Aerosol Optical Depth from MODIS satellite data above the Pierre Auger Observatory

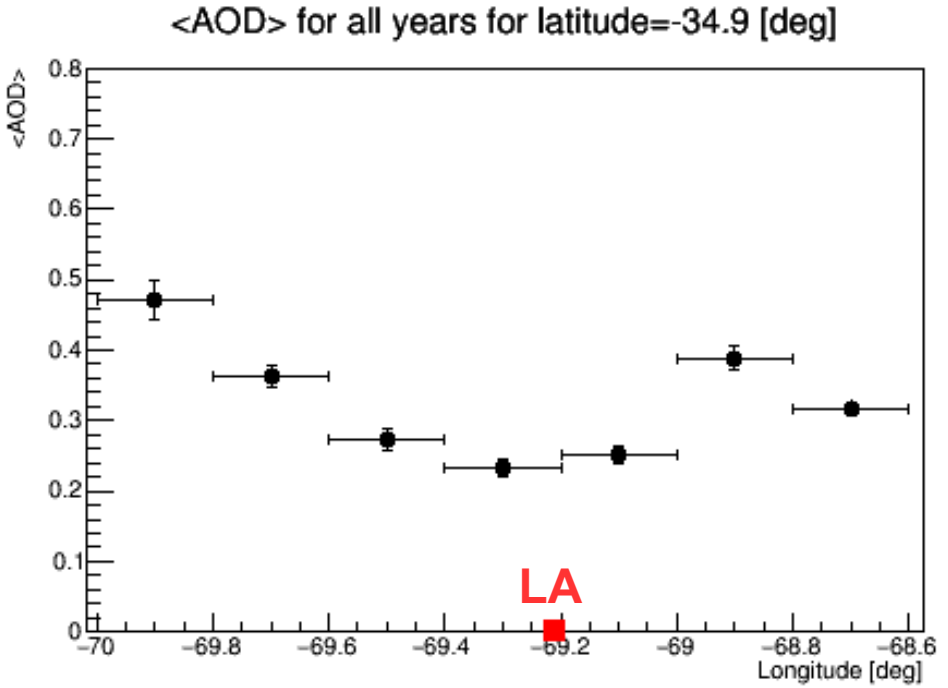
Nataliia Borodai

Institute of Nuclear Physics PAN, Kraków

Motivation

- **Possibility to investigate “new” technique for estimation of aerosol content above the Pierre Auger Observatory**

- **Find explanation for large absolute aerosol optical depth (AOD) values observed in the previous analyses, such as for OMI satellite measurements: e.g. <AOD> for Loma Amarilla (LA) fluorescence detector site ~ 0.24**

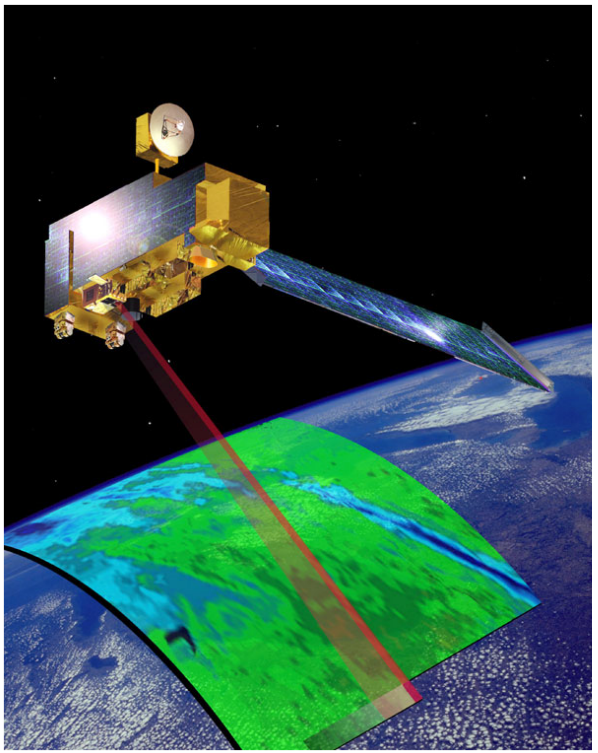


[N. Borodai, EPJ Web of Conf., 144 (2017) 01006, doi: 10.1051/epjconf/201714401006]

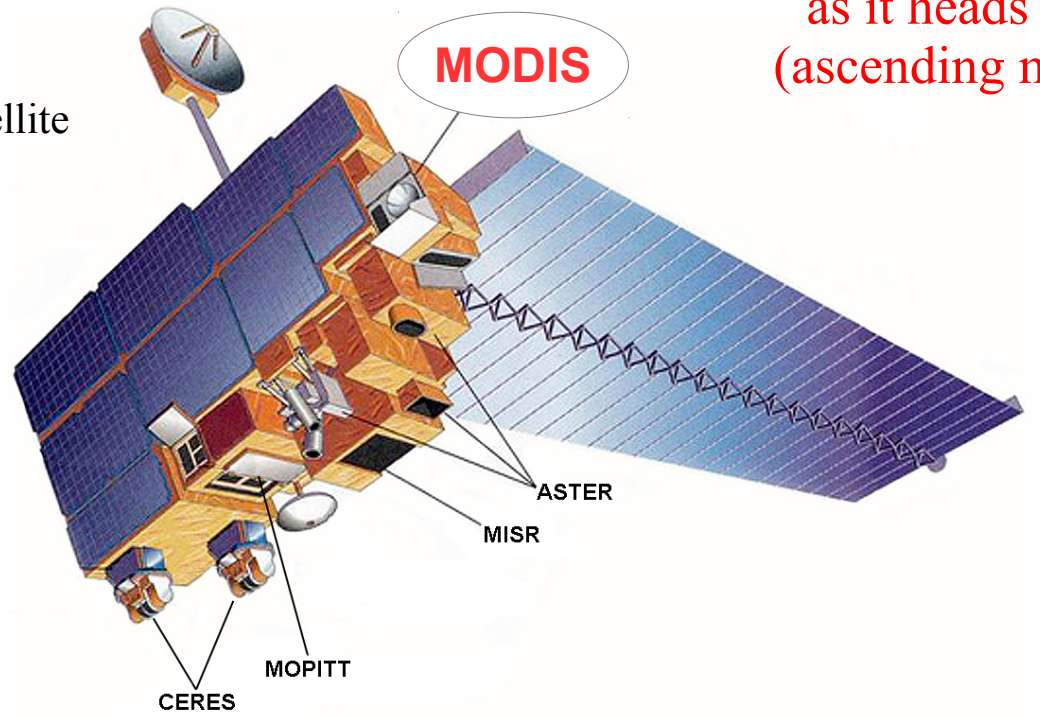
Terra and Aqua satellites

- Terra was launched in 1999 and Aqua in 2002;
- they are circling the Earth at an altitude of 705 km;
- on a sun-synchronous polar orbit => data is collected on the sunlit side of the Earth, and satellites pass over the same spot of the Earth at about the same local time every day;
- each orbit takes 99 minutes.

Terra crosses the area of the Pierre Auger Observatory daily during the morning hours as it heads south (descending mode) in contrast to Aqua, which crosses the Observatory daily during the afternoon hours as it heads north (ascending mode).



Terra satellite



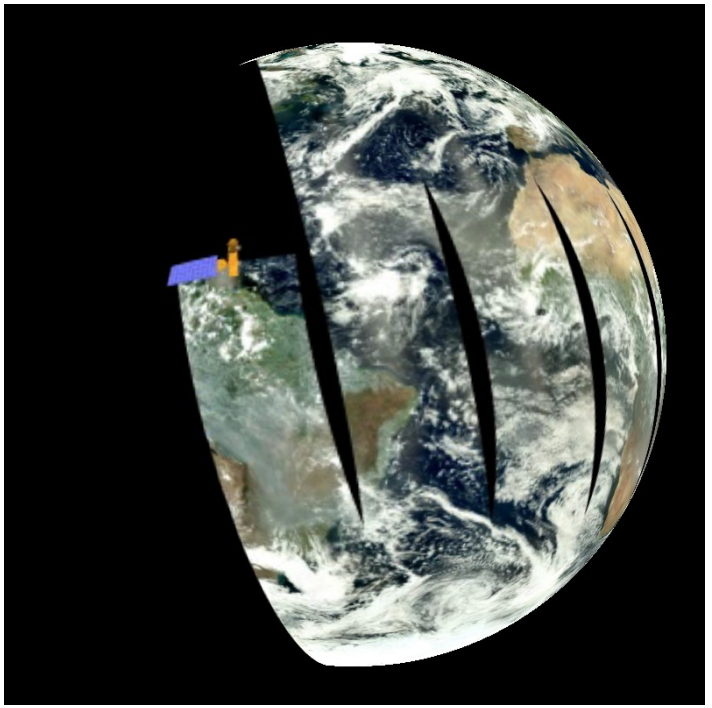
[Source of the images is a catalog of NASA images - Earth Missions Image Gallery]

The Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS is a passive imaging radiometer.

- It measures reflected solar and emitted thermal radiation in a total of 36 bands with wavelengths between 0.41 μm and 14.4 μm for the entire MODIS field of view.

- The swath of data collected by MODIS is over 2300 km wide => MODIS is able to observe almost the entire Earth surface every day.



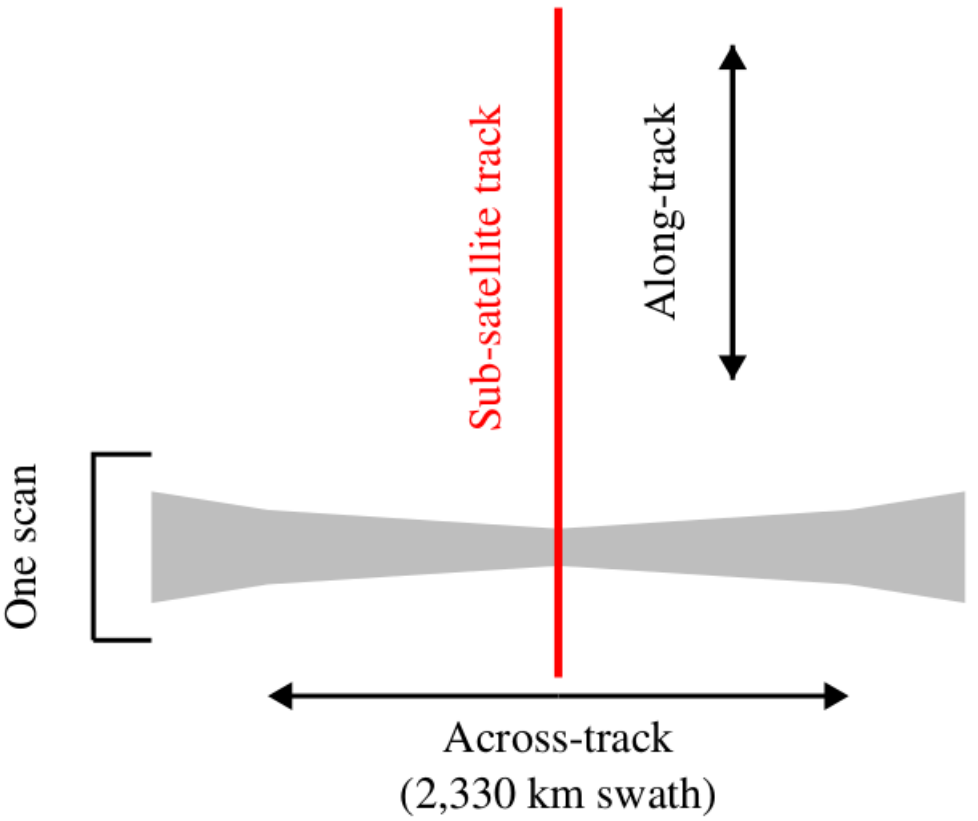
[Source of the image is NOAA]

The total area of the Pierre Auger Observatory can be observed by satellite during 1 orbit period or during 2 orbits (if divided between two swaths).

MODIS scan geometry

MODIS level 2 aerosol data products

- are generated from level 1B calibrated radiance data measured by the MODIS instruments.
- The level 1B MODIS data are organized into 5 min granules.
- Each granule consist of 203 scans along-track, with 1354 pixels across-track per scan.
- The size of a single measured pixel at nadir is 250 m, 500 m, or 1 km, depending on the measured band. These are called "sensor pixels".



[A. M. Sayer et al., Atm. Meas. Tech. 8, 5277–5288 (2015)]

- To decrease noise in the retrieval, the standard level 2 products are provided at a nominal horizontal pixel size of 10 km (referred to as "retrieval pixels").

Two MODIS-over-land algorithms

- The Dark Target (DT) over land algorithm was developed to retrieve AOD over dense, dark vegetation surfaces.

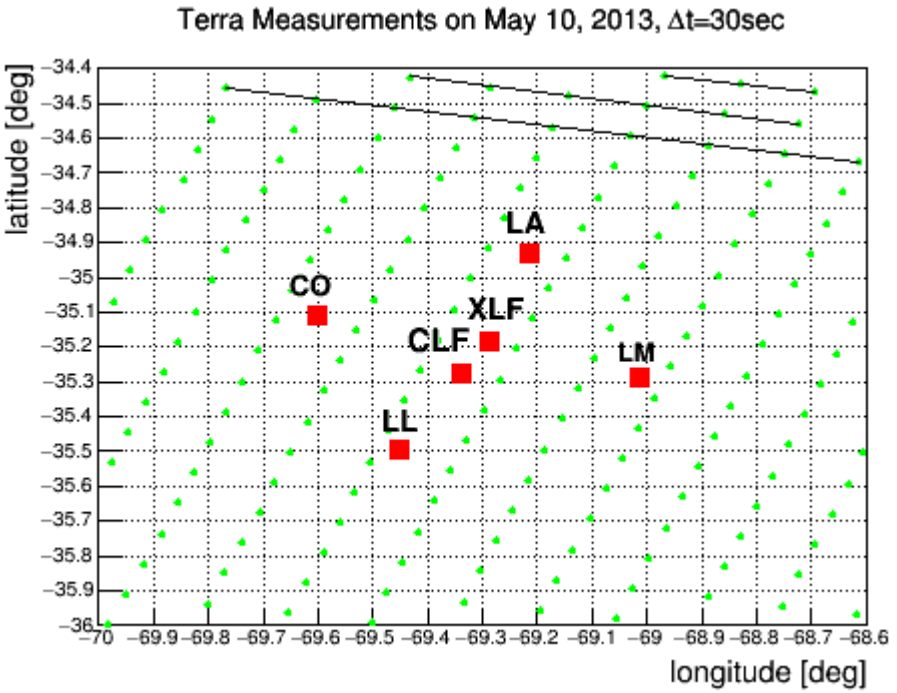
- The Enhanced Deep Blue (DB) algorithm was developed to cover brighter arid and semi-arid surfaces (such as deserts), later was expanded to cover vegetated land surfaces.

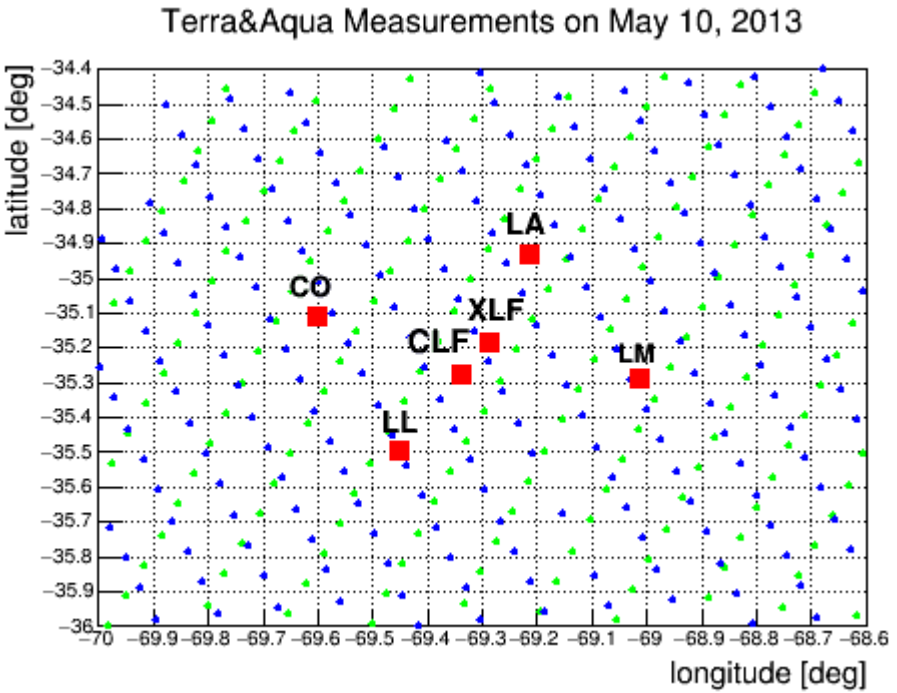
The DT aerosol retrieval algorithm is unable to provide aerosol properties over bright reflecting regions, as the top-of-atmosphere (TOA) reflectances acquired by the satellite sensors at red and near-infrared wavelengths are overwhelmed by the surface contributions over desert and semi-desert regions, making it difficult to separate the contribution of aerosols to the TOA signal from that of the surface. This explains large absolute AOD values observed in the previous analyses over the Pierre Auger Observatory, when the DT algorithm is used.

The DB algorithm enables performing aerosol retrievals over bright reflecting surfaces, as it utilizes the blue wavelength measurements from instruments, where the surface reflectance over the land is much lower than for longer wavelength bands.

Aerosol grid map

Single retrieval pixel size at nadir is 10km × 10km (≈ 0.1° × 0.1°).
Each retrieval pixel is described in the database by:
- the AOD value (Deep_Blue_Aerosol_Optical_Depth_550_Land);
- pixel center coordinates (longitude and latitude).





Green points represent retrieval pixel centers for Terra MODIS measurements.

Blue points represent retrieval pixel centers for Aqua MODIS measurements.

Lines in Figure link up the centers of retrieval pixels of the same swath, they also illustrate the sequence of measurements (the uppermost line represent the first swath on the map, next one is measured in approximately 1.6 sec, and so on). The duration of all measurements was about 30 sec.

Selection criteria(1)

Wavelength of AOD measurements = 550nm.
MODIS data from both satellites (Terra and Aqua) are analyzed.

The following selection criteria are necessary for the MODIS AOD data to be qualified to analysis procedure:

(1) Quality Flag = 3 – only data of the best quality (Deep_Blue_Aerosol_Optical_Depth_550_Land_QA_Flag, very good = 3), data with the largest confidence level.

Selection criteria(2)

PN parameter is used to estimate the cloud fraction in a single retrieval pixel.
(Deep_Blue_Number_Pixels_Used_550_Land)
It represents the number of suitable (cloud-free, snow-free) sensor pixels inside the retrieval pixel.

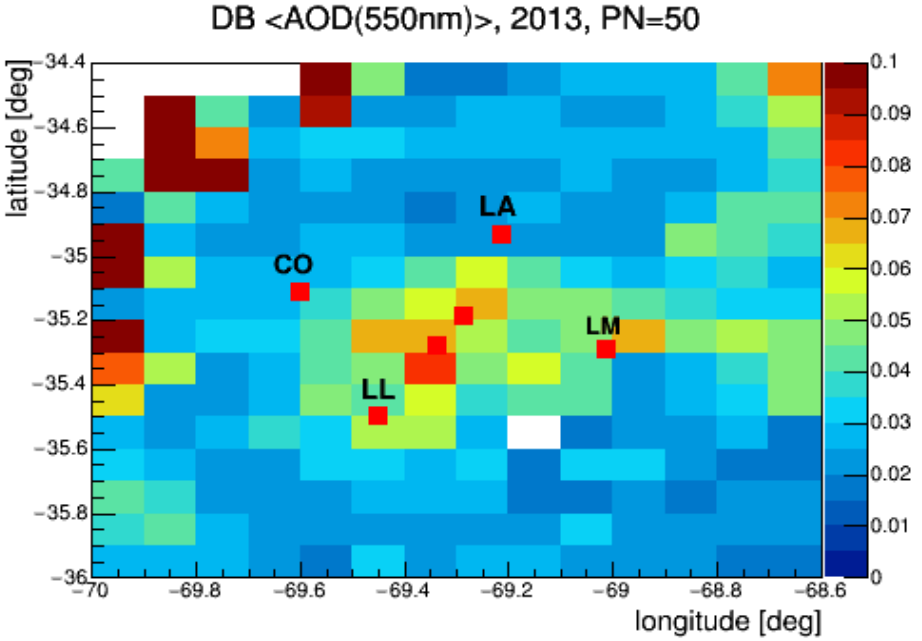
The PN criterion varies in the table from 50 to 100, causing the changes of the <AOD> values as well as changes of the number of measurements.

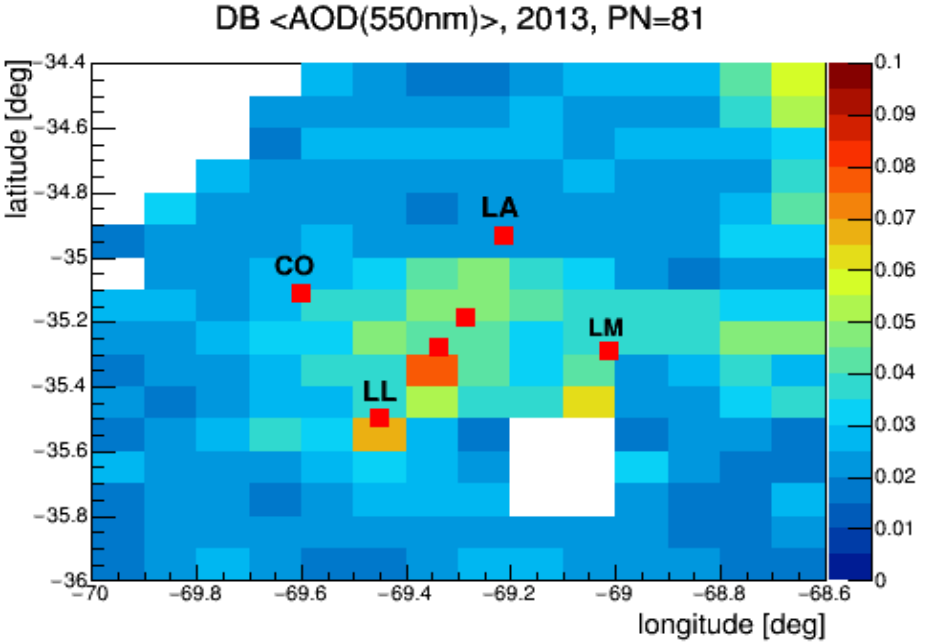
If some fraction of cloud sensor pixels is inside a retrieval pixel => unreasonably high <AOD> in this "cloud-free" retrieval pixel.

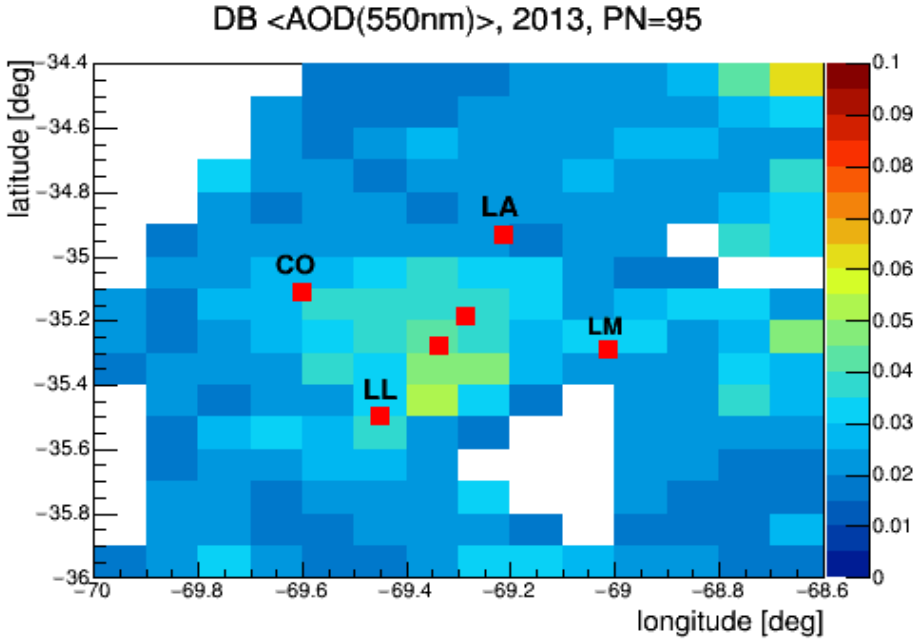
! Select pixels with PN=100, i.e. all sensor pixels are cloud-free.

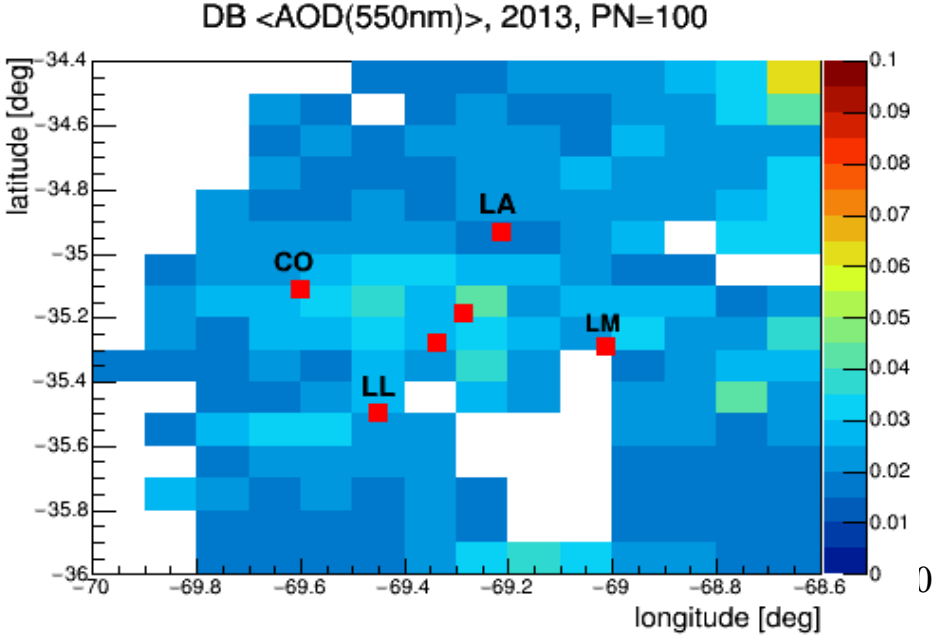
Number of Sensor Pixels (PN) per Retrieval Pixel	Total number of measurements in year 2013	<AOD> in June	<AOD> in November
over 50 pixels	28719	0.0315 +/- 0.1411	0.0306 +/- 0.0404
over 81pixels	22549	0.0255 +/- 0.0833	0.0291 +/- 0.0252
over 95 pixels	14270	0.0225 +/- 0.0395	0.0287 +/- 0.0262
100 pixels	8740	0.0205 +/- 0.0075	0.0282 +/- 0.0298

Selection criteria(2)









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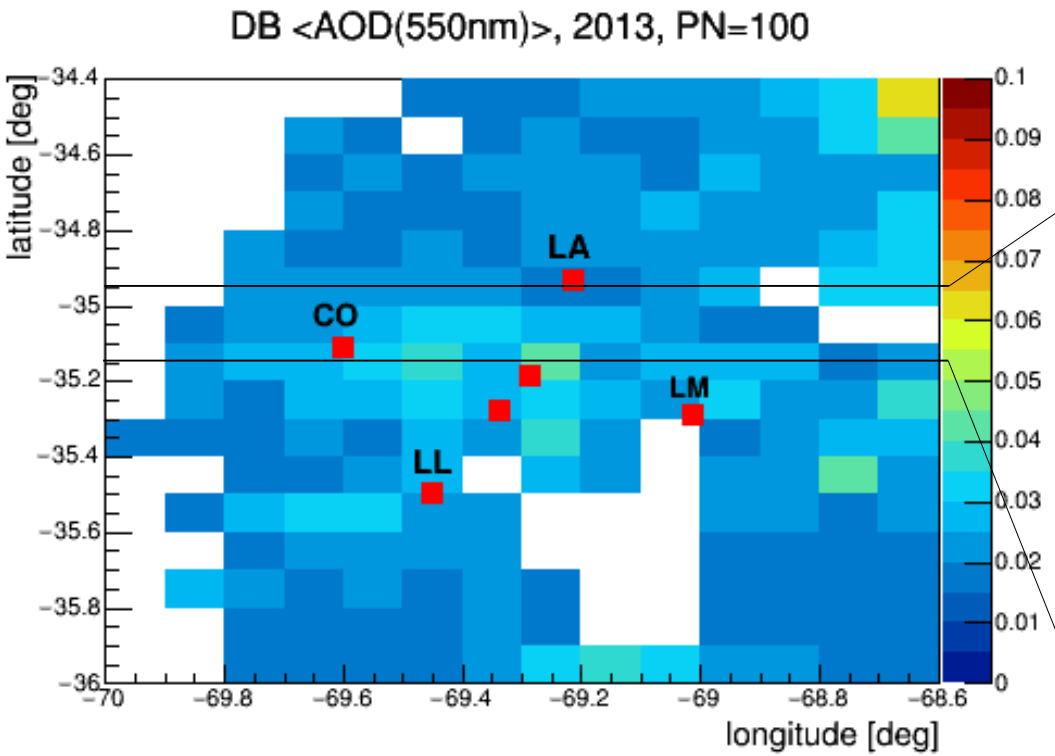
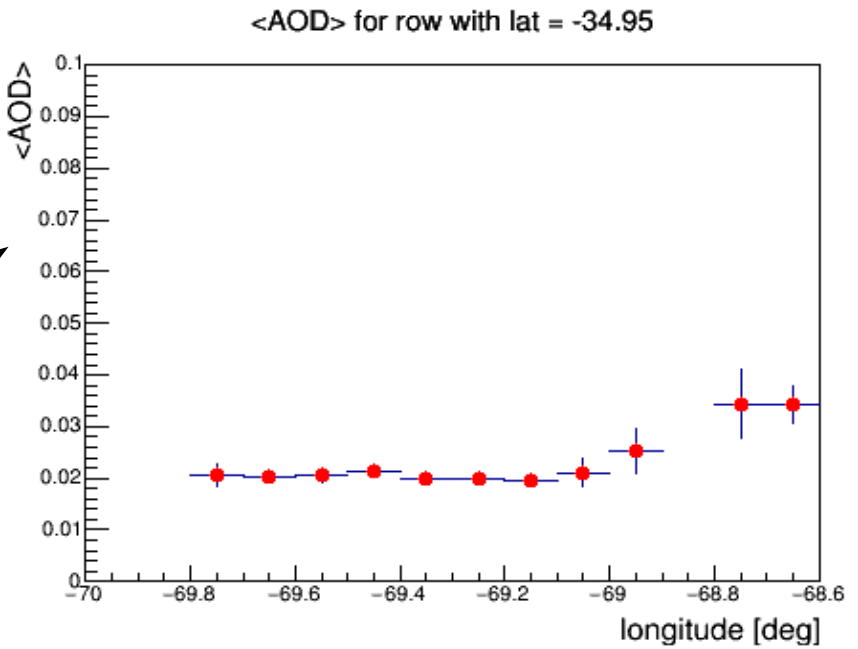
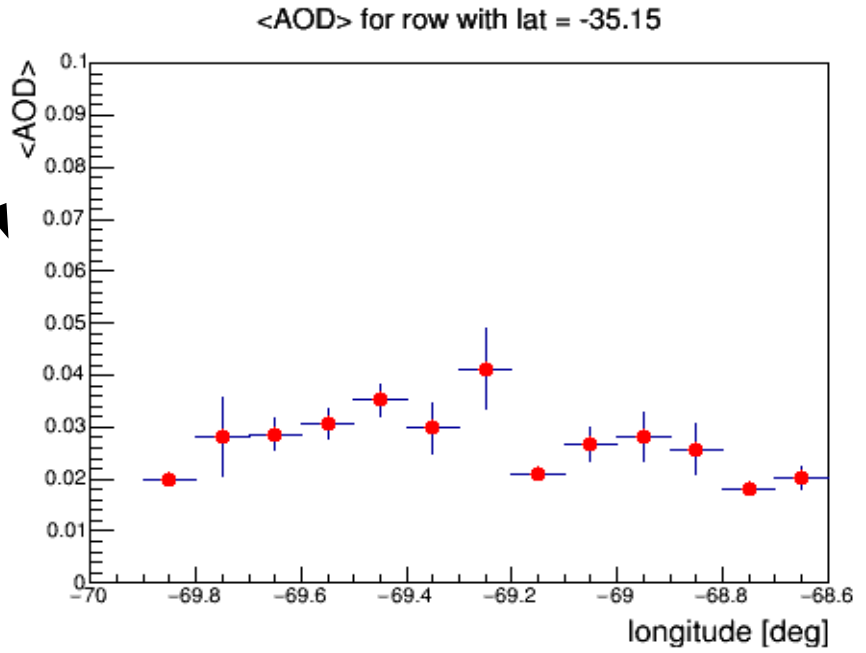
(2) PN = 100 – to eliminate any cloud impact.

Selection criteria (3) - DB <AOD> values at different longitudes



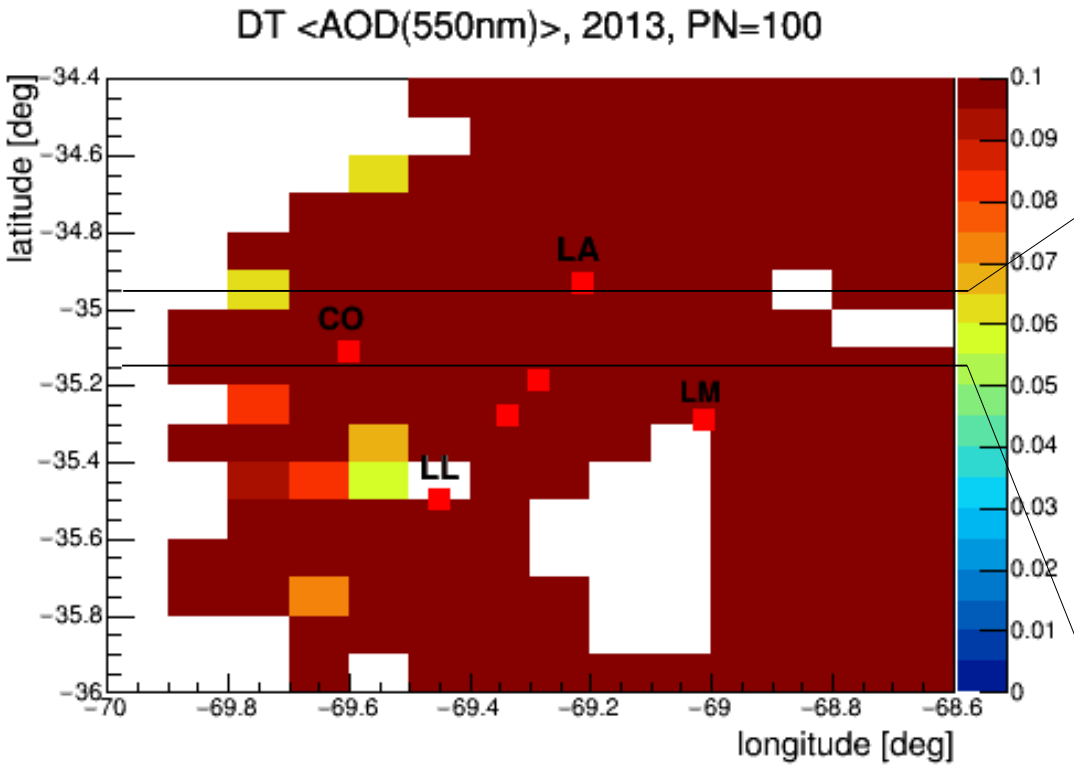


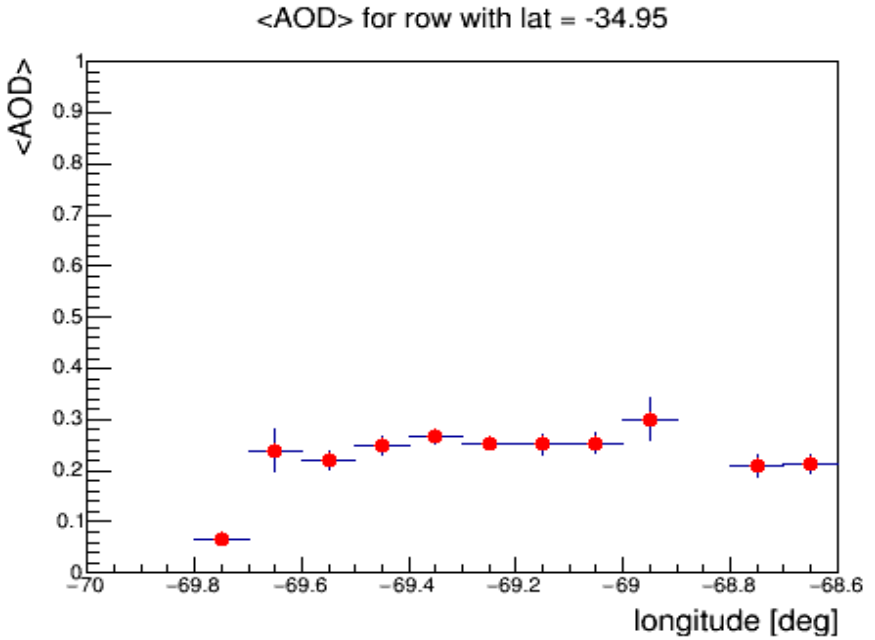


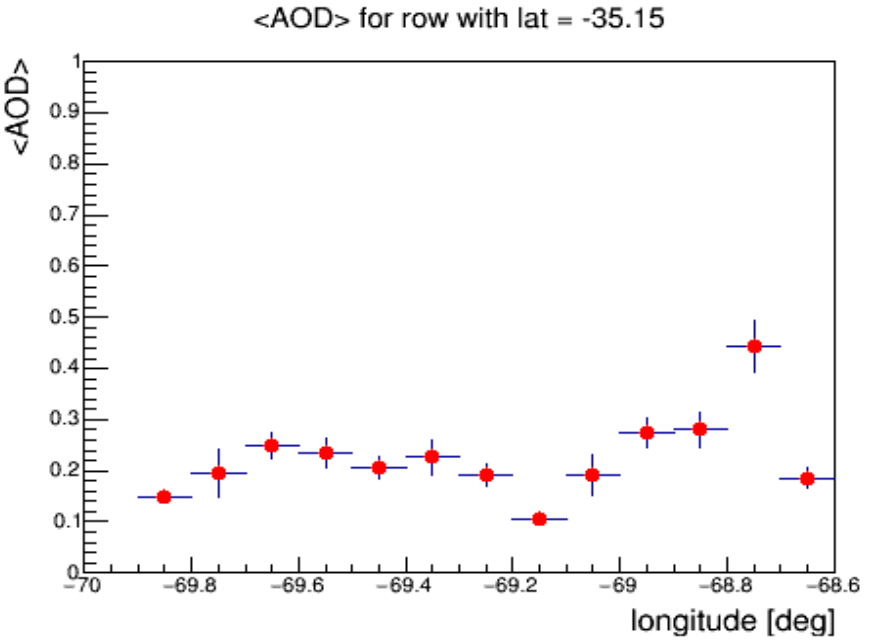
<AOD> for LA ~ 0.02

<AOD> for CO ~ 0.03

DT <AOD> values at different longitudes







<AOD> for LA ~ 0.26

<AOD> for CO ~ 0.18

Selection criteria (3)

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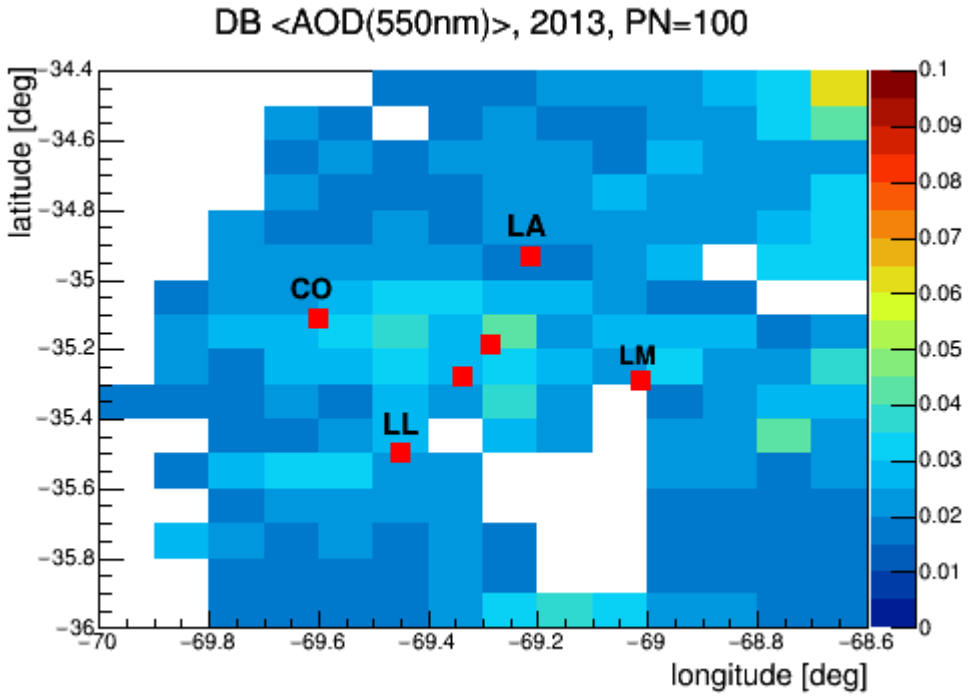
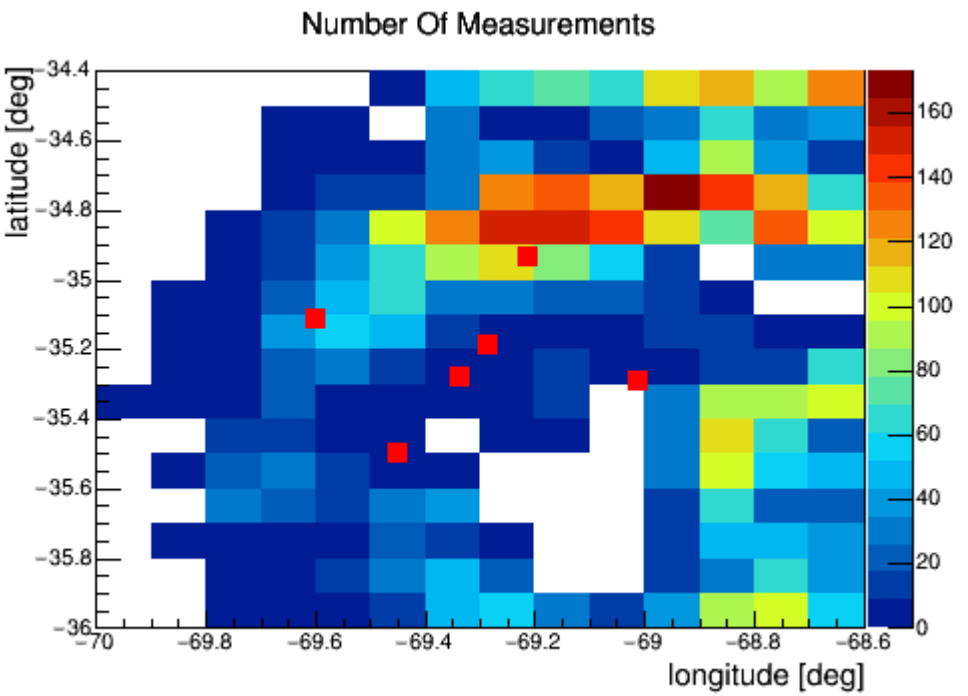
(2) PN = 100 – to eliminate any cloud impact.
(3) DB algorithm data should be used for the Pierre Auger Observatory area.

About 10% of all the DB MODIS data remain for the analysis after applying these cuts.

<AOD> map for the year 2013

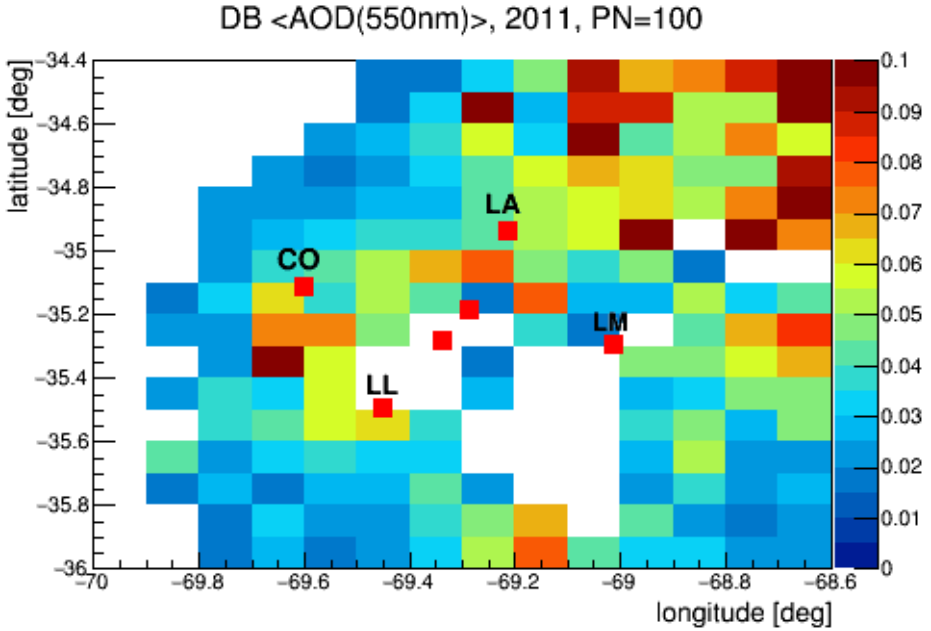




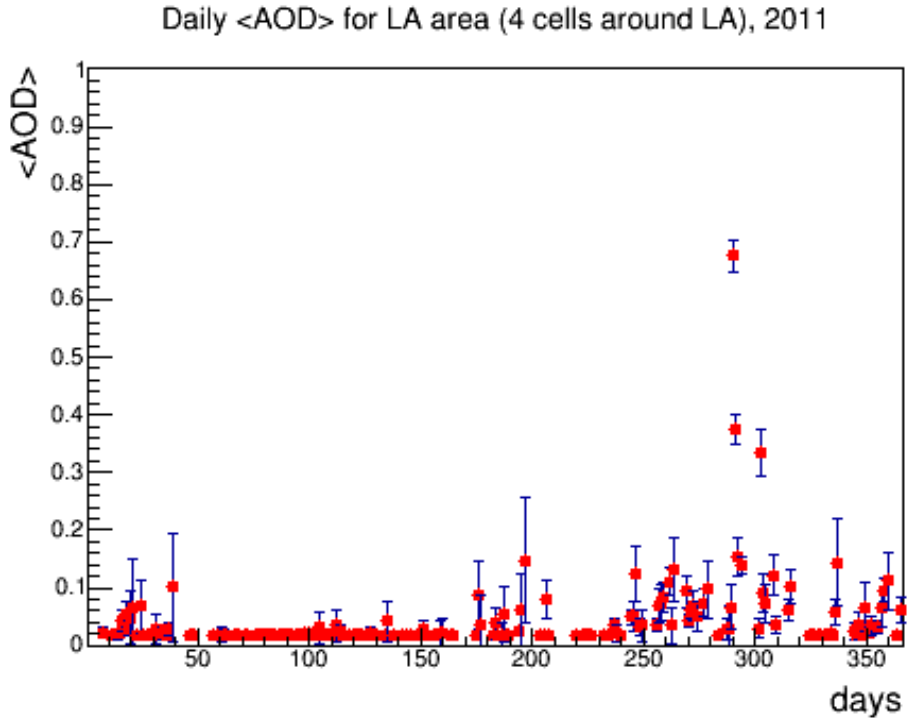
With the AOD and coordinates for retrieval pixels the 0.1º × 0.1º AOD map can be created: all the retrieval pixels are mapped to 0.1º × 0.1º grid cells according to the positions of their centers.

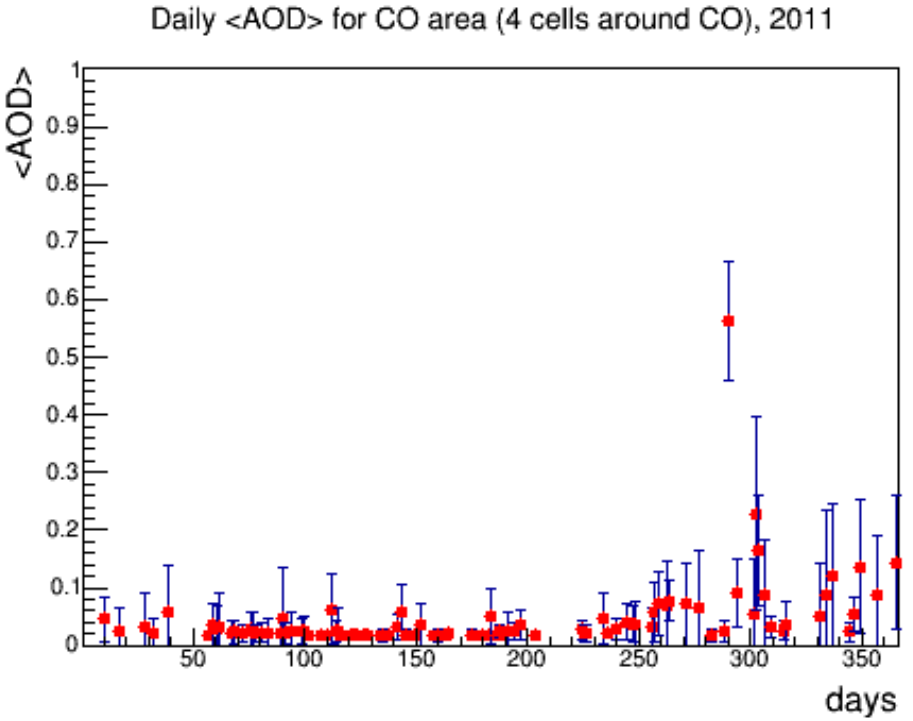
Two large empty regions with no data on maps:
1- is between LL and LM detectors, corresponds to the Llancanelo Lake and so cannot be retrieved by DB or DT over land algorithms as it is not land.
2- is on the left-hand side of the maps, corresponds to snowy Andes Mountains and so also cannot be retrieved by the discussed algorithms.

Interpretation of maps and plots



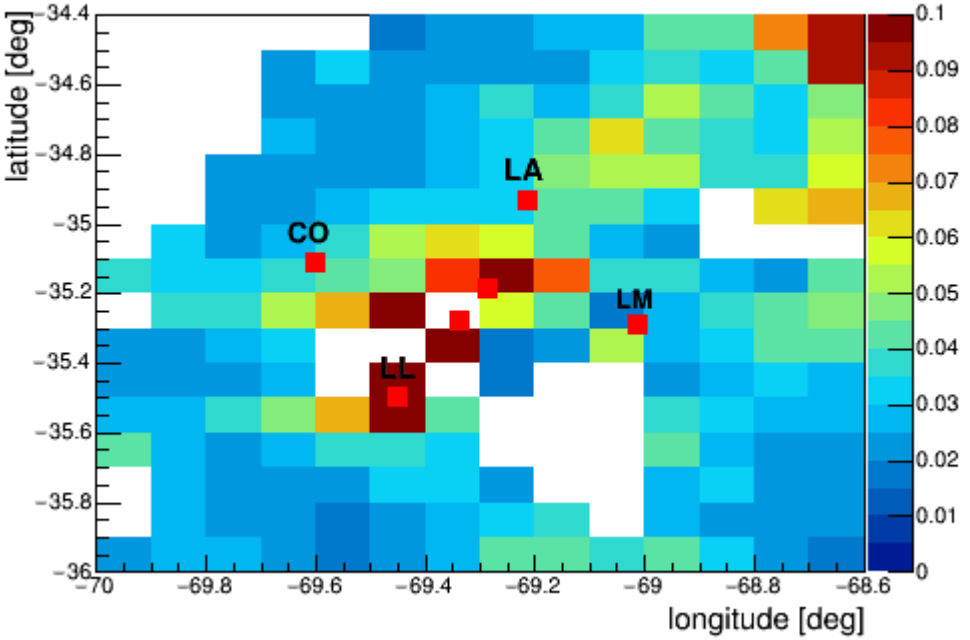
Increase in <AOD> after 170th day of a year (corresponding to 19 June 2011) and continued up to the end of the year, can be caused by appearing of clouds with volcanic ash in the atmosphere above the Pierre Auger Observatory, taken there by the strong winds. These clouds were formed in June 2011 because of eruption from Puyehue–Cordón Caulle Volcanic Complex in Chile.



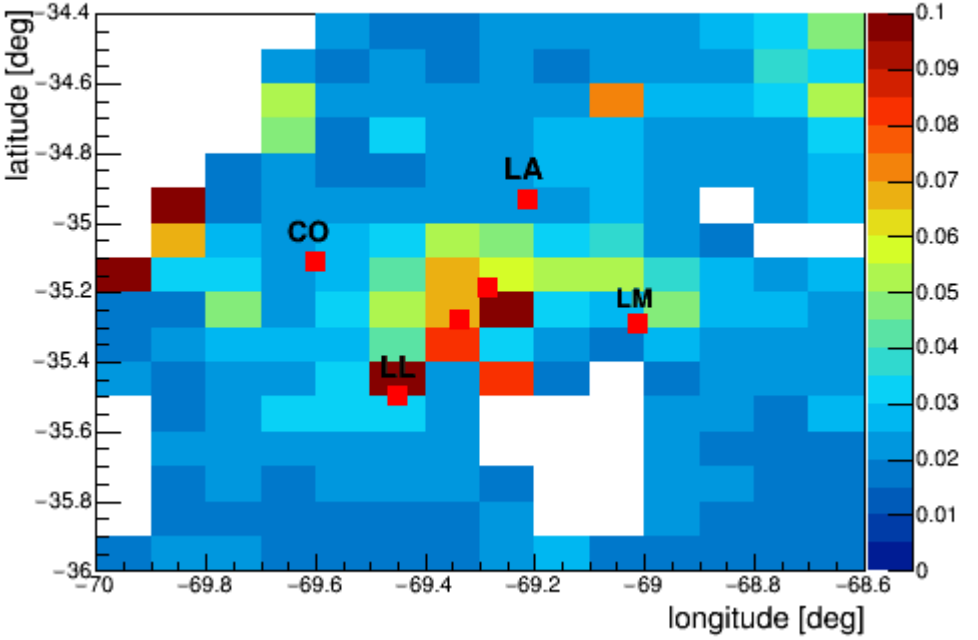


Seasonal DB <AOD> maps for years 2004 to 2017

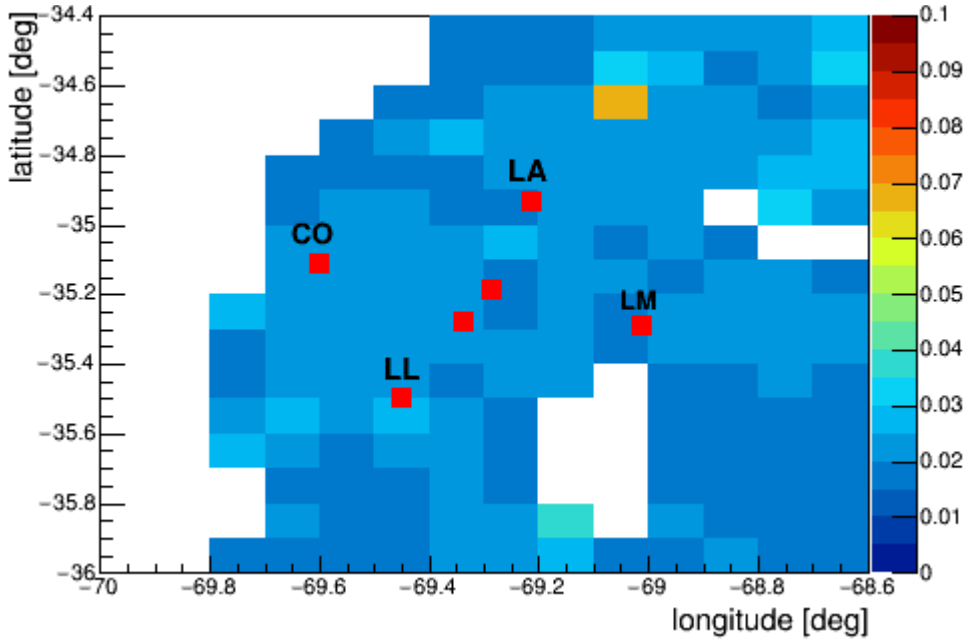
<AOD> map for summer months (12,1,2)



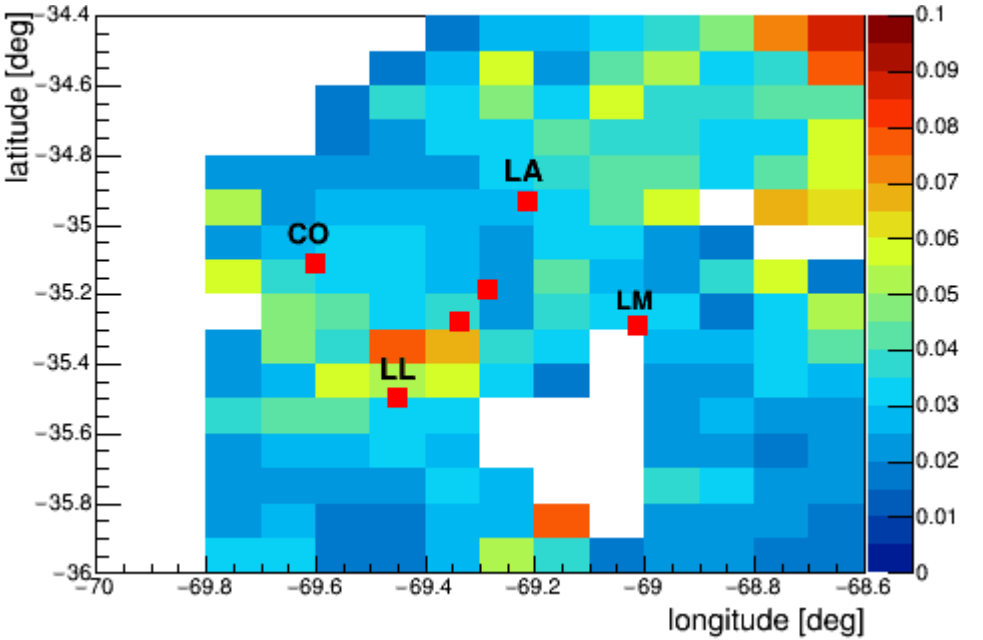
<AOD> map for autumn months (3,4,5)



<AOD> map for winter months (6,7,8)



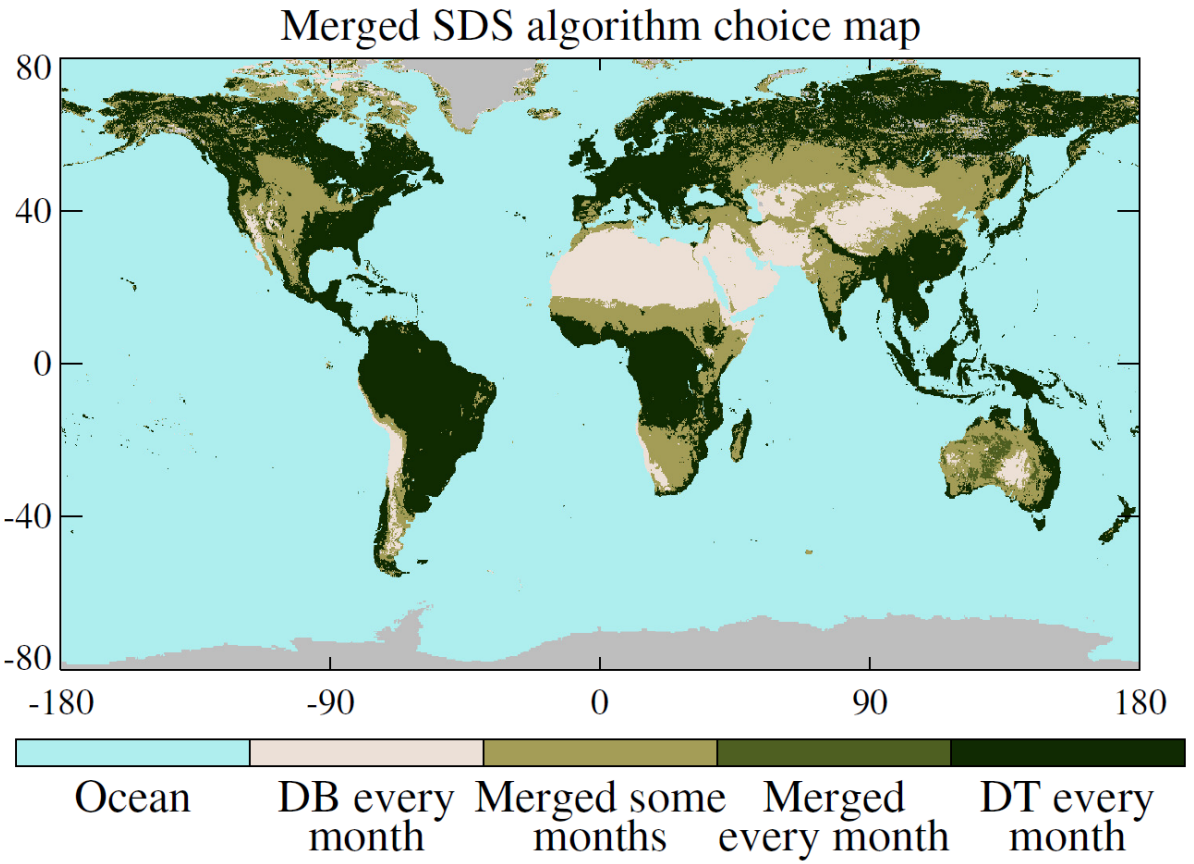
<AOD> map for spring months (9,10,11)



CONCLUSION

- The MODIS Terra and Aqua datasets were analyzed.
- Comparison of AOD values obtained using the Dark Target and Deep Blue algorithms shows that they differ much. The reason for this difference is the bright land surface of the Pierre Auger Observatory for which the DB algorithm (and not DT) should be used.
- By observing the aerosol maps for single years it is possible to find anomalies in aerosol optical depth distribution. More careful study may point out transient events which take place during that year. So, the volcanic ash resuspension event, which happened in the middle of October 2011, can be traced using MODIS data over the area of the Pierre Auger Observatory.
- Seasonal dependence of aerosol content is observed.
- Other satellite instruments, SeaWiFS, and VIIRS, also provide data with Deep Blue algorithm. An analysis using DB data from these instruments can be useful for comparison with MODIS and ground-based aerosol measurements.

Additional slides – MODIS merged algorithm



[A. M. Sayer et al., J. Geo-phys. Res. Atmos., 119, 13965–13989 (2014)]

DB <AOD> map and the East-West profiles for 412 nm for the year 2013