Implementation of a Lidar System and its Usage in Characterization of Aerosols in the Atmospheric Column

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Abstract: - Light Detection and Ranging (LIDAR) is a recent remote sensing system which has been gradually expanding as a network among the countries actively concerned about the atmospheric contaminants, earth radiation budget, rain variations, clean air index, etc. In this work, the design of a typical Lidar, ground based system for three wavelengths is explained. Essential parameters for the atmospheric characterizations such as Aerosol Optical Depth (AOD), Angstrom coefficient (Å), and Aerosol Size Distribution (ASD) are explored and the obtained results are discussed. These parameters have been calculated and plotted based on three Lidar system wavelengths of 355, 532, and 1064 nm using the data obtained from Lidar in the Western part of Puerto Rico (location of UPRM Lidar system). The relationship between the essential parameters presented by the plots and the atmospheric behavior is explained using the collected data during two different days.

Key-Words: - Lidar system, AERONET station, Planetary Boundary Layer, Aerosol Optical Depth, Aerosol Size Distribution, Air Quality Index

1 Introduction

It has been recognized that aerosol is the key factor in climate change, and that multidisciplinary work must take place to address the large uncertainty that still exist in applying the effect of aerosol into the climate model. The multidisciplinary work must integrate observations from ground truth, Lidar, satellite sensors, and aircrafts. See NASA Jan. 16, 2009 report [1]. The Intergovernmental Panel on climate Change (IPCC) on their 2007 climate assessment report diagram show that there is a reciprocal effect between aerosol (and greenhouse gases) and the climate change.

The climate change consists of temperature and precipitation changes, sea level rise and extreme events. On the other hand socio-economic development and climate process drivers mutually affect one another [2]. Aerosols have different shapes and sizes. Typically they range from nanometers to a few tens of micrometer sizes. But aerosols that have direct interaction with the sunlight producing changes in cloud properties and precipitation which consequently cause climate change are of 0.05 to 10 micrometers in diameter [1]. Larger aerosols than 10 μ m represent the presence of dust and volcanic ash. In marine zones giant aerosols play an important role in cloud formation [3].

National Academy's National Research Council (2008) expressed the need to observe and analyze the

lowest 2 kilometers of atmosphere, and that near 400 Lidar sites would be required for such a global observation.Work is in progress toward bringing about a network of Lidars which permit Planetary Boundary Layer (PBL) observations.

At the present time, the UPRM Lidar is part of a small network of Liars known as CREST Lidar Network (CLN). The UPRM Lidar system became operational in Dec. 2008, and the atmospheric profile data acquired from the western Puerto Rico (PR) region has been used to determine fundamental parameters which are needed in the prediction of climate change, such as Aerosol Optical Depth (AOD), Angstrom coefficient (Å), and Aerosol Size Distribution (ASD).

2 UPRM Lidar System

The UPRM Lidar laboratory is located at $18^{0}12'4N$, $67^{0}08'24W$ with an elevation of 10m in West part of the island of Puerto Rico (Fig. 1). It is a stationary Lidar which transmits three basic wavelengths of 355, 532, and 1064 nm at 120, 300, and 700 mJoules, respectively.

The laser beam is transmitted to the atmosphere coaxial to the telescope axis, eliminating the overlap problem between the reflected spot and telescope field of view (FOV). There are three guide mirrors installed at 45 degrees on the exterior part of the telescope which

guide the laser beam up to the atmosphere.



Figure 1UPRM Lidar geographical location.

A very weak light beam is received by the telescope and is focused on a focal point of a lens (f=30mm) which transmits a parallel beam of 8mm diameter. The beam is split twice by two bi-directional selectors positioned at 45 degrees to the incident beam (See figure 2).

The results are three 8mm beams of wavelengths approximately: $\lambda 1 < 400$ nm, 400nm $< \lambda 2 < 900$ nm and 900nm $< \lambda 3$. These beams after passing through attenuators are submitted to three interference filters which allow only the passing of 355, 532, and 1064nm wavelengths. Three very sensitive PMT sensors have been acquired to collect the signal at the three mentioned wavelengths[4,5].



Figure 2 UPRM Lidar Systems, where the beam expander is optional.

The three wavelength data is used to determine the extinction and backscatter coefficients. These two coefficients are being used to determine aerosol, cloud levels, AOD, and microphysical parameters such as size distribution.

3 Atmosphere Profile

High resolution images obtained from Lidar make it an appropriate tool for the study of aerosols causing climate change, air pollution, air quality problems, clouds formation, boundary layer (PBL) effects, etc.

The received backscatter signal of UPRM Lidar system on March 24^{TH} , 2009 illustrates a vertical atmospheric profile over the UPRM consisting of small layers of clouds in altitudes close to 1.5km, 9km and 13km (Fig. 3). This figure shows the logarithmic range corrected power profiles images at the elastic channels (355, 532, and 1064nm). The 355nm channel shows more intensity than the other two channels, since it is more sensitive in the detection of small particles suspended in the air. Meanwhile, the 532nm channel detects mid-size particles which can be a mixing of small and larger particles. This channel detected an aerosol layer close to 2.1km (Fig.3 middle). The 1064nm detects larger particles such as clouds, water, dust, etc. The small artifacts in the upper altitudes in these images are noise caused by signal attenuation due to absorption by larger particles present in the clouds, as well as possibly a need for further sensor alignment, and sensors signal to noise limitations.





Figure 3 UPRM logarithmic range corrected power images at the three fundamental wavelengths of 355, 532, and 1064nm (3 successive images, respectively) on March 24^{TH} , 2009 in the time interval of 1:30PM to 3:30PM.

3.1 Clouds and Aerosols Discrimination

Broken red lines, in Fig 3, at the 1064nm image, and at an altitude of 1.5km, show clouds on top of the PBL aerosols. The presence of aerosols is visible in the 355 and 532nm channels at lower altitudes, as well as a layer of cloud which is present at 1.5km.

Fig. 4 shows the range corrected raw signal collected at 2:41PM and plotted for up to the altitude of 4km. The blue, green, and red signals are 355, 532, and 1064nms, respectively. At 2:41PM, the PBL appears to be of 250m deep, extending from 1.25Km to 1.5km of altitude, the top of which is marked by a vertical line (Fig. 4).



Figure 4 UPRM Lidar range corrected signals at the three operational wavelengths at 2:41PM.

Using the range corrected signal presented in fig.4 and the methodology discussed and presented in [4,6], the aerosol extinction and backscatter coefficients are determined at the three fundamental wavelengths as shown in figures 5 & 6. The aerosol extinction and backscatter coefficients are fundamental parameters in the determination of other important parameters in the characterization of aerosols.



Figure 5 Aerosol extinction coefficients at the three wavelengths.



Figure 6 Aerosol backscatter coefficients at the three wavelengths.

In fig. 7, using Å coefficient, Eq.1, depicts the plot Å-vs-range, using the combination of backscatter coefficients of two wavelengths of 355/1064 (green), and 532/1064 (red).

Angstrom
$$= \frac{\ln\left(\frac{\beta_{aer \lambda_2}}{\beta_{aer \lambda_1}}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)} \quad (1)$$



Figure 7 Angstrom Coefficient based on the wavelength combinations of 355/1064nm (green), and 532/1064nm (red).

The Angstrom parameter (Å) is important for the determination of different particles present in the atmosphere. Larger particles have an Angstrom exponent close to zero or less (eg. water vapor particles), meanwhile smaller particles (aerosols) increase the exponent value. The results of Angstrom plot, Fig. 7, shows the presence of clouds at about 9 and 13 Kms. Water vapor molecules in the cloud being of larger size aerosols reflect 1064nm wavelength more which increases the Angstrom coefficient negatively.

In Fig. 7, the Å exponent values in the interval of 2 to 4 represent small size particles with relatively high concentration. Å above 4 in this figure is due to small particles of low concentration.

3.2 Aerosol Optical Depth Determination

Another important aerosol parameter calculated is the AOD. The AOD measures the atmospheric transparency at the vertical path form the Earth's surface, and is affected by the climate change. Determination of AOD requires a sunny day as clouds affect the results. The AOD plots are determined using AOD matching method.

3.2.1 AOD matching method

The AERONET reports the AOD corresponding to the total Atmospheric column at 340, 380, 440, 500, 675, 870, and 1020nm. The AOD measured by AERONET was recalculated at the UPRM-Lidar wavelengths of 355, 532, and 1064nm, using a wavelength dependency law, Eq.2. The AERONET and UPRM-Lidar data were taken at the same time.

$$\frac{AOD(\lambda_1)}{AOD(\lambda_2)} = \left(\frac{\lambda_1}{\lambda_2}\right)^{-A}$$
(2)

The matching method is used to estimate the Lidar Ratio (L_{aer}) from AERONET, see diagram of Fig. 8. In this Diagram, Atmospheric Standard Assumption ASA76 is used for the molecular extinction and backscatter coefficient calculations. β_{ref} is an assumed value from 1.0 to 1.2, at an assumed R_0 range, both of which are varied until acceptable Backscatter coefficient, β , distribution is obtained.



Fig. 8 Algorithm to determine L_{aer}

The AOD matching algorithm determined the Lidar Ratio values, Table 1, with an error of less than 4.5%.

	Wavelength	355nm	32nm	1064nm
ſ	L _{aer} est.	30	45	14

Table 1 Aerosol Lidar Ratio estimation.

Fig. 9 shows the resulting Lidar AOD plots for each wavelength at different altitudes for up to 8.2km, to avoid clouds starting at 8.5 Km.



Figure 9 AOD at the three wavelengths (355(blue), 532(green), and 1064(red)).

3.3 ASD and Climate Process

Climate process is dependent upon the aerosols size distribution. Changes in cloud properties and precipitation which consequently cause climate change are caused by aerosols of 0.01 to 10 micrometers in diameter. Aerosol between 0.1 μ m and 2.5 μ m are known as *accumulation mode* and are the largest amount of aerosols present in the Atmosphere. Aerosols smaller than 0.1 μ m are known as *Aitken nuclei mode*, and serve as cloud condensation *nuclei (CCN)*for forming larger aerosols and finally form part of the *accumulation mode*. These aerosols have varied life times in the atmosphere. The aerosol sources can be divided into anthropogenic (from industrial emissions or human made), and natural [6].

The method of regularization [7] was used to calculate the ASD for number concentration (Fig. 10), surface area (Fig. 11), and volume distribution (Fig.12). The study of these plots reveals the presence of aerosols of sizes from 1.2 to 1.6 μ m (accumulation mode). The number concentration is used to estimate the number of particles or aerosols per cm³, the surface-area is used to estimate the total area of each particle, and the volume distribution is used to estimate the total volume of each particle. These terms are known as aerosol microphysical parameters.



Figure 10 ASD in terms of number concentration as a function of radius for the column of 8.2km.



Figure 11 ASD in terms of surface area as a function of radius for the column of 8.2km.



Figure 12 ASD in terms volume concentration as a function of radius for the column of 8.2km.

3.4 Burning Biomass Smoke and Local Air Quality

Heavy smoke activity was detected on April 16th, 2009 from approximately 50m up to 1.6km above UPRM Lidar site. To identify the smoke the logarithmic range adjusted power intensity images at the three fundamental wavelengths were used. The smoke was detected from 10:40Am to 12:25Pm (Fig. 13), where the smoke is occasioned by the burning biomass in land parcels close to the campus. This type of fire is normal during the months of April to August due to the dry season in the western region of Puerto Rico.

Analyzing the three logarithmic range adjusted power images at the three channels, figure 13, shows the presence of clouds on the top of PBL. In altitudes between ground and the PBL one can discern smoke over the campus, where the 355nm cannot detect as well as the other two channels. The 355nm channels cannot detect the smoke very well due to the presence of large particles with large absorption coefficients. Comparing the three channels, one can conclude that the 1064nm channel can detect best the smoke as it is very sensitive to the detection of large particles.





Figure 13 UPRM logarithmic range corrected power images at the three fundamental wavelengths of 355, 532, and 1064nm (3 successive images, respectively) on April 16, 2009 in the time interval of 10:30PM to 2:00PM.

To identify the smoke particles it is required to have the aerosol backscatter coefficient for two channels. In this case the combination of 532nm & 1064nm, and 355 &1064nm channels are used. Some particular events can easily be distinguished from the weather conditions and the visual observations during the data collection time, but the angstrom coefficients is the best way to obtain an idea of these events. Smoke and dust plumes are made of very large absorbing particles, having smaller angstrom coefficients, less than unity or smaller than zero in some occasions [8].

The two parameters needed for smoke determination, the aerosol backscatter and extinction coefficients have been determined using the same procedure described above. Both coefficients have high backscatter and extinction values at altitudes less than 1.5km, which represents a preliminary show of the presence of smoke. Fig. 14 & 15 show the extinction and backscatter coefficients, where the smoke is detected in the PBL region. The light has been attenuated very fast in the PBL region for the 532 and 1064nm channels. This observation is not very common for these channels, since normally the PBL region is covered with smaller particles due to the high concentration of oxygen, nitrogen, carbons particles from emissions process, and others, which caused fast attenuation at the 355nm At altitudes from 2km to 5km, some channel. oscillations are observed due to the interaction or mixing of high absorption (smoke) particles with other particles.



Figure 14 Aerosol extinction coefficients at the three wavelengths.



Figure 15 Aerosol extinction coefficients at the three wavelengths.

The aerosol extinction coefficient is used to determine the AOD coefficient, which represents a measure of the atmospheric column transparency. Normally, the AOD values at each wavelength decreases if the wavelengths increase, see Fig. 9. The reason for this change, Fig. 16, has been proved in previous publications [4, 8-10, 12]. Fig. 16 shows the AOD values during the smoke detection, where the AOD decreases in inverse proportional with the wavelength. These curves confirm that the detected matter is really smoke because the 1064nm channel has a high AOD value in comparison with the other two channels. From an altitude of ground to 1.5km, the AOD increases very fast due to the smoke concentration at these altitudes. Table 2 presents the column AOD values at the three operational channels with their respective aerosol lidar ratios (Laer). These values are used based on theoretical values presented in [9] and in other works.



Figure 16 AOD at the three wavelengths (355(blue), 532(green), and 1064(red)).

Wavelength (nm)	AOD	L _{aer}
355	0.0101	65
532	0.0355	70
1064	0.0452	18

Table 2 Total column AOD values with the used Laer.

Using the aerosol backscatter data, the angstrom coefficient has been determined, see Fig. 17. The angstrom exponent is a very helpful tool to obtain an idea about the particles sizes. Based on the angstrom results, larger particles are observed in altitudes less than 1.5km which represent smoke particles. Then these particles start to come up and mix with other atmospheric constituents to form other particles with high angstrom coefficients. At altitude of 2km the angstrom coefficient increases up to 6 and then decreases down to 5 due to the cloud formation at an altitude of about 2.5km (red plot).

The cloud formation in the PBL and on top of the UPRM region is very common due to the orographic movements occasioned by the mountains close to the coastal region where the sea-salt particles play an important role in the cloud formation process. The smoke particles are composed of high carbon solution, which affect the clouds properties, creating dry droplet clouds.

Aerosols particles give rise to form secondary particles through gas particle conversion; for example, particles that consist of sulfate are created from sulfur dioxide oxidation in cloud droplets. Other particles are simply formed via condensation of hot gases emitted during combustion, or generated from oxidation of low vapor pressure organics released from vegetation or burning biomass [11].

High angstrom exponent values permit distinction between the small and large size particles. Particle matters are divided into two groups, known and PM2.5 and PM10. PM2.5 are particles with a radius less than 2.5 μ m, which affect the human health, causing respiratory problems. PM10 are particles with a radius between 2.5 and 10 μ m, which also have a negative impact in the human health, but this type of concentration, is removed easily from the lungs by mucus.



Figure 17 Angstrom Coefficient based on the wavelength combinations of 355/1064nm (green), and 532/1064nm (red).

The air quality index can be estimated using the AOD values for 532 and 1064nm. The 532nm is used to estimate the PM2.5 concentration, meanwhile the 1064nm is used to estimate the PM10 concentration. The PM2.5 value is used to estimate the air quality index as it is the most common and dangerous concentration of particles present in the atmosphere. In the data used for this research, the PM10 concentration was larger than PM2.5, due to the high concentration of larger particles. Usually, the larger particles concentrations are in higher altitudes, such as dust, industrial emissions, volcanic ash, and other events of this magnitude.

Table 3 shows the Particle matter concentrations and the air quality index (AQI) which is estimated using the EPA's calculator [13, 14]. Based on the EPA's air quality index presented in Appendix A, the air quality was in the moderate level. The numerical value of moderate level is between 51 and 100, meaning that the air quality is acceptable, but can be of concern to the health of people who are sensitive to air pollution if are exposed during a given time interval.

Particle Matter Concentration					
PM2.5	PM10	AQI			
2.47	4.96	10-15			

Table 3 PM concentration and AQI.

4 Conclusion & Future Work

The Lidar has stability and potential for long-term monitoring different Tropospheric properties. Outstanding in this region is the PBL which needs to be monitored globally by a network of Lidars. The aerosol parameters derived from Lidar data, such as AOD and ASD over an extended time period and obtained globally are essential input data for the prediction of climate change by climate models, air quality [8], etc...

Based on the obtained results, we can conclude that there are certain particles in the atmosphere which play an important role in the atmospheric process, some particles have positive, while others have negative, effects on the climate. For instance, the presence of smoke and combustion in many atmospheric regions are responsible of the global warming problem. These emissions cause increase in the local temperature, and affecting the air quality causing unnecessary health problem, and as can be seen today with increasing number of people suffering from respiratory problems.

The regional air quality monitoring for the western part of the island of Puerto Rico will be continued using the combination of AERONET, UPRM-Lidar, and a regional EPA station near UPRM. The station data will be helpful in the calibration of UPRM Lidar system.

At UPRM, work is in progress to extend the Lidar system to obtain Raman channel capability at 407nm for water vapor and 387nm for nitrogen determination. The system enhancement will permit the study of water vapor mixing ratio for PR region, and climate change as a function of particle sizes. Also, we are evaluating the installation of depolarization channel for 532nm for the study of the particles shapes.

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Aappendix A

The air quality is calculated by AQI (air quality index) an index for reporting daily air quality. It reports how clean is the air, and if your health is at risk. The health effects are associated with the inhalation of polluted air over a few hours or days. EPA calculates the AQI for the following air pollutants: ground-level ozone, particle pollution or particle matter (PM2.5), carbon monoxide, sulfur dioxide, and nitrogen dioxide [13,14]. For each of these pollutants, EPA has established national air quality standards to protect public health. Ozone and airborne particles in the PBL are the two principal pollutants that cause greatest threat to the human health in USA [14].

Fig. 18 shows the air index based on EPA's classifications, meanwhile Fig. 19 present the EPA's air quality calculator using the PM2.5 concentration.

Air Quality Index Levels of Health Concern	Numerical Value	Meaning	
Good	0-50	Air quality is considered satisfactory, and air pollution poses little or no risk.	
Moderate	51-100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.	
Unhealthy for Sensitive Groups	101-150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.	
Unhealthy	151-200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.	
Very Unhealthy	201-300	Health alert: everyone may experience more serious health effects.	
Hazardous > 300 Health warnings of emergency conditions population is more likely to be affected.		Health warnings of emergency conditions. The entire population is more likely to be affected.	

Figure 18 Air Quality levels in relation with human health {source: [14]}.

AQI Calculator: Concentration to AQI



Select a criteria pollutant and enter the pollutant concentration in the specified units above; the Air Quality Index and associated information are calculated below

Select a Po	lutant	
PM2.5 - Particulate <2.5 m	crons (24hr avg) 💌	
Units Required: ug/m3		
Enter the Concentration:	1.26 Calculate Reset	
AQI AQI Cat	egory	
4 Goo	d	
Sensitive Groups	Health Effects Statements	Cautionary Statements
People with respiratory or hear disease, the elderl	None t y	None

Figure 19 Air Quality Index calculator {source: [14]}.

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groups most at risk.

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