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HIGH ALTITUDE TURBULENCE DETECTION USING AN AIRBORNE DOPPLER LIDAR

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Abstract

Air turbulence is a serious problem that affects airline operations. The Japan Aerospace Exploration Agency (JAXA) is developing an airborne Doppler LIDAR (Light Detection and Ranging) for on-board turbulence detection. Flight experiments demonstrated that a high-altitude prototype can measure wind speeds at the more than 9 km range at altitude of 12 km. This paper describes the development of the airborne Doppler LIDAR and presents sample high-altitude flight experiment results.

1 Introduction

An analysis of the causes of airliner accidents in Japan in the decade between 2003 and 2012 reveals that about half were related to air turbulence. With onboard weather radar, airliners can avoid cumulonimbi that generate severe turbulence, but weather radar is unable to detect CAT (Clear Air Turbulence) and so cannot prevent all turbulence-related accidents.

Doppler LIDAR [1] has been developed to remotely observe winds in clear weather conditions. This emits an infrared laser light into the atmosphere and measures the frequency change due to Doppler shift of light backscattered by airborne particles such as aerosols to obtain wind speeds. Ground-based Doppler LIDARs operated at some major airports are used to detect low-level turbulence or aircraft wake vortex hazards in the vicinity of runways, and have an effective range of about 10 km. However, they are not effective at detecting air turbulence beyond that. CAT, which occurs at high altitudes, is also a hazard to flight operations. It is considered that if Doppler LIDAR could be installed on aircraft, it could warn of CAT encounters and thus reduce turbulence-related accidents.

Based on this consideration, JAXA is developing a Doppler LIDAR turbulence sensor which can be installed on aircraft. This is technically challenging since not only must the device be small and light, but wind detection is more difficult at high altitudes than on the ground because the low density of aerosol particles at high altitude reduces the backscattered light's intensity [2], so decreasing effective range. Nevertheless, to provide sufficient advance warning of CAT to be useful, JAXA's high altitude LIDAR is specified to achieve a detection range of at least 5 nautical miles (9 km) at high altitude.

1.1 Aircraft Accidents

Figure 1 shows a breakdown of the causes of large airliner accidents during the 10 years from 2003 to 2012, based on an analysis of aircraft accident reports published by the Japan Transport Safety Board [3]. There were a total of 29 airliner accidents during this period, of which 14 were caused by air turbulence and 2 are judged to be due to human factors related to air turbulence. It therefore appears that about half of the accidents are related to air turbulence. Those 16 turbulence-related accidents caused serious injuries and fatalities.

In turbulence-related accidents, severe aircraft motions when the aircraft encounters turbulence can cause unsecured objects and people to fly around the cabin, potentially causing injuries, and turbulence encountered on final approach can lead to flight path instability and hard landings. Although pilot error is sometimes identified as a factor in turbulence-related accidents, it is considered that advance warning of turbulent conditions would allow crews to prepare and so eliminate human error as a cause.

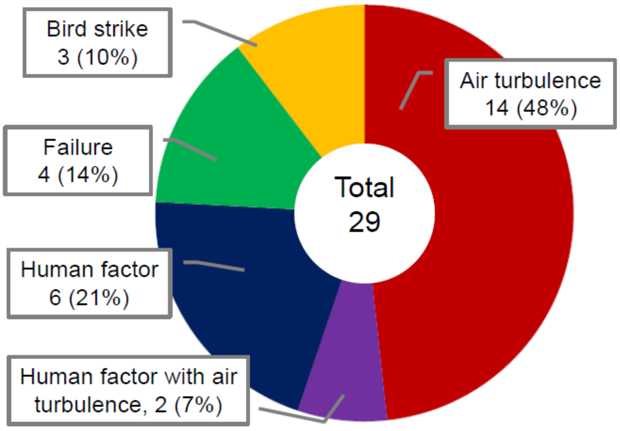

Fig. 1. Aircraft Accidents to Large Civil Airplanes in Japan (2003-2012).

1.2 Air Turbulence

There are four main types of air turbulence which can seriously affect aircraft: thunderstorm turbulence (shown in Fig. 2(a)), mountain wave turbulence (Fig. 2(b)), wake vortex (Fig. 2(c)), and CAT (Fig. 2(d)). Thunderstorm turbulence occurs within and around thunderstorms or cumulonimbus clouds. A cumulonimbus cloud with hanging protuberances or virga are usually indicative of severe turbulence. Mountain wave turbulence is the result of air blowing over a mountain range or a sharp bluff causing a series of updrafts and downdrafts. Wake vortex is turbulence that forms behind an aircraft as it passes through the air. CAT is high altitude turbulence not normally associated with cumuliform clouds; it is produced by vertical windshear and concentrations of potential temperature.

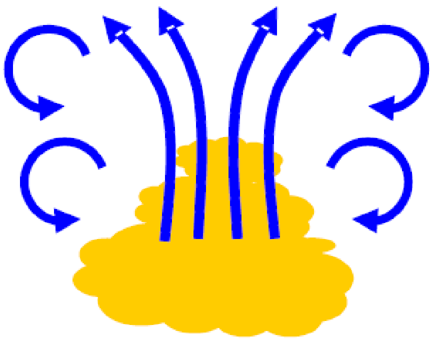

Fig. 2(a). Thunderstorm Turbulence.

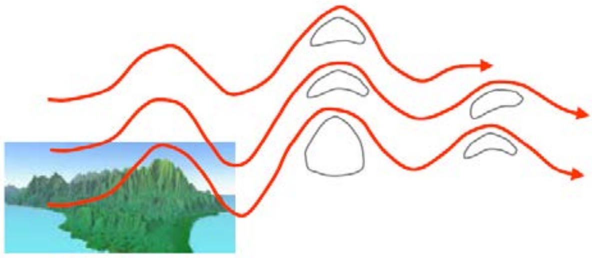

Fig. 2(b). Mountain Wave Turbulence.

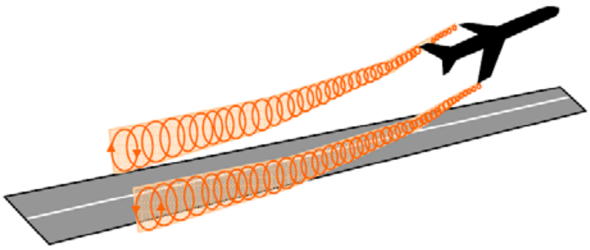

Fig. 2(c). Wake Vortex.

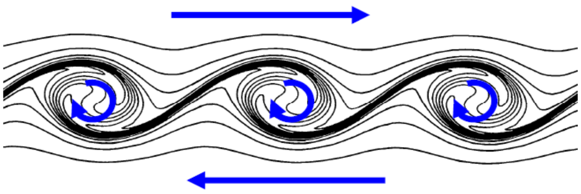

Fig. 2(d). Clear Air Turbulence.

2 Airborne Doppler LIDAR

2.1 Principle of Doppler LIDAR

Doppler LIDAR has attracted attention in recent years as a sensor for the remote observation of air flow. In coherent systems using an infrared laser, a laser transceiver emits a single-frequency pulsed laser light from an optical antenna into the air and receives light backscattered by aerosol particles, as shown in Fig. 3, to observe a distant airflow. By time division of the received light, we can “bin” the received signals based on the round-trip time of light into desired observation ranges. The intensity of the received light decreases with distance, and the maximum range is given by the longest round-trip time of signals above the noise floor.

The aerosol particles remaining in the atmosphere at high altitude have sizes of several μm or less and are very light. These particles move with the air flow and scatter laser light. By measuring the frequency shift of backscattered light due to the Doppler effect, we can observe the component of wind speed along the optical axis. While Doppler LIDAR is effective so long as aerosol particles are present, even in fine weather, its range is limited to the area penetrated by the laser light and so it is not possible to observe through thick cloud. Furthermore, since aerosol density decreases with altitude, the LIDAR's maximum range tends to decrease as the intensity of the backscattered light is reduced.

In the sections that follow, we introduce the incremental development of JAXA's airborne Doppler LIDAR.

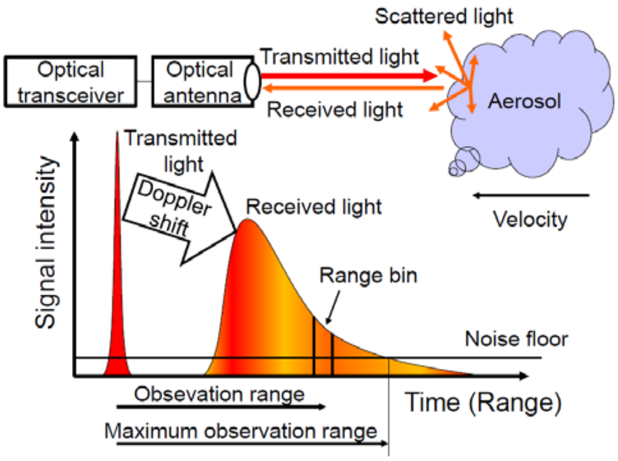

Fig. 3. Principle of Doppler LIDAR.

2.2 1NM class LIDAR

A 1NM class LIDAR [4] (Nautical Mile: 1NM = 1852 meters) was developed in FY (Japanese Fiscal Year) 2001 as a low-output prototype airborne Doppler LIDAR to prove basic functions. Its laser transceiver includes a master laser oscillator, a commercial optical communication fiber amplifier, and a heterodyne detector. An optical antenna is connected to the laser transceiver by a 10 m flexible optical fiber cable, and a desktop computer is used for signal processing, control and analysis. The scanner has a double wedge prism to deflect the transmitted laser light through ±10 degrees. The steering mirror is mounted on the top of the aircraft's fuselage through a hole in the cabin ceiling. Flight experiments in 2002 demonstrated a remote wind measurement accuracy of 0.7 m/s or better [5].

2.3 3NM class LIDAR

A 3NM (5.6 km) class prototype airborne Doppler LIDAR was developed in FY 2006 to demonstrate a practically useful detection range by increasing the laser output to about ten times that of the 1NM class LIDAR. A high output amplifier using a short (3.5 m) large-diameter (9.1 μm) optical fiber with a high erbium doping density (7600 wt-ppm) was developed for the LIDAR [6]. The laser PRF (pulse repetition frequency) was 4 kHz and the number of incoherent integrations was 4,000, giving a measurement rate of 1 Hz.

The LIDAR was installed in JAXA's Beechcraft Model 65 research aircraft, and demonstrated detection of remote turbulence in flight in clear weather.

2.4 5NM class LIDAR

A 5NM (9.3 km) class prototype airborne Doppler LIDAR was developed in FY 2007 to improve the detection range by increasing the laser output to about three times that of the 3NM class LIDAR. A high output amplifier using a large core diameter (25 μm) optical fiber was developed and inserted as a second amplifier behind the 3NM class LIDAR amplifier [7].

Flight experiments demonstrated that the LIDAR was able to measure wind speeds at a maximum distance of approximately 9 km in flight in clear weather.

2.5 High-Altitude LIDAR

Pilots were surveyed to find the minimum requirements for a practical turbulence warning device. They requested at least 30 s warning of turbulence encounter to allow actions such as turning on seat belt signs to be taken. As an immediate goal, we set the LIDAR's design observation range to 5NM (9 km) at aircraft cruising altitudes. This required greater performance than the 5NM-class LIDAR, so a Waveguide Amplifier (WGA) was developed in 2008 [8] and used in an experimental high-altitude Doppler LIDAR (Fig. 4) designed to detect winds at the low aerosol densities of jet aircraft cruise altitudes.

The signal light generated by the optical transceiver is amplified by the pump light and emitted from an optical antenna with an effective diameter of 150 mm. Backscattered light is condensed in the optical antenna, its Doppler shift is measured in the optical transceiver and converted to a wind speed signal by a signal processer. The range bin size can be set in multiples of 150 m, and up to 80 range bins can be measured at a time. The WGA initially had a signal pulse energy of 225 μJ, but by suppressing ASE (Amplified Spontaneous Emission) generated in the laser material, which limits the amplification of a desired light signal, 1,925 μJ was achieved in 2012. As a result, wind speeds could be sensed at ranges of greater than 30 km on the ground [9].

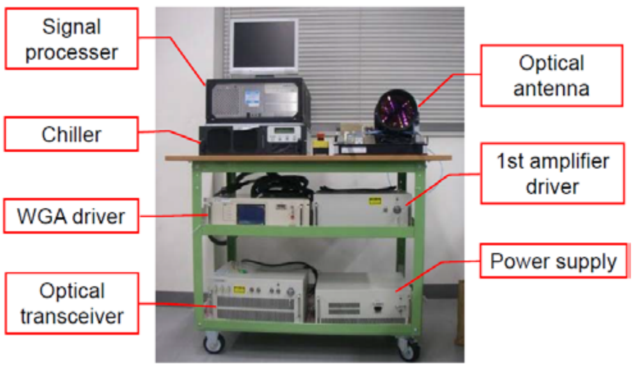

Fig. 4. High-Altitude Airborne LIDAR

3 Laser Output

Laser output power, the factor that primarily determines a LIDAR's performance, is conventionally expressed by average power or pulse energy. However, these indices are insufficient to express the performance of a LIDAR that uses pulse integration. When performing incoherent integration to increase the signal-to-noise ratio (SNR), in general N iterations of integration increases the signal intensity by N times and the white noise intensity by $N^{1/2}$ times, thereby increasing the SNR by a factor of $N^{1/2}$. Noting this fact, in this paper we define Figure Of Merit (FOM) as a performance index that can be used in relative comparisons of Doppler LIDAR laser output. FOM is defined as

$$FOM = E \times N^{1/2} \quad (1)$$

where E is the optical energy per pulse of the transmission laser light, and N is the number of integrations performed during each one-second interval (the same value as the PRF). N in used in the definition to make the units of FOM equivalent to that of E.

Table 1 compares the laser outputs of the airborne Doppler LIDARs developed by JAXA so far by the FOM index. Each successive model has substantially increased the laser output.

Table 1. Laser Output of Airborne Doppler LIDARs

Model	E [μJ]	PRF [kHz]	Average power [W]	FOM [mJ]
1NM	4.5	50	0.225	1.006
3NM	58	4	0.232	3.668
5NM	179	4	0.716	11.32
High Alt.	1,925	4	7.7	121.7

4 Flight Experiment

4.1 Aircraft Installation

The high-altitude LIDAR model was installed in a Gulfstream II jet aircraft and demonstrated wind measurement capability at high speed and high altitude [10]. Experimental components were installed in a rack on the left side of the aircraft's cabin as shown in Fig. 5. The optical antenna was mounted in a fairing on the bottom of the fuselage. Laser light was emitted forward from the aircraft.

A series of flight experiments was conducted over the land and sea around the Chubu area of central Japan. Meteorological information and numerical forecasts were used to search for significant turbulence to enable the LIDAR to be tested.

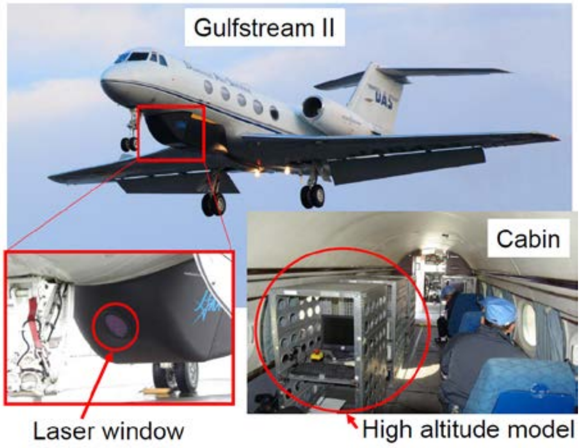

Fig. 5. Experimental System Installation

4.2 CAT Detection

Figure 6 shows an example of CAT detected ahead of the aircraft while flying at 10,500 ft (3,200 m) in clear air conditions [11]. Range is given by the ordinate of the upper graph, so the aircraft flies along the upward direction of the graph. Time is shown along the abscissa, and vertical lines are plotted at one-second intervals. Each vertical column of blocks shows color-coded wind speed variances (Wlos) in each range bin observed each second. Wlos is used as an index of turbulence intensity. As shown in the key in the upper right corner of the figure, the color changes toward red as the Wlos value increases to indicate greater turbulence. Since the signal level weakens with distance, black is used to represent no Wlos measurement due to insufficient signal level of the received laser light.

A region of turbulence detected ahead of the aircraft gets closer with time as the aircraft flies towards it. Therefore, if turbulence is detected, a downward-sloping line will appear in the graph. The upper and middle plots in Fig. 6 show that a periodic change in vertical acceleration (Az) was measured and Wlos increased corresponding to the increases in Az. A periodic change of outside air temperature (OAT), shown in the bottom plot of Fig. 6, was also observed that corresponded to the change of Az. Although the flight altitude fluctuated over a range of 25 m during the period of the observations shown, this is too small to account for the change in OAT. Since it is known that temperature variations are associated with CAT [12], this observation example indicates that the aircraft had encountered CAT. A concentration of potential temperature was also confirmed in weather information.

As the data here show, the high-altitude LIDAR was able to detect moderate turbulence a full 30 seconds before the aircraft started to be affected.

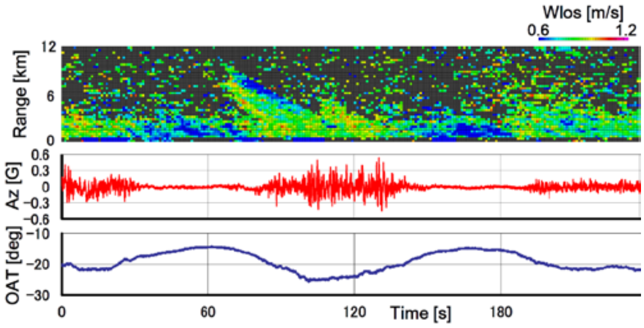

Fig. 6. CAT Detection Sample

4.3 High-Altitude Observation

Figure 7 shows an example of data obtained at 40,000 ft (12,200 m), the highest test altitude. Wlos values are color-coded as indicated by the key on the right of the graph. Since color variations that appear to be noise are not seen below 9 km range, it is considered that the LIDAR's detection range is at least 9 km.

In the portion of the graph below 9 km (i.e. the area of valid data), Wlos indications above the light blue background intensity are observed in the interval between 30 s and 60 s, indicating a region of slight turbulence, and we can see how the region approaches as the aircraft moves forward. Slight changes in vertical acceleration (Az), shown in the bottom of Fig. 7, are observed when the range of this region approaches zero, so we recognize in this example that the aircraft encountered very weak turbulence which had been displayed over 30 s previously.

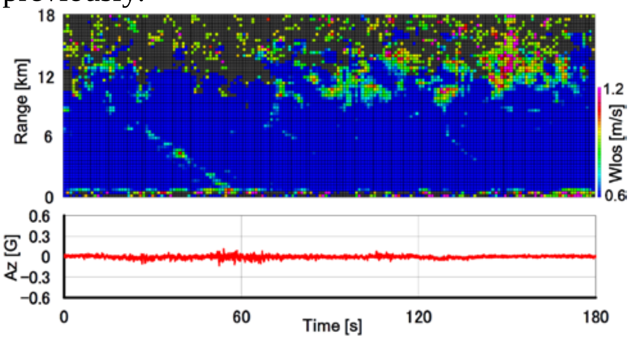

Fig. 7. Example of High-Altitude Observation.

5 Concluding Remarks

About half of the accidents to large aircraft in Japan are related to air turbulence. However, there is currently no sensor that can warn of CAT and so no effective means to prevent those accidents. For this reason, JAXA is developing a compact high-power airborne Doppler LIDAR as a sensor to warn of turbulence encounters, aiming to contribute to greater aviation safety. JAXA has progressively increased the laser output power of the experimental devices it has developed thus far, and the latest device has a FOM (defined in Section 3) that reached 121.7 mJ. During flight tests, we detected moderate CAT at an altitude of 10,500 ft (3,200 m) and confirmed a detection range of up to 9 km at 40,000 ft (12,200 m), showing that the device can be used even at high altitudes where there are less aerosols to scatter the laser light.

The device must output suitable information to pilots. In order to determine an index of turbulence risk and an alert threshold, we plan to analyze turbulence observation data and evaluate the device's accuracy, as well as to verify the correlation with the aircraft's gust response by simulation.

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