Initial analysis from a Lidar observation campaign of sugar cane fires in the Central and Western portion of the São Paulo State - Brazil

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ABSTRACT

The central and western portion of the São Paulo State has large areas of sugar cane plantations, and due to the growing demand for biofuels, the production is increasing every year. During the harvest period some plantation areas are burnt a few hours before the manual cutting, causing significant quantities of biomass burning aerosol to be injected into the atmosphere. During August 2010, a field campaign has been carried out in Ourinhos, situated in the south-western region of São Paulo State. A 2-channel Raman Lidar system and two meteorological S-Band Doppler Radars are used to indentify and quantify the biomass burning plumes. In addiction, CALIPSO Satellite observations were used to compare the aerosol optical properties detected in that region with those retrieved by Raman Lidar system. Although the campaign yielded 30 days of measurements, this paper will be focusing only one case study, when aerosols released from nearby sugar cane fires were detected by the Lidar system during a CALIPSO overpass. The meteorological radar, installed in Bauru, approximately 110 km northeast from the experimental site, had recorded "echoes" (dense smoke comprising aerosols) from several fires occurring close to the Raman Lidar system, which also detected an intense load of aerosol in the atmosphere. HYSPLIT model forward trajectories presented a strong indication that both instruments have measured the same air masss parcels, corroborated with the Lidar Ratio values from the 532 nm elastic and 607 nm Raman N_2 channel analyses and data retrieved from CALIPSO have indicated the predominance of aerosol from biomass burning sources.

Keywords: LIDAR, CALIPSO, aerosols, biomass burning, Radar

1. INTRODUCTION

In the recent years, aerosols from biomass burning have been demanding special attention in studies of the optical properties of particles in the atmosphere.[1] According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change - IPCC,[2] biomass burning aerosols are one of the most important radiative forcing in the atmosphere, contributing to a global radiance of $+0.04 \pm 0.07\, Wm^{-2}$. However, there are still many uncertainties about these values and the real contribution of this aerosol type on the global climate change processes. For that reason, several studies have been conducted in order to better understand the interaction processes between aerosols and radiation, as well as their influence on the processes of cloud formation and climate change. Balis et al.[3] used several instruments such as a two-wavelength lidar system that combines Raman and elastic-backscatter observations, a Brewer spectrophotometer, a nephelometer and a multi-filter rotating shadowband radiometer to investigate the optical properties of biomass burning aerosol in Greece. Jaffe et al.[4] used the Naval Research Laboratory Aerosol Analysis and Prediction System (NAAPS) model to forecast the transport of the smoke of fires from Siberia to western North America, and confirmed their impact by aircraft

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and surface observations. These biomass burning aerosols resulted in enhancements of background CO and O_3 during the summer. Arola et al.[5] monitored the temporal/spatial evolutions and transport of the biomass burning aerosol using the Moderate Resolution Imaging Spectroradiometer (MODIS) retrieved aerosol optical depth (AOD) imagery at visible wavelengths and compared the UV radiation at the surface for this episode to typical aerosol conditions.

According to CPTEC/INPE (www.cptec.inpe.br/queimadas), the South America region, mainly Brazil, which has a large territorial extension, suffers from intense anthropogenic biomass burning activities, such as forest and sugar cane plantation fires, during the so-called dry season. High concentrations of biomass burning aerosol particles, produced mainly in the Amazon basin and the Brazilian mid-western region, can be detected due to these fire activities in the tropical forest, savanna and pasture during the dry season.[6] On the another hand, in the Northeast and Southeast regions of Brazil, the harvesting of sugar cane plays an important economic role in the production of ethanol. Therefore, it is still a common practice to burn the sugar cane fields prior to manual harvesting, resulting in large quantities of aerosols being injected into the atmosphere. So far, few studies using Lidar were made concerning the biomass burning. Landulfo et al.[7] deployed an elastic lidar to detect the presence of highly absorbent particles, characteristic of biomass burning aerosol, in the Metropolitan area of São Paulo and four-day air mass backtrajectories analysis and satellite data showed that these aerosols originated from the Amazon region. The aerosol transport processes over great distances can be monitored using both ground-based and satellite systems.[8]

The city of Ourinhos ($22°56'S, 49°53'W$) is situated in one of the major sugar cane producing regions in the São Paulo State, where the sugar cane is harvested from April until November. These activities result in large quantities of aerosols being emitted into the atmosphere and thus affect local towns and also regions much further away, like the Metropolitan area of São Paulo.[9] Therefore, a one-month campaign was executed during August 2010, to characterize the effects of those emissions on the atmosphere around Ourinhos and the central portion of São Paulo State. In the absence of rain during the dry austral winter season, the aerosol plumes from biomass burning were tracked by IPMet's two S-band Doppler radars, while a mobile Lidar system with Raman channel observed the type of aerosols in elevated layers. This study focuses on one case of biomass burning aerossol detection using data retrieved from the Raman Lidar system and the Cloud-Aerosol Lidar with Orthogonal Polarization Lidar, the two-wavelength Lidar system on board of the Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations - CALIPSO satellite. The biomass burning plumes were monitored by the two S-band Doppler radars, using the TITAN (Thunderstorm, Identification, Tracking, Analysis and Nowcasting)[10] software of NCAR (National Center for Atmospheric Research) to track and quantify them. Forward trajectories from the HYSPLIT model have also been used to verify the origin of the air masses in order to show that both instruments have sampled the same air mass parcels.

2. INSTRUMENTATION

The Lidar deployed in this campaign is a single-wavelength backscatter system pointing vertically to the zenith and operating in the biaxial mode. The light source is based on a commercial Nd:YAG laser (CFR 200) operating at the second harmonic frequency (SHF), at 532 nm, with a fixed repetition rate of 20 Hz. The emitted laser pulses have a divergence of less than 0.5 mrad after expansion ($\approx 4\times$). A 20 cm diameter Cassegranian telescope (F# = 4.5) is used to collect the backscattered laser light. The telescope's field of view (FOV) is variable (1-2 mrad) by using a small diaphragm. The lidar is currently used with a fixed FOV, which permits a full overlap between the telescope FOV and the laser beam at height around 180 m above the lidar system. This FOV value, in accordance with the detection electronics, permits the probing of the atmosphere up to the free troposphere (12-15 km asl). The backscattered laser radiation is then sent to two photomultiplier tubes (PMTs) coupled to a narrowband (1 nm FWHM) interference filter to assure the reduction of the solar background during daytime operation and to improve the signal-to-noise ratio (SNR) at altitudes greater than 3 km. The PMT output signal is recorded by a Transient Recorder Licel GmbH in both analog and photocounting mode. Data are averaged between 2 and 5 min and then summed up over a period of about 30 minutes to 1 hour, with a typical spatial resolution of 7.5 m, which corresponds to a 100 ns temporal resolution. For the Raman channel at 607 nm longer integration times are applied.

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The CALIPSO payload consists of three co-aligned nadir-pointing instruments designed to operate autonomously and continuously. A two-polarization Lidar system referred to as Cloud and Aerosol Lidar with Orthogonal Polarization - CALIOP, a three-wavelength Imaging Infrared Radiometer - IIR, and a Wide Field Camera - WFC.[11,12] The CALIOP laser transmitter subsystem consists of two identical lasers, each with a beam expander to reduce the divergence of the laser beam at the Earth's surface and a beam steering system that ensures the alignment between the transmitter and the receiver. These Nd:YAG lasers are diode-pumped and operate at 1064 nm and 532 nm with a pulse repetition rate of 20.25 Hz. Each laser generates a total of 220 mJ per pulse which is frequency-doubled to produce about 110 mJ of pulse energy at each of the two wavelengths. The lasers are Q-Switched to provide a pulse length of about 20 ns. The receiver subsystems measure the backscattering signal intensity at 1064 nm and the two orthogonal polarization components at 532 nm.[13]

IPMet's radars are located in the central and western State of São Paulo, in Bauru $(22°21'S, 49°01'W)$ and Presidente Prudente $(22°10'S, 51°22'W)$, respectively. Both have a 2° beam width and a range of 450 km for surveillance (0,3 PPI every 30 or 15 min), covering the entire State, but when operated in volume-scan mode every 7.5 minutes it is limited to 240km, with a resolution of 250 m radially and 1° in azimuth, recording reflectivities and radial velocities at 16 elevations. However, in order to register and track the biomass burning plumes, a special scanning cycle was introduced to provide a better vertical resolution up to the anticipated detectable top of the plumes: 10.0°; 8.0°; 6.5°; 5.0°; 4.0°; 3.2°; 2.4°; 1.6°; 0.8°; 0.3°, with each "sweep" (PPI) having 360 rays with 957 range bins each. Two different systems of Software were deployed, viz. IRIS (Interactive Radar Information System) Analysis, to first generate CAPPIs (Constant Alitude PPIs) at 1.5 and 2.0 km amsl, in order to identify all biomass burning plumes within the 240 km range of the radars, followed by zooming on the south-west sector, which incorporates the Ourinhos region, to quantify plumes possibly impacting on the town. Once a plume was identified to pass over the monitoring site, it was tracked by TITAN to determine its intensity (based on radar reflectivity in dBZ), horizontal and vertical dimensions, and the velocity of dispersion. The thresholds used for tracking were $\geq 10\,dBZ$ with a minimum volume of $2\,km^3$. It should be noted that TITAN uses Coordinated Universal Time.

3. METHODOLOGY

In the region of interest, viz., in São Paulo State, atmospheric aerosols originate mostly from biomass burning activities and are considered as an important source of regional-scale pollution, especially during the dry winter season (May to September). The short- and long-range transport of aerosols can affect the air quality in local cities and other regions. Therefore, the campaign in Ourinhos was scheduled for August 2010, a typically dry month characterized by stable atmospheric conditions, with intensive measurements using several instruments for chemical composition analyses, as well as physical and optical properties of the atmospheric aerosols. However, in this study we will focus only on the results from physical and optical aerosol properties retrieved by the Raman Lidar system and also the CALIOP system. This campaign was held between 01 and 31 August 2010, comprising a total of 28 days of intensive measurements with the Raman Lidar system, yielding about 310 hours of vertical profile monitoring. Several measurements were taken continuously during >24 hours in order to observe the evolution of the Planetary Boundary Layer (PBL). In addition, correlative measures between the Raman Lidar and CALIPSO satellite were conducted in order to compare aerosol optical properties retrieved from both remote sensing systems. The Doppler Radars installed in Bauru and Presidente Prudente, as showed in figure 1, performed continuous measurements during the whole campaign, generating complete Volume Scans every 7.5 min, in order to detect biomass burning plumes over the major portion of the State of São Paulo. Thus, those days which had been identified with major biomass burning plumes in the Ourinhos region were selected. For these days correlative measurements between the Raman Lidar system and the CALIOP system on board the CALIPSO satellite using the COVERLAI/MCSA algorithms were determined.[14] The first algorithm identified the CALIPSO overpasses within 100 km of closest separation distance between the satellite ground track and the ground-based Lidar site. The MCSA Algorithm selects only those correlative measurements between both systems.

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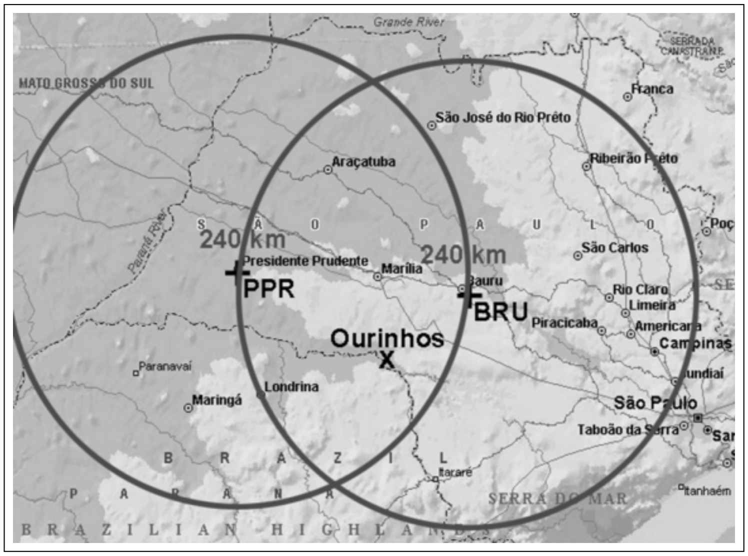

Figure 1. IPMet's radars with their quantitative range of 240 km each, covering a large area of the São Paulo State, and the location of Ourinhos.

The CALIOP operational algorithms produces Level 1 and Level 2 science data products. The Level 1 data products are calibrated, geolocated and include profiles of 532 nm total attenuated backscatter (i.e., parallel plus perpendicular), 532 nm perpendicular attenuated backscatter and 1064 nm attenuated backscatter.[15] The Level 2 data products are separated into three types, viz., the layer, profile and the vertical feature mask products (VFM).[12] The layer Level 2 products are divided in two types, 5 km horizontal resolution for aerosol and 333 m, 1 and 5 km horizontal resolution for clouds. The profile Level 2 produts are composed for 5 km horizontal resolution for both aerosol and cloud. Once the COVERLAI/MCSA algorithms have identified the CALIOP and Raman Lidar system correlative mesurements, 5 km resolution Level 2 cloud layer products were used to identify profiles with cloud-free conditions. The "backscatter centroid", i.e., the aerosol layer centroid, was calculated using the 5 km resolution Level 2 aerosol layer and profile products for those profiles with cloud-free conditions.[14] These "backscatter centroid" values were used as initial altitudes in the air mass parcels trajectories generated by the HYSPLIT Model[16] for several CALIOP 5 km resolution profiles. For those conditions which achieved significant coincidences of air masses trajectories between the CALIPSO ground track and the Raman Lidar site using the HYSPLIT model, the aerosol optical properties retrieved by the CALIOP algorithms,[17–20] such as the AOD and Lidar Ratio values (i.e., the ratio of particle extinction to backscatter) were analysed . In turn, these CALIOP's AOD and Lidar Ratio values were compared with those retrieved by the Raman Lidar system installed at the Ourinhos site.

4. RESULTS

Initially, during the night of 23 to 24 August 2010, several biomass burning plumes have been identified to the west, east and northeast of Ourinhos. Such plumes have been detected by the IPMet radars using IRIS analysis software which generated CAPPI products at 1.5 and 2.0 km asml in intervals of 7.5 minutes. The same plumes have been identified by TITAN and were subsequently tracked, providing the velocity of dispersion, intensity in terms of radar reflectivity in dBZ, as well as their horizontal and vertical dimensions. Figure 2 shows 1.5 km amsl CAPPIs, generated by TITAN, of two particularly intense plumes shortly after the sugar cane fires were lit. The vertical cross-sections indicate the plume (10 dBZ) to reach up to >6 km amsl and with lower intensity even higher. Tracks of biomass burning aerosol plumes, generated by TITAN for the period between 23:00 and 02:00 UTC, as can be seen in Figure 3, indicated dispersion velocities of $25-35\,km\,h^{-1}$ towards south-southeast.

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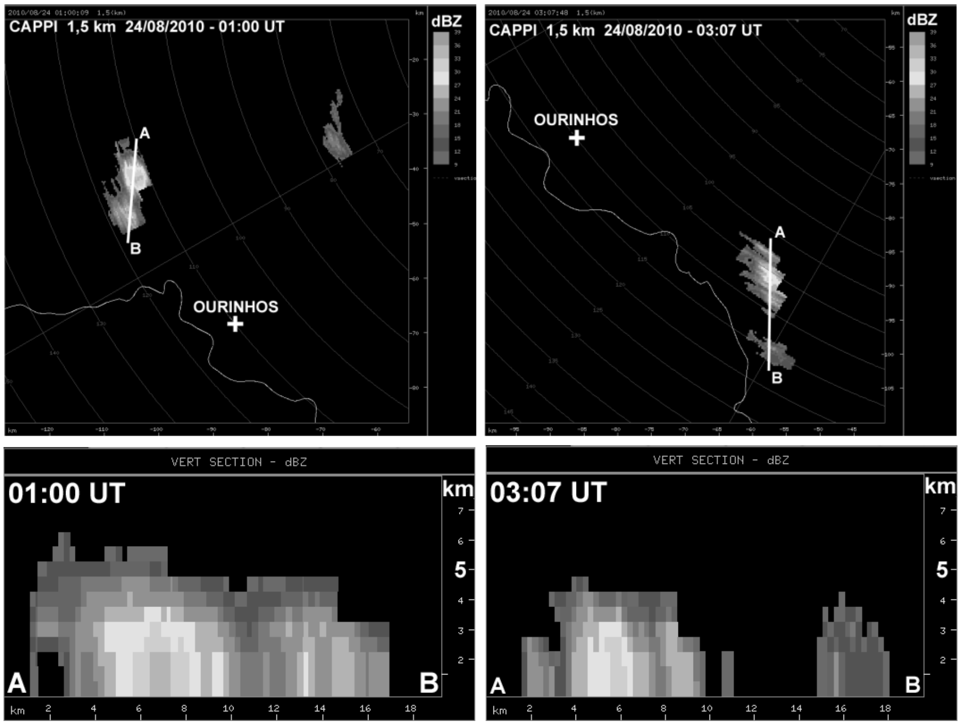

Figure 2. CAPPIs generated by TITAN at 1.5 km amsl on 24 August 2010 at 01:00 and 03:07 UT, respectively, show radar echoes of biomass burning plumes in the Ourinhos region (Top panel). Vertical cross-sections along the base lines A-B indicate plume heights of >6 km (Bottom panel).

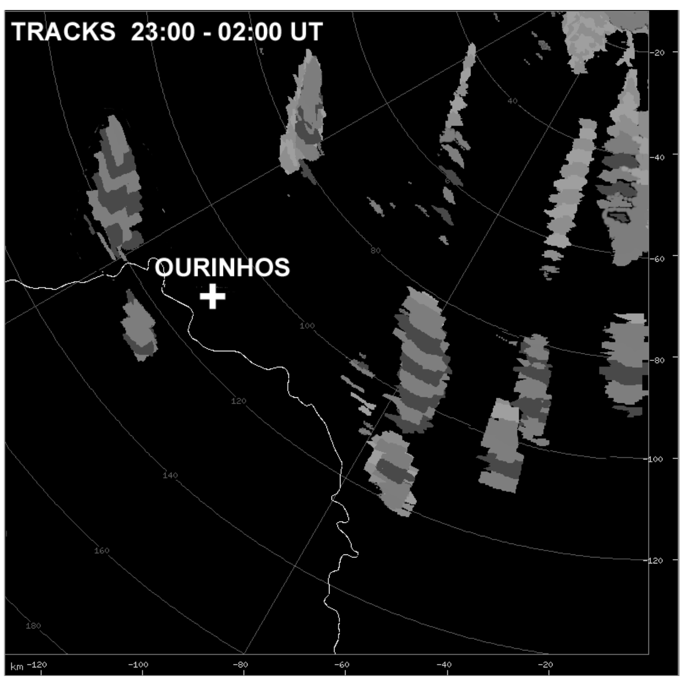

Figure 3. Consolidated TITAN tracks, based on Volume Scans every 7.5 min (thresholds of $\geq 10\,dBZ$ and $2\,km^3$) from 23-24 August 2010, 23:00 to 02:00 UTC.

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Using the COVERLAI algorithm, all CALIPSO satellite trajectories during the campaign period were determined for distances of less than 100 km between the CALIPSO ground-track and Raman Lidar site. A total of 8 day and nighttime overpasses have been identified during the campaign. The MCSA algorithm determined the time and date schedule for all coincident Raman Lidar and CALIPSO measurements, selecting a total of 5 days, distributed in day and nighttime measurements. The combined results from COVERLAI/MCSA algorithms are shown in table 1. We shall focus on the analysis of the coincident measurements for August 24, 2010, when CALIPSO passed over Ourinhos at a distance about 69 km at 04:48 UTC, as shown in figure 4.

Table 1. COVERLAI/MCSA algorithms output for the CALIPSO overpasses in August 2010.

Distance (km)	Day	Month	Year	Time (UTC)	Lat.	Long	Coincidence
68.53	08	August	2010	04:48	-23.160	-49.266	No
73.99	13	August	2010	17:15	-22.814	-49.189	Yes
86.98	15	August	2010	04:54	-22.724	-50.707	No
80.68	20	August	2010	17:21	-23.188	-50.639	Yes
68.81	24	August	2010	04:48	-23.139	-49.253	Yes
76.35	29	August	2010	17:15	-22.724	-49.192	Yes
85.09	31	August	2010	04:54	-22.850	-50.717	Yes

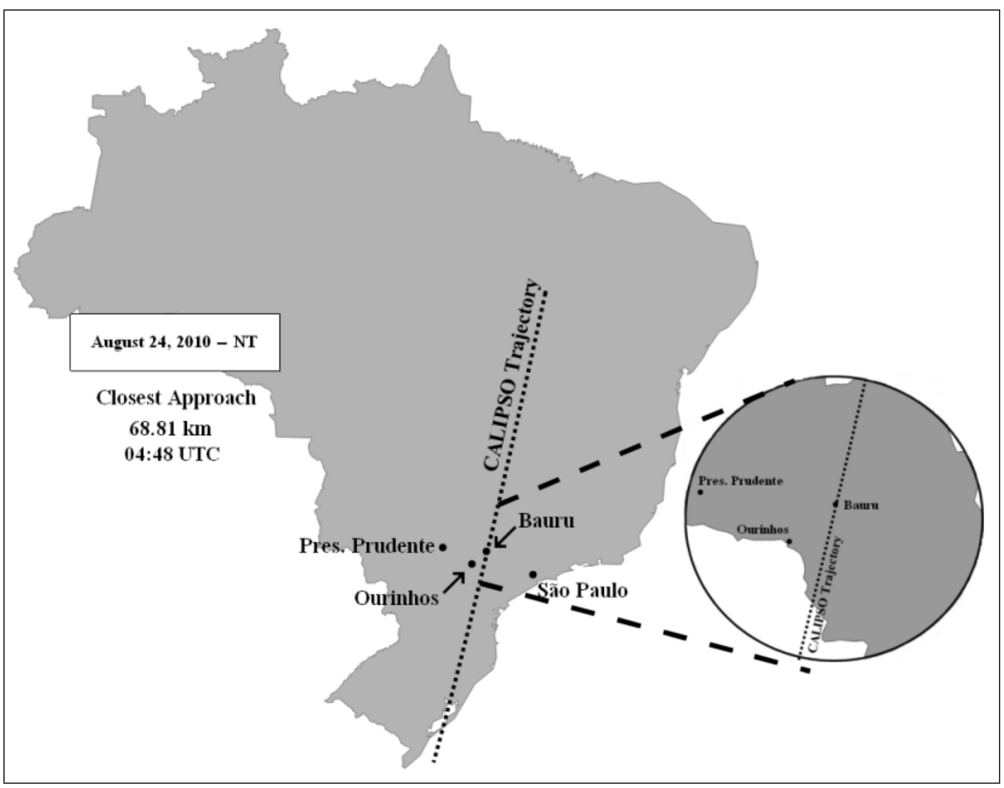

Figure 4. CALIPSO ground tracking over Brazil for August 24, 2010. The CALIPSO satellite passed over Bauru and was very close to Ourinhos, with the closest distance being 68.81 km at 04:48 UTC. The zoomed frame shows the CALIPSO ground-track in the Ourinhos region.

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Due to the distance between the Raman Lidar site and the CALIPSO satellite ground-track, air mass trajectories using the HYSPLIT model were generated in order to verify the possibility of both instruments more or less sampling the same air parcel containing the same type of aerosol. Forward trajectories were generated starting at the Raman Lidar site at around 00:00 UTC, using as starting altitudes the backscatter centroids calculated from the 5 km resolution Level 2 aerosol layer and profile products, i.e. 1500 and 1700 m. The forward trajectories have reached the CALIPSO trajectory area approximately in his overpass time, at around 04:48 UTC, suggesting that both systems have measured the same aerosol load in the atmosphere at their respective times. Figure 5 shows the parcels of air masses moving from the Raman Lidar site towards CALIPSO trajectory. This trajectory is consistent with the TITAN track observations and dispersion velocities, as well as winds observed above Ourinhos by the Sodar and the Meso-Eta model in the layer between 400 and about 4000 m.

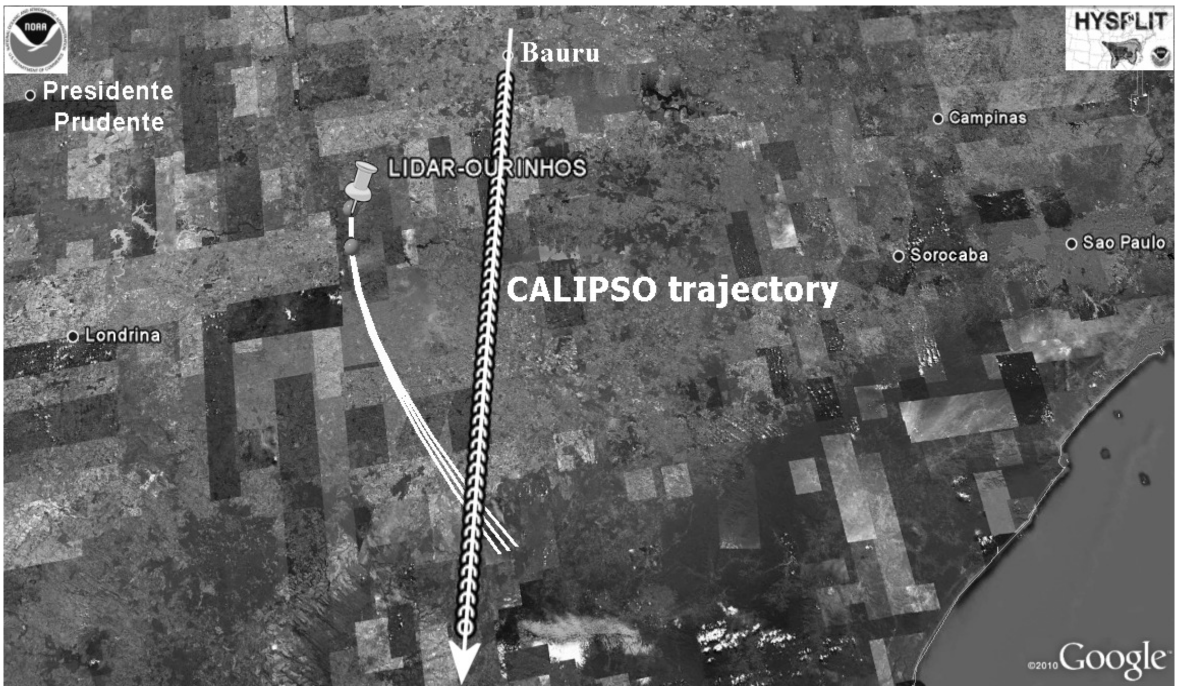

Figure 5. CALIPSO ground tracking in the region of Ourinhos for August 24, 2010 and the HYSPLIT forward trajectories. The HYSPLIT trajectories indicate that CALIPSO and the ground-based Raman Lidar measured the same air mass parcel.

Analyzing the range corrected signal profile provided by the Raman Lidar system, it can be seen that the atmosphere is loaded with aerosols up to 2.0 to 2.5 km altitude, as well as a smooth layer between 3.5 and 4.5 km, as shown in figure 6. It is most probable that these aerosol layers were injected into the atmosphere by the sugar cane fires in that region, as shown by the CAPPIs and TITAN tracks from IPMet's Radars (figure 2 and 3). Therefore, atmospheric optical properties, such as AOD and Lidar Ratio retrieved by the CALIPSO satellite were analyzed, using 5 km resolution aerosol layer products for all those profiles corresponding to the area intercepted by the HYSPLIT trajectories. These AOD and Lidar Ratio values were compared with those values retrieved by the Raman Lidar system, as shown in table 2.

Table 2. Optical properties retrieved by CALIOP and Raman Lidar systems

	AOD	**Lidar Ratio (sr)**	**Lat.**	**Long**
CALIOP	0.136	70	-24.195	-49.507
Raman Lidar	0.554	71	-22.949	-49.895

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The Lidar Ratio values retrieved by both systems agree with those found in the literature for biomass burning aerosol[18,21] and draw some preliminary conclusions that both CALIPSO and the Raman Lidar system had detected the same type of aerosol, once the HYSPLIT model has shown that air mass trajectories from the Raman Lidar site have been moving forward to the CALIPSO ground-track area. However, the AOD values are very different. High AOD values retrieved by the Raman Lidar system are a strong indication of an intense aerosol load in the atmosphere above the Ourinhos site. The CALIOP system presents a low AOD value, probably due the high speed at which the satellite traverses the ground track (about $7\,km\,s^{-1}$), thus an estimate of the AOD from the CALIOP can invariably neglect some small amounts of aerosol measurable by any ground-based Lidar system.[22,23] However, it could also be due to dilution along the 140 km trajectory, where no additional sources had been identified by the radars.

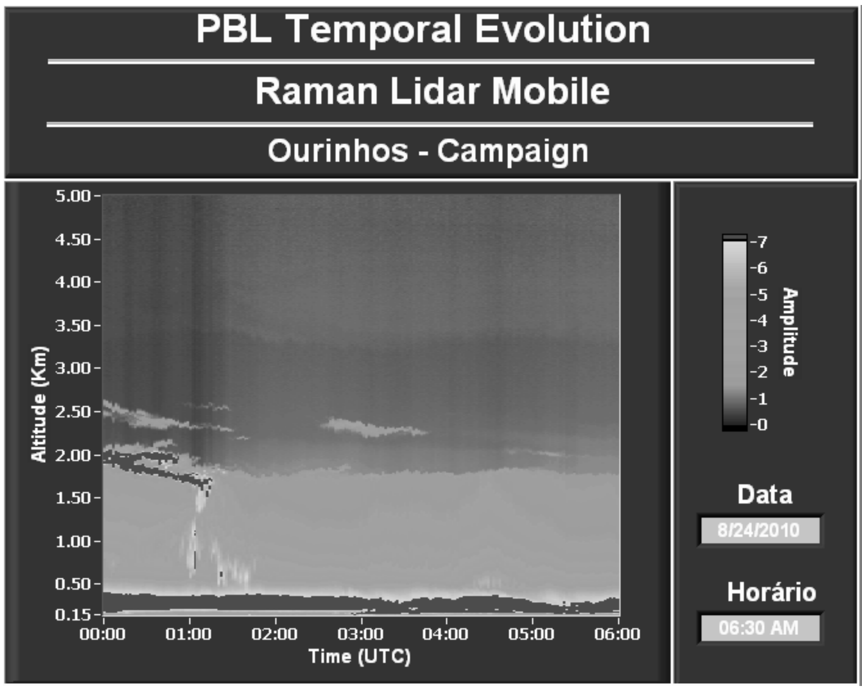

Figure 6. Range corrected backscatter signal from the Raman Lidar system, visualized from 00:00 to 06:00 UTC up to 5 km AGL. The backscatter profiles show a loaded atmosphere up to 2.0-2.5 km and a smooth layer between 3.5 and 4.5 km.

5. CONCLUSIONS

During August 2010, a field campaign had been carried out in Ourinhos, situated in the south-western region of So Paulo State, using a ground-based Raman Lidar system and two S-band Doppler Radars in order to identify and classify biomass burning plumes injected into the atmosphere from sugar cane fires. The radars detected and identified several fire plumes spread all over the Ourinhos region, visualized by the TITAN software and CAPPI images. Two algorithms were used to determine the CALIPSO overpasses during the campaign and select those measurements coincident with the Raman Lidar system. The HYSPLIT model has shown that air mass trajectories from the Raman Lidar site have been moving towards the CALIPSO ground-track area, a strong indication that both instruments measured the same aerosol parcels. Analysis of AOD and Lidar ratios retrieved from CALIOP and the Raman Lidar system showed that both systems detected biomass burning type aerosol, based on the Lidar ratio value of 70 sr. The results indicate that S-band radars are a valuable tool for identifying

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the locations and dimensions of fires and subsequent plumes during rain-free periods. Both ground-based and satellite Lidar systems are complementary tools for studying the atmosphere optical properties.

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