# DEVELOPMENT OF A LONG RANGE AIRBORNE DOPPLER LIDAR

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## Abstract

*Air turbulence is a serious problem that affects airline operations. At present there is no sure way of avoiding encounters with clear air turbulence (CAT) because it cannot be detected by conventional airborne weather radars. The Japan Aerospace Exploration Agency (JAXA) is therefore developing a Doppler LIDAR [1] (Light Detection and Ranging) which can measure the wind velocity ahead of an aircraft even in clear air. The latest prototype has demonstrated turbulence detection up to 15 km ahead at low altitudes, and wind velocity measurement up to 3 km ahead at high altitudes. Wind velocity measurement by a LIDAR is difficult at high altitudes because of low aerosol particle density. Regular atmospheric observation flights are therefore being made to determine the basic performance requirements for a practical device. This paper describes the development of a long range airborne Doppler LIDAR and presents examples of flight experiment results.*

## 1 Introduction

In Japanese aviation law, an “accident” is defined as a case where a person suffers death or serious injury, or an aircraft receives substantial damage. Accidents in Japan are investigated by the Japan Transport Safety Board (JTSB).

Figure 1 shows aviation accidents to large civil airplanes which occurred in Japan between 1990 and 2008 classified according to cause, based on a report [2] by the JTSB. There were sixty aviation accidents during this period, of which 29, nearly half the total, were caused by turbulence. Moreover, it is estimated from media reports that the number of turbulence encounters that result only in minor injury, and are therefore not classified as accidents, is ten times greater than the number of turbulence accidents reported by the JTSB. Turbulence is therefore the most important flight safety issue that needs to be urgently addressed by preventive measures.

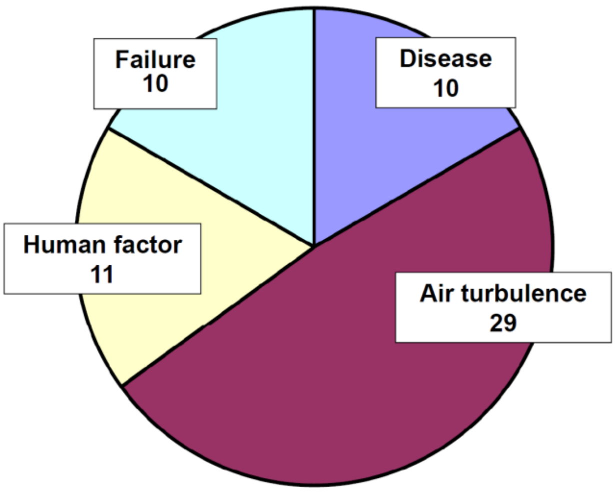


Fig. 1. Aviation accidents to large civil airplanes in Japan (1990-2008).

Conventional weather radar, which is mandatory equipment for airliners, can detect of turbulence associated with thick cloud, but since it cannot detect turbulence in clear air, there is currently no effective means to predict CAT encounters.

To address this problem, the Japan Aerospace Exploration Agency is developing a LIDAR device to detect turbulence ahead of an aircraft even in clear air conditions to give advance warning. A LIDAR detects wind by measuring the Doppler shift of light backscattered by aerosol particles in the atmosphere. However, aerosol particle density decreases as altitude increases, and so wind velocity measurement becomes more difficult at high altitudes. Regular atmospheric observation flights are therefore being made to confirm aerosol densities and to determine the basic performance requirements for a practical wind measurement device. Much data on aerosol density at all altitudes has already been accumulated, and more data will be gathered particularly at high altitudes when a jet-powered observation aircraft becomes more readily available.

A first prototype coherent Doppler LIDAR [3], named the 1 NM (Nautical Mile: 1NM = 1,852 meters) model [4], was developed in 2001. This used a commercial optical communications fiber amplifier with an output pulse energy of 4.5 µJ, and demonstrated basic functions installed in a JAXA research aircraft [5], [6]. A second model developed in 2006, named the 3 NM model [7], increased the laser output pulse energy to 58 µJ and demonstrated an in-flight turbulence prediction capability [8]. A third model, named the 5 NM model [9], was developed in 2007 to give greater range performance by increasing the laser output pulse energy to 179 µJ, and this model demonstrated a maximum wind measurement range of approximately 8.7 km in flight [10].

In 2009, JAXA developed a high altitude long range LIDAR model with even higher laser power to demonstrate practical CAT detection at jet airliner cruising altitudes. A high speed, high altitude flight demonstration of this LIDAR was carried out in 2010. Some results of these flight experiments are introduced in this paper.

## 2 Airborne Doppler LIDAR

### 2.1 Concept

The concept of an airborne Doppler LIDAR [11], [12] is shown in Fig. 2. The Doppler LIDAR is installed in an aircraft to measure air turbulence ahead of it in flight. Pulsed laser light emitted forward from the aircraft is scattered by aerosol particles in the atmosphere, such as fine water droplets and dust, and some of the backscattered radiation is received back at the aircraft. Light aerosol particles travel with the wind so the wavelength of the scattered laser light is shifted in proportion to the velocity of the particles due to the Doppler effect, enabling measurement of wind velocity. Range information can be obtained by measuring the delay between the transmission of a pulse of laser light and the reception of backscattered radiation.

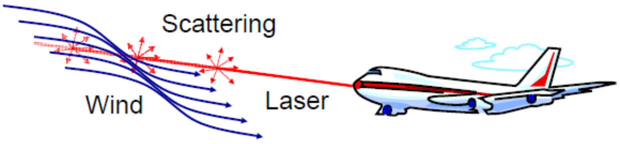


Fig. 2. Concept of an Airborne Doppler LIDAR.

JAXA's LIDAR uses optical amplifiers, which have a number of features that make them suitable for airborne application. The optical devices are small, have low electrical power consumption and do not need a large cooling system. They are also dustproof and have low electromagnetic noise emission. Because optical fiber is flexible, the laser source and detector can be installed in a different location to the emitter/receiver window. The 1.5 µm wavelength of the emitter is the safest for human eyes [13].

### 2.2 Latest prototype

Because the aerosol density is low at jet airliner cruising altitudes, somewhat higher laser output than previous prototypes is necessary in order to achieve an effective turbulence detection range of 5 nautical miles. To this end, we developed a high peak power optical waveguide amplifier (WGA) [14] for the LIDAR which achieved a laser pulse energy of 0.96 mJ in ground tests. However the WGA was sometimes damaged during these tests by excessive energy, so it was decided to operate the device at a low power level of about 0.2 mJ for initial flight experiments, and to demonstrate full power operation in later flight experiments after ground-based endurance tests.

Figure 3 shows the high altitude LIDAR model developed based on the WGA. The optical transceiver includes a master laser oscillator and a heterodyne detector, while the optical antenna contains an optical telescope and optical amplifiers. A personal computer with a flat panel display provides signal processing. A chiller provides liquid cooling of the WGA, and three amplifier drivers control the excitation light sources for the optical amplifiers.

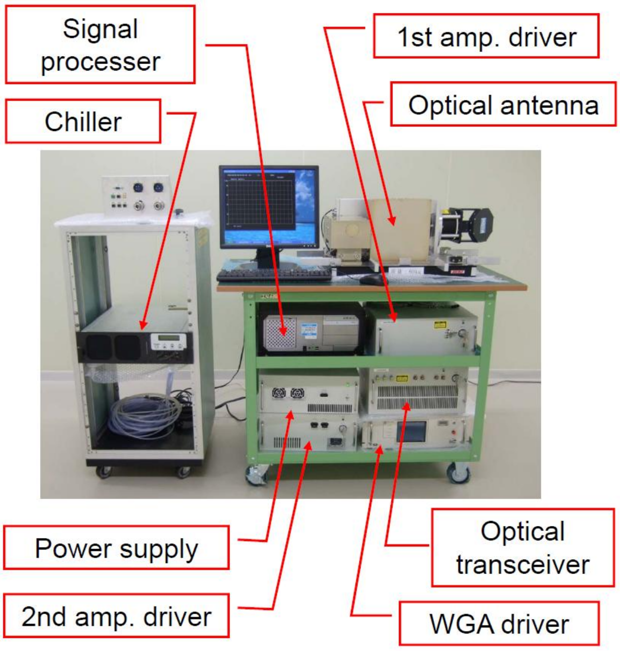


Fig. 3. High Altitude LIDAR Model.

## 2.3 Installation to an aircraft

The high altitude LIDAR model was installed in a Gulfstream II jet aircraft, and demonstrated wind measurement capability at high speed and high altitude in January 2010. The experimental system was installed in a rack on the left side of the aircraft's cabin as shown in Fig. 4. The optical antenna was mounted in a fairing on the bottom of the fuselage. Laser light was emitted forward from the aircraft.

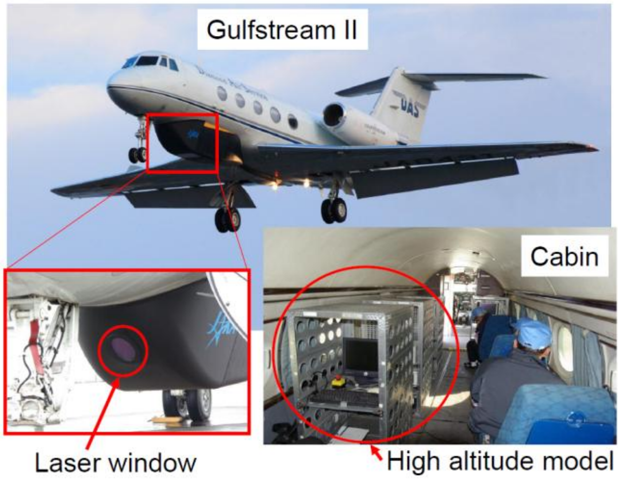


Fig. 4. Installation of the experimental system.

## 2.4 Fh-factor

JAXA has proposed a method for detecting clear air turbulence using the Fh-factor (*Fh*). The Fh-factor is an index that represents the intensity of wind turbulence as the rate of change of the horizontal component of the headwind to the aircraft, and is defined as

$$Fh = -(dU/dt)/g \qquad (1)$$

where $U$ is the headwind component of the wind velocity, $t$ is time, and $g$ is the acceleration due to gravity. The Fh-factor is useful because it is a non-dimensional quantity and the headwind component is measurable by a LIDAR without having to scan the laser direction; the vertical wind component is not required to derive it.

Figure 5 shows a sample of in-flight measurement data. Absolute values of Fh-factor are compared with absolute values of vertical acceleration ratio (|ΔG|). The data shows a good correlation between |ΔG| and |Fh|; when |ΔG| is high, |Fh| is also high. In order to predict turbulence, the Fh-factor in the area ahead of the aircraft should be monitored during flight by a LIDAR.

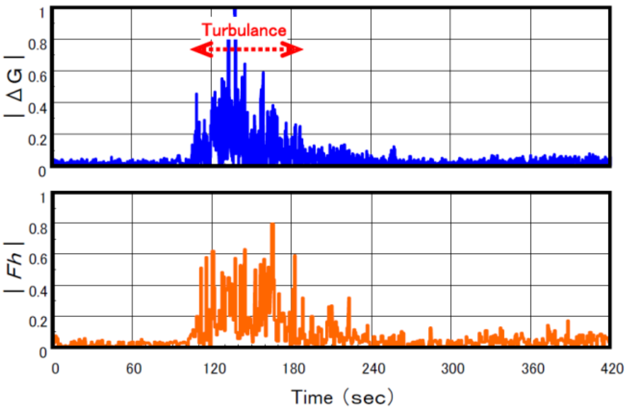


Fig. 5. Correlation between vertical acceleration ratio and Fh-factor.

## 2.5 Sample flight experiment results

Figure 6 shows the predicted intensity of turbulence weighted by Fh-factor at an altitude of 2,000 ft (600 meters) in clear air conditions, when the density of aerosol particles larger than a diameter of 0.3 µm was approximately 16.6 particles/cm$^3$. The airplane was flying at a constant true airspeed of about 260 kt (130 m/s) in the direction of the vertical axis of the figure. The *y*-axis in the upper plot represents range (distance in front of the aircraft), and each small square in the figure has an extent in this direction of 300 meters. The *x*-axis represents time, and each vertical column indicates the turbulence intensities measured simultaneously at each range at an instance in time. Turbulence intensity data were acquired at one second intervals. Each row of the figure therefore indicates the time history of turbulence intensity at a certain distance in front of the aircraft out to a maximum of 18 km. Each square is color-coded according to Fh-factor value as shown on the right of the figure, and black squares indicate invalid data due to low signal strength. The Fh-factors at extremely short ranges are not reliable due to internal reflection of the laser light. The slanted line in Fig. 6 corresponds to the aircraft's 130 m/s airspeed, and turbulence approaches the airplane along this line. The time history of ΔG is shown in the lower graph for comparison. In this low altitude flight experiment, we were able to obtain wind velocity measurements up to about 15 km ahead. As the data here show, there is a correlation between Fh-factor and ΔG even though the aircraft encountered only light turbulence.

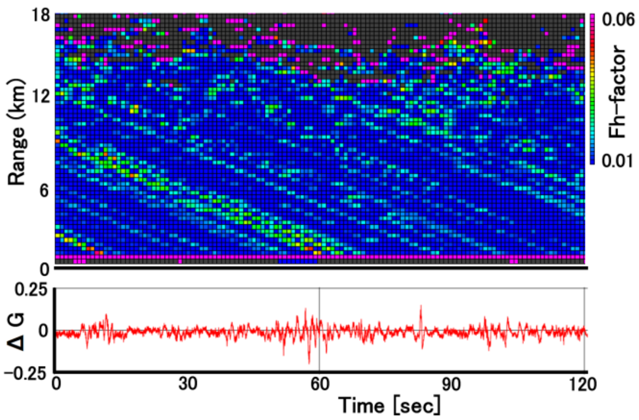


Fig. 6. Prediction of air turbulence.

Figure 7 shows LIDAR measured Fh-factors at an altitude of 5,000 ft (1,500 meters), where the density of aerosol particles larger than 0.3 µm was approximately 5.3 particles/cm$^3$. The airplane was flying at a constant true airspeed of about 280 kt (140 m/s). In this mid-altitude experiment, the maximum range of the LIDAR was about 10 km. The airplane did not encounter any significant turbulence in this case.

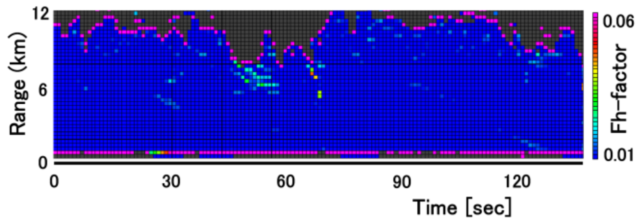


Fig. 7. LIDAR data at middle altitude.

Figure 8 shows LIDAR measured Fh-factors at an altitude of 28,500 ft (8,700 meters), where the density of aerosol particles larger than 0.3µm was approximately 2.7 particles/cm$^3$. The airplane was flying at a constant true airspeed of about 400 kt (200 m/s). In this high altitude experiment, the maximum range of the LIDAR was about 3 km although no significant turbulence was encountered.

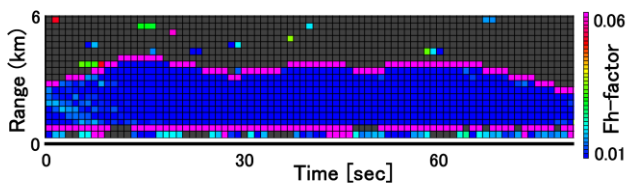


Fig. 8. LIDAR data at high altitude.

Figure 9 shows LIDAR measured wind speeds in the same conditions as in Fig. 8. It was confirmed that wind speed was stable in this flight case. In still air conditions, the measured wind speed corresponds to the aircraft's true airspeed.

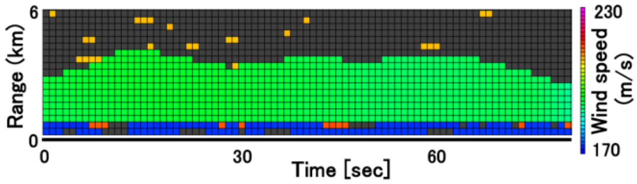


Fig. 9. Wind speed measured by the LIDAR.

Figure 10 shows LIDAR measured wind speeds while the aircraft's airspeed was gradually reduced during flight in calm conditions at 28,500 ft (8,700 meters), where the density of aerosol particles larger than 0.3μm was approximately 2.9 particles/cm$^3$. It was confirmed that the true airspeed could be measured without position error, and that the measurement range was between 900 meters and 3,000 meters. However, the accuracy of the TAS measurement has yet to be verified.

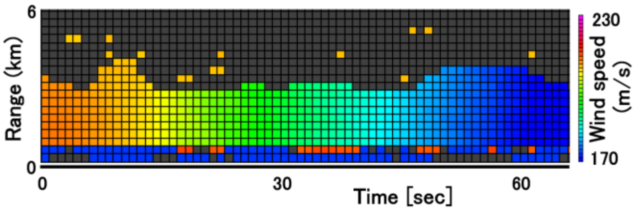


Fig. 10. True airspeed measured by the LIDAR.

During a flight experiment at altitudes of up to 43,000 ft (13,000 meters), the maximum range of the LIDAR was found to be less than 2 km because of the very low aerosol particle density.

A full power demonstration of the LIDAR in flight using a jet aircraft is planned in January 2011 after the completion of endurance tests.

## 3 Aerosol Particle Observation Flights

Atmospheric observation flights to measure aerosol densities at different altitudes are being made regularly to determine the basic specifications for a practical wind measurement LIDAR and to confirm the availability of a sufficient aerosol density for turbulence detection. Due to the ceiling limitation of JAXA's present propeller driven research aircraft, data can usually only be gathered at altitudes up to 7,000 meters. However, some aerosol data were also acquired by a Gulfstream II at high altitudes. In addition, a business jet will be delivered to JAXA in 2011 for flight experiments, and this will enable the observation altitude to be increased.

Figure 11 shows the densities of aerosol particles larger than 0.3 μm in diameter measured over the sea south of Tokyo. The red broken line indicates the average of data from 31 observation flights. Orange stars indicate the densities of aerosol particles measured by a Gulfstream II over land and sea around the Chubu area in central Honshu. The aerosol particle density decreases with increasing altitude, but there is a large variability between observations.

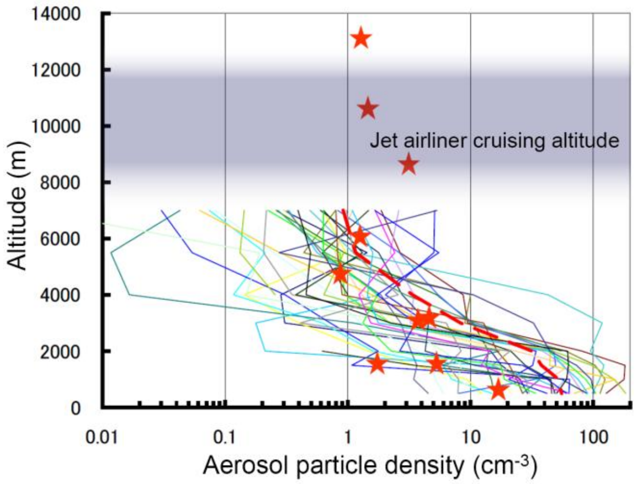


Fig. 11. Correlation between aerosol particle density and altitude.

Figure 12 shows the relationship between aerosol particle density and the LIDAR system's detectability ($D$), defined as

$$D = SNR \times N^{1/2} \qquad (2)$$

where $SNR$ is the signal-to-noise ratio of one received laser pulse and $N$ is the incoherent integration number. The detectability of the 600–750 m range bin is shown in the figure. Although the backscattering coefficient was not measured, there is an obvious strong correlation between detectability and aerosol particle density. Observation flights are therefore being continued to accumulate data to feed back into the design of a practical LIDAR.

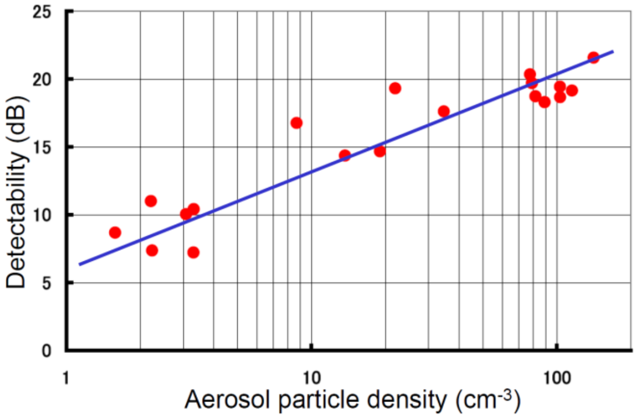


Fig. 12. Correlation between aerosol particle density and LIDAR detectability.

## 4 Concluding Remarks

The results of JAXA's LIDAR development program are summarized as follows:

- A high-altitude LIDAR has been developed, but it has been decided to operate it at low power for initial flight trials to reduce the chance of malfunction. Consequently, the performance of this LIDAR has not yet been confirmed. Flight demonstration of full power operation is planned in January 2011 after endurance tests.
- Demonstration flights at low altitude have been carried out to predict air turbulence at a range of 8 nautical miles (15 km).
- Demonstration flights at high altitude have been carried out to measure wind speed and true airspeed at a range of 1.5 nautical miles (3 km).
- Aerosol observation data have been acquired at a range of altitudes between 2,000 ft (600 m) and 43,000 ft (13,000 m).

It is difficult for the present high-altitude LIDAR to be used for guiding turbulence evasion maneuvers during cruise. The main aim of the turbulence detection function is to provide sufficient advance warning of turbulence to allow passengers to be secured. However, at low altitudes or airspeeds a LIDAR will enable vertical avoidance maneuvers to be provided similarly to a TCAS (Traffic Alert Collision Avoidance System).

Further improving the detection range of the LIDAR will result in an increase of size, weight and power consumption, with attendant higher installation cost. Consequently, we will now focus on downsizing the device and improving its reliability rather than on achieving greater detection range.

It is also considered that measured wind data will be communicated directly to the aircraft's automatic flight control system, and we have recently started researches on this topic.

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