6 Wind Profile Measurements by Coherent Doppler Lidar

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Global wind profiling by a space-borne Doppler lidar with an eye-safe laser is expected to bring big progress in numerical weather prediction and the studies on global climate modeling. CRL has been conducting studies on the lasers for the space-borne coherent Doppler lidar to observe wind and aerosol profiles and developing the algorithm for the wind profiling through ground-based and airborne wind observations by a coherent Doppler lidar. We are also making studies on systems for a demonstration of the global wind profiling by the space-borne coherent Doppler lidar.

Keywords
Coherent, Doppler lidar, Eye-safe laser, Space-borne, Wind profile

1 Introduction

Space-borne lidar with eye-safe laser is expected to be able to measure directly altitude profiles of many kinds of atmospheric parameters such as aerosols, clouds, some kinds of molecules, and water vapers, which are not observable by passive sensors. One of the desired meteorological parameters to be implemented is the global wind profile, lidar observations of which may be a promising method. A space-borne Doppler lidar is considered to be the observation system capable of such global measurement of wind profiles in the troposphere and urgently needed [1]. Development of a space-borne Doppler lidar using an all-solid-state eye-safe laser has recently begun and it has not been applied to space. Aiming at full time operation satellites for wind profiling, it is necessary to develop the basic technology of Doppler lidar and a system for a demonstration mission of technology and availability. With the intention of performing the demonstration of the space-borne Doppler lidar, we are making research on coherent Doppler lidar (CDL) having 2μm solid-state lasers for the observation of wind profiles in the troposphere. Using coherent lidars, we may be possible to measure aerosols and CO2 profiles, which are related to the evaluation of the global change models.

2 Eye-safe solid laser and Doppler lidar

Eye-safety is necessary for space-borne lidars because of laser beam direction to the earth. Lasers emitting in 1.5μm or longer wavelength, where the output level in eye-safety is high, are suitable for space-borne instruments. We have been engaged in the research and development of 2 μm solid-state laser as candidate laser for space-borne experiments. On the point of view of space deployment, all-solid-state system pumped by Laser Diodes (LD) is preferable. We are investigating all-solid-state laser of high efficiency and high output energy, which are necessary for space-borne Doppler lidar in the future.

R&D of coherent Doppler lidars using

2 μm solid-state laser started in 1990'. It is compact and efficient; it is thus suitable for mobile, air-borne and space-borne system. Coherent detection is performed by coherent Doppler lidar, which determines the frequency of a beat signal with a local laser to deduce an Doppler shift of return signal with a high degree of accuracy. The objects reflecting laser light are aerosols and clouds in the troposphere. As shown in Fig.1, coherent Doppler lidar uses a injection locking pulse laser which is seeded and wavelength controlled by a master laser. The laser light backscattered and Doppler shifted by aerosols is mixed with the local laser light (sometime the same as the master laser) and combined in a detector. Low frequency beat signals are amplified with an IF amplifier, A/D converted, and recorded as digital signals. Doppler frequency is derived and converted to a wind velocity after analysis in frequency domain and subtraction of the offset component. At a wavelength of 2 μm, a frequency shift of 1 MHz corresponds to 1 m/s of wind velocity along the line of sight. We can also derived aerosol distributions from intensity profiles of signals.

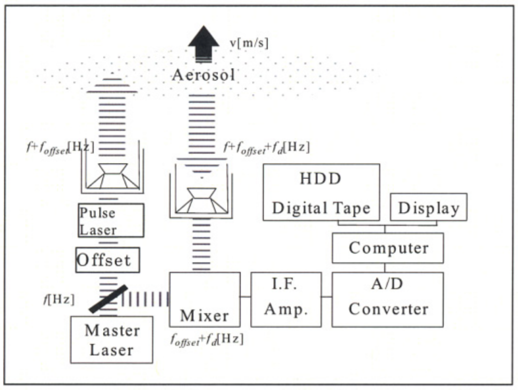

Fig. 1 Schematic of Coherent Doppler lidar

3 2 μm laser crystals

Rare-earth ion, Er, Tm, Ho etc., doped crystals are used for 1.5-2 μm laser. We made research on Tm:YAG lasers in cw and pulse oscillation modes[2][3]. As high efficiency and powerful output energy is needed for space-based application, we are investigating basic lasing properties of new 2 μm laser crystals to realize higher performance. Tm and Ho doped crystals are promising because of its possibility of powerful output power. Table 1 shows lasing properties of the materials which were measured in a laser resonator configuration.

Table 1 Lasing properties of 2 μm laser crystals

	$YLiF_4$ 5%Tm, 0.5%Ho	LuAG 5%Tm, 0.5%Ho	$GdVO_4$ 3%Tm, 0.3%Ho	$LuLiF_4$ 5%Tm, 0.5%Ho
Threshold energy	116 mJ	151 mJ	151 mJ	132 mJ
Slope efficiency	7.3%	10.8%	12.1%	12.6%
Output energy	15.7 mJ	20.0 mJ	24.1 mJ	26.8 mJ

Rods of host materials, LuLiF and GdVO, seem to be efficient. Threshold energy of YLF, which was well studied in the past, is low and it lases easily.

4 Ground-based and airborne observations

We are developing an airborne Doppler lidar with 2 μm laser to observe wind profiles downward from a jet plane. Figure 2 shows the jet plane equipped with the system (Wind Tracer: CLR) at the upper picture and the uncovered pod holding it at the lower picture. We will investigate the algorithms required to extract the Doppler shift, compensate for airplane attitude and velocity, and measure wind profiles through airborne experiment. The transceiver of the Doppler lidar is placed in a pod attached to the bottom of the jet plane body and is controlled from the inside of the jet plane. A silicon wedge is rotated to scan a laser beam downward along a cone with a nadir angle of 20 degrees. The Doppler lidar features a Tm:YAG laser of an output wavelength of 2.01 μm and output energy of 6mJ at a repetition rate of 100 Hz.

The lidar can be removed from the pod and be placed on the ground to transmit laser light upward for wind measurements of the

Fig.2 Airborne coherent Doppler lidar

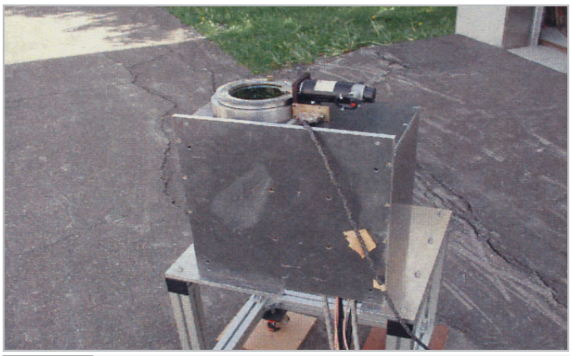

Fig.3 Ground-based coherent Doppler lidar

troposphere. The photograph in Fig.3 shows the experimental system. The same scanner is used to select the beam direction and the observation cone has a zenith angle of 20 degrees in this case. Figure 4 shows the altitude change of spectrum intensities which are derived from FFT analysis of each range data of one shot. We can recognize gradual change of wind with altitude, and see the spectral peak around 0 m/s by the scattering inside of the system under the altitude of about 600 m. The lower limit of the measurement is actually determined by this altitude (about 600 m). Wind vector profiles are measured in a few minutes, after repeating rotation of the scanner, stop and measurement (for about 1000 shots), rotation of the scanner.... Figure 5 shows the results of wind velocity and direction observed simultaneously by the Doppler lidar, VHF radar and radio sonde at Wakkanai in September, 2002. Wind profiles from these three instruments agree well until the altitude

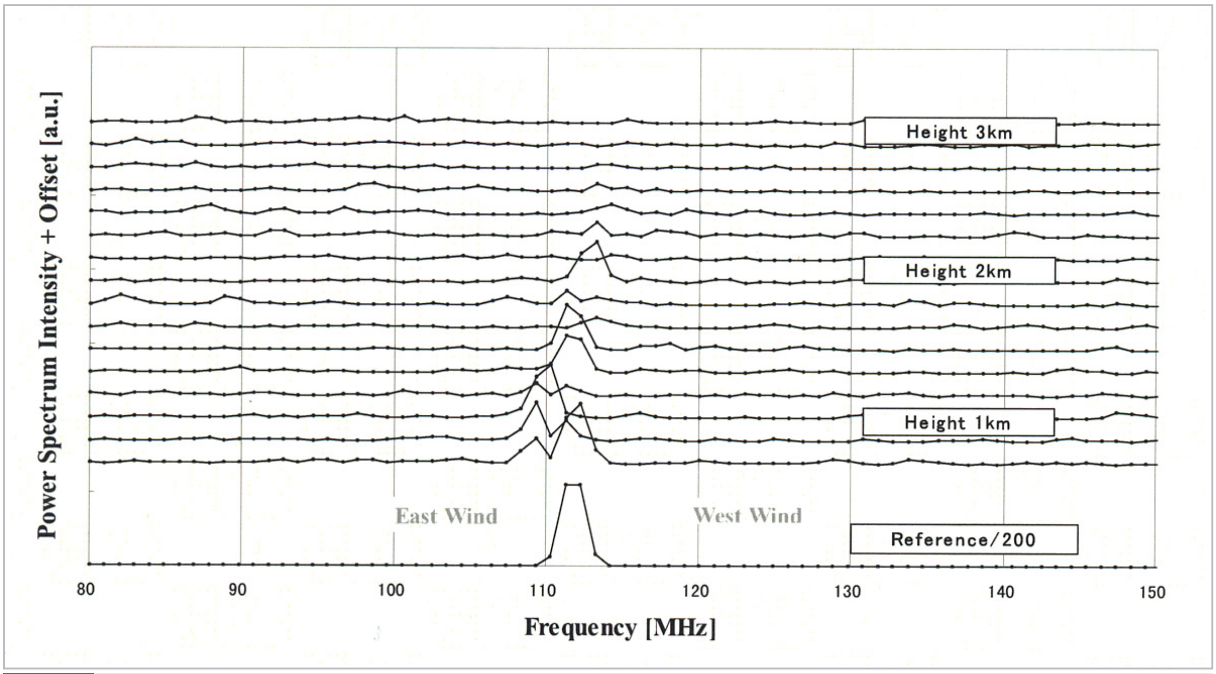

Fig.4 Spectrum intensities derived from one shot data

of 9 km, which was the observation limit of the Doppler lidar in that time. The agreement of the Doppler lidar and radio sonde is especially good. These results show that we can measure the accurate wind profiles with the Doppler lidar. In Fig.6, time series of wind profiles near Kiyokawa of Yamagata prefecture from 15:00 to 24:00 in August 6, 2003 are shown and these data are used for the analysis of local wind.

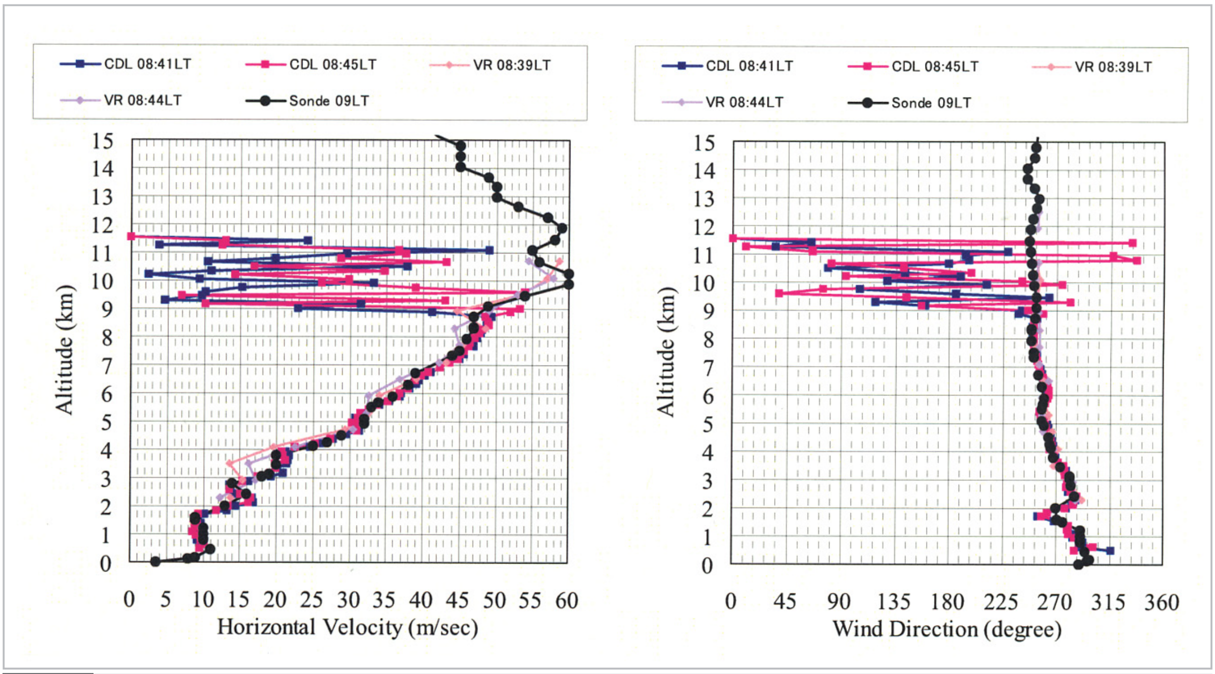

Fig.5 *Wind velocity and direction observed by coherent Doppler lidar(CDL), VHF radar(VR), and radio sonde (Sonde)*

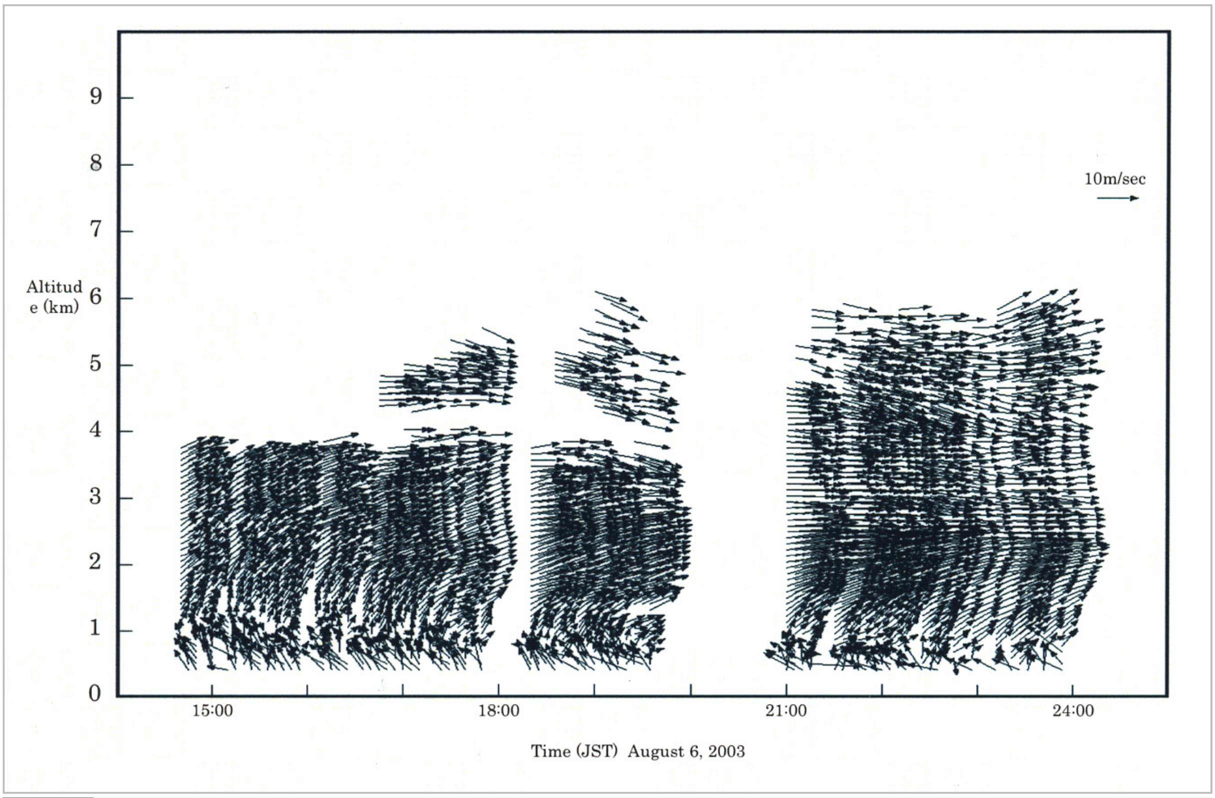

Fig.6 *Time series of wind profiles observed near Kiyokawa on August 8, 2003*

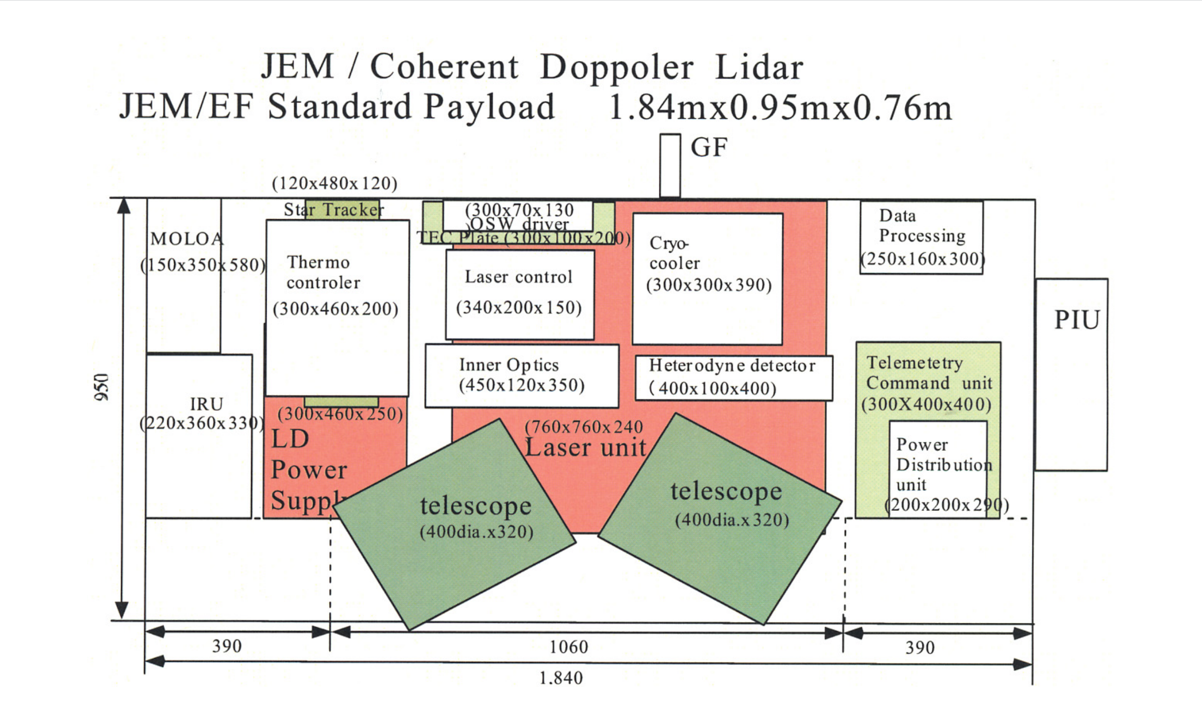

Fig.7 *Layout of JEM/CDL*

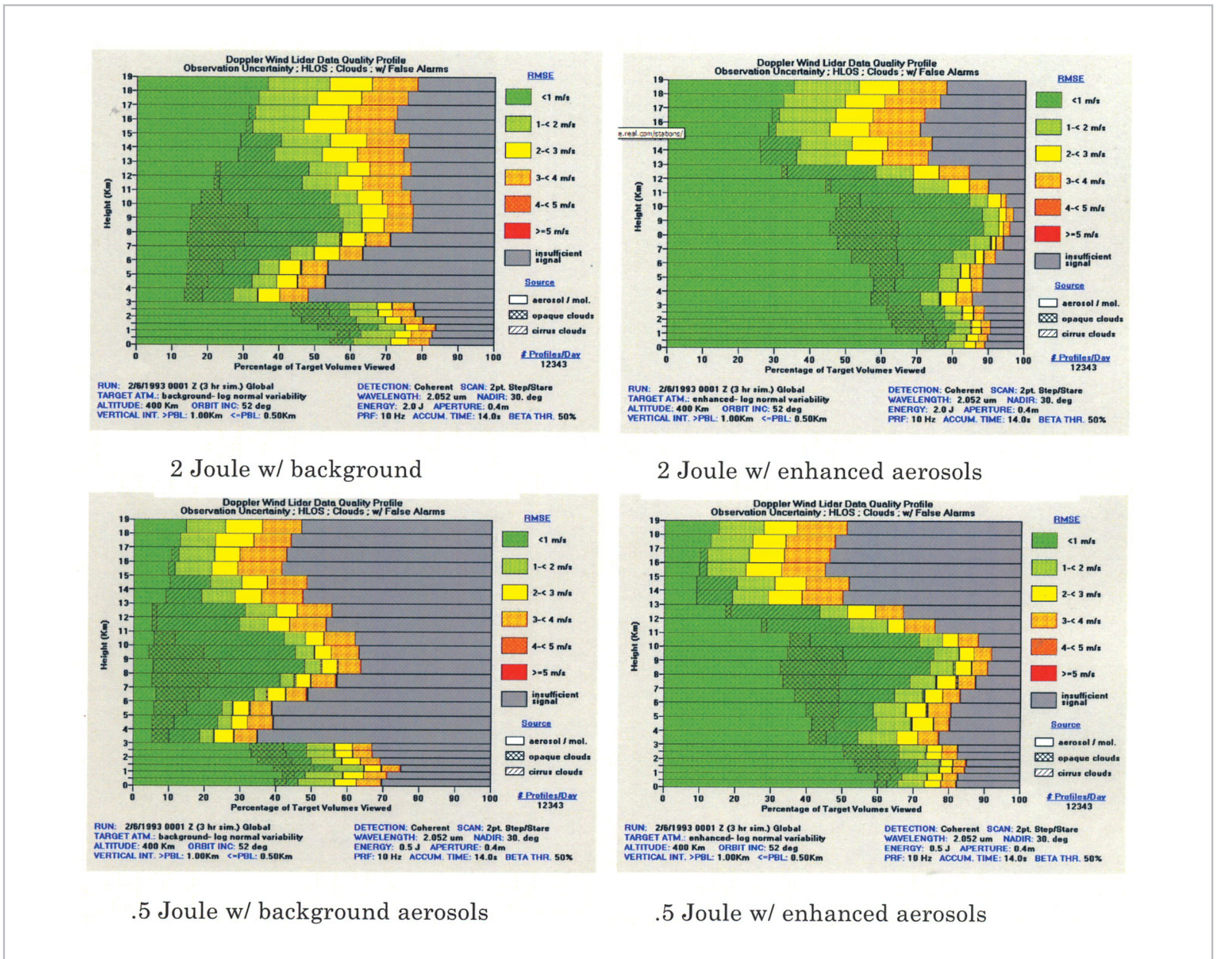

Fig.8 *Doppler wind lidar data quality profiles simulated for JEM/CDL (upper figures) and reduced energy model (lower figures)*

5 Research on space-borne Doppler lidar

5.1 Space-borne Doppler lidar

Prior to deployment of operational satellite, it will be necessary to demonstrate that a Doppler lidar system is practical and useful in operational measurement of global winds. We have studied a coherent Doppler lidar system (CDL) capable of deployment on board the exposed facilities (EF) of the Japanese Experiment Module (JEM) of the International Space Station (ISS) as a candidate demonstration system. In a sub-group meeting of the former Earth Observation Committee (Chief Examiner: Prof. T. Iwasaki, Tohoku University) dealing with coherent Doppler lidar, a report entitled "Science plan on the wind measurements by the ISS (International Space Station)/JEM-borne coherent Doppler lidar" was proposed [1]. In this report, the required levels of accuracy for the horizontal wind vector observed by the JEM/CDL were 2 m/s to 3 m/s for a horizontal resolution of 100 km in the lower troposphere.

A wind velocity along the line of sight is measured by heterodyne detection of backscattered light from aerosols 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 a satellite). Thus it is necessary to employ a mechanism that may be used to measure wind velocities in two directions. Then, we are considering the use of two fixed 40-cm telescopes. We are also investigating Tm,Ho:YLF laser (λ:2.06μm) as a candidate fully solid-state laser of 2-Joule output power and 10 Hz repeatability, and are making a trial manufacture of a sub-scale laser as described in the following section. Figure 7 is a schematic layout of the JEM/CDL. Using pulse 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 acceptable range specified in the Science Plan. It should be noted that the predicted errors would depend heavily on the assumed profile of aerosol.

The exposed facility's standard payload is limited to 500 kg in weight and 3 kW of electric power [4]. The present model weighs 470 kg and needs a power supply of 1489 W, both of which values are below the limits. The entire power supply for the JEM is, however, only 5.4 kW. Thus reduced consumption of power may be important. The lasers consume the most of the power, as well as generate heat that must be dissipated by JEM's liquid cooling system of fluorinert. In this regard, we are conducting further investigation of 2 μm laser crystals of high efficiency and a trial manufacture of a sub-scale laser, as highly efficient lasers 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 cooling apparatuses of laser-rod and LD to a liquid coolant. If the liquid coolant system is replaced by radiation cooling system, the reduction in power may be as much as 500 W. Radiation cooling will be available for a demonstration mission by a Free Flyer Unit, and eventual deployment in a future operational satellite (in addition to possible JEM/CDL applications in part).

Results of observation simulation on wind measurement quality distributions are shown in Fig.8 (in cooperation with Dr.G.D.Emmitt at Simpson Weather Associates). Simulations were performed in the cases of background aerosol model and enhanced aerosol model. According to the simulation, chance with accuracy of 1m/s or better in JEM/CDL model is about 80% in the enhanced aerosol model and is between 30% and 60% in the background aerosol model, where existences of clouds increase the chance of observation with high quality. The lower two figures in Fig.8 show the results of simulation with 500 mJ laser output instead of 2 J. The simulation indicates that the probability of observations with accuracy of 2 m/s or better is not small even in the case of a laser output of a quarter of 2 J. Thus, we can reduce the resource by employment of radiation cooling and reduction of laser output power in a satellite, which can not prepare sufficient resource.

5.2 Sub-scale laser experiment

The most important component for the space-borne coherent Doppler lidar is a spceborne 2 μm laser. We are developing a sub-

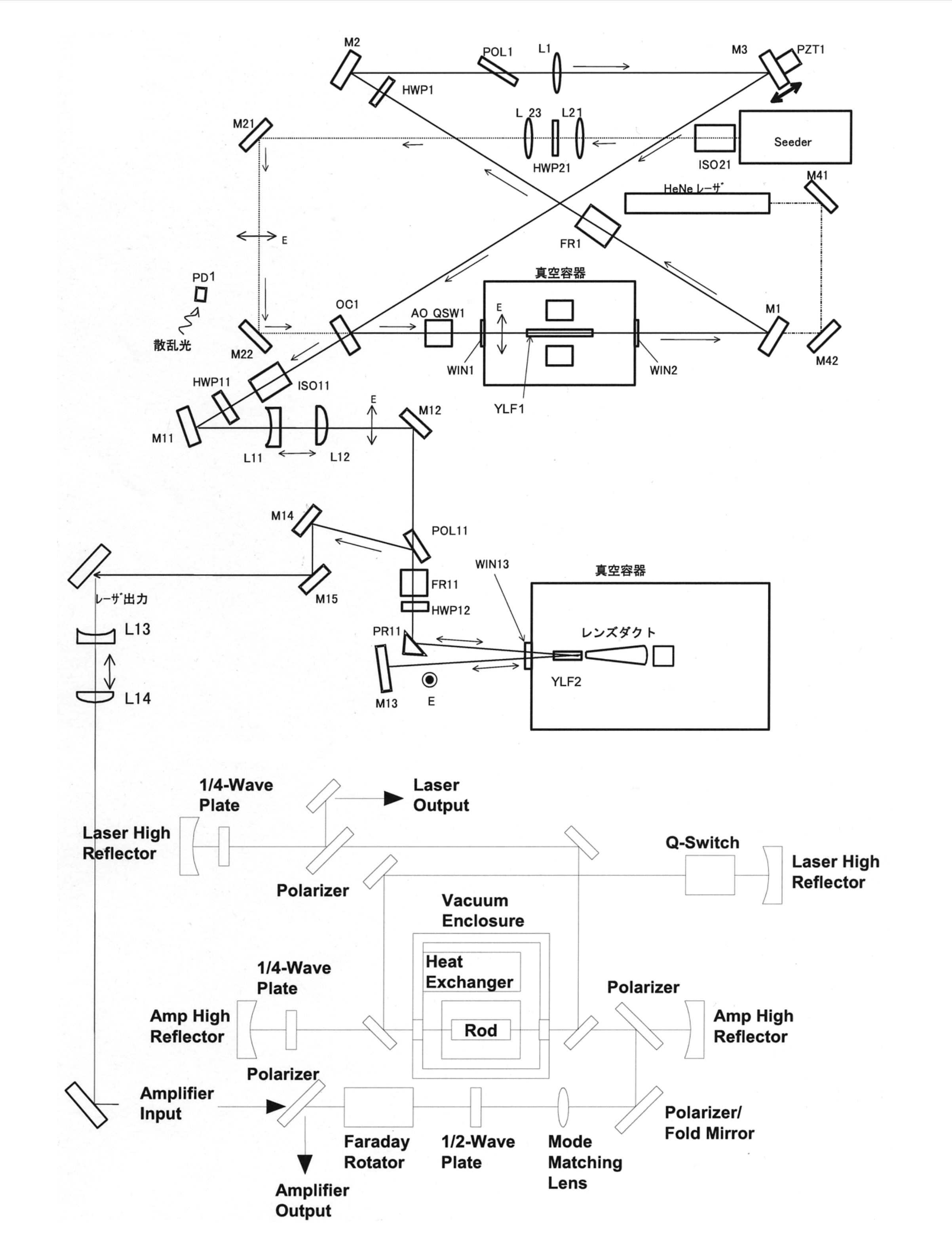

Fig.9 *Layout of the sub-scale laser*

scale laser with 500 mJ output, in which conduction cooling of Tm,Ho:YLF laser rods is used to be applicable to the space model. Figure 9 shows the layout of this laser. Unidirectional operation is performed in the slave oscillator, the laser rod of which is side-pumped. The injection seeding enables the laser to oscillate in the single longitudinal mode needed for the Doppler lidar [5]. The pre-amp is a 4-pass amp with a end pump configuration. The post-amp was designed as a 4-pass amp with a side pump configuration, but it is actually used in 2-pass because of sufficient amplification in 2-pass [6]. The sub-scale laser is installed in an optical table and the evaluation of it is now proceeding (Fig.10). The pre-amp does not work properly in sufficient output at 10 Hz because of a thermal problem in it. Then we are now operate the whole system at 1 Hz and in the output pulse energy of about 400 mJ. The post-amp is pumped at 10 Hz even in this case. Thus, the amplification of the post-amp to 500 mJ at 10 Hz, is mostly proved. The problem of isolation between pre-amp and post-amp, which limits the maximum output energy, will be settled soon by adjustments of the suitable parts.

We have good prospects to get capability of generating 500 mJ pulse at 10Hz. Considering applications to space-borne model, measurements with accuracy of acceptable level may be possible in fairly wide regions by the instrument of this level of output pulse energy. Thus, a small lidar model of a free flyer with a laser of 500 mJ at 10 Hz may be another possibility for the demonstration mission, considering the present status of the satellite schedule. A smaller model with a laser of 200 mJ may be considerable to demonstrate only the technology feasibility by a coherent Doppler lidar which can measure backscattering from the ground, planetary boundary layer, and clouds. If we adopt more efficient laser rod like Tm,Ho:LuLiF, realization of higher efficiency in generating laser pulse and reduction of power consumption may be possible.

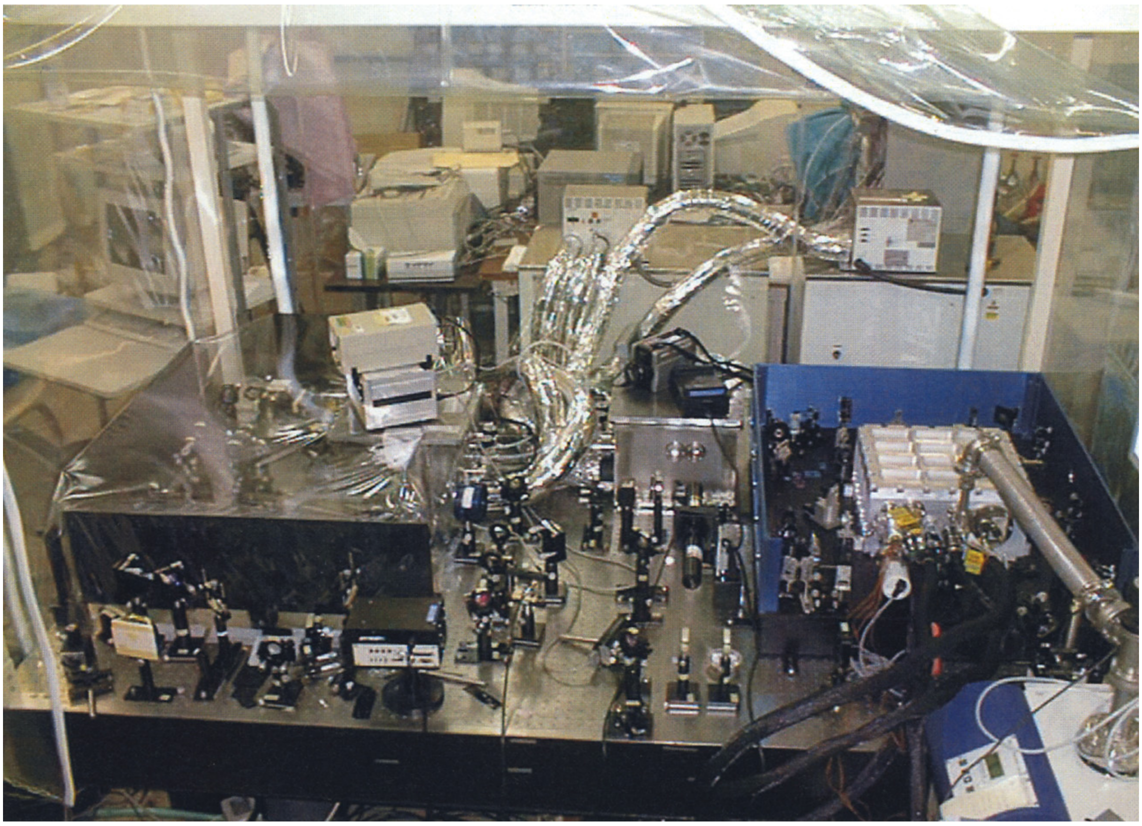

Fig.10 *The sub-scale laser*

6 Conclusion

Space-borne Doppler lidar may permit observation of vertical profiles of winds on a global scale with an accuracy of 1 to 2 m/s. This is expected to be a promising means to solve the problem of the shortage of the accuracy and distribution in the current wind data. As Doppler lidar provides direct observations of winds, it may be used for verification and calibration of other types of observed data. Since a Doppler lidar has never been used in space, we must demonstrate its feasibility in space. Moreover, as there are vibration-rotation lines of CO_2 and H_2O in the wavelength range of 2 μm solid lasers, coherent lidar may used as a DIAL for these absorption lines in the future. The measurement of CO_2 with 1 ppm accuracy is especially needed. We should investigate further the possibility of such measurements by space-borne coherent lidar.

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 have good prospects of 500 mJ output at 10 Hz in the conduction cooling sub-scale laser which could be a small model of space-borne laser for JEM/CDL. We need to continue the work on improving the system's efficiency, reducing its weight, and establishing the fundamental technologies involved. Another possibility, e.g. a free flyer, for a demonstration mission besides of JEM/CDL is also valuable to be considered. Development of an algorithm for application of the lidar system will also be necessary, using an air-borne lidar system for wind observations.

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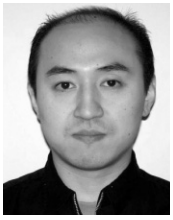

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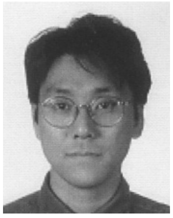

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