Karlsruhe Institute of Technology

PIERRE AUGER OBSERVATORY

Updates of the atmospheric monitoring at the Pierre Auger Observatory

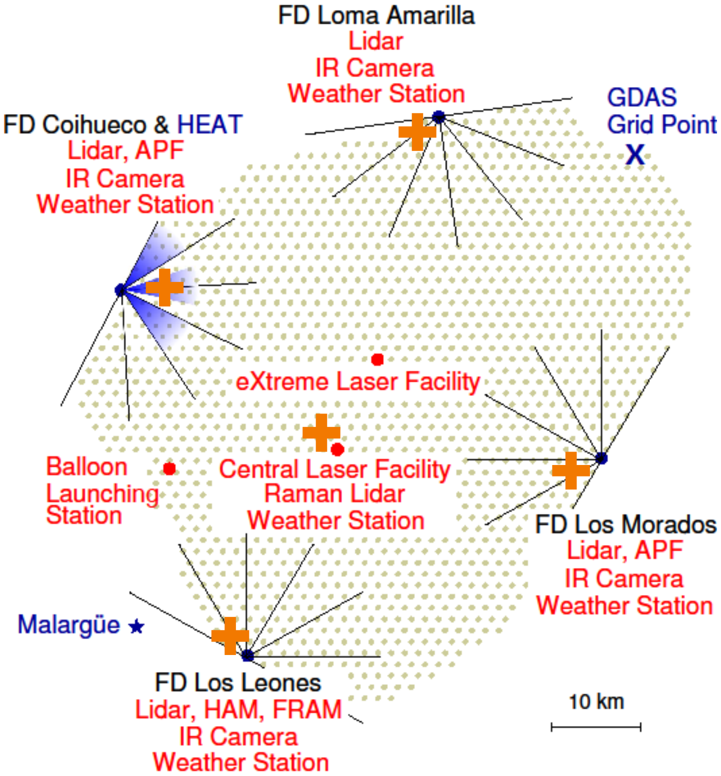
Bianca Keilhauer and Max Büsken,

with input from J. Ahumada-Becerra, V. Harvey, R. Mussa, and J. Pallotta

Atmospheric monitoring at the Auger Observatory

Main instruments for recording

- Aerosols
  - CLF / XLF
  - Elastic lidars
  - Raman lidar
- Clouds
  - IR Cameras
  - Elastic lidars
  - CLF / XLF
- Electric Field
  - E-Field Mills (✚ in map)



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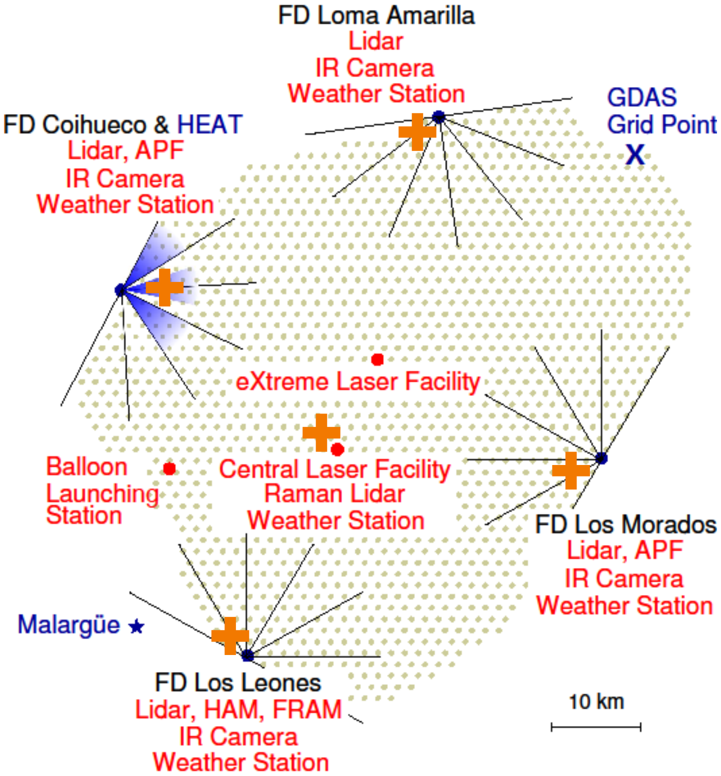
Atmospheric monitoring at the Auger Observatory

Status of instruments

- Aerosols
  - CLF → being upgraded / XLF → running
  - Elastic lidars → operated at CO+LA
  - Raman lidar → being upgraded
- Clouds
  - IR Cameras → to be phased out
  - Elastic lidars
  - CLF / XLF
- Electric Field
  - E-Field Mills (✚ in map) → running



Outline of presentation

- Substitution of Cloud Cameras by Night-Sky Background data from the Fluorescence Detector
- New setup for E-field measurements and its Application to the AugerPrime Radio
- Recent developments for the Cloud Cuts to Fluorescence Detector data

Substitution of Cloud Cameras by Night-Sky Background data from FD

Master thesis by
Jason Ahumada, U Adelaide

Principle idea

Fluorescence Detector (FD) is recording Night-Sky Background (NSB)

- Permanently during DAQ
- Every 30 sec
- For each individual pixel of every telescope

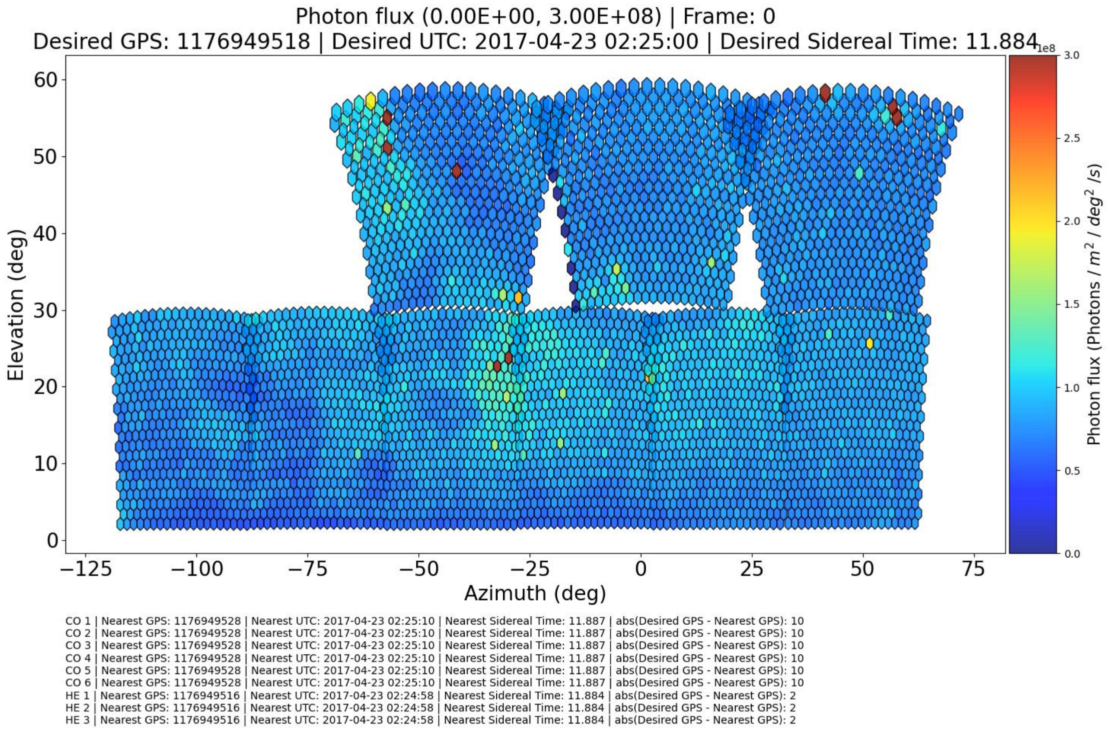
Use NSB data to determine photon flux for „clear" conditions for every pixel and sidereal time

Estimate clouds in FOV from NSB photon flux variations

Night-Sky Background data from FD

Data example

NSB data
for FD Coihueco + HEAT
for a period of 17 min
during April 2017



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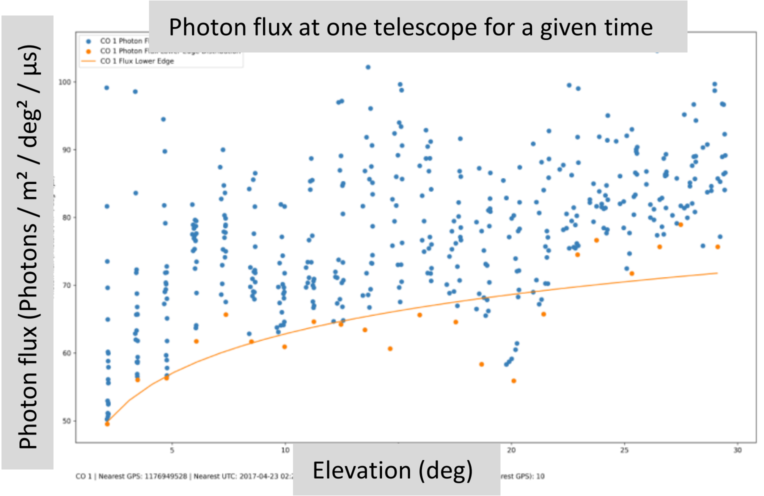
Identifying Clouds Using NSB Photon Flux Thresholds

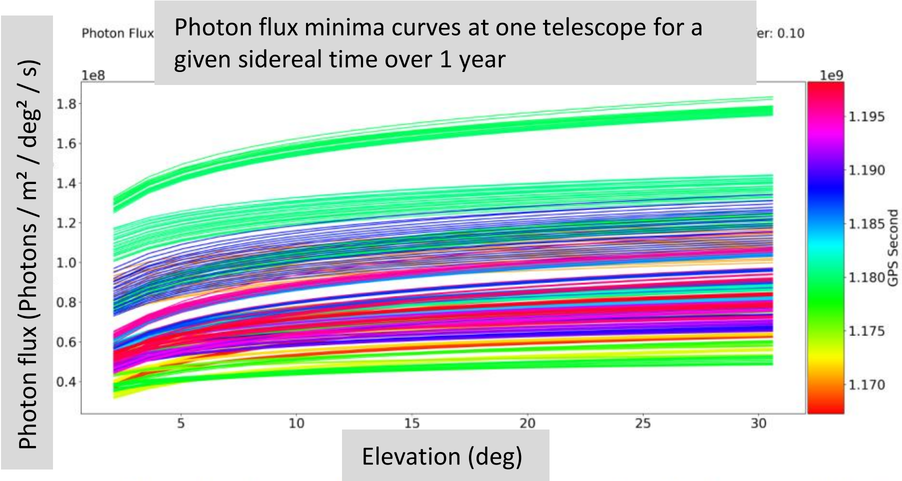
Setting the limit between „clear“ and „cloudy“

Determining the NSB photon flux threshold for each telescope and sidereal time

- Plot photon flux for each telescope and sidereal time with pixels grouped into rows of elevation
- Find the minimum flux per elevation



NSB flux vs elevation plot for **Figure 4.3a**. Blue points represent the photon flux for each pixel plotted by elevation. Orange points represent minimum photon flux-elevation pairs and photon flux lower edge plotted as logarithmic fit to set of orange points.



Example of messy plot for photon flux lower edges for Coihueco 1 sidereal time 6h where the colour bar represents GPS seconds. Vibrant colours are used to distinguish the time of each lower edge throughout 2017.

Identifying Clouds Using NSB Photon Flux Thresholds

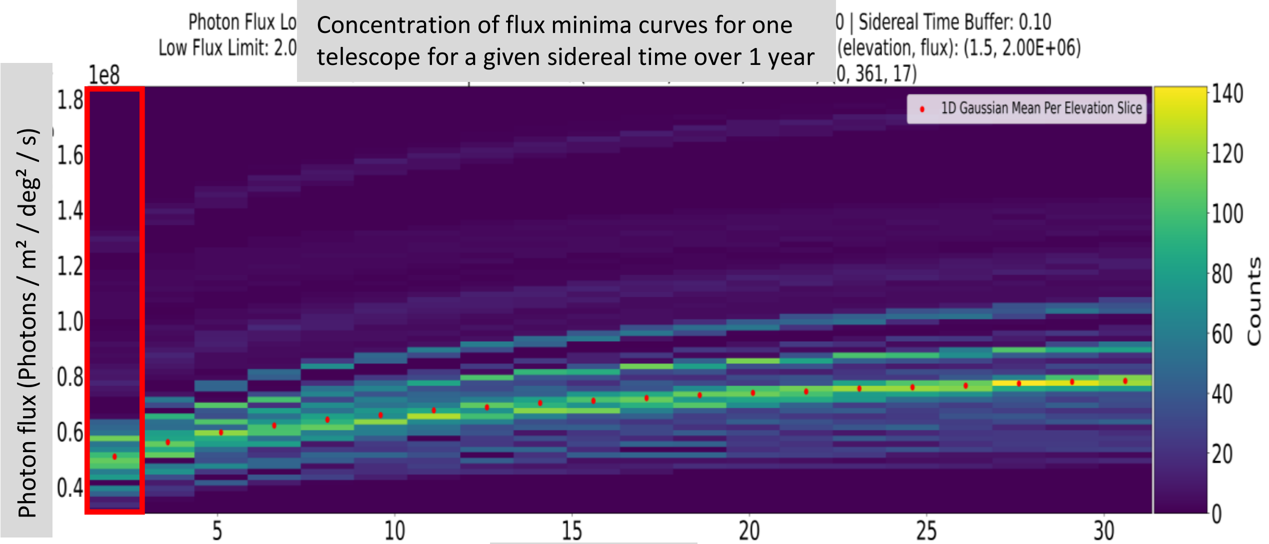
Setting the limit between „clear“ and „cloudy“

Determining the NSB photon flux threshold for each telescope and sidereal time

- Plot concentration of flux minima curves
- Extracting threshold

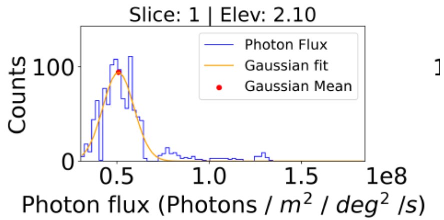
Work in progress

Concentration of flux minima curves for one telescope for a given sidereal time over 1 year



Elevation (deg)

for every elevation



Clear-sky threshold as a function of elevation, for each telescope at each sidereal time

B. Keilhauer

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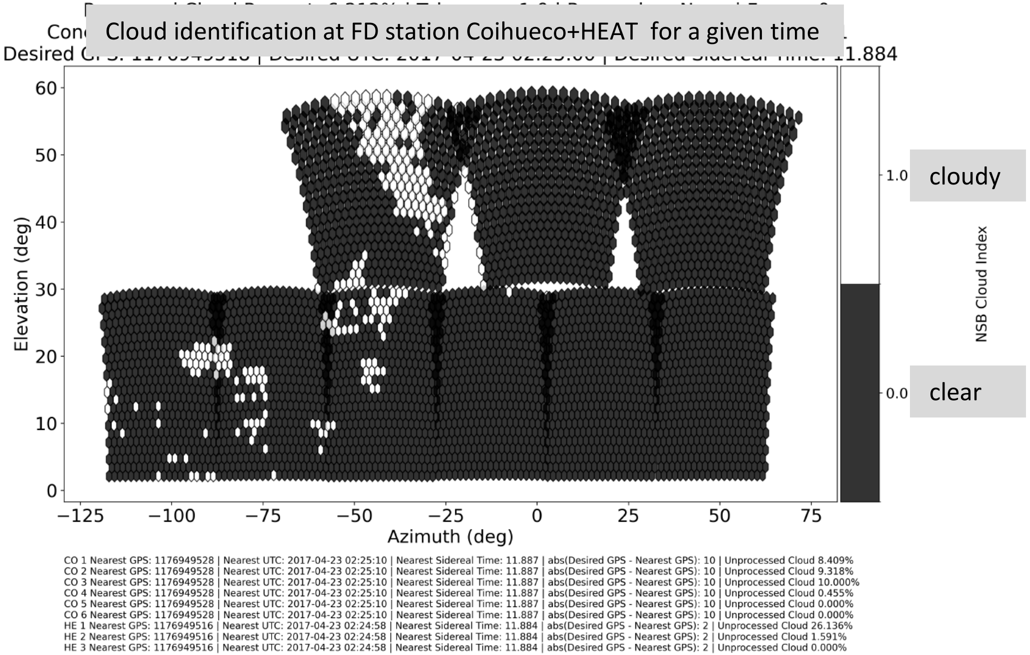
Cloud images

Applying photon flux threshold and a tolerance factor to NSB data

$$\text{pixel\_class} = \begin{cases} \text{Clear}, & \text{if flux(pix\_elev)} > \text{tolerance} \times \text{concentration\_threshold(pix\_elev)} \\ \text{Cloud}, & \text{otherwise.} \end{cases}$$



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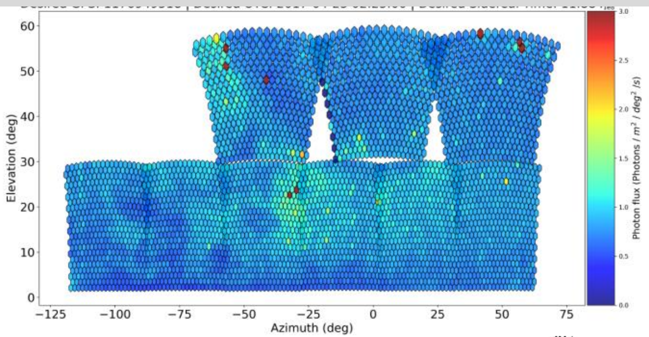
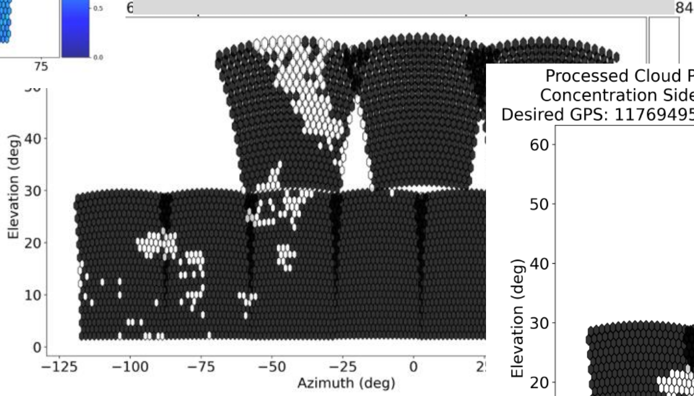
Cloud images

Apply some further imaging processing to smooth out cloud shapes and reduce noise

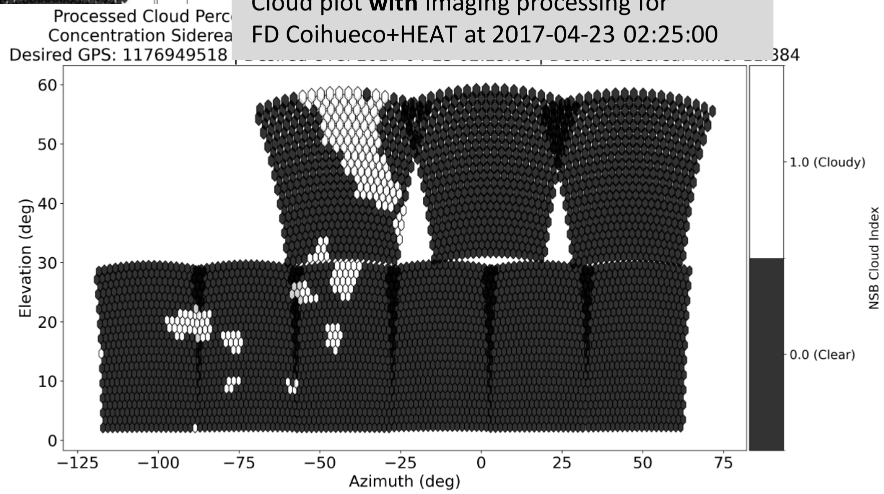
NSB plot for FD Coihueco+HEAT at 2017-04-23 02:25:00



Cloud plot without imaging processing for FD Coihueco+HEAT at 2017-04-23 02:25:00



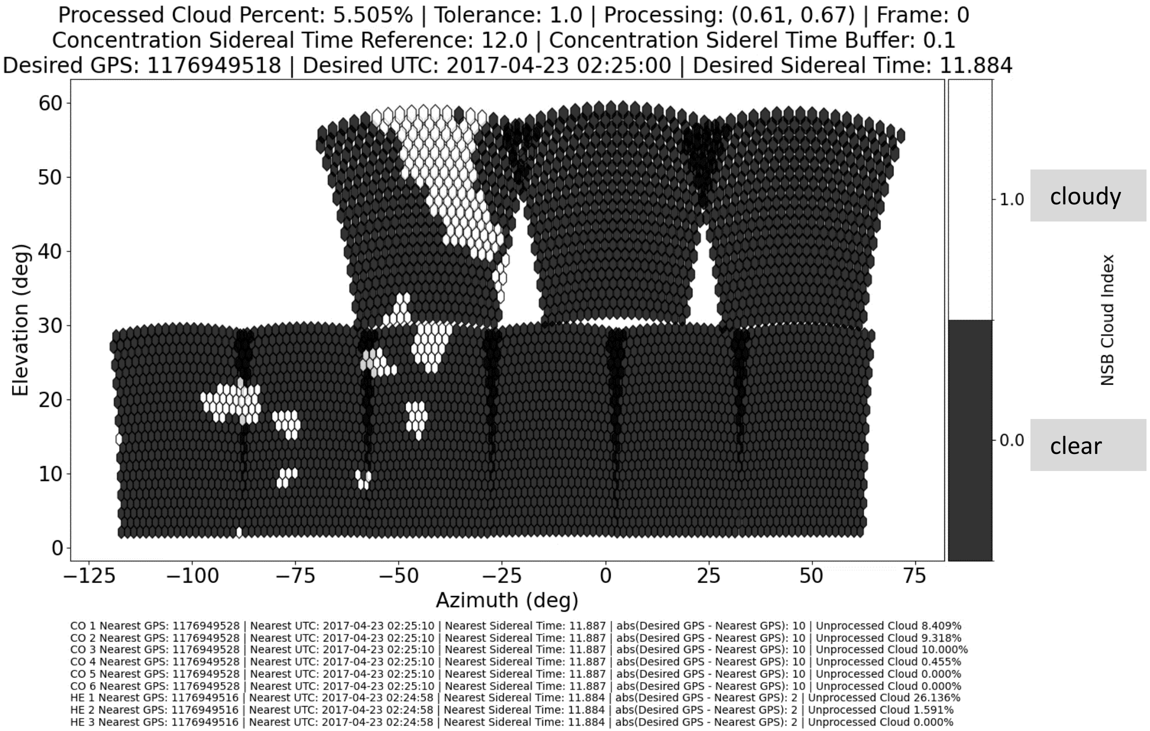
Cloud plot **with** imaging processing for FD Coihueco+HEAT at 2017-04-23 02:25:00



Cloud images

Data example

Cloud images from NSB for FD Coihueco + HEAT for a period of 17 min during April 2017



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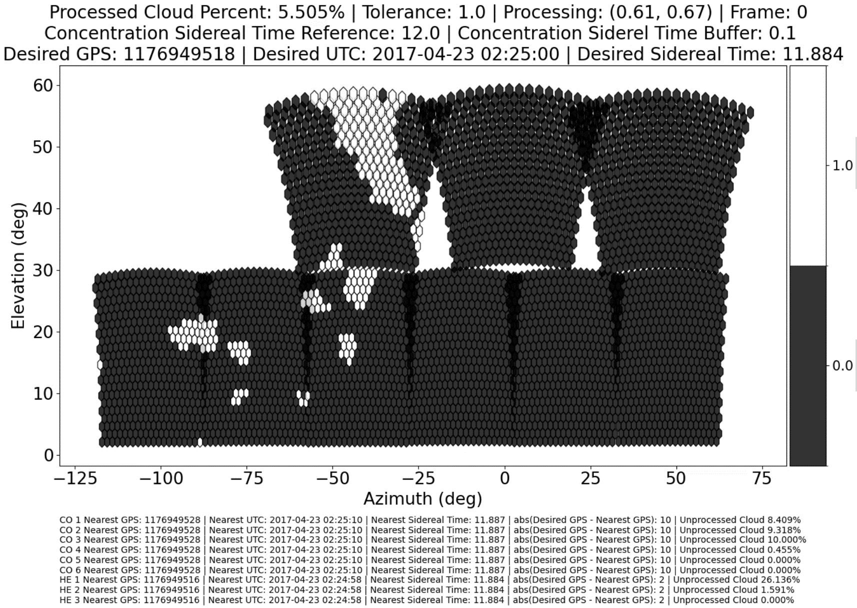
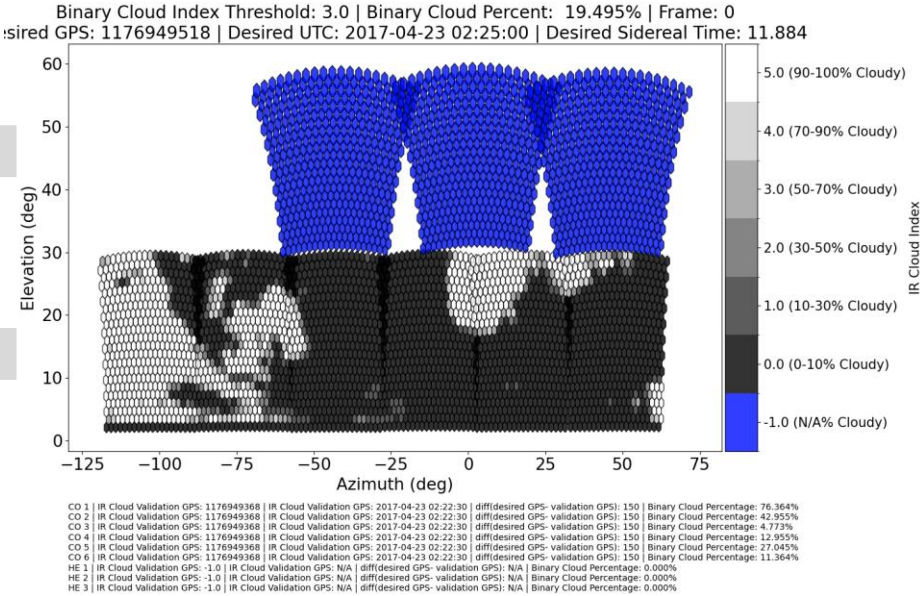
Comparison of Cloud images from NSB with IR camera data



cloudy

clear

Picture every 30 sec



Picture every 5 min

Comparison of Cloud images from NSB with IR camera data

NSB approach

- Every 30 sec
- Binary result: 0 = clear,
  1 = cloudy

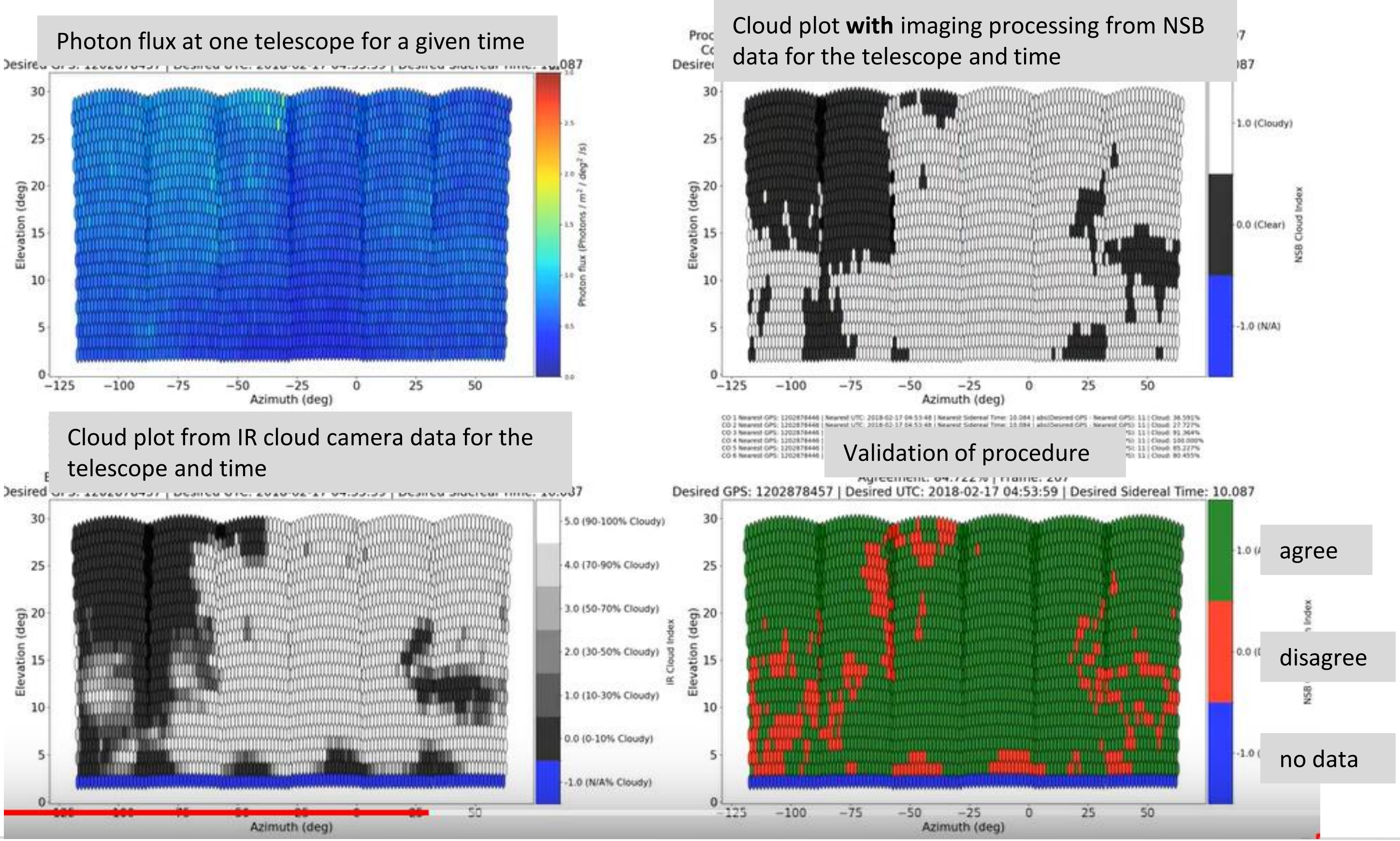
IR cloud cameras

- Every 5 min
- Cloud index range between
  0 (0%-10% cloudy) to
  5 (90%-100% cloudy),
  -1 (no data)

For comparison, adjust cloud camera index:

$$\text{Binary\_IR\_Cloud\_Index} = \begin{cases} \text{Clear (0.0)}, & \text{if } 0 \leq \text{IR\_Cloud\_Index} < 3 \\ \text{Cloudy (1.0)}, & \text{else if } 3 \leq \text{IR\_Cloud\_Index} \leq 5 \\ \text{N/A (-1.0)}, & \text{else if IR\_Cloud\_Index} = -1 \end{cases}$$

Apply thresholds derived from 2017 data to 2018 NSB data



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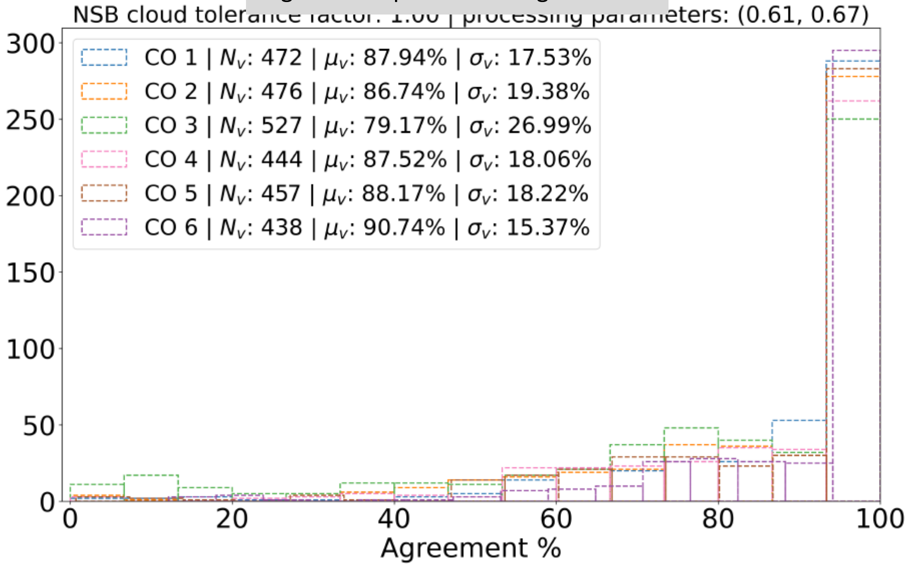
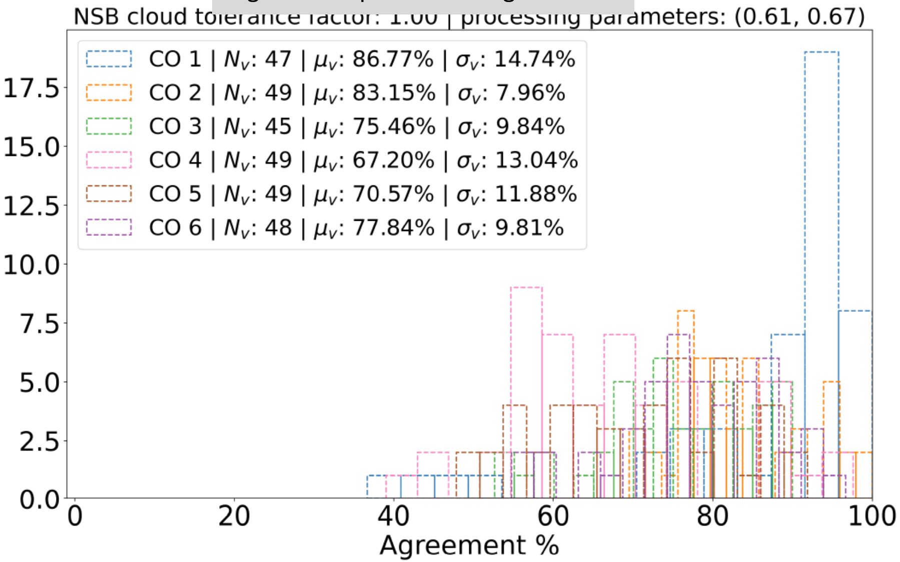
Apply thresholds derived from 2017 data to 2018 NSB data

Agreement percent histogramm



Data period February 2018

Agreement percent histogramm



Data period 6 hours on
20 February 2018 with
partially cloudy conditions

Next steps

Work in progress

- Improve threshold determination
- Evaluate the tolerance factor
- Determine the threshold for all telescopes and relevant sidereal times
- Apply this procedure to further periods and telescopes to compare with results from IR cloud cameras
- Apply this procedure to periods when no IR cloud camera data are available

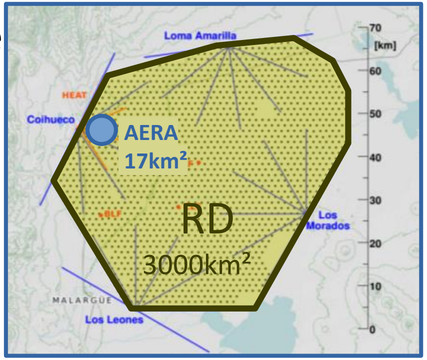
Outline of presentation

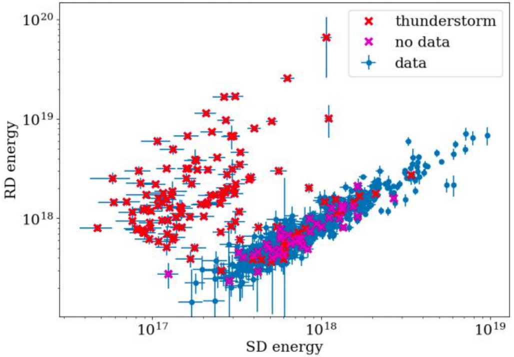
- Substitution of Cloud Cameras by Night-Sky Background data from the Fluorescence Detector
- New setup for E-field measurements and its Application to the AugerPrime Radio
- Recent developments for the Cloud Cuts to Fluorescence Detector data

New E-Field Mills at the Pierre Auger Observatory

PhD thesis by
Max Büsken, KIT Karlsruhe

- Radio detection of UHECRs maturing at the Pierre Auger Observatory
  - since 2011: **AERA** (Auger Engineering Radio Array)
  - deployment to be finished in 2024: **AugerPrime Radio Detector (RD)**
  - Measuring 30-80 MHz emission from el.-mag. air-shower component
- Radio signals get heavily altered by E-fields during thunderstorms (TS)
- Need to expand existing E-field monitoring for AERA to larger scale for RD
  - Plan presented at AtmoHEAD 2022





[M. Büsken for the Pierre Auger Collaboration, 2022 J. Phys.: Conf. Ser. 2398 012004]

AtmoHEAD 2022
Journal of Physics: Conference Series **2398** (2022) 012004 doi:10.108

AtmoHEAD

A new network of electric field mills at the Pierre Auger Observatory

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[2] Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Av. General Paz 1555 (B1630KNA), San Martín, Buenos Aires, Argentina
[3] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina (Full author list: http://www.auger.org/archive/authors_2022_06.html)
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Abstract. The Pierre Auger Observatory is the largest ground-based experiment for the detection of ultra-high energy cosmic rays. In a hybrid approach, many detectors – including radio antennas – observe the extensive air showers induced by cosmic rays. As part of the AugerPrime upgrade, new antennas will be installed on each of the surface-detector stations covering a total area of around 3000 km². This will allow us to study the mass composition of cosmic rays arriving with large inclination angles.
The radio emission of air showers is heavily influenced in the presence of strong atmospheric electric fields during thunderstorm conditions. In that case measured data are difficult to interpret and therefore the atmospheric electric field over the array has to be monitored. We present the design and status of a new network of electric field mills (EFM) that will be used to take on this task. We show how we plan to perform the measurements with an absolute calibration. In addition, the electric-field data will be useful for other studies related to atmospheric electricity.

1. Introduction
Radio emission of extensive air showers initiated by cosmic rays is well-understood [1]. The mechanisms that lead to the emission of radio signals from showers can be described as a superposition of the geomagnetic [2] and the charge-excess [3] contributions. Similarly to how electrons and positrons get deflected in the Earth's magnetic field, causing them to emit radiation, they are influenced by the presence of a strong atmospheric electric field. Under fair weather conditions this electric field is of the order of 100 V/m and its contribution to the radio emission from extensive air showers is negligible. However, during thunderstorms electric field strengths in the atmosphere can rise to levels of the order of 10 kV/m. This can amplify the radio signals by large factors and make the measurement very difficult to interpret [4, 5, 6].
Therefore, the atmospheric electric field has to be monitored permanently in the vicinity of a radio-based cosmic-ray experiment. We show how this monitoring is done so far at the Pierre Auger Observatory near Malargüe, Argentina, and present the plan for an extended network of EFMs, where we also aim for an absolute calibration of the electric-field mea… Furthermore, we show studies of the correlation between different EFM… variations of the electric field. The latter are a known phenomenon, d…

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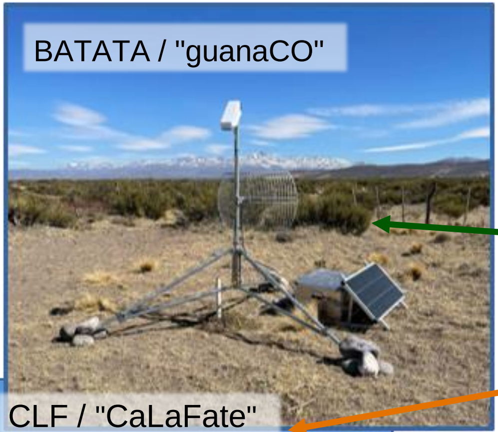
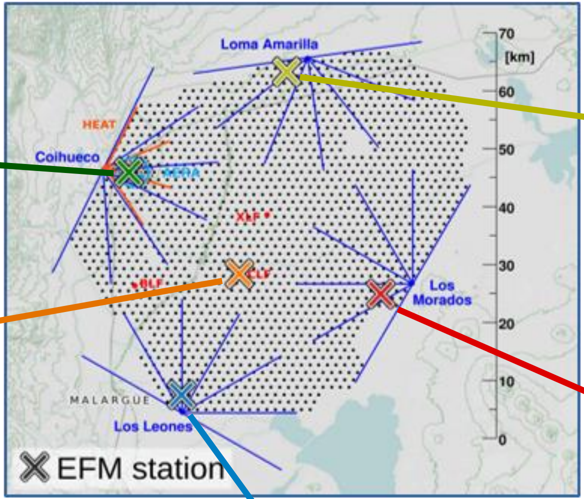
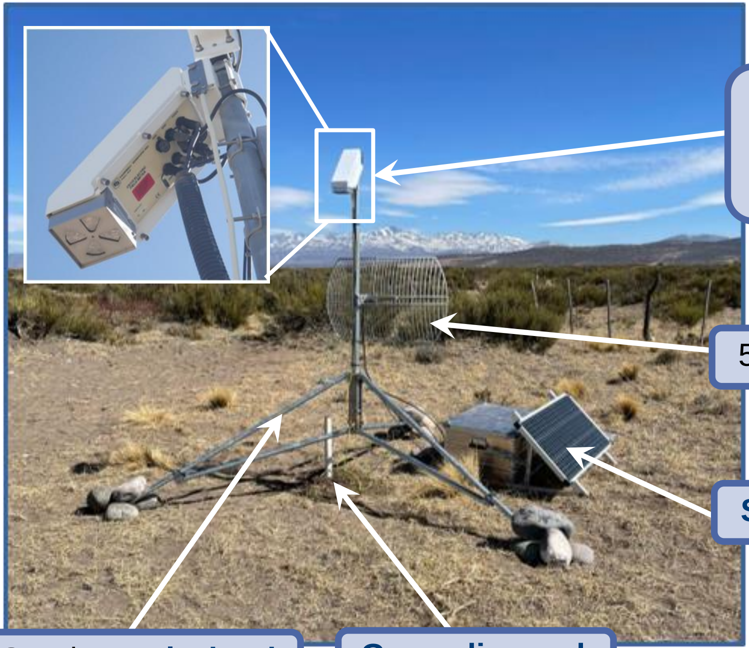
5 New E-Field Mill Stations

Deployed in Aug &Nov 2022





Design of the E-Field Mill Stations



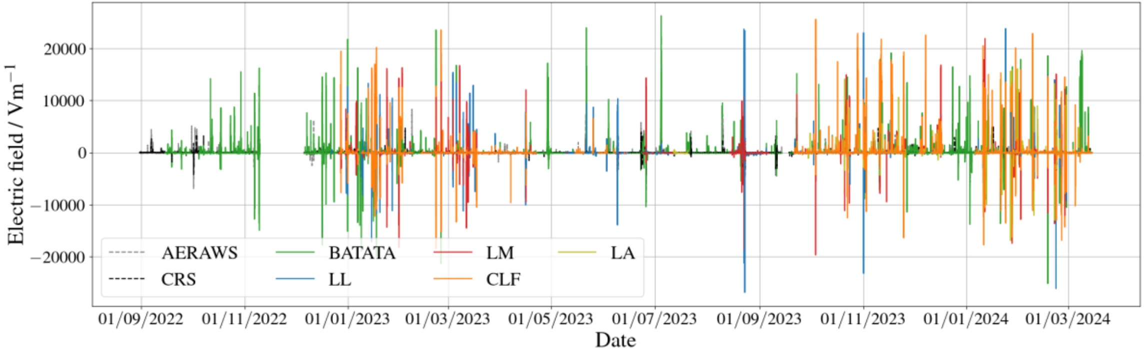
- Same design for all stations
  - Robust for 10+ years operation in the pampa
  - Meet requirement for absolute calibration of E-field measurement
    - *2 meter mounting height*
    - *No large vegetation*
    - *No buildings / objects nearby*
    - …
- Systematic uncertainty of recorded E-fields estimated at 6.5 %

Source of uncertainty	σ_E
CS110 $M_{parallel\_plate}$ calibration	1%
C_{site} calibration	4%
Expected range of drift over time	5%
Drift due to growing vegetation	?
Total estimated uncertainty	6.5%

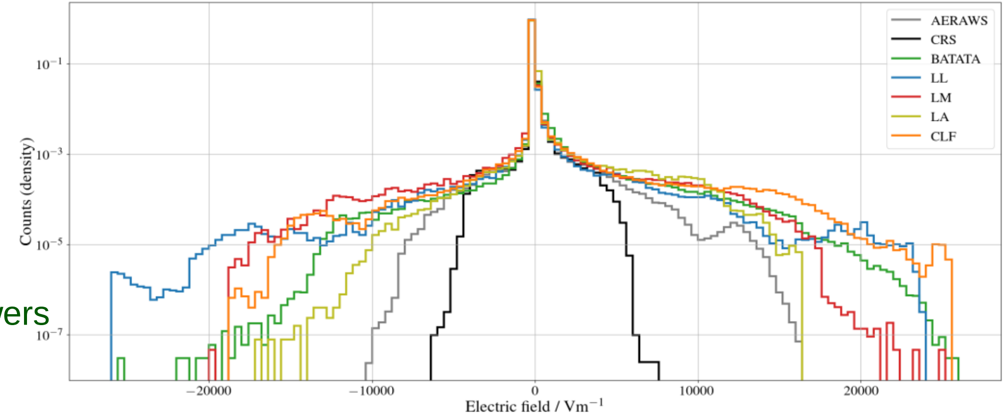
E-field Data Recorded Until Now

AERAWS & CRS:
two old EFM stations for AERA
not calibrated
close to BATATA

- Over 1.5 year of data recorded so far
  - Oct-March: high rate of TS
  - April-Sep: "TS-quiet"
- Full data to be evaluated
- Expecting cosmo-geophysics use-cases
- → please contact if interested



- Histogram shows the range of atmospheric electric fields
  - Below ±400 V/m for most of the time
  - ➢ Probably safe for radio signals from air-showers
  - Large E-fields are predominantly positive



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Large-scale TS veto for radio detection

- Goal for radio detector:
  - ➢ Construct smart "TS-Veto"
- Individual TS events give idea to track TS movement
  - ➢ partial veto of radio detector array

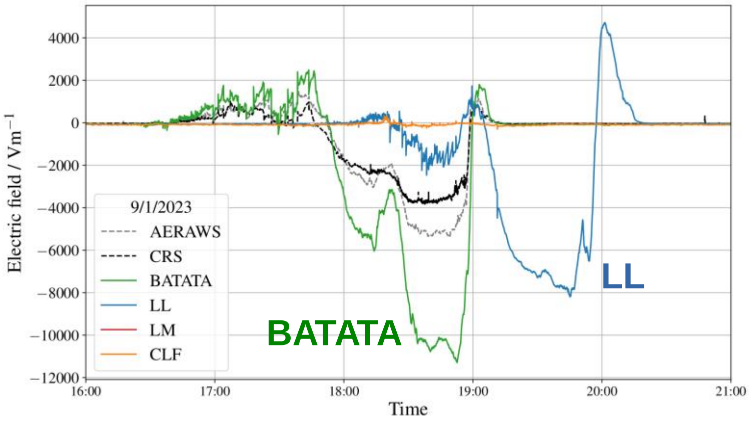
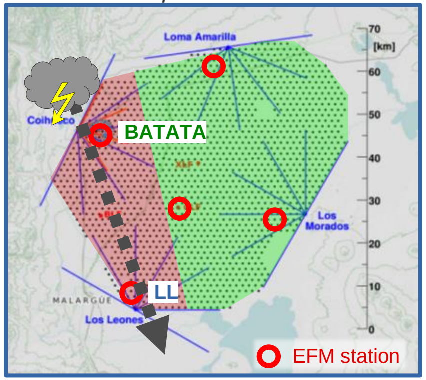
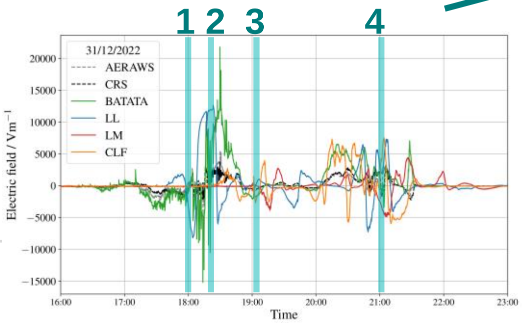
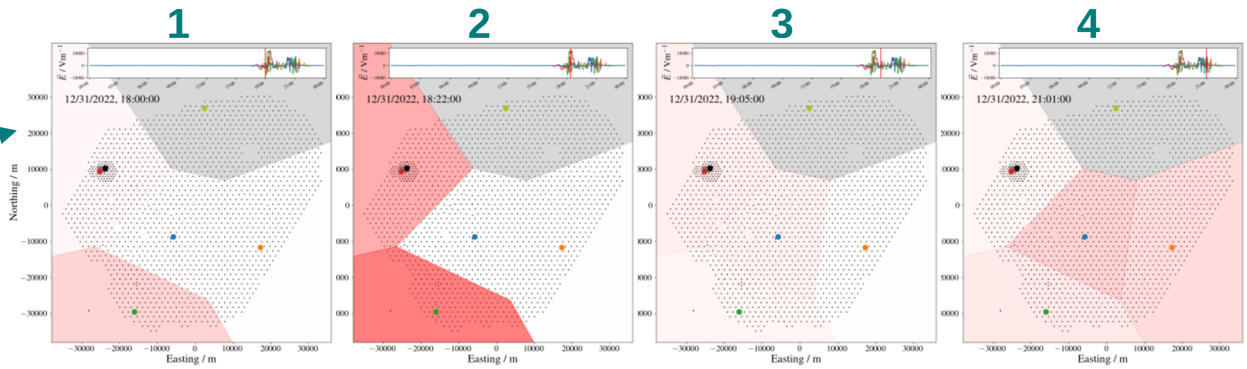


illustration of possible TS movement



- One idea: Split array into regions of closest EFM station
  - ➢ veto individual regions





color = E-field strength

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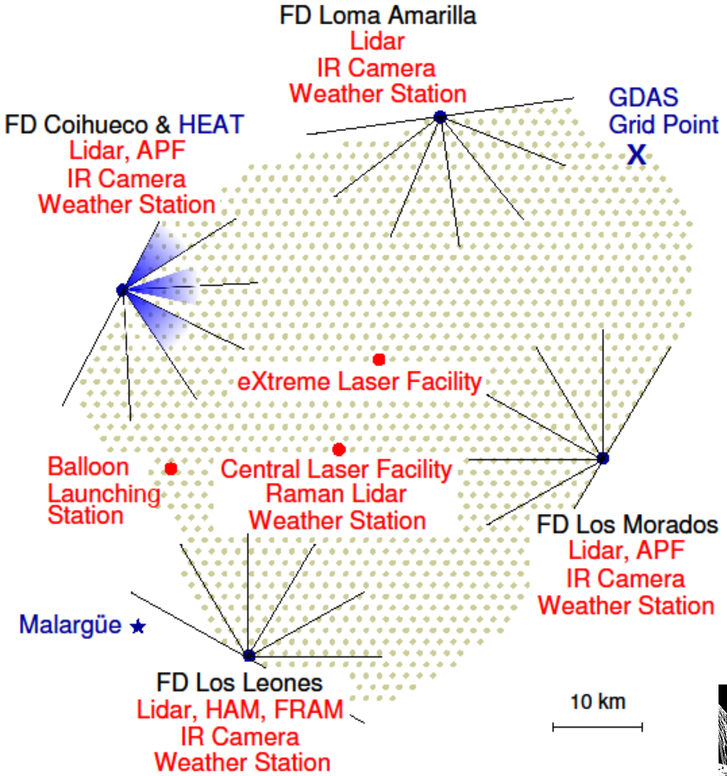
Lidar data at the Auger Observatory

Original plan to operate a lidar at each FD station

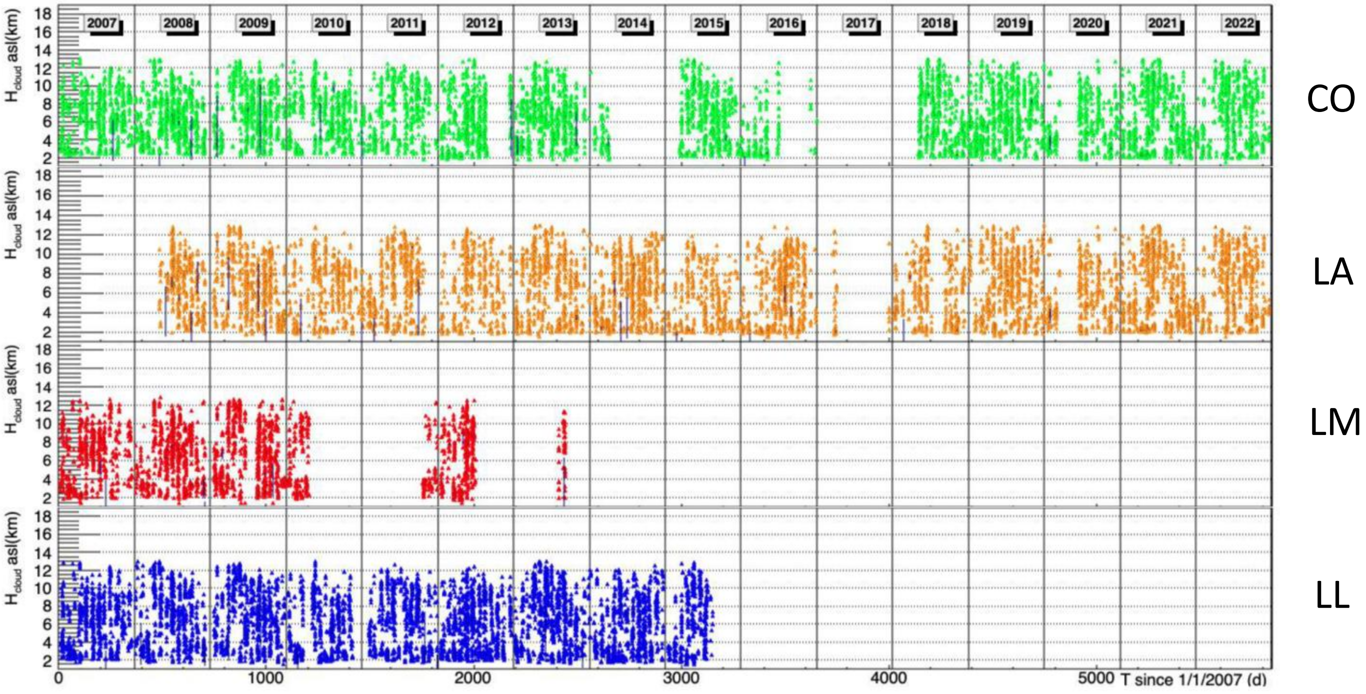
- Reanalysis of all lidar data recorded 2007 - 2022
  - At LL 2007 to mid 2015
  - At LM 2007 to March 2010, and few periods in 2011-2013
  - At LA April 2008 to 2022
  - At CO 2007 to 2022
  - With almost no data for 2017 at LA and CO
  - CO had also hardware failures for long periods in 2014 and 2016

- Average lidar data taking compared with FD data taking: 70% - 80%



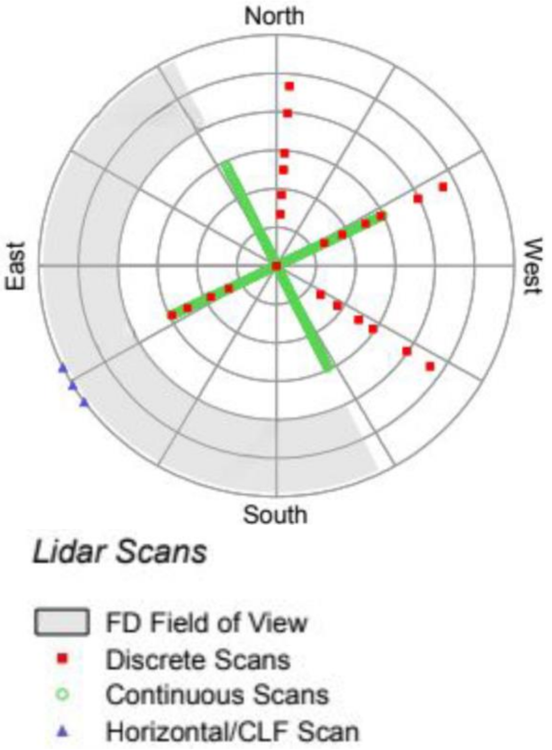
Lidar data at the Auger Observatory

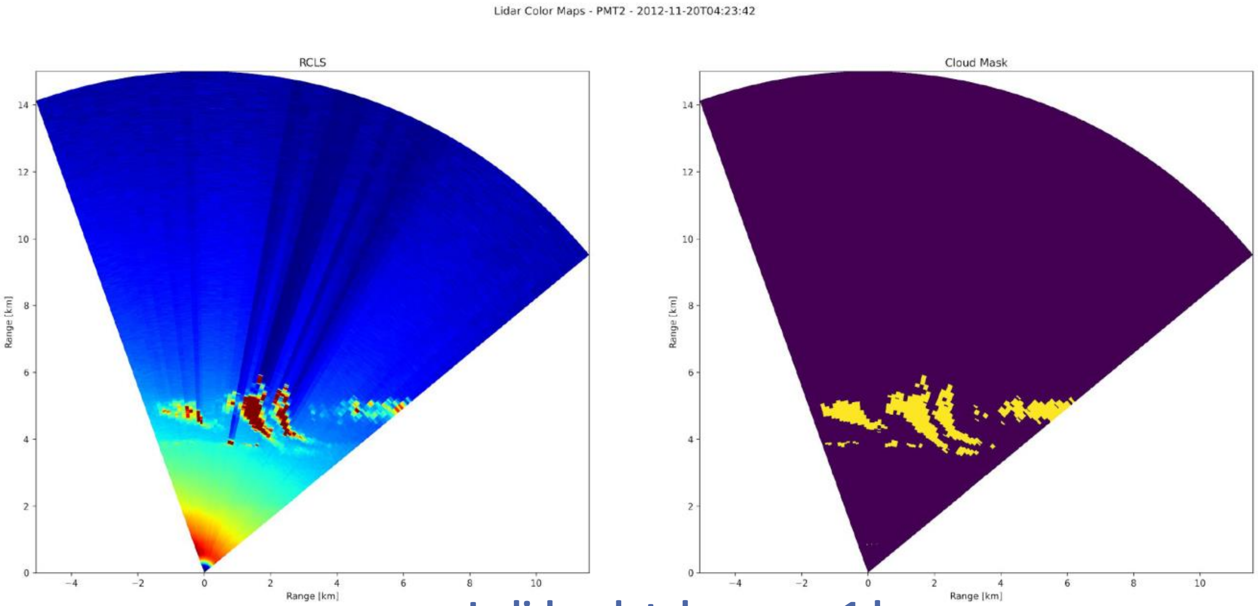
Original plan to operate a lidar at each FD station



Lidar data at the Auger Observatory

Scan procedure and cloud detection





In lidar database per 1 hour

- Cloud coverage
- Cloud base height
- Cloud optical depth

Cloud Coverage

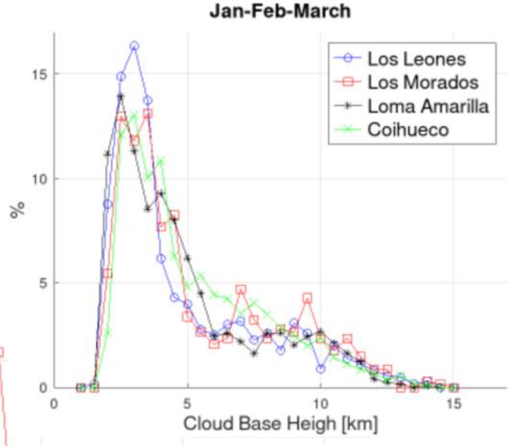
$$COV = \frac{\#Lidar\ Profiles\ with\ Clouds}{\#Total\ Lidar\ Profiles\ of\ the\ Scan}$$

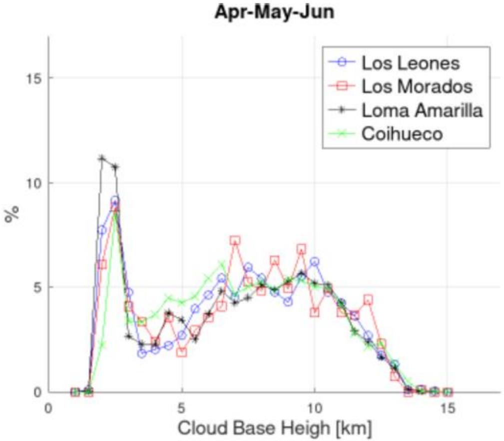
Site	Tot. Meas. Hours	COV ≤ 0.1 (COV=0)	0.1 < COV < 0.9	COV ≥ 0.9
LL	11256	43 % (42 %)	14 %	43 %
LM	5174	48 % (46 %)	15 %	37 %
LA	16293	53 % (51 %)	18 %	29 %
CO	17180	52 % (51 %)	17 %	31 %

- Assuming 20% - 30% of FD data taking with NO lidar DAQ
- About half of the missing lidar data are due to bad weather conditions
- Then low cloud coverage almost equal to highest cloud coverage

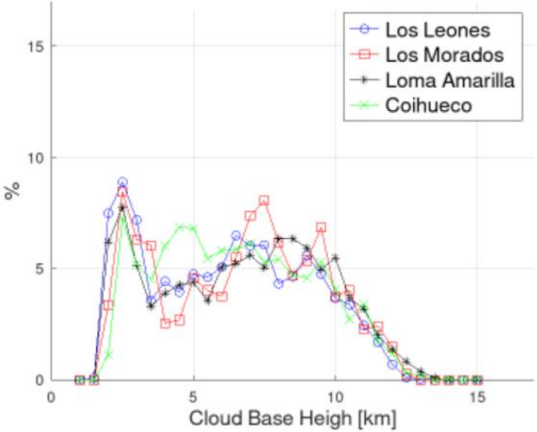
Cloud Base Height

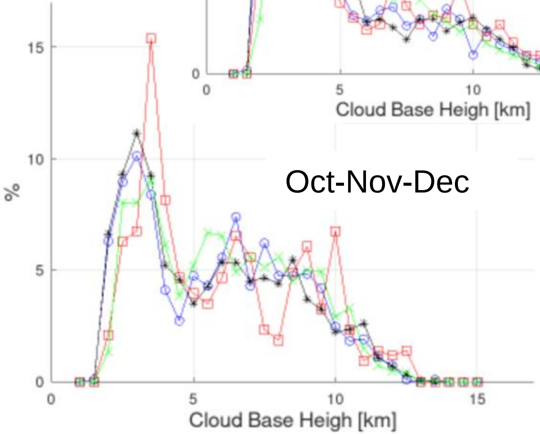
Plots only for conditions with clouds, cloud-free periods are excluded





Jul-Aug-Sep





Oct-Nov-Dec

Homogeneity between FD sites

Based on coincident period between the two respective sites and on cloud coverage

	LL	LM	LA	CO
LL	X	28 %	23 %	24 %
LM	36 %	X	22 %	23 %
LA	34 %	38 %	X	19 %
CO	39 %	39 %	44 %	X

$COV \geq 0.9$ on both sites

$COV \leq 0.1$ on both sites

- Under low cloud coverage conditions, CO and LA agree best (nearest sides)
- … and LA and LL agree least (farest sides)
- Under high cloud coverage conditions, CO behaves special because of downwind turbulances from the Andes

Homogeneity between FD sites

Based on coincident period between the two respective sites and on cloud base height

	LL	LM	LA	CO
LL	X	55 %	55 %	58 %
LM	30 %	X	59 %	57 %
LA	28 %	28 %	X	55 %
CO	26 %	24 %	30 %	X

H_{ij}:CBH $>$ 5 km on both sites

L_{ij}:CBH $\leq$ 5 km on both sites

- If clouds are high, they are typically at more than 1 site
- Lower clouds are often more local
- Adding up these conditions of agreement, the pair LM-LA are most homogeneous, while LM-CO is maximal inhomogenious

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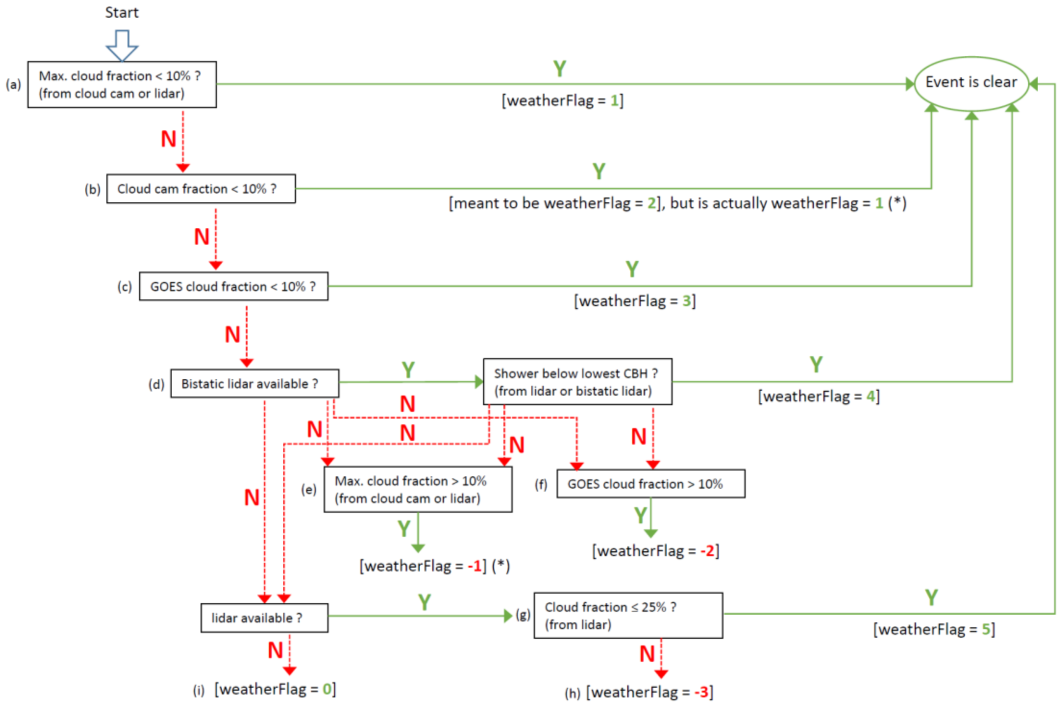
Application of lidar DB to CR events detected with FD

Discarding of CR events based on cloud cameras, GOES satellite, lidars, and bistatic lidars



for high-level analyses, only weatherFlag = 1 is accepted

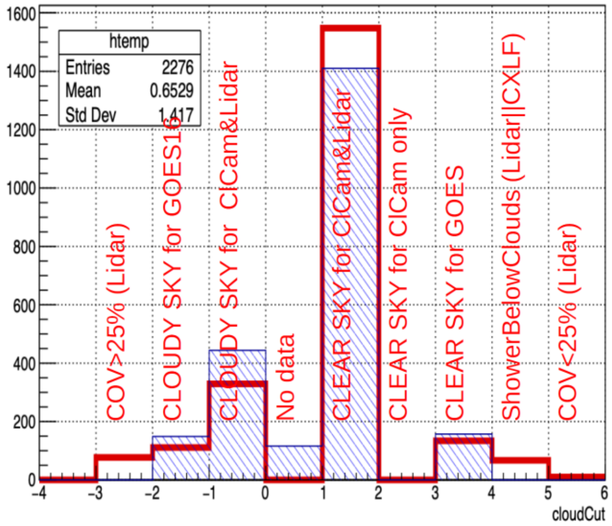
(*) currently two cases are not properly separated
=> work in progress

Ongoing studies to evaluate the influence of the upgraded lidar DB

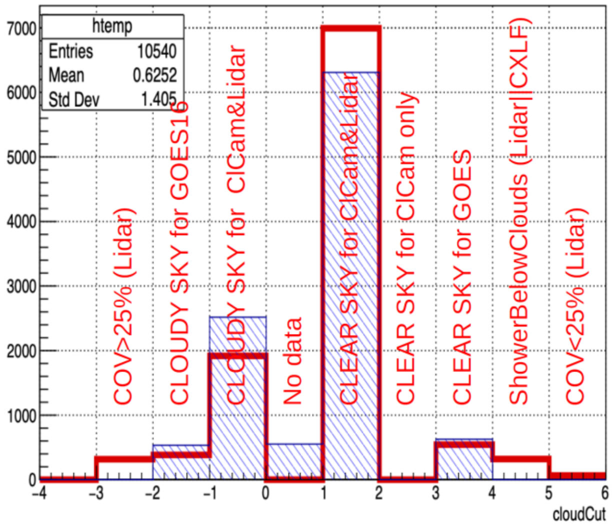
Check of the frequency of different cuts

- Blue: no lidar data available
  Red: with upgraded lidar DB

E> 3·10^{18}eV



E< 3·10^{18}eV



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Ongoing studies to evaluate the influence of the upgraded lidar DB

Work in progress

- Compare typically E and X_{max} of CR events with weatherFlag=1 for
  - Old vs new lidar data analysis
  - Cloud camera vs lidar data based decisions

- Check particularly new „survived“ CR events which are classified based on the new lidar DB as „below cloud base height“

Summary

- The Pierre Auger Observatory improves continuously its atmospheric monitoring for aerosols, clouds, and electric fields
- An alternative method for cloud detection has been developed
- A new net of electric field mills has been installed to meet the requirements for the new Radio Detector of the AugerPrime upgrade
- The lidar data of all years have been analysed and will be part of the standard CR reconstruction quality assurance soon