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Development of an Onboard Doppler Lidar for Flight Safety

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Air turbulence has become a major cause of significant injuries and aircraft damages. Timely advanced warning of turbulence ahead of an aircraft may allow pilots to take appropriate action to minimize potential 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, Lidar-based proactive sensor that will detect air turbulence in clear air at a range of 5 n miles (9.3 km) at cruising altitudes. In February 2007 we successfully measured wind speeds approximately 3 n miles (5.6 km) ahead of an aircraft in low-altitude flight experiments, and in a subsequent experiment in July of the same year, we succeeded in detecting air turbulence before encountering it. An upgraded 5-n-mile Lidar for low altitudes was developed in fiscal year 2007, and has successfully measured wind speeds at ranges up to 5 n miles in ground tests. This paper describes the master development plan of our Lidar turbulence sensor and the results of basic flight and ground experiments.

I. Introduction

WHEN assessed in term of travel distance, aircraft travel is safe with a low accident rate. However, accidents can occur due to unpredictable factors. Although the number of aircraft crashes is decreasing, accidents in which crew members and passengers have been injured due to turbulence have occurred frequently in Japan in recent years. In most such accidents, unsecured articles, such as service carts or crew and passengers, are caused to jump up by negative vertical acceleration due to turbulence, then they are often slammed violently into the ceiling and drop to the cabin floor or onto seats causing damage or injury.

The most direct and effective means of preventing such accidents is detecting turbulence ahead of an aircraft in-flight and giving advanced warning to the pilots. If the pilots have adequate warning of an area of turbulence and its intensity, they can turn on seat belt signs and order that the cabin be secured. Also, if sufficient time is available, pilots may reduce the shaking of the aircraft by reducing speed, add positive vertical acceleration by turning, or change course to avoid the turbulent area.

With the aim of reducing such accidents, the JAXA (Japan Aerospace Exploration Agency) launched the research and development of an onboard proactive wind measurement sensor in 1999 [1]. The aim is to develop a practical onboard Doppler Lidar (Light Detection and Ranging), which can detect windshear, downbursts, wake-vortex, clear air turbulence, and mountain wave in clear air conditions at a range of 5 n miles ahead of an aircraft at cruising altitude. A typical jet airliner cruises at an airspeed of about 250 m/s, and takes about 37 s to fly this distance. Although this was never considered to be sufficient time for turbulence evasion, it should enable some precautions to be taken. Thus, 5 n miles was decided as the tentative target value for present practical application in consideration of the feasibility of development and effectiveness of the device. In addition, the state of air turbulence changes every few minutes.

II. Aircraft Accidents and the Preventive Measures

Aviation accidents to large civil airplanes that occurred in Japan between 1990 and 2006 were classified according to cause based on a report [2] by the Japanese Aircraft and Railway Accidents Investigation Commission (ARAIC). The breakdown of all accidents on which aircraft accident investigation reports were published up to 12 March 2008 are shown in the upper part of Fig. 1.

Wind turbulence accounted for about 50% (25 cases) of the total number of aviation accidents, but if accidents due to nonoperational causes (death or injury due to disease, etc.) are excluded, turbulence accounts for nearly 70% of the remaining 36 accidents that resulted in serious injury or death, including those that occurred when the aircraft was on the ground. However, this underrepresents the number of cases of damage due to turbulence because cases that result in only minor injury are not investigated by the ARAIC, as they are not recognized as aviation accidents under the aviation law. Although cases of turbulence that result in minor injury are often reported by the media, figures for the number of damaged articles and mental loss incurred are not available. Although the numbers are uncertain, it is estimated that cases of damage by air turbulence is considerably larger than indicated by accident statistics, as shown in the lower part of Fig. 1.

There are a number of means to warn pilots of turbulence at present. Ground-based weather observation equipment at airports can detect windshear, aircraft operators can receive meteorological observations and forecasts, pilot reports of turbulence encounters and observation data on air routes are available to some extent, and pilots can detect areas of clouds causing turbulence during flight in real time using onboard weather RADAR (Radio Detection and Ranging). However, these measures are still not adequate because they cannot predict or observe clear air turbulence (CAT), which occurs suddenly at high altitudes in the absence of clouds or precipitation.

For a proactive turbulence sensor, we, therefore, selected a Doppler Lidar using a laser beam, which can detect CAT at a distance from an observer [3]. Based on the results of a feasibility study [4],

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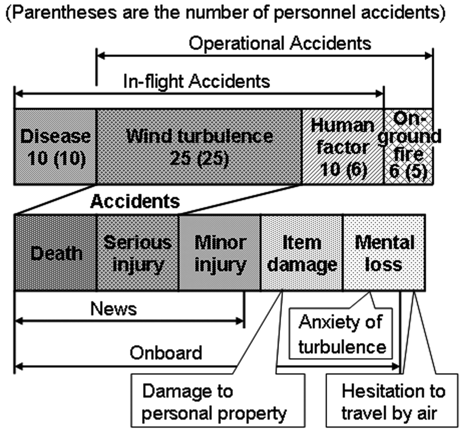

Fig. 1 Cause of aircraft accident and damage by turbulence.

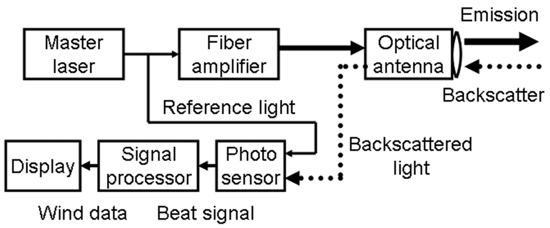

Fig. 3 Block diagram of coherent doppler Lidar based on optical heterodyning technique.

we concluded that a 1.5 μm pulsed coherent Doppler Lidar with optical fiber amplifiers is currently the most suitable technology for an onboard remote wind measurement sensor, because the laser beam wavelength of 1.5 μm has the greatest eye safety [5], and optical fiber amplifiers are small and highly reliable as well as affording high installation flexibility. A practical onboard wind measurement Lidar seems to be a feasible proposition given the recent rapid advancement of optical fiber communication technology, and the use of commercial parts developed for optical fiber communication may result in considerable miniaturization as well as power saving and cost reduction. Accordingly, development of a prototype onboard wind measurement Lidar was initiated in fiscal year (FY) 1999.

Concerning large-sized Doppler LIDARs that use a high-output laser oscillator, flight experiments have already been accomplished in the U.S. in the 1990s [6]. European countries have also been investigating Doppler Lidar for short-range measurement and have carried out flight experiments 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 with a measurement range of 50–150 m was developed. The system is designed to feed back turbulence data into the aircraft flight control system in order to directly counteract the effects of turbulence.

III. Doppler Lidar

A. 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 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 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 the transmission of a pulse of laser light and the reception of the backscattered radiation.

Figure 3 shows a block diagram of JAXA's coherent Doppler Lidar based on the optical heterodyning technique [9]. A single frequency laser is used as a master oscillator, of which a part of the output is used as seeding light for pulse amplification and the reminder is used as reference light. The seeding light is amplified by an optical fiber amplifier, transferred to an optical antenna through an optical circulator, and finally radiated to atmosphere. The optical antenna also receives weak backscattered light from distant natural aerosols whose frequencies are shifted by the Doppler effect. The aerosol velocity, and, hence, the wind velocity, is proportional to the Doppler shift in the beat signal. This Doppler shift can be evaluated from the power spectra of the beat signals that are generated by optically combining the backscattered light with the reference light. Range information is determined by segmentation of the beat signals taking into account the time-of-flight. Thus, an onboard Lidar can simultaneously measure the wind velocity in multiple range segments in real time.

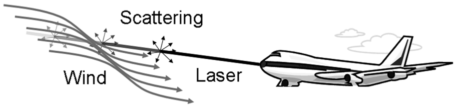

Fig. 2 Concept of an onboard doppler Lidar.

For airborne applications, the optical fiber amplifier adopted in our Lidar is vastly superior to a conventional laser oscillator. Its principle advantages are smaller device size, lower weight, lower power consumption, lower electromagnetic noise, high layout flexibility, reduced susceptibility to vibration, a high degree of dust proofness, relatively loose manufacturing tolerance requirements, and cooling without the use of liquid coolants.

B. 1-Nautical-Mile-Class Lidar

The 1 n mile class Lidar [10] shown in Fig. 4 (1 n mile = 1852 m) is a low-output breadboard prototype Doppler Lidar, which was developed in FY 2001 using a commercial optical communication fiber amplifier in order to prove the basic functions. The Lidar consists of a laser transceiver that includes a master laser oscillator, fiber amplifier and heterodyne detector, an optical antenna connected to the laser transceiver by a 10-m-long flexible optical fiber cable, and a desktop computer for signal processing, control, and analysis. The scanner has a double-wedge prism to deflect the direction of the transmitting laser beam from −10 to 10 deg. The steering mirror is mounted on the top of the aircraft fuselage through a hole in the cabin ceiling. Flight experiments in 2002 revealed a wind measurement accuracy of 0.7 m per second or better [11].

C. 3-Nautical-Mile-Class Lidar

A 3-n-mile-class (5.6 km) prototype Doppler Lidar was developed in FY 2006 to demonstrate a practically useful detection range by increasing the laser output to about 10 times that of the 1-n-mile-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 [12]. The 3-n-mile-class Lidar was installed in JAXA's Beechcraft model 65 research aircraft (see

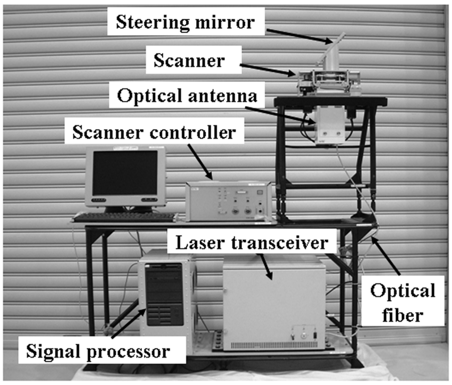

Fig. 4 1-n-mile-class Lidar.

Fig. 5). The experimental system was installed in a rack in the left side of the cabin as shown in Fig. 6. The optical antenna without a scanner was installed on the cabin ceiling with its axis pointing vertically upward, and the emitted laser light was reflected forward by the steering mirror on top of the fuselage.

The first flight experiment was conducted in 2007 at an altitude of 300 to 600 m above mean sea level in calm, clear air conditions. A sample of the in-flight measured data at an altitude of 600 m is shown in Fig. 7. The density of aerosol particles with a diameter less than 0.3 μm was approximately 12,000 count/liter in the case. The wind velocity is calculated by subtracting the aircraft's true airspeed from the value measured by the Lidar. The measurable distance (range) is defined as that at which the detectability is greater than 4.5 dB, which is the noise level. Detectability (D) is defined by Eq. (1):

$$D = \mathrm{SNR} \times N^{1/2} \tag{1}$$

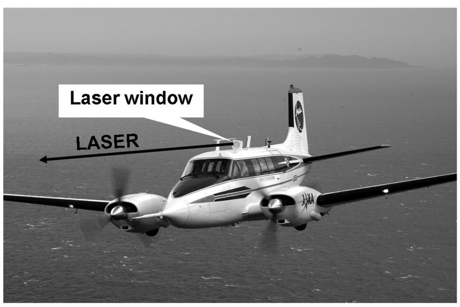

Fig. 5 JAXA's Beechcraft model 65.

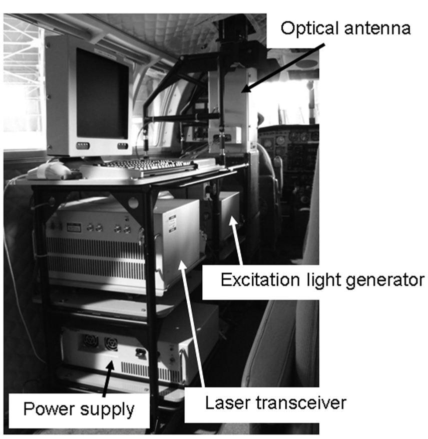

Fig. 6 Installation of the experimental system.

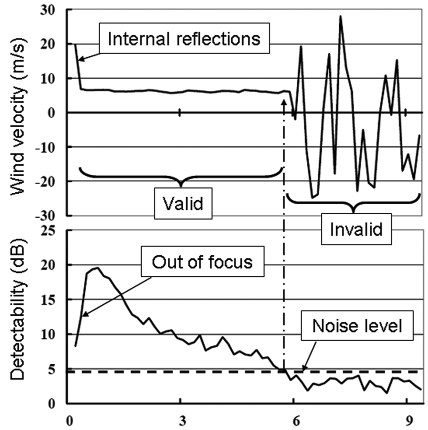

Fig. 7 In-Flight measured data by the 3-n-mile-class Lidar.

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

where SNR is the signal-to-noise ratio of one received laser pulse and N is the incoherent integration number. The flight experiment confirmed that when detectability was less than 4.5 dB, valid wind velocity data could not be obtained.

The flight experiment demonstrated that the 3-n-mile-class Lidar was able to measure wind speed at a maximum distance of approximately 6 km in-flight in clear weather. The laser pulse repetition frequency was 4 kHz and the incoherent integration number was 4000, giving a measurement rate of 1 Hz. Because the focal length of the optical telescope was set to approximately 2 km, detectability deteriorated at short range due to backscattered radiation being of out of focus. Moreover, at extremely short ranges signal strength increases by internal reflections of the laser light may invalidate measurements even if the detectability is sufficient.

Figure 8 compares true airspeed measured by the Lidar with true airspeed measured by a Pitot tube corrected by static pressure. The twin parallel broken lines indicate the airspeed indication tolerance standard of specified in FAR (Federal Aviation Regulations) 23.1323 [13]. The figure shows that the Lidar and Pitot data are in good agreement, and the airspeed errors are within the tolerances. Regarding the part indicated by the oval, it was confirmed by other data that the airplane flew through a gusty area during the experiment.

The accuracy of the Lidar airspeed measurement is shown in Table 1. The rather large standard deviations at greater ranges are considered to be due to the actual airstream ahead of the aircraft not being calm, as assumed. It was confirmed that the Lidar gives measurements equivalent to or better than the Pitot tube, because the values of standard deviation are equivalent to accuracy of the Pitot tube. In addition, no significant bias was observed.

Figure 9 shows raw in-flight data measured by the Lidar during a windshear encounter at an altitude of 600 m, and the density of aerosol particles less than a diameter of 0.3 μm was approximately 12,000 count/liter in the case. The airplane was flying at an airspeed of 60 m/s in the vertical direction of the figure. The y axis represents range, each small square has a vertical length of 150 m. The x axis represents time, and each vertical column indicates the wind speeds measured simultaneously at each range at an instance in time. Wind speed data were acquired at 1 s intervals. Each row, therefore, indicates the time history of wind speed at a certain distance in front of the aircraft, with a maximum distance of 6 km. Each square is color-coded with wind speed values as shown on the right of the figure, with a positive value indicating a head wind. The slanted red line corresponds to 60 m/s airspeed, and the turbulence approaches the airplane along this line. In this case, it is easy to recognize the

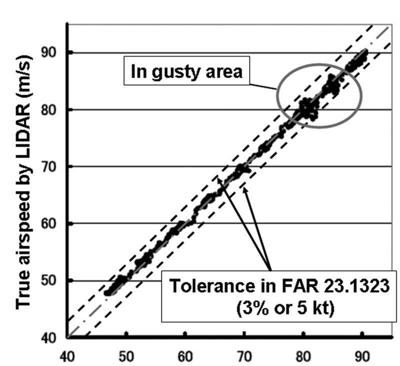

Fig. 8 Comparison of true airspeed.

Table 2 Specifications of developed LIDARs

	1-n-mile model	3-n-mile model	5-n-mile 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	110 mm	110 mm
Range segmentation	15	80	80
Power consumption	420 W	306 W	374 W
Weight	105 kg	51 kg	82 kg

presence of a windshear from the figure, and it is possible to predict the airstream from 40 to 50 s before the encounter.

Figure 10 shows the same data set as Fig. 9 with data with a detectability of less than 4.5 dB omitted. The reliability of turbulence detection improves as most of the invalid data are not displayed.

Figure 11 shows the predicted intensity of the turbulence weighted by the Fh-factor proposed by JAXA at an altitude of 1200 m and the density of aerosol particles less than a diameter of 0.3 μm was approximately 6000 count/liter in the case. Vertical acceleration is compared with the airstream data at each range as time histories. Each colored square in the upper figure shows an absolute value of the Fh-factor and black squares indicate invalid data. The Fh-factor (Fh) is an index representing the intensity of the wind turbulence as a rate of change of the horizontal wind, and it is defined by Eq. (2)

$$\mathrm{Fh} = -(\mathrm{d}U/\mathrm{d}t)/g \tag{2}$$

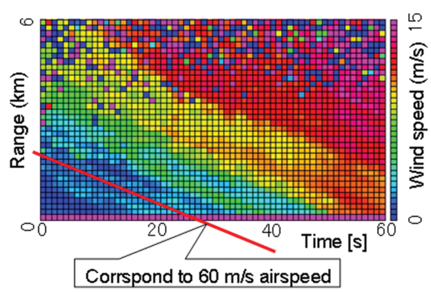

Fig. 9 Wind measurement raw data.

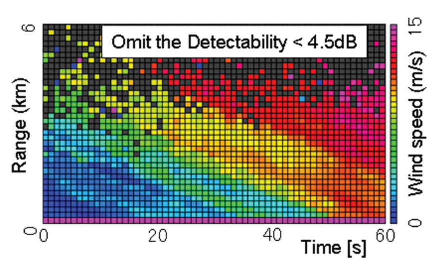

Fig. 10 Wind measurement cleaned data.

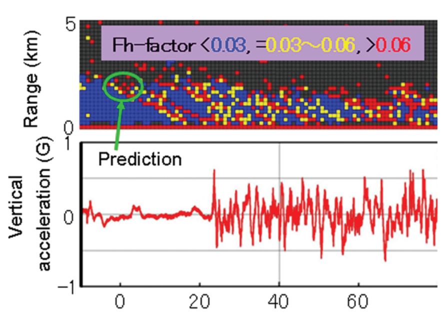

Fig. 11 Prediction of wind turbulence.

where U is the headwind component of the wind velocity, t is the unit time, and g is the acceleration due to gravity.

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

D. 5-Nautical-Mile-Class Lidar

A 5-n-mile-class (9.3 km) prototype Doppler Lidar shown in Fig. 12 was developed in FY 2007 to demonstrate greater long-range performance obtained by increasing the laser output to about 3 times that of the 3-n-mile-class Lidar. A high-output amplifier using a large core diameter (25 μm) optical fiber was developed and was inserted as a second amplifier behind the 3-n-mile-class Lidar amplifier [14]. The Lidar 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.

The results of a ground experiment in ordinary aerosol conditions are shown in Fig. 13. The 5-n-mile-class Lidar demonstrated a

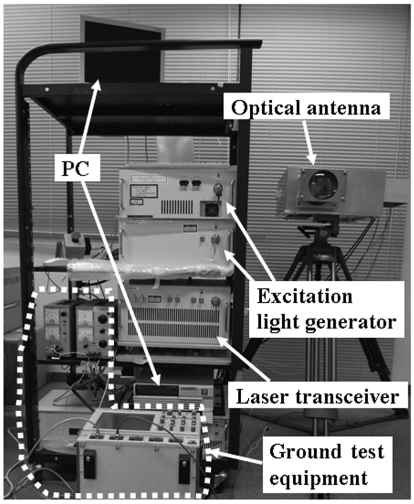

Fig. 12 5-n-mile-class Lidar.

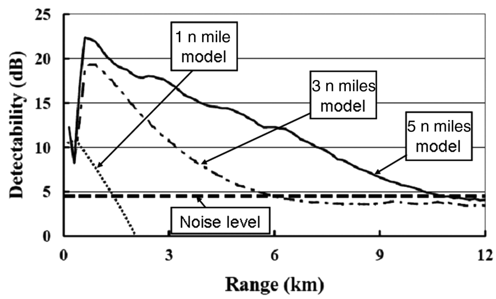

Fig. 13 Ground measured data by each Lidar.

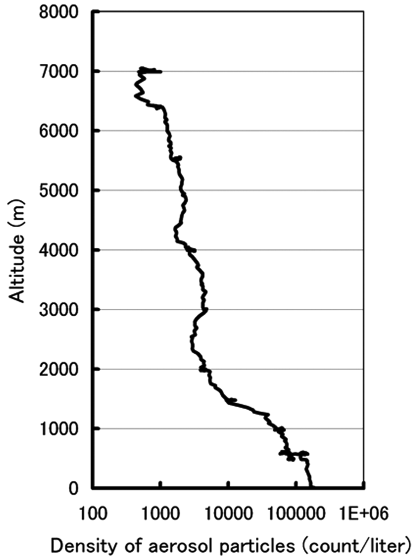

Fig. 14 Density of aerosol particles vs altitudes.

maximum measurable distance of approximately 10 km, a dramatic improvement over the previous models.

The major specifications of the three developed LIDARs are shown in Table 2. The 3-n-mile and 5-n-mile models can measure wind velocities in 80 range bins simultaneously. The range performance depends mainly on the output laser pulse energy, the pulse repetition frequency, and the effective aperture diameter of optical antenna. Increasing the laser peak power is important for achieving greater range resolution.

Although the output laser power has been improved steadily, the system's total electrical power consumption and weight do not change so much. These quantities depend mainly on the experimental peripheral devices.

IV. Plans for the Future

Flight experiments of the 5-n-mile-class Lidar are planned in FY 2008 to demonstrate long-range performance at low altitude. However, the maximum effective measurement range decreases at high altitudes due to the diminishing density of aerosol particles in the atmosphere with increasing altitude. Figure 14 shows a typical variation of the density of aerosol particles less than a diameter of 0.3 μm vs altitudes. These data were acquired by JAXA's Beechcraft model 65, and a maximum operating altitude of the aircraft is approximately 7000 m. As the next stage, JAXA plans to develop a Doppler Lidar with an effective range is 5 n miles at jet airliner cruising altitudes in FY 2008. A high-output optical waveguide amplifier [15] will be inserted as a third amplifier behind the second amplifier in the 5-n-mile-class Lidar. Flight experiments to demonstrate high-altitude performance using a jet airplane are planned in FY 2009. Once these goals are accomplished, we will begin working toward the practical application of this system by reducing its size, enhancing its reliability and durability, and making other improvements.

V. Conclusions

The summary is as follows:

1) Flight demonstrations to measure wind speeds at a range of 3 n miles (5.6 km) at low altitude were carried out in 2007.

2) Ground-based demonstrations to measure wind speeds at a range of 5 n miles (9.3 km) were carried out in FY 2007.

3) JAXA plans to develop a Lidar with an effective range of 5 n miles at high altitude in FY 2008.

The present research will only result in the 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 have recently begun such research.

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