Atmospheric simulations for the Cherenkov Telescope Array

Cameron Rulten* and Sam Nolan

The Cherenkov Telescope Array (CTA) will be the world's first observatory for detecting gamma-rays from astrophysical phenomena and is now in its prototyping phase with construction expected to begin in 2015/16. In this talk we will discuss the detailed simulation studies performed to assess the need for atmospheric monitoring and the methods by which correction for atmospheric variation may be achieved. This will include discussion of some lidar analysis methods with a view to determining a range resolved atmospheric transmission in order to determine an appropriate atmospheric model for use in simulations.

"Studies of Lidar Calibration for the Next Generation of Imaging Atmospheric Cherenkov Telescopes", Sam Nolan, Cameron Rulten for the CTA Consortium, OG2.7 Session, Proceedings of the 31st International Cosmic-Ray Conference, Lodz, Poland, 7-15th July 2009

(Early attempts at) Atmospheric simulations for the Cherenkov Telescope Array

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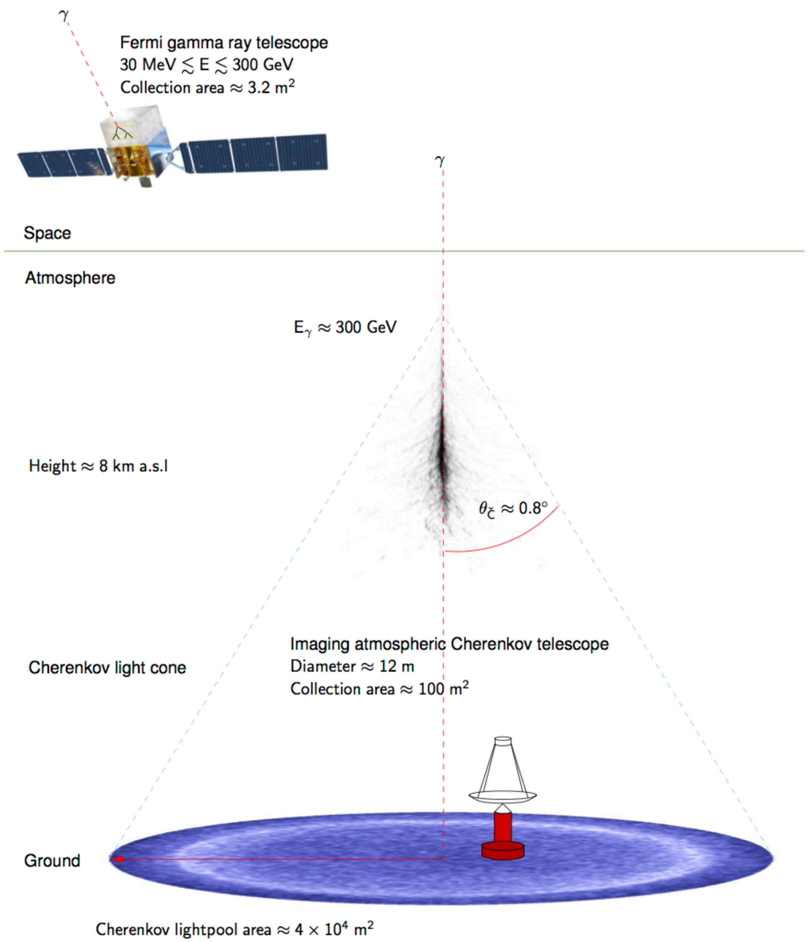
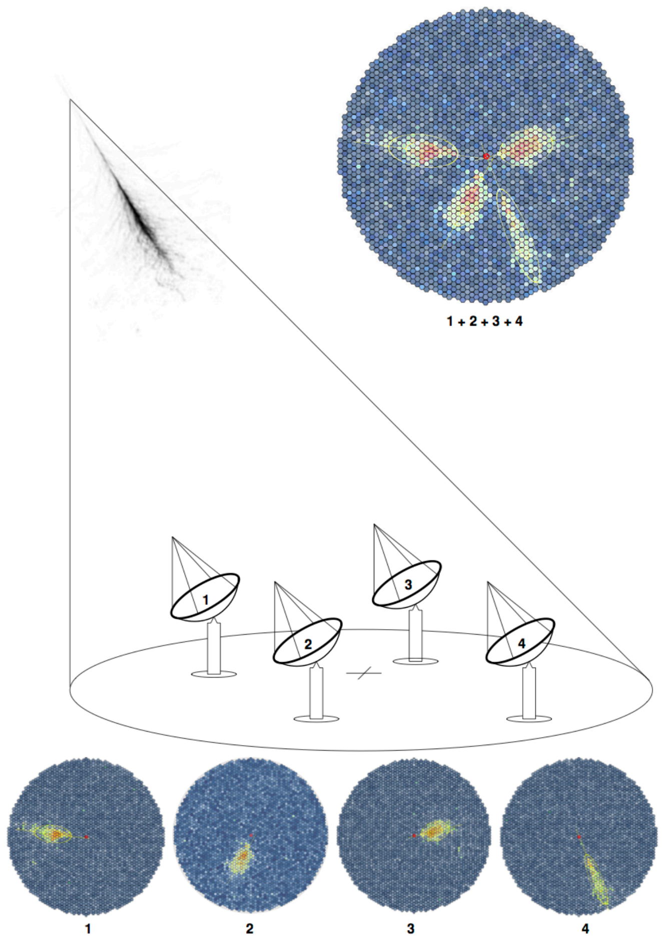
Outline

- Ground-based gamma-ray astronomy
  - Atmospheric considerations
  - Motivations for CTA
- Atmospheric simulation study
  - Shower & telescope simulations conducted for study
- Lidar analysis
  - Effect on reconstructed data
- Conclusions and future work

GROUND-BASED GAMMA-RAY ASTRONOMY

The Atmospheric Cherenkov Technique





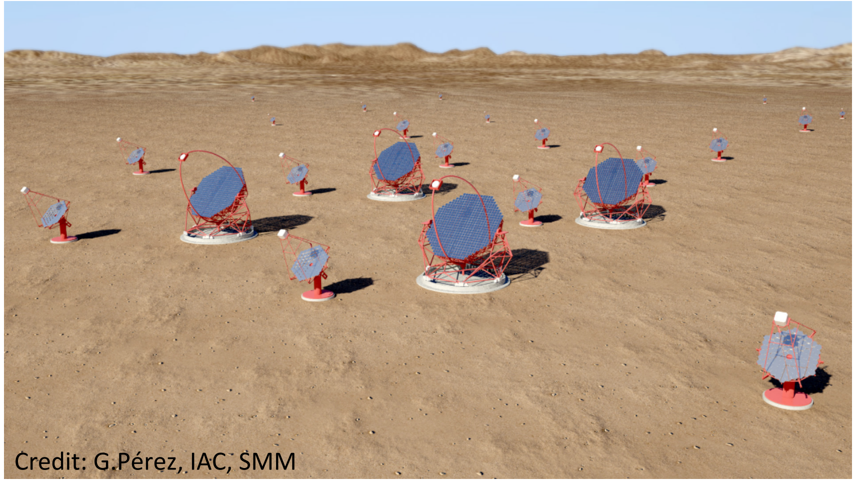
Current generation of ground-based gamma-ray telescopes (IACTs)

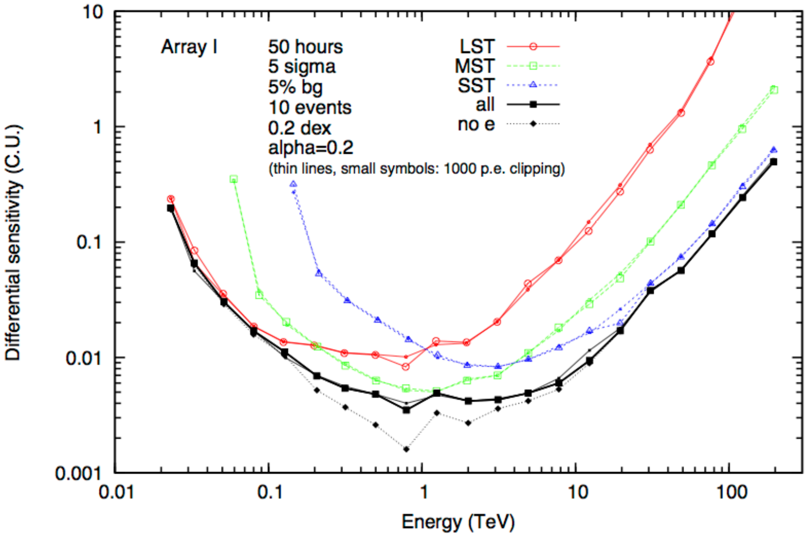
Credit: The VERITAS Collaboration

Credit: The H.E.S.S. Collaboration

Credit: The MAGIC Collaboration

The Cherenkov Telescope Array





Ref: K. Bernlöhr et al., Astroparticle Physics, 43 (2013), p.171–188

CTA array-I: 3 LSTs (D=23m, FOV=4.9°), 18 MSTs (D=12m, FOV=8°) and 56 SSTs (D=7.4m, FOV=9°)

Atmospheric considerations

For IACT's atmospheric quality affects shower development and Cherenkov yield in two ways:

production of Cherenkov light

loss of Cherenkov light

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- the vertical profile of the atmospheric density and hence refractive index of the air
  - variation is seasonal
  - effects mid-latitudes worse than the tropics
  - profile can be measured using radiosondes

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- through Rayleigh & Mie scattering of the Cherenkov light
  - lowers the brightness of an image
  - using a lidar measurement
  - possible to derive the probability of transmission

Motivation

- Systematic uncertainties
- Better energy reconstruction
- Duty cycle
- Resurrection of otherwise unusable data

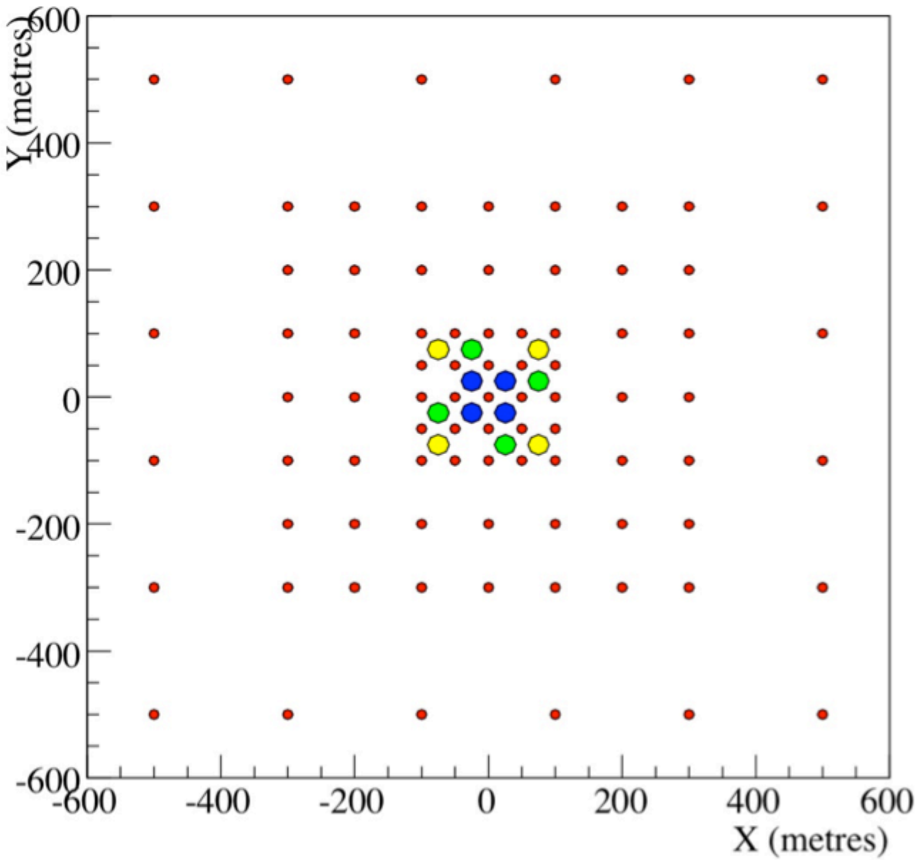
Approach

- Simulation studies of atmospheric effects on imaging with ground-based Cherenkov telescopes
- Experience with a single-scattering lidar
- Explore how in-situ atmospheric measurements could be incorporated into data analysis & reconstruction

ATMOSPHERIC SIMULATION STUDY

CTA test array

- Not the current version of CTA array layouts
- 12 x 600m^2 telescopes
- 85 x 100m^2 telescopes
- 40% larger field of view than H.E.S.S.
- 50% higher quantum efficiency than H.E.S.S.



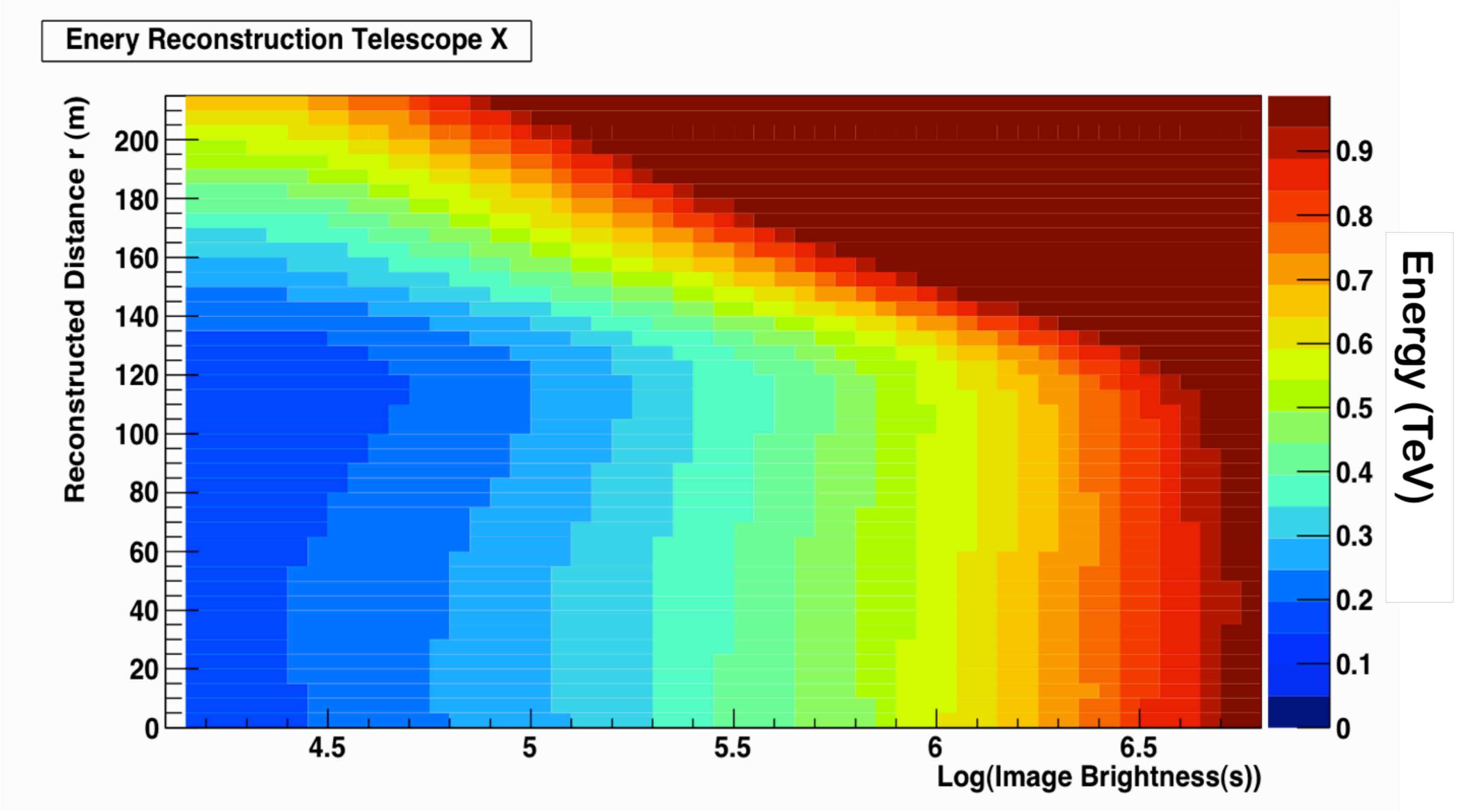
Simulations database

- CORSIKA & sim_telarray
- Very limited shower database ~10^6 γ's
- 20 degree zenith angle
- Energies from 5 GeV – 20 TeV with E^{-2} spectrum
- Generated lookups derived from a tropical atmospheric profile including standard aerosol model (global desert-dust)
- Fake spectrum
- Sampling from an E^{-2} spectrum of 100k simulated triggers
- Used lookups to reconstruct spectra
- Everything else is fixed

Analysis method

- Followed current methods adopted by existing telescopes
- To form an array trigger we require:
  - Min. 5 telescope trigger
  - Min. 10 pixels in an image cut
  - Background removal by image shape cuts
  - Form lookup table for energy and reconstructed effective area
- Not optimal for low energy events
- Only interested in comparing the response under different atmospheric conditions

Energy calculation



What we might expect to happen

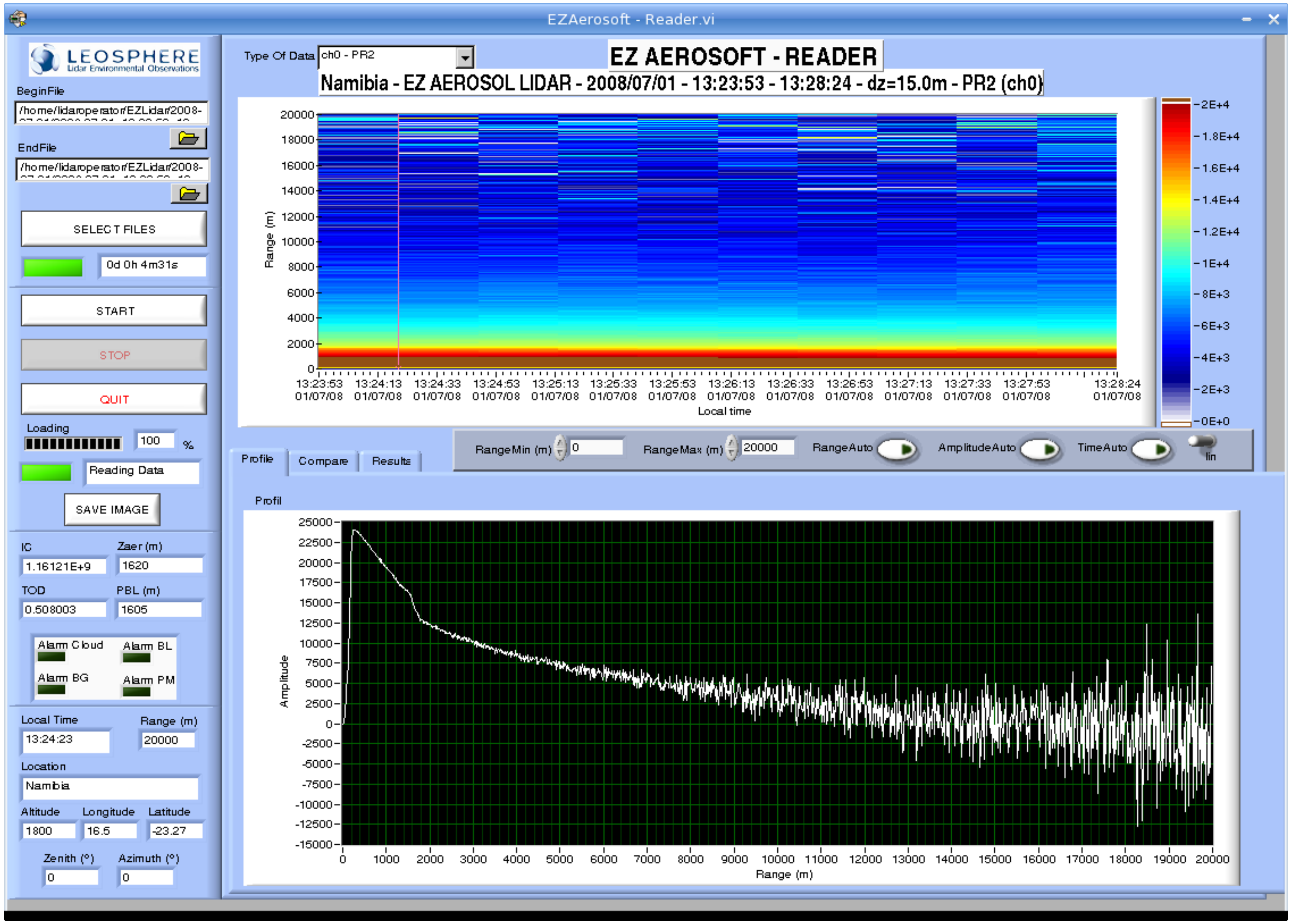
- Low-level aerosols reduce the Cherenkov yield from a shower of a given energy and impact parameter.
- Thus without correction, they soften spectra, by moving reconstructed events artificially to lower energies.
- Using a lidar it is possible to measure aerosol properties

LIDAR ANALYSIS

Lidar at H.E.S.S. site

Lidar specifications:		
Wavelength:	355nm	355nm, 532nm, 1064nm
Frequency:	10Hz	10Hz
Pulse width:	5ns	4ns
Energy/pulse:	20mJ	65mJ
Range:	15km	25km
Resolution:	1.5m	1.5m
Operator:	Durham (Leosphere)	Montpellier
Status:	Defunct	Operational

Typical lidar return



Lidar analysis methods

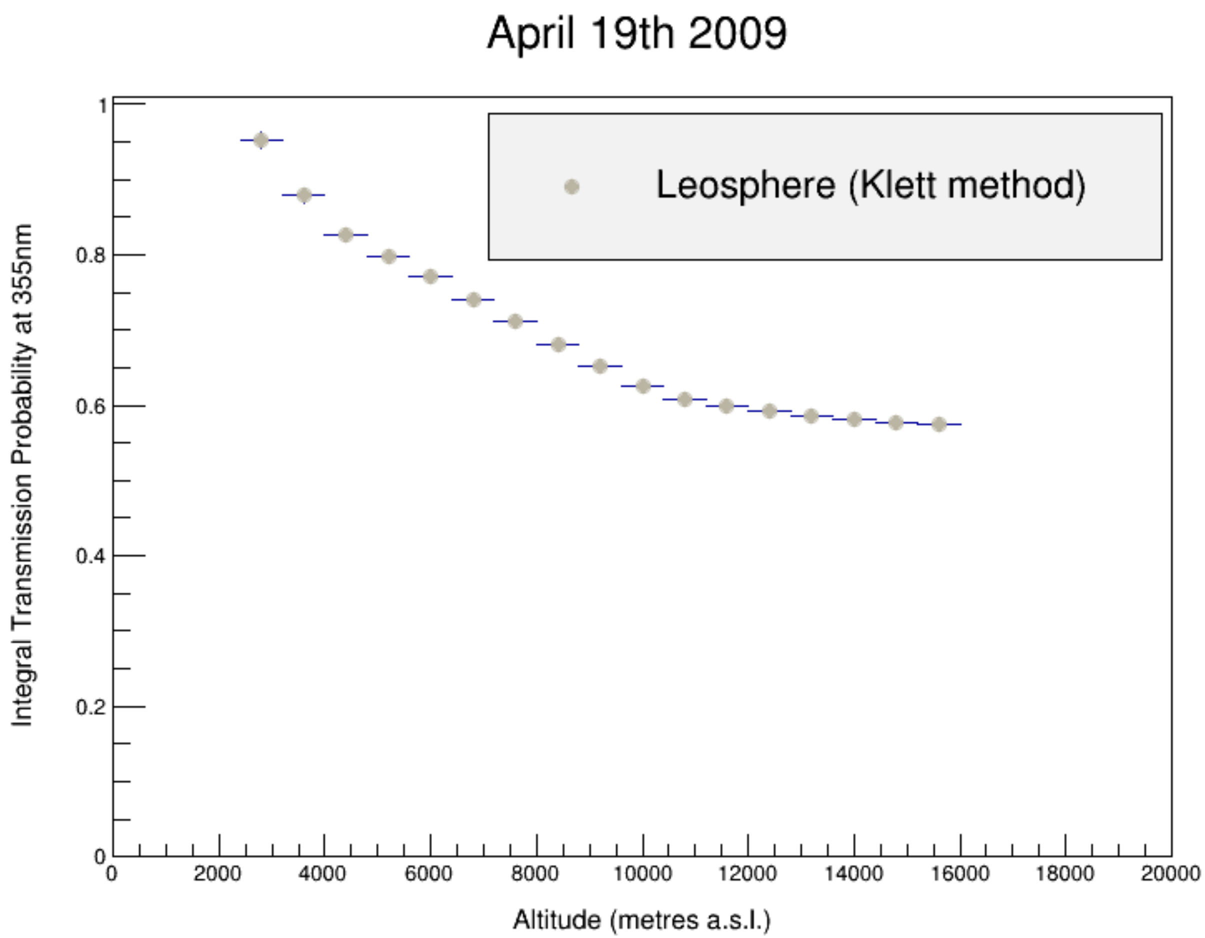
- lidar analysis techniques implemented:

- Klett Method - *Klett.J.D Applied Optics 20(2):211-220 (1981)*
- Fernald Method – *Fernald.F.G Applied Optics 23(5):652-653 (1984)*
- Multi-angle Method – *Filipčič,A et al. Astroparticle Physics 18:501-512 (2003)*

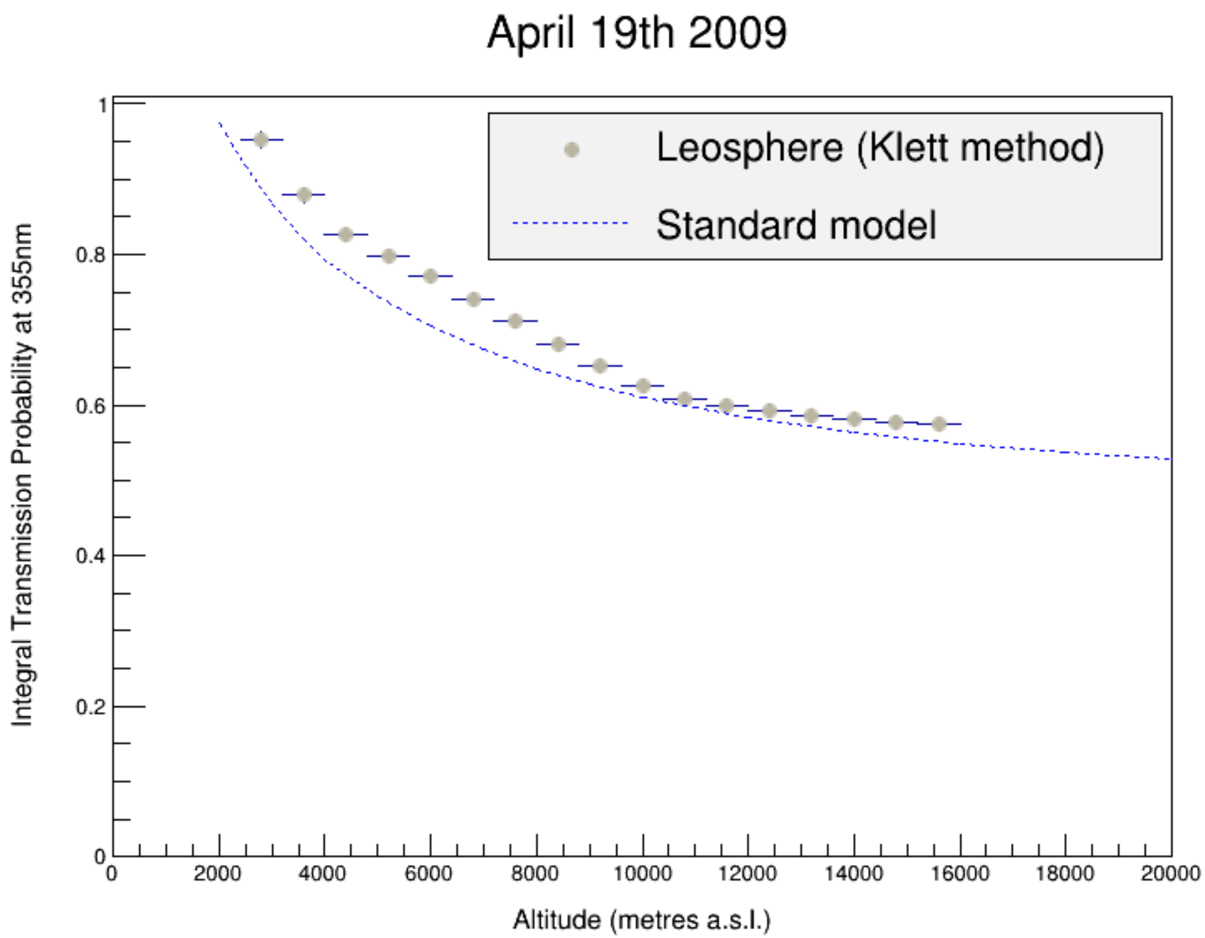
- assumptions
- lidar range
- large systematic uncertainties
- 2 unknowns 1 measurement

- need to derive probability of transmission for the Cherenkov spectrum

Probability of transmission

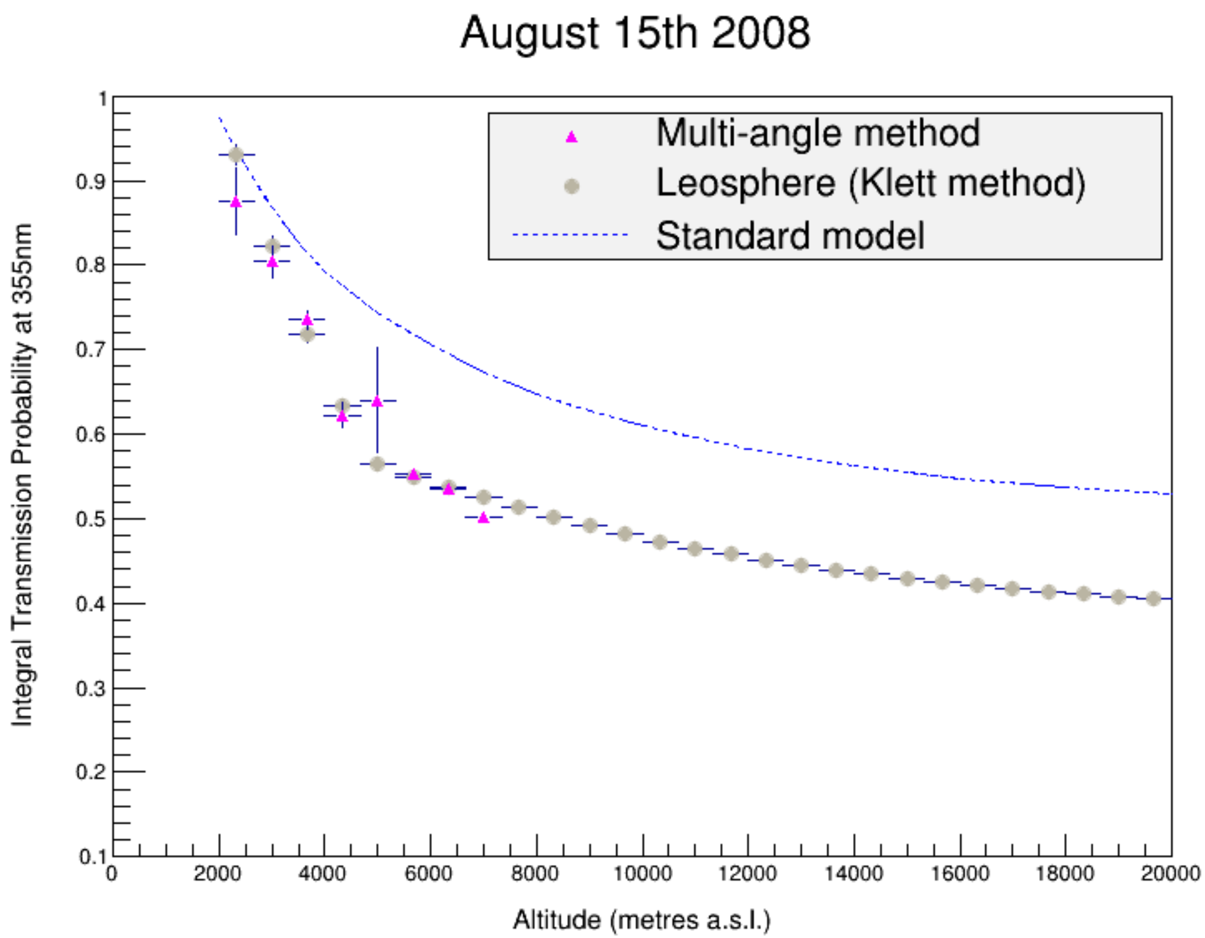


Transmission with model

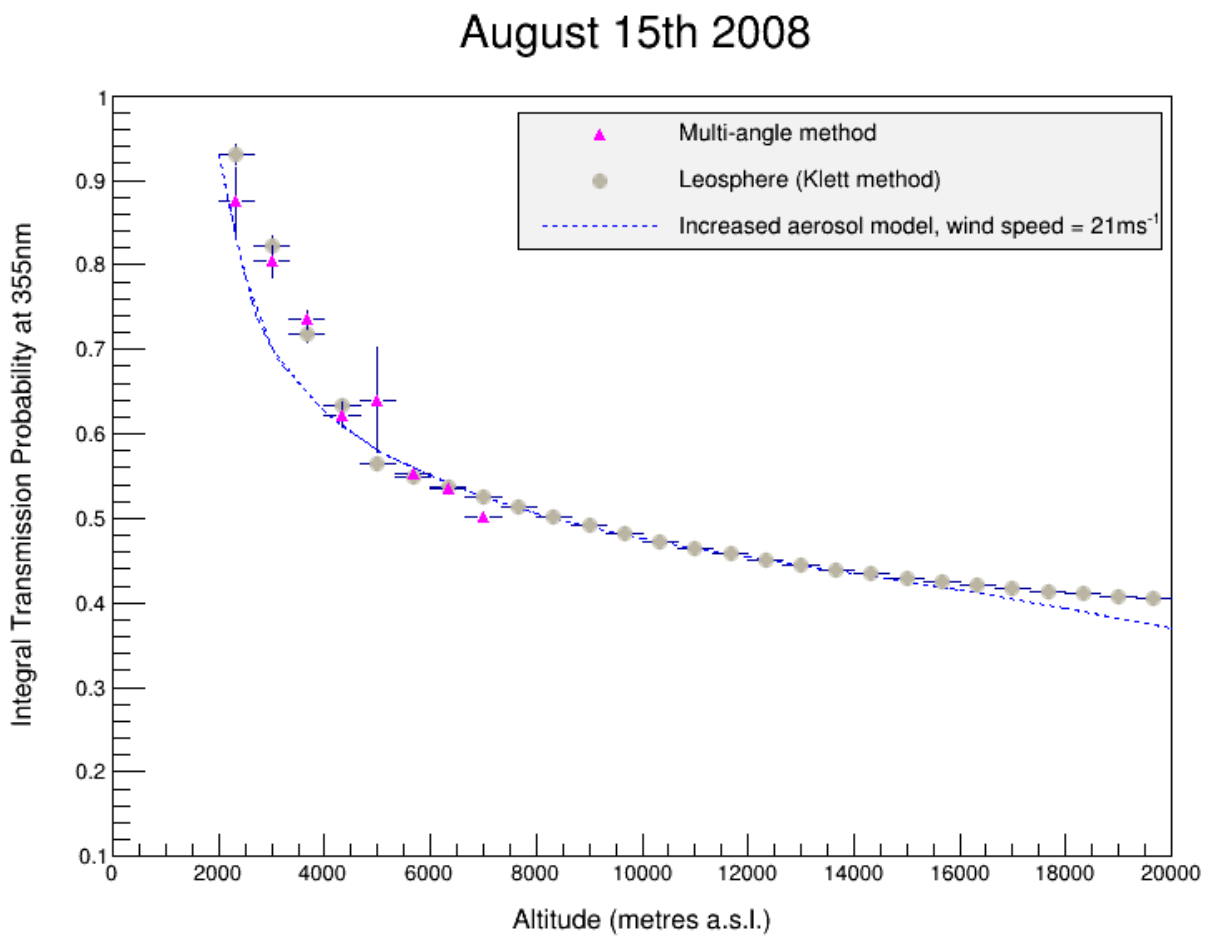


INCREASED AEROSOL ANALYSIS

Transmission during increased aerosols



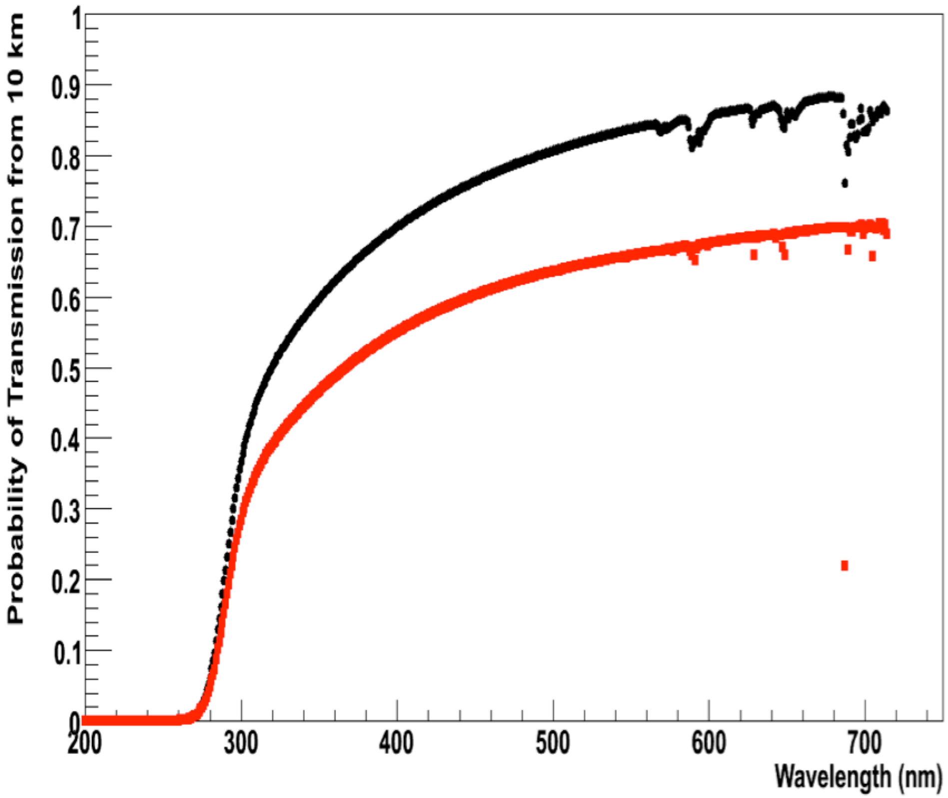
Derive new transmission model



An increased aerosol model is created by tuning the MODTRAN standard model

Transmission model

- Transmission from 10km versus wavelength
- Standard model (black)
- Increased aerosol model (red)
- Derived by tuning the standard MODTRAN aerosol model
- Fit model to single data point at 355nm
- Assume model correct for all other wavelengths



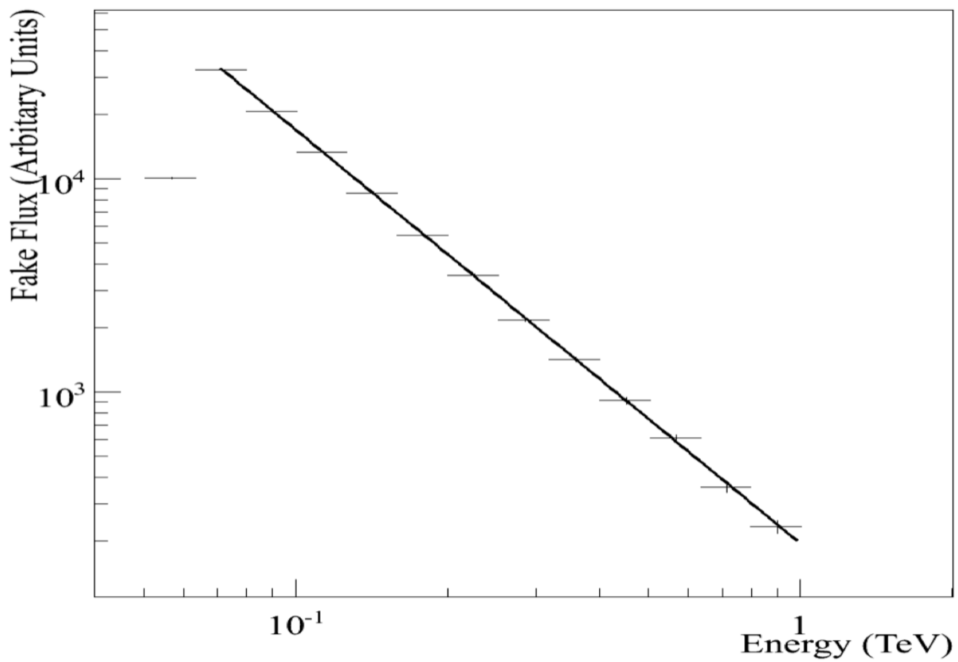
Fake spectrum

Lookup table: Standard model

Simulations: Standard model

Normalisation: 0.2

Slope: 1.93



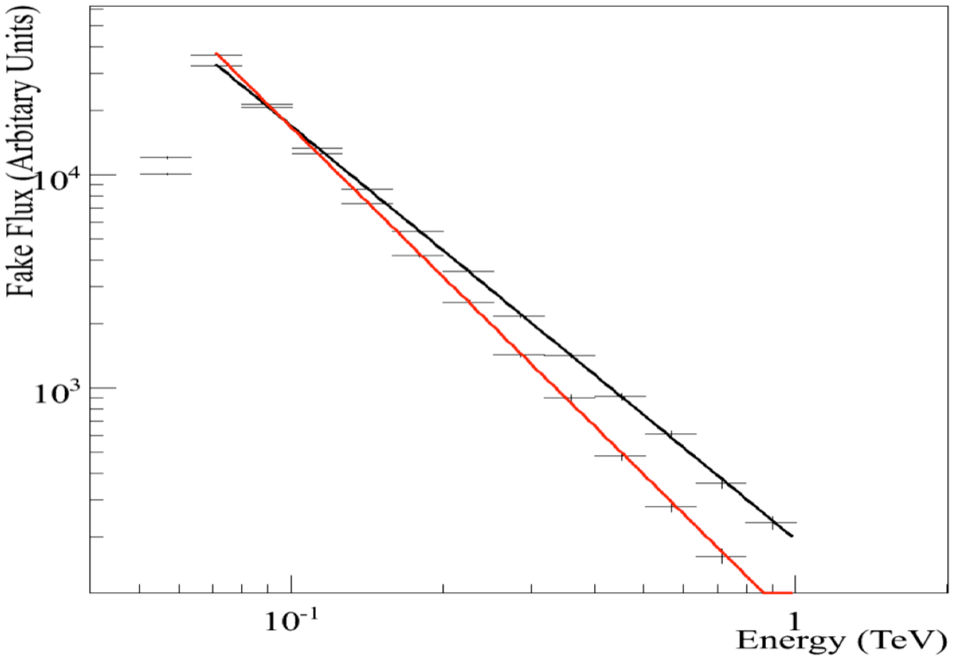
Softer spectrum

Lookup table: Standard model

Simulations: Increased aerosol model

Normalisation: 0.1

Slope: 2.33



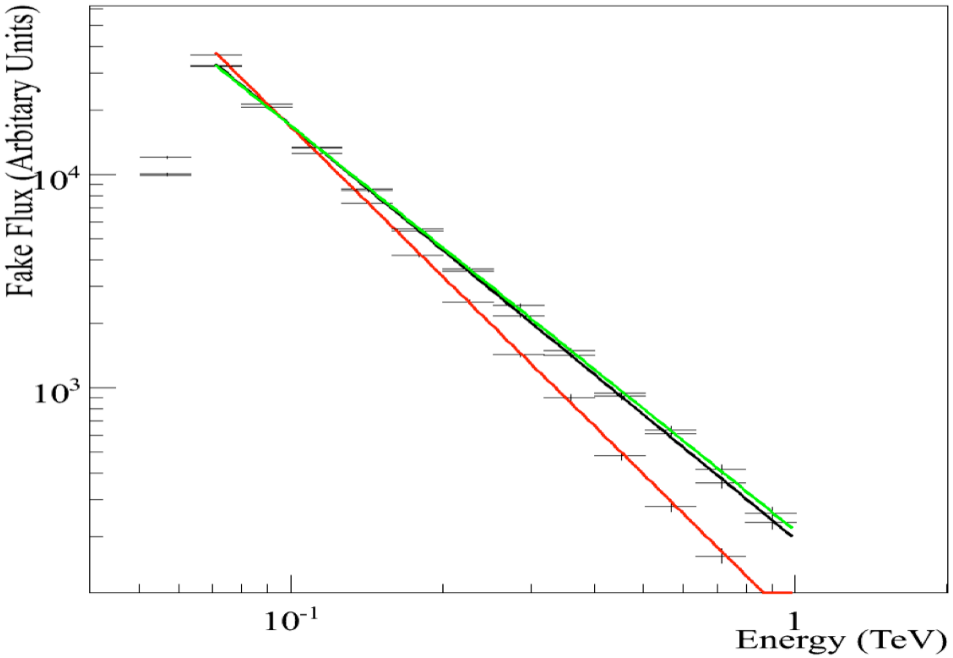
Resurrected spectrum

Lookup table: Increased aerosol model

Simulations: Increased aerosol model

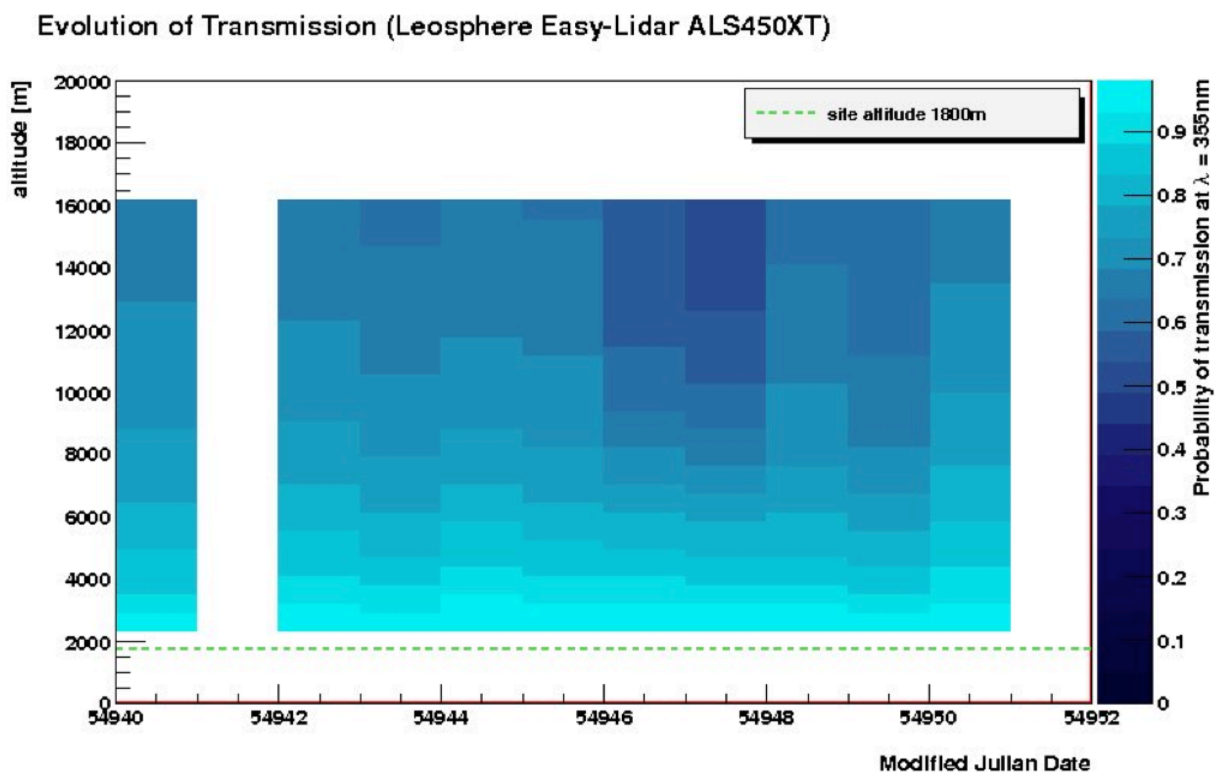
Normalisation: 0.18

Slope: 1.91



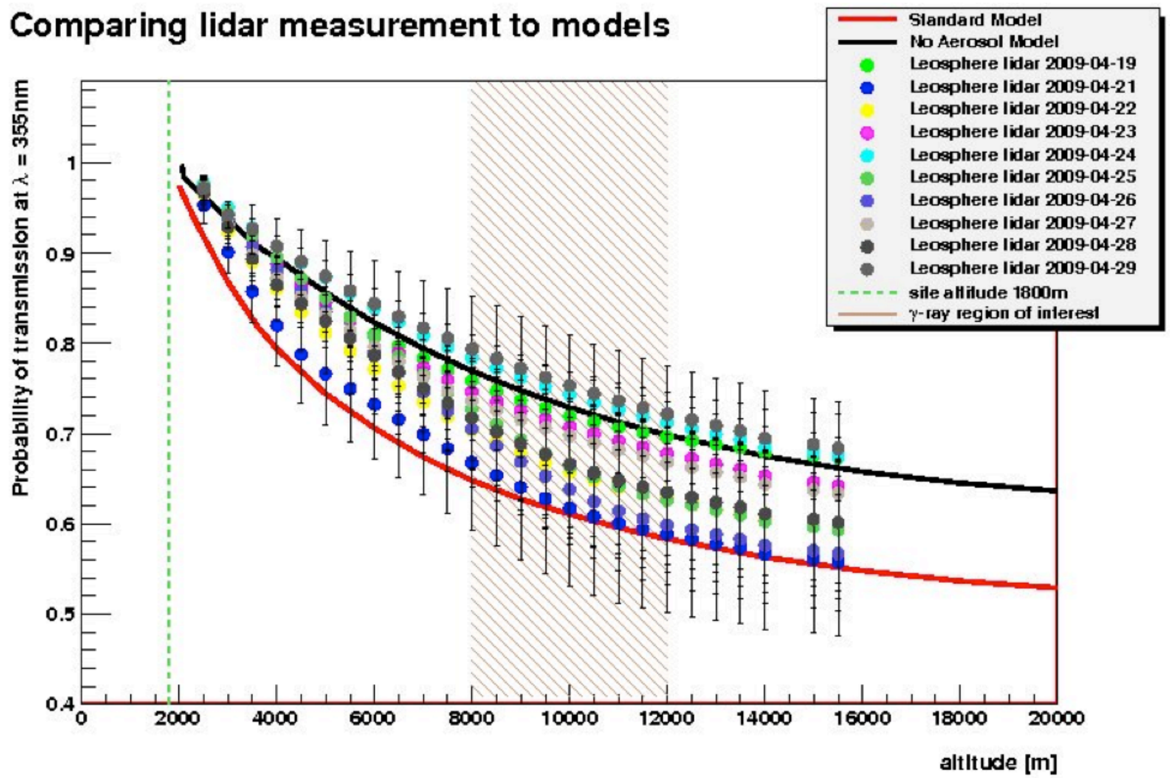
CONSTRAINING AEROSOL MODELS

Relatively normal conditions



- lidar wavelength λ = 355nm
- 10 days, 19th – 29th April 2009

Transmission during normal conditions

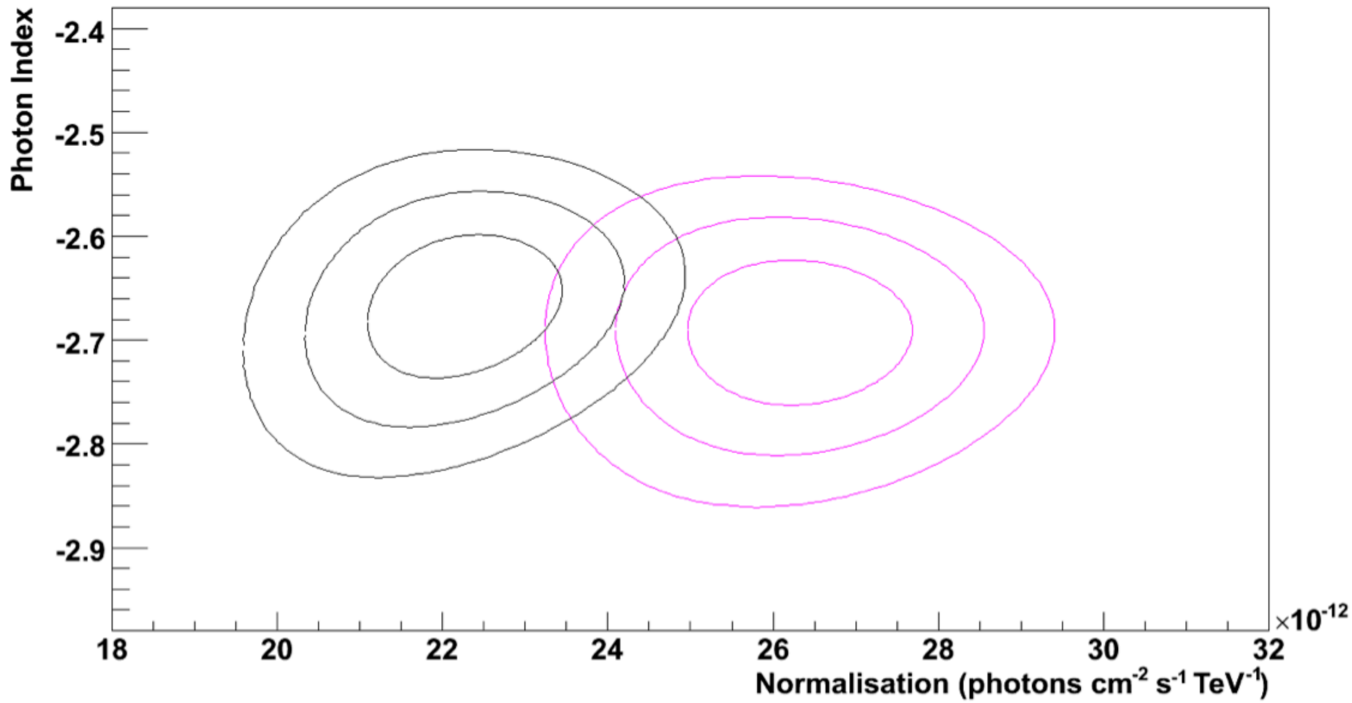


- average transmission falls between 2 models
- MODTRAN desert model (red line) and no-aerosol model (black line)

Model analysis

- systematic errors are big and are not included
- looked at the difference between 2 different MODTRAN models which lidar data spans.
- constructed gamma-ray lookup-tables based on these models
- analyzed Crab data as if it were being observed to see effect

Crab spectrum



change in reconstructed Crab flux of ~15%

Analysis summary

Increased aerosols

- Tuned aerosol model to match lidar measurements
- Generated lookup-tables from matched atmosphere
- Applied these to a simulated spectrum

Normal conditions

- Constrained two different aerosol models
- Generated lookup-tables using the different models
- Applied these to (non-contemporaneous) real Crab data

Conclusions – increased aerosols

- For increased aerosols, without data correction
  - Images of a given energy have less light than under clear/normal conditions
  - If this effect is ignored, events are reconstructed to have a much lower energy than their true energy
  - This leads to artificial softening of reconstructed spectra
- By a precise measurement of the transmission profile and through incorporation with simulation, otherwise unusable data may be resurrected

Conclusions – normal conditions

- lidar analysis
- derived transmissions from lidar measurements
- used to constrain atmospheric model
- change in reconstructed Crab flux of ~ 15%
- systematic errors ignored

- Need a better measurement of atmospheric transmission (independent of telescope)

Future work

- Need to simulate:
  - More showers
  - Latest CTA array layouts
  - Different zenith angles
  - Background
  - North and South for geomagnetic fields
- Under investigation by all current IACTs and CTA

END