# Satellite Data for Atmospheric Monitoring at the Pierre Auger Observatory

Speaker: Andrew Puyleart for the Pierre Auger Collaboration

07/02/2021

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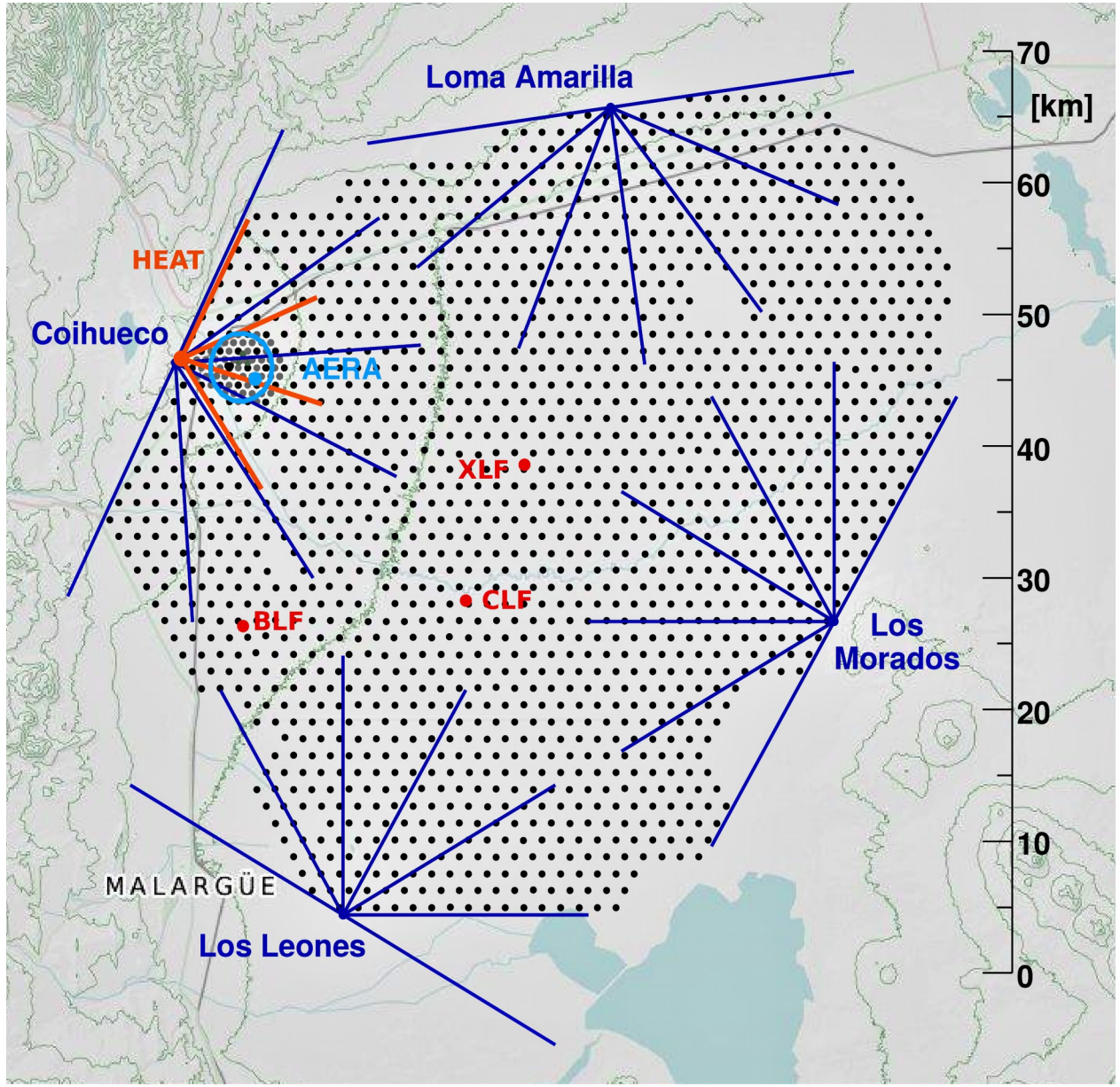
# The Pierre Auger Observatory

- Covers an area of 3000 km$^2$
- 1660 Cherenkov water tank detectors (black)
- 4 Fluorescence Detectors (blue)
- 2 laser facilities; XLF, CLF (red)
- 1 High Altitude FD (orange)
- Engineering array; AERA (teal)



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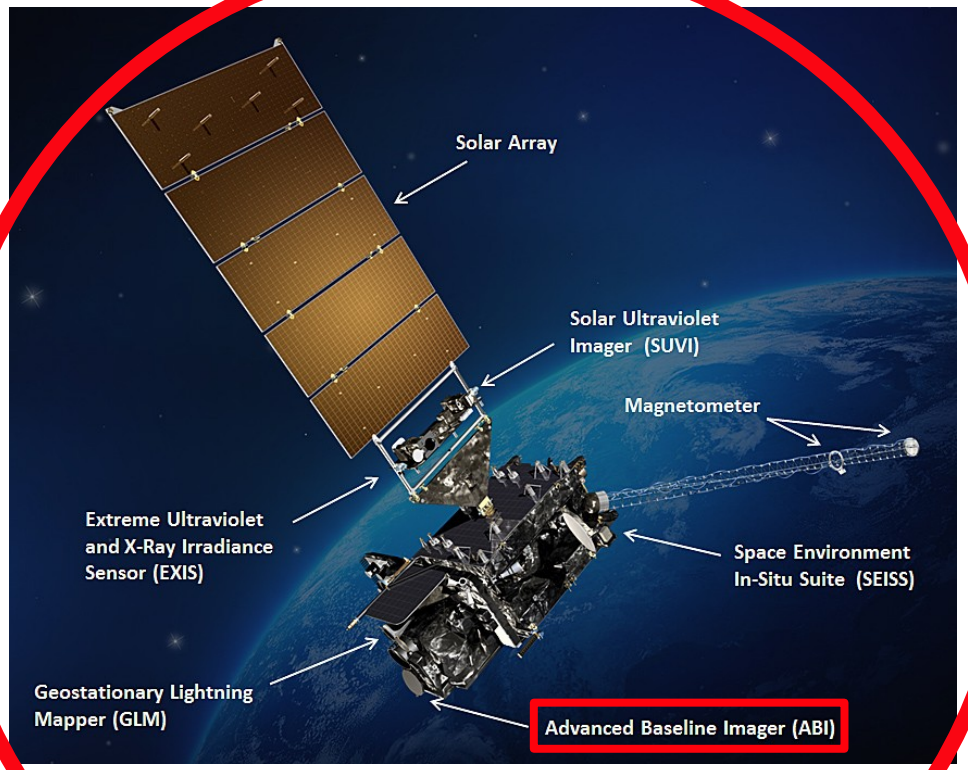
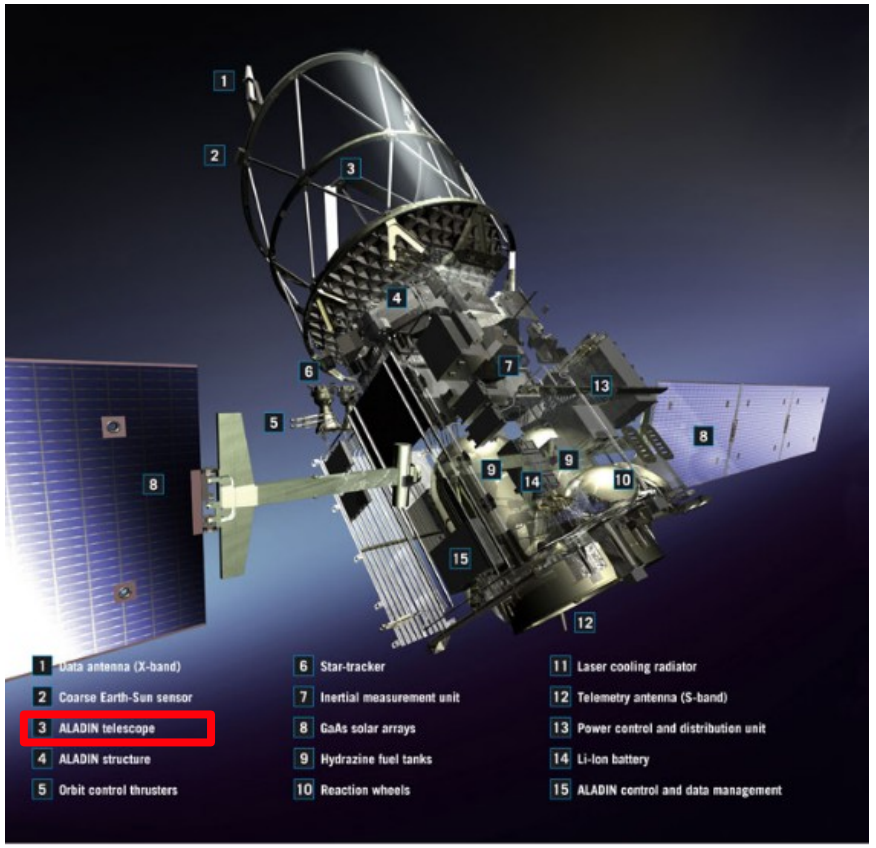
# GOES-16 and Aeolus




GOES-16

- Geostationary: Observes the same area 24 hours a day.
- Data is free to use and available on AWS.




Aeolus

- Sun-Synchronous: Has the same rotational period as Earth (pass same location at the same local time each day).
- Uses a UV lidar of 354.89nm which is visible to Pierre Auger FDs.

2. Images: https://www.goes-r.gov/spacesegment/spacecraft.html
ESA/ATG medialab

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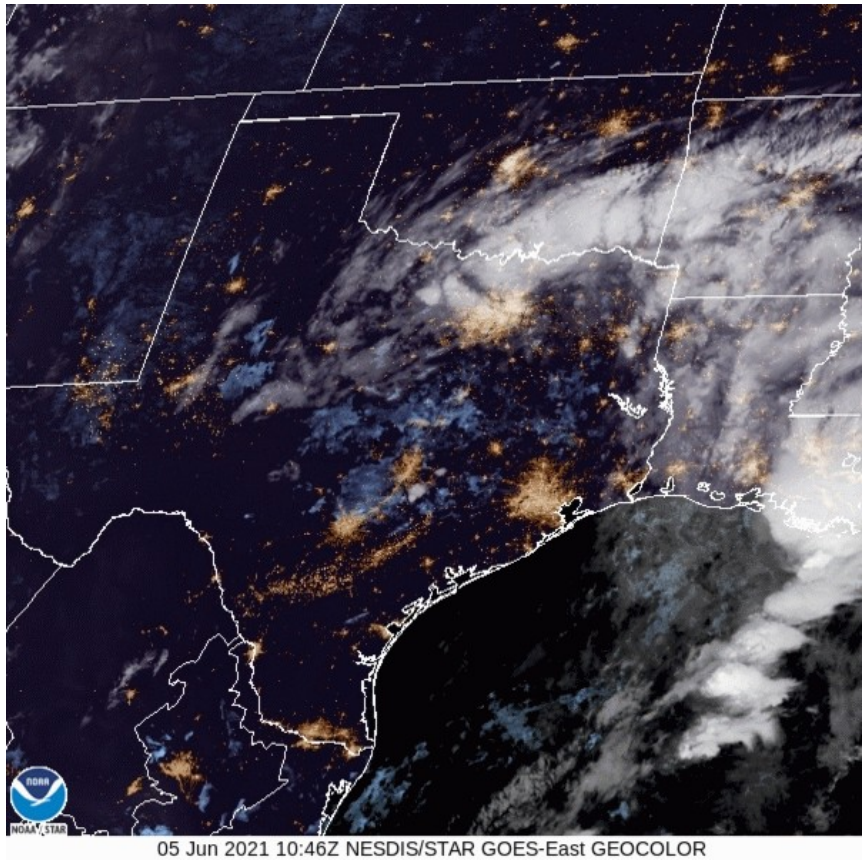
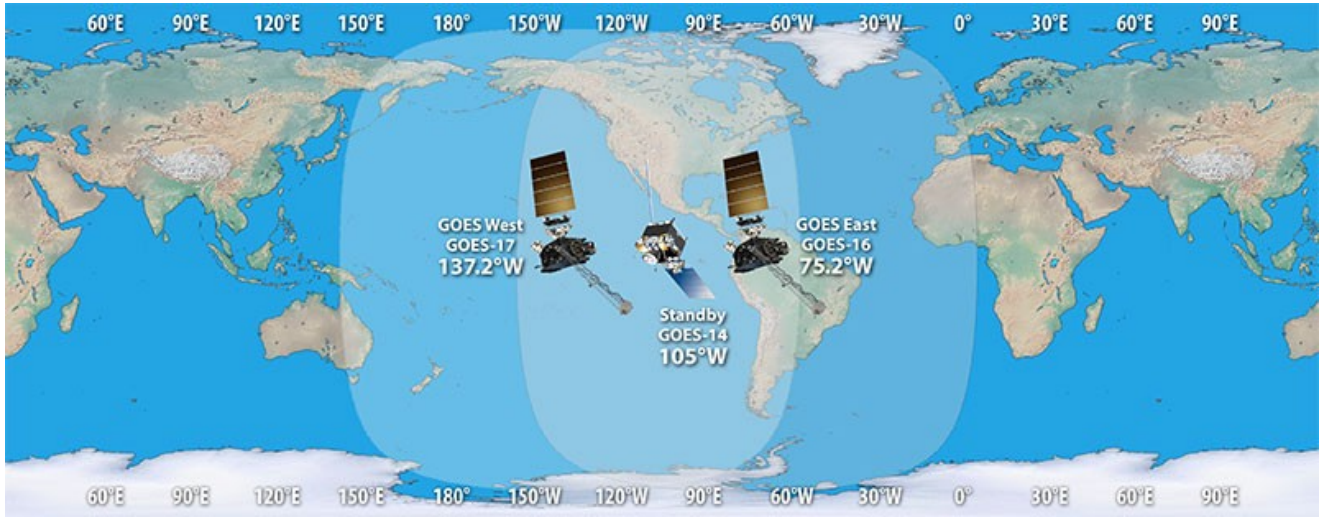
# GOES-16 Weather Satellite




GOES-16 is primarily used for weather observations.

Some of its products include: Aerosol optical depth, Ice concentration, Cloud top height, Snow cover, Total precipitation, Clear-Sky Mask.

Its observation range covers North and South America.




3. Images: https://www.star.nesdis.noaa.gov/GOES/index.php, https://www.goes-r.gov/mission/mission.html

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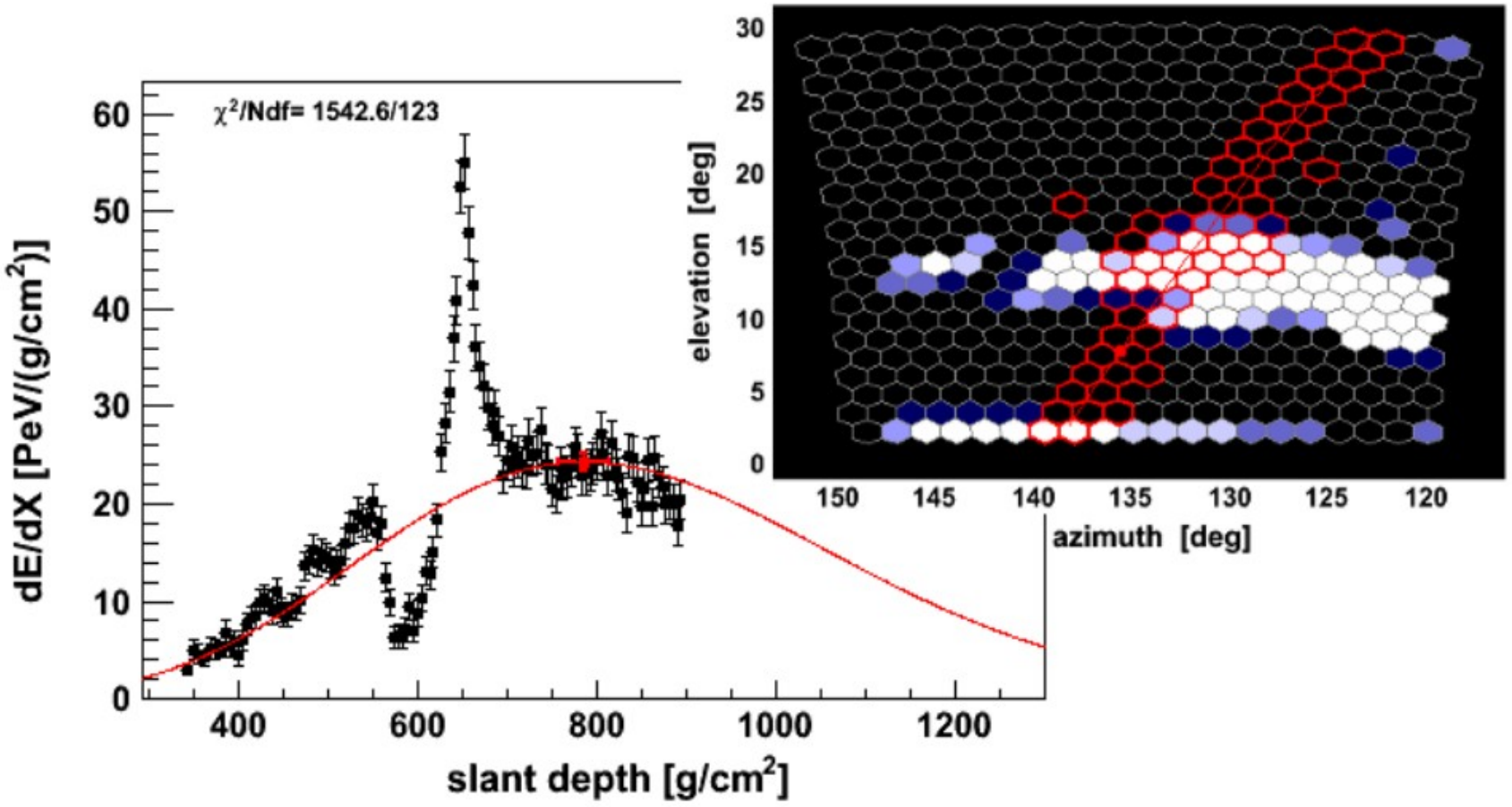
# Cloud Monitor at the Pierre Auger Observatory

- Clouds effect energy reconstruction with the fluorescence detector.
- Clouds scatter UV photons that are produced by extensive air showers.
- Cloudy air showers need to be removed from data-sets.



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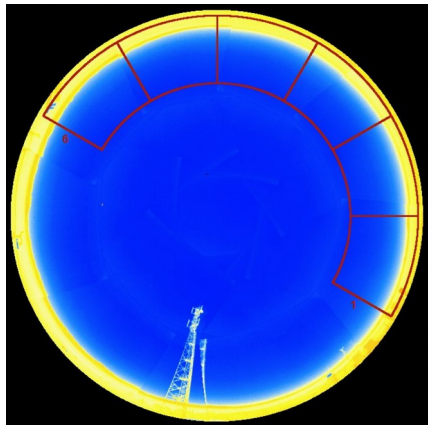
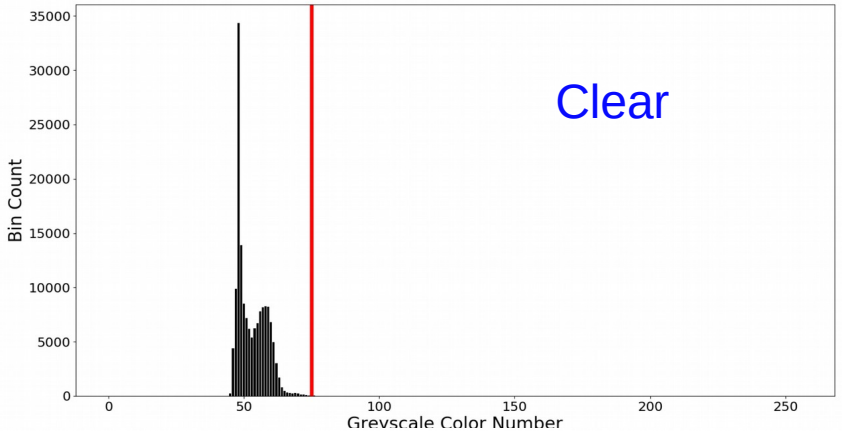
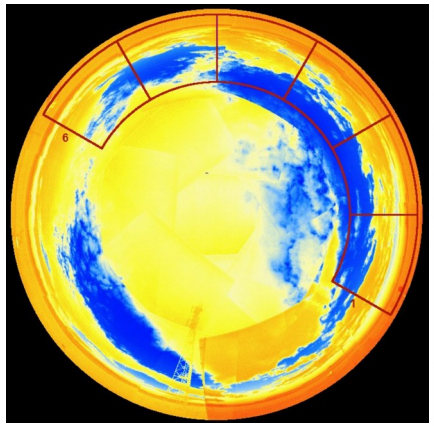
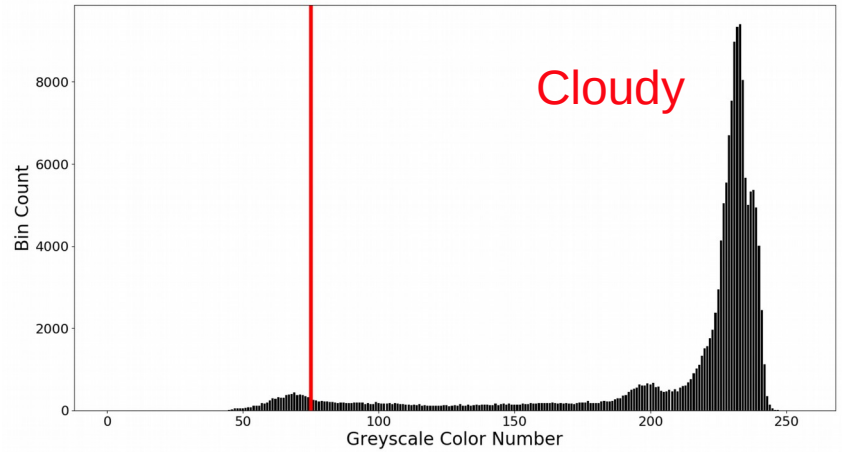
# Ground Truthing GOES-16

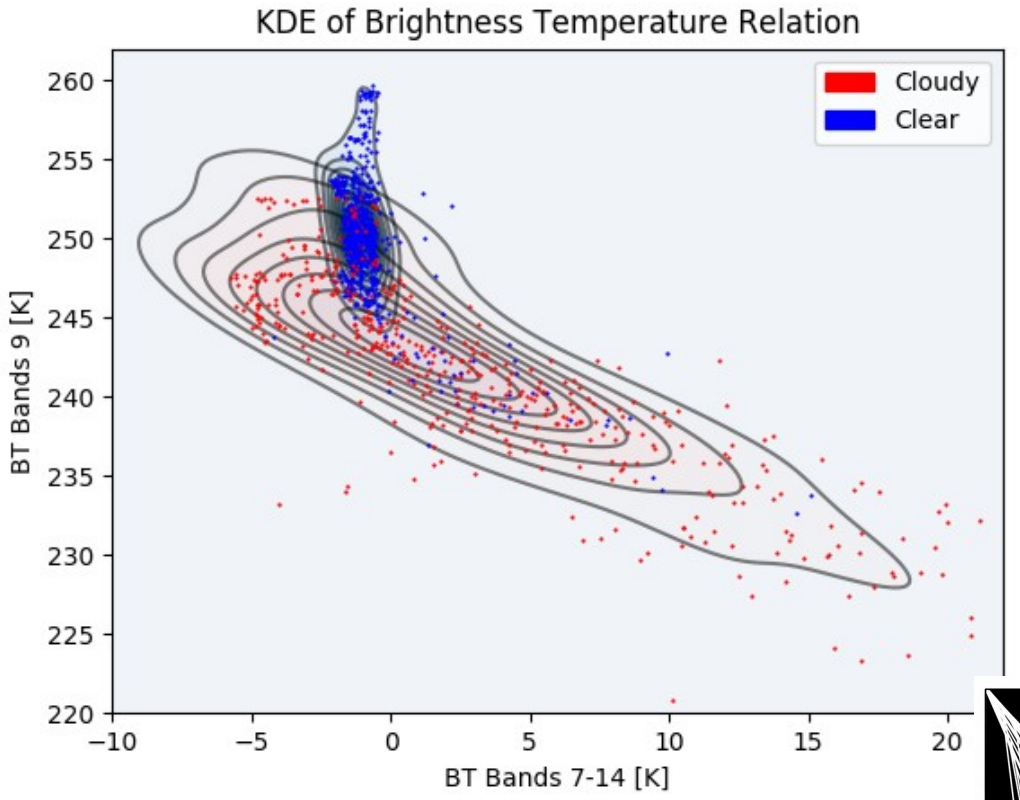
- We ground truthed GOES-16 using our cloud cameras on Los Leones.
- Camera images with large response beyond color number 75 are considered cloudy.
- Two KDE's of clear, and cloudy pixels were generated from the labeled data.







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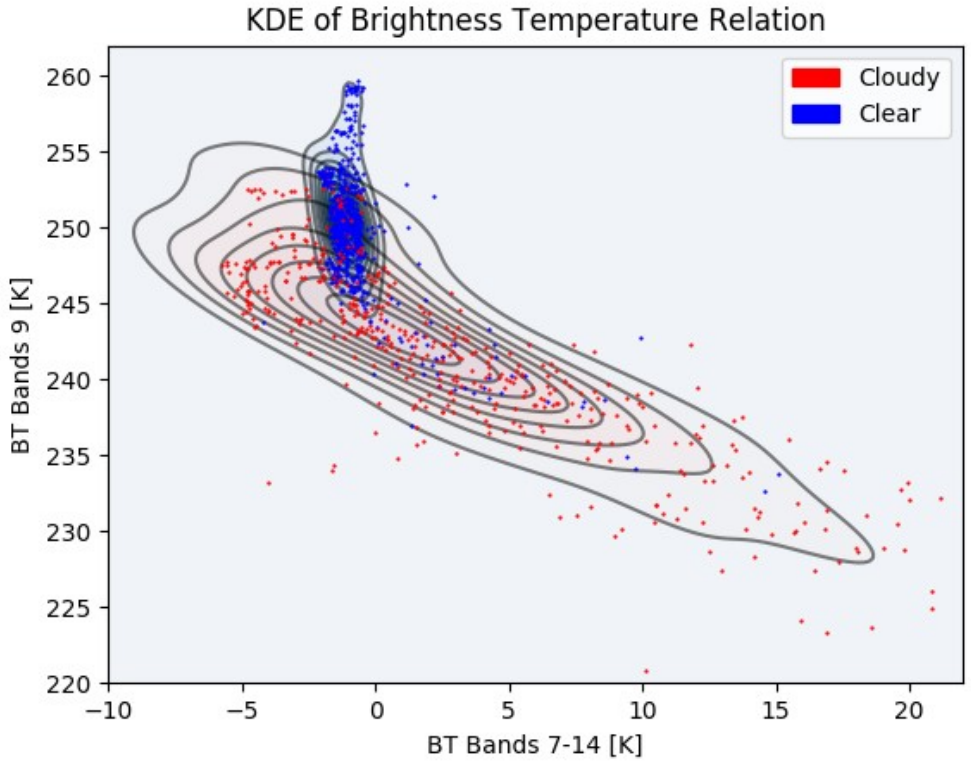
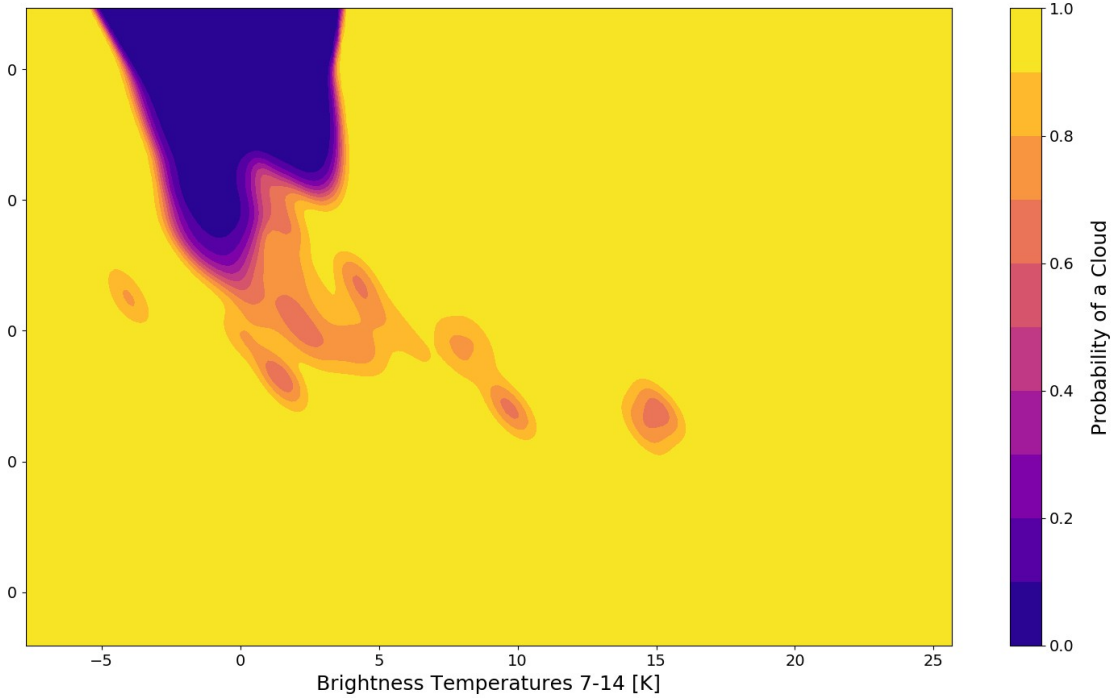
# Cloud Probability

- We used a form of Bayesian probability below and values of the KDE's to give a final probability of cloud cover.

$$P(Cloud|x) = \frac{P(x|Cloud) \cdot P(Cloud)}{P(x|Cloud) \cdot P(Cloud) + P(x|Clear) \cdot P(Clear)}$$



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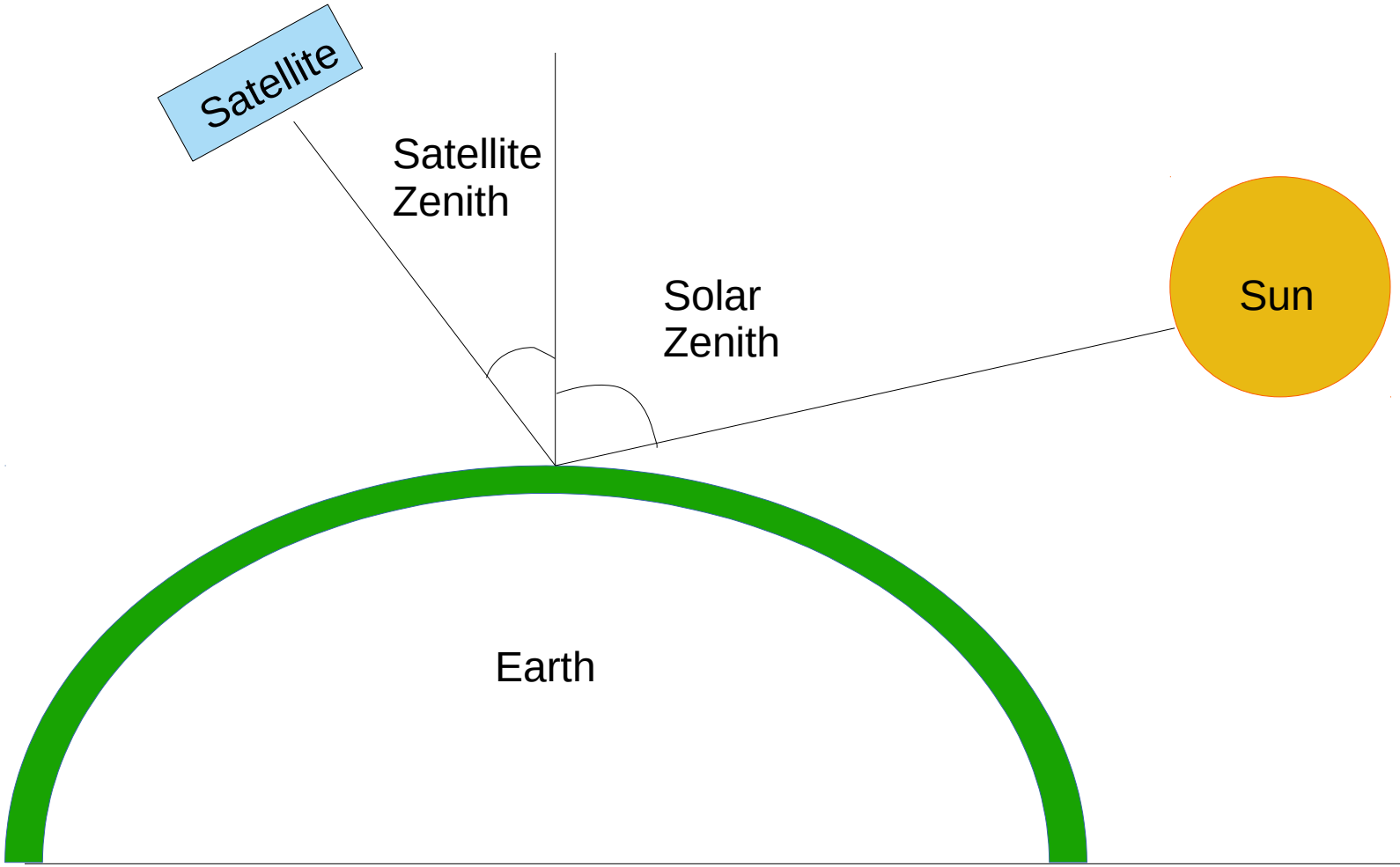
# NOAA: Clear-Sky Mask




The Clear-Sky Mask has a guaranteed accuracy of 87% when the solar zenith angle is less than 80°.

During night time hours the Pierre Auger Observatory is always at Solar zenith angles larger than 80°.

We want to optimize the night time performance of GOES-16.

# Laser Facility Test

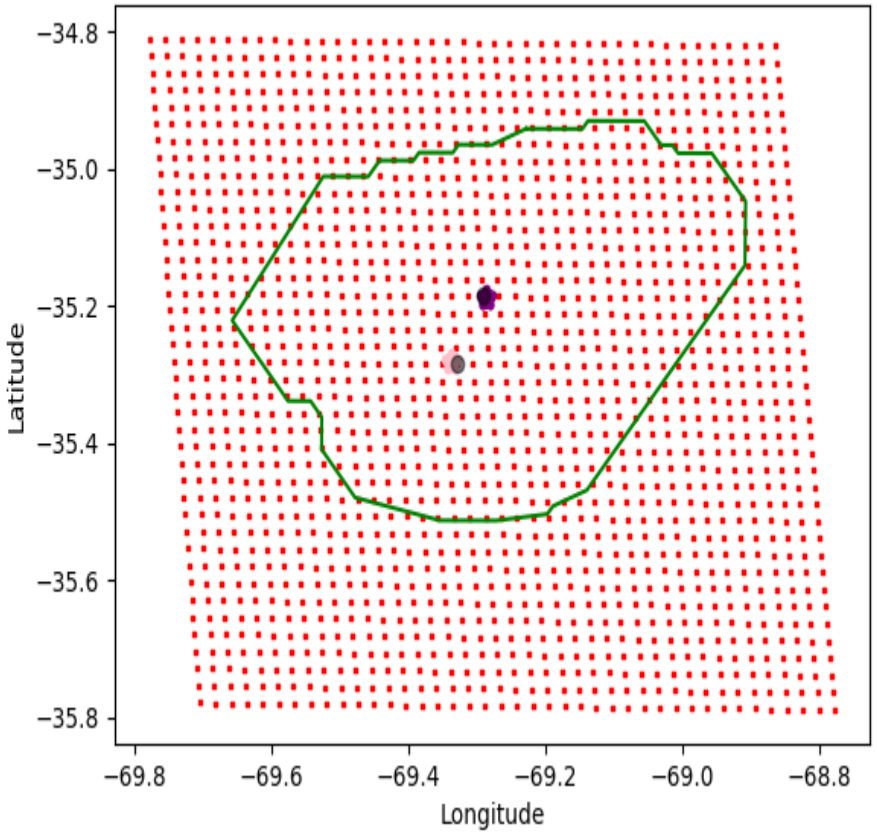


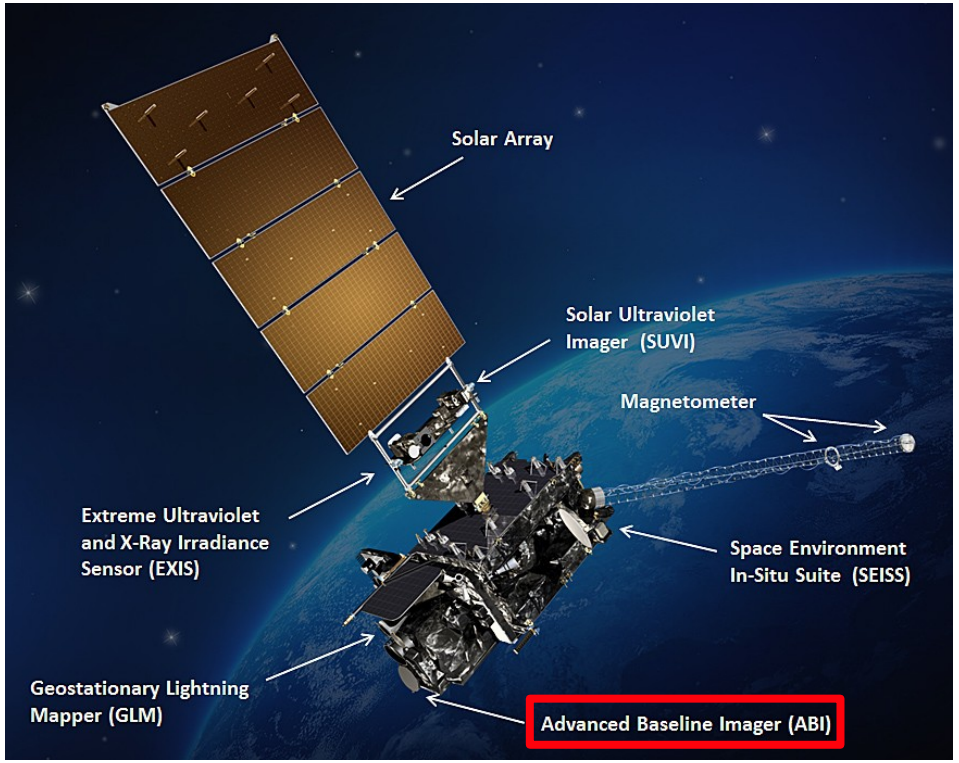

**Table 1:** GOES-16 and NOAA's Clear-Sky Mask ground-truthing with the CLF.

| CLF | Bayesian | Clear-Sky Mask |
|---|---|---|
| Agree | 387 | 156 |
| Disagree | 46 | 38 |
| Total | 433 | 194 |
| Percent Agreement | 89.4 | 80.4 |
| False Positives | 19 | 28 |

**Table 2:** GOES-16 and NOAA's Clear-Sky Mask ground-truthing with the XLF.

| XLF | Bayesian | Clear-Sky Mask |
|---|---|---|
| Agree | 677 | 258 |
| Disagree | 78 | 68 |
| Total | 755 | 326 |
| Percent Agreement | 89.7 | 79.1 |
| False Positives | 39 | 60 |

# GOES-16 and Aeolus

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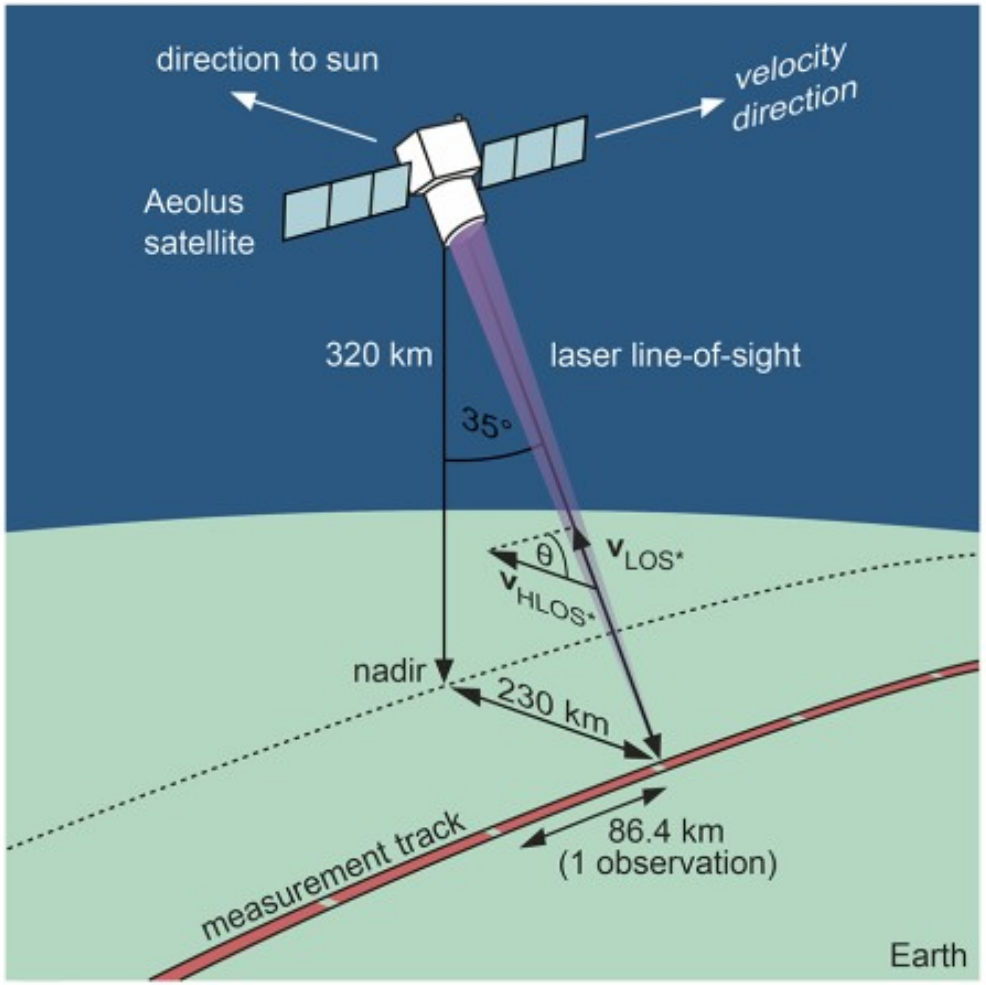
# Aeolus Satellite




Aeolus mission is to use its lidar to measure wind profiles across the globe.

The measurements Aeolus takes are used to increase accuracy of numerical weather models.

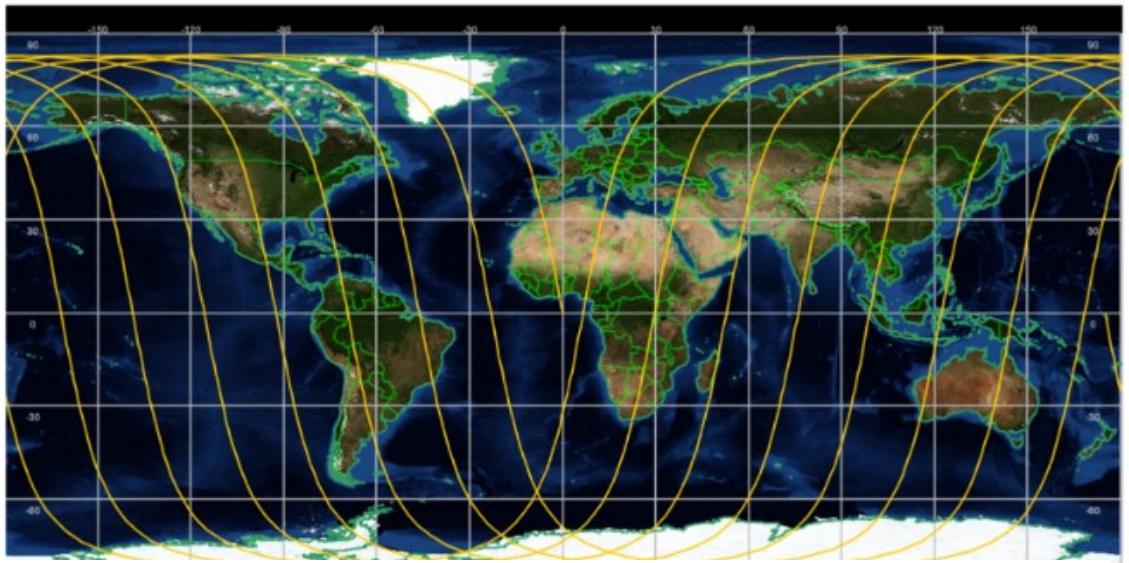
Aeolus data can also be used to study the mechanisms for aerosol, water, dust, and pollution transportation in our atmosphere.

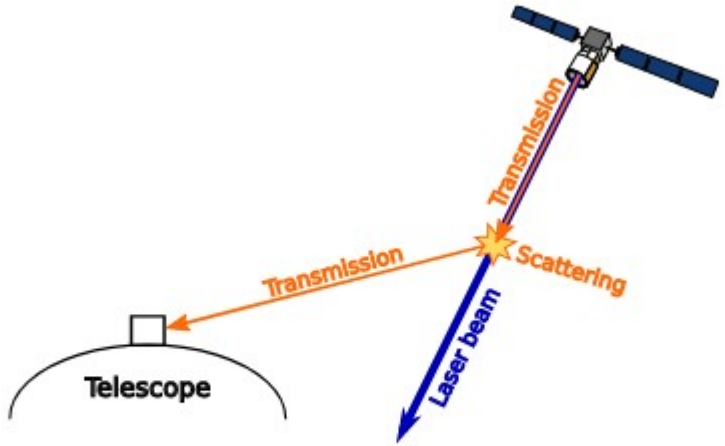


Image: https://amt.copernicus.org/articles/13/2075/2020/

# Seeing Aeolus with the FD

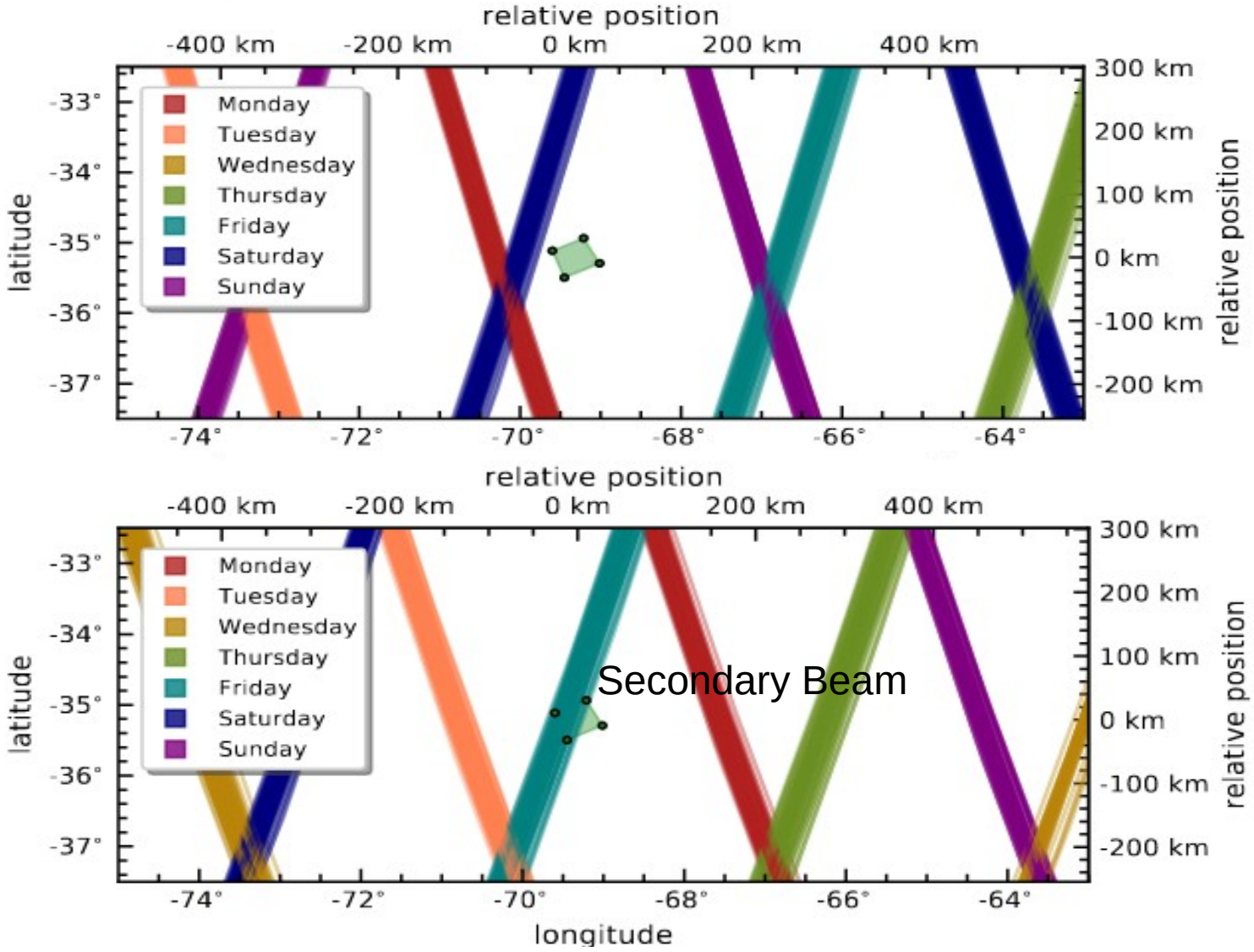
- Aeolus's Sun-Synchronous orbit passes near the Pierre Auger Observatory.
- Laser beams are detectable by fluorescence light scattering off of atmospheric particles and aerosols.
- The energy of the beam can be reconstructed with the FD with some modifications to existing code.
- The main beam is well defined in energy.
- The secondary beam is used to divert unwanted light away from optical instruments in the Aeolus satellite and is not well documented but stated to have ~1% of the main beams energy.



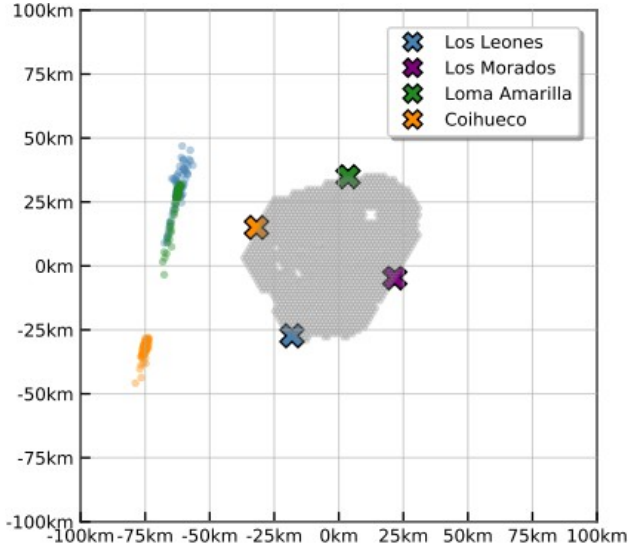



11. Images: P. Ingmann et al., ADM-Aeolus Mission Requirements Document. Science Division, 2016. ESA Mission

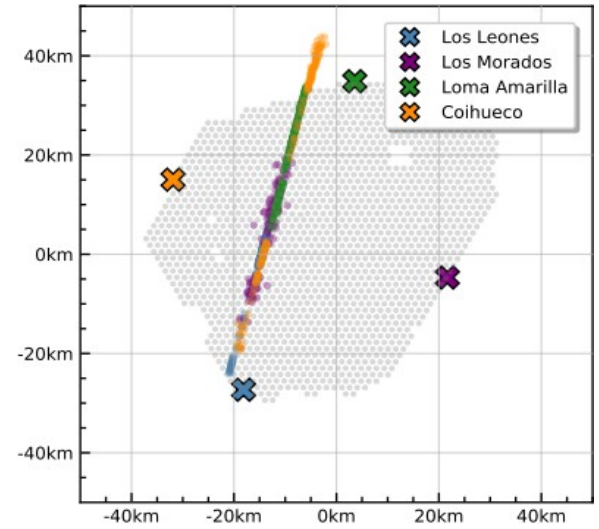
# Aeolus Passes




Secondary Beam




Main Beam




Secondary Beam



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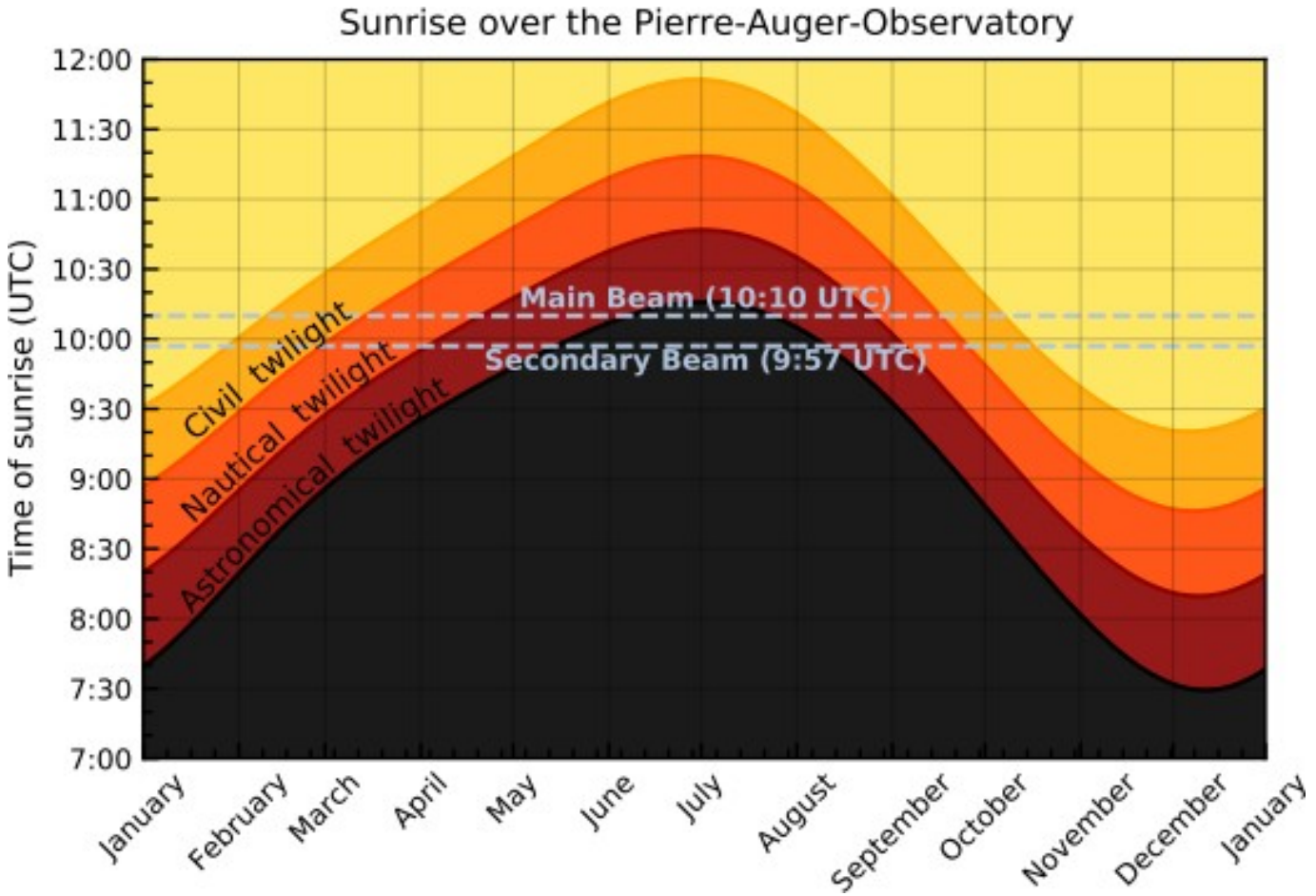
# Season Effects Limit Availability




- Aeolus's Sun-Synchronous orbit creates a season effect.
- Pierre Auger FD's can detect the laser beams in May-August.



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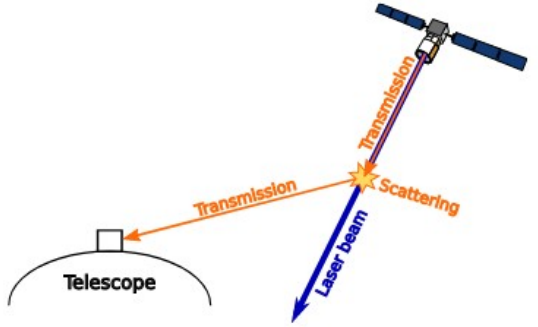
# VAOD and Aerosol Attenuation

- The **V**ertical **A**erosol **O**ptical **D**epth (VAOD) refers to the amount of light aerosols attenuate in a vertical column of air.
- Usually this measurement is done by the Central laser facilities of the Pierre Auger Observatory.
- We use the Aeolus UV lidar to measure the VAOD to directly compare it to the CLF.
- VAOD is integral to correcting energy reconstruction of extensive air showers seen with the FD.
- Since photons are captured by the FD happen across a range of heights and across the entire transition of the array a the VAOD and Energy of the beam are combined into a maximum likelihood fit of these two parameters.



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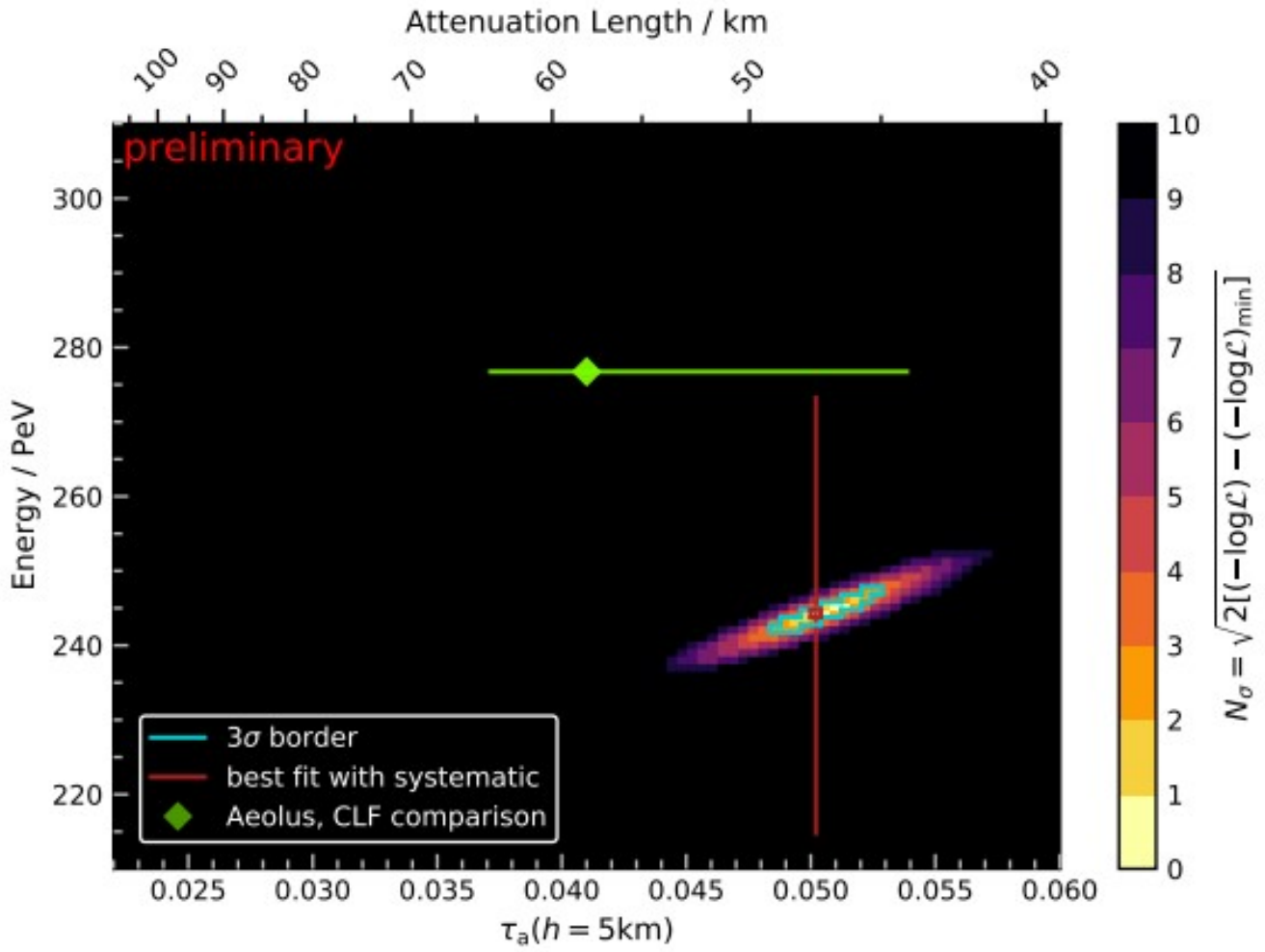
# Aerosol Measurements




Here the measured attenuation length is shown on the top axis and it is converted to VAOD on the bottom.

The energy of the beam is shown on the left. The log likelihood is converted to a measure of number of sigma.

You can see the a good statistical agreement between the expected VAOD and E in green and the measured values for this specific laser transition in the color contours.



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# Satellite Outlooks

## GOES-16 Outlooks:

- GOES-16 will continue its surveying for the foreseeable future.
- Until GOES-16's retirement GOES-16 will be used for cloud cover cross-checks at the Pierre Auger observatory.

## Aeolus Outlooks:

- Aeolus's duty cycle has been extended further until 2022 allowing for more laser shots to be collected for analysis.
- A study of aerosol homogeneity across the Pierre Auger Observatory is also possible which would provide a cross-check to existing lidars.

# Thank You!