Monitoring the environmental impact of aerosol loading and dispersion from distinct industrial sources in Cubatao, Brazil, using a scanning lidar

Renata F. da Costa[a*], Márcia Talita Amorim Marques[b], Daniel Silveira Lopes[c], Maria Lucia Goncalves Guardani[c], Fernanda de Mendonça Macedo[b], Eduardo Landulfo[b], Roberto Guardani[a]
[a]University of São Paulo, Chemical Engineering Department, Avenida Luciano Gualberto 2345, São Paulo, Brazil, 05508-970; [b]IPEN – Energy and Nuclear Power Research Institute, Avenida Lineu Prestes 2242, São Paulo, Brazil, 05508-000; [c]CETESB – São Paulo State Environmental Agency, Av. Frederico Hermann Jr., 345, São Paulo, Brazil 05459-900.

ABSTRACT

This paper reports the results of campaigns carried out with a scanning lidar system in an industrial area for monitoring the spatial distribution of atmospheric aerosol. The aim of the study was to verify the possibility of applying a lidar system to identify fixed sources of aerosol emission, as well as to monitor the dispersion of the emitted plume, and the ability of the system to evaluate pertinent properties of the suspended particles, such as particle number concentration and representative particle size.

The data collection was carried out with a scanning backscatter lidar system in the biaxial mode with a three-wavelength light source, based on a commercial Nd:YAG laser, operating at 355 nm, 532 nm, and 1064 nm. The campaigns were carried out in an industrial site close to the city of Cubatao, Brazil, 23º 53' S and 46º 25' W, one of the largest industrial sites of the Country, comprising a steel plant, two fertilizer complexes, a cement plant and a petrochemical complex.

Backscattered light intensity plots were made from the primary data collected via 360-degree scans at 15 degree elevation. The collected data correspond to distances ranging from 200 m to 1500 m from the measurement location. The results indicate that the technique can provide valuable information on the spatial and temporal distribution of aerosol concentration in the area, which therefore can represent a valuable tool in source apportionment and to validate plume dispersion models.

Keywords: Lidar; Industrial aerosol emission; Aerosol dispersion; Air quality; Pollutant sources; PPI plot

1. INTRODUCTION

The study was carried out in the industrial area of Cubatao, in the Southeast of Brazil, located at the Atlantic coast, sea level, ca. 50 km from São Paulo, and one of the largest industrial sites in the country. In a region with ca. 40 km^2 there are 23 large industries, including a steel plant, an oil refinery, 7 fertilizer plants, a cement plant, and 11 chemical/petrochemical plants, adding up to 260 pollutant emission sources, besides the urban area, with ca 130 thousand inhabitants. A number of initiatives adopted since the 80´s have led to significant reductions in industrial emissions. However, the region still deserves much concern by authorities [1]. The environmental problems caused by the industrial activities are aggravated by the climate and topography of the site, unfavorable to pollutant dispersion. Cubatao is located in a narrow coastal plain surrounded by a steep mountain range to the north, west, and east, and by the sea to the south. At ca. 1 km west and northwest a 600-1000 m high mountain shell retains air circulation. Depending on meteorological conditions the atmospheric emissions by industries and local road traffic can accumulate, resulting in events of peak air pollution levels. During the day, winds blow from the sea to the continent, carrying pollutants to the mountains, where they are channeled into narrow valleys. Thermal inversions often occur during winter months [2]. Due

* Renata.facundes.costa@usp.br; phone 55 13 3362-9367

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to the local topography and proximity of the ocean, wind direction and velocity show daily changes that affect air quality, and frequent events of high pollutants concentration in the industrial area are recorded. A significant number of events of high levels of PM2.5, PM10, O_3, NO_2 and SO_2, are recorded by the local authority (CETESB), which operates 5 air quality monitoring stations in the region.

2. SYSTEM SETUP

The measurement equipment consists of a multiwavelength elastic lidar by Raymetrics, operating in the biaxial mode, consisting of a three-wavelength elastic backscatter system (Figure 1). The light source is a Nd:YAG laser (CFR 450, Quantel S.A.) operating at 355 nm, 532 nm, and 1064 nm, transmitting pulses of 7±2 ns in duration at a fixed repetition rate of 20 Hz. The emitted laser pulses have a divergence of less than 0.3 mrad. The receiver used to collect the backscattered laser light is a 150 mm diameter Dall-Kirkham telescope with an e□ective focal length of 1000 mm. The lidar is currently operated with a fixed field of view (FOV) of 1 mrad, which permits a full overlap between the telescope FOV and the transmitted laser beam at a range of approximately 140 m from the lidar system. A 20 MHz sampling rate of the detection electronics results in a resolution range of 7.5 m. The instrument was found to be sensitive to backscatter at distances of up to 7 km [3]. The backscattered laser radiation is detected by two photomultiplier tubes (PMT) (Hamamatsu) and one Si-avalanche photodiode (EG&G) coupled to narrowband interference filters to assure the reduction of the solar background during daytime operation and to improve the signal-to-noise ratio (SNR). The PMT output signal is recorded by a Transient Recorder (Licel) in both analog and photon counting modes. The laser and telescope are attached to a scanning base adapted from a 2AP sun tracker (Kipp&Zonen) that performs changes in both azimuthal and polar angles with an accuracy of less than 0.02 degrees. This system has two stepper motors controlled by an on-board microcomputer to allow full scanning over a desired angle range [3].

Local surface wind velocity and direction at 10 m height was continuously recorded by a 2D sonic anemometer (Gill Instruments), located in an air quality monitoring station at the same location.

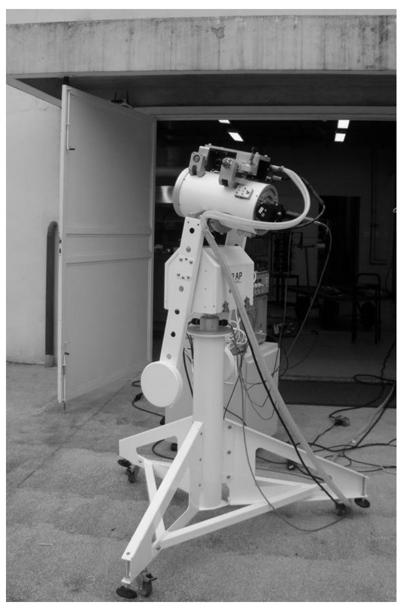

Figure 1. Multiwavelength scanning elastic lidar system used in the study.

3. METHODOLOGY

The campaigns for data collection were carried out in Cubatao during September 2015 with the propose of monitoring the spatial and temporal distribution of aerosols in the region. The site where the lidar system was installed is located in the center of an industrial complex composed of several industrial plants, as shown in Figure 2.

Figure 2. View of the acquisition site. Source: Google earth V 7.1.5.1557. (July 6, 2016). Cubatão, Brazil. 23°50'57.71"S, 46°23'19.80"W, Eye alt 7.81 km. CNES/Astrium 2016. http://www.earth.google.com [September 1, 2016].

3.1 Data Acquisition

A 360-degree mapping in three different elevations (15, 20 and 25 degrees) was carried out. For each elevation, the azimuthal angles were scanned in 5-degree steps with an integration time of one minute.

3.2 Data Analysis

The range corrected lidar backscattered signal at a given distance from the system is expressed as:

$$\text{R.C.S.}(\lambda) = \text{KO}(r)\beta(\lambda)e^{-2\int_{r_0}^{r}\alpha(\zeta,\lambda)\mathrm{d}\zeta} \tag{1}$$

where R.C.S.(λ) is the range corrected lidar signal for dark-current, zero-bin, background and range-squared distance at the wavelength λ [4], K is an instrumental constant accounting for the effective telescope area, pulse length and optical efficiency, O(r) is the overlap function, which reports on the geometrical overlap between the laser beam and the telescope field of view depending on the distance r from the lidar system, $\beta(\lambda)$ is the atmospheric backscatter coefficient for both molecules and particle contributions. $\alpha(\zeta, \lambda)$ is the atmospheric extinction coefficient (molecule plus particle contribution) which depends on the wavelength and the traveling distance ζ. Forming the ratio at the leading and trailing edge of the plume.

In order to analyze the data, plan position indicator (PPI) plots of the R.C.S. were created for each of the three wavelengths, by interpolating the data between azimuth angle steps. In all the plots, the full circumferences represent distances from the lidar. Numbers in the dotted arcs indicate the altitude from the ground at 15 degrees elevation. The start and end time of data collection is indicated in local time (HL). Arrows show the direction and the magnitude of the 10 m wind.

4. RESULTS

Figures 3, 4 and 5 show the R.C.S. for 355, 532, 1064 nm signals respectively, at 15 degrees elevation, in a 120-degree PPI plot superimposed to the region map, which involves the region where fertilizer plants are located, and part of the steel plants. The scattered light intensity plots refer to distances ranging from ca. 200 m to ca. 1800 m. Azimuth angles larger than 120 degrees could not be included in the monitoring due to the presence of hills in the optical path. Due to the more efficient Rayleigh scattering for 355 and 532 nm, the strong signal that appears closer to the lidar monitor, compared to 1064 nm, can be associated with a higher concentration of small particles in this region. These particles might be originated by aerosol resuspension close to the monitoring site. The plots show distributed regions with higher backscattered light intensity, especially for 1064 nm light radiation in the region located ca. 500 m to 1000 m east and southeast from the monitoring site. This pattern can be associated with the transport of aerosols emitted by the steel plants southwards from the monitoring site, since the wind was regularly blowing from southwest to northeast at ca. 2.4 m/s. The region located to the north of the lidar location concentrates the fertilizer plants.

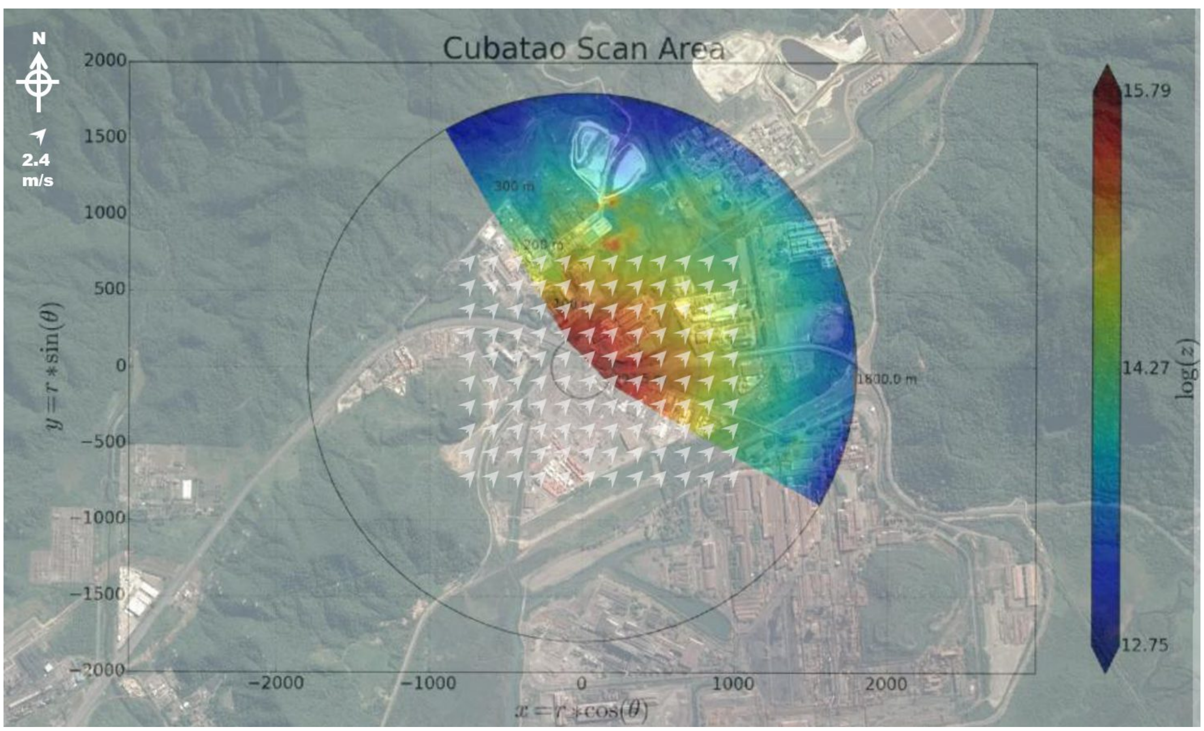

Figure 3. 120-degree PPI plot of 355 nm R.C.S. Source: Google earth V 7.1.5.1557. (July 6, 2016). Cubatão, Brazil. 23°50'57.71"S, 46°23'19.80"W, Eye alt 7.81 km. CNES/Astrium 2016. http://www.earth.google.com [September 1, 2016].

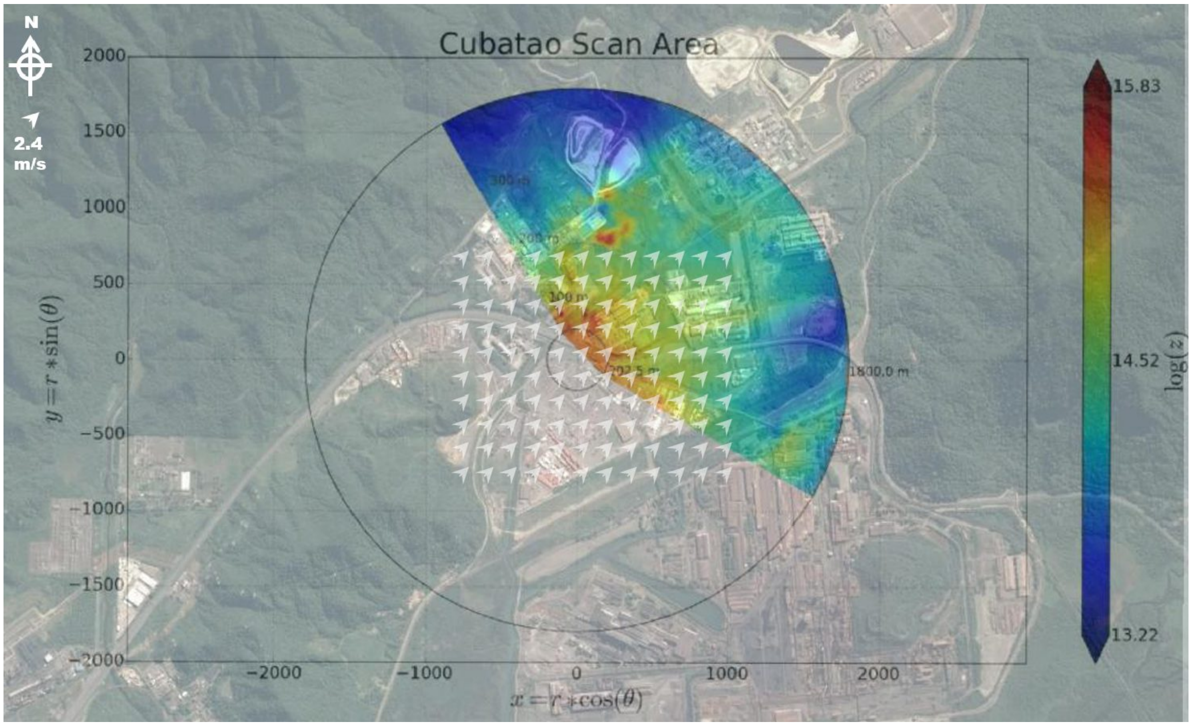

Figure 4. 120-degree PPI plot of 532 nm R.C.S. Source: Google earth V 7.1.5.1557. (July 6, 2016). Cubatão, Brazil. 23°50'57.71"S, 46°23'19.80"W, Eye alt 7.81 km. CNES/Astrium 2016. http://www.earth.google.com [September 1, 2016].

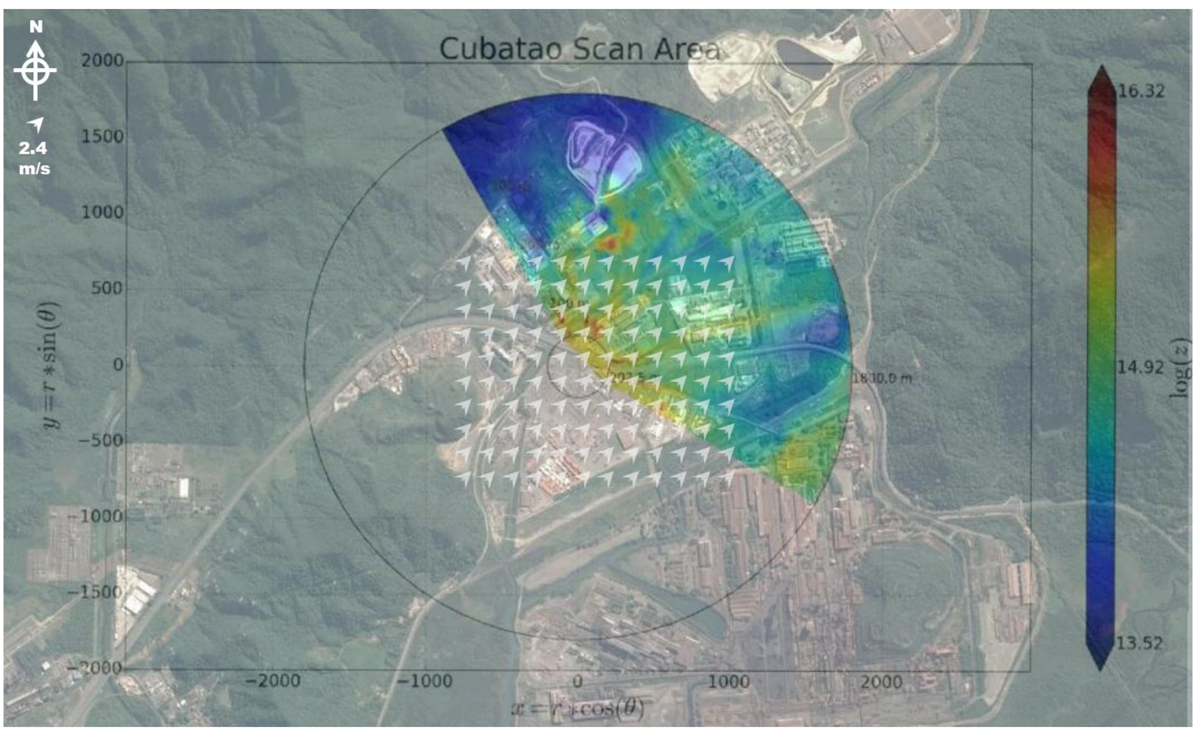

Figure 5. 120-degree PPI plot of 1064 nm R.C.S. Source: Google earth V 7.1.5.1557. (July 6, 2016). Cubatão, Brazil. 23°50'57.71"S, 46°23'19.80"W, Eye alt 7.81 km. CNES/Astrium 2016. http://www.earth.google.com [September 1, 2016].

Figures 6, 7 and 8 show the R.C.S. for 355, 532, and 1064 nm signals respectively, in a 30-degree PPI plot at 15 degrees elevation, focusing the region where fertilizer plants are located. Spots of high intensity of backscattered light are seen for the three wavelengths at distances of ca. 200 m and ca. 300 m from the monitoring location. Theses spots correspond to high aerosol concentrations and can be associated to point sources of atmospheric emissions from the fertilizer plants. However, due to the relatively long acquisition time in these measurements, it is possible that both spots correspond to the same emitted plume transported by the wind, and detected at different times. Nevertheless, the data collected in this specific monitoring campaign correspond to relatively steady conditions of wind velocity and direction, and since industrial emissions by large capacity plants are normally steady, too, the results shown are relatively less affected by fluctuations in these factors.

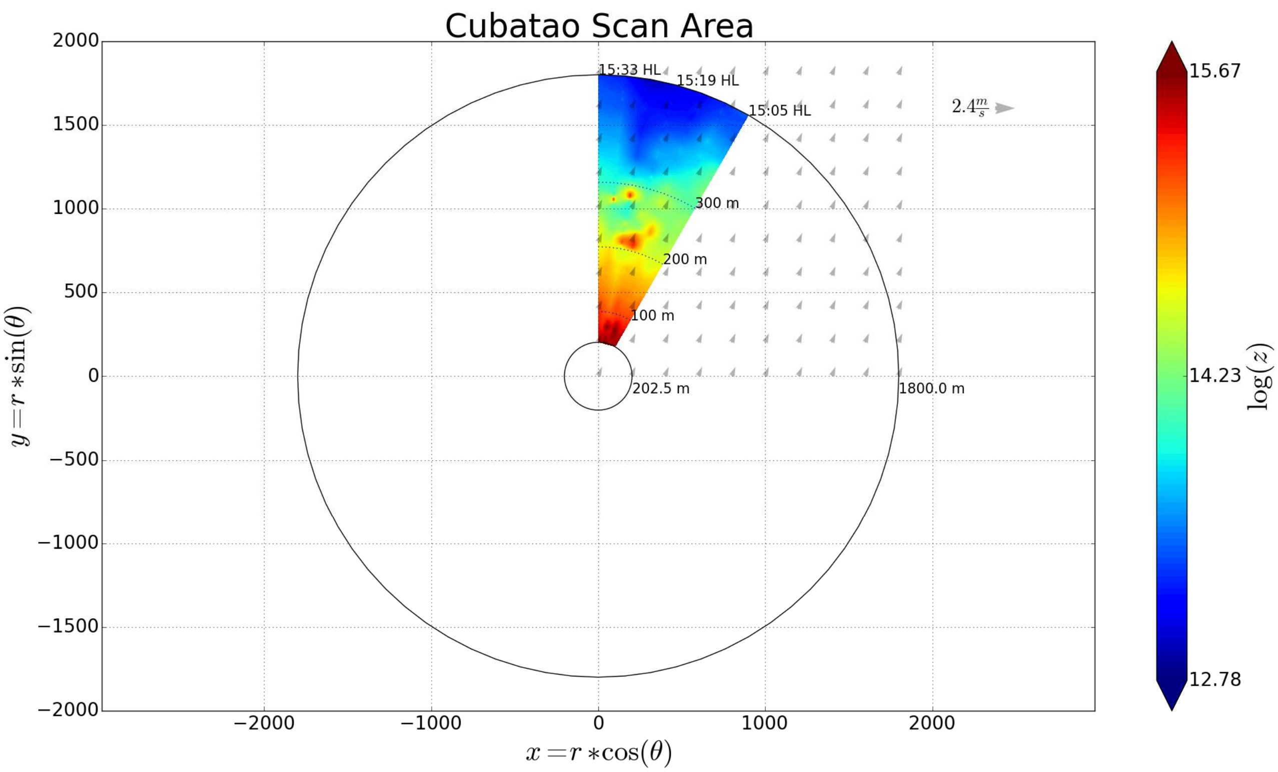

Figure 6. 30-degree PPI plot of 355 nm R.C.S.

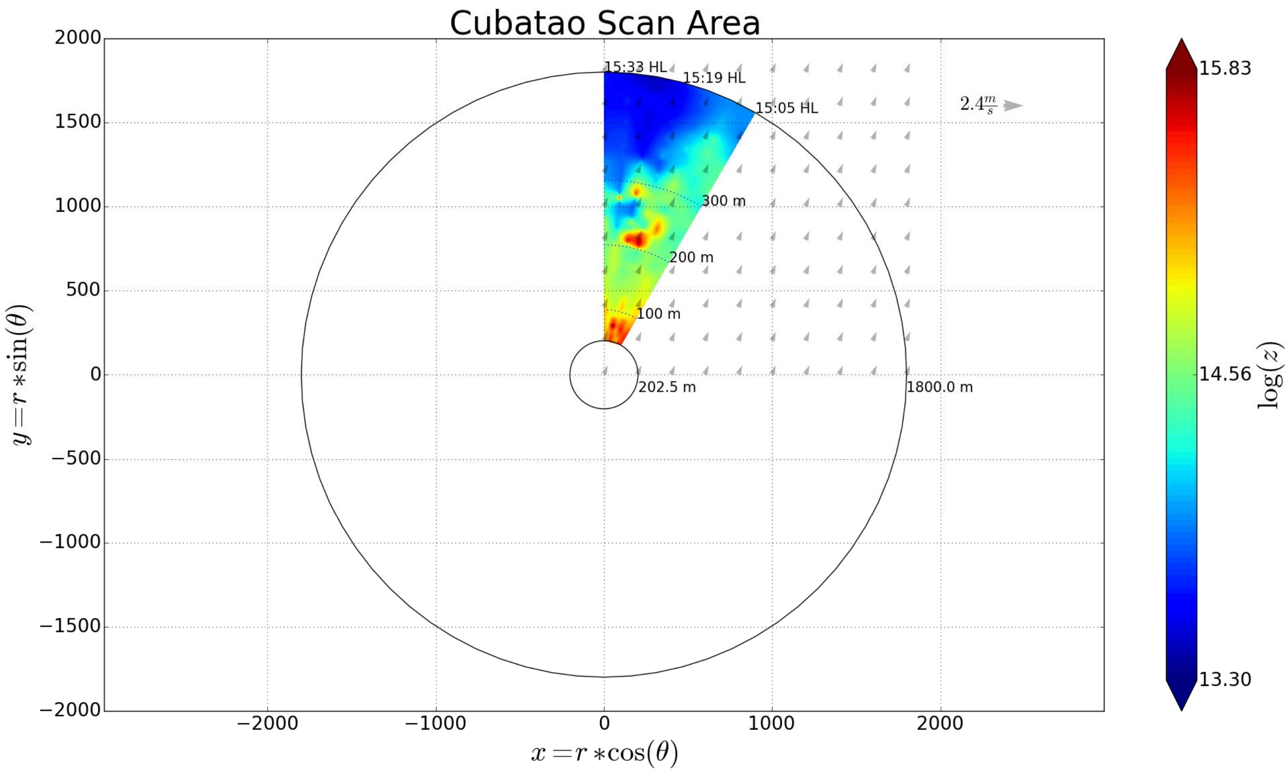

Figure 7. 30-degree PPI plot of 532 nm R.C.S.

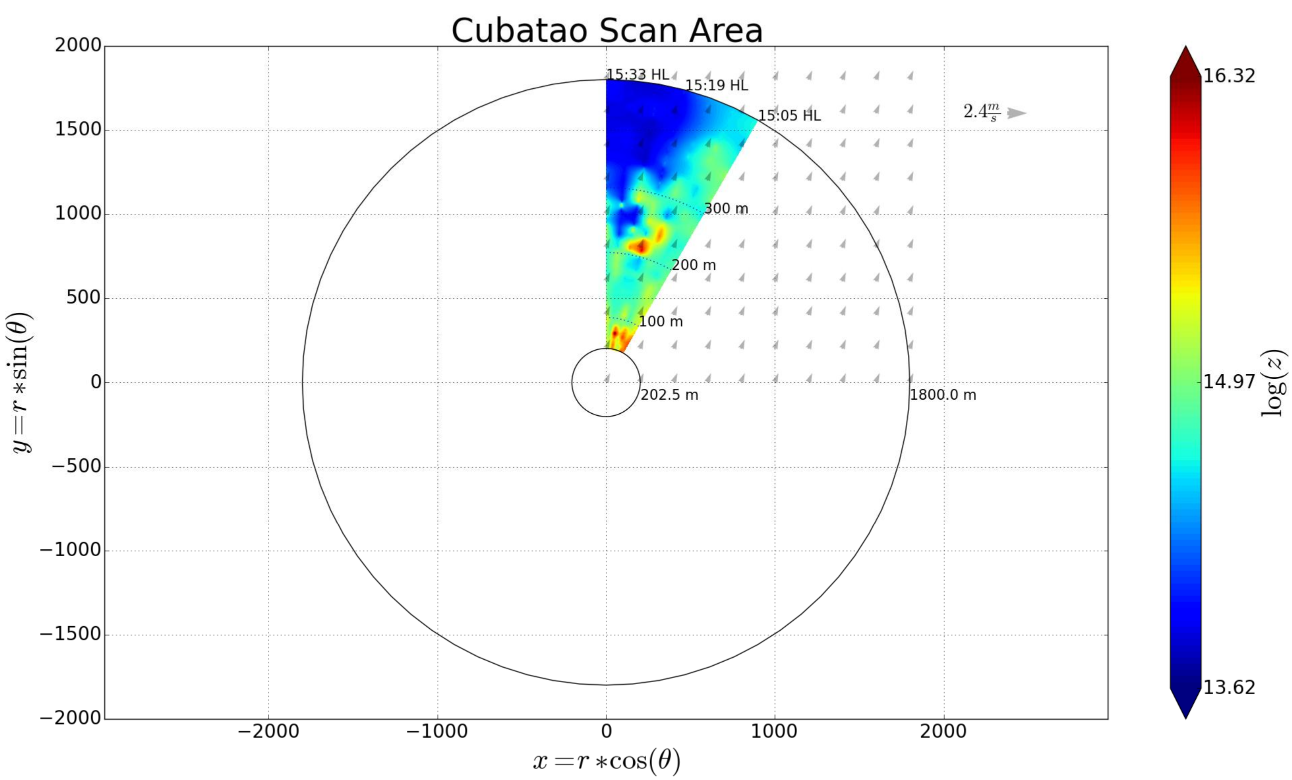

Figure 8. 30-degree PPI plot of 1064 nm R.C.S.

5. CONCLUSIONS

The preliminary results shown in this study indicate that a scanning elastic lidar can provide a large amount of valuable information on aerosol concentration in regions of environmental interest from the point of view of air quality control, since the technique can provide information not only on the aerosol concentration over a region of interest, but also detect specific locations where aerosols are emitted to the atmosphere, as, for instance, industrial stacks.

By adequately calibrating the system, and by using adequate inversion techniques, valuable information on emission rates, as well as representative aerosol particle size and concentration can remotely be obtained in short time. However, as observed in the results, the time necessary to collect the backscattered data with an adequate signal to noise ratio can be too long when there is interest in monitoring the dynamics of plume dispersion. This limitation should be overcome by means of specific studies aimed at minimizing the data collection time. This can be the object of further developments of the technique.

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