2-4 Space-borne coherent Doppler lidar

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Global wind profiling with a space-borne Doppler lidar is expected to bring big progress in the studies on global climate modeling and accurate numerical weather prediction. This research program aims at a demonstration of the coherent Doppler lidar technology in space. CRL has been conducting feasibility study on the coherent Doppler lidar aiming at demonstration onboard the Japanese Experiment module of the International Space Station. We are in parallel developing an airborne coherent Doppler lidar system to measure wind profile under a jet plane for simulation of the Doppler lidar measurement in space. This system is also operated in the ground to develop algorithm of the wind measurements.

Keywords
Coherent, Doppler lidar, Space-borne, Wind

1 Introduction

Information on the global wind field is essential in studying climate change and making weather forecasts. A radio sonde is a standard observation tool for determining the vertical profile of such winds. This type of observation is common in developed nations in the northern hemisphere; however, observation data is lacking above the ocean and within continents. Data relating to winds on the earth's surface can be obtained from stationary observatories on the ground and by a space-borne microwave radar scatterometer above the ocean. Along air routes, airplanes observe winds and provide a limited amount of information. In addition, meteorological satellites provide images of cloud changes over time, which can be used to provide data on the behavior of winds along cloud edges.

All of the foregoing data can help in making forecasts; nonetheless, available wind data is clearly limited. It is urgently needed to develop the technology to obtain global wind profile from a satellite[1]. A space-borne Doppler lidar is considered to be the only observation system capable of such global measurement of wind profiles in the troposphere, and researchers eagerly await its development.

Development of a space-borne Doppler lidar using an all-solid-state laser has recently begun and appears promising, but it has yet to be applied in space. Prior to satellite deployment, it will be necessary to develop a system to verify the applicability of such a lidar. With the intention of performing this verification in space, we are researching a coherent Doppler lidar (CDL) having 2-μm solid-state lasers for the observation of atmospheric winds in the troposphere.

2 Coherent Doppler Lidar

2.1 Principle

Lidar stands for “light detection and ranging.” It is different from radar (“radio detection and ranging”) in that the former uses laser light instead of radio waves as a transmitter. For radar, coherent detection is performed through the receipt of reflected waves from an object. For lidar, direct detection is often applied to obtain a profile of the object based on the time resolved intensity of the reflected waves. On the other hand, coherent detection is also performed by coherent Doppler lidar, which determines the frequency of a beat signal with a local laser to detect an object's Doppler shift with a high degree of accuracy.

In this study, the objects reflecting laser light consisted of aerosols and clouds in the tropospheric atmosphere. With sufficient sensitivity, it should be possible to observe such aerosols at altitudes as high as 30 km. To observe molecules at high altitudes—i.e., several kilometers above the surface or higher—we analyzed Rayleigh scattering light by atmospheric molecules. In such applications, incoherent Doppler lidar, which directly detects spectroscopic light produced by a high-resolution spectroscope, is capable of uniform observation (regardless of the quantity of aerosol), but features low resolution. Coherent Doppler lidar is better for high-resolution observation. We therefore intend to develop the latter type of lidar for satellite deployment.

As shown in Fig.1, coherent Doppler lidar uses a master laser and a pulse laser. The seed laser (master laser) controls the wavelength of the injection locking pulse laser. The light is reflected and Doppler-shifted by the aerosol, returning to the lidar. The reflected light is mixed with the local laser (master laser) light and combined in a detector. Among the detected signals, low-frequency beat signals are amplified with an IF amplifier, A/D converted, and recorded as digital signals. The final signals are analyzed in terms of frequency to obtain the Doppler shift, which is converted to a wind velocity after removing the offset components. For a wavelength of 2μm, a shift of 1 MHz corresponds to 1 m/s of wind velocity along the line of sight.

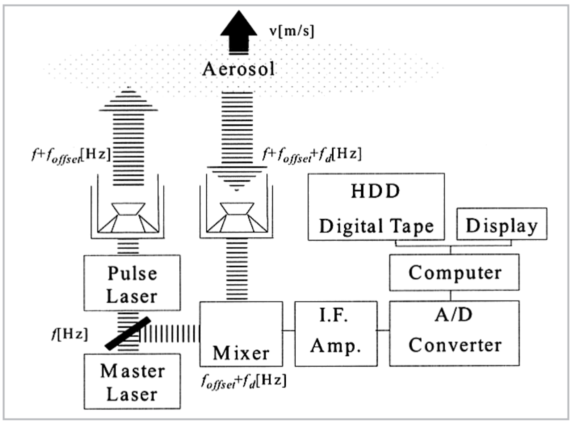

Fig.1 Measurement principle of coherent Doppler lidar

In practical applications, part of the pulse laser output is combined with the master laser output. The offset of the output laser is monitored as a monitor signal.

2.2 History

In the 1980s, CO_2 gas laser systems with an output wavelength of 10μm were used in coherent Doppler lidar studies[2][3]. Since these systems were heavy and required large power resources, they were not deployed on satellites. In the 1990s, a solid-state laser using laser diodes was developed to transmit eye safe laser light that were 1.5-μm or longer[4]. This type of laser is compact, requiring limited resources; it is thus easy to carry on satellites and aircraft. At present, various laser crystals are available between 1.5μm and 2μm. A Tm,Ho:YLF laser emits in the 2-μm band and is a promising candidate for a high-output power device that may be deployed on a satellite.

3 Observation on the Ground and from Aircraft

We are currently developing air-borne Doppler lidar for the observation of atmospheric winds, to perform simulations of space-borne lidar activity. Fig.2 outlines the lidar system in question. A coherent Doppler lidar will be installed on an airplane as part of an investigation of the algorithms required to extract the Doppler shift, compensate for airplane attitude and velocity, and measure wind profiles. The lidar unit will serve to verify the kinds of data to be obtained in future space-borne lidar experiments. In this application a Doppler lidar transceiver is placed in a pod attached to the bottom of the airplane body and is controlled from within the airplane. A silicon wedge is rotated to move a laser beam downward along a cone with an angle of 20 degrees. The lidar features a Tm:YAG laser

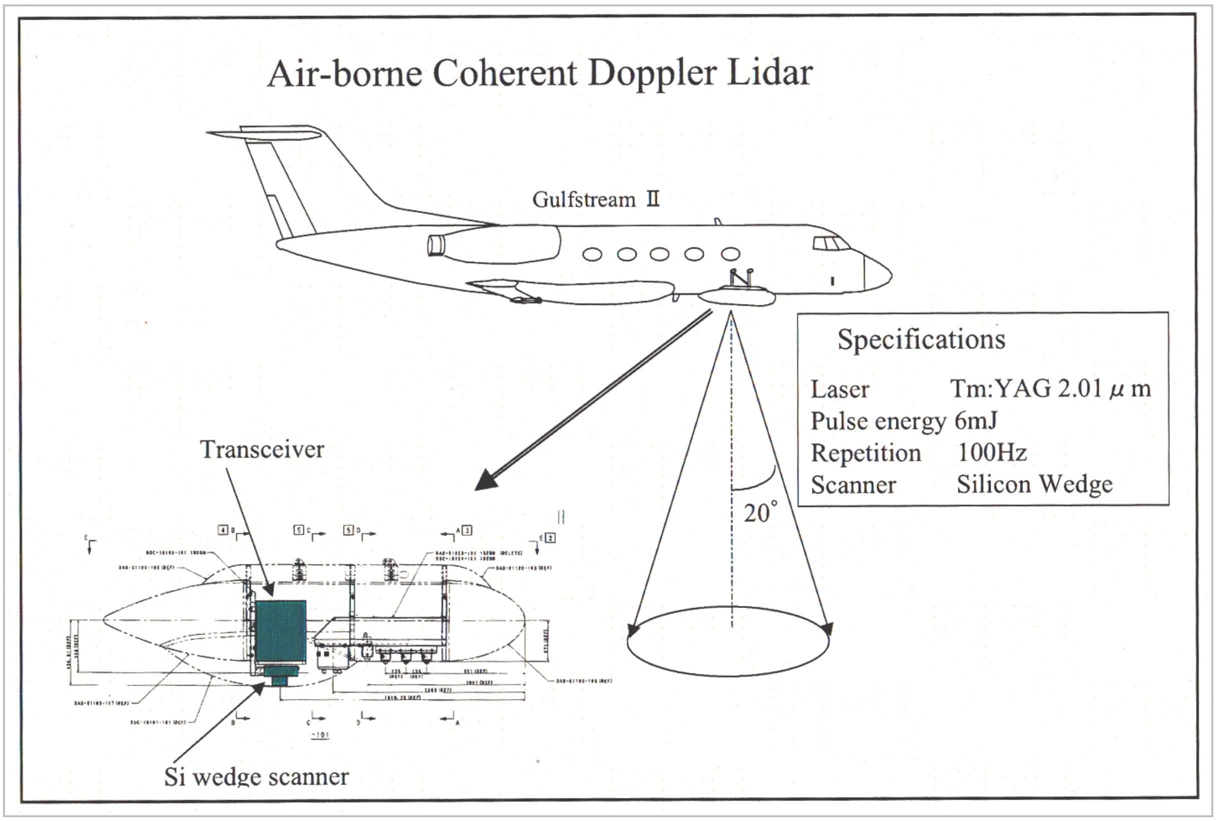

Fig.2 *Outline of air-borne coherent Doppler lidar*

Laser light comes out of a telescope 10-cm in diameter placed in a transceiver, passes through a silicon wedge scanner, and scans downward in a 20 degree cone.

with an output wavelength of 2.01μm.

The lidar can be placed on the ground to transmit laser light upward to measure winds in the troposphere. The photograph in Fig.3 shows the experimental unit located at CRL, Koganei-shi. The observation cone had an zenith angle of 20 degrees, and the observation orientation was selected by rotation with a scanner. Fig.4 shows the data results of a single pulse obtained in this experiment. This figure represents both a monitor signal and the received signals backscattered by aerosol. The received signals included a signal that appeared to come from clouds at an altitude of 7.2 km. At other altitudes signals seem to be noise-like beat light. Fig.5 shows a received signal at an altitude of 1.4 km and an FFT analysis of this signal. This analysis indicates a peak at 113.5 MHz, which was compared with the monitor signal peak at 111.2 MHz to give a Doppler shift due to aerosol of +2.3 MHz. Since a wavelength of 2μm corresponds to a wind velocity of 1 m/s for a Doppler shift of 1 MHz, the experimental results reveal that the wind featured a horizontal component of 6.7 m/s (2.3 m/s divided by sin20°).

Fig.6 shows the altitudinal change of a spectrum that was obtained by averaging 1,000 shot, indicating a smooth change with altitude. Fig.7 shows a comparison of horizontal-wind data obtained by the lidar and by a microwave wind profiler. The data were in good agreement up to an altitude of 3 km, attesting to the ability of the coherent Doppler lidar (CDL) to measure the altitude profile of winds through ground-based observation.

4 Space-borne Doppler lidar

4.1 JEM/CDL

Doppler lidar has never been used in space. Our aim is thus to show that it will be practical and useful in operational measurement of global winds. We have studied a coherent Doppler lidar system capable of

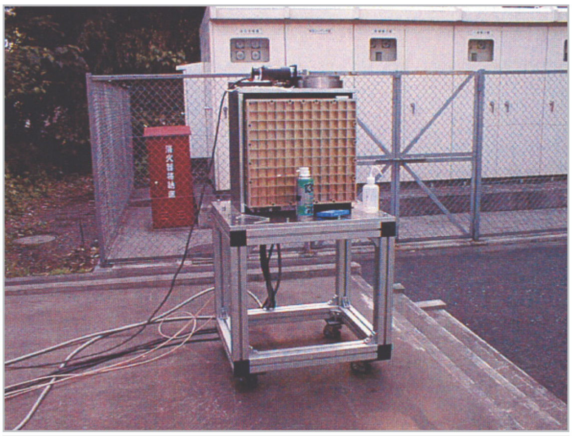

Fig.3 *Coherent Doppler lidar placed on the ground to observe a profile of wind velocities*

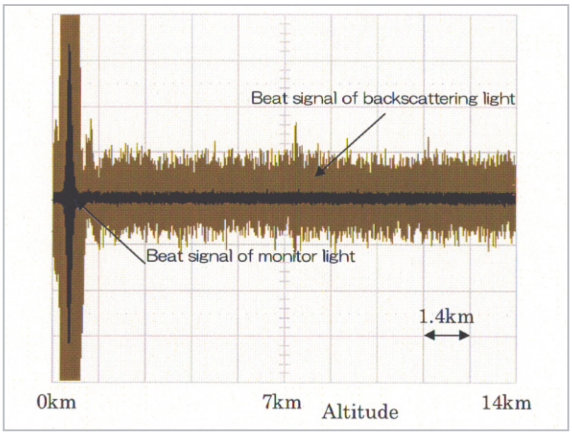

Fig.4 *Signals received by coherent Doppler lidar*

The narrow signal is a monitor signal of emitted light for a frequency monitor.

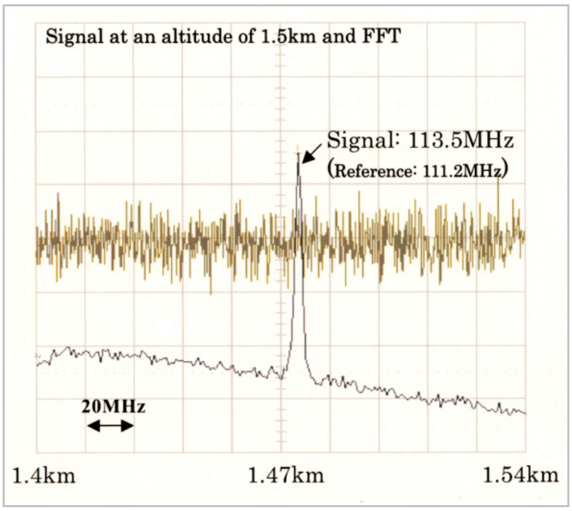

Fig.5 *Signal received from altitudes near 1.5 km and the spectrum obtained by FFT*

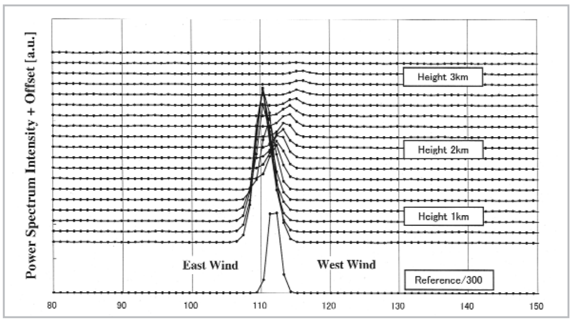

Fig.6 *Frequency spectra obtained by averaging observations made by coherent Doppler lidar at various altitudes*

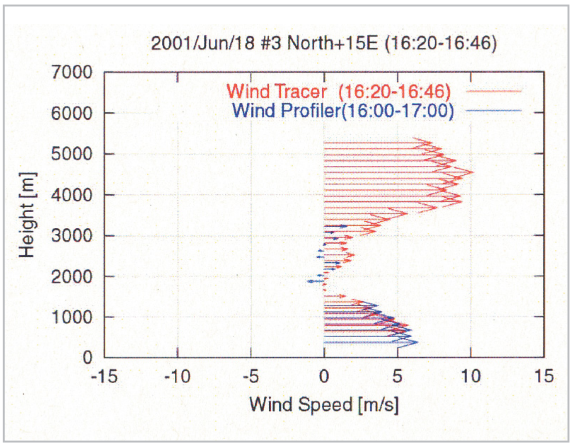

Fig.7 *Comparison of observations by coherent Doppler lidar (in red) and by a microwave wind profiler (in blue), made in Koganei*

deployment on board the exposed facilities (EF) of the Japanese Experiment Module (JEM) of the International Space Station (ISS). In a meeting of the Earth Observation Committee (Chief Examiner: Prof. T. Iwasaki, Tohoku University) dealing with coherent Doppler lidar, a report entitled the "Science Plan for Wind Observation by Space-Station-Borne Coherent Doppler Lidar" was proposed[1]. For this report, the required levels of accuracy for wind observation by the JEM/CDL were given, with an eye on such observation's usefullness based on a four-dimensional assimulation of numerical weather prediction, as shown in Table 1.

The required accuracy for observing vector winds was 2 m/s to 3 m/s for a horizontal resolution of 100 km in the troposphere. Thus, the target accuracy of the JEM/CDL is 2 to 3 m/s for global measurement of the horizontal wind vector in the troposphere.

A wind velocity along the line of sight is

Table 1 Required accuracy levels of wind observation in the troposphere

	Boundary layer	Lower troposphere	Upper troposphere
	0 – 2km	2 – 6km	6 – 15km
Vertical resolution	0.5km	1.0km	1.0km
Horizontal resolution	100km	100km	100km
Accuracy (for vector winds)	2.0m/sec	3.0m/sec	5.0m/sec

measured by heterodyne detection of backscattered light from aerosol in the atmosphere. The horizontal velocity of wind is obtained by combining line-of-sight velocities in two diagonal directions (to the front of and behind of satellite). Thus it is necessary to employ a mechanism that may be used to measure wind velocities in two directions; to this end, we are currently considering the use of two fixed 40-cm telescopes. We will also require a fully solid-state laser featuring 2-Joule output power and 10-Hz repeatability. We are presently preparing a small experimental model with a candidate Tm,Ho:YLF laser (λ: 2.06μm). A JEM-borne lidar is expected to feature a laser with a master-laser injection-locking oscillator and two to five stages of amplifiers. This unit should be capable of 2-Joule output power and 10-Hz repeatability, requiring a 1,250-W power supply and featuring an energy efficiency of 1.6 percent.

Fig.8 is a schematic diagram of the JEM/CDL. Using repeated pulses of laser light at a rate of 10 Hz, 70 pulses correspond to a horizontal distance of 100 km. We expect that the averaging of measurements made at these pulses will result in error levels for wind velocity that are within the accepted range specified under the Science Plan. It should be noted that the predicted errors will depend heavily on the profile of aerosol.

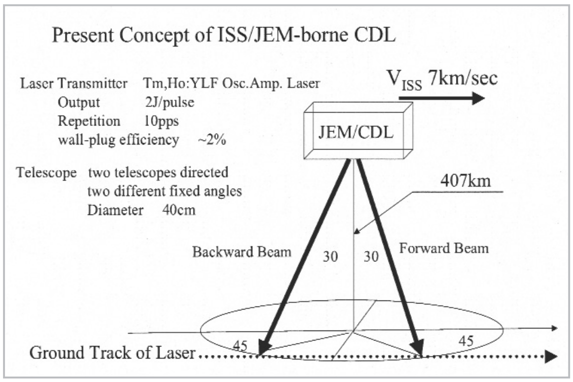

Fig.8 Schematic diagram of JEM/CDL

The exposed facility's standard payload is limited to 500 kg in weight and 3 kW of electric power[5]. The present model weighs 470 kg and needs a power supply of 1.489 kW, both of which values are below the stipulated limits. The entire power supply for the JEM is, however, only 5.4 kW. Thus, it will be necessary to adjust the schedule of operation or to lower the power consumption, based on the requirements of concurrent projects. In this context, reduced consumption of power may prove essential.

The laser consumes most of the power, as well as generate heat that must be dissipated by JEM's cooling system. This heat-dissipation procedure is especially important. In this regard, we must conduct further investigation into ways of increasing laser efficiency, as highly efficient laser will contribute to reductions not only in power consumption but also in exhaust heat. The present JEM/CDL model is designed to release the heat of laser-rod cooling apparatuses to a liquid cooler. If the liquid coolant system is replaced by one employing radiation cooling, the reduction in power may be as much as 500 W. Radiation cooling will be available for testing using the Free Flyer Unit, for eventual deployment in a future operational observation satellite (in addition to possible JEM/CDL applications).

4.2 International Cooperation

The European Space Agency (ESA) has initiated an Atmospheric Dynamics Mission, providing global observations of one direction of wind by means of incoherent Doppler lidar[6]. NASA is considering a hybrid Doppler lidar system that permits observation of wind fields using coherent Doppler lidar for the lower troposphere and incoherent Doppler lidar for the upper troposphere. We have compared the performance of the two types of lidar on a theoretical basis. According to our calculations, it will prove difficult for an incoherent system to feature an observation accuracy better than 2 m/s[7].

The ESA's incoherent Doppler lidar would appear to complement CRL's coherent Doppler lidar in verifying the effectiveness of observing wind fields from space. NASA, for its part, is considering simultaneous application of the two lidar systems. We believe that it will be necessary to cooperate with NASA in the development of the coherent system, as we also conduct cooperative studies with European (specifically German and French) groups that use such coherent systems.

5 Concluding Remarks

Space-borne Doppler lidar may permit observation of a vertical profile of winds on a global scale with an accuracy of 1 to 2 m/s. This is the most promising and perhaps only means to measure such profiles accurately. In the future, the lidar system may form the basis of weather observations to be made from polar satellites on a operational basis. Doppler lidar will provide direct observations of winds, and may also permit verification and calibration of other types of observed data. Since a Doppler lidar system has never been used in space, we must demonstrate that it will be applicable in space and that the results of observation will contribute to improved weather forecasts and climate models.

So far we have studied models that could be deployed on JEM's exposed facilities and that would meet the requirements described in the Science Plan. We need to continue to work on improving the system's efficiency, reducing its weight, and establishing the fundamental technologies involved. Development of an algorithm for application of the lidar system will also be necessary, using an air-borne lidar system for wind observation.

We also must cooperate with ESA and NASA in the development of procedures for verifying Doppler lidar systems and in future global observations using such operational systems. For example, the launch of Doppler lidar systems for operational use by CRL, ESA, and NASA will result in a greater quantity of available observation data, contributing to higher overall accuracy in numerical weather forecast.

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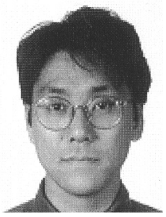

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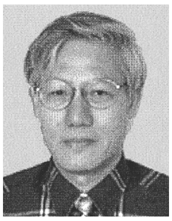

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