GAP2018-011

THE UNIVERSITY of ADELAIDE

Energy Systematics and Long Term Performance of the Pierre Auger Observatory's Fluorescence Telescopes

Phong Huy Nguyen

A thesis submitted to the University of Adelaide in fulfilment of the requirements for the degree of Doctor of Philosophy.

School of Physical Sciences
Department of Physics

2017

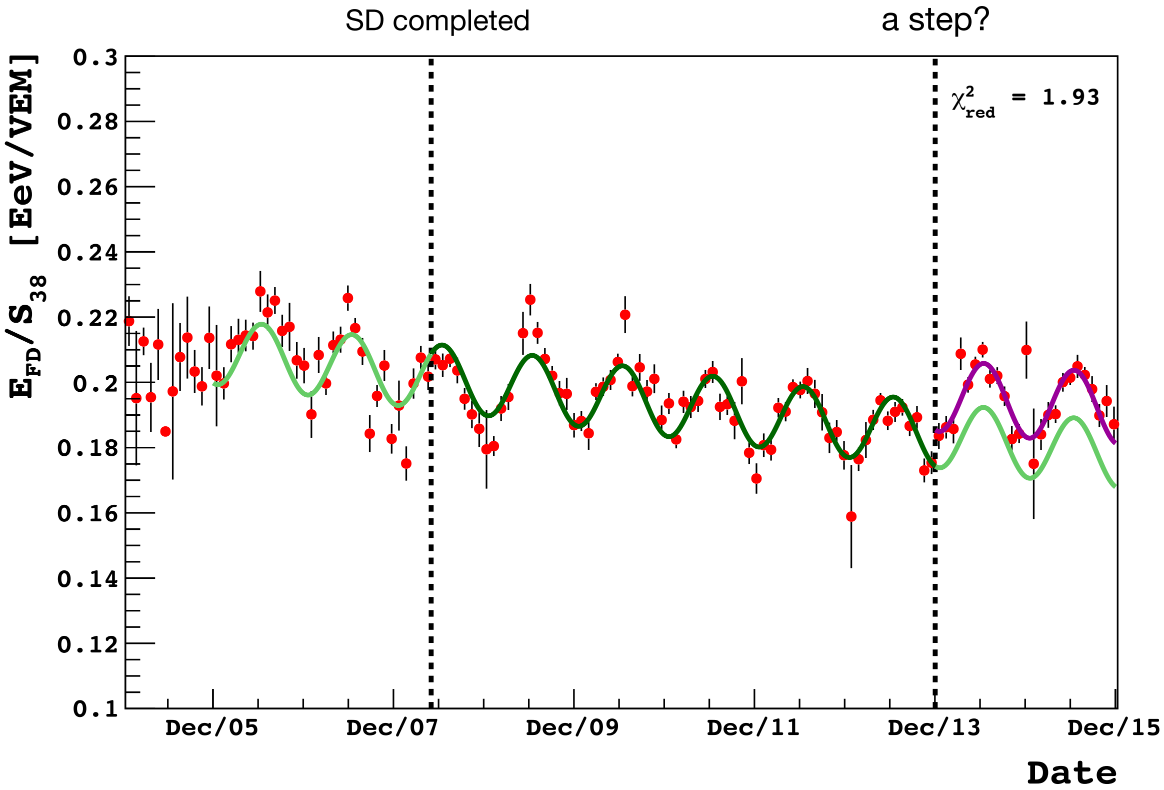


Figure 5.16: Fitting the ESR from the completed Observatory with a function consisting of one empirically defined breakpoint. The fit function from mid-2008 through to 2014 is extrapolated on either side of the vertical rails.

With updates to aerosol DB, SD weather corrections, etc

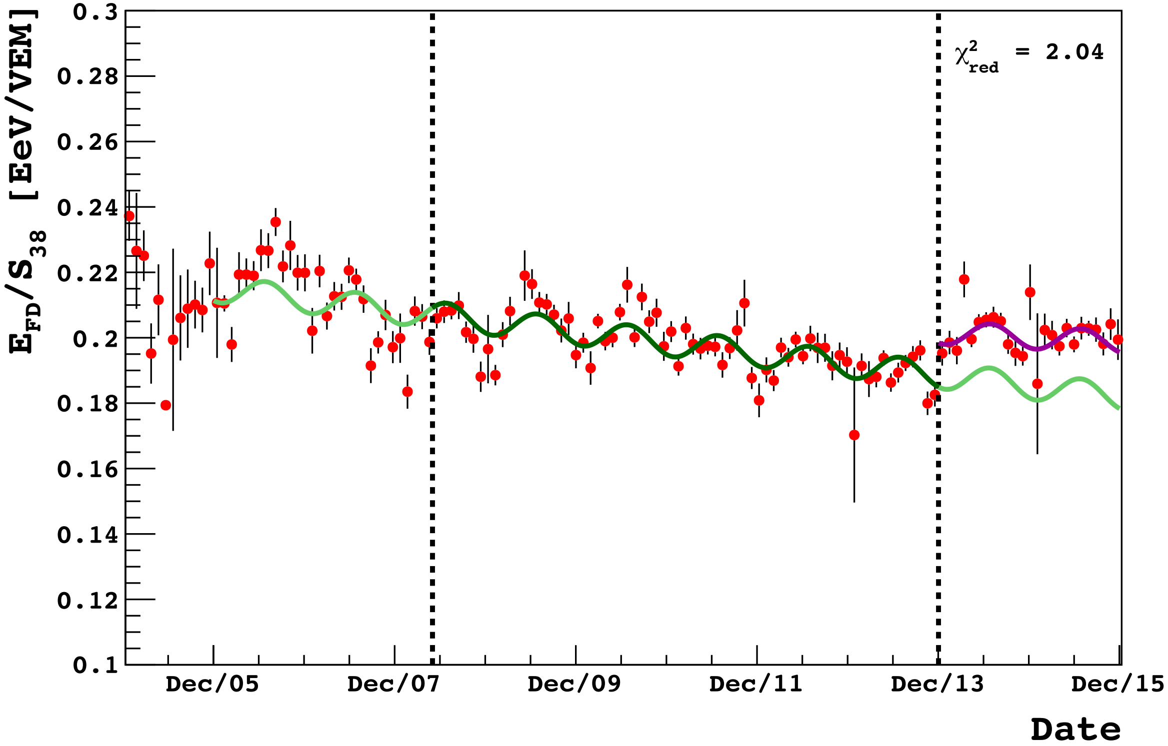


Figure 5.25: The ESR profile following the improvements to the aerosol database, the SD weather correction on the shower size and (for completeness) a geomagnetic shower size correction.

	χ^2_{red}	Drift [% per year] (pre 2014)	Modulation [%] (pre 2014)	Drift [% per year] (post 2014)	Modulation [%] (post 2014)
Nominal Energy Scale	1.93	-1.6 ± 0.2	5.1 ± 0.4	-1.0 ± 0.8	5.5 ± 0.7
+ Aero. DB	2.16	-1.7 ± 0.2	4.3 ± 0.4	-0.6 ± 0.9	4.0 ± 0.7
+ SD WC (old aero. DB)	1.76	-1.6 ± 0.2	2.7 ± 0.4	-1.2 ± 0.8	3.4 ± 0.7
+ Aero. DB + SD WC + Geo.	2.04	-1.6 ± 0.2	2.0 ± 0.4	-0.7 ± 0.9	1.7 ± 0.7

Table 5.2: Summary of the optimal broken fit parameters for different SD and FD corrections.

Some drift in S38? Yes, of the 1.6% per year, 0.3% per year comes from the SD

SD event rate above 3EeV

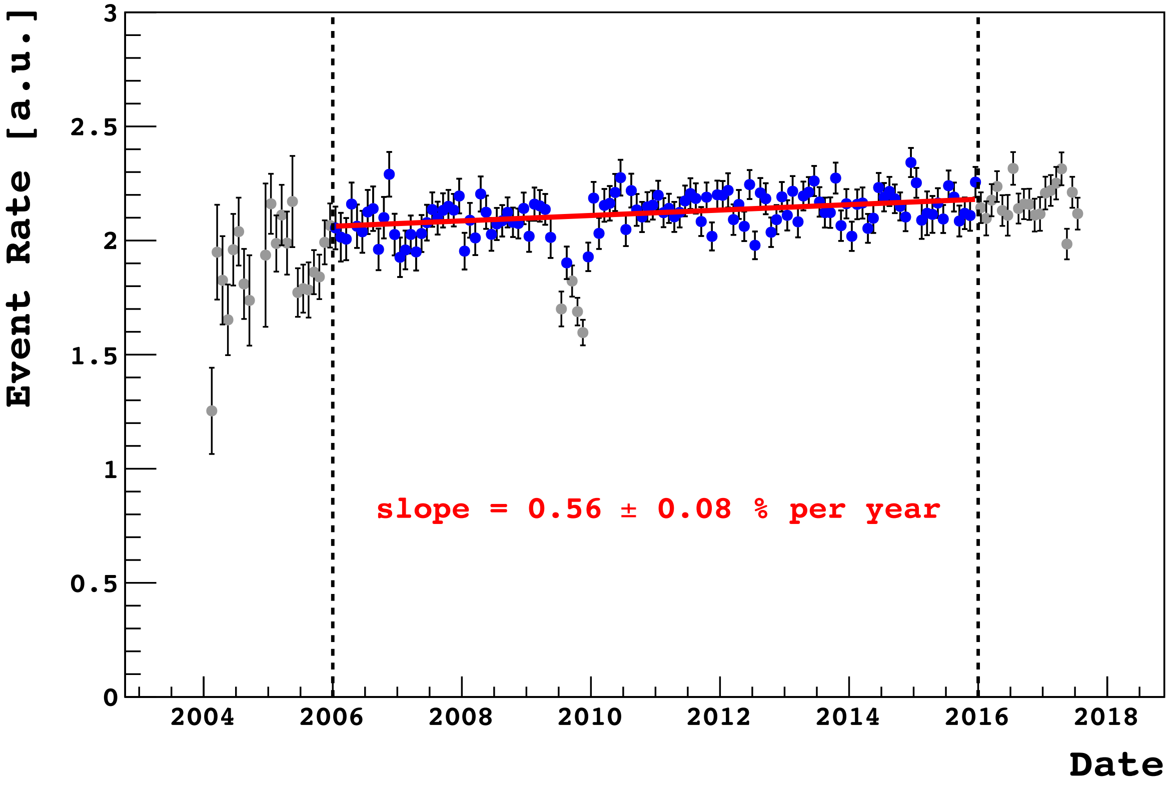


Figure 5.23: The monthly SD event rate (arbitrary units) for a threshold energy of 3 EeV post-SD weather correction. The events used here were taken from the Observer reconstruction. The linear function (red) is fitted across the same time period (blue profile) as the data set defined earlier in this Chapter.

$$\frac{d(Event\ Rate)}{Event\ Rate} = \frac{-kE_{th}^{-3}dE_{th}}{(k/2)E_{th}^{-2}} = -2\frac{dE_{th}}{E_{th}}$$

So showers are being reconstructed with a larger S38 by 0.3% per year, increasing the rate.

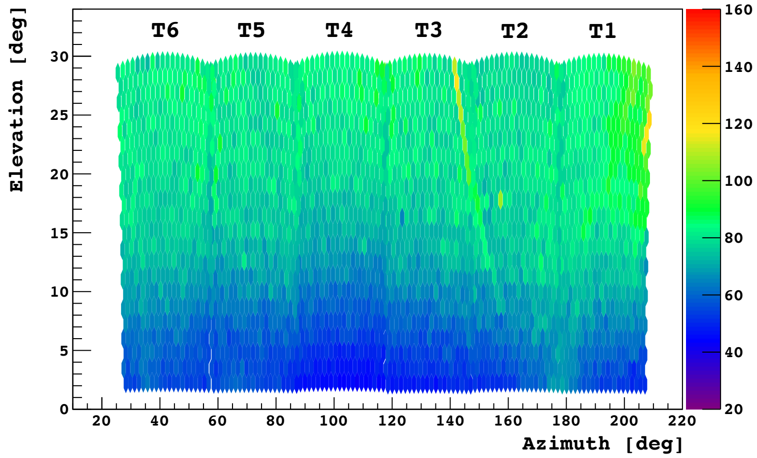
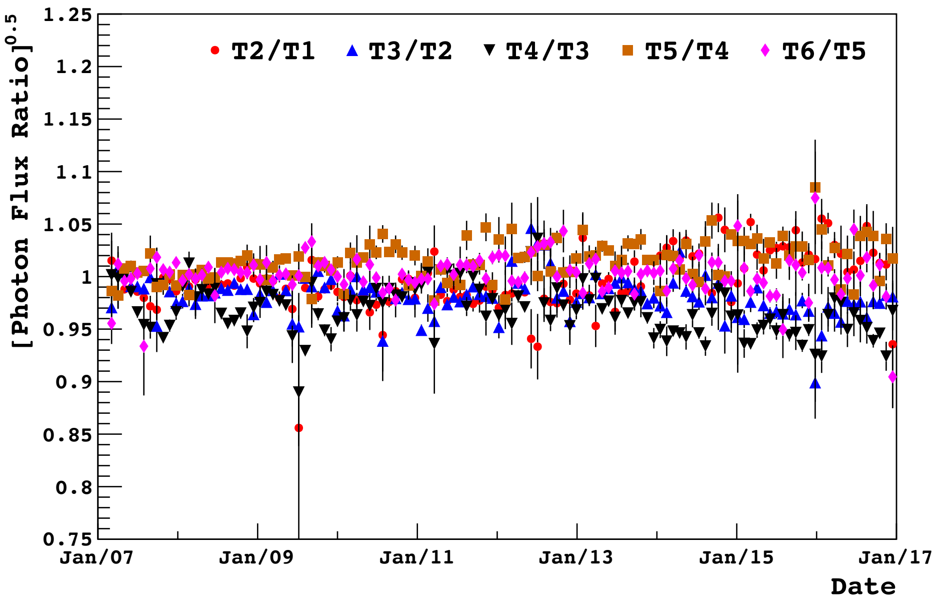


Figure 6.5: The average NSB photon flux observed by the six telescopes (labelled) of the Coihueco fluorescence detector during a single night. The colour scale represents the photon flux in units of 375 nm-equivalent photons/m^2/deg^2/μs. FD

Checking RELATIVE calibration between neighbouring telescopes using NSB

	T2/T1	T3/T2	T4/T3	T5/T4	T6/T5
Los Leones	0.70 ± 0.08	0.28 ± 0.03	-0.13 ± 0.03	0.12 ± 0.04	-0.01 ± 0.02
Los Morados	0.07 ± 0.05	0.04 ± 0.07	-0.14 ± 0.03	0.08 ± 0.04	0.03 ± 0.02
Loma Amarilla	-0.13 ± 0.04	0.11 ± 0.02	0.07 ± 0.03	-0.63 ± 0.06	0.12 ± 0.03
Coihueco	0.43 ± 0.01	-0.16 ± 0.03	-0.34 ± 0.07	0.43 ± 0.04	-0.08 ± 0.10

Table 6.3: Fitted slopes (in % per year) using the K_v method.



Averaged over 24 telescopes and all time, the relative calibration is good to 2%.

Figure 6.7: Results for Coihueco using the K_v Method for calculating the photon flux. The vertical axis is given in terms of $\sqrt{\text{Photon Flux Ratio}}$ - to allow for direct comparison with results obtained from the Identical Pixel Method. An interesting note is the increased spread beyond $\sim$ 2014, which is perhaps due to the lack of absolute calibration campaigns in recent years (the most recent occurring in April of 2013 [135]).

Star track analysis (inspired by Alberto Segretto's work, but many problems solved)

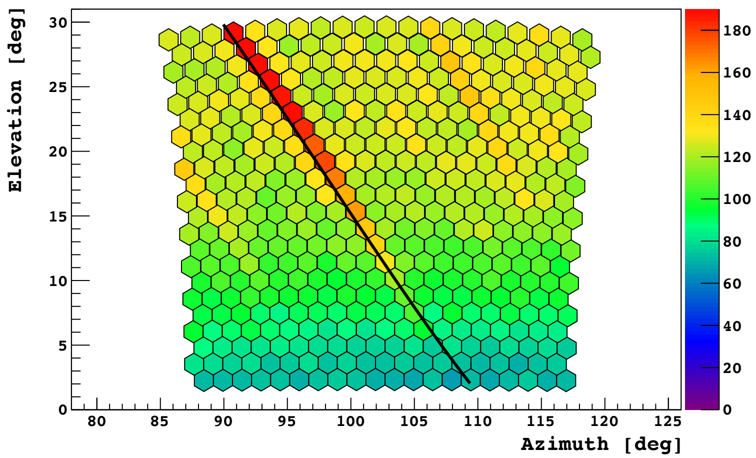


Figure 7.2: The NSB photon flux observed by the pixels of CO 4 averaged over a period of less than 2 hours. The colour scale here indicates the average photon flux in units of 375 nm-equivalent photons/m^2/μs. The track of bright PMTs can be attributed to the transit of Sirius (which begins at an elevation of $\sim 10^\circ$ for the time period considered here). The expected path of Sirius is overlaid in black. It should be noted that the brightness of the star (and the NSB) increases with elevation. NSB photons viewed at higher elevations propagate through less atmosphere, suffering from less atmospheric attenuation on their paths towards the detector.

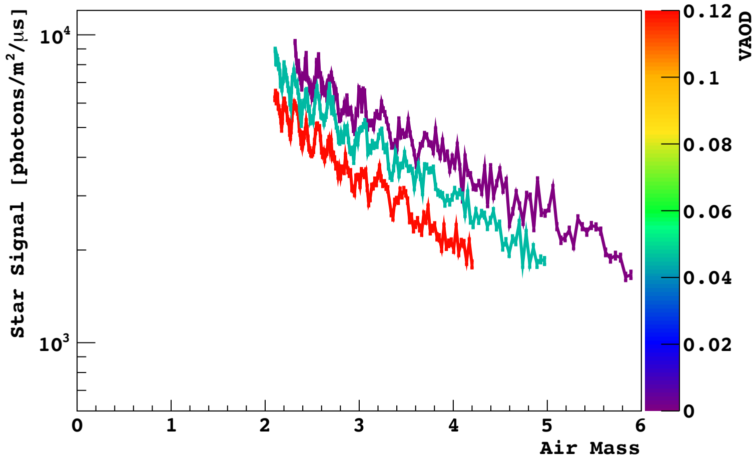


Figure 7.7: The star signal from Sirius observed by CO 4 over several nights. The colour scale here represents the average VAOD (up to a reference height of 4.5 km a.s.l) as measured by the CLF.

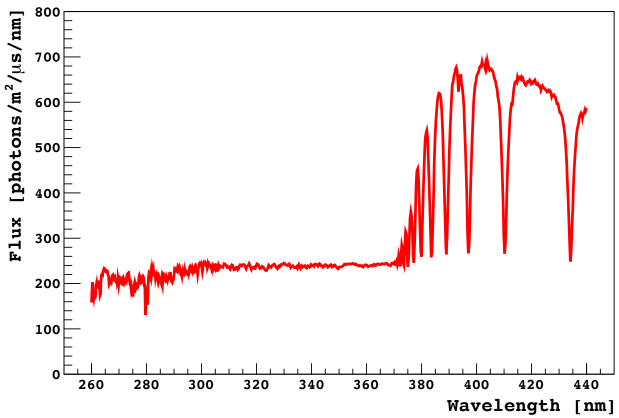


Figure 7.8: The spectrum of Sirius measured by the STIS. The large absorption features above a wavelength of ~ 365 nm correspond to the Balmer series.

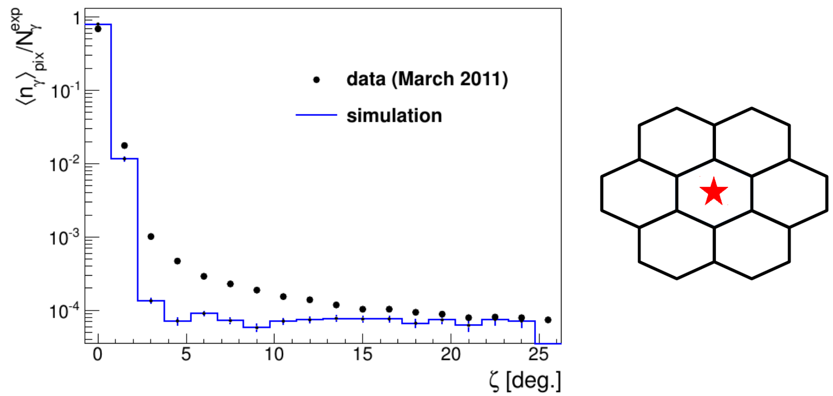
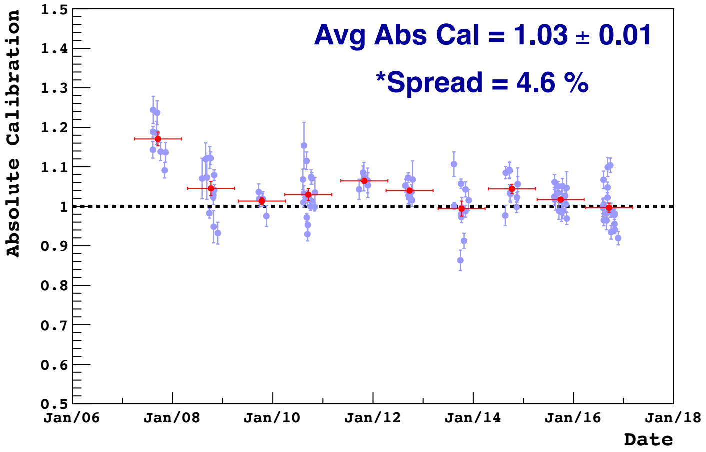
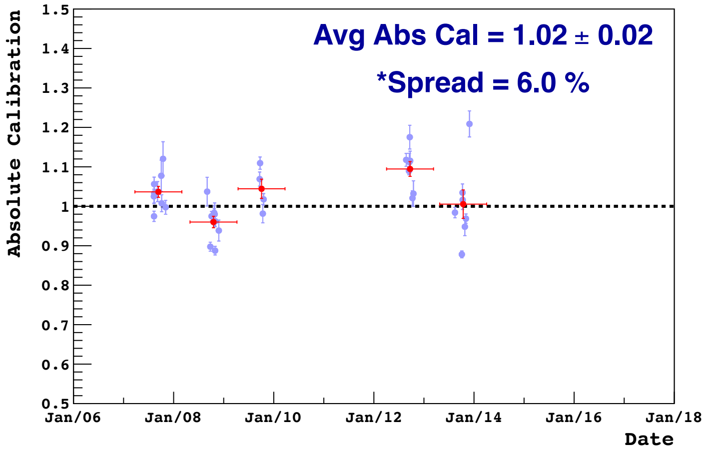


Figure 7.27: The differential light distribution for an FD camera (Los Leones telescope 3) measured using a point-like light source mounted on an octocopter. The vertical axis represents the average number of detected photons per pixel $\langle n_\gamma \rangle_{pix}$ divided by the expected number of photons N_γ^{exp}. Additional details are provided in [144].

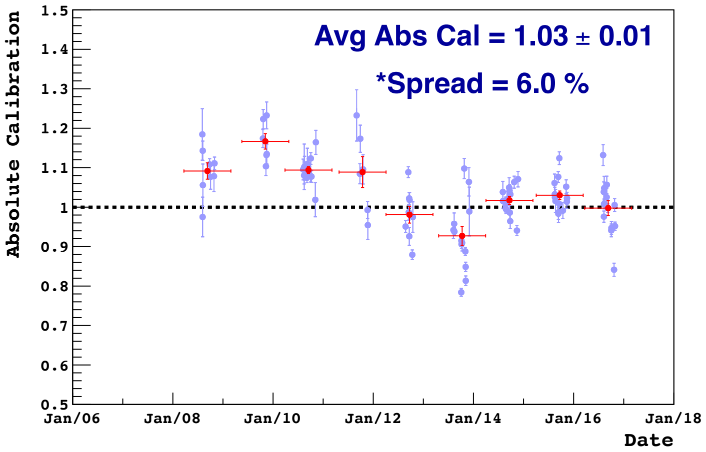
Star track results (Sirius)



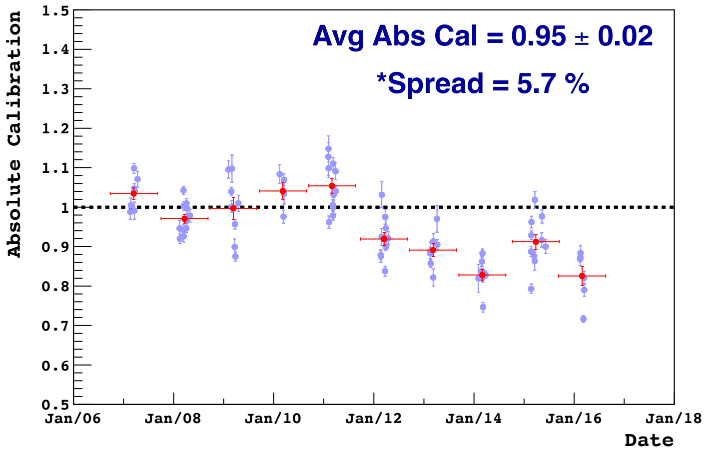
(a) Coihueco telescope 4



(b) Los Leones telescope 1



(c) Loma Amarilla telescope 6

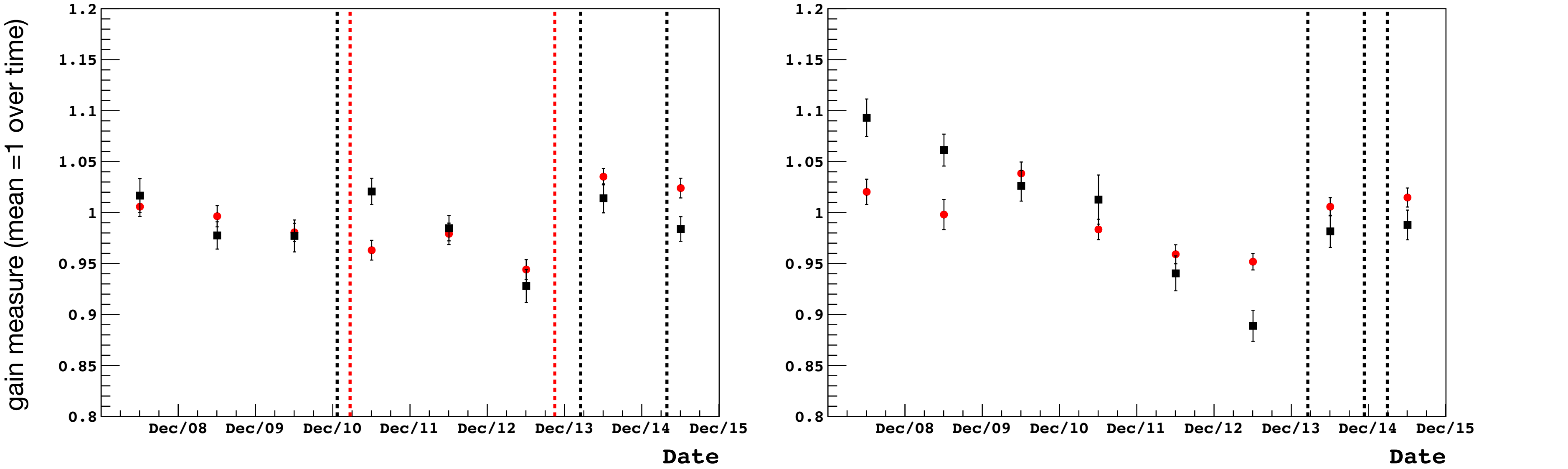


(d) Los Morados telescope 5

Figure 7.37: The absolute star calibration profiles for CO 4, LL 1, LA 6 and LM 5 estimated using Sirius. Sirius is observed rising in the East by CO 4, LL 1 and LA 6 between August and November, and setting in the West by LM 5 between February and June. The quoted spread is with respect to the mean value of each year.

Source	**Contribution [%]**
Optical Halo	3.5
Star Spectrum	5*
FD Efficiency	2-5**
Fitting Algorithm	<1
Angstrom Coefficient	<1
Rayleigh Optical Depth	1
Template Estimate	2
Total	**7-8**

Comparing star track and EFD/S38 results (the latter is called “ESR”)



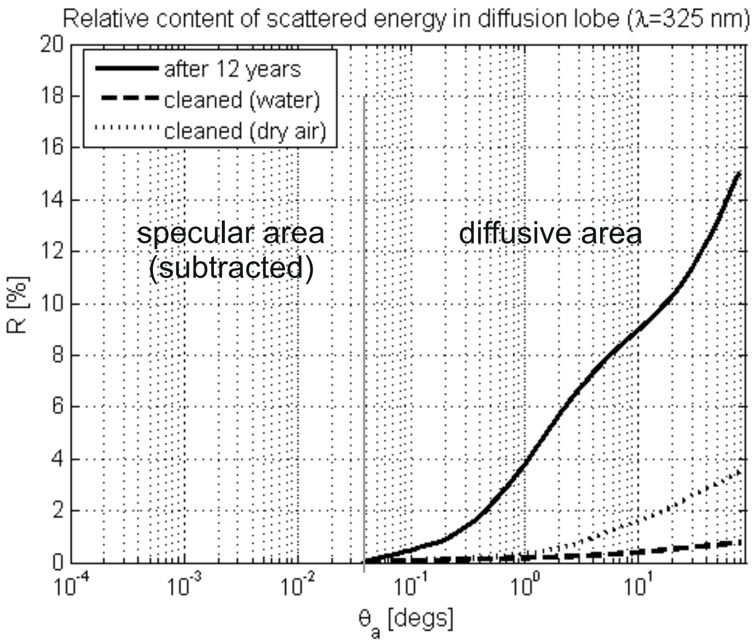
(a) Coihueco (b) Loma Amarilla

Figure 7.49: Normalised ESR (red circles) and star calibration (black squares) profiles for Coihueco and Loma Amarilla. The dashed black lines indicate the dates of the filter cleaning campaigns. The dashed red line indicates the date of a mirror cleaning campaign for Coihueco (no mirror cleaning campaigns for Loma Amarilla were listed over the time period considered here).

- filter cleanings produce step (almost all filters cleaned in March 2004)
- lack of mirror/filter cleanings seem to correlate with drift
- interestingly, the drift does not seem to be affected by drum calibrations

https://www.auger.unam.mx/AugerWiki/MergedListOfCleanings

Long term drift (plausible explanation):



Phong p161:

Recent efforts have been made by members of the Collaboration to study the effect of the deposition of dust on the reflective properties of the FD mirrors [146]. More specifically, the study involved the measurement of the fraction of signal (from a portable light source) which was diffusely scattered off the mirror. This fraction, referred to as the diffusion reflectivity, is naturally anti-correlated with the specular scattering of light off the mirror. If it is assumed that all of the diffusely scattered light contributes to the broadening of the PSF, then the diffusion reflectivity can be interpreted as a measure of the broadening of the PSF. For the mirror monitored in [146][15] it was found that the dust layer which had accumulated on the mirror's surface after 12 years of operation caused the diffusion reflectivity to increase by 15% at a wavelength of 325 nm. This is equivalent to an increase in the broadening of the PSF of ∼ 1.25% per year (assuming this effect is linear in time), a rate which is comparable to the long term drift of the FD calibration.

[146] L. Nozka *et al* 2018 *JINST* **13** T05005

Note: even the drum calibration is blind to this effect and can't correct for it

Filter Cleaning: explanation of step at start of 2014

Filter cleaning can cause a 10% step.
Almost all filters were cleaned in March 2014.

The drum/XY scanner would, in principle, correct for dirty filters.

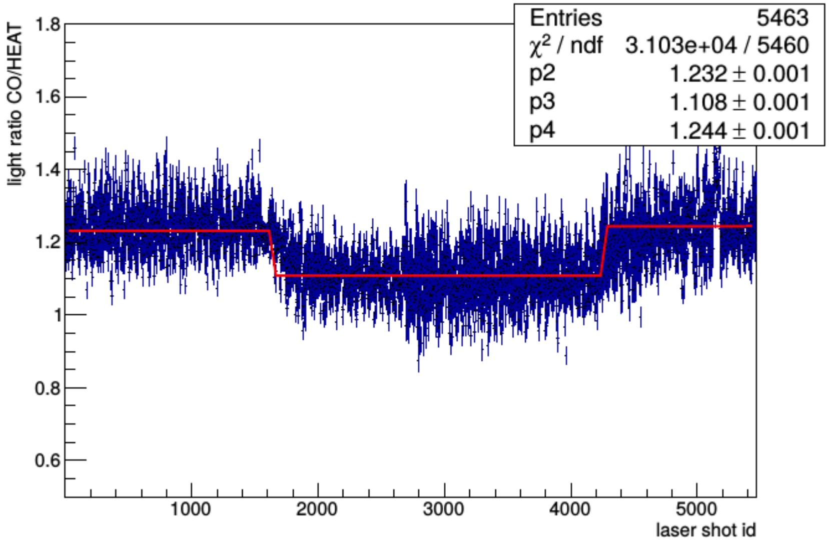


Figure 7.48: The ratio of CLF signals detected by CO 3 and HEAT 1 over an eight day period in March 2014. The downwards step corresponds to the filter of HEAT 1 being cleaned. The upwards step corresponds to the cleaning of the filter of CO 3 [164].

Joachim Debatin
Master's thesis

- See Phong's thesis, Chapter 8, for list of conclusions
- Relative calibration between telescopes seems fine (using NSB), but there exists a drift and a step in the absolute calibration across all telescopes

- Typical drift (up to 01/2014) in EFD/S38 is ~1.6% per year, including ~0.3%/year from the SD side.
  - confirmed by star track analysis
  - plausible explanation is the accumulation of dust on the mirrors, broadening the PSF (Nozka et al.), affecting shower (and star) analysis.
  - Drum/(XY scanner) calibration is "blind" to this. Only solution is cleaning.

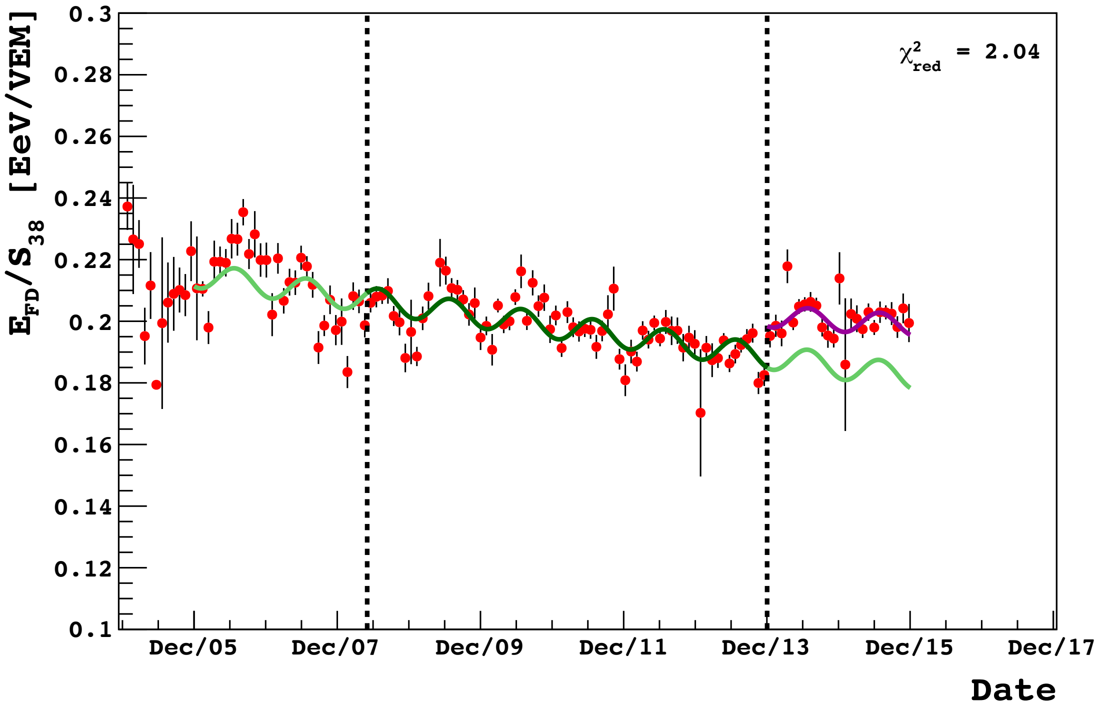
- Steps in absolute calibration caused by filter cleaning (well known).
  - relative calibration is "blind" to this
  - (Drum/XY scanner would correct for dirty filters, but in-between drum calibrations, filters getting dirty would contribute to the drift.)

- Emphasises the importance of regular cleaning of
  - mirrors (big job, 5 year cycle? - suggested by Olomouc colleagues)
  - filters (now done every 4 months I think)

More recent data (post-Phong) …

Fig 5.25 from Phong's thesis

(Weather and geomagnetic corrections to SD, Max's improvements to DB)



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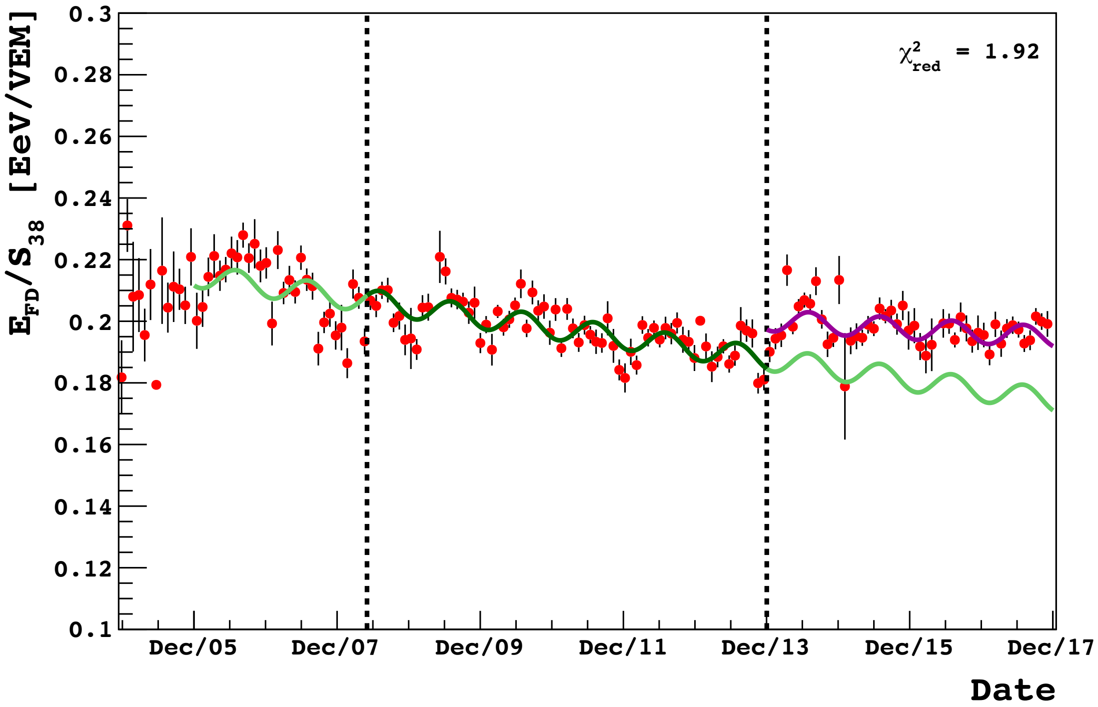
→ **+ Aero. DB + SD WC + Geo.**	2.04	-1.6 ± 0.2	2.0 ± 0.4	-0.7 ± 0.9	1.7 ± 0.7

Table 5.2: Summary of the optimal broken fit parameters for different SD and FD corrections.

ICRC19 production

(Weather and geomagnetic corrections to SD)



drift (pre 2014): -1.69 +/- 0.19 % per year amplitude (pre 2014): 1.88 +/- 0.42 %
drift (post 2014): -0.68 +/- 0.28 % per year amplitude (post 2014): 1.72 +/- 0.52 %

reduced drift rate “post-2014”
(regular filter cleaning?)

cause of remaining
sinusoid amplitude?