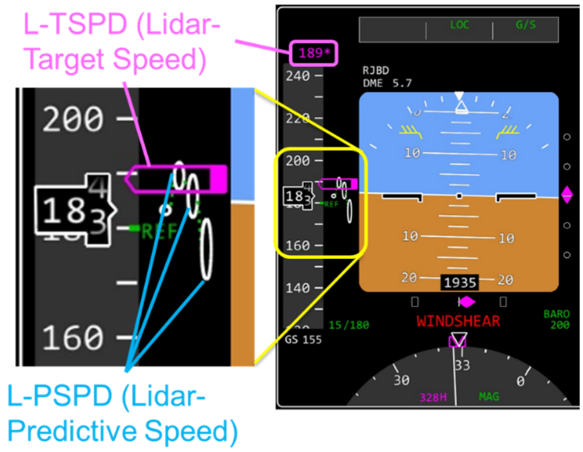


Fig. 6. Airspeed advisory display.

height of the ellipse indicates the predicted airspeed variation. In case of the example shown in figure 6, the L-PSPD predicts that airspeed once increases up to 190 kt in 5 seconds and drops down to 175 kt in 20 seconds, accompanied with nearly 10kt airspeed fluctuations. The target airspeed calculated by the L-TSPD is shown as magenta colored symbol. In figure 6, the L-TSPD suggests the target airspeed of 190 kt, which is 10 kt faster than reference airspeed of 180 kt, considering the expected airspeed drop in 20 seconds.

3 Flight Evaluation of Turbulence/ Windshear Detection

3.1 System Installation

To evaluate the turbulence/windshear detection capability of the SafeAvio system in real flight environment, the JAXA installed the SafeAvio system on a Gulfstream II aircraft (Fig. 7). The lidar optics was installed in the belly pod beneath the fuselage and other instruments were installed in the cabin. For safety and compliance reasons, the SafeAvio table display for pilots was not fixed in the cockpit, but held by the pilot-not-flying during the flight test.

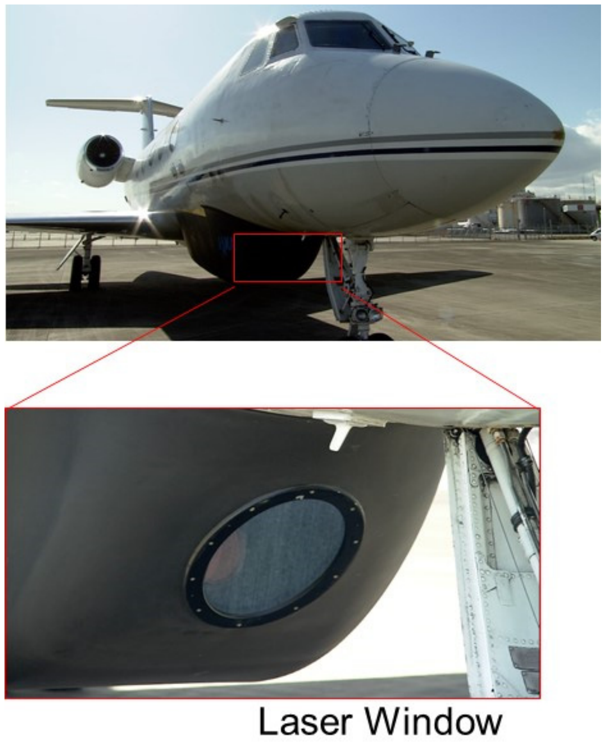
3.2 Overview of Flight Test

Sixteen flights were conducted in Japan from January to February 2017. There were mainly two flight patterns: 1) level flights at altitudes of 2,000 – 40,000 ft for evaluating lidar measurement range; 2) landing approach to the airport in gusty wind condition for evaluating turbulence/windshear detection. In the approaches, the aircraft did not land, but made go-around maneuvers at 200 ft above ground for safety reason. An airport with high probability of turbulence/windshear occurrence on the approach path was selected for the approaches based on the statistical survey of the flight data of the airline scheduled flights. During the approaches, conducted 46 times in total, the aircraft encountered turbulence 20 times and windshear 13 times. No turbulence/windshear encounter occurred in the level flights.

3.3 Flight Test Result

3.3.1 Measurement Range

The lidar measurement range observed in the flight test is shown in Fig. 8. The measurement range averaged of all altitudes was 17.5 km, exceeding the target of 14 km. Still, measurement range has a lot of fluctuations. Figure 9 is a cross-plot of the lidar measurement range and the density of aerosols that are major scattering source of the lidar laser beam. The measurement range is strongly correlated to the density of aerosols. Figure 8 indicates that the measurement range decreases at higher altitudes. Although the measurement range reaches up to over 20 km below 5,000 ft, it drops down to less than 10 km at 40,000 ft where the density of aerosols is low. Figure 10 exemplifies the observed aerosol density in the flight test. The aerosol density at altitudes above 20,000 ft is less than 1/100 of that at altitudes below 5,000 ft.



(a) Outside of aircraft

(b) Cabin / cockpit

Fig. 7. SafeAvio system installation.

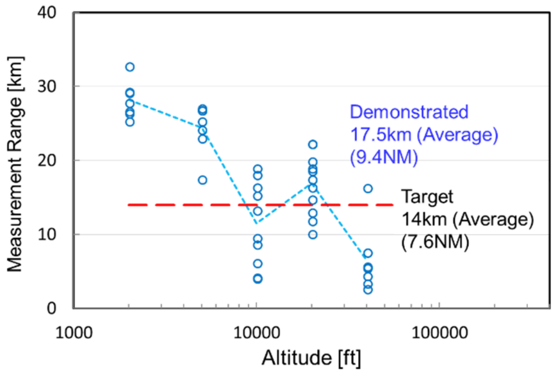


Fig. 8. Lidar measurement range.

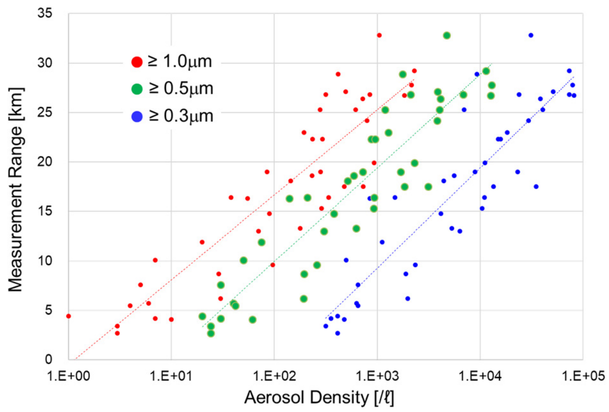


Fig. 9. Relationship between lidar measurement range and aerosol density.

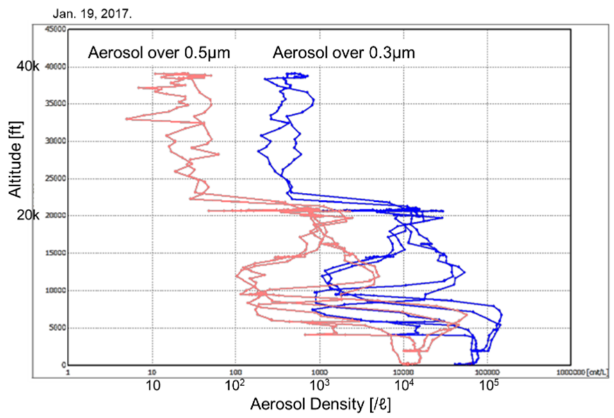


Fig. 10. Example of observed aerosol density.

3.3.2 Windshear Detection

The SafeAvio system detected windshear in 11 cases out of 13 windshear encounters. A nuisance alert occurred in 3 cases (Table 3). The resulting detection rate and nuisance alarm rate were 85% and 27%, respectively. The radar performance requirement [5] does not define the requirements for windshear detection/nuisance alarm rates to be proved in the real flight environment. However, the nuisance alarm rate should be as low as possible, considering the practical use.

Table 3. Windshear/turbulence detection result.

	Windshear	Turbulence
Encounter	13	20
Detection	11	10
Nuisance alarm	4	1

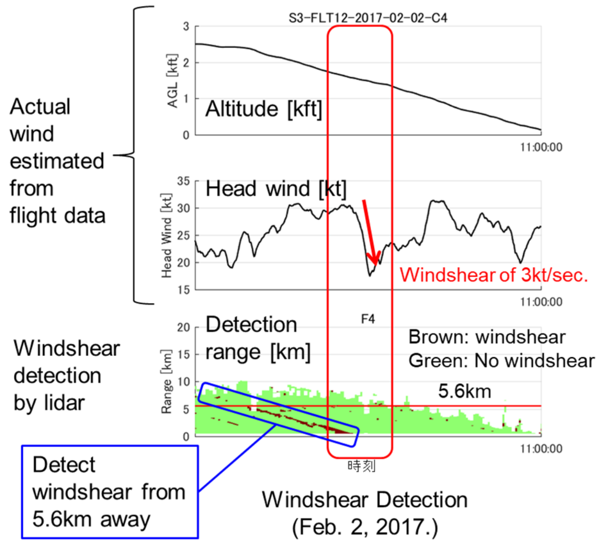


Fig. 11. Example of windshear detection.

Figure 11 shows the example of windshear detection. The aircraft experienced the windshear of 3 kt/sec in this case. The system successfully detected this windshear from over 5.6 km away. The windshear detection range was 9.5km (average) and 6.7 km (minimum), satisfying the requirement of 5.6 km (Table 1). Since the approaches were performed at a low altitude of 3,000 ft or less, the lidar measurement range usually reached 20 km or more. However, the windshear detection range often remained around 10 km because the deviation between the laser irradiation direction and the flight path became large in the distance farther than 10 km.

3.3.3 Turbulence Detection

Originally, we planned to conduct the evaluation of turbulence detection at cruising altitude. However, we encountered turbulence only in the approaches at low altitudes. In addition, the encountered turbulences were not severe enough to reach the detection threshold of 0.3 g for $\sigma_{\Delta n}$ (Table 1). We therefore conducted the evaluation of turbulence detection by using turbulence data in the approaches and by relaxing the turbulence detection threshold down to 0.2 g.

The SafeAvio system detected turbulence in 10 cases out of 20 turbulence encounters, exceeding 0.2 g threshold. The nuisance alarm occurred in one case (Table 3). The detection rate and nuisance alarm rate were 50% and 9%, respectively. The detection rate was lower than windshear detection. There would be two reasons for this: 1) the assumption of isotropic turbulence, the premise of the turbulence detection using the Fh-factor, is difficult to be satisfied in low altitudes; 2) the weak turbulence that does not reach 0.3 g threshold is difficult to be detected compared to more severe turbulence. Figure 12 exemplifies the turbulence detection. The aircraft experienced over ± 0.3 g variation of the vertical acceleration while $\sigma_{\Delta n}$ barely exceeded 0.2 g threshold. The system successfully detected this turbulence from over 5.6 km away.

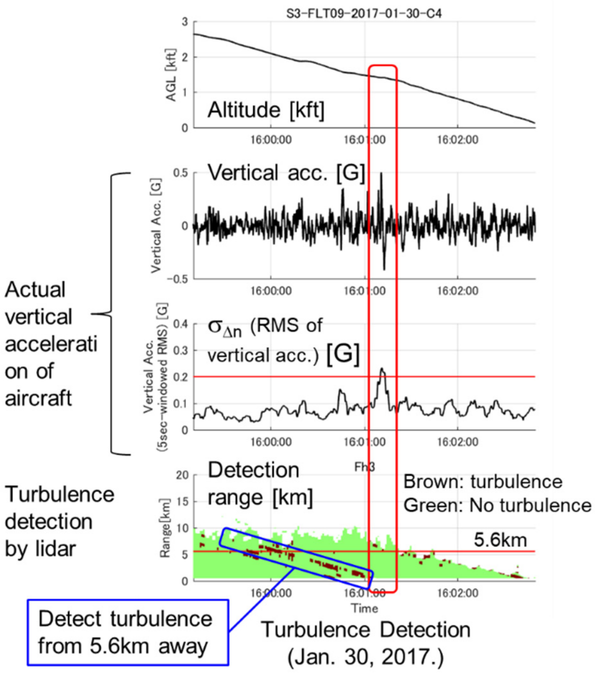


Fig. 12. Example of turbulence detection.

3.3.4 Display for Pilots

In the flight tests, the pilots confirmed that turbulence/windshear information was displayed in a timely manner in the cases of turbulence/ windshear detections. For the airspeed advisory display, the evaluation was carried out separately by the flight simulation.

4 Flight Simulation Evaluation of Airspeed Advisory Display

The effectiveness of the airspeed advisory display is evaluated by the piloted flight simulation in order to compare the airspeed maintenance performance and the pilot workload with or without the airspeed advisory display, under the same windshear condition [4].

4.1 Simulation Design

The JAXA's full flight simulator (Fig. 13) was used for the simulation, programmed with the non-linear flight dynamics of a Boeing 737 class passenger plane. The control columns, yokes and rudder pedals were electrically loaded to simulate control forces. Motion simulation was not used. The cockpit layout simulates that of a modern jet transport. It has a PFD, ND and a simple Engine Indication & Crew Alerting System (EICAS). The eight experienced airline pilots (including one retired pilot) participated in the simulation.

The pilots conducted ILS approaches under windshear condition with four different displays: 1) conventional display, 2) conventional display with additional L-PSPD, 3) conventional display with additional L-TSPD, and 4) conventional display with additional L-PSPD and L-TSPD. The secondary task of pushing switch according to the change of displayed marking was also used to clarify the differences in pilot performance or workload between four displays [4].

Fig. 13. JAXA’s full flight simulator.

4.2 Simulation Result

Figures 14 and 15 respectively compare the airspeed maintenance performance and the pilot’s subjective mental demand between four displays. Both the L-PSPD and the L-TSPD improved the performance and lower the mental demand. The pilot comments suggested that the L-PSPD supports the intuitive awareness of airspeed changes, while the L-TSPD supports airspeed control decision-making.

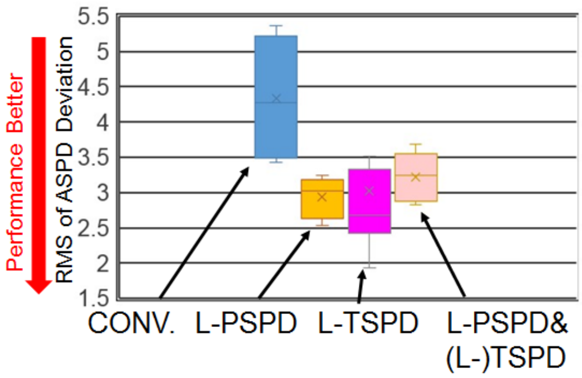


Fig. 14. Airspeed maintenance performance with secondary task.

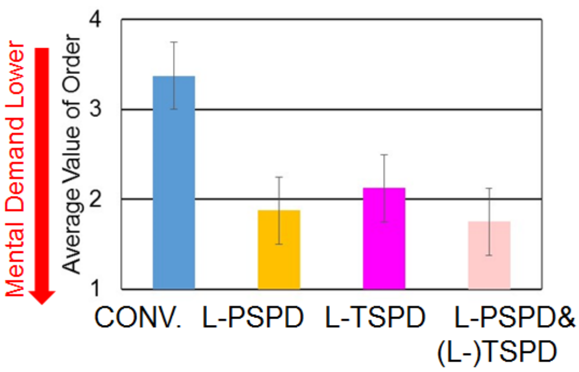


Fig. 15. Ranking of subjective mental demand with secondary task.

Fig. 16 shows the percentage of eye dwelling time in each area of interest (Fig. 17) without the secondary task, averaged for seven pilots. The eye dwelling time on airspeed indication area (ASPD) increased when the L-PSPD or the L-TSPD was shown, resulting in the decrease of eye dwelling time in other areas, especially in altitude indication area (ALT). The pilots might pay more attention to airspeed indication area to handle additional information by the L-PSPD or the L-TSPD. However, no apparent hindrance to proper attention allocation was observed in the flight simulations.

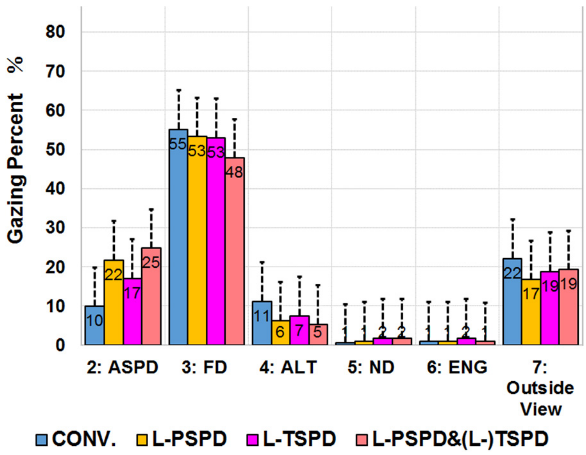


Fig. 16. Eye dwelling time percentage on each display without secondary task.

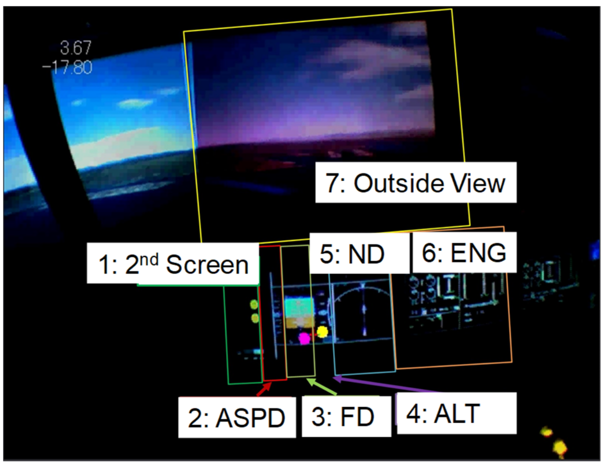


Fig. 17. Areas of interest.

5 Conclusion

This paper reports the JAXA's SafeAvio system including its design and flight evaluation results. The system uses the airborne Doppler lidar to inform pilots of preceding turbulence or windshear in clear sky condition, in which the existing airborne Doppler radar does not work. As airspeed advisory, the system also provides the predicted airspeed (L-PSPD) and the target airspeed (L-TSPD) information to pilots, considering headwind change observed by the lidar. The JAXA installed the system on a small jet aircraft and successfully flight-demonstrated its turbulence and windshear detection capability. The flight simulation results indicate that both the L-PSPD and the L-TSPD improve the airspeed maintenance performance and lower the pilot's mental demand at flights in windshear condition. The JAXA will use these demonstrated results to support the standardization process of the airborne Doppler lidar for turbulence/windshear detection.

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