Muon calibration: a brief introduction.

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Muon ring: a method to calibrate the total optical throughput of practically all previous IACTs.

<table>
<tr><td>

The question:
Can muons be successfully used as calibrators for the various CTA telescopes?

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The answer:
Yes, better if certain requirements are met.

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Details are the body of the 'Using Muon Rings for the Optical Throughput Calibration of the Cherenkov Telescope Array', also known as '**Muons for CTA**' document, **COM-CCF/150310**, result of the effort of the entire CCF-Muon group involving all the CTA telescopes teams.

Using Muon Rings for the Optical Throughput Calibration of the Cherenkov Telescope Array	Ref: COM-CCF/150310 Version: 4.7 Date: September 22, 2015 Page: 1/96

Using Muon Rings for the Optical Throughput Calibration of the Cherenkov Telescope Array

The '**Muons for CTA**' document is a **feasibility study** of the muon ring strategy for all the CTA telescopes. The study, started two years ago, is at a **well advanced stage** (ver.4.7) although **not yet completed**.

In the feasibility study, we

- investigate for which telescopes the method will work, and derive estimates of the statistical and systematic precision of the method,

- establish telescope requirements for a successful muon calibration, and derive expected event rates;

- propose a strategy to implement the muon calibration in the CTA data pipeline.

assessing the viability to use muon images for the

- ✓ calibration of the optical throughput,

- ✓ monitoring of the optical PSF,

- ✓ monitoring the flat-fielding of the camera, and

- ✓ monitoring the uniformity of the mirror reflectivity

for all the different CTA telescopes.

The final outcome is that the **muon ring analysis** can be considered as the **principal calibration method using CTA data**.

Moreover, to ensure the required precision, **new level-B requirements** for all telescopes have been suggested.

What we need? Trigger efficiency

Can all telescopes trigger on (mono)-muons?

LST:

- **Not foreseen**, since no previously requested; stereo muons will be used (however monitoring the **stereo bias** with time)

- Could also run the LST without requiring the LST-stereo trigger, worsen a bit the trigger threshold, but can still fulfill the required performance.

- Can run **dedicated muon runs.**

All Other Telescopes:

- **Yes**

...but need to **flag muons** efficiently at level of the **camera server** even if they don't come along with a stereo trigger *new requirement (next slides)*

What we need? Trigger efficiency, Statistics

The estimated muon image rates have been obtained assuming a dedicated mono trigger. A stereo trigger would reduce the rates according to the distance between telescopes.

	ER_{good} at $\theta = 0°$ (Hz)	Time needed to obtain sufficient usable events at $\theta = 0°$	ER_{good} at $\theta = 60°$ (Hz)	Time needed to obtain sufficient usable events at $\theta = 60°$	comments
LST (mono)	18	3 s	6.5	8 s	for 50 usable events
MST	5	10 s	2	30 s	for 50 usable events
SCT	1.5	1 min	0.5	3 min	for 100 usable events
SST (ASTRI)	0.2	40 min	0.06	1.8 hr	with SiPMs used for the prototype, using strong analysis cuts, for 400 usable events
SST (GCT with CHEC-M)	0.85	8 min	0.3	22 min	preliminary, for 400 usable events
SST-1M	2	3 min	0.7	9 min	with very loose analysis cuts, for 400 usable events

Target: extract sufficient usable muon rings from the regular data taken in less than one night (*new requirements, next slide*).

What we need? Trigger efficiency, Statistics

It's necessary to **flag muons** efficiently at level of the **camera server**, from un-calibrated images, so ensuring that all 'usable' estimated muon rings are written on disc even if they don't come along with a stereo trigger and at an acceptable residual (mono) cosmic rate.

New requirement proposed for muon trigger

B-M/SST-1300 *The camera must be able to trigger on, and flag from pre-calibration data, fully contained muon rings impacting the mirror with an energy >20 GeV with an efficiency greater than 90%, even if visible in only one telescope camera.*

The requirement, currently under investigation by all camera teams, should **not cause a problem** to the currently designed telescopes and cameras.

Presentations and discussion this afternoon and tomorrow morning

What we need? Spectral acceptance

PMT-based cameras need to ensure that the camera becomes sufficiently opaque to light below 290 nm wavelength. This is the range where Cherenkov light from air showers is completely absorbed, but the one from muons still gets through to the camera.

Normalized Cherenkov Spectra

- Muons SST
- Muons MST
- gamma Spectrum
- QE PMT
- QE SiPM
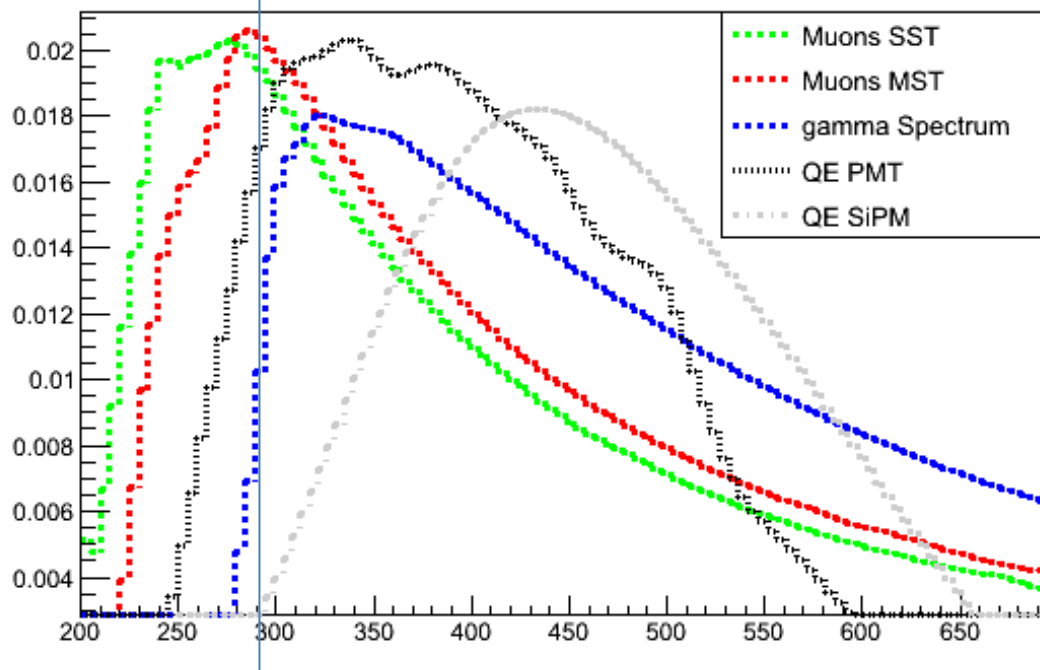
Normalized Cherenkov spectra of muons arriving from 270 m distance (green line), representative for the case of a SST, from 540 m distance (red line), representative for the case of an MST, and the Cherenkov spectrum from a gamma-ray shower emitted at 8 km above ground (blue line).

Cameras equipped with SiPMs will observe very similar muon and gamma-ray spectra, while **Cameras equipped with PMTs** will have efficiency for muon light at a wavelength range where gamma-ray showers do not emit light.

A 10-30% systematic effect of the muon calibration may be expected **unless** the degradation of the spectral acceptance in the middle UV is monitored, or this part is cut out in its way through the optical chain.

What we need? Spectral acceptance

To reduce the systematic effect due to the spectral acceptance ...

New requirement proposed

B-xST-1500 *The optical elements of the telescope (mirrors and camera) must be chosen such that the part of the Cherenkov light spectrum from local muons, which stems from wavelengths below 290 nm, must contribute by less than 5% to the observed muon image size, where "size" is understood as the sum of all photo-electrons contained in the ring image.*

This requirement should **not cause a problem** to the currently designed telescopes and cameras.

Probably the LST has found a technical solution: Acrylite / ShinkoLite protecting PMMA window in front of the camera cuts exactly below 290 nm.
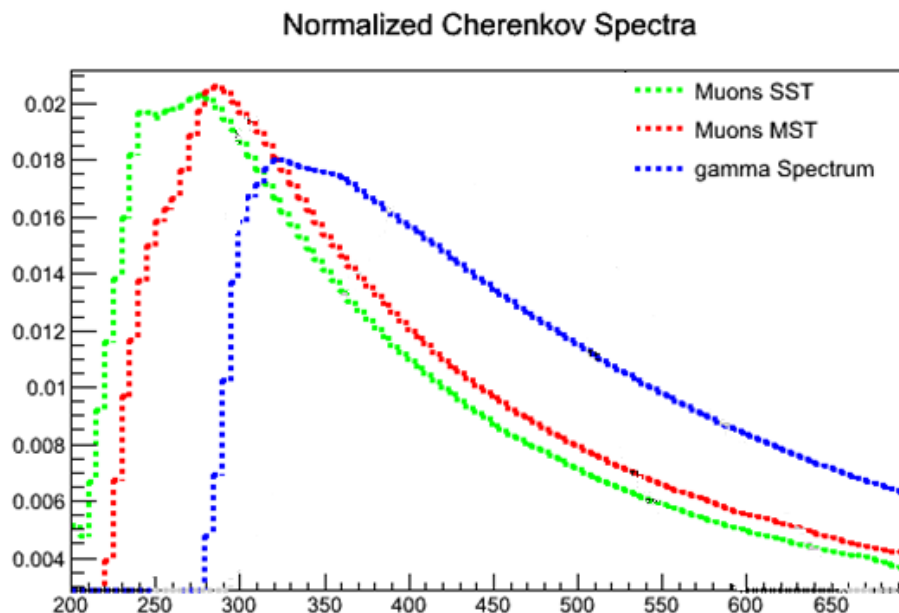
What we need? Chromaticity monitoring

Given the different spectra of Cherenkov light from muons and gammas, **un-recognized chromatic** changes in the telescope elements may lead to **un-recognized changes** in the conversion from muon to gamma efficiency: the muon efficiency degrades, but differently to the corresponding gamma efficiency, and **corrections only based on the muon efficiency may over-estimate the telescope' optical throughput for Cherenkov photons from gamma showers.**

The incorrect estimates can reach values of the **order of 13%**, depending on:
- material of the protecting window
- photo multiplier quantum efficiency
- focused mirror reflectivity
- …

and the muon calibration **without wavelength-dependent direct measurements** could result (depending on the degradation time) in about **6% systematic error for the LSTs/MSTs, and 4% for SSTs**.

Normalized Cherenkov Spectra

····· Muons SST
····· Muons MST
····· gamma Spectrum

With an additional assessment of the wavelength dependency of the degradation, the precision can be improved to 3%.

What we need? Chromaticity monitoring

How to define the precision with which the chromaticity of the degradation of optical elements needs to be (externally) controlled? The easiest way is with respect to a reference wavelength, e.g. 400 nm above/below which about half of the Cherenkov light falls.

New requirements proposed

B-xST-1600 *The degradation of the optical throughput of the telescope must always be controlled such that the degradation at a wavelength measured 10 nm around 350 nm is known to better than 10% with respect to the degradation measured 10nm around 450 nm.*

This requirement should **not cause a problem** to the designed telescopes and cameras.

The requirement can be fulfilled using e.g. the "illuminator".

Presentation and discussion this morning and tomorrow morning

What we need? Precision

The feasibility of the method is related to the determination **as precisely as possible** of several parameters that play their essential role in the reconstruction procedure; among them:

- **Cherenkov angle**

- **Impact parameter**

- **Muon size, total number of observed photoelectrons**

- **Local atmospheric transmission**

- **Spectral correction from Cherenkov light from muons to gamma-ray showers**

- **…**

The total systematic uncertainties achieved in the feasibility study are currently about 4%.

Some of these parameters are related to the telescopes characteristics; their knowledge contributes to answer the question:

> *What is the **precision** of the method for each telescope?*

This is the main content of the next presentations
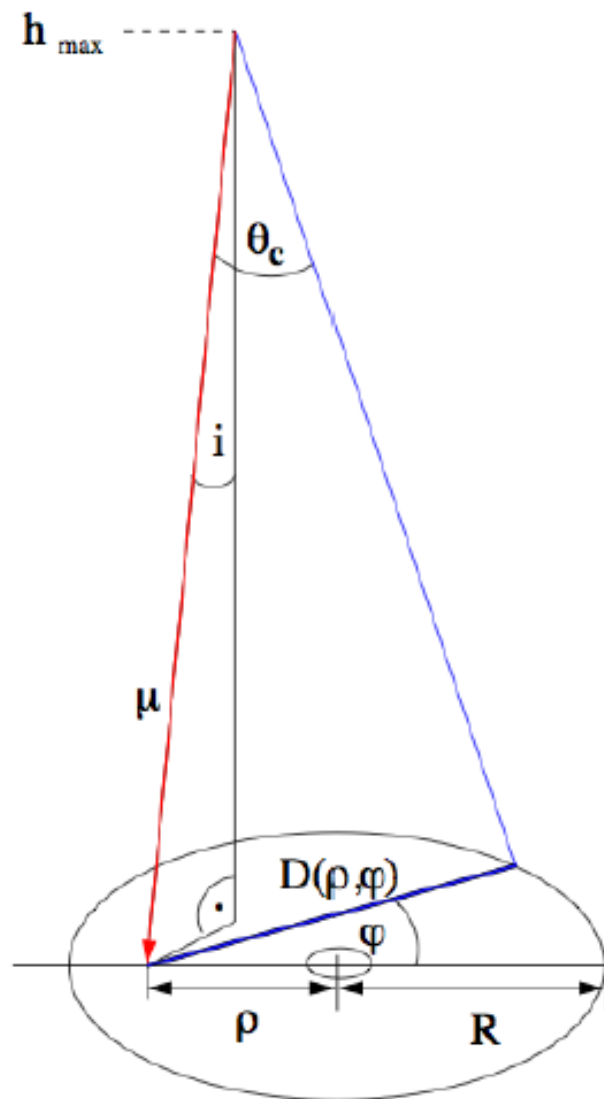
Main CCF-Muons interrelations within CTA groups
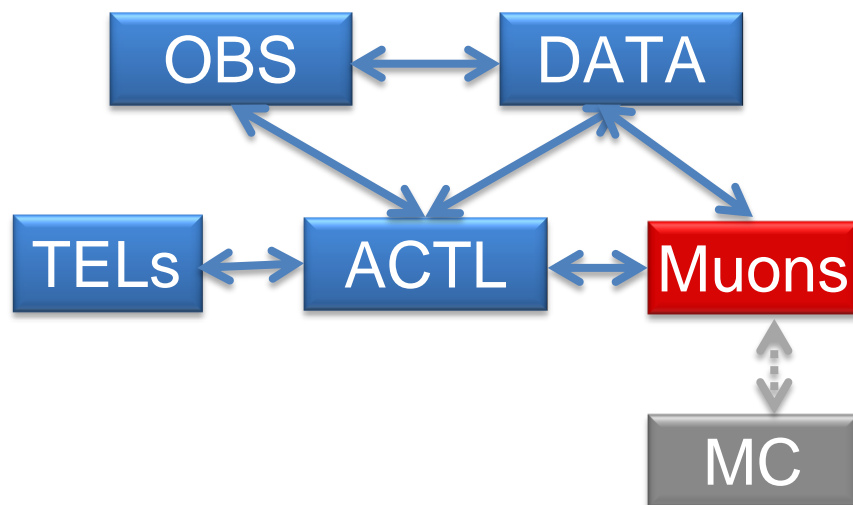
- ICDs
- Prod-3 MC simul.
- DATA
- TEL/Camera Servers
- ACTL and SWAT
- OBS

Presentations and discussion this afternoon and tomorrow morning

Backup Slides

What we need? Precision

Cherenkov angle, θ_c

Impact distance, ρ

Figure 6: Sketch of the introduced parameters to describe the geometry of a local muon μ and its image in an IACT camera: The muon emits Cherenkov light under the Cherenkov angle θ_c along its trajectory, which is inclined by the angle i with respect to the optical axis of the telescope. It finally hits the telescope mirror, of radius R, at an impact distance ρ from its center (figure from Bolz, 2004).

Moreover, to ensure the required precision, new level-B requirements for all telescopes have been suggested. A set of ICD has been already defined, needed for the definition of DATA pipelines. Work is in progress for some improved camera triggers. Under development are the algorithms to flag events as possible muons at level of camera server.

"The analysis of muon ring images can be a powerful tool to calibrate the response of a single telescope and a precision below 5% seems attainable for those telescopes providing sufficient mirror area and easily triggered images."

"The technique can be applied even in the relative calibration among telescopes, whenever they are not so far each another so that the same muon event be detected in two telescopes, at least."
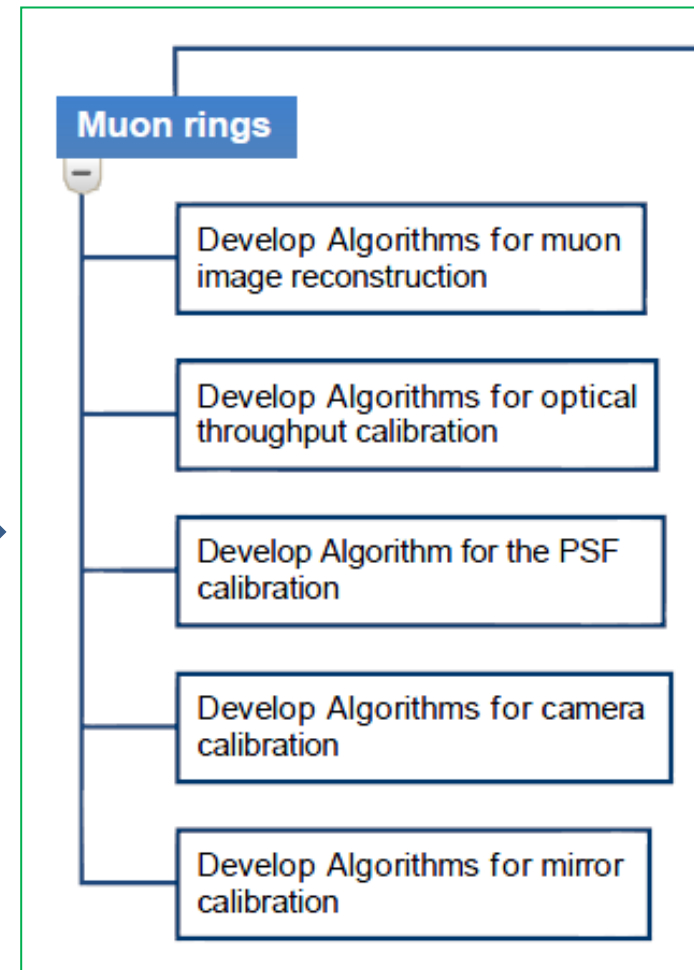
CCF – Methods for Array Calibration: Muon ring analysis

Pre-production phase

To conclude the pre-construction phase:

- Estimates of precision to reconstruct any muon ring parameter

- Definition of algorithms for muon ring pre-selection, enrichment in the camera server

- Completion of the ICD-DATA documents

- Improvements of dedicated muon triggers for some specific cameras

Muon rings

- Develop Algorithms for muon image reconstruction

- Develop Algorithms for optical throughput calibration

- Develop Algorithm for the PSF calibration

- Develop Algorithms for camera calibration

- Develop Algorithms for mirror calibration

Ref. COM-TDR/140721, v. 5.1, 13 May 2015

Preliminary results on the muons as 'calibrators'

We have assessed the viability to use muon images for the calibration of the optical throughput, monitoring of the optical PSF, the flat-fielding of the camera, and uniformity of the mirror reflectivity for the different telescopes currently designed for the CTA. If certain design requirements are met, like separate mono triggers, possibly adjusted to the expected shapes of muon images, and design of the telescope and camera components which ensure that the transmitted part of the muon spectrum below 290 nm becomes negligible, such a calibration scheme seems viable for all telescopes, using regular data taken in less than one night.

All implementations of an SST are able to provide sufficient high-quality muon images per night and seem to be free of, or show only negligible, trigger biases. If the mirrors degradation is maintained within current requirements, muon images are adequately selected (ASTRI and GCT-M option) and a low trigger threshold is adopted (SST-1M), at least for observations of extra-galactic sources.

Preliminary results of the feasibility study

Calibration of optical throughput:

for each telescope it can be calculated with **better than 2% systematic uncertainty** for any achromatic degradation of the optical throughput and **at least on a night-per-night basis**. An automatic monitoring of the muon efficiency should be implemented both for the on-site, as for the off-site analysis.

Corrections to the muon calibration:

The muon calibration **without wavelength-dependent direct measurements** will result in about **6% systematic precision for the L/MSTs (4% for the SSTs**), after a long period of degradation of the optical elements. With an additional assessment of the wavelength dependency of the degradation, **the precision can be improved to 2-3% again.**