Calibration of the SST

Michael Daniel

Desirables

Some of the calibration issues we need to think about

- Absolute Calibration
  - single p.e.
  - alignment
  - pointing
- Relative Calibration
  - flat-fielding
  - gain & linearity
  - timing?
  - optical efficiency

with so many telescopes we need to be able to do all of this simply, inexpensively and in a fashion where the equipment lasts/is easily replaceable.

Simple:

- Few components
- Well understood components
- Easily swappable/replaceable
- Commercial components or solutions where available

Reliable:

- Few components
- No moving parts
  (ie no filter wheels)
- Long-life components
  (eg LEDs)

Low-cost:

- Few components
- Cheap components
  (eg LEDs)
- Long-life components
  (eg LEDs)

An Example: Simple comparison of properties between laser and LEDs

VERITAS are moving to an LED flasher system housed in a Maglite®

It goes from single p.e. illumination to tripping the low gain channel by selecting between 1 to 7 LEDs being pulsed.
It also costs 1000s less than the old laser system.

D. Hanna et al. NIM A **612**, 278 (2010).

cf. H.E.S.S./MAGIC already have LED based systems

	laser	LED
pulse rate	~10 Hz	~100 Hz
lifetime	~1,000,000 shots*	~10,000 hours
cost	~1000 per tube	~few
brightness	1000s pe	10s-100s pe

To get desired illumination

need lots of attenuation to avoid saturation

can sum LEDs

* 1,000,000 shots @ 10 Hz ~27 hours

numbers are approximate, order of magnitude

Questions ATAC need to ask the other work packages

MC: to what accuracy do we need to measure calibration parameters?

MC/FPI: what wavelength range will we need to calibrate photodetectors over?

ELEC/FPI: What dynamic range will we need to cover? From 1 p.e. to several 1000?

TEL/FPI: What is the fov/lightcone acceptance? Will there be secondary optics? Where can we mount equipment & what will be the distance to the camera?

ELEC: will we have independent calibration runs, or will we be able to inject calibration events into observing runs? (need to mark trigger & event types, DATA?)

DATA/[ELEC/FPI]: what data will be accessible, what will be saved? ped. vars, currents

How many of these can change from *will we* to we **must** be able to?

Potential complications

Non-linear gain readout system? – requires large dynamic range of light output

Single p.e. capability? -- requires dynamic range of light output to go low and a dark place to point

Wide field of view – quantum/collection efficiency changes as a function of incident angle plus lightcone effects...

Secondary optics suggested for some telescope designs – where to mount box? Curved camera surfaces? ...

Multi-anode PMTs – can not control the gain on individual pixels

Mirror Alignment

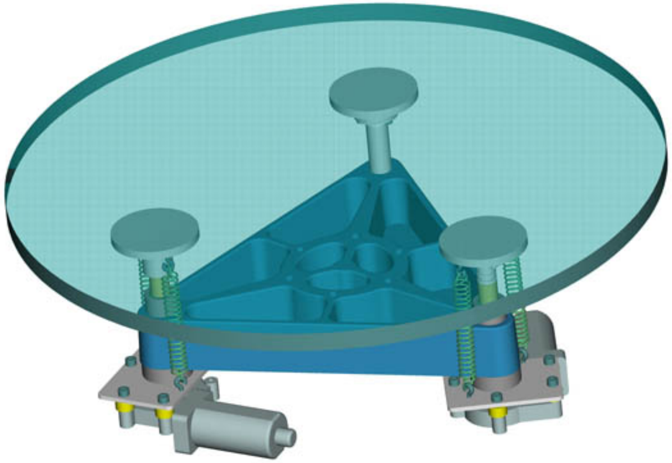
How often does this need to be performed?
When mounting mirrors
After replacing mirrors
When changing focus
for bias alignment?

Where are you focusing on? Infinity? Shower Max.? Are you changing between those?

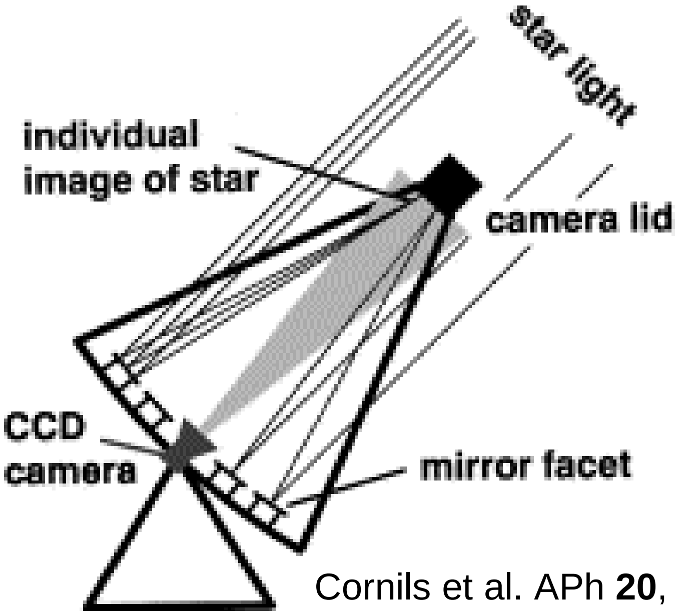
Are mirrors automated (quick, but €$£ expensive) or hand aligned (cost cheap, time expensive)

See talk on alignment by Rodolfo Canestrari for more focussed discussion on alignment

Mirror Alignment: automated mirrors



motors on the back of mirror allow it to be automatically repositioned

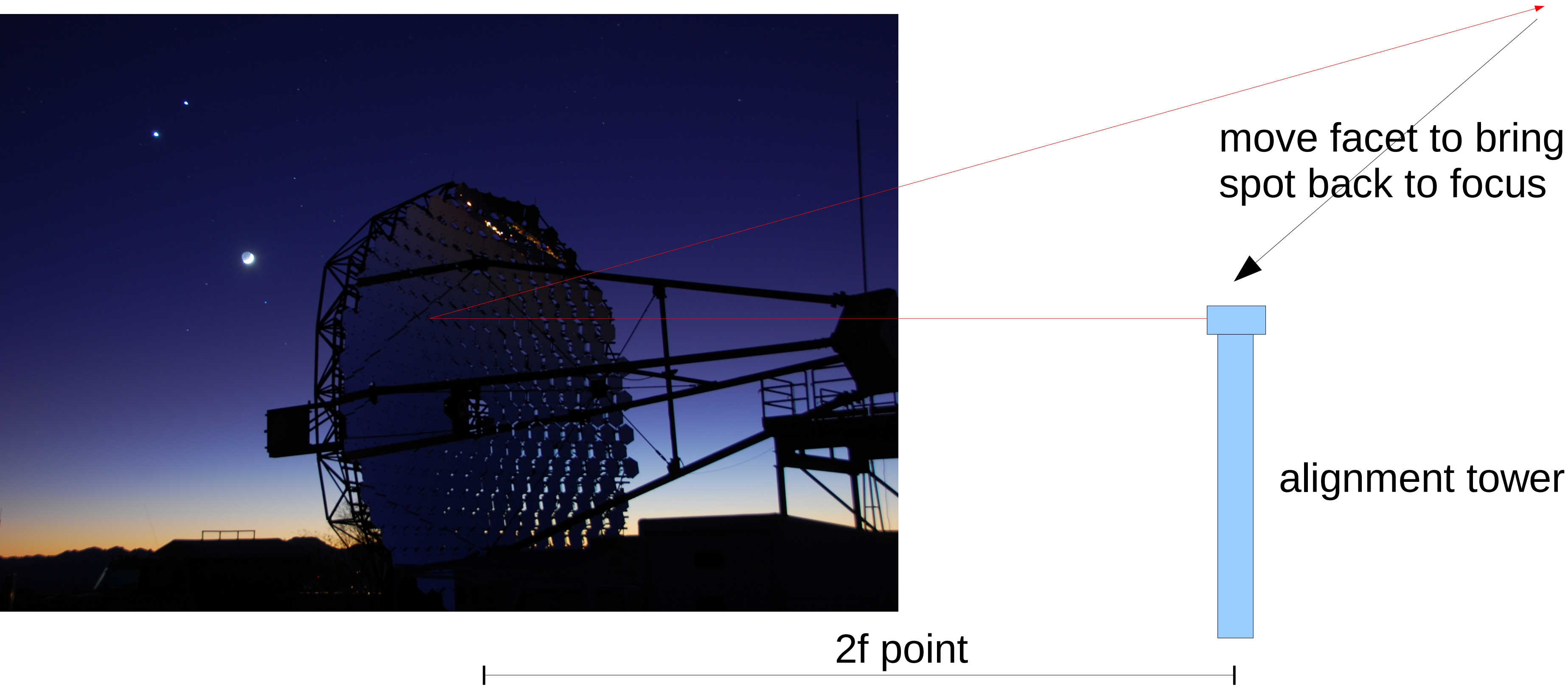


Cornils et al. APh **20**, 129 (2003).

Take measurements using starlight as point source
- ✔Can be fully automated
- ✔Already aligned for optimal viewing elevations
- ✔Easy to re-focus on the fly: e.g. between infinity and shower max.
- ✗Extra cost in having motors
- ✗May be used only once
- ✗If motor fails (e.g. dust build up) you're stuck

Mirror Alignment: 2f Method

Telescope at park



move facet to bring spot back to focus

alignment tower

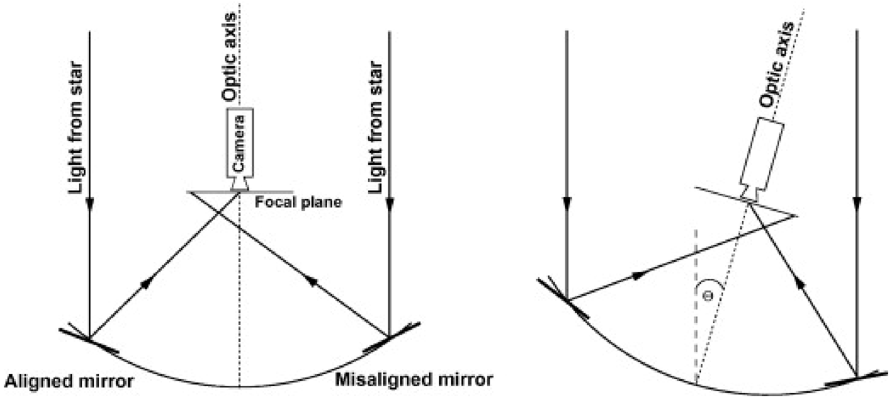
2f point

✔Can be done during moonlight and under most weather conditions
✔Inexpensive
✗Takes a lot of time & manpower (especially if you have set up the alignment tower again)
✗Results aren't always reproducible
✗Camera shadowing means inner mirrors can't be finely aligned
✗Requires extra measurements for facets to be bias aligned to account for gravitational slumping at observation elevations.

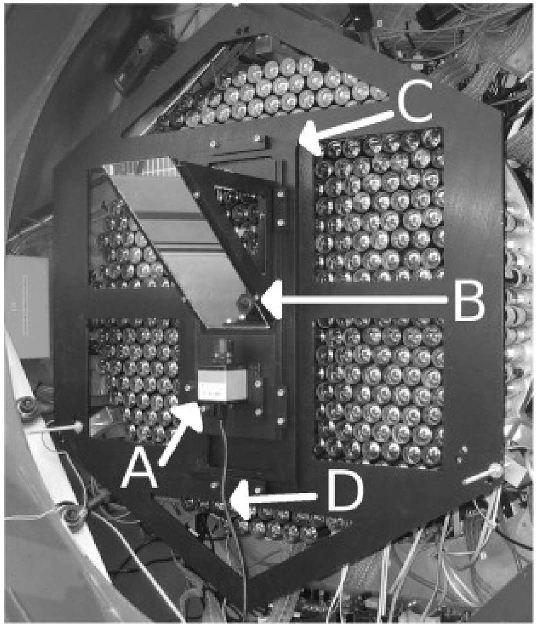
Toner et al. Proc. 30th ICRC (2008).

Mirror Alignment: Raster Scan Method

Consists of
A mounting plate
a digital camera with wide-angle lens (A)
a 45 degree plane mirror (B)
an x-y positional stage (C)



(a) On axis (b) Off axis



Take measurements using starlight as point source
✔Automatically aligned for optimal viewing
✔Can take measurements at night & then align by day
✗Good for facets (i.e. DC) not monolithic mirror (i.e. secondary optics)

Proposed by Arqueros et al. APh **24**, 137 (2005). Implemented by McCann et al. APh **32**, 325 (2010).

Pointing

Shaft encoder limits and mechanical imperfections of telescope mean its pointing is not fully described by the axes positions.

Reproducible mechanical errors, e.g. bending of the structure due to gravity, can be measured once and then modelled out.

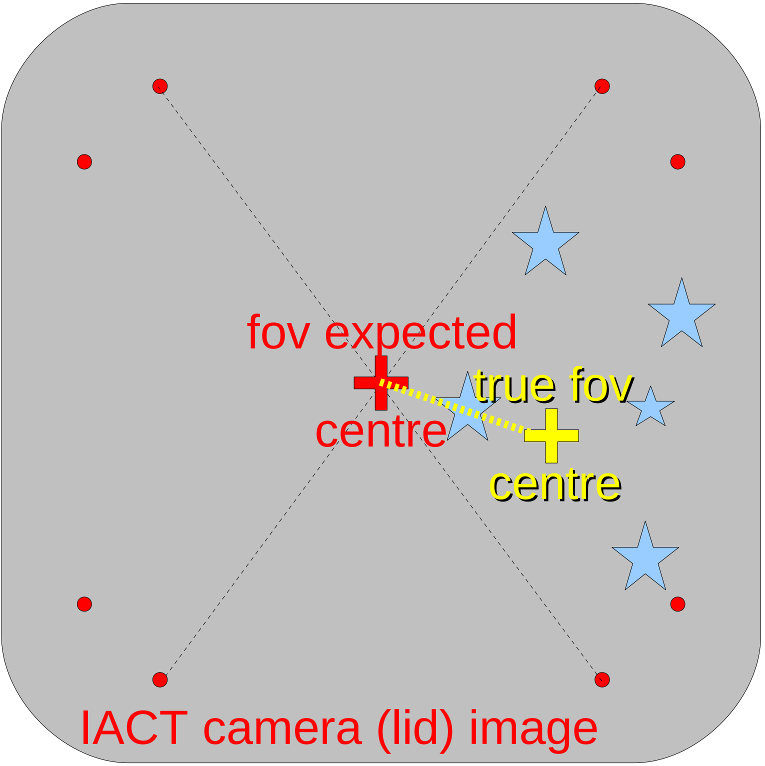
Irreproducible errors, e.g. wind loads, need to be measured at time of observation wrt a known reference, e.g. starlight.

Pointing – sky/lid model

CMOS cheaper than CCD – potential cost saving?

observations of the sky during observing runs gives the mismatch to known star positions

pointing runs then give the mismatch of the IACT camera to the sky view camera.



Pointing – projecting starlight on to camera lid

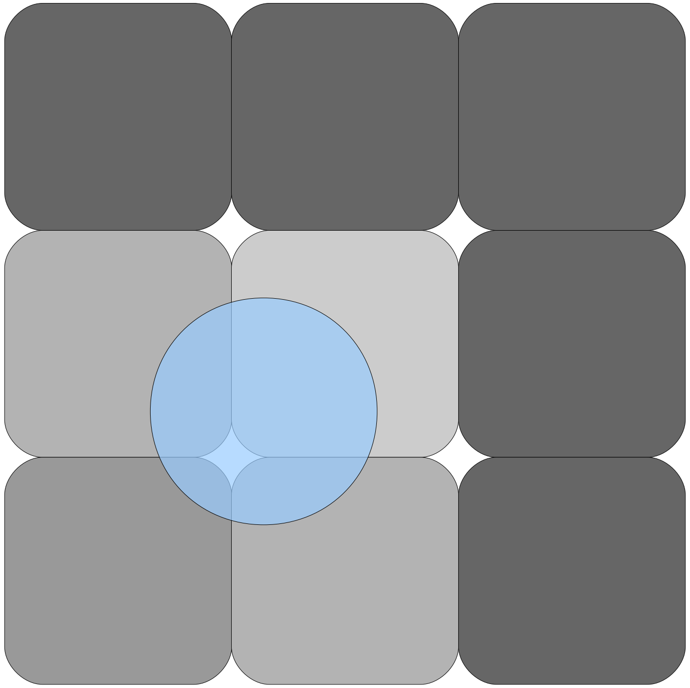
Secondary Experiments Issue:
If other equipment mounted on lid then can't do it.

Secondary Optics Issue:
Projecting stars onto shutter will alter focus by too much, unless shutter is ~mm thickness from surface of camera

Pointing – using pixel currents to determine star positions

With a long integration (~ms) to measure a current

we can measure pointing from camera pixels themselves



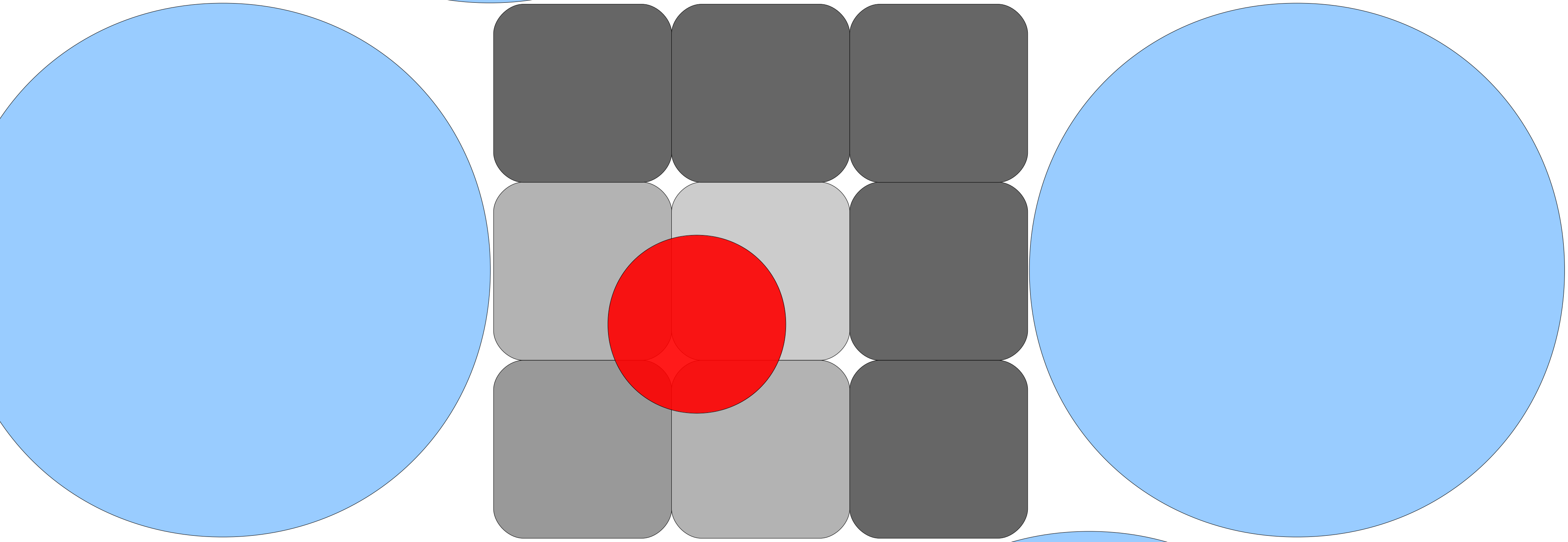
Need good knowledge of interpixel response to ensure the star psf is accurately reproduced to find centroid

Will centroid placement be accurate enough?

If PSF>>pixel size light distribution can be fit over several pixels. If PSF<pixel size star transiting between pixels is used, accuracy comes from field of view rotation – so the component perpendicular to the radius is best measured, but is it accurate enough to provide a stringent test? If PSF~pixel size neither procedure works well.

Pointing – use laser spot & pin diode array to determine camera movement

replace central pixel with a fine resolution pin diode array



shine a laser spot at the centre, displacement of centroid gives camera movement

see Feinstein presentation at ATAC Montpellier meeting, Feb. 2010.

Methods for calculating the **Absolute** Gain

(1) Direct measurement of the single photo-electron pulse spectrum

(2) Differentiate the single PMT bias curve

(3) Muon rings

(4) Photon-statistics: evaluation of the variance and mean of bright pulses

(5) Reproducing the trigger rate with simulations

Some references:

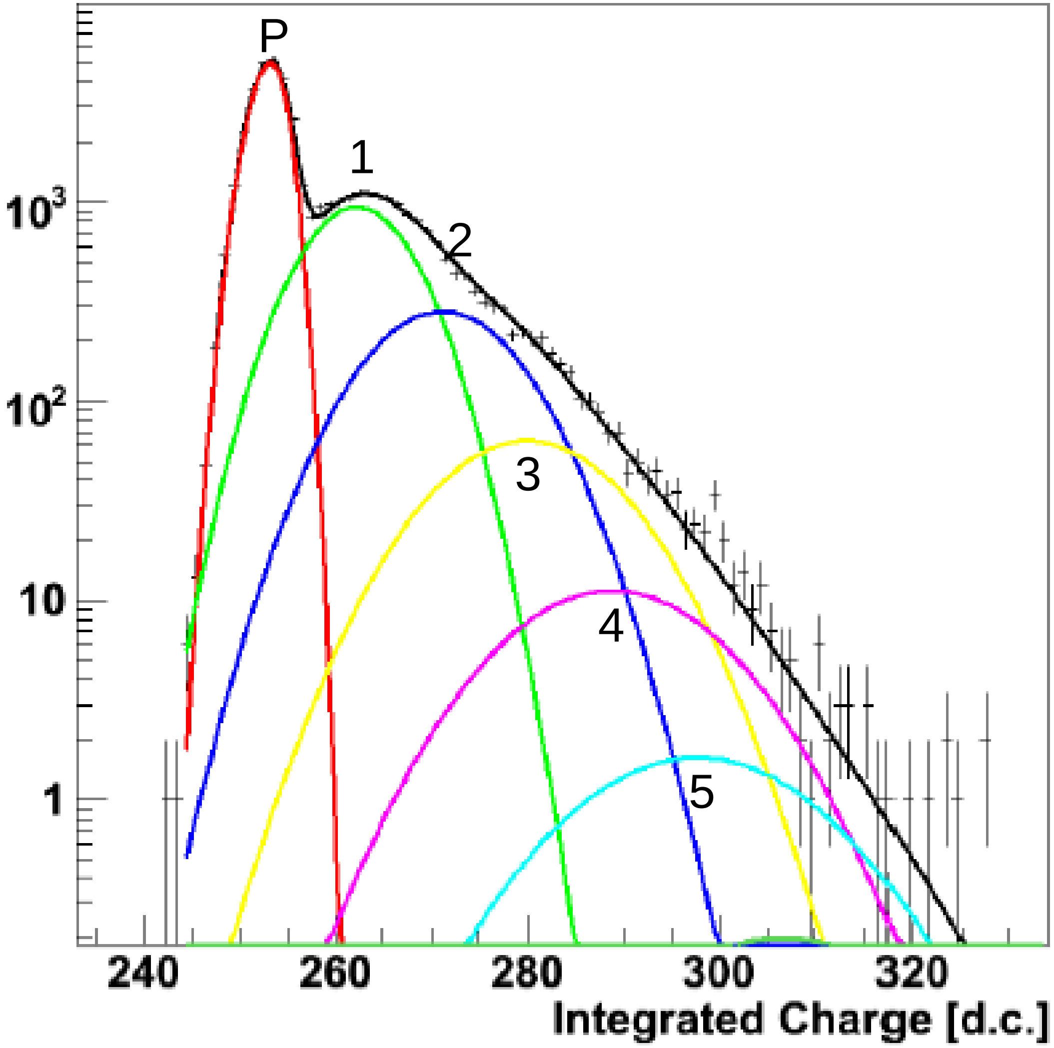
Biller et al. 'Calibration Techniques for Air Cherenkov Telescopes', Proc. of the 24th ICRC **3**, 412 (1995)

Gemmeke, Kleifges & Menshikov 'Statistical Calibration and Background Measurements of the Auger Fluorescence Detector' Proc. of the 28th ICRC, 891 (2003).

Hanna et al 'AN LED based flasher system for VERITAS' NIM A **612**, 278 (2010).

Hanna et al. 'Calibration Techniques for VERITAS' Proc. of the 30th ICRC **3**, 1417 (2007).

Absolute Calibration: single photo-electron pulse size spectrum



D. Hanna et al. NIM A **612**, 278 (2010).

In dark conditions illuminate the PMT such that a p.e. will be generated only every ≤ N pulses.
The resulting size spectrum will give the absolute gain of the system.

Problems:

Need it to be really dark to ensure a single p.e. peak is resolved.
(H.E.S.S. use camera shed, MAGIC use a blinded pixel, VERITAS have a screen with very small holes drilled above PMT face).

Need an external trigger scheme since single p.e. is below the trigger threshold.

Require wasted dynamic range to resolve single p.e.

Things we can do for “free”: single p.e.?

For a small secondary optics telescope the time between NSB photons could allow us to do single p.e. studies without any specialised hardware...

NSB ~2.2-2.6 x 10^{12} ph/s/m^2/sr for La Palma & Namibia *S. Preuß et al NIM A* ***481****, 229 (2002).*
(300-650nm)

pixel size ~0.2° <QE> ~ 25%

DC: telescope diameter 6m ~20 x 10^7 ph/s or 1 photon every ~5ns

SO: telescope diameter 3.5m ~6.2 x 10^7 ph/s or 1 photon every ~16ns

Potential issues:

Require pointing at a dark patch still
Still expect some signal pile-up
FADC clocking noise can bias result

something we can do for “free”

Absolute Calibration: single PMT bias curve.

Probability of *n* photo-electrons in time τ arriving with a frequency *b*

$$P(n, b\tau) = (b\tau)^n \frac{e^{-b\tau}}{n!}$$

At the anode one assumes/approximates a Gaussian number of electrons with fluctuations of variance σ from the single p.e. emission from the cathode. Let ν_0 be the mean rate of hits then the frequency of single p.e. events can be found

$$f(s) = \frac{1}{\tau} P(1, b\tau) \int_s^{\infty} \left(e^{-(\nu-\nu_0)/2\sigma^2} / \sigma\sqrt{2\pi}\right) d\nu$$

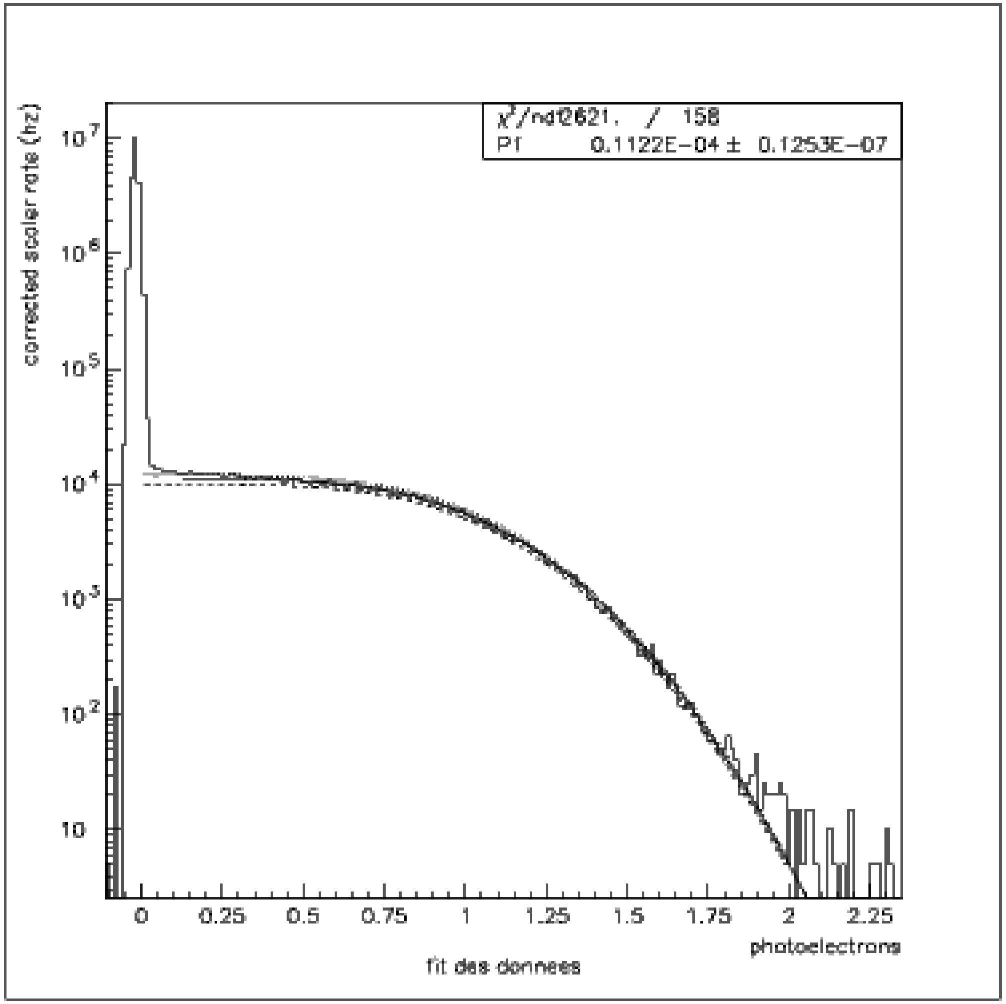
let s < 1/3 p.e.

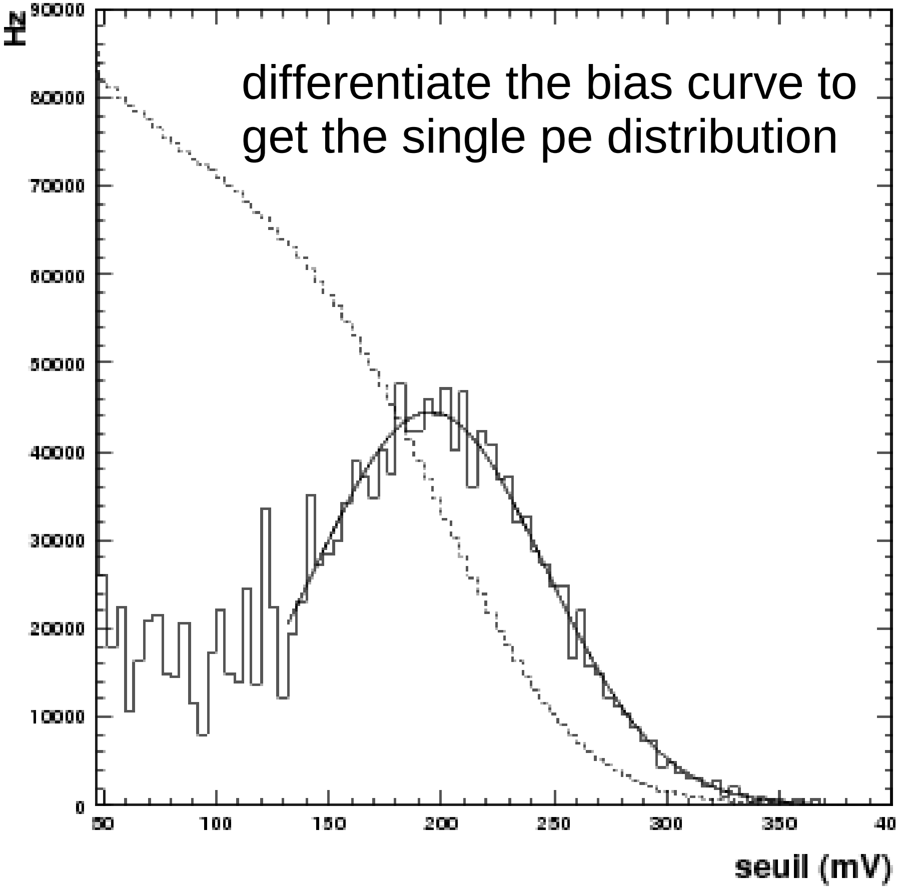
Giebels, PhD thesis (1998).

Absolute Calibration: single PMT bias curve.

something we can do for “free”

In low light level condition, scan through discriminator setting values to get the rates.
Differentiate that bias curve will give the single p.e. spectrum.
Method used for CELESTE and prototype VERITAS system.





differentiate the bias curve to get the single pe distribution

B. Giebels PhD thesis

something we can do for “free”

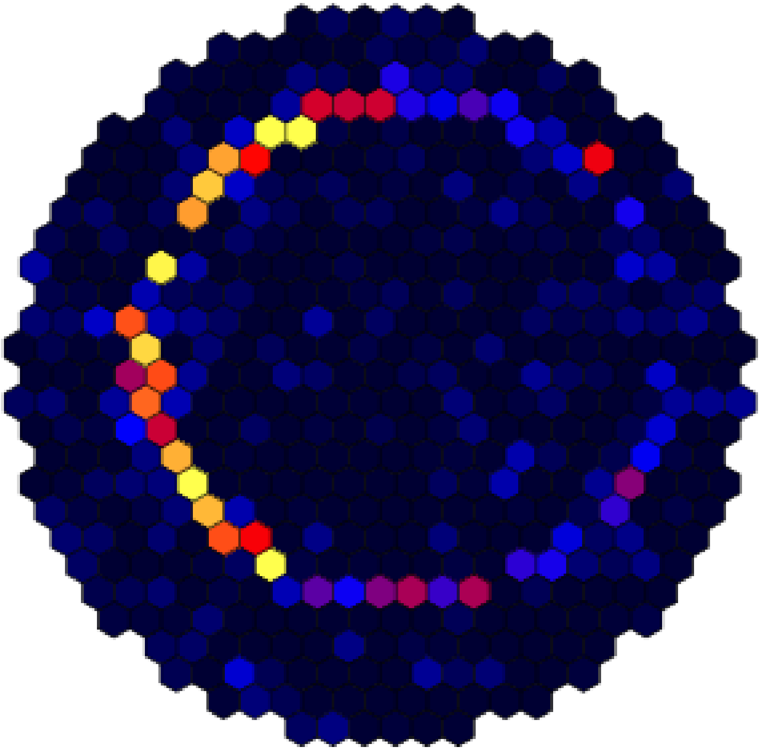
Absolute Calibration: muon rings

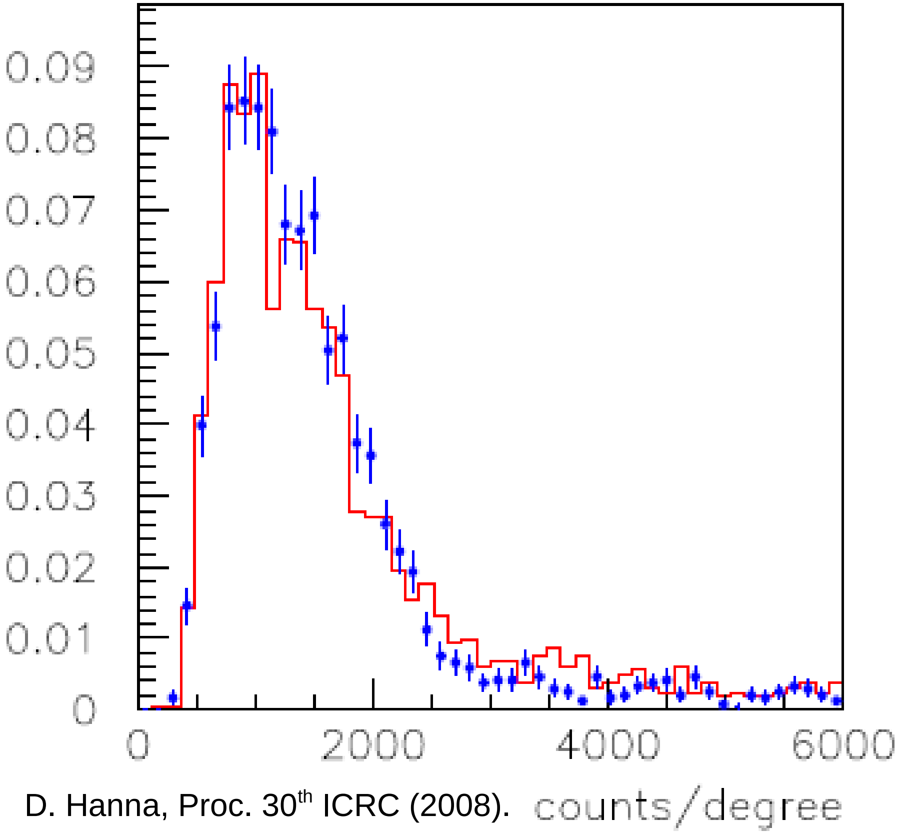
“Overall, absolute calibration is achieved by reconstructing the rings generated by local muons”
Design Concepts for the Cherenkov Telescope Array

The number of Cherenkov photons provides a well known absolute light source

$$\frac{dN}{dX}=2\pi\alpha z^2\int_{\lambda_1}^{\lambda_2}\left(1-\frac{1}{(\beta n(\lambda))^2}\frac{1}{\lambda^2}d\lambda\right)$$

(provided you know the density/refractive index & UV transmission/reflectance/QE very well!)





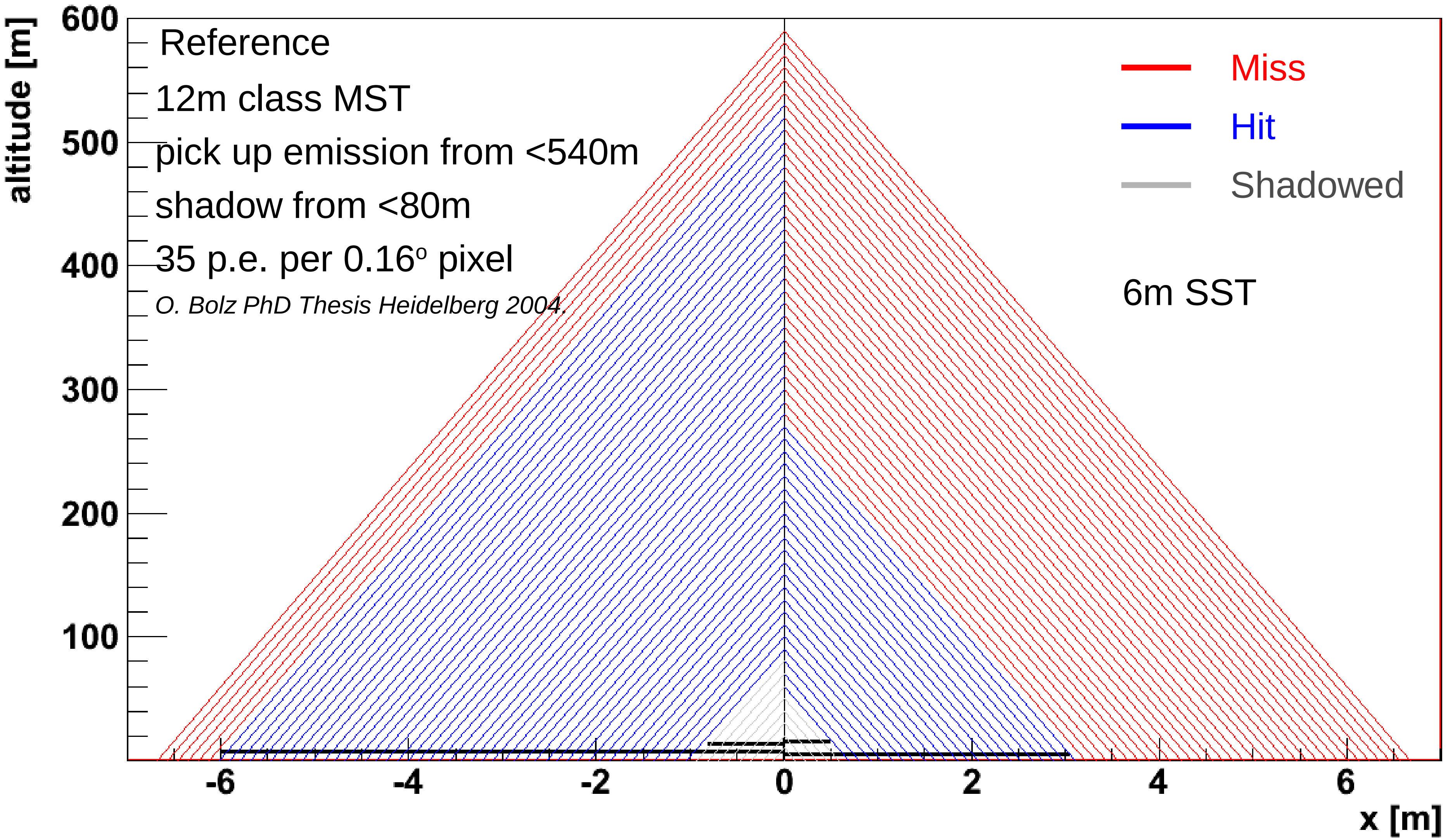
D. Hanna, Proc. 30th ICRC (2008).

Absolute Calibration: muon rings

something we can do for “free”?

When we take a look at light from muon path

Compare DC optics



Reference

12m class MST

pick up emission from <540m

shadow from <80m

35 p.e. per 0.16^{o} pixel

O. Bolz PhD Thesis Heidelberg 2004.

6m SST

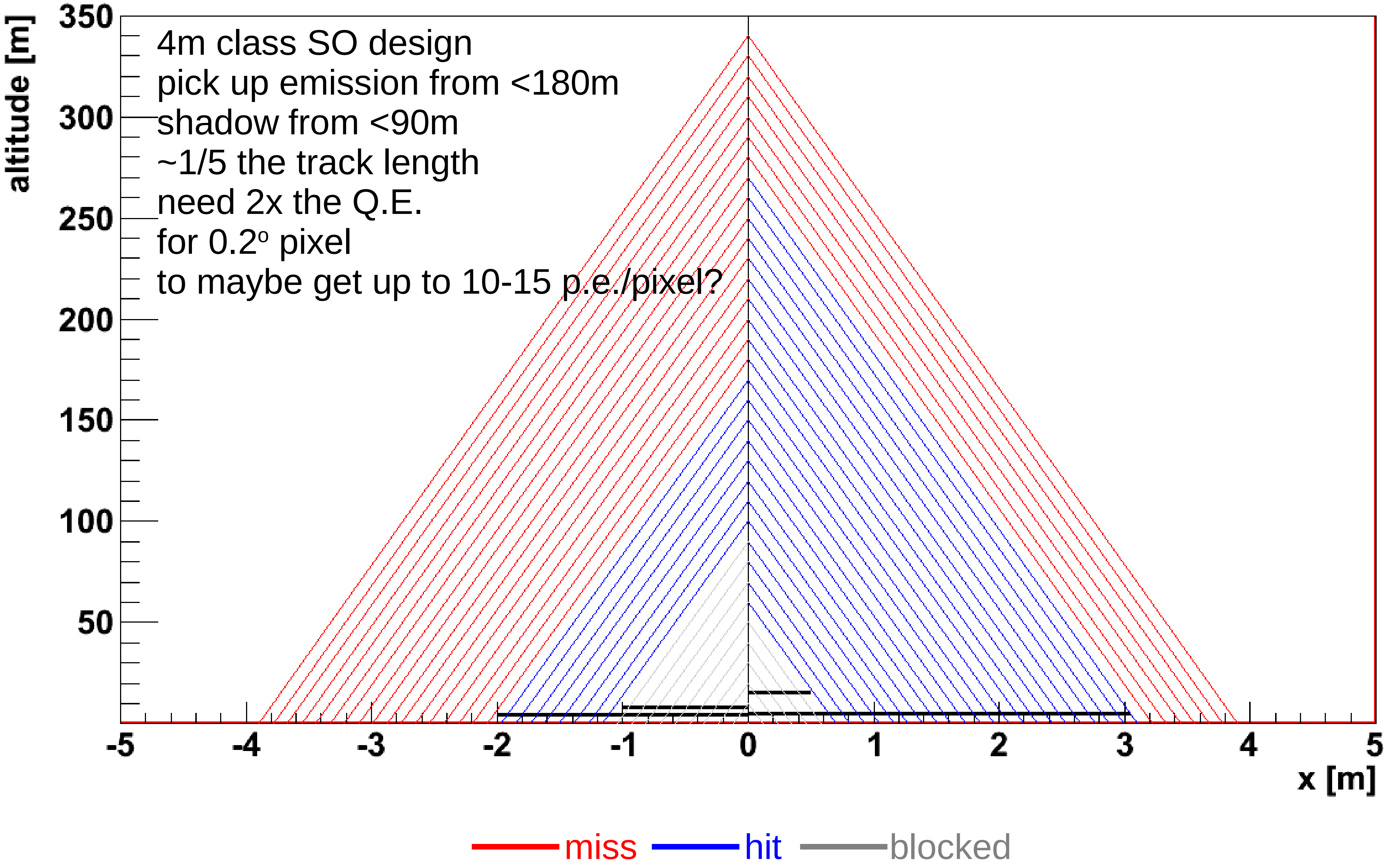
It would be very hard to trigger on, and make use of, muon rings in a small telescope of any type?

Absolute Calibration: ~~muon rings~~

something we can do at all?

Which means you may not be able to rely on muon rings as a calibration light source

Compare SO vs DC optics SST designs



4m class SO design
pick up emission from <180m
shadow from <90m
~1/5 the track length
need 2x the Q.E.
for 0.2° pixel
to maybe get up to 10-15 p.e./pixel?

Absolute Calibration: photon statistics:

After folding out pedestal fluctuations and pulse size fluctuations
the mean number of photoelectrons hitting the first dynode for a given light level is N_{pe}
with fluctuations about this of

$$\sigma_{pe} \simeq \sqrt{N_{pe}}$$

After amplification we have mean (μ) and variance (σ)

$$\mu = GN_{pe} \quad \text{and} \quad \sigma = G\sqrt{N_{pe}}$$

and thus we expect

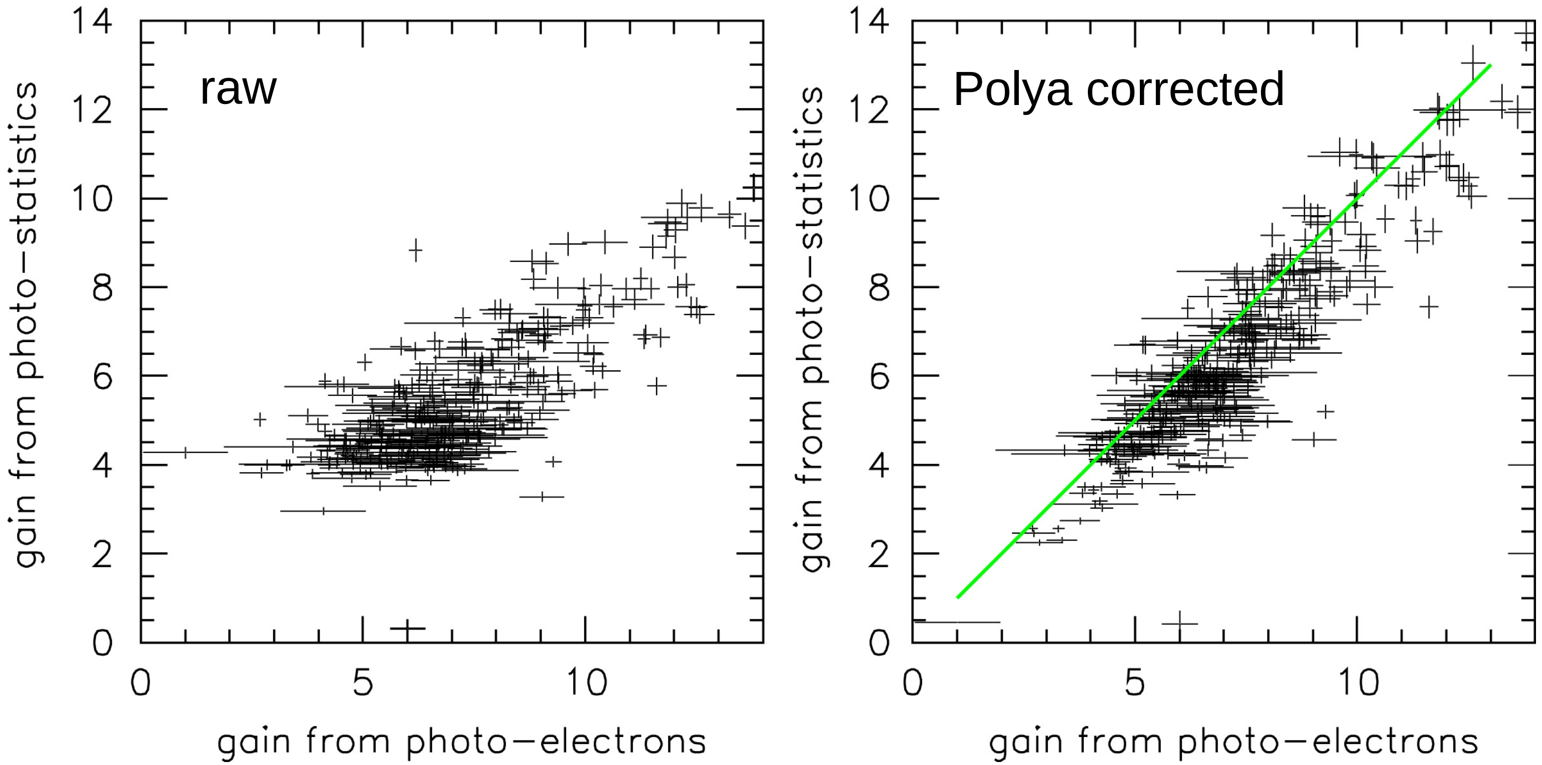
$$\sigma^2 = G^2 N_{pe} = G\mu$$

so by plotting the mean versus the variance at several light levels the slope will give an estimate of the absolute gain without the use of a calibrated monitor to indicate the light level.

Absolute Calibration: photon statistics:

something we can do for “cheap”

method used by VERITAS (laser & filters, LEDs) & Whipple 10m (nitrogen flasher)



D. Hanna et al. NIM A **612**, 278 (2010).

The difference between methods is an indication of the scale of systematic uncertainties in gain measurement procedures.

MAGIC also have done this, but have additional issues due to electronic (e.g. VCSEL fluctuations) and NSB (pedestal uncertainty) noise that limit the success of the method. These are not issues that should necessarily affect the SST.

something we can do for “free”

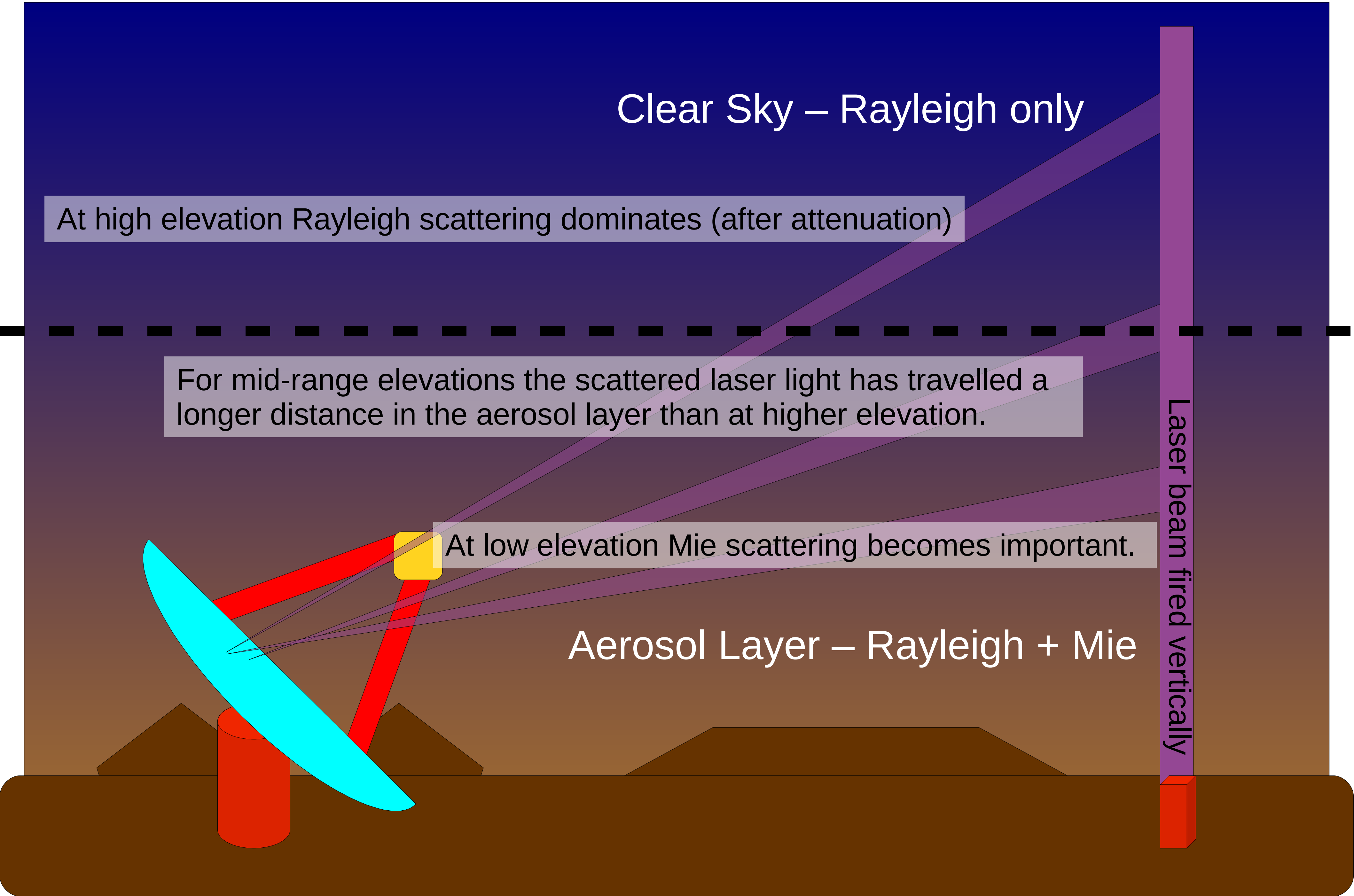
Absolute Calibration: photon statistics: currents v ped. vars

The Poisson process of bombarding the photocathode with a sequence of photons holds whether you are using LEDs or starlight in the NSB as your source of photons. This means you can perform a similar photon statistics process by plotting the PMT currents versus the pedestal variations, something which has been done for both STACEE and the Auger fluorescence detector PMTs.

Anything from 7th magnitude stars are used for this by Auger.

D Hanna 'Absolute Calibration of the PMTs for STACEE', internal note.
Gemmeke, Kleifges & Menshikov 'Statistical Calbration and Background Measurements of the Auger Fluorescence Detector' Proc. 28th ICRC (2003).

Central Laser Facility: Basic Principle



Clear Sky – Rayleigh only

At high elevation Rayleigh scattering dominates (after attenuation)

For mid-range elevations the scattered laser light has travelled a longer distance in the aerosol layer than at higher elevation.

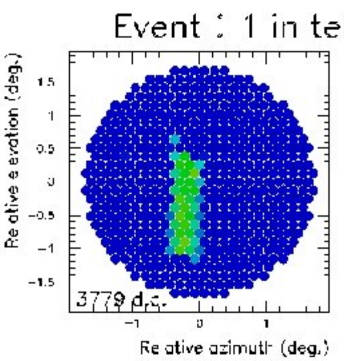
At low elevation Mie scattering becomes important.

Aerosol Layer – Rayleigh + Mie

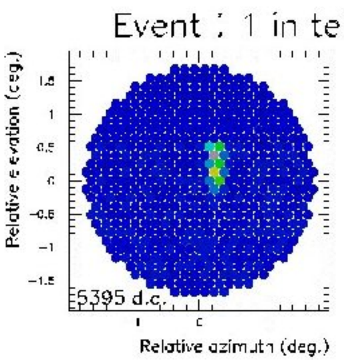
Laser beam fired vertically

something we can do for “free”

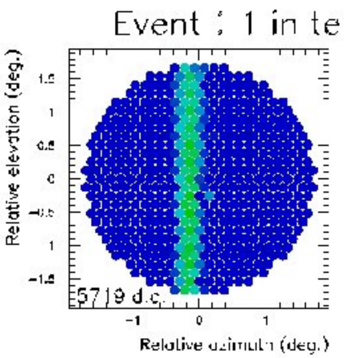
Central Laser Facility would be very nice please, thankyou.



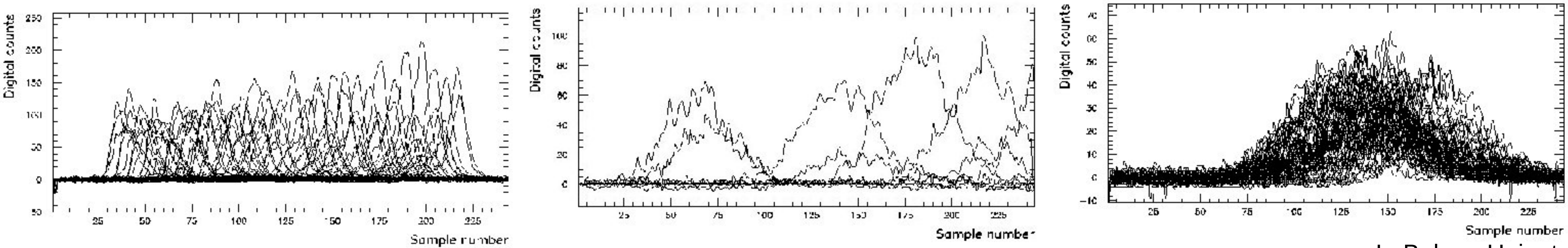
at 20 deg elevation
(altitude 0.5km),
timing not adjusted



at 60 deg elevation
(altitude 2km),
timing not adjusted



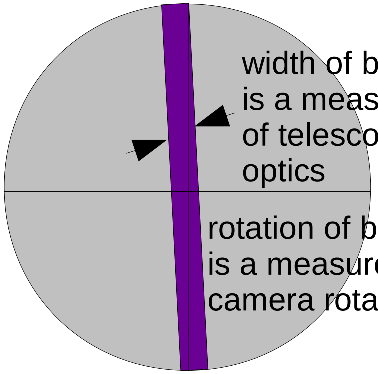
at 60 deg elevation
(altitude 2km),
timing adjusted



LeBohec, Hui, etal.

Intertelescope calibration, using the same optics (therefore pixel collection efficiency) also provides a measure of pointing, psf & camera rotation

Requires long timescale integration of signal, e.g. FADC or a good external trigger to fix beam location in camera.



width of beam
is a measure
of telescope
optics

rotation of beam
is a measure of
camera rotation

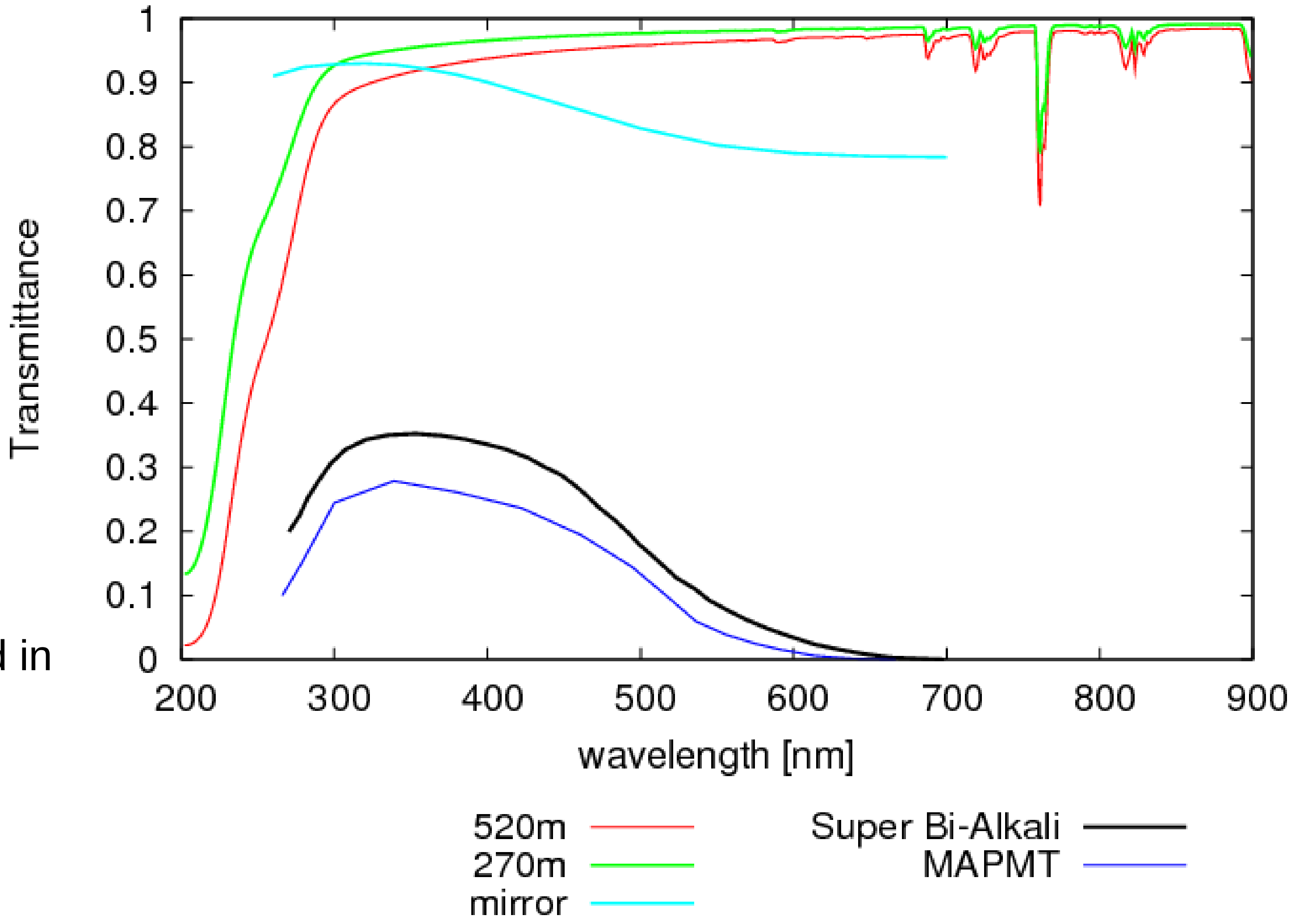
position of beam is a
measure of pointing

Flat-fielding

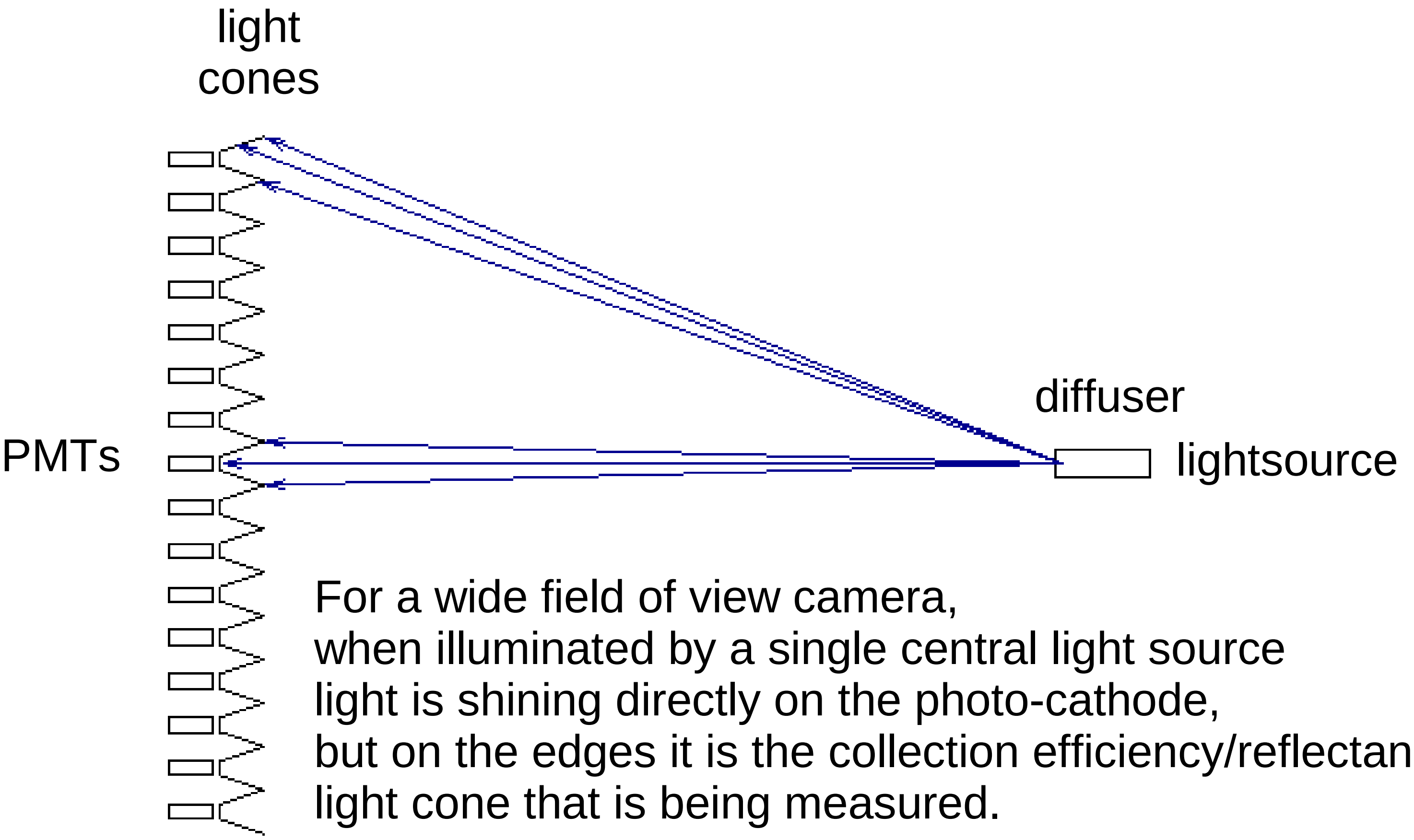
Flat-field at 1 wavelength, doesn't mean it is flat at another because of the distribution in Q.E.

Can flat-field unit be monochrome or does it need to work at many wavelengths?

How stable in wavelength? Determines whether temperature control needed in calibration unit.



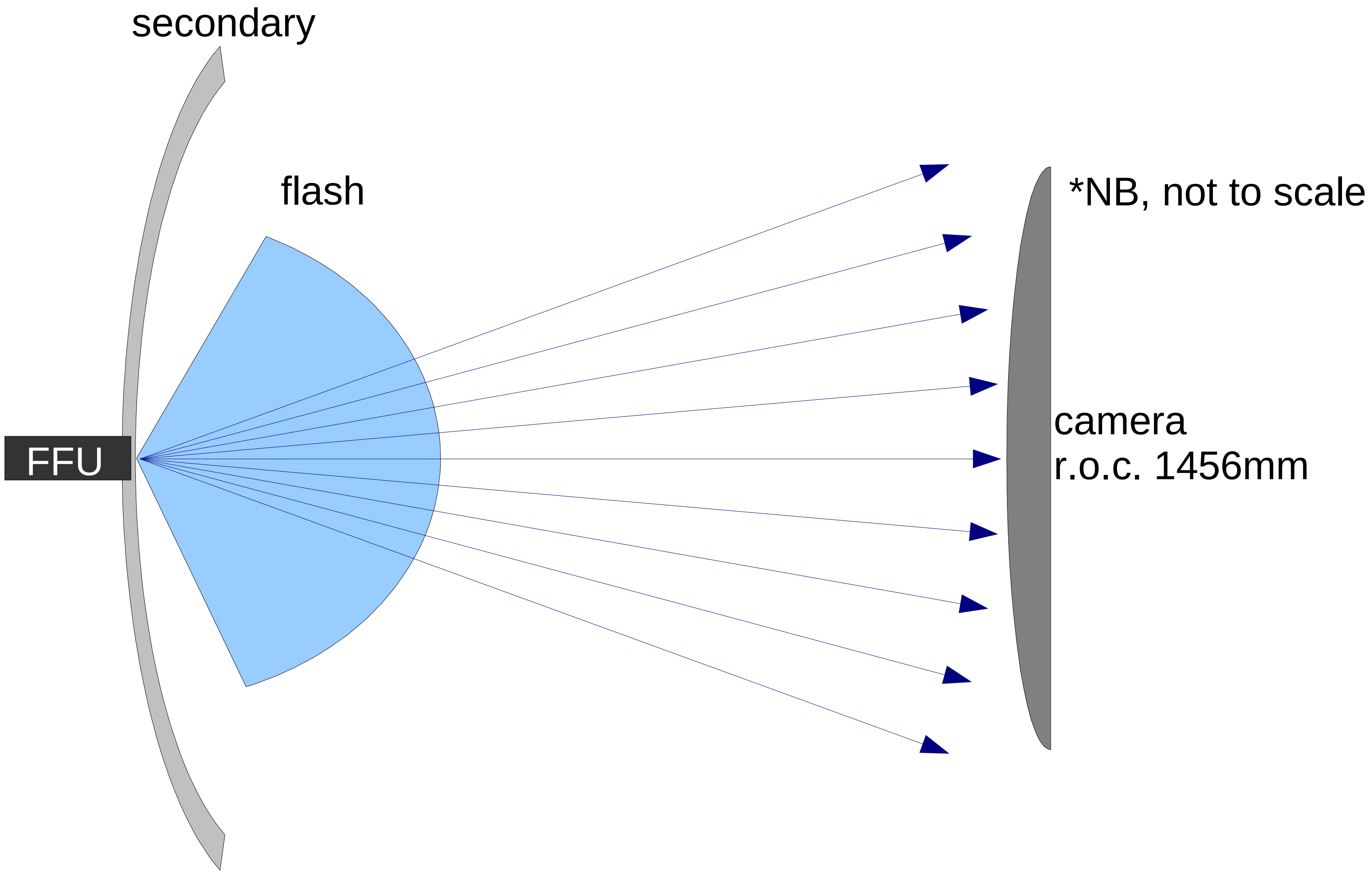
Flat-fielding: wide field of view camera, centrally mounted lightsource



For a wide field of view camera,
when illuminated by a single central light source
light is shining directly on the photo-cathode,
but on the edges it is the collection efficiency/reflectance of the
light cone that is being measured.

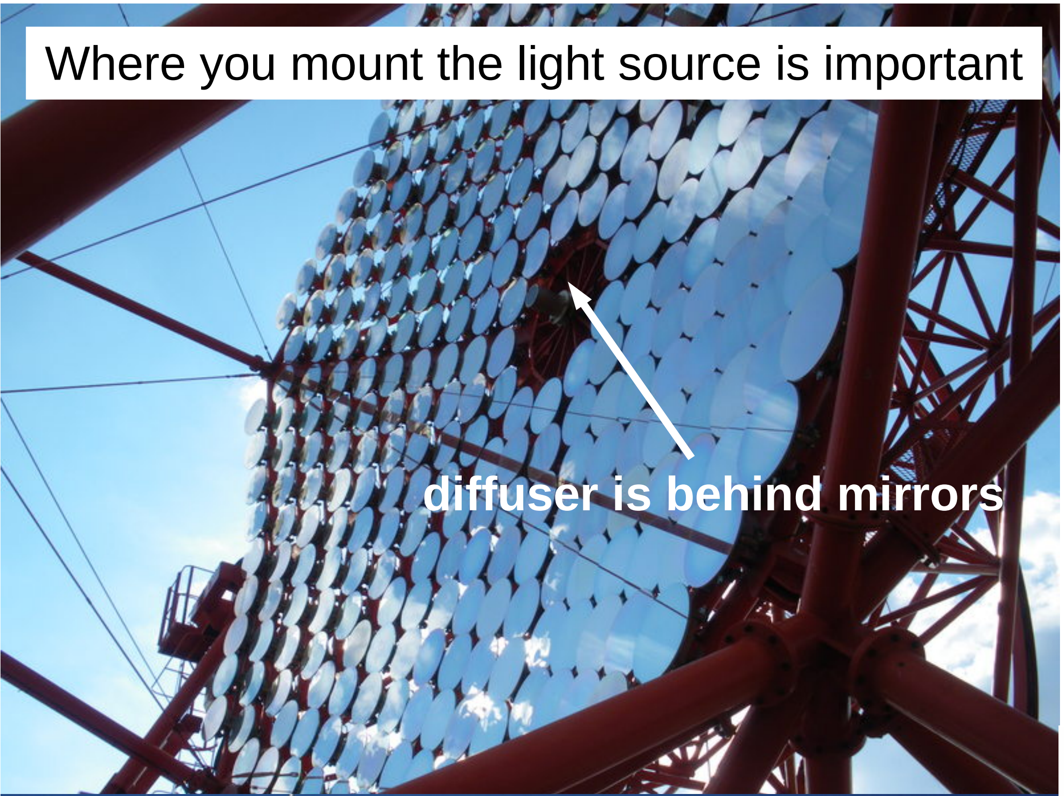
If the light distribution is not properly accounted for then a gain gradient is programmed into the camera (this will show up in the pedestal variations as function of distance from the centre of the camera, which is usually how this form of systematic bias is identified).

Flat-fielding: secondary optics, wide field of view camera, centrally mounted lightsource



PROBLEM: convex light front incident upon convex camera front – different collection efficiency at camera edge than camera centre, even without lightcones...

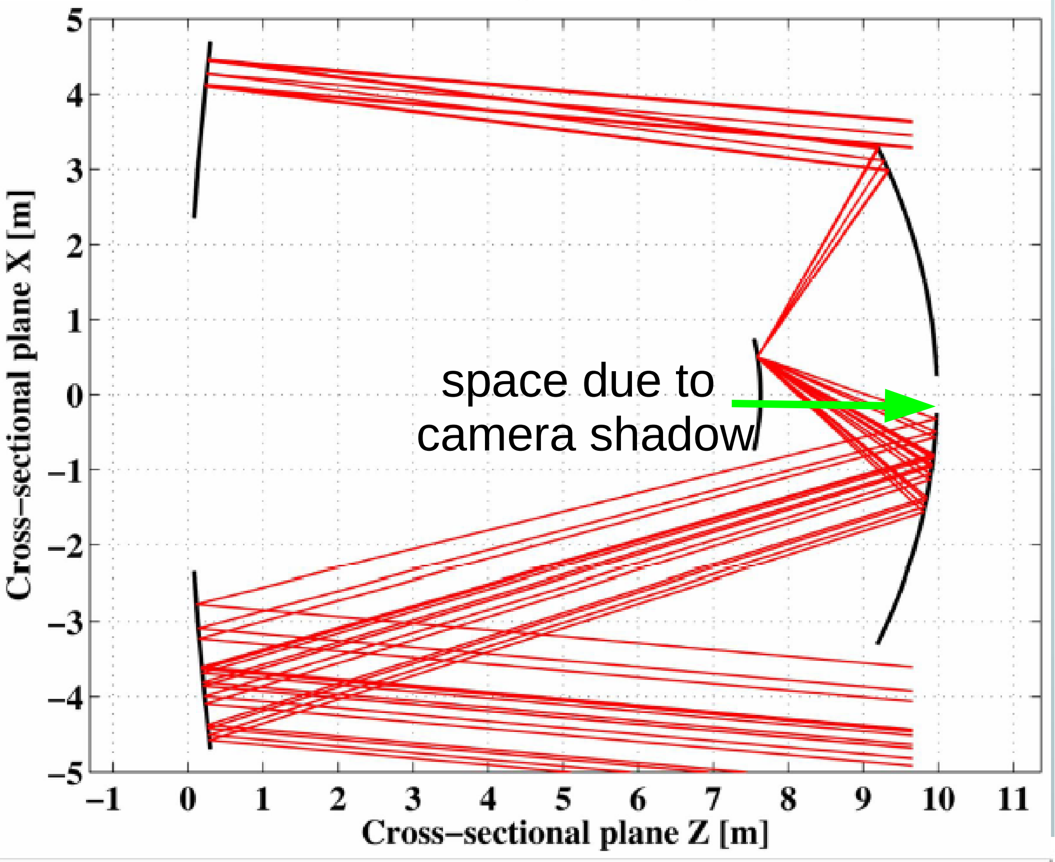
Where you mount the light source is important



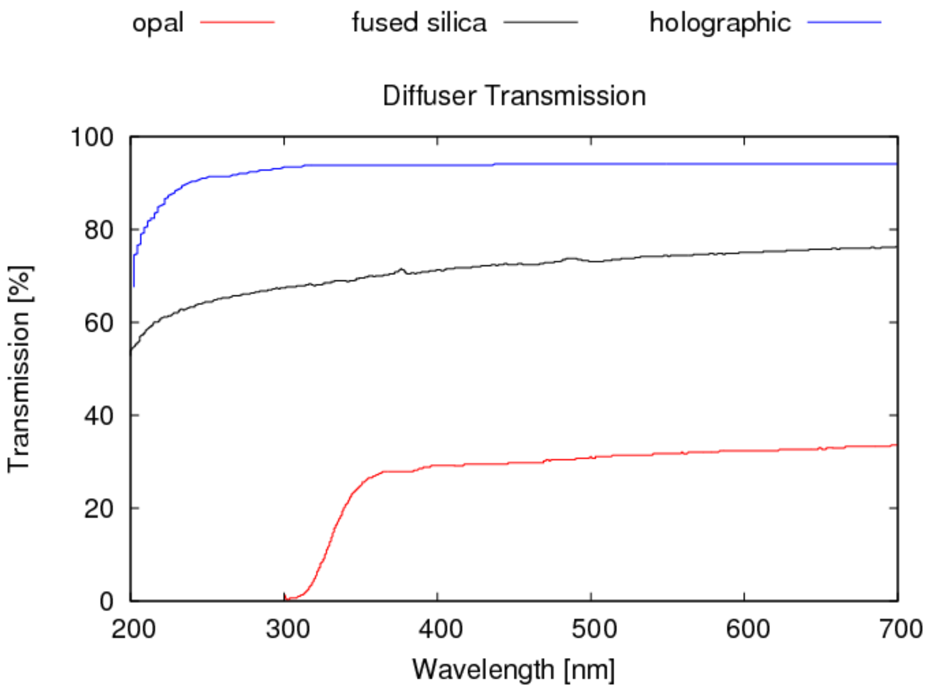
Geometry is an important factor in what form of diffuser can be used & how many photons reach the camera:
the closer to the camera, the wider opening angle you need a Lambertian response for.

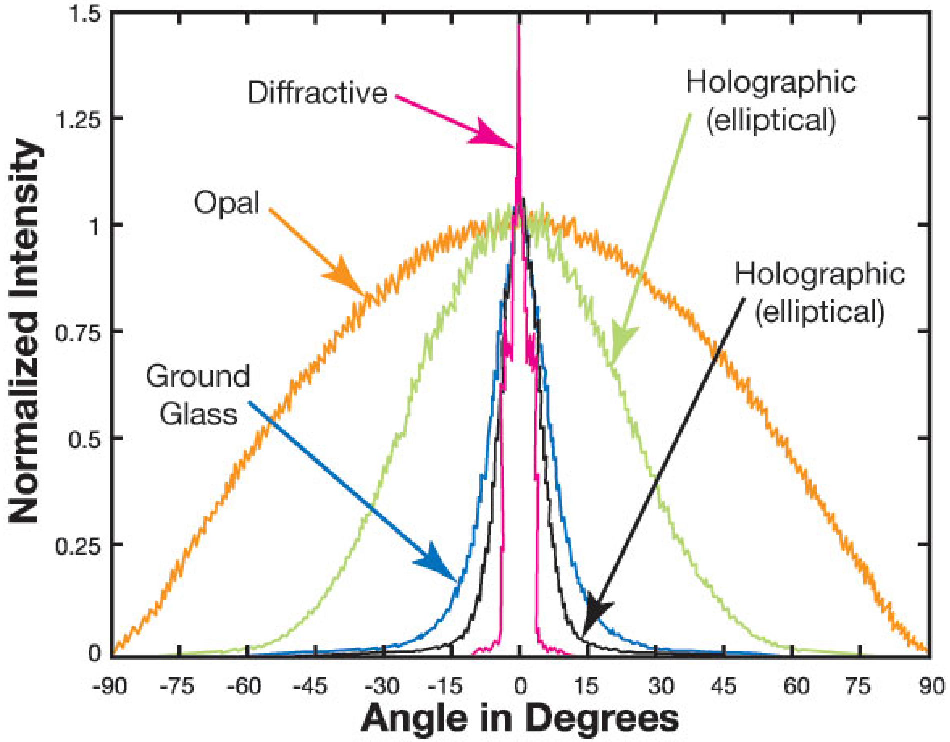
Holographic diffuser: >80% transmission, ~20 degree usable field.
Opal diffuser <50% transmission, near Lambertian illumination.

Shadowing will also determine where we can place the diffuser



Transmission & intensity distribution for various diffusers



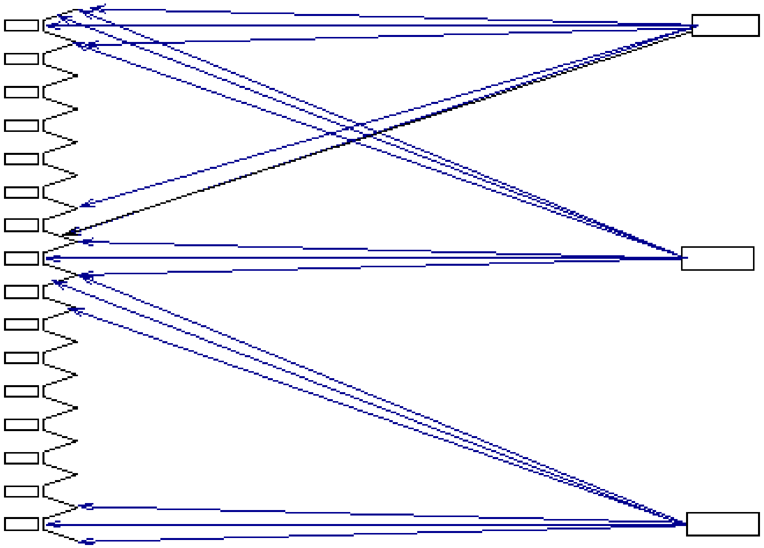


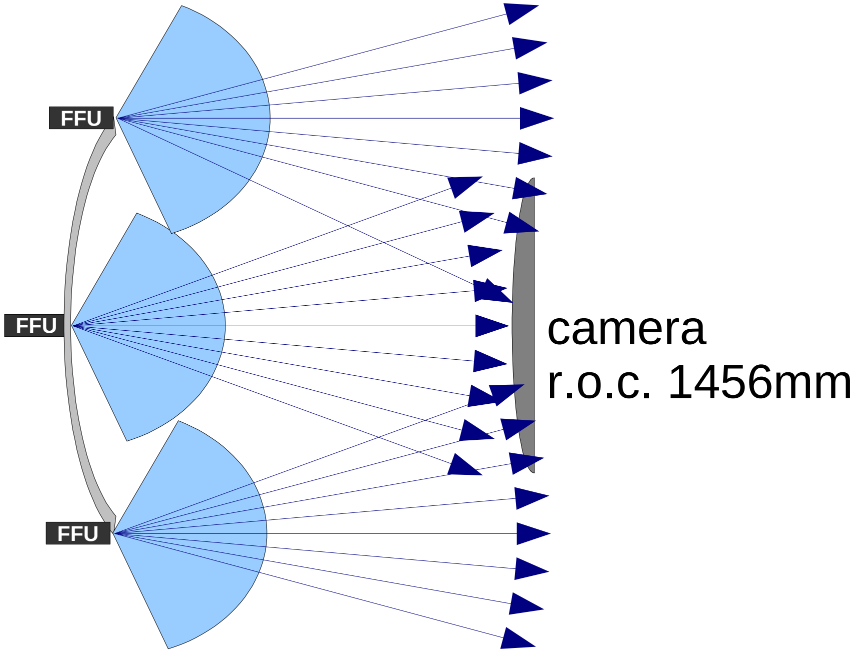
Intensity Distributions for Various Diffusers

Holographic diffuser is 30x cost of opal diffuser & could make up ¼ cost of entire calibration unit. Fused silica light distribution is strongly peaked in the centre, making it difficult to integrate out. Opal diffuser is not ideal in the UV.

Flat-fielding: wide field of view camera, many light sources

*NB, not to scale





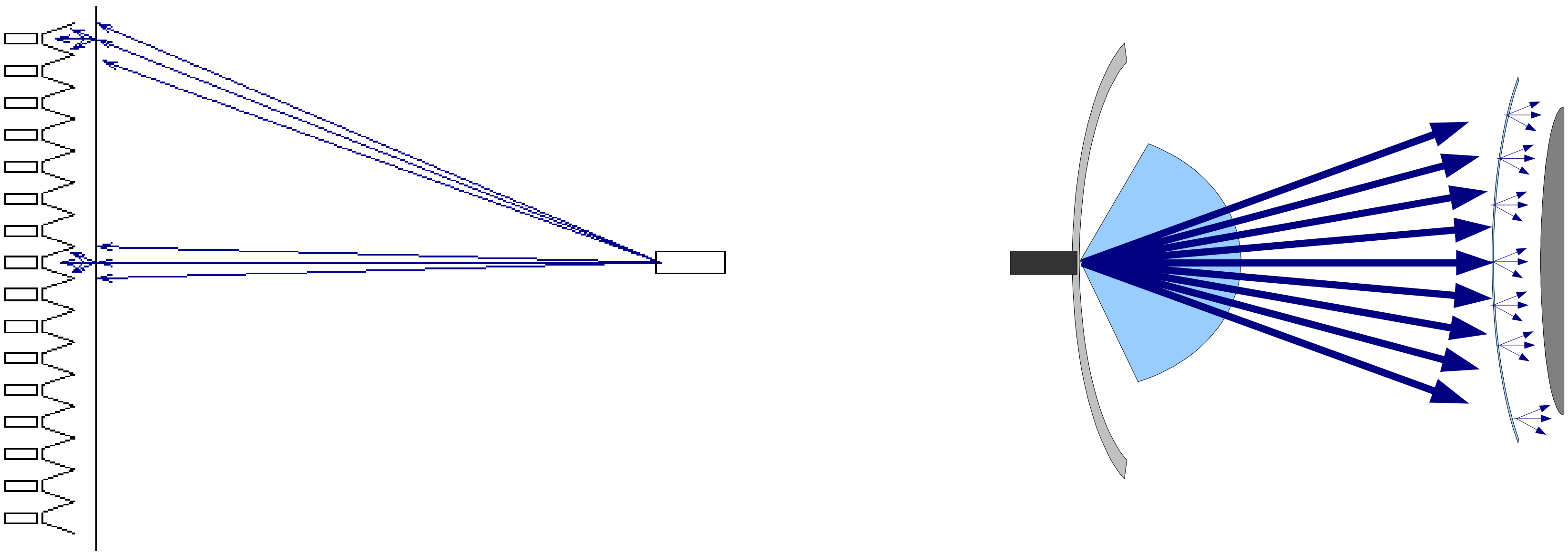
SOLUTION?

with many flat-field units covering all angles
or split into optical fibre and rediffuse at multiple locations.

BUT:

intensity variations, timing, complex, N times the expense, where to mount them all...

Flat-fielding: wide field of view camera, rediffuse light in front of pixels



SOLUTION?

Have a secondary diffusive screen in front of the camera.

Or use diffusive drum (like Auger) in front of the camera

Teflon diffusive reflective

Tyvek diffusive transmissive

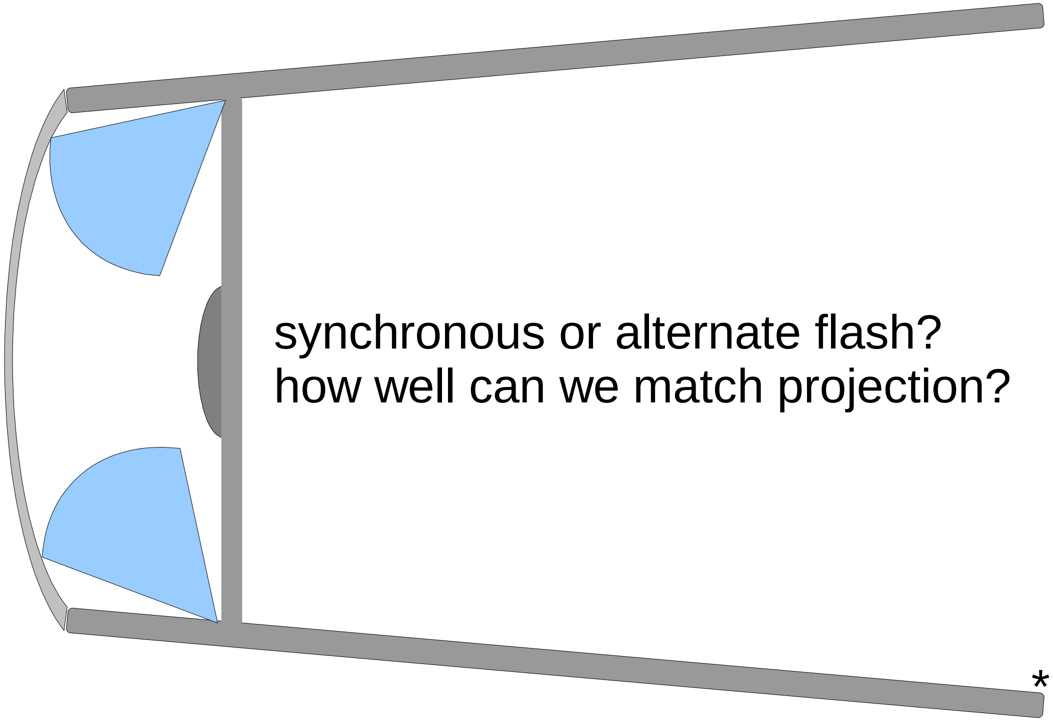
BUT

Need large surface area diffuser, what to make it from? Tyvek?

Additional Problem for Secondary Optics System!

Desire to minimise stuff on secondary – means not mounting calibration box there?

Since light distribution profile needs to be known, rather than completely uniform, can we launch from the support arms and reflect off the secondary instead?

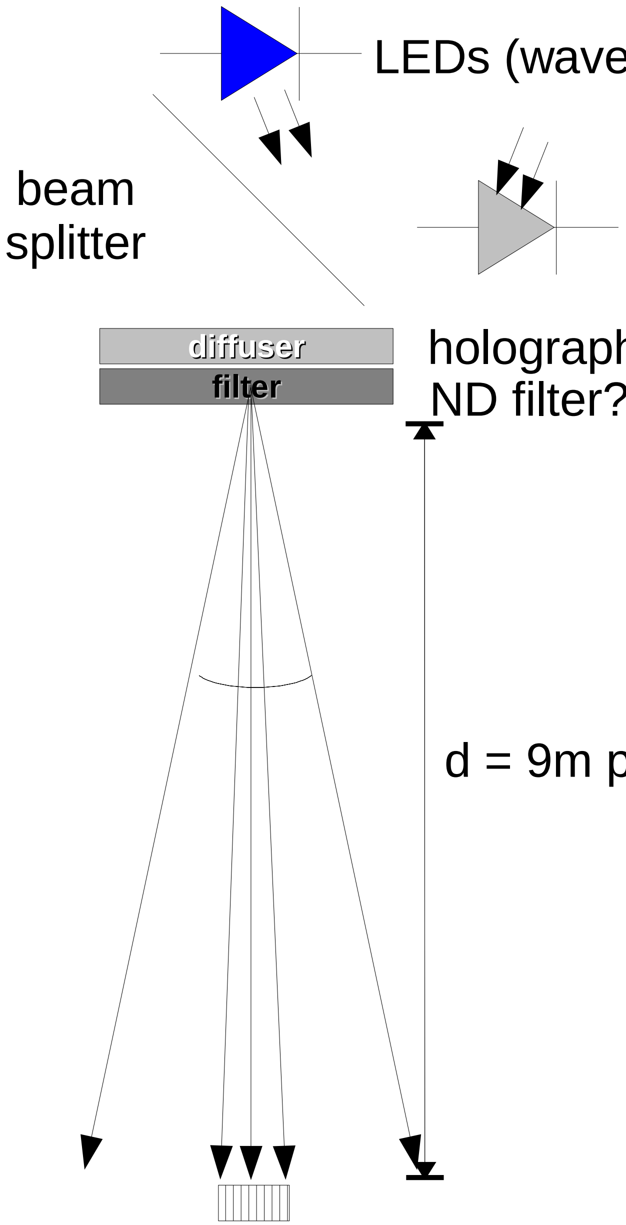


synchronous or alternate flash?
how well can we match projection?

*NB, not to scale

Flat-fielding Units

Simple model for calculating # p.e.'s illuminating PMTs



LEDs (wavelength range 390-420nm)

+ free parameter of light pulse width...

Photodiode (N_{pd} = integrate pulse for current, convert to p.e.)

holographic diffuser: spread over 50 degrees, 90% transmission

ND filter? => or just a window?

d = 9m path dispersed over

$$\boxed{N_{pe} = (0.33*0.9*N_{pd}) / (2\pi*d^2 (1-\cos(50))\ A_{PMT})}$$

3 LEDs	H.E.S.S.	SST	
ND filter	1	--	10x
d [m]	13	9	2x
<QE>	0.25	0.33	1.3x
pixel fov	0.12	0.2	2.7x
N_{pe}	~50±18	~3000	~70x

Super Bi-Alkali PMT Q.E. ~33%
pixel fov ~0.2 degree

Summary

Dedicated calibration equipment on the SST needs some thinking in terms of dynamic range & location on the telescope.

There are a number of calibration options that can be done for “free”, but probably not muons, and a number that are viable in conjunction with the Central Laser Facility.

Absolute calibration is probably best done one-off/infrequently with something akin to the Auger drum concept and monitored with more frequent relative measurements (e.g. photon-statistics) to determine the systematics.

Backup Slides

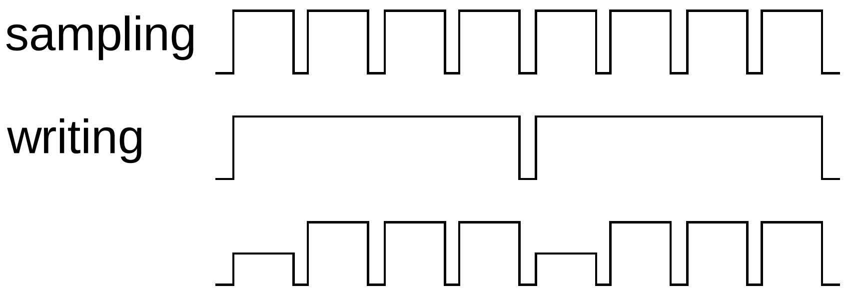
clocking noise:

VERITAS FADC runs at 500 MegaSamplesPerSecond (2ns width per sample) but this is 4x overclocked;

FADC implement clocking at 125MHz which write 4 bytes into pipeline burst RAM for each channel.

Result, every 4th sample can introduce a dip into the digitised trace (not channel to channel consistent)

∴ measured size < actual size



skewed trace, also appears in FFT

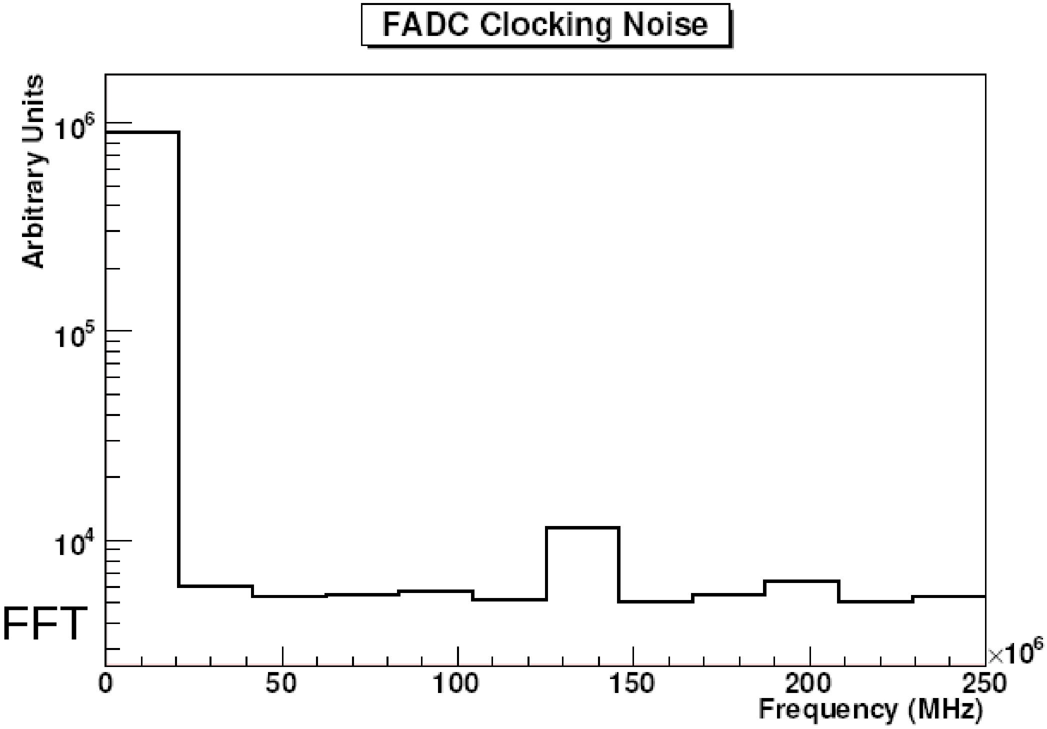
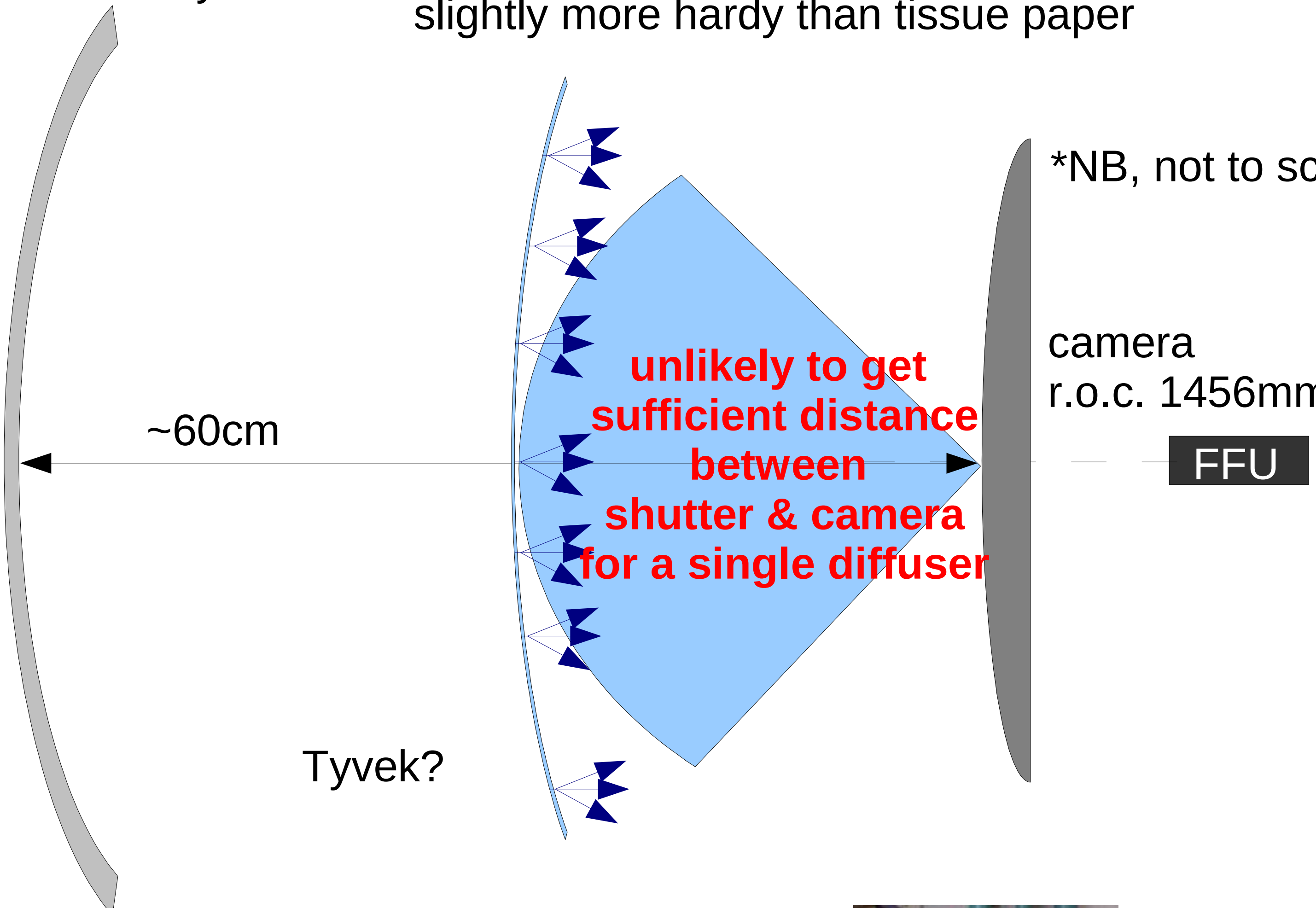


Figure 5.3: Summed FFT for a large number of raw FADC traces for a single channel. The large peak at 0 Mhz is the pedestal, or DC component. The second peak at 125 Mhz is a manifestation of the clocking noise. Cogan PhD Thesis UCD 2006

S.C. Optics, wide field of view camera, rediffuse the light in front of the camera?



secondary

some form of diffuse media
slightly more hardy than tissue paper

*NB, not to scale

camera
r.o.c. 1456mm

~60cm

FFU

unlikely to get sufficient distance between shutter & camera for a single diffuser

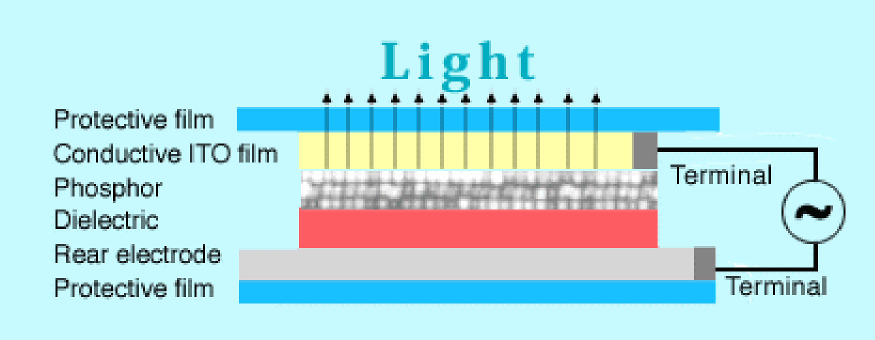
Tyvek?

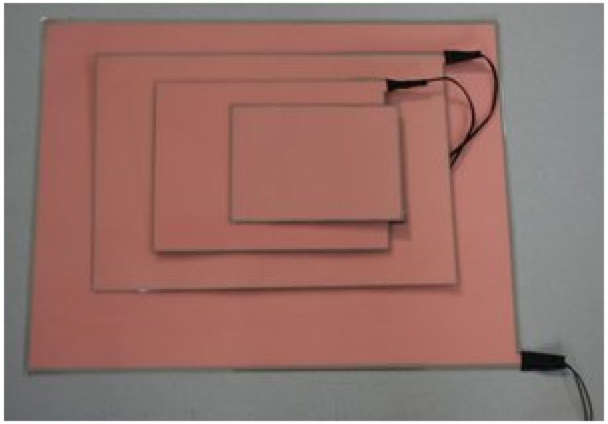
SOLUTION: convert convex into concave
~~by having a reflective second diffusive layer inside the lid~~...
or diffusive drum (like Auger)

Teflon diffusive reflective

Tyvek diffusive transmissive

What about something inside the shutter?





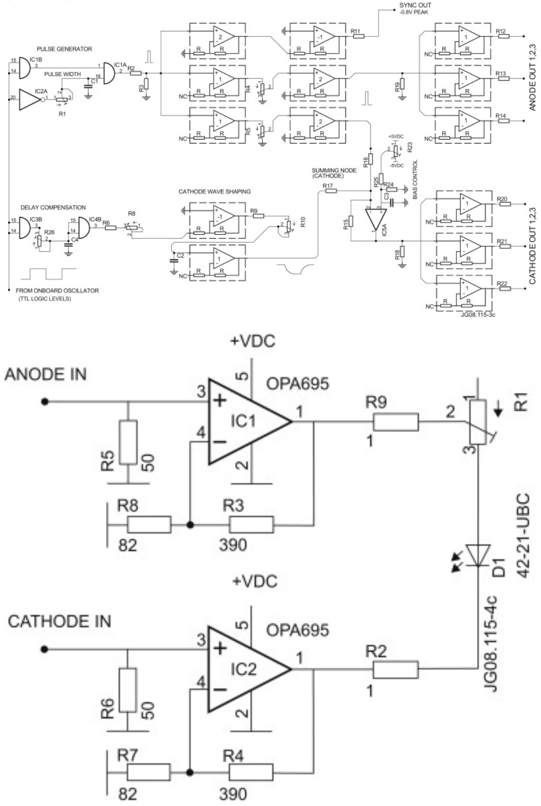
Electroluminescent Panels?
✔ cheap flat-fielding by amateur astronomers
✔ can be cut to any size
✗ no UV
✗ Phosphorescence timescales

OLED Panels?
✔ cheap way to cover ~large area
? Wavelength range?
✗ Lifetime is low compared to LEDs
✗ Not very robust in harsh environments

Time Multiplexed Optical Shutter (TMOS) panel?
Next generation – so not in cheap production yet
RGB from single pixel shutter -> probably not UV?
Flash speed may still not be sufficiently fast

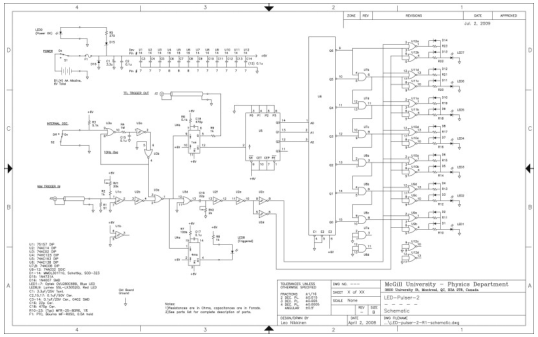
A number of LED driver and pulse shape circuits are under investigation.

A bipolar technique with op-amps for high performance, stability and power. Will provide very fast pulses, but at a greater expense than simple transistor circuits.



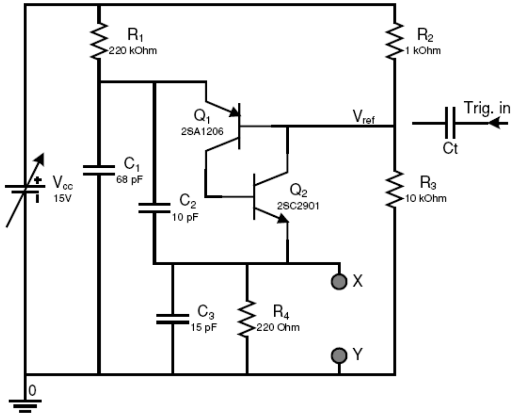
Ronchi et al. NIM A **599**, 243 (2009).

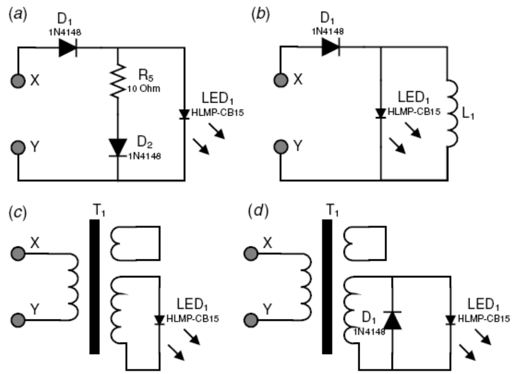
A simple gate based on fast pulse based on fast pulse generator, light pulse width limited based on LED afterglow.



D. Hanna et al. NIM A **612**, 278 (2010).

A transistor based regenerative switch, again get faster pulses, but requires custom built circuit that may not be easily reproducible in bulk.





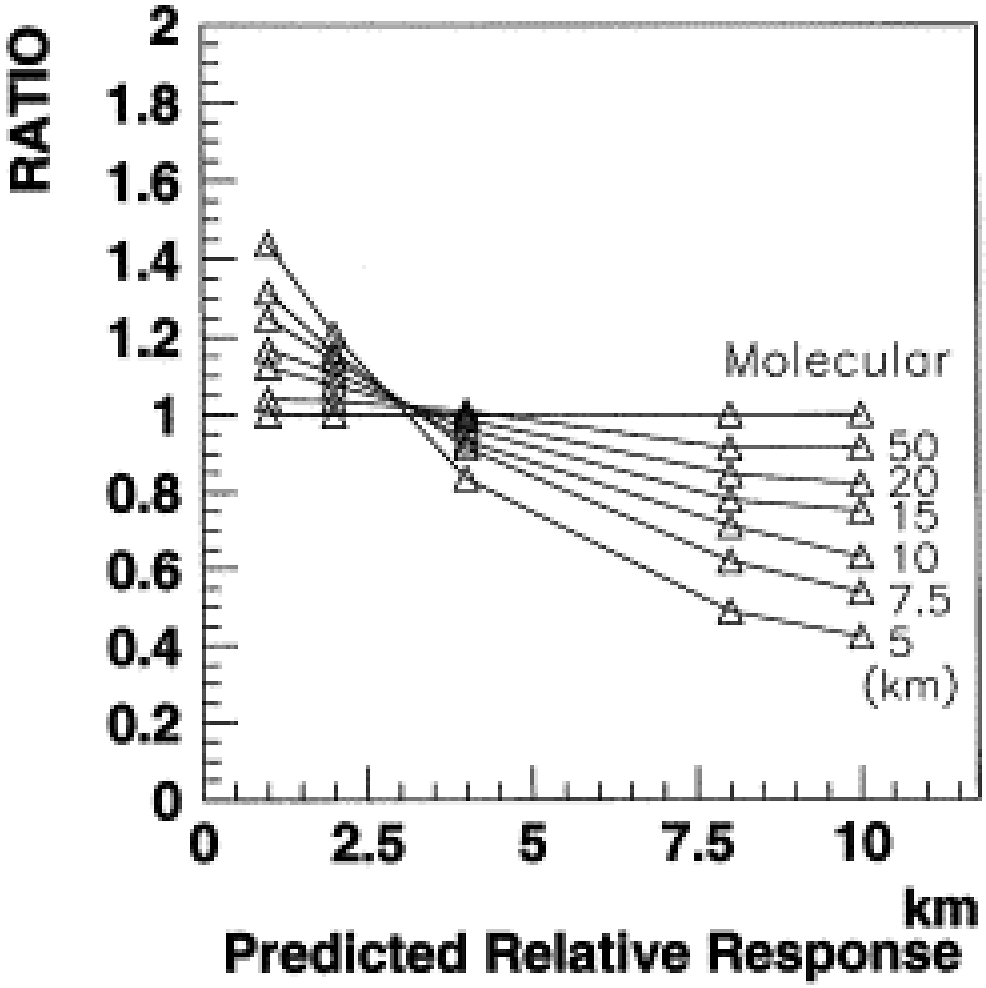
Veledar et al. MeScT **18**, 131 (2007).

[cf Aye et al. Proc. 28th ICRC 5, 2975 (2003).]

Central Laser Facility extra slides

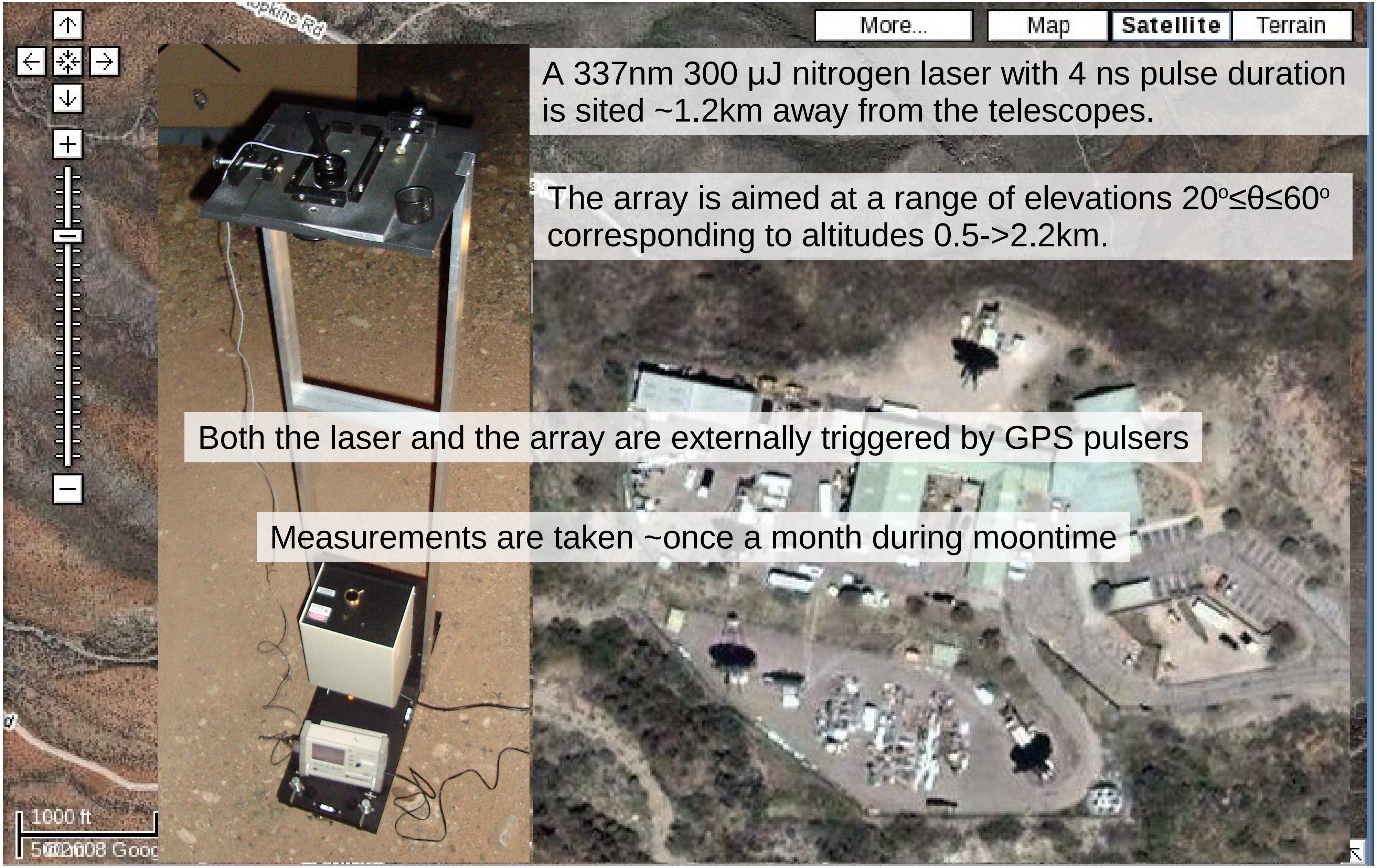
Atmospheric Monitoring

A distance to the laser can be chosen to minimise the aerosol scattering/losses.
Night to night fluctuations can then be used to determine changes in aerosol density.



Wiencke et al NIM A 428, 593 (1999).

VERITAS Distant Laser system



A 337nm 300 μJ nitrogen laser with 4 ns pulse duration is sited ~1.2km away from the telescopes.

The array is aimed at a range of elevations $20^o \leq \theta \leq 60^o$ corresponding to altitudes 0.5->2.2km.

Both the laser and the array are externally triggered by GPS pulsers

Measurements are taken ~once a month during moontime

Central Laser Facility extra slides

Measuring the effective light collection area of a telescope

Simulations provide the expected detector output from Rayleigh scattered light, comparison to measurements taken at high elevation can then be used to calculate the effective light collection area of the telescope.

e.g. for a VERITAS telescope of ~110m^2 mirror area
the linear intensity of the beam image is 3.7x10^4 dc/deg
from simulations there were 515 photons/m^2/deg
=> ~72 dc m^2/photon
single photoelectron measurements of the camera show ~5 dc/photon
giving the effective light collection area of the telescope to be ~14.4 m^2

If we look at the individual elements for a telescope:
the mirror reflectivity @ 337 nm is ~92%
the quantum efficiency @ 337nm is ~18%
the collection efficiency of the camera is ~81%
so 110 x 0.92 x 0.81 x 0.18 = 14.75m^2