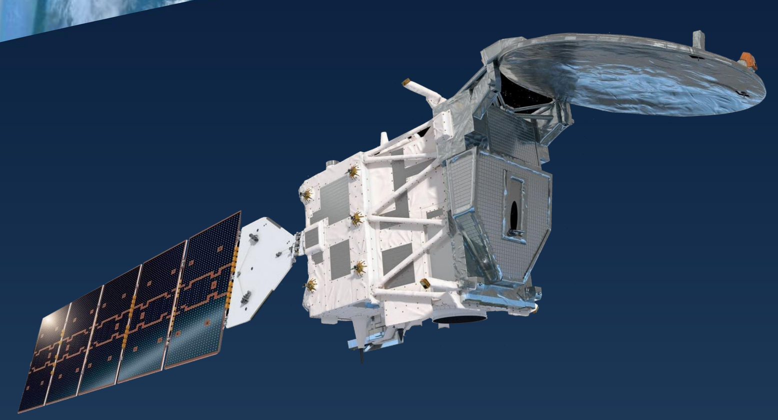

Ground Measurements of the ATLID Laser Beam at Ultra-High-Energy Cosmic Ray Observatories

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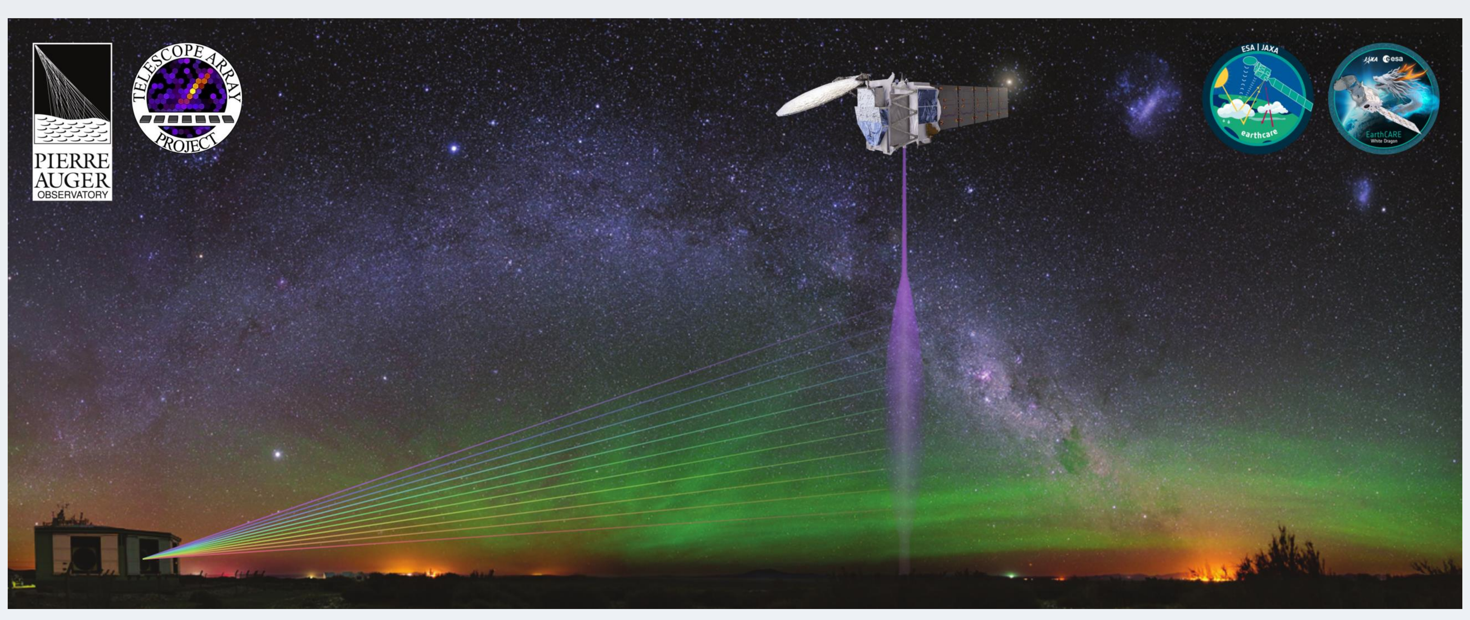
Earth Observation Meets Astroparticle Physics

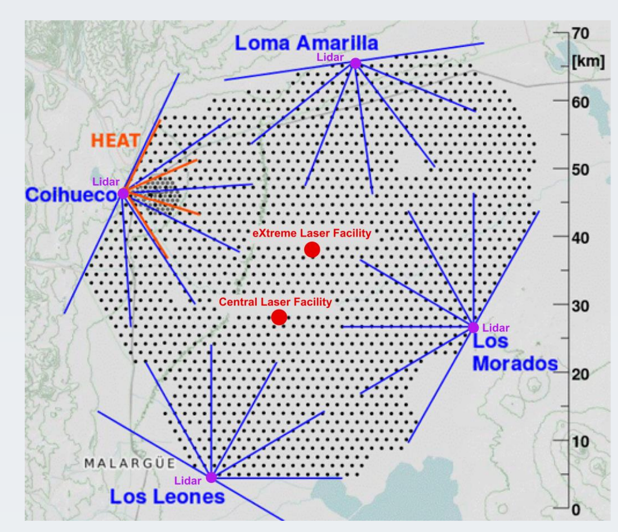
- **Bridging space and ground science:** ATLID's laser pulses are observed by the Pierre Auger Observatory (Argentina) and Telescope Array (USA), linking satellite remote sensing with astroparticle research.
- **Laser beam detection mimics cosmic ray fluorescence:** Ground-based telescopes record side-scattered UV light similarly to cosmic ray air showers, enabling precise reconstruction of the laser beam path.
- **Ground-truth validation for satellite performance:** These regular observations provide independent verification of ATLID's laser energy and geolocation of its ground track.
- **ATLID as a "calibration star":** Coordinated observations from both hemispheres help cross-calibrate the energy scales of Auger and TA which is essential for mapping ultra-high-energy cosmic ray origins.
- **Mutual benefits across disciplines:** This collaboration improves the accuracy of the EarthCARE mission while enhancing astrophysical insights into the most energetic particles in the universe.



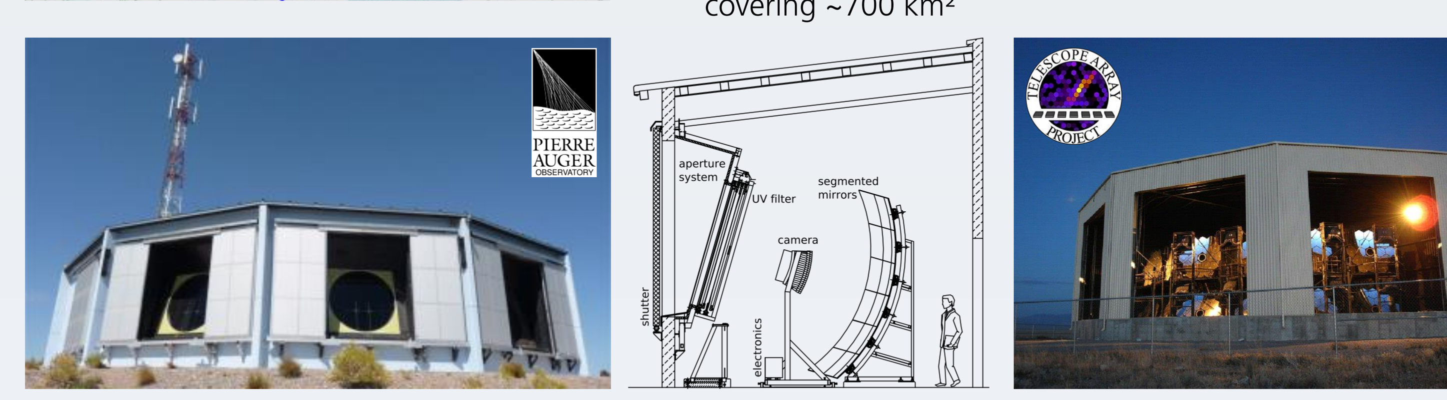
Artist's impression of the EarthCARE satellite passing over a fluorescence detector site of the Pierre Auger Observatory. The ultraviolet laser beam from the satellite's space-based lidar instrument is scattered by molecules, clouds, and aerosols as it travels through the atmosphere. The scattered light is detected in a manner similar to the fluorescence light emitted by secondary particles resulting from high-energy cosmic radiation. (Graphic: S. Saffi, O. Lux)

Pierre Auger Observatory and Telescope Array Project

- The **Pierre Auger Observatory** (Argentina) and the **Telescope Array Project** (USA) are the **world's leading experiments** for measuring **ultra-high-energy cosmic radiation** in the Earth's atmosphere.
- One method is **fluorescence detection in the UV wavelength range** between 280 nm and 430 nm.



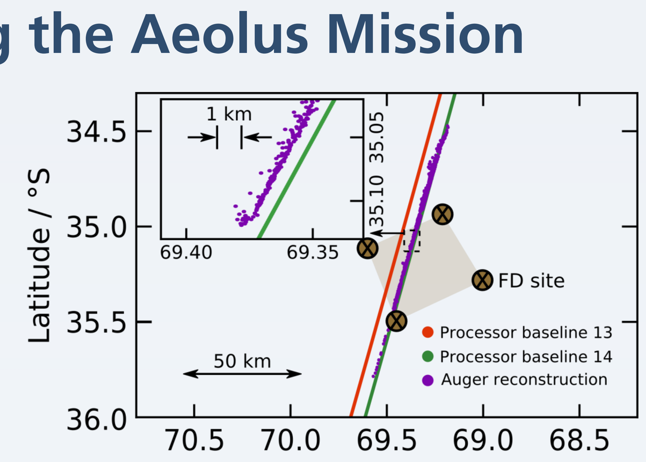
- **Pierre Auger Observatory:**
  - 4 fluorescence detector sites spaced ~40 km apart
  - 24 telescopes (13 m² aperture), each with 440 PMTs
  - 1,660 surface detector tanks, each filled with 12 t of ultra-pure water, covering ≈3,000 km²
  - Extensive lidar equipment (elastic backscatter, Raman) for aerosol characterization and instrument calibration
- **Telescope Array Project:**
  - 3 fluorescence detector sites arranged in a 30 km triangle
  - 38 telescopes, each with 256 PMTs
  - 507 scintillator surface detectors on a square grid, covering ~700 km²



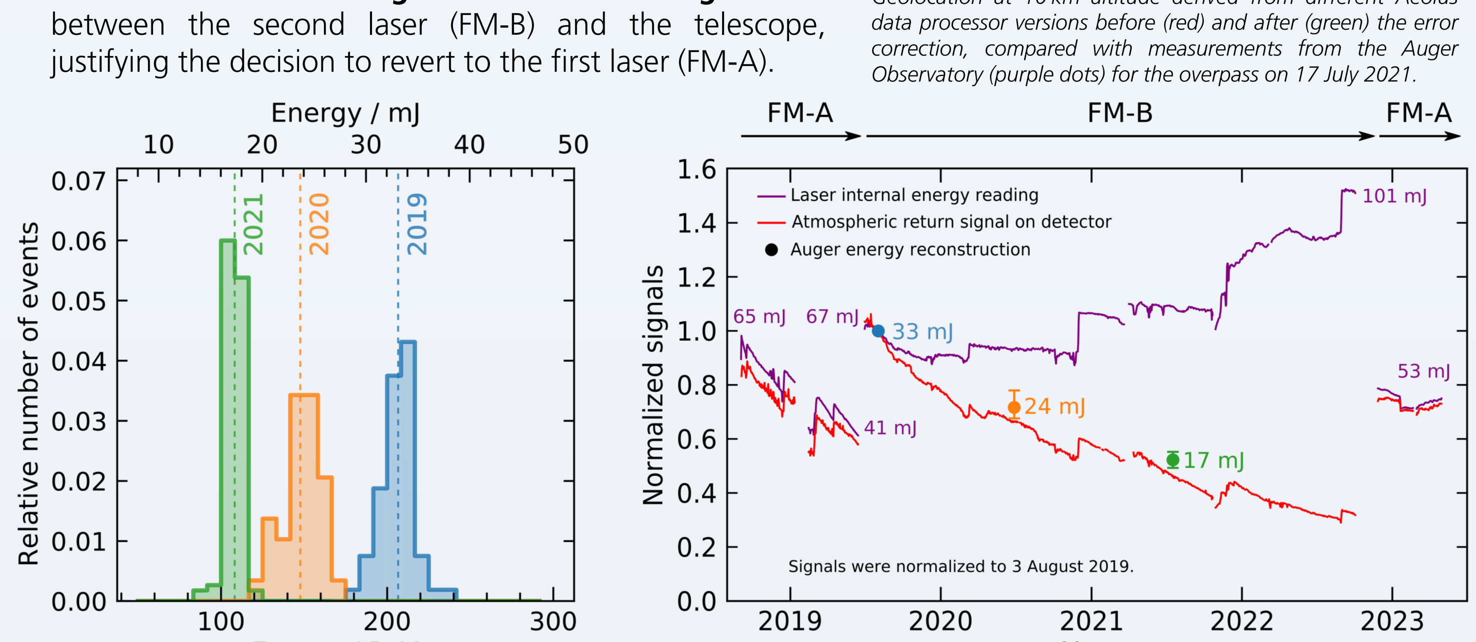
Top left: Map of the Pierre Auger Observatory in Argentina showing the locations of the four fluorescence detector (FD) sites and their individual fields of view (blue lines) along the perimeter of the surface detector array (black dots). Bottom left: Photograph of one FD site containing six fluorescence detectors. Middle: Schematic illustration of a fluorescence detector. Bottom right: Photograph of a similar FD site from the Telescope Array Project in Utah, USA.

Auger Observations During the Aeolus Mission

- **Pioneering detection of UV laser pulses** at Auger from ESA's Doppler wind lidar onboard the Aeolus satellite [1].
- **Accurate reconstruction of the beam path** through the atmosphere, revealing key performance details of Aeolus:
  - Accurate determination of the laser beam ground track
  - Independent measurement of the emitted laser energy
- **Improvement of the ground track accuracy** from 7 km to 1 km by identifying an error in the Aeolus L1 processor.
- **Confirmation of the origin of instrument's signal loss** between the second laser (FM-B) and the telescope, justifying the decision to revert to the first laser (FM-A).



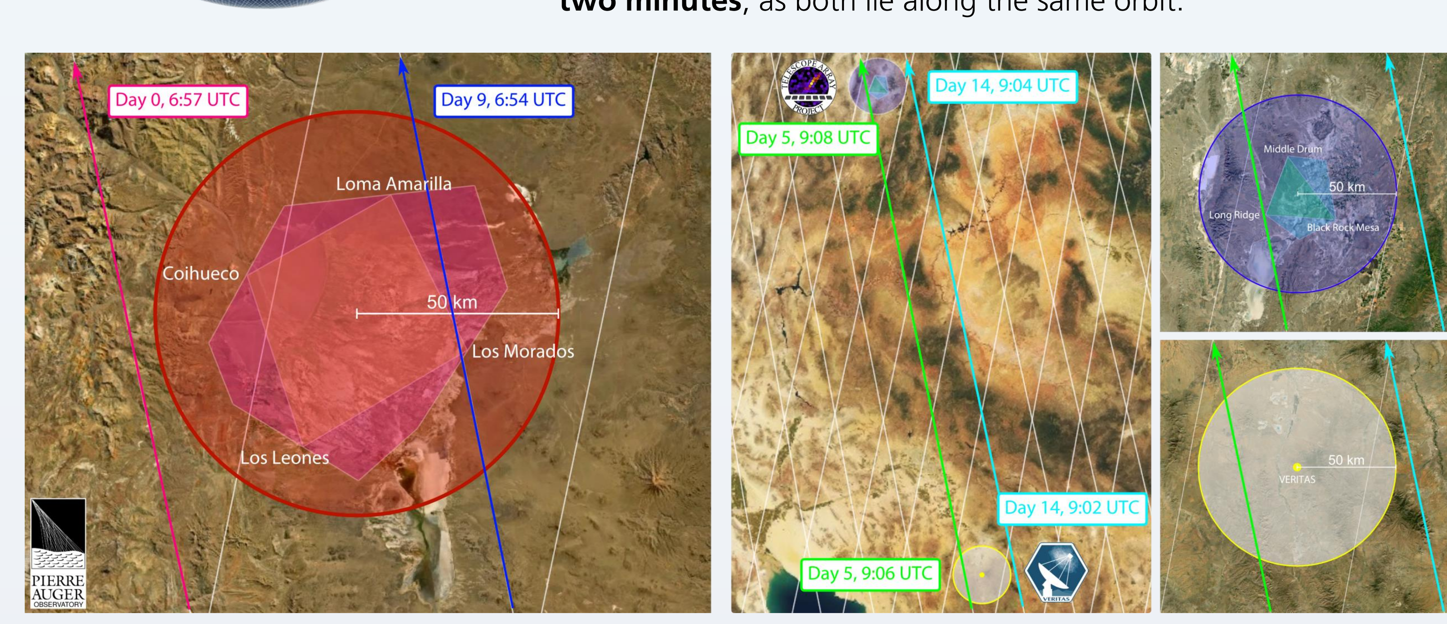
Geolocation at 10 km altitude derived from different Aeolus data processor versions before (red) and after (green) the error correction, compared with measurements from the Auger Observatory (purple dots) for the overpass on 17 July 2021.



Left: Reconstructed laser pulse energies for three Aeolus overpasses of the Pierre Auger Observatory during the FM-B period (2019–2021). Right: Signal evolution of the laser energy (purple line), the atmospheric return signal under clear-air conditions (red line), and the Auger measurements (colored dots).

EarthCARE Overpasses of the Ground Observatories

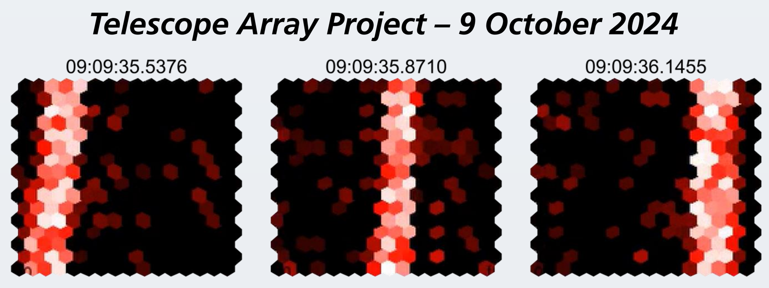
- Each observatory experiences **two EarthCARE overpasses during each 25-day orbital cycle**.
- **Dark conditions for ascending orbits are available year-round**, except the weeks around the full moon.
- **Aeolus was only visible at Auger from May to August** due to its dawn–dusk orbit.
- **VERITAS observations** (gamma-ray detection with four Cherenkov telescopes) **require precise azimuth and elevation predictions** because of the telescopes' narrow 3.5° field of view.
- **Telescope Array and VERITAS overpasses occur within only two minutes**, as both lie along the same orbit.



Maps showing the overpass trajectories of the ATLID laser beam over the Pierre Auger Observatory (left) and the Telescope Array Project (right) during one orbit repeat cycle of 25 days. The right panel also includes overpasses of the gamma-ray observatory VERITAS in Arizona, USA.

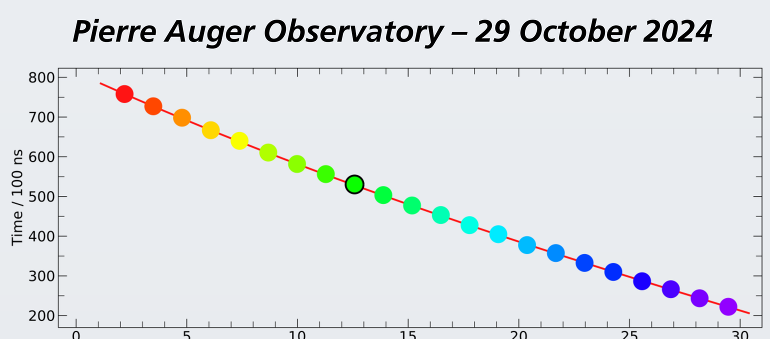
Detection of the ATLID Laser Beam

Telescope Array Project – 9 October 2024

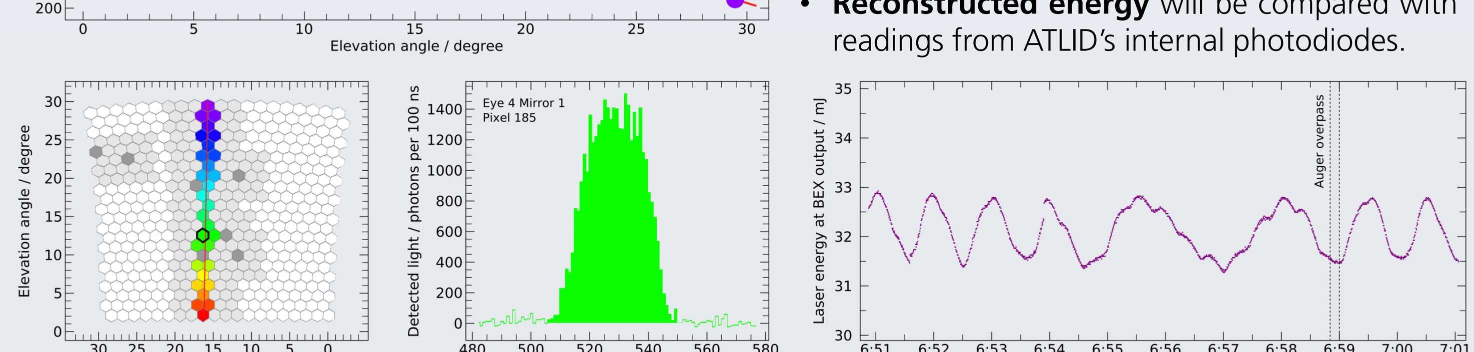


Camera images from one of the 14 fluorescence detectors at Black Rock Mesa, part of the TA Project, showing the detection of the ATLID laser beam passing over the observatory. The images are separated in time by approximately 300 ms.

Pierre Auger Observatory – 29 October 2024



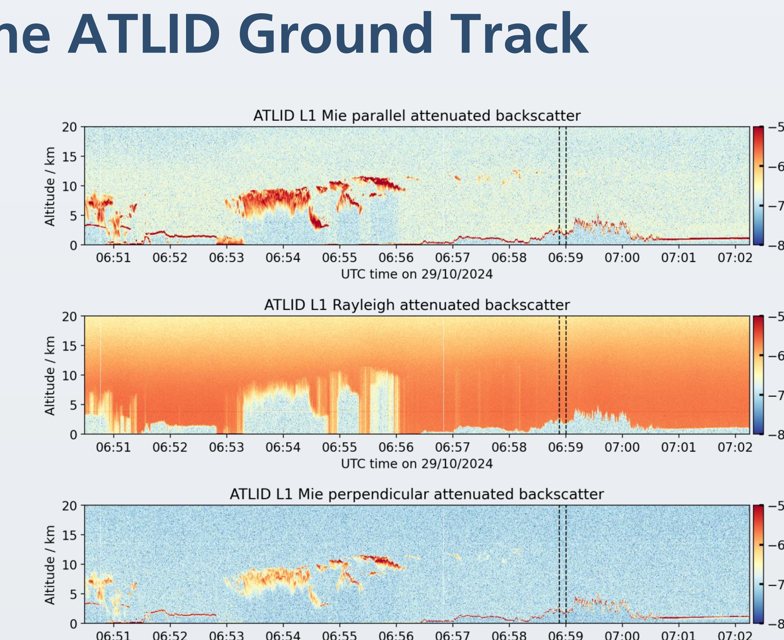
- **Multiple successful detections of ATLID's UV laser beam** at both observatories since the instrument switch-on in August 2024.
- **Strong signal recorded** across all telescopes at Black Rock Mesa (Telescope Array site) as the beam passed over the area on 9 October 2024.
- **Excellent measurement conditions** during the Auger overpass on 29 October 2024.
- **Side-scattered UV light detected** at varying times depending on telescope pointing angles.
- **Temporal signal distribution is analyzed** individually on each camera pixel (PMT).
- **Accurate energy estimation** at instrument output requires precise calibration informed by atmospheric conditions (e.g., aerosol loads).
- **Reconstructed energy** will be compared with readings from ATLID's internal photodiodes.



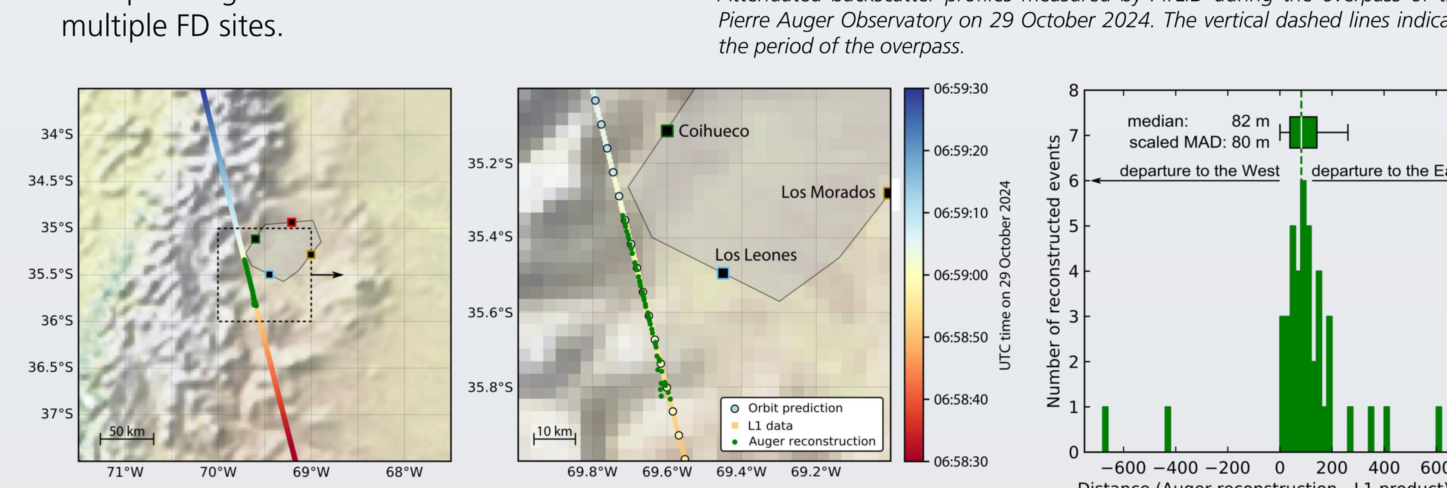
Left: Detection of the ATLID laser beam by one of the 6 telescopes at Coihueco, part of the Pierre Auger Observatory. Side-scattered UV light is recorded at different times depending on the elevation angle (top panel), and the temporal distribution of detected photons is measured for each pixel (bottom panels). Right: Temporal evolution of the UV laser energy from the ATLID lidar at the output of the beam expander (BEX) during the overpass on 29 October 2024.

Verification of the ATLID Ground Track

- **ATLID Mie and Rayleigh backscatter profiles confirm favorable conditions** during the overpass on 29 October 2024 (low aerosol content, no clouds over Auger).
- **Ground tracks from orbit predictions and the ATLID L1B product agree very well,** with only a temporal offset of a few seconds.
- **Laser beam ground track reconstructed from Auger measurements at Coihueco closely aligns with the L1B product.**
- **Median deviation is below 100 meters,** though results are still preliminary.
- **Accuracy can be further improved** by incorporating stereo reconstructions from multiple FD sites.



Attenuated backscatter profiles measured by ATLID during the overpass of the Pierre Auger Observatory on 29 October 2024. The vertical dashed lines indicate the period of the overpass.



Left: Geolocation of the ATLID laser beam ground track, as reported in the Level-1B product (color-coded squares) and as reconstructed from the FD site at Coihueco of the Pierre Auger Observatory (green dots). Right: Histogram of the spatial distance between the Auger reconstruction and the Level-1B data.

Deutsches Zentrum für Luft- und Raumfahrt

[1] The Pierre Auger Collaboration, O. Lux, I. Krisch, O. Reitebuch, D. Huber, D. Wernham, and T. Parrinello, "Ground observations of a space laser for the assessment of its in-orbit performance," Optica 11, 263-272 (2024).

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