Performance of the Cherenkov Telescope Array in the presence of clouds

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Motivation

- The effect of the presence of clouds is primarily observed through the reduced number of emitted Cherenkov photons in the shower development, which yields an energy bias, decreased angular and energy resolution, decreased sensitivity, bias in reconstructed spectra, etc.

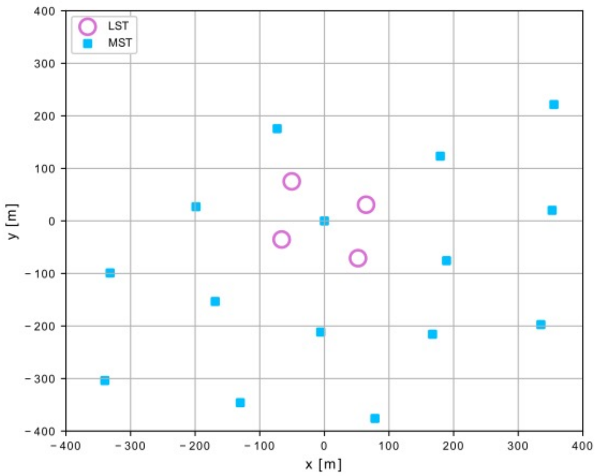
- The shower maximum for high-energy primary gamma ray is deeper in the atmosphere, which means the major fraction of Cherenkov photons is not affected by clouds, thus, the telescopes can be triggered.

- Production of dedicated MCs for specific atmospheric conditions requires a lot of resources and it is time-consuming → Is it possible to obtain a good spectra without dedicated MC simulations for the presence of clouds?

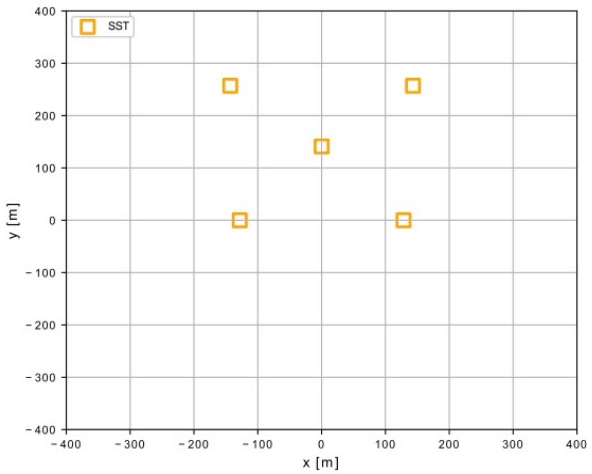
Simulation chain

- CORSIKA code version 7.7 with QGSJET-II interaction model
- Study was performed both for Northern and Southern site
- Note that the layout of the two sites is the one implemented in Prod3.

CTA-N



CTA-S



- CTA-N 20 degrees in Zenith, 180 degrees in Azimuth
- CTA-S 20 degrees in Zenith, 0 degrees in Azimuth
- Atmospheric transmission → within sim_telarray code (Prod3b)

Simulation chain

- **CTA-N (La Palma, Spain)**
  - MODerate resolution atmospheric TRANsmission (MODTRAN), ver. 5.2.2
  - US Standard Atmosphere, desert extinction
  - Wavelength range from 200 nm to 1000 nm
  - Ground altitude: 2147 m a.s.l.
  - 1 km thick altostratus clouds at 3 km a.g.l. and 9 km a.g.l.
  - Simulated transmissions T = 1.0, 0.8 and 0.6

- **CTA-S (Atacama Desert, Chile)**
  - The Armazones site atmospheric model was used as a base
  - Additional extinction due to clouds presence calculated using eq. (3.11) from A. Kokhanovsky, *Earth-Science Reviews*, 64 (2004)
  - Wavelength range from 250 nm to 700 nm
  - Ground altitude: 2500 m a.s.l.
  - 0.5 km thick clouds at 2.5 km a.g.l. and 4.5 km a.g.l.
  - Simulated transmissions T = 1.0, 0.8, 0.6, 0.4 and 0.2

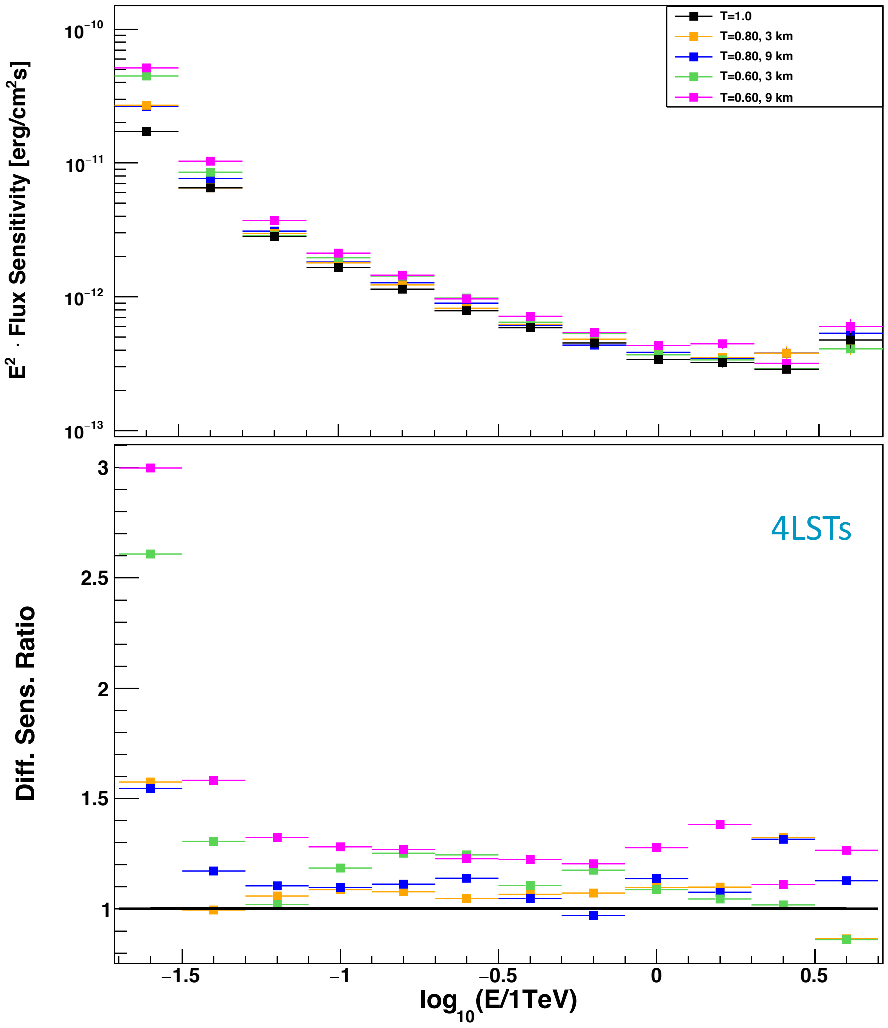
Analysis chain

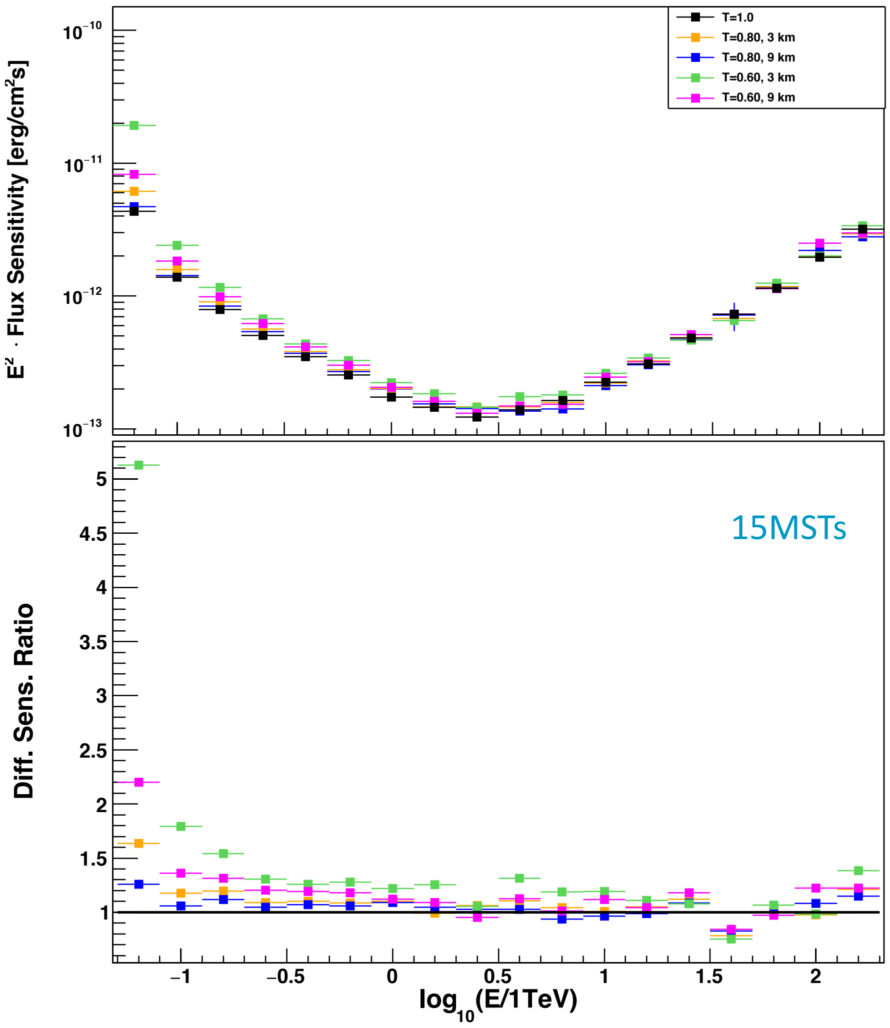
- Convert Hessio to MARS Input (chimp)
  - Signal extraction
  - Calibration
  - Image parametrization

- MAGIC Analysis and Reconstruction Software (MARS)
  - Direction training → direction look-up table
  - Energy and gamma/hadron separation training → Random Forests

- Final output:
  - Differential sensitivity
  - Energy resolution
  - Angular resolution

Differential sensitivity

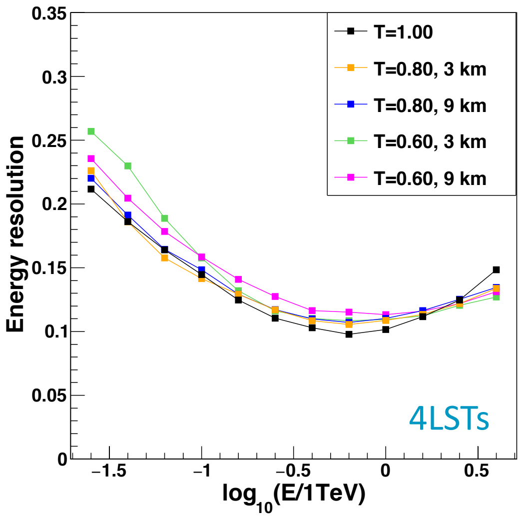


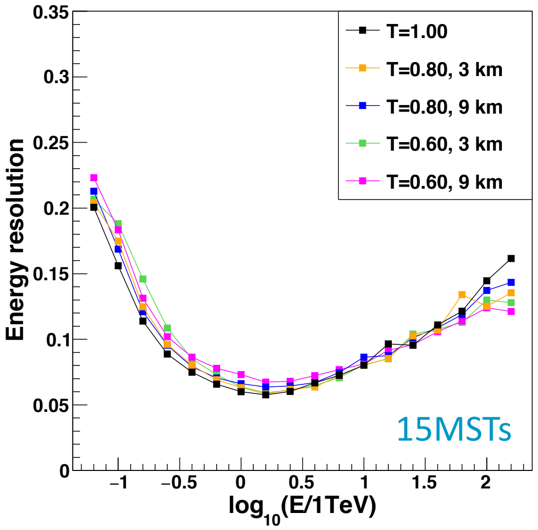


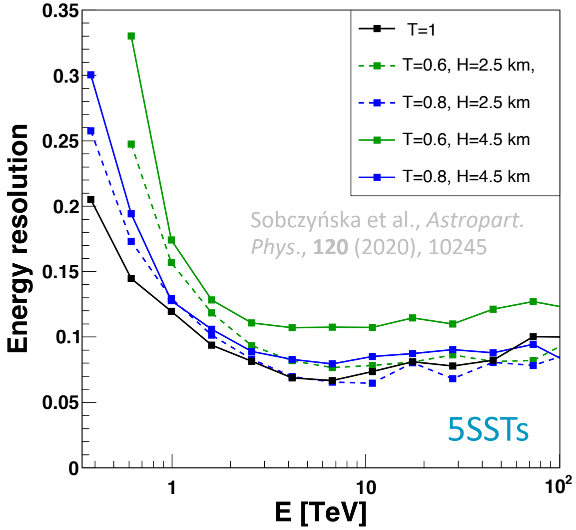
Differential sensitivity

- In the case of 4 LSTs, the most significant impact on the performance of the telescopes have the clouds with the higher cloud base at 9 km a.g.l. and $T = 0.6$, reducing the sensitivity of the telescopes by the factor of ~ 3 at the energy threshold, with the average reduction of 1.42 in the LSTs sensitivity range.
- For the layout of 15 MSTs, the most prominent impact on the sensitivity of the telescopes have clouds with the lower cloud base at 3 km a.g.l. and $T = 0.6$, reducing the sensitivity of the telescopes in the lowest energy bin by the factor of ~ 5, with the average reduction of 1.44 in the MSTs sensitivity range.
- In the common energy range from 0.1 TeV to 4 TeV for the cloud at 3 km a.g.l. with $T = 0.6$, the average reductions for 4 LSTs and 15 MSTs are, respectively, 1.11 and 1.33. The higher clouds have a greater impact on the sensitivity of the LSTs than on the MSTs – might be due to the dependence of shower maximum position on the primary energy; further studies are required and planned.

Energy resolution







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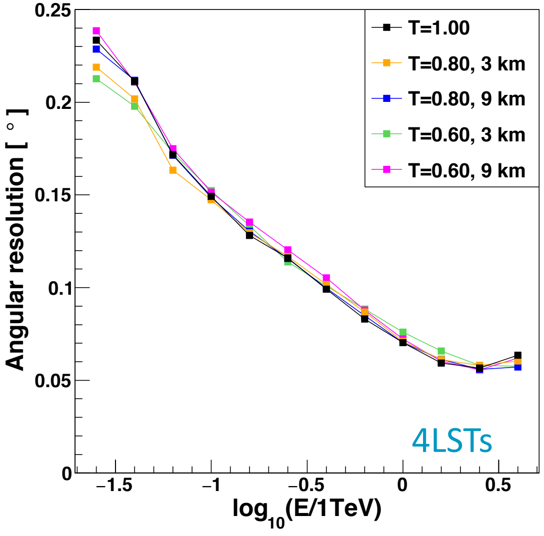
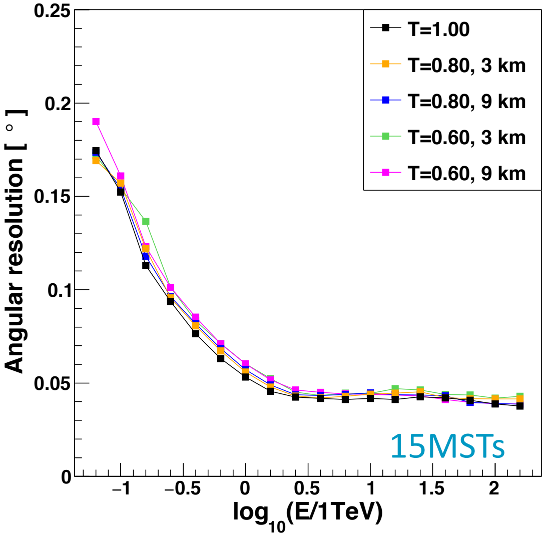
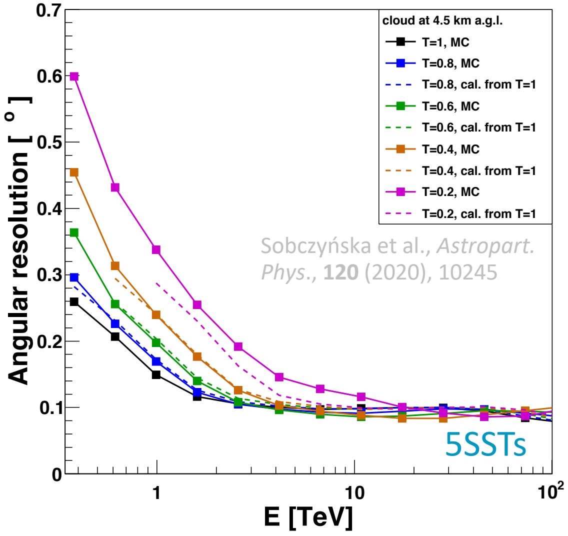
- For the layouts of 4 LSTs and 15 MSTs, the worst-case scenario appears in the lowest energy bin in the case of clouds with $T = 0.6$, with a reduction in the energy resolution by a factor of ∼ 1.20 for 4 LSTs, and ∼ 1.03 for 15 MSTs.
- In the case of 5 SSTs, the energy resolution reaches its plateau at a value of ∼ 13% in the case of $T \geq 0.6$ and $E > 2$ TeV; for lower energies, the energy resolution is poor due to threshold effects.

Angular resolution







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- In the case of 4 LSTs, the impact of clouds on the angular resolution is negligible, with largest differences up to ~ 5%.
- For the layout of 15 MSTs, the angular resolution reaches its plateau for $E > 2.5$ TeV; in that region the worst case ($T = 0.6$, 3 km a.g.l.) angular resolution amounts to 0.05 degrees, while the largest difference is ~ 15%.
- In the case of 5 SSTs for $T \geq 0.4$, the angular resolution decreases at $E < 4$ TeV, whereupon a plateau is reached; in the case of clouds with $T = 0.2$, the plateau is reached only for $E > 10$ TeV.

Data analysis method for VHE

- The fraction of Cherenkov photons created above the cloud is obtained from CORSIKA (Rayleigh and Mie scattering included).

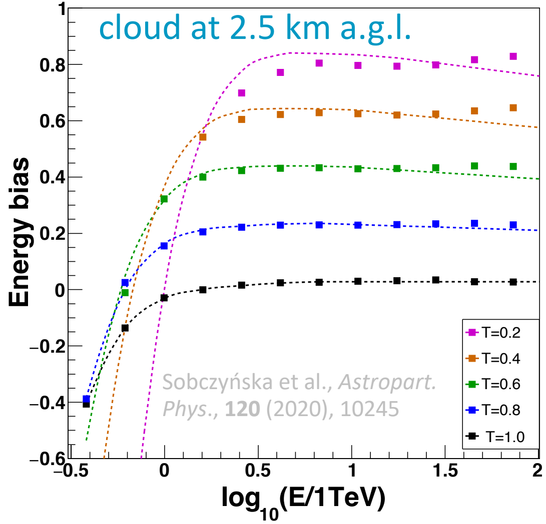
- The total atmospheric transmission is obtained from the assumption that Cherenkov photons created above the cloud participate in the energy reconstruction with a weight equal to *T*, while those created below the base have a weight equal to 1.

- For energy scaling, the corrected total atmospheric transmission is used (phenomenological parameter *A*, depends on the array; 1.2 for 5 SSTs):

$$\boldsymbol{\tau_A(E_{true}, T, H) = 1 - A\tau(E_{true}, T, H)}$$

Data analysis method for VHE

- The method is based on the energy bias calculated for clear atmosphere (to take into account the energy threshold effects) and the corrected total atmospheric transmission.
- Energy bias is defined as a relative difference between estimated and true energy.
- Due to low statistics, in some energy bins biases cannot be determined.
- For lower energies, the threshold effects are dominant; bias increases with energy.
- Approximation as proposed in the method may be used to get the corrected energy of reconstructed events (points – results obtained with the method, dashed lines – MC simulations).


cloud at 2.5 km a.g.l.

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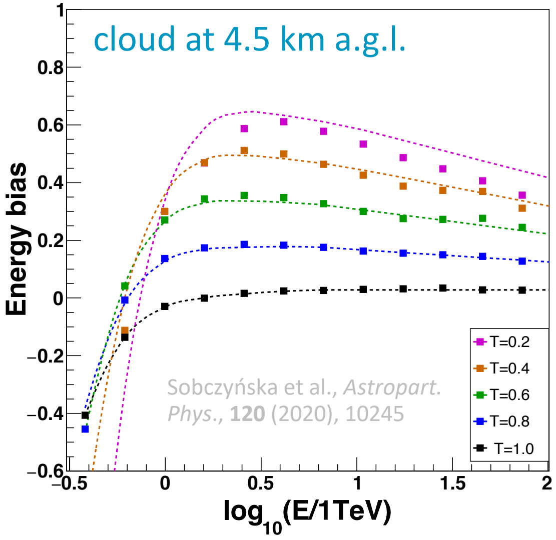
cloud at 4.5 km a.g.l.

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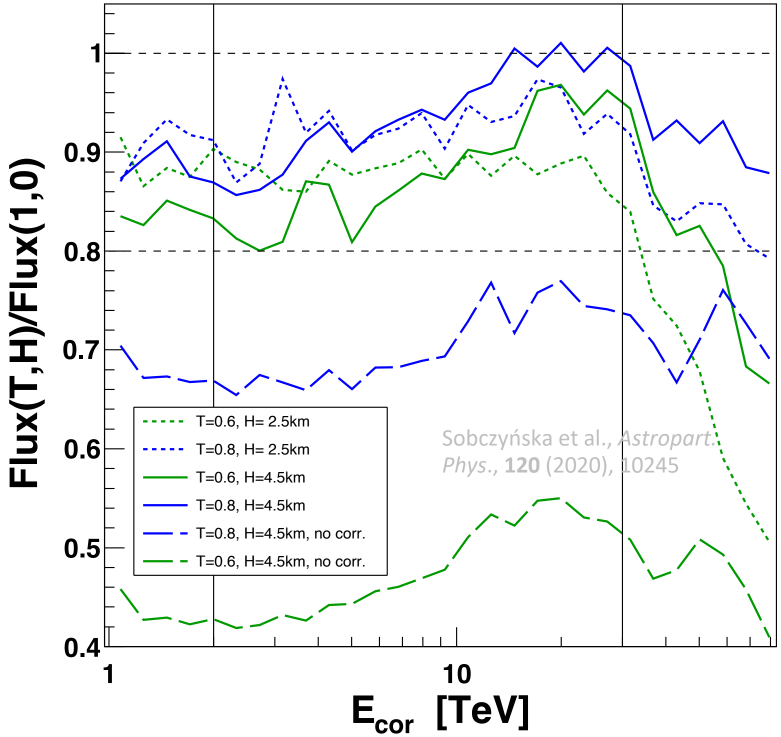
Data analysis method for VHE

- The spectrum of the potential source can be estimated from the events classified as a gamma-like with cuts optimized using MCs for T=1.0.
- The flux is calculated in standard way but using corrected effective collection area and corrected energy.
- The ratio of spectrum of the potential source and the fluxes obtained from MCs for T=1.0:



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→ in the energy range between 2 TeV and 30 TeV the expected spectra are underestimated only by less than 20% for $T \geq 0.6$

- When no corrections are applied (long dashed lines), the underestimation of the spectra is much higher.

Conclusion

- In the presence of high-density clouds with low transmissions through the atmosphere, it is shown that the performance of all three types of CTA telescopes (LSTs, MSTs and SSTs) degrades.
- Although the degradation effects are most prominent at the energy thresholds, the effects of the clouds are evident across the entire energy range for each telescope type.
- In the low (LSTs) and middle (MSTs) energy range, detailed MC simulations are necessary to properly assess telescope response in the given atmospheric conditions.
- For high energy range (SSTs), extremely time-consuming MC simulations can be avoided using the correction method proposed in this study.
- The method in the energy range between 2 TeV and 30 TeV underestimates the spectra only by less than 20% for $T \geq 0.6$.

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Thank you for your attention!