ON SOME LIDAR DEVELOPMENTS FOR ATMOSPHERIC RESEARCH

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ABSTRACT

About 40 years have passed since lidar experiments were taken. In this paper we present mainly our progress of Mie lidar for aerosol observation and differential absorption lidar (DIAL) for atmospheric ozone and water vapor measurement. Some lidar observational results are also reported.

1. MIE LIDAR

Soon after a ruby laser was invented in 1960, a pulsed ruby laser was applied to lidar. Enhanced stratospheric aerosols after the volcanic eruption of Mt. Agung (8.2S, 115.4E) in 1963 were detected by lidar [1]. Our lidar construction started at Kyushu University in Fukuoka (33N) from 1971 [2].

The transmitter consisted of a ruby laser, a refracting telescope of 10- cm diameter and a plane mirror (60x70 cm^2). The receiver consisted of the same plane mirror and a 30-cm diameter reflecting telescope of Cassegrain type. The output energy of the laser was 0.5 J with a pulse width of 50 ns. The laser was fired at a rate of 1 pulse every 20-30 s.

Each time that the laser was fired the return signal was detected by a photomultiplier (PMT), displayed on a synchroscope and the sychroscope trace photographed. The output signal of analog mode was read directly from the photograph. Also the number of the photoelectrons in each 1.5 km height interval was available for a return from above 12 km.

A rotating shutter was attached to cut off the fluorescent emission from the ruby. Then a rotating shutter was also used to prevent the PMT from strong lidar signals from the lower atmosphere.

1.1 Observations of stratospheric aerosols

Increased stratospheric aerosols were observed after the volcanic eruptions of Fuego (14.5N, 90.9W, October 1974) and La Soufriere (13.3N, 61.2W, April 1974) by the ruby lidar. The observed decrease rate of the aerosol content was not explained by then a well-known two-dimensional atmospheric model and the gas to particle conversion processes were necessary for account of the observational results by lidar [3].

As we took a long time to analyze lidar signals, a photon counter was developed in cooperation with a small local company. A cooling system was developed for reducing thermal noise from the PMT. Then a high-repetition-rate Nd:YAG laser was introduced to monitor stratospheric aerosols at the wavelengths of 1064 nm and 532 nm with a new type of near-infrared-sensitive PMT [4]. It facilitated the alignment of optical axes of transmitter and receiver of lidar system.

Using the Nd:YAG lidar, increased stratospheric aerosols were detected over Fukuoka after some volcanic eruptions: Sierra Negra (0.8S, 91.7 W, November 1979), Mt. St. Helens (46.2N, 122.2 W, May 1980) and El Chichon (17.3N, 93.2W, April 1982). The El Chichon volcanic clouds have been observed at many lidar stations: Mauna Loa (20N), Nagoya (34N), Tsukuba (36N), NASA Langley (37N), and Garmisch-Partenkirchen (48N).

The dispersion processes of the El Chichon dust particles in the lower stratosphere were discussed using lidar data and compared with a trajectory analysis using wind data. The mean meridional speed of the leading edge of the particles was about one degree per day in latitude range of 17.5-47.5N [5].

In 1990s a compact and stable Nd:YAG laser became available commercially, and we could assemble a mobile lidar in a few months using the laser, ready-made telescope, PMT, analog-digital converter and photon counter. And a lidar network could be built easily. After the explosive volcanic eruptions of Mt. Pinatubo (15.1N, 120.4E) on June 15, 1991, we started measurements of drastically increased stratospheric aerosols by a lidar network extending from Naha (26N) to Wakkanai (45N) in Japan [6] and then by the EPIC (Effects of the Pinatubo Eruption on Climate) global lidar network [7].

From the EPIC project (April 1992 - March 1994), following scientific results are obtained. The stratospheric aerosols increased dramatically after the eruption and had a major impact on climate. The lower stratospheric temperature increased significantly. The tropospheric temperature decreased in spite of the warm episode of ENSO in 1991/1992. The Pinatubo eruption had also a major impact on stratospheric species such as nitrogen dioxide, nitric acid vapor and ozone through heterogeneous chemical reaction [8] due to increased aerosol surface [9].

Two or multi-color lidar measurements give us information on particle size. Lidar measurement of the depolarization ratio of particles offers us information on particle shape, i.e., spherical or non-spherical.

A two-wavelength polarization lidar is useful for classifying polar stratospheric clouds (PSCs) which are very important for heterogeneous chemical ozone depletion. PSCs have been observed at Eureka (80N) in the Canadian Arctic during winter seasons of 1994/95, 1995/96, 1996/97 and 1999/2000 [10], and significant chemical ozone loss occurred in the same winters [11].

1.2 Observations of tropospheric aerosols

In Japan we experience yellowish sky in spring. This is because a large amount of dust, called Kosa is transported by westerly wind from deserts [12], [13]. Dust and anthropogenic aerosol plumes were observed by onbard lidar [14]. Some lidar networks have been measuring Kosa for understanding their effects on climate [15].

The World Meteorological Organization/Global Atmosphere Watch (WMO/GAW) aerosol program is to determine spatio-temporal distribution of aerosol properties related to climate forcing and air quality up to multidecadal time scales. The Japan Meteorological Agency (JMA) started routine aerosol lidar measurement at the Ryori WMO/GAW station (39N) from March 2002. Raman scattering from nitrogen can be also received to estimate aerosol extinction coefficient and optical depth. Observational results are presented at this conference.

2. TUNABLE, NARROW-BAND, AND HIGH POWER LASERS FOR RESONANCE LIDAR AND WATER VAPOR DIAL

Bowman et al., succeeded in an observation of the resonance scattering from atmospheric sodium using Rhodamine 6G dye laser tuned at the sodium D line [16]. We also developed flashlamp-pumped tunable and narrow-band Rhodamine 6G dye lasers with Fabry-Perot etalons, and obtained the output energy of 4 J (4.5 MW) within a spectral width of 5 pm from the forced oscillator when a tuned narrow-band emission of 15 mJ was injected [17]. A reliable forced oscillator dye laser was developed and used to measure the upper atmospheric sodium layer [18].

Recently high power dye and Ti:sapphire lasers pumped by the second harmonic of a Nd:YAG laser are used to resonance scattering lidar for measurements of mesospheric Na, K, Fe and Ca+ layers in Koto Tabang, Indonesia (0.2S) [19].

A tuning method on the absorption of water vapor at 725.8 nm was made using the opto-galvanic effect in an Xe discharge tube, and compared it with absorption cell and photoacoustic cell methods [20]. Finally we adopted the double cell photoacoustic technique for fine tuning of laser on the absorption line of water vapor [21].

We developed a triple-pulse Ti:sapphire laser with three wavelengths of strong, weak and non-absorption line of water vapor. These triple pulses were emitted every 1.2 ms, and the repetition rate was 50 Hz. The pumping source was the second harmonic of a conduction-cooled laser diode (LD) pumped Nd:YLF laser of which output power was 72 W at 1053 nm with a pulse repetition rate of 150 Hz [22]. Spectral tuning of a Ti:sapphire laser with a ring cavity was obtained by seeding of three CW LDs. Their spectral width and stability were 0.045 pm and 0.06 pm respectively. The output power was 6.8 W (45 mJ/pulse, 150 Hz). This laser was used for airborne water vapor DIAL measurement of which data were in agreement with those obtained by Raman lidar.

3. OZONE DIAL

3.1 Stratospheric ozone DIAL

DIAL measurement of stratospheric ozone was conducted using a frequency-doubled flash-lamp pumped dye laser [23]. We have measured ozone profiles in the lower stratosphere using a lidar incorporating XeCl laser with supporting meteorological data.

The first laser for ozone measurements was a pre-ionized discharge-pumped XeCl excimer laser with two parallel pulse-forming lines of plane Myler sheet capacitors [24]. The maximum output energy of 128 mJ (20ns FWHM) was obtained in a gas mixture of HCl/Xe/He=3.5 torr/7 torr/3 atm at a supplied voltage 25 kV. Three lasing lines 307.6, 307.9, and 308.2 nm was observed. One-half of the output energy was concentrated within 5 mrad beam divergence. Observations were made using the receiver of the Nd:YAG lidar during the night of 12 June 1978 at Fukuoka and the total shot number was 1050 pulses. The obtained ozone profile in an altitude range of 15-25 km was in good agreement with that measured by ozonesonde.

Next a LC inversion type of XeCl laser was developed. Typical output energy was 50 mJ per pulse with a repetition rate of 5 Hz. The observation time was shortened to 2-3 hours from 8 hours. The vertical ozone distributions in the lower stratosphere were observed during September 1979 through December 1981 by the XeCl lidar. The observational result showed the XeCl DIAL was very promising for monitoring stratospheric ozone.

In 1988 we developed the Meteorological Research Institute (MRI) ozone lidar for simultaneous measurements of ozone, aerosols and temperature, in the stratosphere [25]. The lidar consisted of a XeCl laser (8.8 W at 308 nm), a Nd:YAG laser (2.6 W at 355 nm, 2.0 W at 532 nm), and an 80-cm diameter receiving telescope. Four year intercomparison of the MRI ozone lidar with ozonesondes and SAGE II was made and showed good agreement; lidar-SAGE II within 10 % for 20-38 km, and lidar-ozonesondes within 10 % for 15-32 km [26].

The error caused by background stratospheric aerosols was corrected from the data of scattering ratio at 532 nm. However, for increased stratospheric aerosols after the Mt. Pinatubo volcanic eruption, Raman DIAL technique was useful for measurements of ozone up to about 25-30 km [27]. We also added two Raman channels at 332 nm and 387 nm instead of aerosol channel of 532 nm. Now the MRI DIAL system for stratospheric ozone measurements consists of four receiving channels of 308, 332, 355, and 387 nm.

Stratospheric ozone layer has been monitored by XeCl laser-based DIAL at stations such as Eureka, Ny-Alesund (79N), Observatoire de Haute Provence (44N), Tsukuba, Mauna Loa, and Lauder (45S) [28].

3.2 Tropospheric ozone DIAL

For tropospheric ozone DIAL measurements we need two wavelengths shorter than 308 nm since troposheric ozone densities are one order magnitude lower than those around 25 km. Dye lasers pumped by Nd:YAG lasers were developed for tropospheric ozone DIAL measurement [29]. We used a XeCl laser (308 nm) and the second Stokes line (290.4 nm) of stimulated Raman scattering (SRS) from methane pumped by a KrF laser [30].

The UV preionized discharge-pumped KrF laser was a type of transfer capacitor. To obtain efficient SRS, an unstable resonator was used for KrF laser. The 1-m-long Raman cell was stainless-steel tube with 3-cm-diameter and 2-cm-thick UV-grade quartz windows. The energy-conversion efficiencies of the first and second Stokes lines were 12.4 % and 3.4 % for methane at 35 atm. We used the second Stokes line of methane whose energy was approximately 2-4 mJ. We had successfully determined the ozone distribution in an altitude range of 4-12 km by the DIAL technique with an excimer-Raman hybrid laser system.

UV lines of SRS of hydrogen and deuterium gas pumped by the fourth harmonic of a Nd:YAG laser were used for tropospheric ozone DIAL measurements [31]. Recently the first and second Stokes lines of carbon dioxide gas pumped by the fourth harmonic of a Nd:YAG laser are used for tropospheric ozone measurements at MRI, JMA. This DIAL system is promising for tropospheric ozone monitoring since it is simple. This DIAL system is presented at this conference.

Rayleigh, Raman, Doppler wind lidars and DIAL for atmospheric pollution measurement could not be mentioned unfortunately as the number of pages is limited, and please refer to respective papers.

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