DEVELOPMENT OF AN ONBOARD DOPPLER LIDAR FOR FLIGHT SAFETY

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Abstract

Wind turbulence has become a major cause of aircraft accidents. Timely advance warning of turbulence ahead of an aircraft may allow the pilot to take appropriate action to minimize any damage, such as reducing speed and securing passengers and unsecured objects, or to avoid the turbulence altogether. The aim of our research is to develop a practical onboard proactive sensor that will be able to detect wind turbulence in clear air condition at the range of 5 nautical miles (9.3 km) at cruising altitude. In February 2007 we completed successful experiments to measure wind speed at a forward distance of approximately 3 nautical miles (5.6 km) far during flight in low altitude. Later, in another experiment conducted in July of the same year, we succeeded in detecting wind turbulence in advance. And the upgraded 5 nautical mile model for low altitude was developed in fiscal 2007. We have already carried out demonstration to measure the wind speed up to the range of 5 nautical miles on ground successfully. This paper describes the results of basic flight and ground experiments and a master plan of the development.

1 Introduction

When assessed in term of travel distance, aircraft travel is safe with a low accident rate. However, accidents caused by unpredictable factors can occur. Although aircraft crashes are decreasing, accidents that crew and passengers are damaged by shaking violently up and down due to wind turbulence occur frequently in recent years in Japan. In most wind turbulence accidents, the articles such as service carts or crew and passengers fly by negative vertical acceleration by wind turbulence, and afterwards they are damaged by dropping the cabin floor. To detect wind turbulence ahead of the aircraft in flight in real time, then to warn the pilot is the most direct and effective in order to prevent such a wind turbulence accident. The pilot can turn on seat belt signs, broadcast the warning or order cabin attendants to interrupt of the cabin service properly, if he recognizes the forward wind turbulence area and the intensity in real time. If there is enough time by the wind turbulence encounter, the pilot may reduce the shake of the aircraft by slowdown of the airspeed, add positive vertical acceleration by turning flight, or change the course to avoid from the wind turbulence area.

Consequently research and development of an onboard proactive wind measurement sensor was launched by JAXA (Japan Aerospace Exploration Agency) in 1999 [1]. The aim is to develop a practical onboard Doppler LIDAR (Light Detection and Ranging) which can detect wind shear, downbursts, wake-vortex, clear air turbulence and mountain wave in clear air condition at the range of 5 nautical miles ahead of the aircraft at cruising altitude. Because the cruising airspeed of a general jet airliner is about 250 m/s at cruising altitude, it takes about 37 seconds to fly distance of 5 nautical miles. We never thought that 37 seconds were sufficient time for a wind turbulence evasion flight, however, some measures can be carry out. Thus 5 nautical miles were decided as the tentative target value of the practical use at present in view of feasibility of the developing device and the effectiveness. In addition, the state of wind turbulence changes every several minutes.

2 Aircraft Accidents and the Preventive Measures

Aircraft accidents of the large size civil airplane in Japan which occurred between 1990 and 2006 were classified according to a cause based on the report [2] of the Aircraft and Railway Accidents Investigation Commission of Japan. Then all accidents that aircraft accident investigation report is published by March 12, 2008 are expressed like the upper part of Fig. 1.

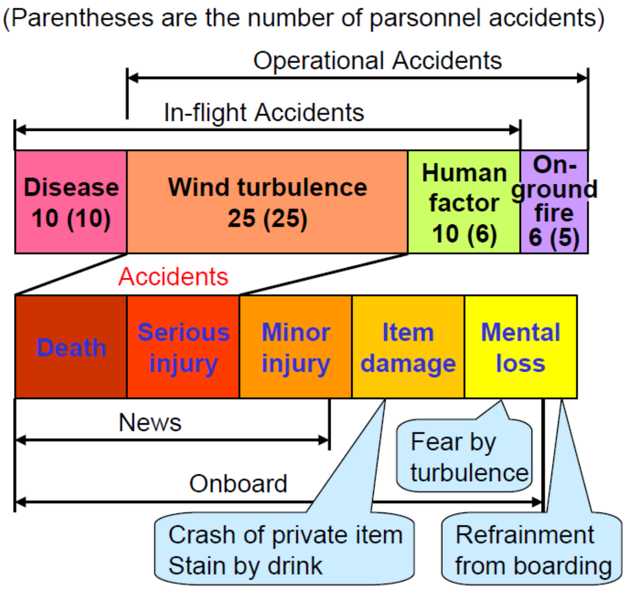

Fig. 1. Cause of Aircraft Accident and Damage by Turbulence

The number of the aviation accidents by the wind turbulence of this term is 25 cases, and the ratio for all aviation accidents is about 50%. Among all accidents, the number of the accidents is 36 cases limited for the accidents resulting in serious injury or death related to the operation of airliners which are included while the aircraft stop on the ground. Therefore, the ratio of accidents by wind turbulence of this case is outstanding with about 70%. In addition, the accident only for the minor injured is not investigated by the Aircraft and Railway Accidents Investigation Commission because the accident is not authorized as an aviation accident by the aviation law. Although the frequency is vague, it is estimated that the damage by the wind turbulence is considerably wide as the lower part of Fig. 1. Because the turbulence accident only for the minor injured is often reported by news, and the number of article damage and mental loss is not announced.

As present measures of the turbulence accident prevention, various weather observation facilities are prepared on the ground at the airport periphery. The aircraft operator can receive observation data and a weather forecasting if necessary. About the weather on the cruise route, observation data of the wide area and information from a precedent aircraft are given to some extent. Pilots can know the area of clouds causing wind turbulence in real time during flight using an onboard weather RADAR (Radio Detection and Ranging). However, the measures are impossible at present because both prediction and observation are not possible about clear air turbulence occurring suddenly in the high altitude without cloud or rain.

Therefore we aimed at a Doppler LIDAR using a laser beam. The Doppler LIDAR can detect clear air turbulence of the remote range from an observer [3]. Based on the results of the feasibility study [4], we came to the conclusion that 1.5-μm pulsed Coherent Doppler LIDAR with optical fiber amplifiers is the most suitable technology for an onboard remote wind measurement sensor. A wavelength of 1.5 μm is the safest for the human retina as a laser beam [5]. The optical fiber amplifier is small size and has high reliability and high flexibility of arrangement. In addition, power-saving and the price reduction may be possible not only considerably miniaturized using commercial parts developed for optical fiber communication. A practical onboard wind measurement LIDAR seems to be a feasible proposition given the recent rapid advancement of optical fiber communication technology. Accordingly, development of a prototype onboard wind measurement LIDAR was initiated in fiscal 1999.

Concerning large-sized Doppler LIDARs using a high-output laser oscillator, flight experiments are already accomplished in U.S.A. in 1990's [6]. The European countries pay attention to a Doppler LIDAR as measurement use of a short range and carried out flight experiments of Doppler LIDAR using an optical fiber amplifier [7]. In addition, within the

European AWIATOR (Aircraft WIng with Advanced Technology OpeRation) project [8], a UV (Ultraviolet) direct-detection LIDAR system of measurement range of 50-150 meters was developed. The system is designed to feed back turbulence data into the aircraft flight control system in order to directly counteract the turbulence influence on the aircraft.

3 Doppler LIDAR

3.1 Concept

The overall concept of the onboard wind measurement LIDAR is shown in Fig. 2. The Doppler LIDAR is installed in an aircraft to measure wind turbulence ahead of the aircraft during 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 wind so that 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 the wind speed. Range information can be obtained by measuring the delay between transmission of a pulse of laser light and reception of the backscattered radiation.

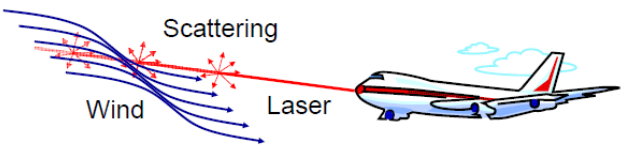

Fig. 2. Concept of an Onboard Doppler LIDAR

Figure 3 shows a block diagram of coherent Doppler LIDAR in JAXA based on optical heterodyning technique [9]. A single frequency laser is used as a master oscillator of which a part of outputs are used as seeding light for pulse amplification, while the reminder as reference light. Seeding light is amplified with an optical fiber amplifier, then transferred to an optical antenna through an optical circulator, and finally irradiated to atmosphere. The optical antenna also receives weak backscattered lights from distant natural aerosols whose frequencies are shifted due to Doppler shifts. The wind velocity is proportional to the Doppler shift in the beat signal. This Doppler shifts can be evaluated with power spectra of the beat signals generated by optically combining the backscattered lights with the reference lights. The range information is also measured from segmentation in the beat signals taking into account of the time-of-flight. All LIDARs to explain after this can monitor wind velocity of each segmented range at the same time on board in real time. A wavelength of 1.5 μm was adopted in the LIDAR of JAXA because of many advantages such as eye safety, reliability and flexibility for an airborne deployment.

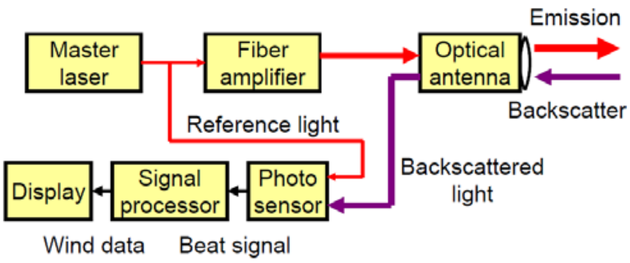

Fig. 3. Block Diagram of Coherent Doppler LIDAR based on Optical Heterodyning Technique

The optical fiber amplifier adopted for our LIDAR is vastly superior to the conventional laser oscillator for an airborne deployment. The principle advantages are a smaller device size, low weight, low electric power burden, low rate of electromagnetic noise, highly flexible layout, reduced susceptibility to vibration, high degree of dust-proofness, relatively loose requirements for fabrication accuracy in manufacturing, and cooling without the use of liquid coolants.

3.2 1NM class LIDAR

A 1NM (Nautical Mile: 1NM = 1852 meters) class LIDAR [10] is a low output breadboard prototype Doppler LIDAR which was developed using a commercial fiber amplifier for optical communication in order to confirm the basic functions. It was developed in fiscal 2001 and the wind measurement accuracy of 0.7

meters per second or less was understood by flight experiments in 2002 [11]. The 1NM class LIDAR is shown in Fig. 4, and consists of the laser transceiver that includes a master laser oscillator, fiber amplifier and heterodyne detector, the optical antenna connected to the laser transceiver by a 10 meter long flexible optical fiber cable, and a desktop computer for signal processing, control and analysis. The scanner has a double wedge prism to scan from -10 degrees to 10 degrees the direction of the transmitting laser beam. The steering mirror is on the outside through the hole of the aircraft ceiling.

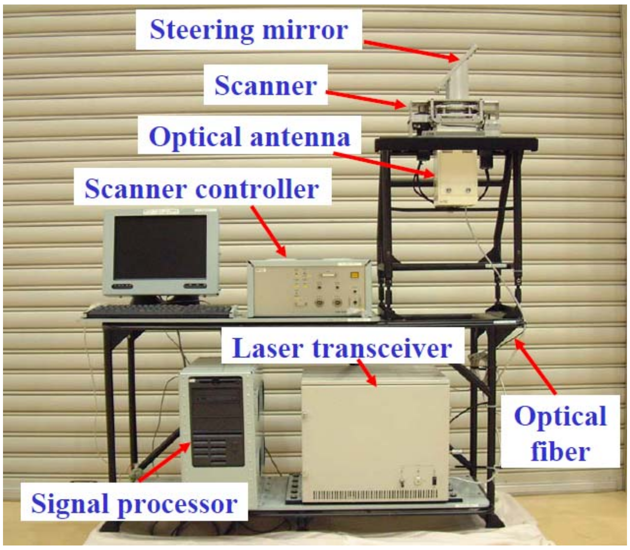

Fig. 4. 1NM Class LIDAR

3.3 3NM class LIDAR

A 3NM (5.6 km) class prototype Doppler LIDAR was developed in fiscal 2006 for demonstration of the practical performance by increasing the laser output to about ten times as much as that of the 1NM class LIDAR. A high output amplifier using a high density of erbium doped (7600 wt-ppm), short length (3.5 meters) and large core diameter (9.1 micrometers) optical fiber was developed, and it was incorporated in the LIDAR [12]. The 3NM class LIDAR was installed in the JAXA's Beechcraft Model 65 research aircraft (see Fig. 5.). The experimental system was installed in a rack in the left side of the cabin of the research aircraft as shown in Fig. 6. The optical antenna without a scanner was installed on the ceiling of the cabin with its axis pointing vertically upwards, and the emitted laser light was reflected forward by a steering mirror.

Fig. 5. JAXA's Beechcraft Model 65

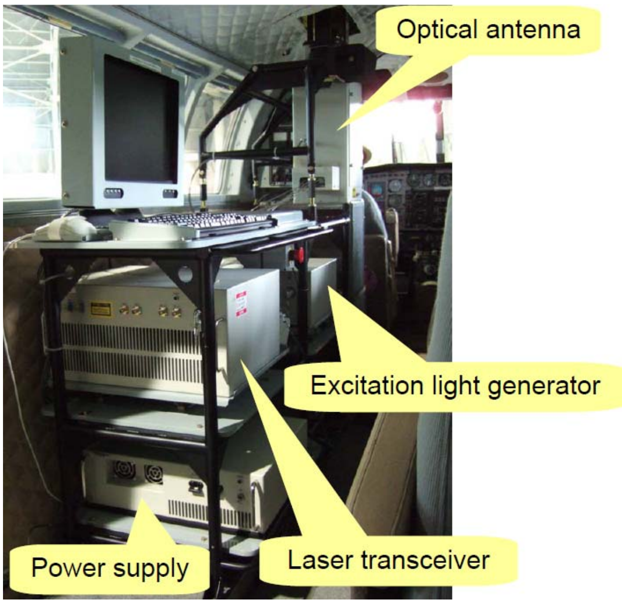

Fig. 6. Installation of the Experimental System

The first flight experiment was conducted at the flight altitude of 300 meters in calm and clear air condition in 2007. A sample of the in-flight measured data is shown in Fig. 7. The wind velocity is calculated by subtracting true airspeed from the measurement value by the LIDAR. Measurable distance range is derived from that the detectability is more than 4.5 dB which is noise level. The detectability (D) is defined by Eq. (1).

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

Where *SNR* is the signal-to-noise ratio at one received laser pulse, and *N* is the incoherent integration number.

It was confirmed that wind velocity data is invalid, in case of detectability is less than 4.5 dB by the experiment.

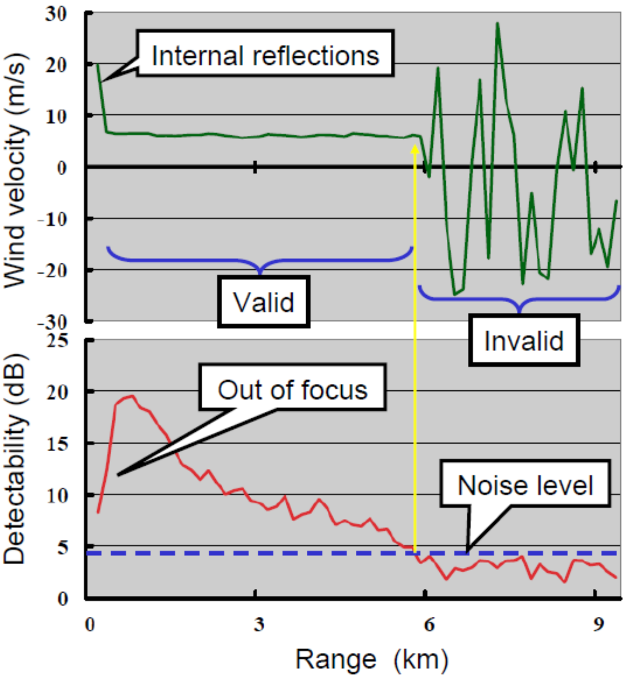

Fig. 7. In-Flight Measured Data by the 3NM Class LIDAR

The flight experiment demonstrated that the 3NM class LIDAR is able to measure wind at a maximum distance of approximately 6 km in flight in clear weather. In this case, the laser pulse repetition frequency is 4 kHz and the incoherent integration number is 4000. Therefore, the display refresh rate is 1 Hz. Concerning the short distance, a focal distance of the optical telescope was set to approximately 2 km, and so the detectability deteriorated without a focus matching in a short distance. Furthermore, even if the detectability is sufficient, measured value may be invalid in the extremely short distance because the signal strength increases by internal reflections of the laser light.

Figure 8 shows comparison of true airspeed measured by the LIDAR with that by a Pitot tube corrected by static pressure. This data indicates good agreement with each other. Twin parallel green broken lines indicate a tolerance standard of airspeed indication provided in the FAR (Federal Aviation Regulations) 23.1323 [13]. It appears that there is an error in tolerance level. As for the part shown with an orange oval, it was confirmed that the airplane flew gusty area in the experiment by another data.

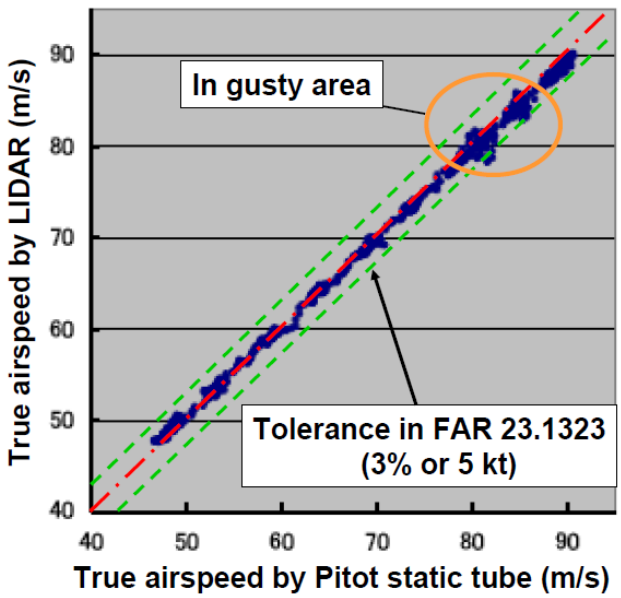

Fig. 8. Comparison of True Airspeed

Accuracy of airspeed measurement by the LIDAR is shown in Table 1. It is considered that the reason why the distant range has a rather large standard deviation is disagreement of real airstream in each range. It was confirmed that the measurement by the LIDAR is equivalent or better than the measurement by the Pitot tube, because the values of standard deviation are equivalent to accuracy of the Pitot tube. In addition, a meaningful bias was not observed.

Table 1. Accuracy of Airspeed Measurement

Measured range (m)	Standard deviation (m/s)
450 – 600	0.63
600 – 750	0.68
750 – 900	0.69
900 – 1050	0.70

Figure 9 shows in-flight measured data by the LIDAR when our airplane went into a wind shear during a flight experiment. The airplane flies at 60 m/s of airspeed in the vertical direction of this figure, and the vertical length of one small square is 150 meters. One vertical line indicates the measured wind speed which can be acquired every one second and a row of the lines shows a time history of the wind speed in front of the aircraft with the 6 km range. Each color shows the wind speed of remote area as shown in the right-side, and the positive means a head wind. The slant red line corresponds to 60 m/s of airspeed, and wind turbulence approaches the airplane along this line. In this case, it is easy to recognize that there is a wind shear, and it is possible to predict the airstream from 40 to 50 seconds before.

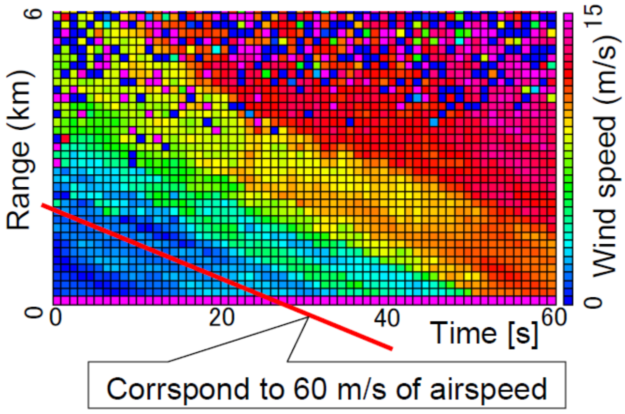

Fig. 9. Wind Measurement Raw Data

Figure 10 shows same data as Fig. 9, however although Fig. 9 just displayed raw data, the data less than detectability of 4.5 dB are omitted in Fig. 10. Reliability improves as most of invalid data are not displayed.

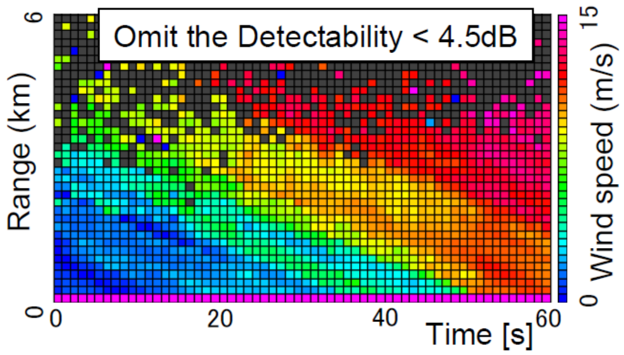

Fig. 10. Wind Measurement Cleaned Data

Figure 11 shows the predicted intensity of the wind turbulence, which is valued by the Fh-factor proposed by JAXA. The vertical acceleration is compared with the airstream data in each range as time histories. Each color in the upper figure shows an absolute value of the Fh-factor and black area shows invalid data. The Fh-factor (*Fh*) is an index representing the intensity of the wind turbulence at a rate of change of the horizontal wind, and it is defined by Eq. (2).

$$Fh = -(dU/dt) / g \qquad (2)$$

Where U is the head component of the wind velocity, t is the unit time, and g is the acceleration of gravity.

In the experiments we conducted in July 2007, we were only able to make measurements up to about 2 km ahead, due to unfavorable air conditions. In our flight experiments, however, we detected wind turbulence a full 20 seconds before the aircraft started to shake up and down (shown by the lower graph of Fig. 11).

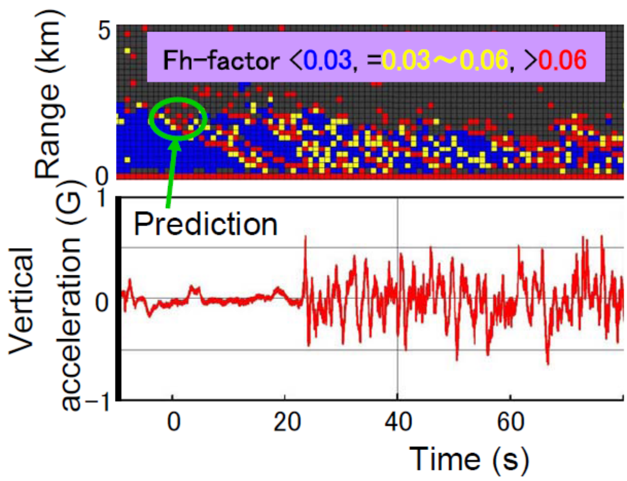

Fig. 11. Prediction of Wind Turbulence

3.4 5NM class LIDAR

A 5NM (9.3 km) class prototype Doppler LIDAR was developed in fiscal 2007 for demonstration of the long range performance by increasing the laser output to about three times as much as that of the 3NM class LIDAR. A high output amplifier using a large core diameter (25 micrometers) optical fiber was developed, and it was inserted behind the former amplifier in the 3NM class LIDAR as a second amplifier [14]. The 5NM class LIDAR is shown in Fig. 12, and consists of a laser transceiver that includes a master laser oscillator and heterodyne detector, an optical antenna that includes two fiber amplifiers, two excitation light generators, and a desktop computer for signal processing, control and analysis.

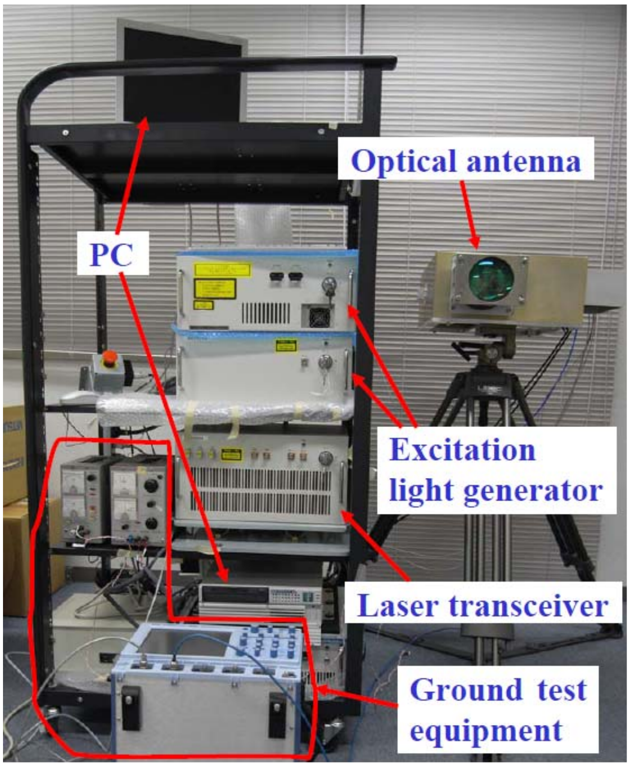

Fig. 12. 5NM Class LIDAR

The result of experiments on ground is shown in Fig. 13. Approximately 10 km of maximum measurable distance was demonstrated by the 5NM class LIDAR. The range performance was improved in comparison with the former models drastically.

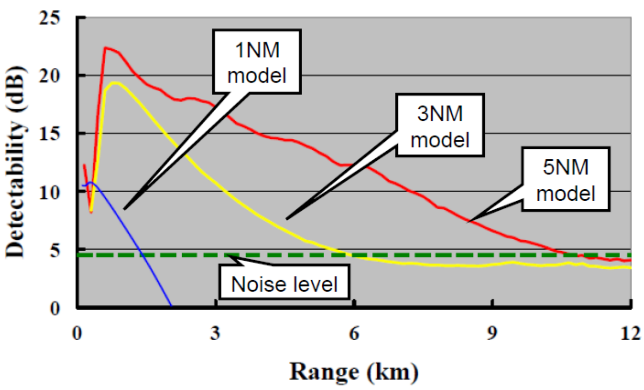

Fig. 13. Ground Measured Data by Each LIDAR

Major specifications of developed three LIDARs are shown in Table 2. 3NM and 5NM models can measure wind velocity of 80 segmented ranges at the same time. The range performance almost depends on the output laser pulse energy, the pulse repetition frequency and the effective aperture diameter of optical antenna. To increase the laser peak power is important for range resolution. The output laser power improves steadily, however the electrical power consumption and the weight of whole system do not change so much. These almost depend on experimental peripheral devices.

Table 2. Specifications of Developed LIDARs

	1NM model	3NM model	5NM model
Laser peak power	10 W	90 W	323 W
Laser pulse energy	4.5 μJ	58 μJ	179 μJ
Pulse repetition frequency	50 kHz	4 kHz	4 kHz
Aperture diameter	50 mm	110mm	110mm
Range segmentation	15	80	80
Power consumption	420 W	306 W	374 W
Weight	105 kg	51 kg	82 kg

4 Plans for the Future

The flight experiment of 5NM class LIDAR for demonstration of the long range performance in low altitude is planned in September 2008. However, the maximum effective measurement range shortens in high altitude because aerosol particles in the atmosphere decrease with increasing altitude. As the next stage, JAXA has a plan that development of a Doppler LIDAR that the effective range is 5 nautical miles in high altitude such as cruising altitude of jetliners in fiscal 2008. A high output optical waveguide amplifier [15] will be inserted behind the former second amplifier in the 5NM class LIDAR as a third amplifier. The flight experiment for demonstration of the high altitude performance using a jet plane is planned in fiscal 2009. Once the goals are accomplished, we will begin working towards the practical application of this system by reducing the size, enhancing reliability and durability, and making other improvements.

5 Concluding Remarks

The summary is as follows:

- Demonstration flight to measure wind speed at the range of 3 nautical miles (5.6 km) in low altitude was carried out in 2007.
- Demonstration to measure wind speed at the range of 5 nautical miles (9.3 km) on ground was carried out in fiscal 2007.
- JAXA has a plan that development of a LIDAR that the effective range is 5 nautical miles in high altitude in fiscal 2008.

The present research will only result in development of a wind measurement remote sensor, and maintainability and reliability aspects will have to be addressed for practical use. The methods of indicating detected wind turbulence, warning pilots and action to minimize any damage will have to be researched in order to develop a useful device that can contribute to flight safety. It is also considered that measured wind data will be communicated directly to the aircraft's automatic flight control system rather than to the human pilots. We already started researches such as the above recently.

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