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"The Application of Lidar for the Antarctic Stratospheric Research"

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"Antarctic Tropospheric Clouds Characterization Using an Elastic Backscattering Lidar"

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THE APPLICATION OF LIDAR FOR THE ANTARCTIC STRATOSPHERIC RESEARCH

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1. THE POLAR STRATOSPHERIC CLOUDS

In the cold antarctic Stratosphere, between 15 and 20 kilometers of altitude, during the winter the formation of clouds occur. Such clouds may start their formation when the temperature reaches values of the order of 195^0 K. At this temperature the Nitric Acid, present as reservoire gas in the Stratosphere, freezes forming the so called Polar Stratospheric Clouds of Type I. Such clouds are formed by hydrated nitric acid $HNO_3.3H_2O$. Their particle diameter is of the order of 0.1 nm and their sedimentation time is quite long (~100 days). When the temperature reaches 187^0 K the so called Polar Stratospheric Clouds of Type II may form. Here the water vapour present into the Stratosphere freezes. Such clouds are therefore formed essentially by water plus traces (HCl,HNO_3,H_2SO_4). These clouds are similar to cirrus clouds and their particle diameters range from 1 to 10 nm. Their expected times to fall 1 kilometer should vary between 1 hour and 3 days. The following heterogeneous reactions occur at the surface of the cloud particles[1,2]:

$$HCl(solid) + ClONO_2\ (gas)\ \text{----->}\ HNO_3\ (solid) + Cl_2(gas)$$
$$H_2O(ice) + ClONO_2(gas)\ \text{----->}\ HNO_3\ (solid) + HOCl\ (gas)$$

The occurrence of the PSC of Type II is one order in magnitude smaller than the occurence of the PSC of Type I. It is assumed therefore that the PSC of Type I may be the main responsible for the detected distribution of the various gaseous species (HCl, $ClONO_2$, ClO) in the Stratosphere, but their role in the removal of solid nitric acid from the Stratosphere may be small, due to their long time for sedimentation. This may be accomplished essentially by the PSC of Type II[1]. The PSCs play therefore a major role in the heterogeneous chemistry of the antarctic Stratosphere and prepare the conditions for the removal of the Ozone. This can happen at the return of the sun radiation at the beginning of the antarctic Spring (see the reactions given above, where the presence of solar radiation is necessary).

2. ROLE OF THE LIDAR IN THE INVESTIGATION OF THE OZONE HOLE

As it has been discussed in the previous paragraphs many parameters play an important role in the Ozone Hole problem. We shall examine here which of such parameters may be measured by means of elastic backscattering Lidar technique and DIAL technique. Substantially we may say that an elastic backscattering Lidar may carry out a large statistical studies on the aerosol load of the Stratosphere, while a DIAL system may perform Ozone measurements in the Ozone Hole.

3. THE ELASTIC BACKSCATTERING LIDAR

A simple elastic backscattering Lidar seems particularly suitable for the observation of PSCs. From the data already available[3,4,5], carried out during the 1987 Antarctic US-NOZE project, it results that such clouds present a quite remarcable backscattering ratio of the order of several unities. This means that in the absence of troposheric clouds regular measurements of PSCs are possible. Furthermore informations on the type of cloud may be obtained from the depolarization characteristics of the return signal, by transmitting a polarized pulse. PSCs of Type I, having particle radii of the order of 1 micron, act substantially as spherical radiators for lidar operating in the visible. A small depolarization has to be expected of the order of some percent. Instead PSCs of Type II, because of the large sizes of their particles similar to cirrus clouds, should introduce very strong depolarizations, with values reaching 50% or more. Because of the low values of the optical thickness of such clouds, it is possible to derive the optical properties with a simple algorithm. If the lidar system is designed carefully enough[6], it is possible to carry out, as shall be shown later, lidar profiles also during the day up to high altitudes, tipically 40 kilometers. For stratospheric clouds and also for cirrus clouds it is generally possible to assume that before and after the cloud there is only a molecular atmosphere. Therefore, if the laser pulse penetrates all through the cloud, and this happens always in the case of stratospheric aerosols and Polar Stratospheric Clouds for a powerful lidar system[7], it is possible to normalize the lidar signature below the cloud with an antarctic molecular atmosphere, which can be determined directly by radiosonde data.

By assuming a linear relation between backscattering and extinction coefficient [8] and an iterative procedure it is possible to invert the Lidar equation. Such inversion technique is discussed more in detail by Morandi et alii in ref [9]. If the measurements are carried out with sufficient frequency (every 15-20 minutes) it may be possible to monitor the falling processes of the ice crystal from the Stratosphere analyzing the depolarization characteristics and plotting the isoplets for the depolarization ratio as a function of the time. It may be possible therefore to show whether PSCs of Type II effectively remove most of the NOx from the Stratosphere by sedimentation processes. In conclusion by means of an elastic backscattering Lidar one may derive some of the most interesting parameters regarding the PSCs, as: cloud top, cloud bottom, and , optical depth, and some general indications on the size distribution.

4. THE 1987/88 LIDAR MEASUREMENTS SUMMER CAMPAIGN: STRATOSPHERIC AEROSOL MEASUREMENTS

The main goal of the 1987/88 Lidar Campaign in Antarctica was to test the instrumentation to be used in subsequent winter and spring operations. The scientific results were valuable by product of such a testing. We will report here some of the observed results regarding the stratospheric aerosol measurements.

Two types of stratospheric lidar signatures have been obtained:

1) lidar profiles to monitor stratospheric aerosols from 10 to 40 kilometers;

2) high altitudes profiles to monitor molecular atmosphere from 25 to 60 kilometers.

Stratospheric measurements were carried out during this first campaign using one single detection channel and consequently one only polarization. Measurements were averaged over 5000 shots, as during the period of January and early February it was necessary to operate the system in the presence of sunlight. Therefore the background level was always not negligible. Only at the beginning of February the sun started to sink below the horizon for a short period of time. During that period the upper stratospheric measurements have been performed. 35 profiles of the antarctic atmosphere between 10 and 40 kilometers have been produced between January, 1 and February, 10, 1988. These signatures have been normalized versus an average molecular atmosphere derived by the daily radiosonde data produced by the Meteorological Office of the Base. Small aerosol layers have been identified between 15 and 25 kilometers. Fig. 2 shows an example of such a measurement. The integrated backscattering has been computed between 12 and 30 kilometers. The values varied between $1.7*10^{-5}$ in early January and $5.8*10^{-5}$ during the first part of February. 3-D plots of the mixing ratio, defined as R-1, where R is the following backscattering ratio:

$$R = \frac{\beta mie + \beta ray}{\beta ray} = 1 + \frac{\beta mie}{\beta ray}$$

have been plotted for the whole period. Fig. 1 shows such a time evolution. Fig. 2 shows instead the same mixing ratio, with a representation by means of isoplets. Such increase in aerosol loading has also been measured by Tomasi et alii [10] at Terra Nova Bay by means of passive ground based photometers.

In Fig. 3 a typical example of aerosol loading is represented. In the lower curve the backscattering coefficient is plotted versus height. The two curves are respectively the molecular backscattering, as obtained by the radiosonde data, and the backscattering profile obtained by lidar. In the upper curve the backscattering ratio R is plotted versus height.

One may notice the deviation of the lidar signature in the area between 15 and 25 km height. The maximum value of R never exceeded 1.1, generally with maximum around 1.05.

From the radiosonde data it appears that the temperature of the Stratosphere is still quite warm, with temperatures at the Tropopause (at heights of about 7-8 kilometers) never below 220° K. This means that background aerosol is observed during the summer period. Probably this background aerosol is constituted of submicroscopical solforic acid particles formed after the return of the sun in September as shown by Hoffmann et alii [11].

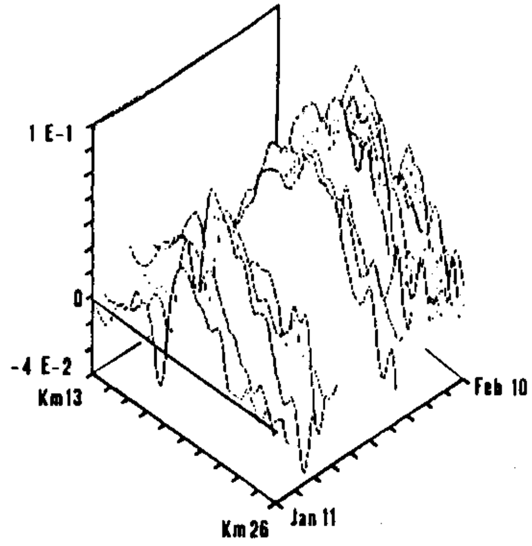

FIG.1

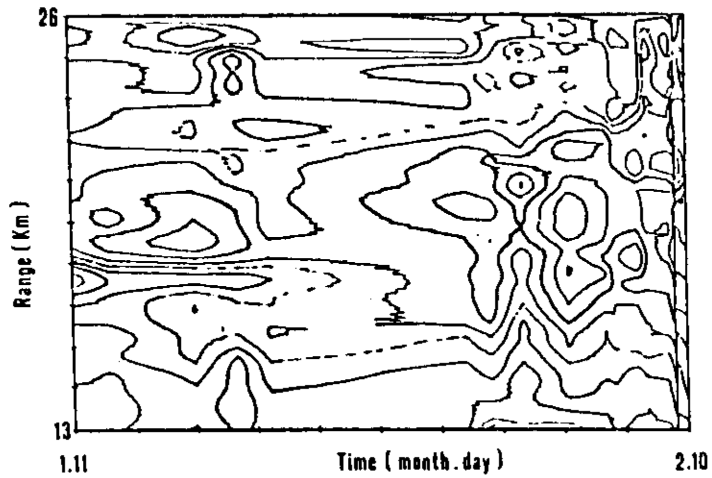

FIG.2

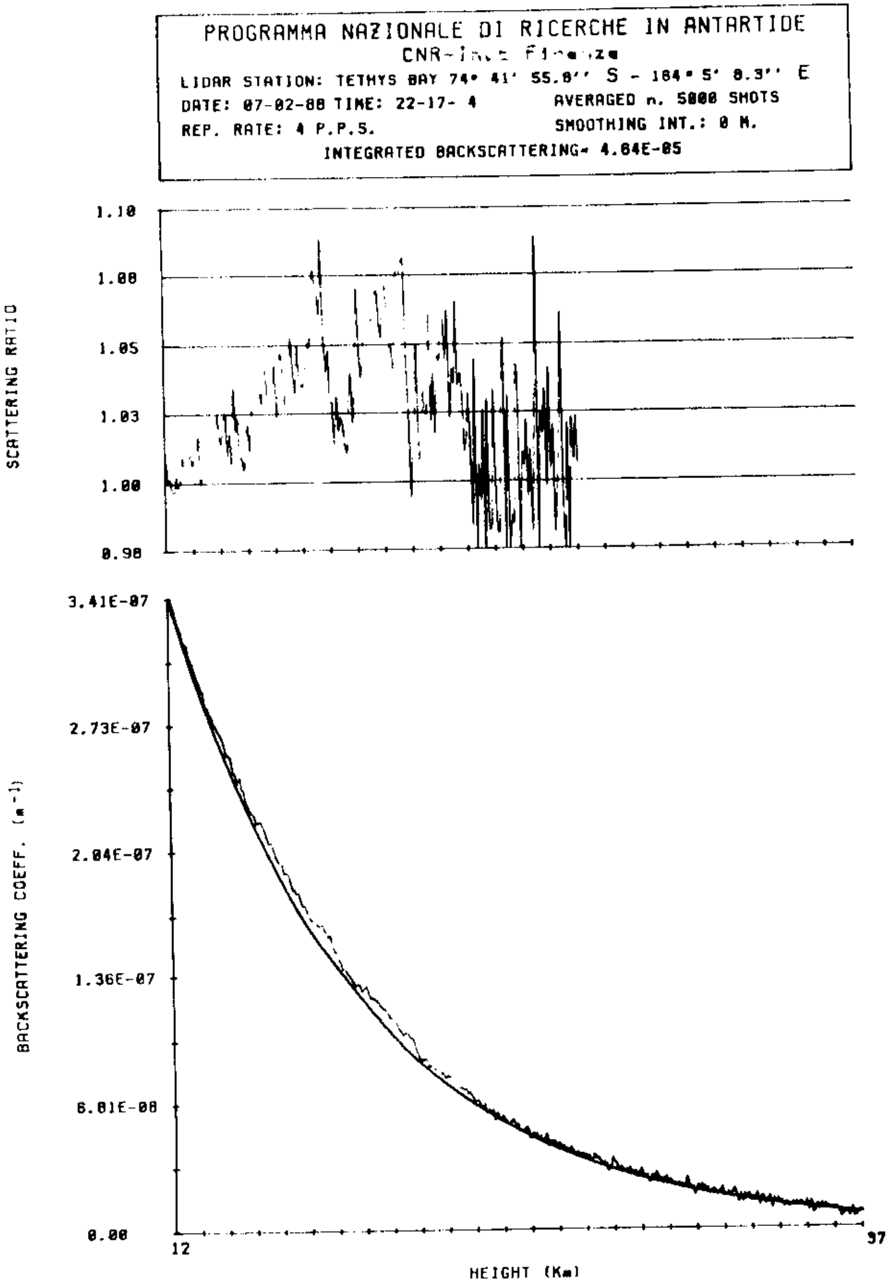

FIG 3

These measurements constitute a baseline for further researches. The system will operate from January 1989 for at least one year at French Base of Dumont d'Urville; the aim of this next campaign is to measure continuosly PSCs. To this end measurements of both polarizations will be performed.

High altitude stratospheric measurements have been carried out averaging over different groups of 10000 shots. Such measurements have been performed during the "night", that is when the sky background was lower. As no photoncounting technique was available, from the results it was not possible to establish clearly if high altitude temperature measurements were possible. The data have been inverted for temperature[12], but due to the high level of noise at heights above 45 Km, the inversion is not sufficiently reliable. Fig. 4 shows an example of such inversions. Finally it is worthwhile noting that:

I) processing separately averages of 10000 shots (1 hour average), it results that the groups of measurements carried out at minimum background present the smallest dispersion;

II) the measurements tend to converge at 25 kilometers to the radiosonde data;

III) a wave analysis of the pattern is certainly possible.

Wave structures have been analyzed and gravity waves can be evidenced (see Fig.5) with typical wavelengths of 5 and 2.5 kilometers.

5. THE DIAL SYSTEM

A complex DIAL Lidar is presently under construction in cooperation with the Service d'Aeronomie du CNRS (France) for the measurement of the Ozone in the Antarctic Ozone Hole. Special attention is given to the design in order to carry out precise measurements of the low stratospheric Ozone, inside the Hole, where the Ozone is depleted up to 80%, and substantial aerosols are present with scattering ratios in the visible as high as 3. In the region between 12 and 20 kilometers altitude it is therefore not possible to neglect the aerosol effect on the propagation; this makes the DIAL system particularely complex in its design. Such a system will have as transmitter two lasers, respectively a Nd-YAG and an Exciplet laser filled with XeCl. Second, third and fourth harmonic generators will be mounted on the Nd-YAG. The fourth harmonic radiation will pump two Raman shifter,

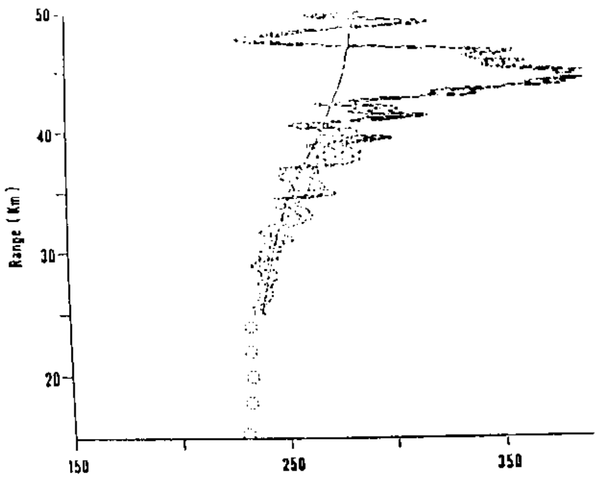

FIG. 4

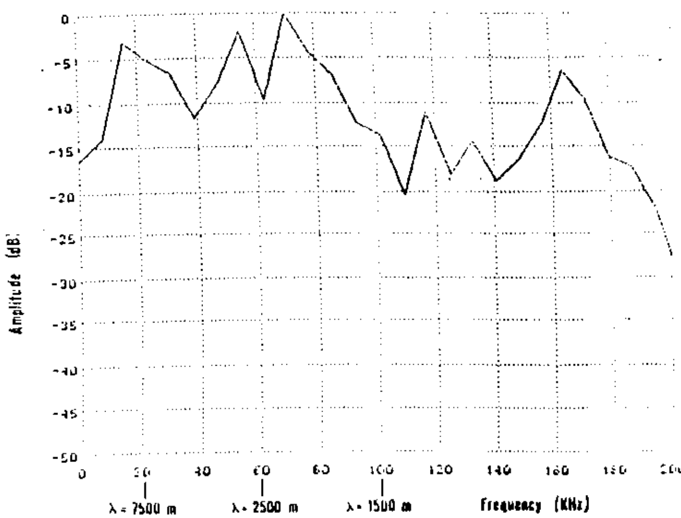

FIG. 5

filled respectively with Hydrogen and Deuterium in order to produce the 289 and 299 nm radiations, which will be used for the DIAL measurement in the Hole [13]. The third harmonic of the Nd-YAG at 355 nm and the 308 nm line of the XeCl will be used as off and on line for the Ozone measurements at high altitude (above 30 kilometers); with the 532 nm line both the tropospheric and stratospheric clouds will be monitored. Such signatures, together with the 355 nm could be used also for aerosol correction in the Ozone measurements in the Hole. The receiver consists of an 80 cm, f/10 alluminum Cassegrain telescope; a monocromator with f/10 optics will separate the UV radiation, while the visible (532 nm) will be separated by a dicroic mirror before the focal plain. Also direct detection and photon counting techniques will be used. Such a system will be assembled inside an ISO 30" shelter and is scheduled to start operations in Antarctica at the beginning of 1990. The DIAL will replace the elastic backscattering Lidar and will constitute a complex system able to perform all the requested measurements. The Lidar program in Antarctica is supposed to last for several years in order to be a useful tool both for the understanding of the Ozone Hole problem and of the climatic events in the White Continent.

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ANTARCTIC TROPOSPHERIC CLOUDS CHARACTERIZATION USING AN ELASTIC BACKSCATTERING LIDAR

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ABSTRACT

The Lidar Group of IROE is involved in the Italian National Program of Research in Antarctica (PNRA) with two programs. The first one concerns the Ozone Hole phenomenon, the second one the Antarctic Climatology. In this paper the research activity on the Antarctic Tropospheric Clouds is illustrated. The Antarctic Campaign 1987-88 at the Italian Base of Terra Nova Bay is described together with the future developments which refer mainly to the ECLIPS (Experimental Clouds LIdar Pilot Study) International Project. Finally some experimental data are presented and the processing methods are discussed.

INTRODUCTION

The "control" function of the clouds is known in the processes of energy exchange between Earth and Atmosphere [1,2,3,4,5]. However the problem of the clouds characterization keeps to be an opened problem. The characterization parameters of the clouds are the optical properties in the visible and infrared spectra, the cloud base height and its thickness. To improve the knowledge level in this field the Project ECLIPS has been funded with the aim of: 1) coordinating the research activities with different techniques (Lidar measurements, radiometric measurement from ground & from satellites etc.), and 2) establishing a data bank which collects with suitable standards all the Clouds Measurements Data in the world. The first objective of ECLIPS is to obtain a better knowledge of cloud base and optical properties in different geographical zones (tropics, desert, polar, oceanic). The second objective is to provide observations of cloud base and optical properties by lidar and other surface data and to correlate these data with satellite imagery and sounding observations in order to determine the viability of satellite-based retrievals of surface energy fluxes [6]. Starting from 1989 the Antarctic Activities of the Lidar Group of IROE will be linked to ECLIPS.

PARAMETERS WHICH CAN BE MEASURED BY LIDAR

A Lidar can furnish an extremely important contribution to the clouds characterization. A first relevant datum is the cloud base height, because, depending on the height, the effect on the ground, in terms of energy exchange, can be positive or negative. An accurate measurement can be obtained by means of Lidar. Besides it is also possible to determine from the lidar signature, if the optical depth is not strong enough to completely extinguish the signal, the cloud thickness and its optical properties. A double channel measurement to simultaneously evaluate the two polarization components allows to determine the phisical phase of the clouds. In Table 1 the parameters which can be measured using a Lidar and the relative symbols are illustrated.

z_0	Base Height
z_T	Top Height (no extinction in the cloud)
σ_M	Extinction Coefficient
β_M	Backscattering Coefficient
$\delta(z_0,z_T)$	Optical Depth
τ_M	Transmittance
ω_M	Opacity

TABLE 1

Due to the dependence of the optical parameters from the wavelength it should be helpful to use for these measurements both the fundamental and the second harmonic of the Nd-YAG (1064 and 532 nm, respectively). In our system we used only the second harmonic radiation for two main reasons: 1) the low quantic efficiency of the detectors at 1064 nm ;2) to semplify as much as possible the receiving optics to minimize the losses and maximize the range of measurements.

THE PROGRAM 1987-88 AND THE FUTURE PROGRAMS

During the third Italian Campaign in Antarctica (1987-88) an elastic backscattering Lidar has been mounted near the Base of Terra Nova Bay [7]. The main characteristics of the Lidar follow.

Transmitter: Laser Nd-YAG

energy:	400mj @ 532 nm
pulse length:	10 ns
divergency:	0.25 mrad
pulse repetition rate:	up to 10 Hz

Receiver:

Newtonian telescope	primary glass diam.	0.5 m
	focal length	2 m
	field of view	0.3 mrad

Interferential filter band 0.15 nm

2 receiving channels to measure the polarization components.

Fotomultipliers THORN-EMI 9658R with gating circuitry to attenuate the signal from the lower layers of the atmosphere. This gating produces a linear attenuation of about 1/800.

Acquisition systems:

2 transient digitizers 8 bit 32 Mhz plus a preamplifier

1 transient digitizer 12 bit 5 Mhz 1-4 channels with an included preamplifier

Personal Computer Olivetti M28.

Two sets of measurements were performed during the Campaign 1987-88: stratospheric and clouds measurements. The Lidar worked hardly in order to perform a severe test reliability of the whole system (3 million of shots during 2 months). Starting from the full housing of the base the measurements were performed all 24 hours long, with particular care to follow the evolution of the atmospheric perturbations. During those events a signature averaged over 50 shots was recorded each minute. The Lidar data were correlated to the meteorological data

furnished by the meteorological Office of the base. A video-recorder system worked together with the Lidar to monitor the cloud coverage. The recorded images allow also the evaluation of the cloud speed.
The future programs will consider the participation to ECLIPS Project, starting from the next antarctic summer 1988-89. Under a scientific cooperation program with Service d'Aeronomie of the French CNRS, the revisioned and slightly modified Lidar will work for a whole year at the French Antarctic Base of Dumont d'Urville. The system will perform stratospheric measurements (aerosols, PSC etc.) and also sistematic measurements of clouds. In this case an average of 10 shots every 10 minutes will be stored. Besides during the ECLIPS campaign, the acquisition will follow suitable rules in correspondence with the flight crossing of the NOAA Polar Orbiter Satellite with AVHRR and TOVS sensors on board. The AVHRR data are suitable for the determination of the optical density of the clouds and the TOVS sensors give cloud cover and cloud top heights, precipitable water, surface temperature and temperature profile. Together with the Lidar a Precision Infrared Radiometer with a field of view of 170° will measure the long wave I.R. emission in the range 5-50 microns. These radiometric measurements are necessary for the optical characterization of the clouds in Thermal Infrared region. The data will be correlated to meteorological measures (ground data and radiosonde data).

THEORY, EXPERIMENTAL DATA & PROCESSING TECHNIQUES

The Lidar equation follows:

$$1) \quad P(z) = P_0 \frac{c\,t_0}{2}\, C\, A_E\, \frac{\beta(z)}{z^2} \exp\left(-2\int_0^z \sigma(z')\,dz'\right)$$

where $P(z)$ is the receiving power at the time $t=2z/c$, z is the distance, c is the light speed, P_0 is the transmitted power, C is the calibration constant of the system, t_0 is the laser pulse length, A_E the effective area of the receiver, $\sigma(z)$ is the extinction coefficient. This last value can be replaced with the sum of two contributions: the molecular diffusion contribution σ_R and the Mie diffusion contribution σ_M due to aerosols, clouds etc. The cloud extinction coefficient σ_M can be related to β_M with the following equation:

$$2) \quad \beta_M(z) = k\, \sigma_M(z)^J$$

where k and J are constants and J, in particular, is function of the wavelength and the type of aerosols. A suitable approximation for homogeneous clouds, in the case of measurements with monochromatic light, is the assumption of a linear relation between σ_M and β_M assuming $J=1$ [8,9]. For the experimental data processing the following relation has been used:

$$3) \quad \sigma_M(z) = K_M\, \beta_M(z)$$

In Antarctica, outside the cloud, a purely molecular atmosphere can be considered. In our case an averaged atmosphere computed from radiosonde data has been used. Let $S(z)$ be the signal corrected for the distance and the molecular extinction. $S(z)$ can be normalized to the values of the molecular backscattering. It follows that:

$$4) \quad S(z) = \beta_R(z) \qquad \text{when } z < z_0$$

$$5) \quad S(z) = (\beta_R+\beta_M)\exp\left[-2K_M\int_{z_0}^{z}\beta_M(z')\,dz'\right] \qquad \text{when } z>z_0$$

The optical depth is defined by the following equation:

$$6) \quad \delta(z_0,z_T) = \int_{z_0}^{z_T}\sigma_M(z)\,dz = K_M\int_{z_0}^{z_T}\beta_M(z)\,dz$$

If $\delta(z_0,z_T)$ does not cause the total extinction of the signal inside the clouds, it is possible to derive directly the value of the optical depth following the equation:

$$7) \quad \delta(z_0,z_T) = [\ln \beta_R(z) - \ln S(z)]/2 \qquad \text{with } z > z_T$$

The data have been processed using both the Klett method [10] and an iterative procedure developed by our group [11]. Some simulations showed for the second method a higer precision . Such procedure is possible only when before and after the cloud there is a molecular atmosphere. In this first analysis multiple scattering has been negleeted. This should be acceptable at least for not too high values of $\delta(z_0,z_T)$ in the case of very narrow field of view of the receiving telescope [12], . This hypotesis will be certified using simulations and suitable models. At the beginning of the iteration one assumes an arbitrary value for K_M, then one computes σ_M for each point, the correction of the signal due to the extinction, the value of the optical depth using 6) on the basis of the values of σ_M. If the obtained value of $\delta(z_0,z_T)$ is greater than (or less than) that computed using eq. 7) the value of K_M is augmented (or reduced). This way the proper values of K_M and $\beta_M(z)$ are determined with consecutive approximation steps.

From the simulation an error less than 1% on the computation of K_M is obtained. With this method all the optical parameters of the cloud can be derived. Using the optical depth the transmittance τ_M and the opacity ω_M can be determined:

8) $\tau_M = \exp[-\delta(z_0, z_T)]$

9) $\omega_M = 1/\tau_M$

Referring to water clouds, some hypotesis on the particles diameter distribution are derivable from the σ_M/β_M ratio [13]. In Figure 1a the time evolution of a cloud is represented, and in Figure 1b the depolarization ratio. The presence of a water cloud is confirmed by the low values of depolarization. In Figure 1c the ratio K_M for each signal is depicted. From the average value $K_M = 23$ it is possible to infer a particle diameter distribution of about 5 microns [13]. We think that an extension of this method to the ice clouds is arbitrary, as the crystals can assume a great variety of shapes and this affects hardly the K_M ratio. In this case an evaluation of the particle dimension on the base of the sedimentation speed is possible [14]. In Figure 2a the time evolution of an atmospheric perturbation is shown, in Figure 2b the backscattering ratio β_M/β_R, in Figure 2c the depolarization ratio. It is noticeable that the comparison between the graphs of Figure 2b and 2c evidences the simultaneous presence of ice and water in clouds (depolarization ratios up to 24%-ice, <5%- water). The water clouds are stable in height, while a sedimentation process is evident for ice. From the sedimentation speed it is possible to assume that the crystals dimensions are of the order of 1 mm [14]. Table 2 shows a comparison of wind velocity measure with radiosonde and Lidar - TV system.

CONCLUSIONS

Our work evidenced that a Lidar Program can give a great contribution to the knowledge of the Antarctic Climatology. The comparison between Lidar data and satellite data (ECLIPS Program) is very important for both the validation and correction of the Satellite data and for an integration on larger scale of the local Lidar data. The measurement program carried out during the Campaign 1987-88 evidenced the reliability of the system and its capability to performe a complete characterization of the clouds. This Program will continue in the next years and operations are scheduled both at the Italian and French Antarctic Bases of Terra Nova Bay and Dumont d'Urville. The statistics obtained

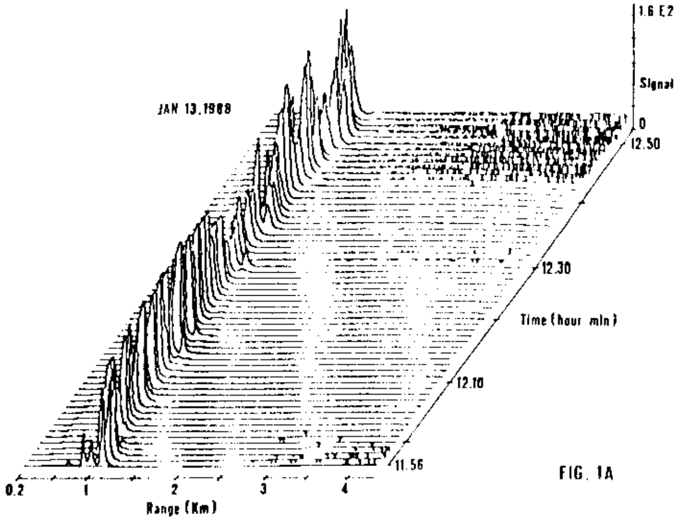

FIG. 1A

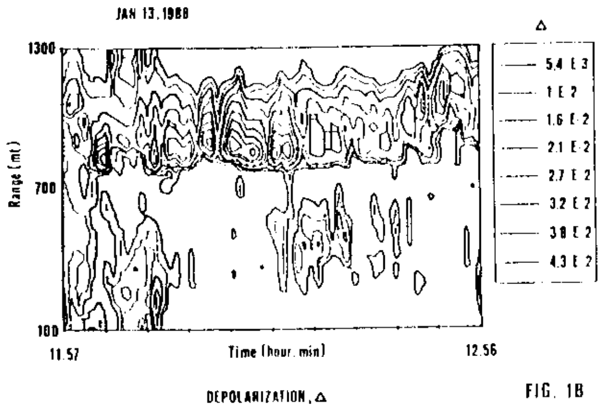

FIG. 1B

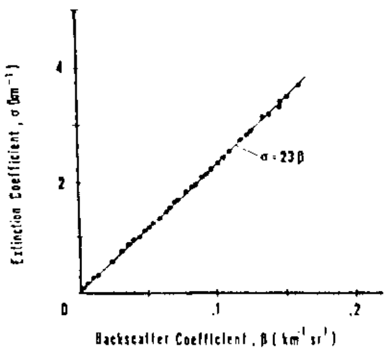

FIG. 1C

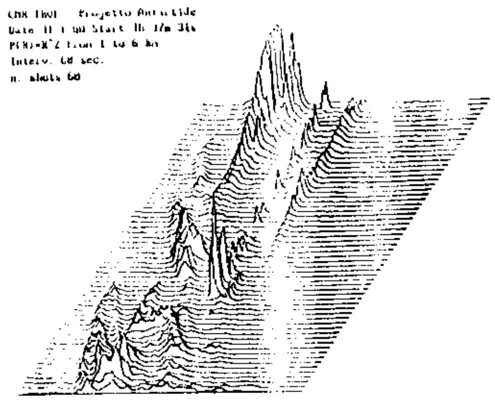

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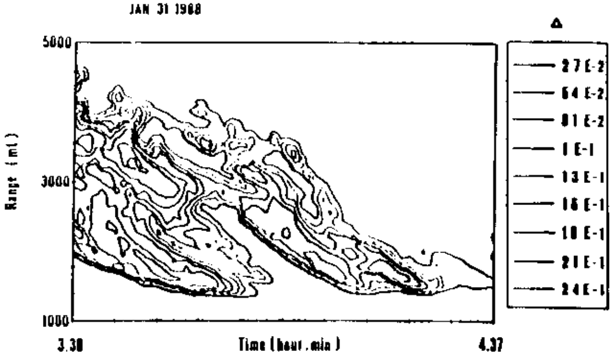
FIG. 2a

BACKSCATTERING RATIO (R-1)

FIG. 2b

JAN 31 1988



DEPOLARIZATION, Δ

FIG. 2c

will contribute to a characterization of the Climatology in that region. A feasibility study to install an automatic system in the future winter base at Terra Nova Bay is presently beeing carried out.

DATE	TIME	HEIGHT (m)	RADIOSONDE (m/s)	LIDAR-TV (m/s)
01.13.88	10:54	1000	2.4	----
	12:54	1107	----	3.9
01.16.88	18:50	8215	----	18.4
	19:00	8215	----	21.7
	20.17	8200	22.0	----
	20.17	6500	24.3	----
	20:20	6650	----	13.6
	20:30	6650	----	13.9
01.31.88	05:20	2800	----	3.8
	12:15	1500	2.1	----
	12:15	2000	2.6	----
	12:15	2500	4.4	----
	12.15	3000	3.8	----
	14.50	1846	----	2.0
02.03.88	23:30	1615	----	2.2
	23.38	1500	4.1	----
	23.38	2000	1.3	----

TABLE 2

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