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The Network for the Detection of Stratospheric Change is an international cooperation providing a set of high-quality, remote-sensing instruments at observing stations around the globe. A brief description of the NDSC and its goals is presented. Lidar has been selected as the NDSC instrument for measurements of stratospheric profiles of ozone, temperature and aerosol. The Jet Propulsion Laboratory has developed and implemented two stratospheric lidar systems for NDSC. These are located at Table Mountain, California, and at Mauna Loa, Hawaii. These systems, which utilize differential absorption lidar, Rayleigh lidar, Raman lidar and backscatter lidar, to measure ozone, temperature and aerosol profiles in the stratosphere are briefly described. Examples of results obtained for both long-term and individual profiles are presented.

Key Words: Observational networks, Lidar, Differential absorption, Ozone, Stratosphere

1. Network for the Detection of Stratospheric Change (NDSC)

The idea for a network of high-quality, remote-sounding research stations for observing and understanding the physical and chemical state of the stratosphere was first discussed at a workshop in 1986[1]. In the ensuing period planning for the network continued and new instruments were designed, implemented and tested leading to the official start of NDSC network operations in January 1991.

The NDSC has three stated primary goals[2].

To make observations through which changes in the physical and chemical state of the stratosphere can be determined and understood. In particular, to make the earliest possible identification of changes in the ozone layer and to discern the causes of the changes.

To provide an independent calibration of satellite sensors of the atmosphere.

To obtain data that can be used to test and improve multidimensional stratospheric chemical and dynamical models, thereby enhancing confidence in the predictive and assessment capabilities of these models.

To achieve these goals a number of species and parameters were identified for which global measurements, in the altitude region from the tropopause to approximately 50 km, are of the highest priority. These measurements and the associated NDSC instruments are summarized in Table I. Not all of the measurements listed in Table I have been fully implemented yet; some are still in an experimental or developmental stage.

From Table I it can be seen that lidar is the chosen instrument for ozone, temperature and aerosol measurements, and also for OH measurements although this is still at an experimental stage. There is a large, and growing, number of operational lidars for these measurements that have been accepted as NDSC instruments. A list of these lidars, the location, and the principal investigator (PI) is given in Table II. It should be noted that while this list is current as of September 1994, new instruments are continually being added based on proposals to NDSC for inclusion in the network. Table II shows only the lidar instruments and sites. A number of other instruments are active at both primary and complementary stations.

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Table I NDSC measurements and instruments.

Species/Parameter	Instrument
O_3 column	Dobson, Brewer, UV/visible spectrmeters
O_3 profile	Differential absorption lider (DIAL), Microwave
Temperature profile	Rayleigh/Raman Lider
ClO	Microwave
H_2O	Balloon hygrometer, Microwave
Aerosols	Backscatter lider
NO_2 strat. column	UV/visible spectrometer
HCl strat. column	Fourier transform IR spectrometer (FTIR)
CH_4 strat. columan	FTIR
N_2O profile	Microwave, FTIR
HNO_3 strat. column	FTIR
$ClONO_2$ strat. column	FTIR
OH profile	Fluorescence lidar
HO_2 profile	Microwave

Table II NDSC Lidar instruments, sites and pricipal investigators, as of September 1994.

	Lidar Instrument	PI
Primary Stations		
Arctic station:		
Eureka, Canada	Ozone-Temperature	A. I. Carswell (ISTS)
	Aerosol	O. Uchino (MRI)
Thule, Greenland	Aerosol	G. Fiocco (Italy)
Ny Ålesund, Norway	Ozone-Aerosol	R. Neuber (AWI)
Alpine station:		
Haute Provence, France	Ozone	G. Megie (CNRS)
	Temperature	A. Hauchecorne (CNRS)
	Aerosol	S. Godin (CNRS)
Mauna Loa, Hawaii, USA	Ozone-Temperature-Aerosol	I. S. McDermid (JPL)
	Aerosol	D. Hofmann (NOAA)
	Tropospheric ozone	M. H. Proffitt (NOAA)
Lauder, New Zealand	Ozone-Temperature-Aerosol	D. P. J. Swart (RIVM)
	Aerosol	O. Uchino (MRI)
	Aerosol	L. Stefanutti (IROE)
Antarctics station:		
Dumont D'Urville	Aerosol	S. Godin (CNRS)
	Ozone	S. Godin (CNRS)
Complementary Stations		
Garmisch-Partenkirchen, Germany	Aerosol	H. Jäger (IFU)
Ile de La Réunion	Temperature	P. Keckhut (CNRS)
Tsukuba, Japan	Ozone	H. Nakane (NIES)
Special Purpose Stations		
Table Mountain, USA Test research site	Ozone-Temperature-Aerosol	I. S. McDermid (JPL)
Mabile Intercomparator	Ozone-Temperature-Aerosol	T. J. McGee (GSFC)
	Temperature-Aerosol	T. J. McGee (GSFC)

2. JPL Stratospheric Lidars

The remainder of this paper is devoted to the JPL stratospheric lidars at Mauna Loa, Hawaii, and Table Mountain, California. At JPL's Table Mountain Facility (TMF, 34.4°N, 117.7°W, elevation 2300 m) in southern California, an excimer laser based differential absorption lidar (DIAL) system has been used since 1988 to make stratospheric ozone concentration profile measurements. In 1990 this was augmented to obtain temperature profiles using Rayleigh lidar measurements at the DIAL reference wavelength. A separate Nd:YAG laser based lidar has been used to measure aerosol backscatter profiles since the eruption of Mount Pinatubo in June 1991. Table Mountain acts as an intercomparison and test research site for the NDSC and the lidars have undergone extensive validation and intercomparison.

From 1990 to 1992 a new lidar system was designed and constructed at TMF for deployment at the NDSC Primary Station at the NOAA Mauna Loa Observatory (MLO, 19.5°N, 155.6°W, elevation 3400 m) in Hawaii. This system was operated at TMF for approximately 9 months and inter-compared with the permanent TMF lidars before being moved to MLO in June 1993. The new lidar is improved significantly compared to the TMF system and incorporates Raman receiver channels to avoid problems caused by volcanic aerosols such as were observed after Mount Pinatubo erupted. Ozone, temperature and aerosol profiles are measured by this single lidar at MLO.

2.1 Table Mountain Lidar

The lidar systems and data analysis procedures at TMF have been extensively described both in a number of open literature publications[3-5]. Ozone is measured by the differential absorption lidar (DIAL) technique using the wavelengths 307.9 nm and 353.2 nm as the probe and reference wavelengths respectively. A high power (100 W) xenon chloride (XeCl) excimer laser is tuned to 307.9 nm and the reference wavelength is generated by stimulated Raman shifting of a portion of the fundamental beam in high pressure hydrogen. The two wavelengths are transmitted simultaneously in time and space and the radiation backscattered by the atmosphere is collected with a 0.9 m diameter telescope. The two wavelengths are separated by a series of dichroic beam-splitters and interference filters and then measured using photomultipliers operating in a photon counting mode. Measurements are made only at night, typically beginning at the end of astronomical twilight, and each experiment averages 10^6 laser pulses which takes approximately two hours.

2.1.1 Ozone

For long-term measurement programs, such as NDSC, to be successful it is necessary to ensure the quality of the results by rigorous calibration procedures and intercomparisons. To evaluate the quality of the TMF lidar results it has participated in a number of intercomparisons[6-8] culminating with the first formal NDSC sponsored campaign, Stratospheric Ozone Intercomparison Campaign 1989 (STOIC '89), which was carried out at TMF during July and August 1989[9]. The STOIC study compared the ozone profiles measured by two DIAL systems, a 110 GHz microwave radiometer, electrochemical concentration cell (ECC) balloon sondes, ROCOZ-A rocket sondes, and SAGE II solar occultation satellite measurements. Some intercomparisons were also made with Umkehr inversions from Dobson and Brewer instruments. STOIC represented a very important stage in the development of stratospheric ozone DIAL systems since it confirmed the power of the technique for making reliable, accurate measurements[5]. When the mean lidar profile from the two week period is compared with the mean of all of the other profiles (> 200) agreement to better than 4 % over the range from 18 to 47 km altitude is observed.

Two longer-term comparisons of ozone results from lidar and SAGE II satellite measurements[6], and from microwave, lidar and SAGE II have also been carried out[10]. These studies showed continuing good agreement between these three instruments with consistent observations of both seasonal and short term ozone variations at this location.

Some of the long-term ozone measurements results are summarized in Fig. 1. Figure 1 shows the monthly mean ozone concentration over the altitude range from 15 to 40 km for the six years of measurements to date. The region below 30 km that was affected by the eruption of Mt. Pinatubo is indicated by the absence of measurements in this region but it is clear that measurements above the aerosol layers were not affected. Seasonal variations are clearly observable in Fig. 1 For example, the oscillations in the 20 to 25 km region are clearly anti-correlated with those in the 25 to 35 km range. The highest ozone concentrations are observed in the wintertime, January-March, in the 20 to 25 km region.

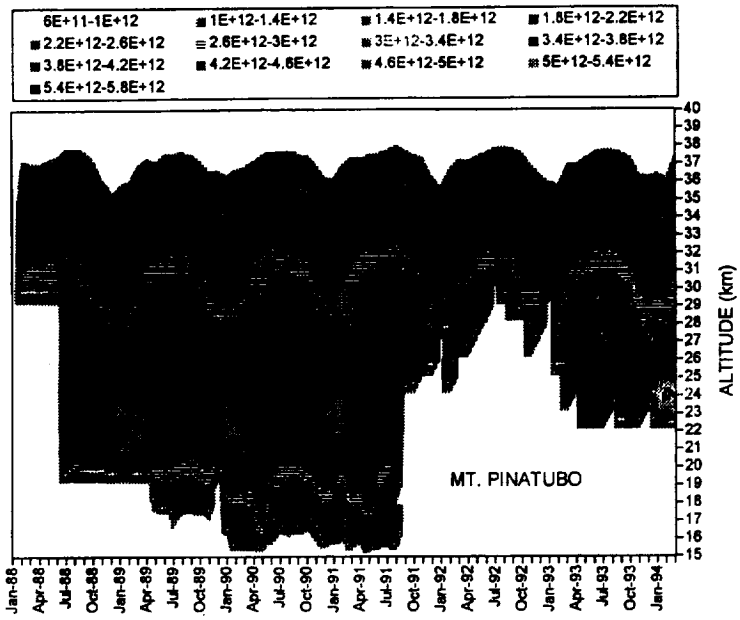

Fig. 1 Contour plot of the monthly mean ozone concentration profile variations in the alttitude range from 15 to 40 km. Note the region of missing measurements caused by the effects of Mt. Pinatubo aerosols. (Ozone concentration units: molecule. cm^{-3}).

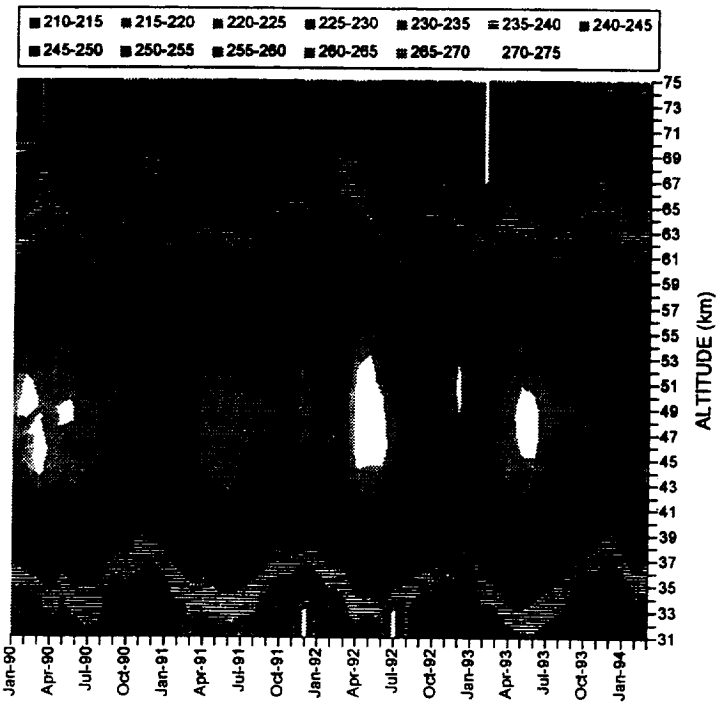

Fig. 2 Contour plot of temperature variations from January 1990-March 1994.

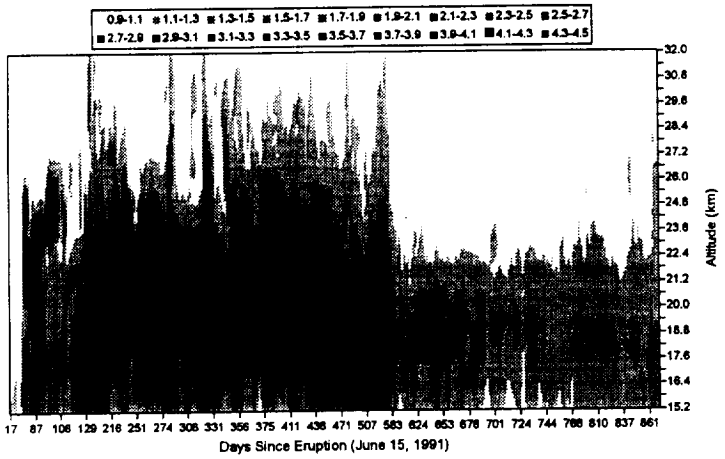

Fig. 3 Aerosol backscatter ratio at 353 nm as a function of altitude and time since the eruption of Mt. Pinatubo. Note: each available profile is plotted as a vertical line and thus the time axis is not exactly linear.

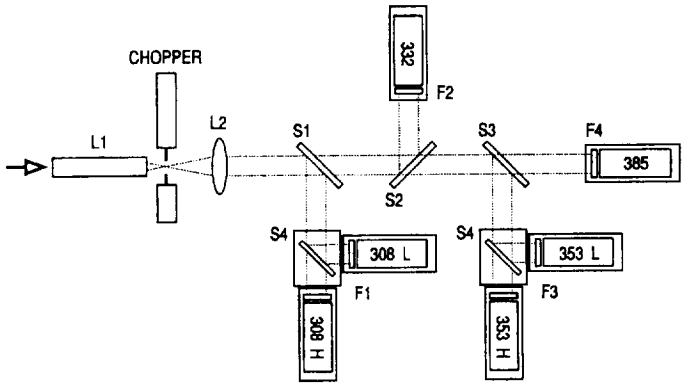

Fig. 4 Schematic diagram of the receiver optical detection system.

2.1.2 Temperature

The temperature profile is obtained from the Rayleigh returns at the reference wavelength, 353.2 nm. The method is only applicable when Mie scattering is negligible and is therefore limited to altitudes above approximately 30 km. Figure 2 shows a summary of the monthly mean temperature profile for the four years that such profiles have been obtained. Repeatable seasonal variations are clearly observed. In the stratosphere there is a general single annual oscillation while in the mesosphere there is a clear semi-annual oscillation. Near the stratopause the oscillations are complex with as many as four identifiable temperature cycles.

2.1.3 Aerosol

Aerosol backscatter profiles in the form of backscatter ratio (i.e., Rayleigh+Mie/Rayleigh) are measured at 353 nm, 532 nm, and 1064 nm. Measurements at multiple wavelengths provide additional information concerning the wavelength dependence of the scattering which in turn contains information about the size distribution of the aerosols.

Figure 3 summarizes the evolution of the atmospheric aerosol loading following the eruption of Mt. Pinatubo in the Philippines (15.1°N) in June 1991. There was a delay of almost two months before the aerosol layers reached the latitude of TMF. Very high scattering ratios, >3 at 353 nm, were observed initially and there were two distinct layers, one centered near 25 km altitude and the other near 20 km. These layers slowly merged and dropped both in altitude and the magnitude of the backscattering which is proportional to the aerosol loading. At the

maximum, aerosol layers extended up to and above 30 km altitude.

2.2 Mauna Loa Lidar

The new lidar system at MLO has not been described in the open literature but it is very similar to the TMF lidar and only a brief description will be given here. The lidar is housed in two custom designed trailers and is transportable. This feature allowed the system to be built, tested and intercompared at TMF before moving it to MLO and also to be deployed at MLO in advance of the NDSC facility there being completed.

Two additional channels have been incorporated into the receiver system[11], shown in Fig. 4, to measure the atmospheric nitrogen Raman returns at 332 nm and 385 nm. These channels are unaffected by aerosols and therefore allow both ozone and temperature profiles to be measured in the lower stratosphere. An optical chopper has also been incorporated into this receiver which greatly reduces the signal induced noise caused by intense lidar returns from the lower atmosphere. The resulting increase in signal-to-noise-ratio allows the profiles to be extended to higher altitudes than is possible with the TMF system. The data acquisition and control system uses PC's linked together by ethernet and IEEE-488 bus.

2.2.1 Ozone

Three separate ozone profiles are generated from the high intensity Rayleigh/Mie DIAL pair, low intensity Rayleigh/Mie pair, and Raman pair. These profiles are then combined, taking into account the location of aerosol layers and the relative errors for each profile, to make a single ozone profile which can extend from about 15 km to 60 km altitude. An example is shown in Fig. 5. The error bars at the bottom of the profile are relatively large because this region is obtained from the Raman pair which has the weakest signal but which is not affected by the aerosol layers.

2.2.2 Temperature

Temperature profiles are obtained in the same manner as with the TMF lidar except that additional information is available using the 385 nm Raman channel. This data can be used to extend the temperature profile downwards to almost 20 km altitude. As for the ozone profile, the error bars from the Raman data are relatively large but temperature profile information is obtained in a region where it was not previously possible. from lidar measurements. Figure 6 shows an example of a temperature profile obtained with the MLO lidar.

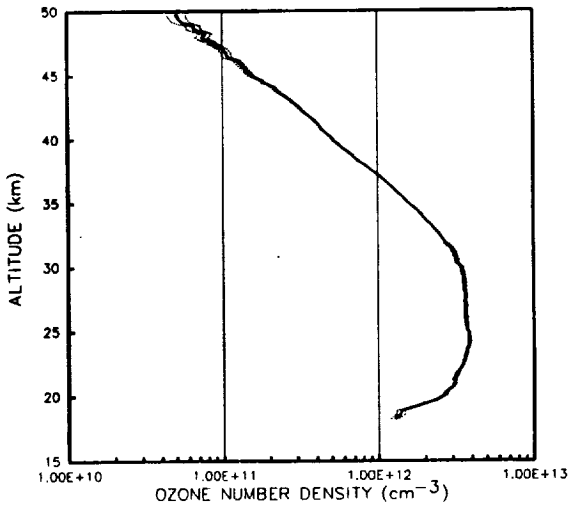

Fig. 5 MLO ozone profile for January 27, 1994.

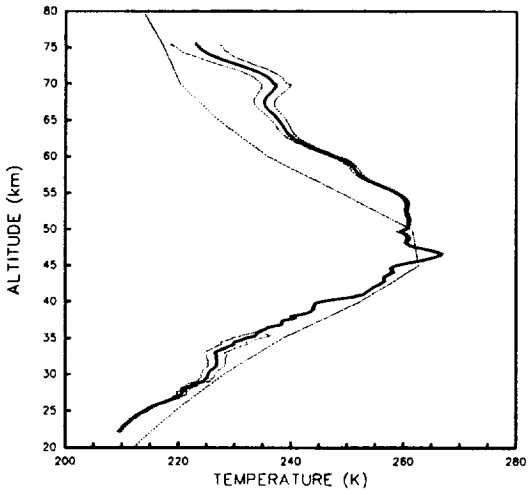

Fig. 6 MLO teperature profile for January 27, 1994. Dashed line is the CIRA reference atmosphere model.

2.2.3 Aerosols

The Raman channel data at 385 nm provides a measure of the atmospheric relative density profile. This can be used, together with the Rayleigh/Mie scattered data at 353 nm, to calculate a backscattering ratio that does not depend on an atmospheric model such as is typically the case. If the relative density profile is normalized, for example, by using results from a coincident balloon sonde, then absolute

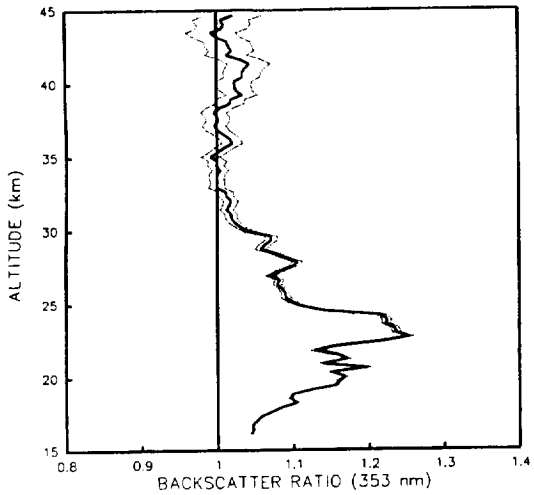

Fig. 7 MLO aerosol profile for January 27, 1994.

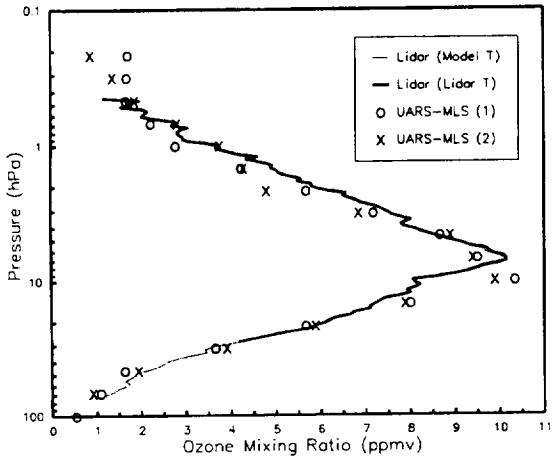

Fig. 8 Lidar MLO ozone profile converted to mixing ratio and comparison with two closest UARS overpasses (January 19, 1994).

backscatter cross sections can be deduced. Figure 7 shows an example of an aerosol backscatter ratio profile. At the latitude of MLO there are still considerable aerosol layers up to at least 30 km altitude.

2.2.4 Inter-comparisons

Figure 8 shows an example where the lidar ozone profile has been converted from number density versus absolute altitude to mixing ratio versus pressure altitude using both the lidar and CIRA model atmospheric temperature/pressure profiles and then compared with results from UARS-MLS. The two closest MLS profiles are used. The agreement between the lidar and MLS is very good over the entire range of the lidar measurement which provides confidence in the Raman augmentation and in both the temperature and density measurements since both are required for the conversion to mixing ratio and pressure altitudes.

Acknowledgments

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Profiling of Ozone in the Free Troposphere by the Lidar Technique

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Measurements of ozone in the troposphere have become increasingly important during the past decade with reports of ozone increases on global scales that not only threaten the vitality of the plant and the animal kingdom, but can also, since ozone is a greenhouse gas, contribute to global warming. The lidar application that is described here is specifically designed to accommodate the needs of the scientific community to accurately measure tropospheric ozone over a period of many years as one indicator of global change, and is intended as a prototype for a network of tropospheric ozone lidars.

Key Words: Ozone, Troposphere, Differential absorption lidar

The vertical distributions of ozone concentrations in our atmosphere have been studied for many decades. In recent years, substantial decreases in stratospheric ozone and increases in tropospheric ozone have been attributed to man. Not only are the tropospheric increases insufficient to offset the large decreases in the stratosphere, these ozone increases in the lower part of the atmosphere may contribute to global warming, can provide a significant human health hazard in urban areas, and appear to adversely affect the vitality of plants and animals. These and other factors have contributed to an escalation of interest in accurate measurement of ozone distributions.

Nature provides a challenge for scientists who wish to extract an anthropogenic signature of ozone change from the measurements. Ozone is naturally produced and destroyed in our atmosphere, resulting in natural ozone variations as a function of altitude, latitude, and time that are not easily separated from changes due to man. Whether we are studying ozone changes in the stratosphere, where concentrations are high, or in the troposphere, where its natural abundance is much less, we need accurate measurements at a variety of latitudes made over periods of many years and at a frequency sufficient to statistically identify increasing anthropogenic components. Requirements of accuracy, long-term consistency, and frequency of the measurements strongly influence the final configuration of ozone lidar systems.

The measurement of ozone in the free troposphere by the differential absorption lidar technique (DIAL) has been practiced for more than a decade. The instruments are usually ground-based although aircraft applications have also been quite successful[1]. The particular configuration we describe is located at Fritz Peak Observatory (40°N, 105° W, 2.7 km ASL), near Boulder, Colorado, USA, and has been making routine ozone observations since September 1992. It provides profiles from 4 km ASL (above mean sea level) up to the tropopause (about 12 to 14 km ASL) day or night in from 1 to 4 minutes with a 1 km altitude resolution and better than 10% absolute accuracy. A second version will be installed at the NDSC site at Mauna Loa, Hawaii.

DIAL designs suitable for tropospheric ozone profiling are significantly different from their stratospheric counterparts[2], the most obvious difference results from the ultraviolet absorption cross section of ozone[3] (Fig. 1) and the vertical distribution of ozone in the atmosphere (Fig. 2). In general, the DIAL method requires two wavelengths with differing ozone absorption cross sections. Since ozone concentrations are much less in the troposphere than in the stratosphere (Fig. 2), wavelengths with a larger absorption cross section are selected

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