LIDAR for Atmosphere Research over Africa

V. SIVAKUMAR[1*], D. MOEMA[1,2], C. BOLLIG[1], A. SHARMA[1], N. MBATHA[3,4], S. MALINGA[3],
G. MENGISTU[5], H.BENCHERIF[4] AND P.KECKHUT[6]
[1] Council for Scientific and Industrial Research, P.O. Box – 395, Pretoria, South Africa.
[2] Tshwane University of Technology, Pretoria, South Africa.
[3] Hermanus Magnetic Observatory, Hermanus, South Africa..
[4] Université de la Réunion, Laboratoire de l'atmosphère et des cyclones, Réunion, France.
[5] Addis Ababa University, Addis Ababa, Ethiopia.
[6] Service d'aéronomie, Paris, France.
Email: svenkataraman@csir.co.za

Abstract

This paper describes the LIDAR for atmosphere research over Africa and current initiatives being undertaken in South Africa. A mobile LIDAR system is being developed at the Council for Scientific and Industrial Research (CSIR) National Laser Centre (NLC), Pretoria (25°5′ S; 28°2′ E), South Africa, for remote sensing the atmosphere. The initial results conclude that the system is capable of providing aerosol/cloud backscatter measurements for the height region from ground to 40 km with a 10 m vertical height resolution.

1. Introduction

The importance of systematic monitoring of the atmospheric structure and dynamics has been the interest of several atmospheric research campaigns across the globe. Laser radar, more popularly known as LIDAR (LIght Detection and Ranging), has become an outstanding instrument for short-term sensing of the atmosphere (seconds to minutes). Lasers offer great advantages over conventional light sources in terms of peak power and narrow spectral/beam width. The discovery of different laser sources and improvements in detection technology, data collection and analysis techniques have made the LIDAR a consistent remote sensing tool for atmospheric studies. In general, LIDAR systems use both continuous wave and pulsed lasers. LIDAR systems are currently operational in different countries and are used for the study of atmospheric structure and dynamics, trace constituents. (Differential absorption), aerosols/clouds (Mie Scattering), atmospheric density and temperature (Rayleigh Scattering), metallic ion species (Resonance Scattering), minor constituents (Raman Scattering) and winds (Doppler LIDAR).

The first development of a LIDAR system took place in 1961, by two groups at Hughes Aircraft Malibu and Culver City, respectively. However, this system was exploited for target range finding. Later, LIDAR studies were carried out using a Ruby laser as source (Ligda, 1963; Fiocco and Smullin, 1963, Fiocco and Grams, 1964) but recent atmospheric studies have taken advantage of the high pulse repetition capability of Neodymium-Yttrium Aluminum Garnet (Nd:YAG) lasers which are usually frequency-doubled to provide a 532 nm output (Chanin and Hauchecorne, 1981). The improved performance of Nd:YAG lasers, the use of shorter wavelengths, and the availability of improved blocking, for rejecting the elastically backscattered return, have led to enhanced interest in atmospheric measurements. The Nd:YAG laser is also advantageous since it can be easily tuned to different wavelengths by means of harmonic generators which allow for different atmospheric measurements.

A web-based survey of ground-based LIDARs around the world was conducted. The location of lidar systems employed for different atmosphere studies is presented in Figure 1. It is noted here that the survey is not complete and needs further attention to provide any substantiate statement. Further, the survey has been made with regards to LIDAR applications for atmosphere studies including pollutant monitoring. It is evident from the figure that:

- around 80 % of the LIDARs are highly concentrated in the northern hemisphere region,
- only a few, approximately 20 %, are located in the southern hemisphere region, with a high concentration in South America,

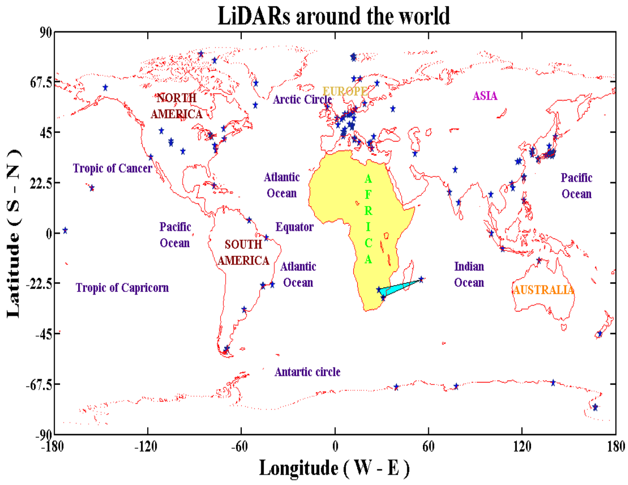

Figure 1: The LIDAR systems are deployed around the world. The lidar stations are represented by a star mark on the map.

- LIDARs on the African continent are limited to two, including the mobile LIDAR system developed at Pretoria (South Africa),
- While there are many ground-based fixed LIDARs, there are not many mobile LIDAR systems for systematic atmosphere measurements.

Hence, LIDAR is yet to be considered as state-of-the-art for South Africa and African countries. We have identified only two LIDAR systems in South Africa. One is located in Durban (South Africa) and operated under a South Africa – France association by the University of KwaZulu-Natal (UKZN) and the other one is the new mobile LIDAR system at the National Laser Centre (NLC), Council for Scientific and Industrial Research (CSIR), Pretoria (Sivakumar, 2008). Our aim is therefore to develop a mobile LIDAR system which will serve as a research platform for monitoring the atmosphere over Africa (LARA).

At present, the NLC mobile LIDAR system is primarily designed for atmospheric studies, including monitoring of various pollutants that contribute to global climate change and global warming. This paper describes the present status of the LIDAR system and the research objectives, and discusses the initial research results obtained.

2. LARA objectives

The research objective is to develop a mobile LIDAR platform for remote sensing the atmosphere. The present research programme is focused towards a better understanding of global climate change (GCC) and global warming (GW). In future, it is planned to use the LIDAR system to measure water vapour and ozone in the atmosphere. Regular monitoring of these constituents is important for a better understanding of GCC and GW. To achieve this, we need a portable instrument which will facilitate measurements at different regions. To achieve the above requirements, the LIDAR has been installed in a mobile vehicle equipped with the necessary optics to make remote measurements possible. Our goal is to utilise the mobile LIDAR system to measure the following;

- Mie scattering of particulate size (µm) matter in the atmosphere
- Aerosol measurements and cloud characteristics
- Smoke/Plume detection
- Lower troposphere water vapour measurements (from ground to 8 km).
- Troposphere ozone measurements (from ground to 18 km)

The study on particulate matter addresses knowledge on particle size and concentrations in the atmosphere. Making observations over different regions/places provides an idea of mass transport between the regions and is able to back-track through trajectory analysis to identify the location of the source, e-g. bio-mass burning. The study on aerosols/clouds plays an important role in the earth-radiation budget (~30 %) and the LIDAR has the unique capability of measuring the particle concentration at a particular place in an effective manner by illuminating different harmonic of laser (Nd:YAG).

The radiative effect of aerosols contributes the largest uncertainty in global climate predictions to quantify climate forcing caused by man-made changes to the composition of the atmosphere (Fiocco, 1984). The LIDAR measurements of aerosols provide reasonably accurate information of its concentrations. It also has potential to locate the height and vertical distribution of various clouds which are present. The relative thermodynamic phase distribution of the cloud, water/super-cooled water, ice and ice crystal, can be examined in some extent, based on the depolarization characteristics of the LIDAR back scattering, normally referred to as linear depolarization ratio (Killinger and Menyuk, 1987, Sassen et al., 1995). The successive plan is to upgrade the LIDAR system for measuring water vapour in the lower troposphere. The water-vapour measurements over different regions will address the level of water vapour present in the atmosphere. It addresses the dry and wet regions, and thereby focuses on the ecological effects (such as agriculture and water scarcity). Since water vapour is a primary green-house gas, the study aims to better understand global climate change and global warming. Besides the water vapour measurements, the aim is to further upgrade the LIDAR system to be capable of making troposphere ozone measurements. This would elucidate the amount of ozone in the different height regions (maximum ~18 km) of the atmosphere and one would be able to infer ozone depletion and increases in temperature (in other words, global warming due to increase in ground ozone).

Besides regular monitoring, measurements at different places will provide a better knowledge of concentrations and its localized variation with respect to place. The mobile LIDAR system will enable us to enhance our objective of making measurements in different places, especially in South Africa and African countries.

We are also focused on strengthening research relationships between South Africa and other countries to improve our understanding of the aerosol and cloud characteristics in the sub-tropical southern hemisphere. A triangular LIDAR research network is established between the LIDARs located at Pretoria (NLC-CSIR Mobile LIDAR), Reunion (Laboratoire de l'Atmosphère et des Cyclones de La Réunion, CNRS 8105) and Durban (University of KwaZulu-Natal (UKZN)). (see Figure 1 with blue colored triangle).

3. Present Status

Using advanced techniques and instrumentation, a mobile **Li**ght **D**etection **a**nd **R**anging (LIDAR) system is being designed and developed at the CSIR-National Laser Centre (NLC), Pretoria (25°45′ S; 28°17′ E) (see Figure 2).

At present, the system is capable of providing aerosol/cloud backscatter measurements for the height region from ground to 20 km with a 10 m vertical height resolution. The major advantage of the LIDAR is its capability to provide the vertical cross-section of clouds including the thickness which is important for better understanding the cloud dynamics and the earth-radiation budget [2]. The cloud information is also useful for predicting convective systems and rain. The LIDAR measurements will also elucidate the aerosol concentration, optical depth, cloud position, thickness and other general properties of the cloud which are important for a better understanding of the earth-radiation budget, global climate change and turbulence. The initial results on cloud detection are presented in this paper.

Figure 2. The external view of mobile LIDAR van.

System description

The LIDAR system comprises a laser transmitter, optical receiver and a data acquisition system. The complete LIDAR system is custom-fitted into a van, using a shock absorber frame. Hydraulic stabilizer feet have been added to the vehicle suspension to ensure stability during measurements (see Figure 3). A Nd:YAG laser is used for transmission which is presently employed at the second harmonic (532 nm) at a repetition rate of 10 Hz.

The receiver system employs a Newtonian telescope configuration with a 16 inch primary mirror. The backscattered signal is subjected to fall on the primary mirror of the telescope and is then focused toward a plane mirror kept at an angle of 45 degrees. It is detected by the Photo-Multiplier Tube (PMT) and the PMT output signal is transmitted to the transient digitizer and PC for analysis and archival. A multimode optical fiber is used to couple the received backscatter optical signal from the telescope to the PMT. To accomplish accurate

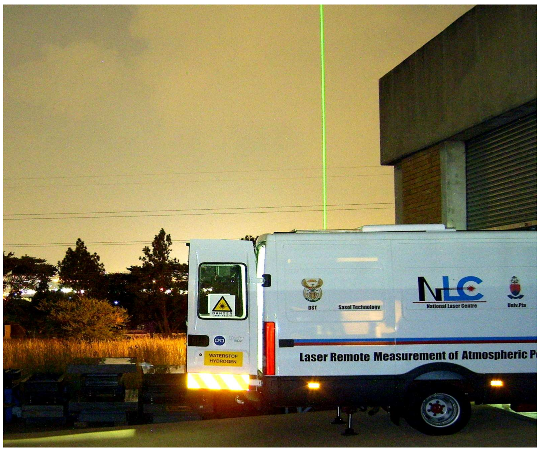

Figure 3: CSIR-NLC-Mobile LIDAR system

alignment of the fiber tip, a motorized 3-D translation stage is used. The optical fiber is connected to an optical baffle which is positioned by the stage. The PMT is installed in an optical tube which converts the optical backscatter signal to an electronic signal and then transferred to PC for storage and analysis.

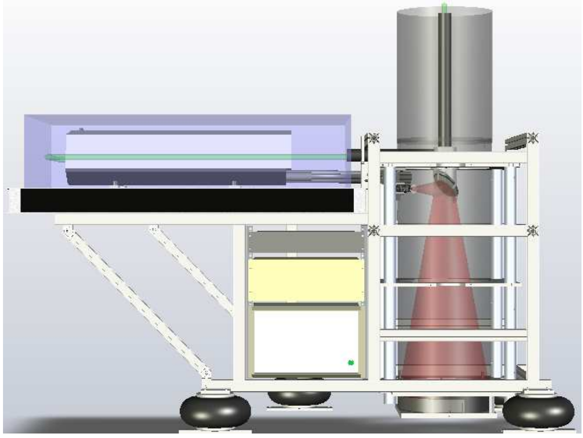

Figure 4. The present LIDAR set-up inside the van.

The data acquisition is performed by a transient recorder which communicates with a host computer for storage and offline processing of data. A Licel® transient digitizer was procured for this purpose. This unit is a data acquisition system optimized for fast, repetitive photomultiplier LIDAR signals in the analog voltage range of 0 - 500 mV. The system is favored due to its capability of simultaneous analog and photon counting detection, which makes it highly suited to LIDAR applications by providing high dynamic range.

The schematic LIDAR setup inside the van is illustrated in Figure 4, and the more important specifications of the mobile LIDAR system are given in Table 1. More details about the system are cited in Sivakumar et al., (2008).

4. Initial Results

After calibration and initial testing, the LIDAR was operated for the first time on 23 February 2008. The laser was directed vertically upward into the sky and the corresponding night was a cloudy sky (see Figure 5). There was a passage of cumulous clouds which is normally found at lower height region from 3 km to 5 km. Since these clouds are generally optically dense, light is prevented from passing through.

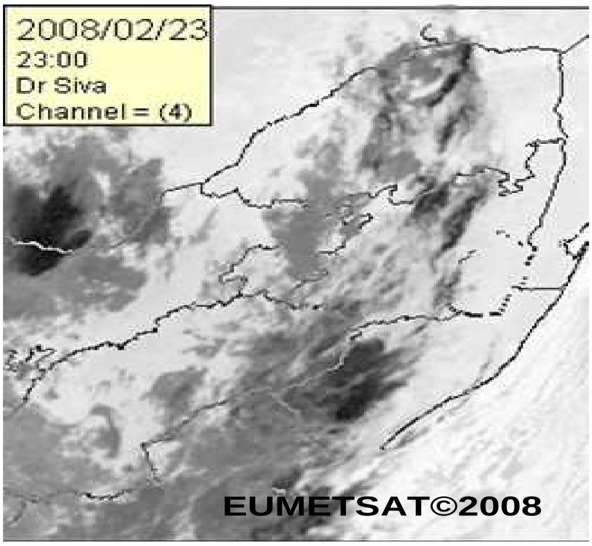

Figure 5: EUMETSAT picture illustrating the cloud over Pretoria (LIDAR site)

The present LIDAR data acquisition is capable of simultaneously acquiring data with a high range resolution (10 m) via both the analog and photon count channels. The present observations were carried out for approximately two hours. The different forms of height-time-backscattered signal (analog, photon counts, Dead-time corrected and glued) returns are presented in Figure 6. The detected analog and photon count signals are displayed in the top panel of Figure 6. The signal has been post processed for the required/corrected information, dead time corrected (3.6 ns for our present case) (see Figure 6, bottom left panel). The simultaneous analog and photon count data are merged appropriately to create a single return signal. A linear correlation analysis was performed on the analog and photon count signals to retrieve the scaled photon counts, i.e,

Scaled photon count = a * analog signal + b

For each single data set, the data range is first identified where both the analog and photon count signals are varying linearly. Then the scaled and dead time corrected photon counts are appropriately merged with some threshold values (obtained from the linear progression). The glued photon count data are displayed in Figure 6 (bottom left panel).

Figure 6 clearly distinguishes the cloud observation from normal scattering from background particulate matter. It shows the sharp enhancement during the presence of cloud around 4.2 km and slowly has moved down to 3.5 km. This figure demonstrates the capability of LIDAR to observe the cloud thickness (less than around 300 m). The measured high resolution data is also important when studying cloud morphology. Otherwise, the lower height regions indicate high intensity signal returns which is due to the presence of dense fog and the boundary layer evolutions. The planetary boundary layer evolution can be detected using the range corrected signal (Signal multiplied by the square of range) and found that the boundary layer is located around 2 km.

It is important to note here that the experiment has been carried out using two neutral density (ND) filters which attenuates 99% of the signal entering the PMT. This means that the backscattered signal represented in the colour-map and in the height profiles corresponds to only 1% of the signal. The ND filters are employed to avoid signal saturation due to the presence of dense cloud at lower height region which significantly interrupts the laser from passing through. In future, we shall experiment with different filter options to allow a greater percentage of the backscattered signal to observe and investigate for higher altitude regions.

5. Concluding remarks and future perspectives

The initial results show that the system is capable of providing aerosol/cloud backscatter measurements for the height region from ground to 40 km with a 10 m vertical height resolution. The measurements will elucidate the aerosol concentration, optical depth, cloud position, thickness and other general properties of the cloud which are important for a better understanding of the earth-radiation budget, global climate change and turbulence.

The LIDAR measurements will be calibrated with other in-situ (e-g., Sun Photometer, Radio-meter, Balloon borne), space-borne (Stratospheric Aerosol and Gas Experiment - SAGE, Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation - CALIPSO, Moderate Resolution Imaging Spectro-radiometer - MODIS) and different network data sets (AErosol RObotic NETwork - AERONET, Network for the Detection of Atmospheric Composition Change - NDACC).

Future plans include qualitative industrial pollutant measurements, 3-D measurements using an XY scanner, a two-channel LIDAR system, water-vapour measurements, the implementation of DIfferential Absorption LIDAR (DIAL) and ozone measurements.

Acknowledgements

The author is grateful to the different South Africa funding agencies, the Council for Scientific and Industrial Research-National Laser Centre (CSIR-NLC), Department of Science and Technology (DST), National Research Foundation (NRF) (Grant no: 65086) and African Laser Centre (ALC). The authors also acknowledge the Centre National de la Recherché Scientifique (CNRS) (France) for funding (under negotiation) in terms of the South Africa/France researcher/student exchange programme. The authors also wish to thank the South African Weather Service for providing the cloud picture.

References

Chanin, M.L, and A. Hauchecorne, LIDAR observation of Gravity and Tidal waves in the stratosphere and mesosphere, J. Geophys. Res., 86, 9715-9721, 1981.

Fiocco, G and L.D. Smullin, Detection of Scattering Layers in the Upper Atmosphere (60Â–140 km) by Optical Radar, Nature, 199, 1275 – 1276, 1963.

Fiocco, G., and G. Grams, Observations of the aerosol layer at 20 km by optical radar, J. Atmos. Sci., 21, 323-324, 1964.

Fiocco, G., Lidar studies of aerosol studies: An outline, MAP Handbook, Ed. R.A.Vincent, 13, 56-59, 1984.

Killinger, D.K., and N. Menyuk, Laser remote sensing of the atmosphere, Science, 235, 37-45, 1987.

Ligda, M.G.H., Proceedings of the First conference on Laser Technology, U.S. Navy, ONR, 63-72, 1963.

Sassen, K., A Lidar Cloud Research, The review of Laser Engineering, 23,2, 148-153, 1995.

Sivakumar, V., A.Sharma, D. Moema, C. Bollig C. van der Westhuizen and H. van Wyk, CSIR-NLC South Africa Mobile LIDAR system description, Proceedings of 24th international laser radar conference, 99-102, 2008.

Sivakumar, V., Lidar research in South Africa, The international society for optical Engineering (SPIE), invited news room article, Doi: 10.1117/2.1200808.1250, 2008.

Table 1: Specifications of the LIDAR system.

Transmitter	
Laser Source	: Nd: YAG, Continuum
Operating Wavelength	: 532 nm
Average energy per pulse	: 167 mJ
Beam Expander	: 3 x
Pulse width	: 7 ns (Typical)
Pulse repetition rate	: 10 Hz
Beam Divergence	: 0.2 mRad
Receiver	
Telescope type	: Newtonian
Diameter	: 404 mm
Field of View	: 1 mRad
Filter band width	: 0.7 nm
Signal and Data Processing	
PC based photon counting system operating under Ethernet controlled LICEL real-time software.	
Bin width (Range Resolution)	: 10 m
Maximum Range	: 4096 bins (40.96 km)

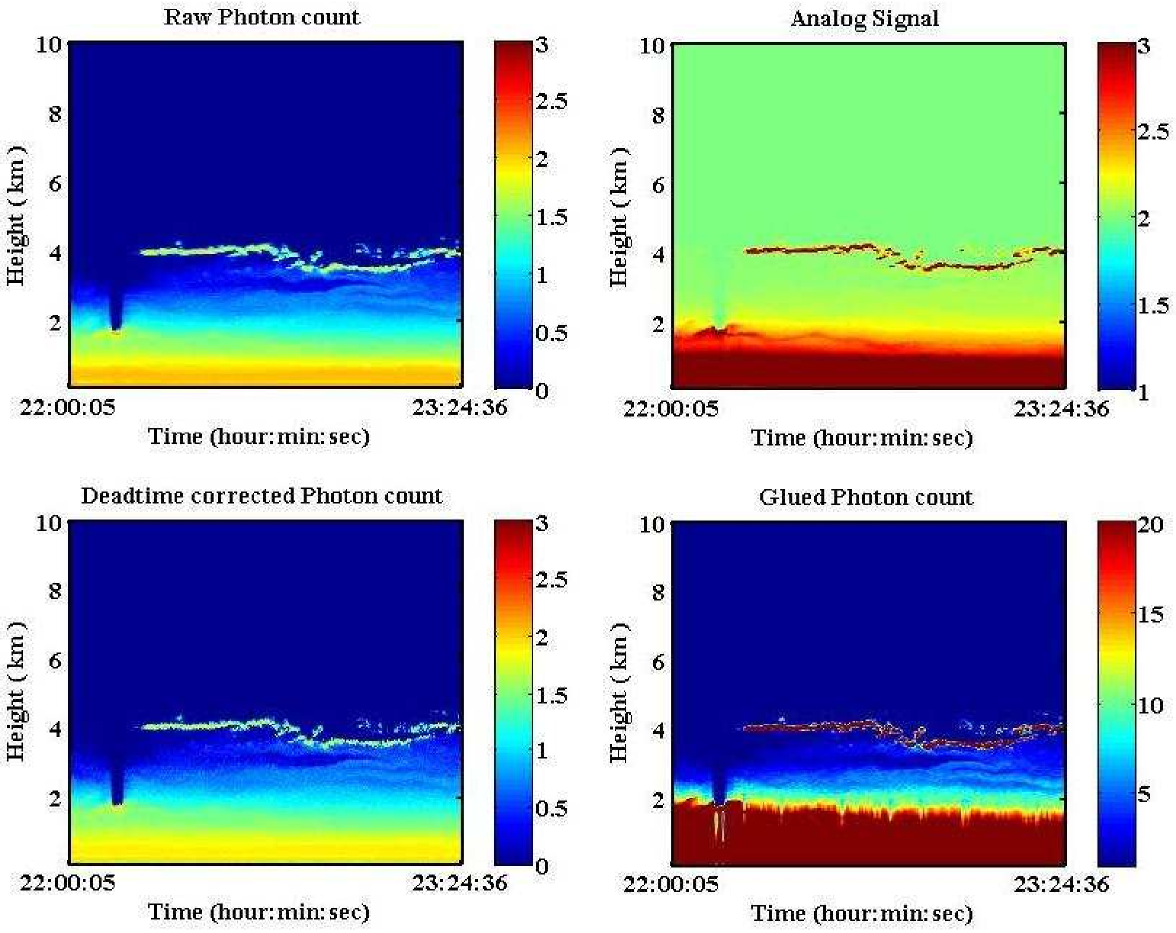

Figure 6: Height-time-colour map of LIDAR signal returns for 23 February 2008.