CTA System-Level Science Performance Requirements

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Table of Contents

1 Introduction

This document summarises the current status of the system-level performance requirements for CTA. The main content is the required performance of the arrays of telescopes at the two CTA observation sites. This document has been endorsed by the CTA consortium and supersedes the set of performance requirements previously endorsed by the CTA consortium [1]. The primary change with respect to the earlier work is the addition of details on sub-system performance. The term 'xST sub-system' is used here to indicate the sub-array formed of all of the telescopes of the specific xST type at a given site. The drive to more fully specify the sub-system performance arises from the need to allocate clear responsibilities and to allow independent development of design solutions for the different telescope sizes. The performance curves presented here were derived in a collaboration between the analysis and simulations working group (ASWG) of CTAC and CTAO. The overall model is that the top-level array performance (which remains unchanged from [1]) should be met at any given energy by a single sub-system alone, such that the required array performance is automatically met if all sub-system requirements are met. The feasibility of these requirements was demonstrated by large scale simulations based on telescope models with a much greater degree of realism and more advanced analysis than used in the original studies.

The CTA baseline is assumed and the sites and telescope layouts described in [2]. Note that hyperlinks exist in the document for the definitions of terms. Data files referred to in some requirements are accessible via the *Jama system* and hyperlinks for the defined terms also direct the reader to this system.

2 Verification Methods

At the design stage the majority of the requirements presented here must be verified via simulations. An accompanying document [3] describes the standardized approach to these simulations, including the properties of the two array sites and the locations of telescopes. During the science verification phase these requirements can be verified for the system as-built using selected gamma-ray targets in conjunction with MC simulations (see [4] for a preliminary discussion).

3 System-level Performance Requirements

A-PERF-0010 Field of View for LST sub-system
The *Gamma-ray Field of View* of the LST sub-system at both array sites must be > 1 degree for gamma-ray energies in the range 0.02 – 3 TeV.

A-PERF-0020 Field of View for MST sub-system
The *Gamma-ray Field of View* of the MST sub-system at both array sites must be >3 degrees for gamma-ray energies in the range 0.1 – 30 TeV.

A-PERF-0030 Field of View for SST sub-system
The *Gamma-ray Field of View* of the SST sub-system must be >3 degrees for gamma-ray energies in the range 3 – 300 TeV.

A-PERF-0220 LST sub-system Source Localisation (precision pointing conditions)
The rms space-angle systematic error on the localisation of a point-like source of gamma-rays (with the *Reference Spectrum*) below 100 GeV, with the LST sub-system under *precision pointing conditions*, must be < 10 arcseconds (per axis).

A-PERF-0222 LST sub-system Source Localisation (standard observing conditions)
The rms space-angle systematic error on the localisation of a point-like source of gamma-rays (with the *Reference Spectrum*) below 100 GeV with the LST sub-system under *standard observing conditions*, must be < 30 arcseconds (per axis).

A-PERF-0230 MST sub-system Source Localisation (precision pointing conditions)
The rms space-angle systematic error on the localisation of a point-like source of gamma-rays (with the *Reference Spectrum*) with the MST sub-system under *precision pointing conditions*, must be < 5 arcseconds (per axis).

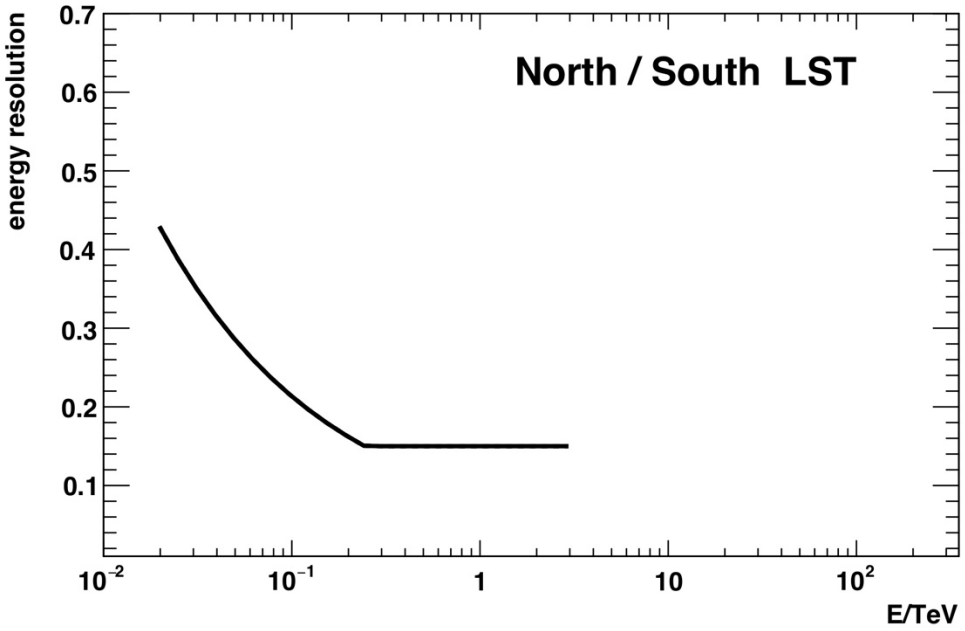
A-PERF-0232 MST sub-system Source Localisation (standard observing conditions)
The rms space-angle systematic error on the localisation of a point-like source of gamma-rays (with the *Reference Spectrum*) with the MST sub-system under *standard observing conditions*, must be < 15 arcseconds (per axis).

A-PERF-0234 SST sub-system Source Localisation (precision pointing conditions)
The rms space-angle systematic error on the localisation of a point-like source of gamma-rays (with the *Reference Spectrum*) with the SST sub-system under *precision pointing conditions*, must be < 5 arcseconds (per axis)

A-PERF-0236 SST sub-system Source Localisation (standard observing conditions)
The rms space-angle systematic error on the localisation of a point-like source of gamma-rays (with the *Reference Spectrum*) with the SST sub-system under *standard observing conditions*, must be < 15 arcseconds (per axis).

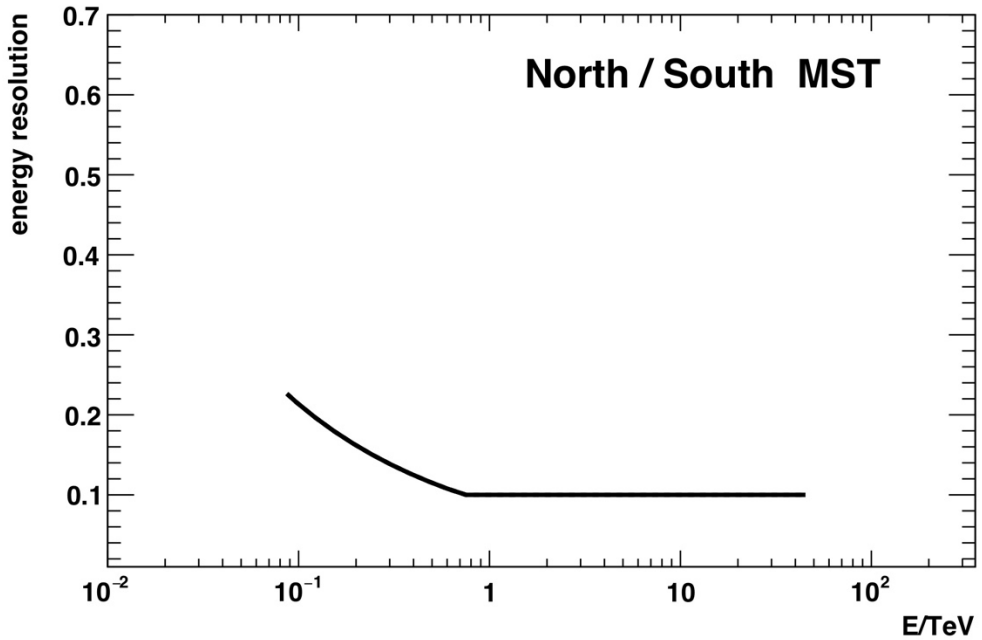
A-PERF-0240 LST sub-system Energy Resolution

The required *Energy Resolution* of the LST sub-system is given in the figure below and data files attached.



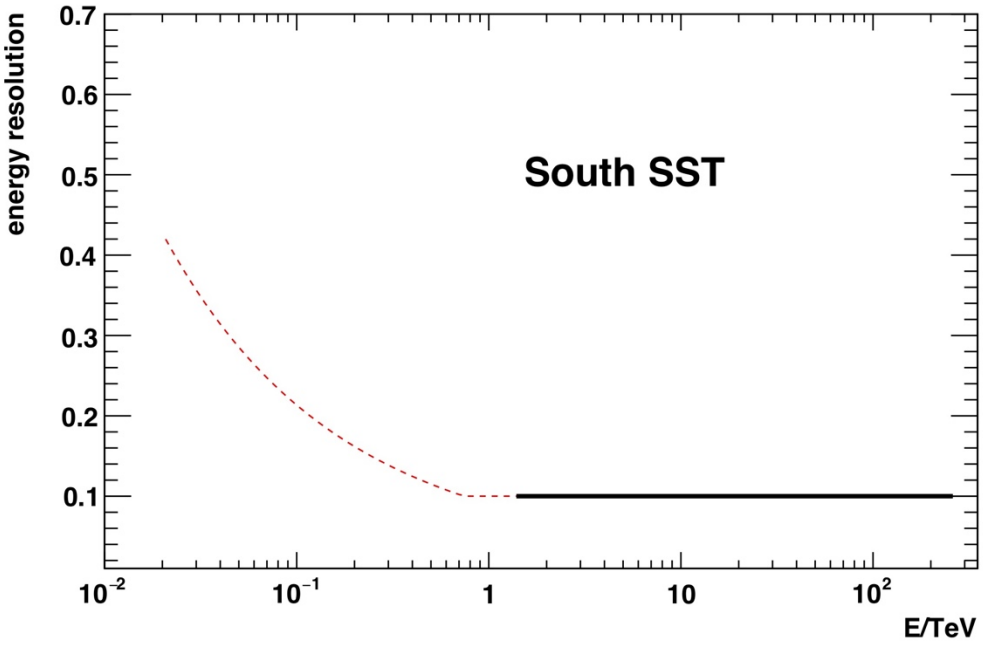
A-PERF-0250 MST sub-system Energy Resolution

The required *Energy Resolution* of the MST sub-system is given in the figure below and data files attached.



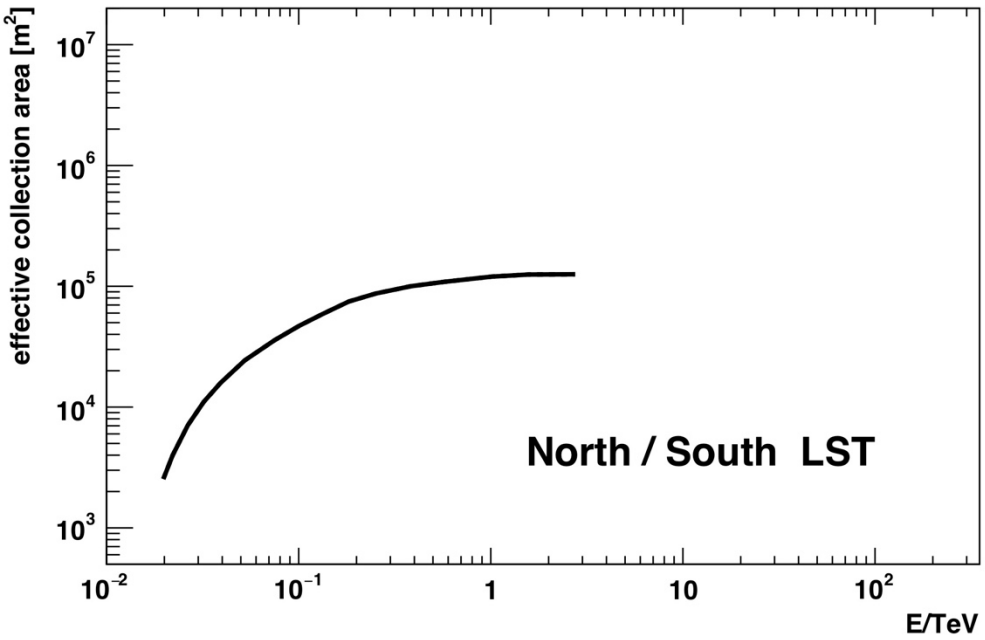
A-PERF-0260 SST sub-system Energy Resolution

The required *Energy Resolution* of the SST sub-system is given in the figure below and data files attached.



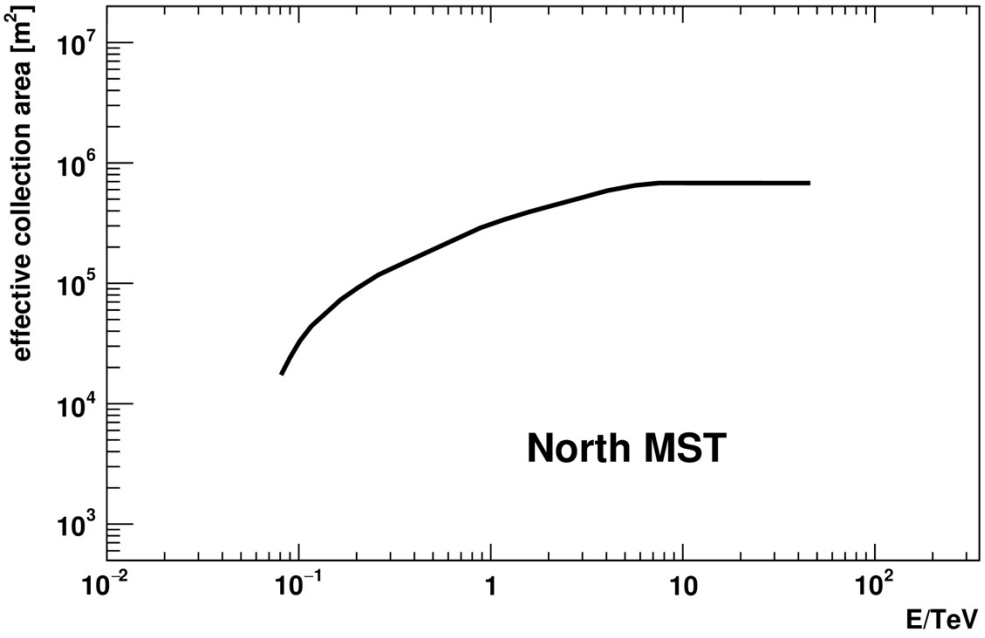
A-PERF-0310 LST sub-system Effective Collection Area

The LST sub-system at both North and South sites (after all event selection cuts required to meet the 30 minute sensitivity requirements) must have an *Effective Collection Area*, under *Reference Conditions*, exceeding the curves given in figure below and data files attached.



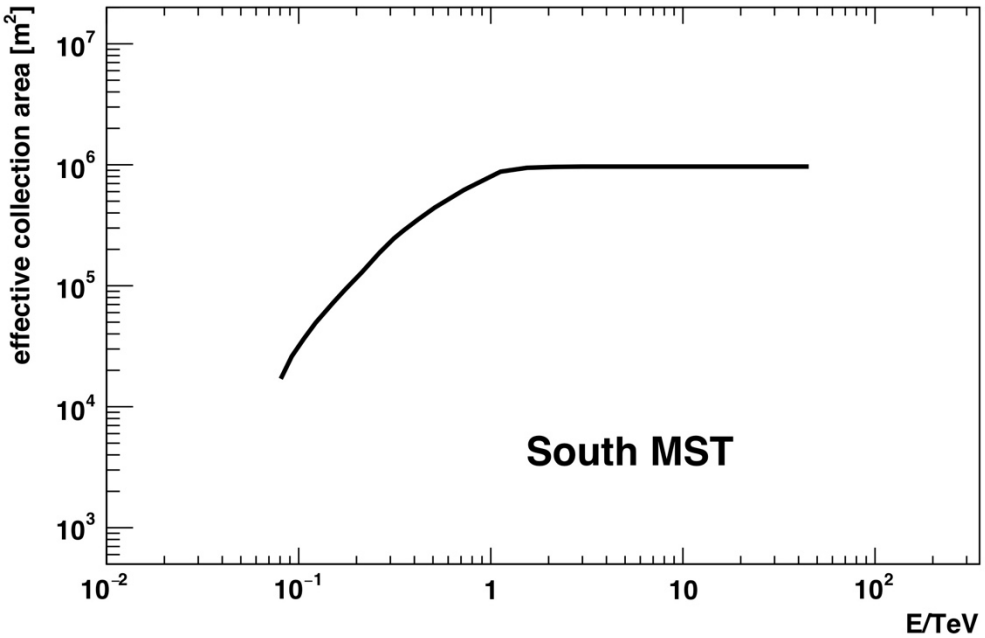
A-PERF-0330 MST sub-system Effective Collection Area (N)

The MST sub-system at the North site (after all event selection cuts required to meet the 30 minute sensitivity requirements) must have an *Effective Collection Area*, under *Reference Conditions*, exceeding the curves given in figure below and data files attached.



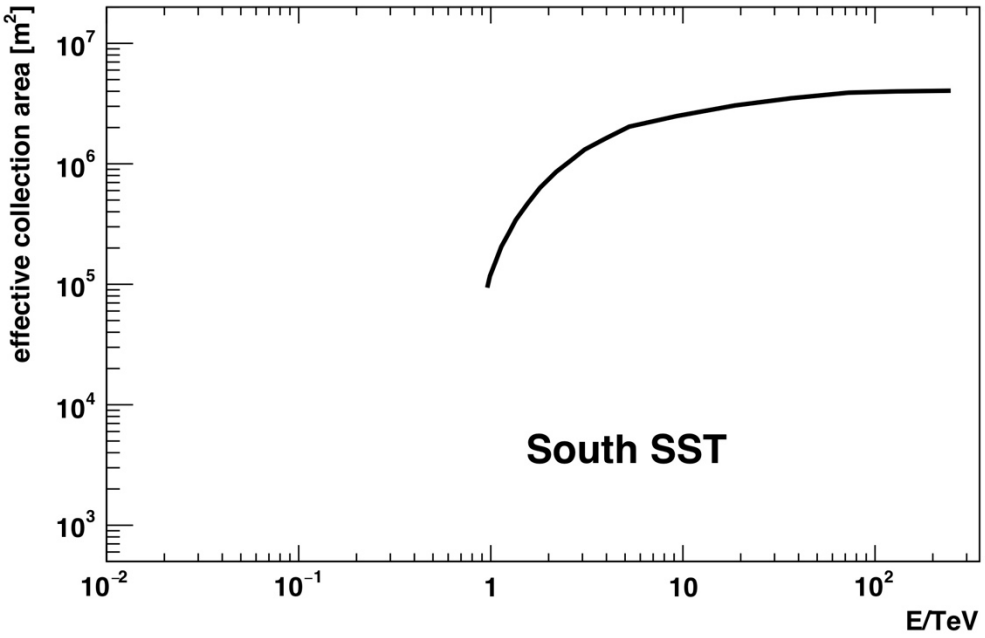
A-PERF-0340 MST sub-system Effective Collection Area (S)

The MST sub-system at the South site (after all event selection cuts required to meet the 30 minute sensitivity requirements) must have an *Effective Collection Area*, under *Reference Conditions*, exceeding the curves given in figure below and data files attached.



A-PERF-0350 SST sub-system Effective Collection Area

The SST sub-system (after all event selection cuts required to meet the 30 minute sensitivity requirements) must have an *Effective Collection Area*, under *Reference Conditions*, exceeding the curves given in figure below and data files attached.



A-PERF-0380 Effective Area Knowledge

The contribution to the uncertainty on the energy-dependent *Effective Collection Area* of the system as a whole at both sites arising from array level analysis and selection must be less than 5% above 40 GeV, under *Reference Conditions*, and over the required *gamma-ray Field of View.*

A-PERF-0410 Exposure Monitoring

The effective integrated exposure time associated with all CTA *Observations* must be known to at least 1% for timescales greater than 10 seconds.

A-PERF-0450 PSF Uncertainty (standard observing conditions)

The uncertainty on the gamma-ray point spread function in the energy range above 40 GeV must not exceed 20% for data taken in *standard observing conditions* for any NSB level up to which sensitivity is required.

A-PERF-0460 PSF Uncertainty (precision pointing conditions)

The uncertainty on the gamma-ray point spread function in the energy range above 40 GeV must not exceed 5% for data taken in *precision pointing observing conditions* for any NSB level up to which sensitivity is required.

A-PERF-0510 Absolute Event Time

The absolute arrival time of on-axis Cherenkov light from a candidate γ-ray Event at ground level must be reconstructed to within 100 ns rms accuracy post-calibration.

A-PERF-0605 Array Trigger

A coincidence system is required that allows the identification of a single air-shower Event which triggered multiple telescopes, before storage of Camera data takes place. The combination of telescope trigger systems and central synchronisation system must allow coincidence recognition with an rms accuracy of < 10 ns.

A-PERF-0710 Target Change Time
The system as a whole must be able to change to a new target anywhere within the observable sky within 90 s.

A-PERF-0720 Observable Sky
The system as a whole must be able to target any astrophysical object in the sky which has an elevation >24 degrees.

A-PERF-0810 System Deadtime
The fraction of the time that the system as a whole (i.e. elements of the system may be unavailable for longer periods) is unavailable for recording of events, due to inefficiency in data collection, transport and storage, during observations (with telescopes on Target) must be <2 %.

A-PERF-0910 Recording of Events
For all air-shower Events in which two or more Telescopes have information, this information (suitably processed) must be stored and uniquely associated.

A-PERF-0920 Event Rate
The system must be able to recognise (trigger on) and capture (store for further processing) background Events initiated by charged cosmic rays, at the rates necessary to achieve the required gamma-ray performance.

A-PERF-0935 Cherenkov Image Information
Information on light level and pulse arrival time from every pixel in all triggering cameras, must be collected for each *Air-Shower Event* and used in image processing and event reconstruction. The light level information must be available over a time window appropriate to the energy range covered by a given telescope type (see figure).

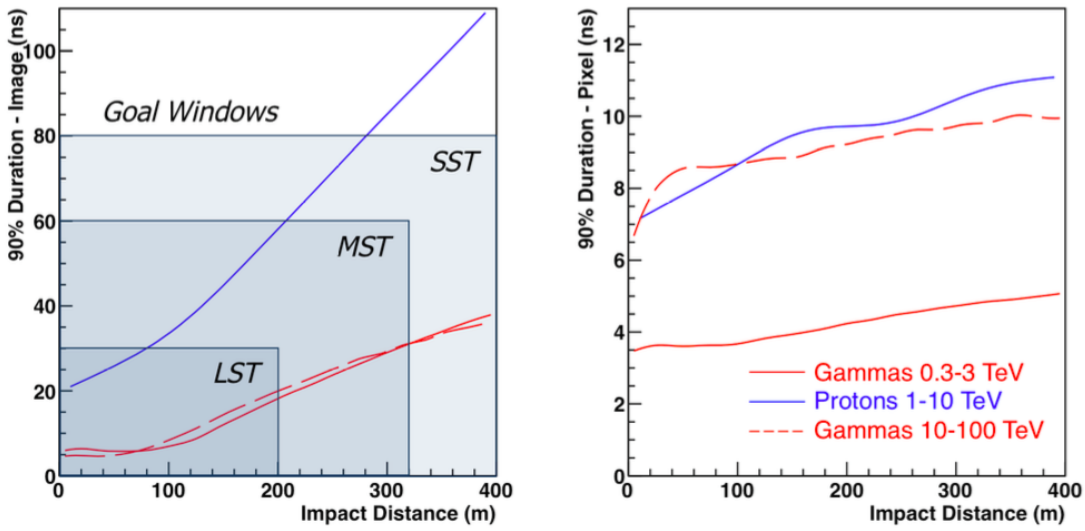


Figure: Left: time duration of Cherenkov images at different impact distances for different primary energies, showing the required readout windows for LST, MST and SST telescope types. Right: time duration within a single pixel (of the maximum allowed angular size). The time duration is defined as the time in which 90% of the light is contained, for 90% of events.

A-PERF-0940 Inter-telescope Timing
It must be possible to synchronise the pixel-level timing information between different telescopes to an accuracy of <3 ns rms after calibration.

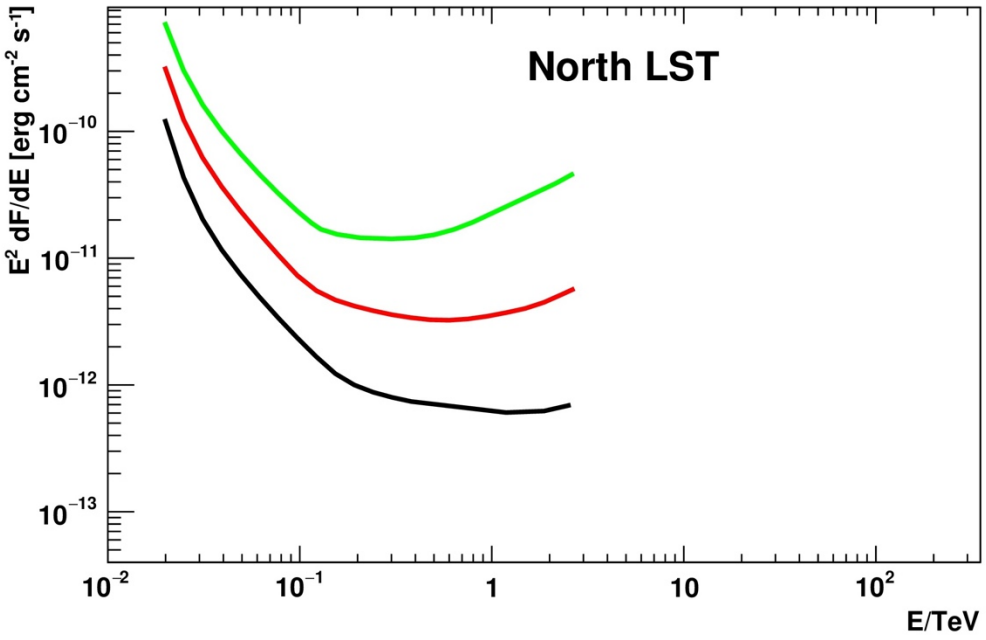
A-PERF-1000 LST sub-system Repositioning

The LST sub-system must be capable of changing *Target* from and to any part of the *observable sky* within 50 s.

A-PERF-1010 LST sub-system Sensitivity (N)

The LST sub-system at the Northern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached under *Reference Conditions* in the three specified observation timescales of 0.5, 5 and 50 hours. Sensitivity is required in the energy range 20 GeV - 3 TeV.

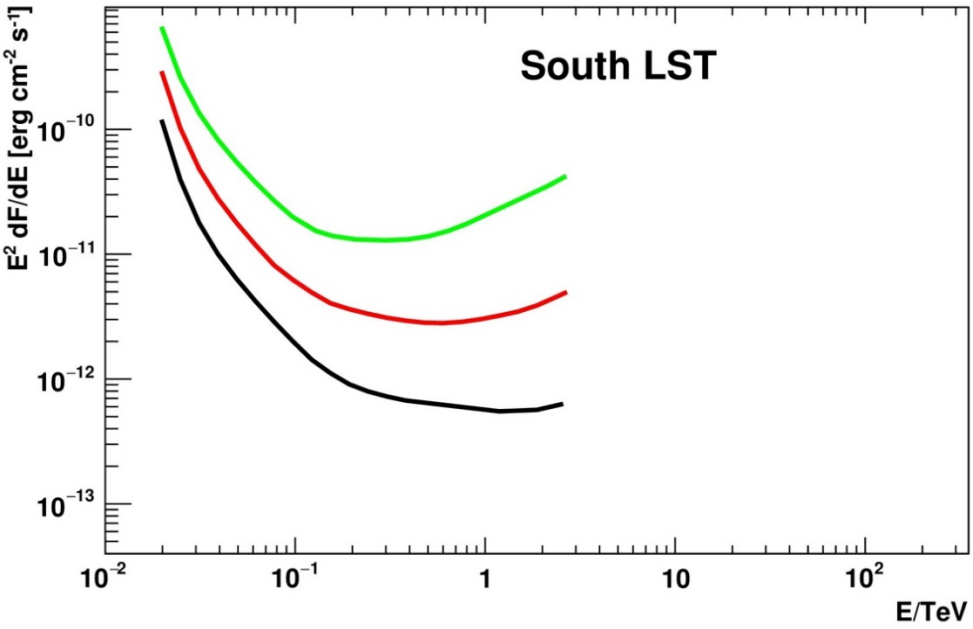
Black line: 50 h observation time. Red line: 5 h observation time. Green line: 30 min observation time.



A-PERF-1020 LST sub-system Sensitivity (S)

The LST sub-system at the Southern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached under *Reference Conditions* in the three specified observation timescales of 0.5, 5 and 50 hours. Sensitivity is required in the energy range 20 GeV – 3 TeV.

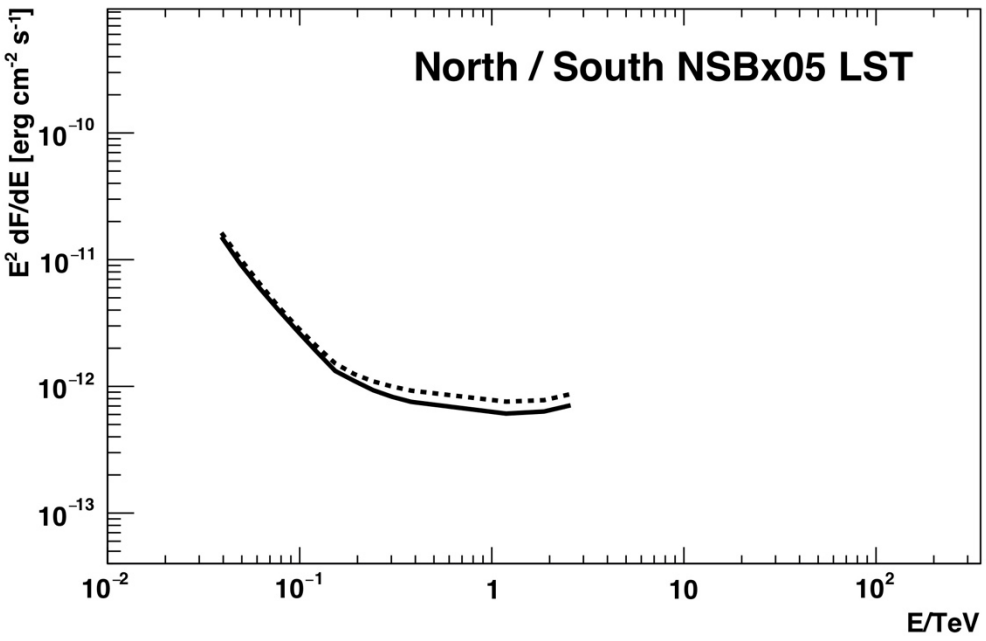
Black line: 50 h observation time. Red line: 5 h observation time. Green line: 30 min observation time.



A-PERF-1030 LST sub-system Sensitivity under Low Moonlight (N)

The LST sub-system at the Northern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached at a background illumination level of 0.9 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm following the Moonlight Reference Spectrum, in a time scale of 50 hours. Sensitivity is required in the energy range 40 GeV - 3 TeV.

Dashed black line: 50 h observation differential sensitivity under Low Moonlight - North

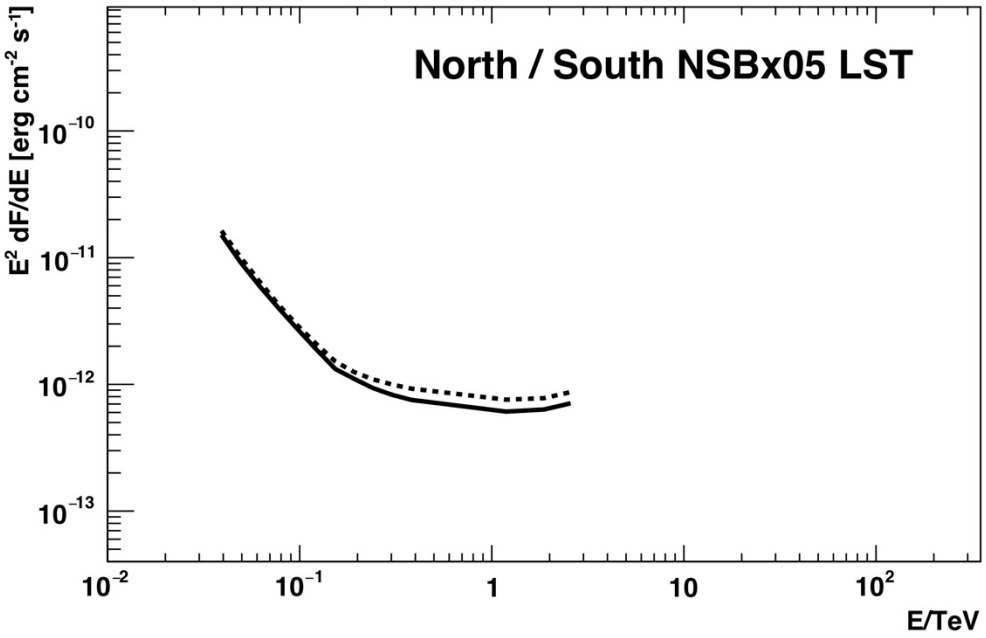


A-PERF-1040 LST sub-system Sensitivity under Low Moonlight (S)

The LST sub-system at the Southern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached at a background

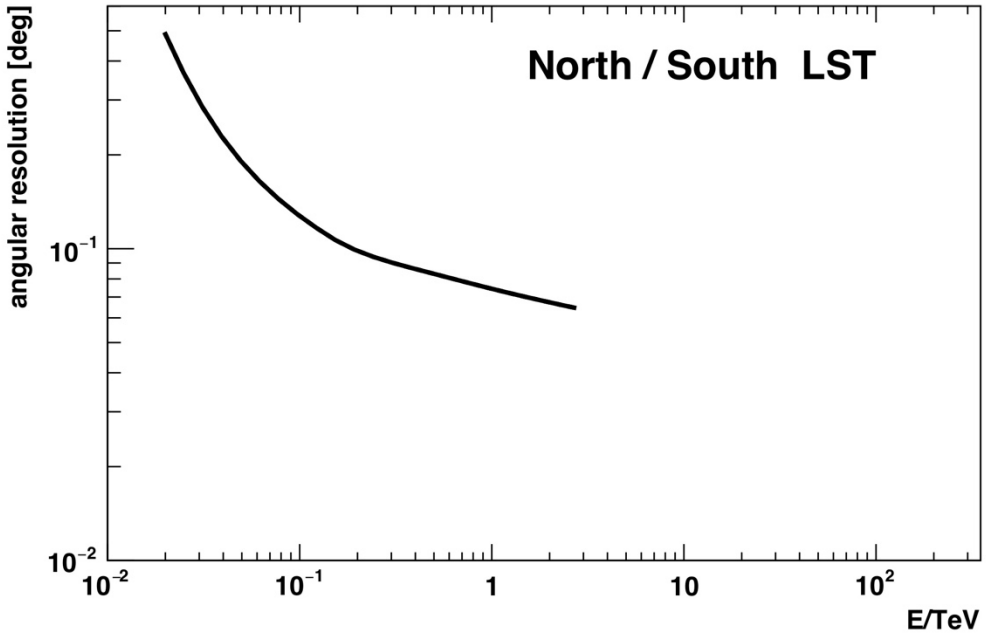
illumination level of 0.9 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm following the Moonlight Reference Spectrum, in a time scale of 50 hours. Sensitivity is required in the energy range 40 GeV - 3 TeV.

Solid black line: 50 h observation differential sensitivity under Low Moonlight – South - LST



A-PERF-1055 LST sub-system Angular Resolution

The LST sub-system at both CTA sites must meet the *Angular Resolution* given in the figure below and attached data files at 20 degrees zenith angle and for the gamma-ray selection corresponding to the 50 h sub-system sensitivity requirement.



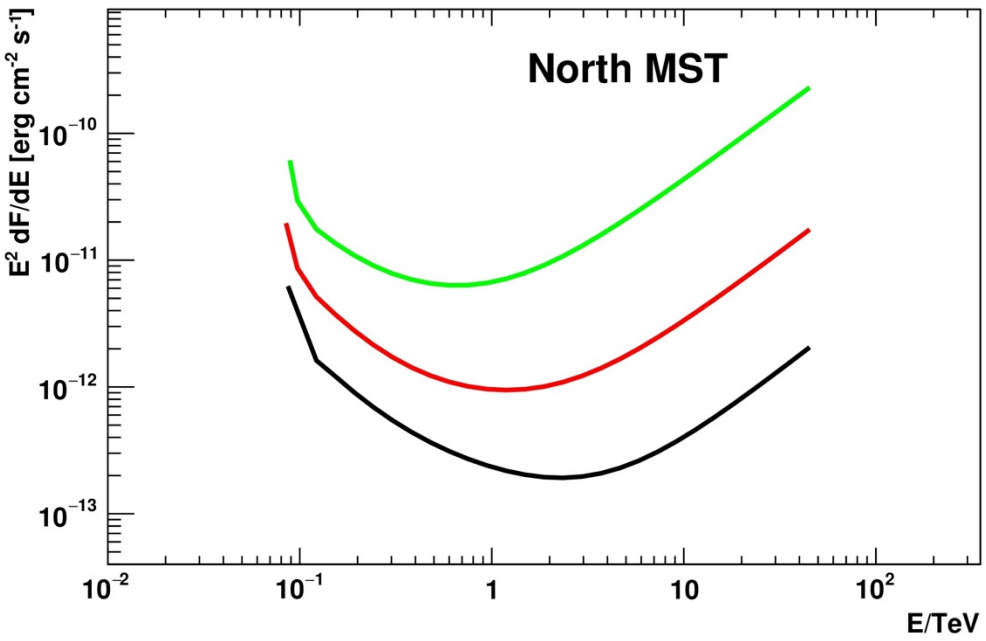
A-PERF-1100 MST sub-system Repositioning

The MST sub-system must be capable of changing target from and to any part of the *observable sky* within 90 s.

A-PERF-1110 MST sub-system Sensitivity (N)

The MST sub-system at the northern site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached under *Reference Conditions* in the three specified observation timescales of 0.5, 5 and 50 hours. Sensitivity is required in the energy range 80 GeV - 50 TeV.

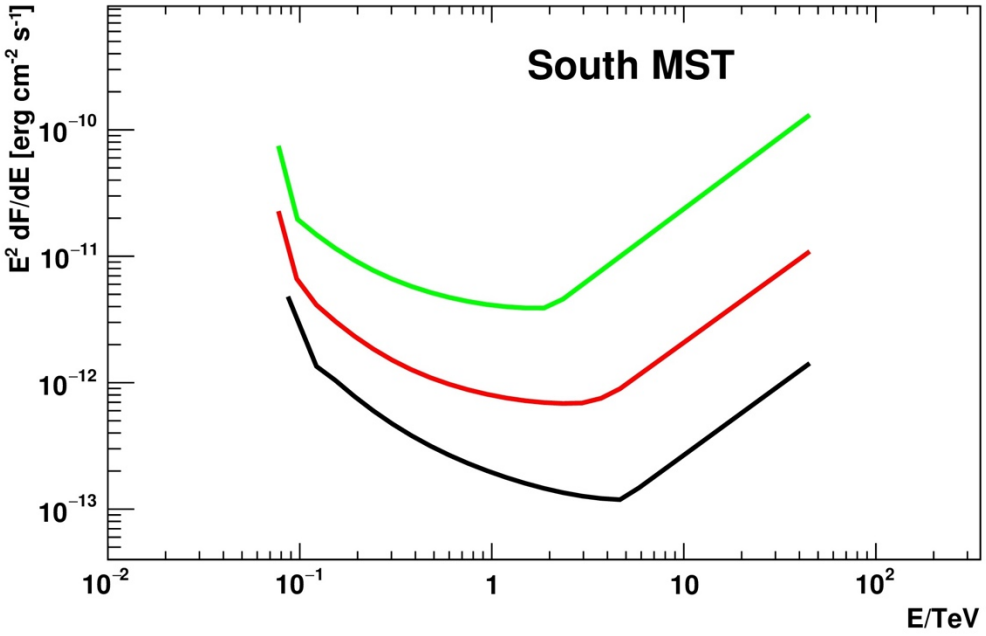
Black line: 50h observation time. Red line: 5 h observation time. Green line: 30 min observation time.



A-PERF-1120 MST sub-system Sensitivity (S)

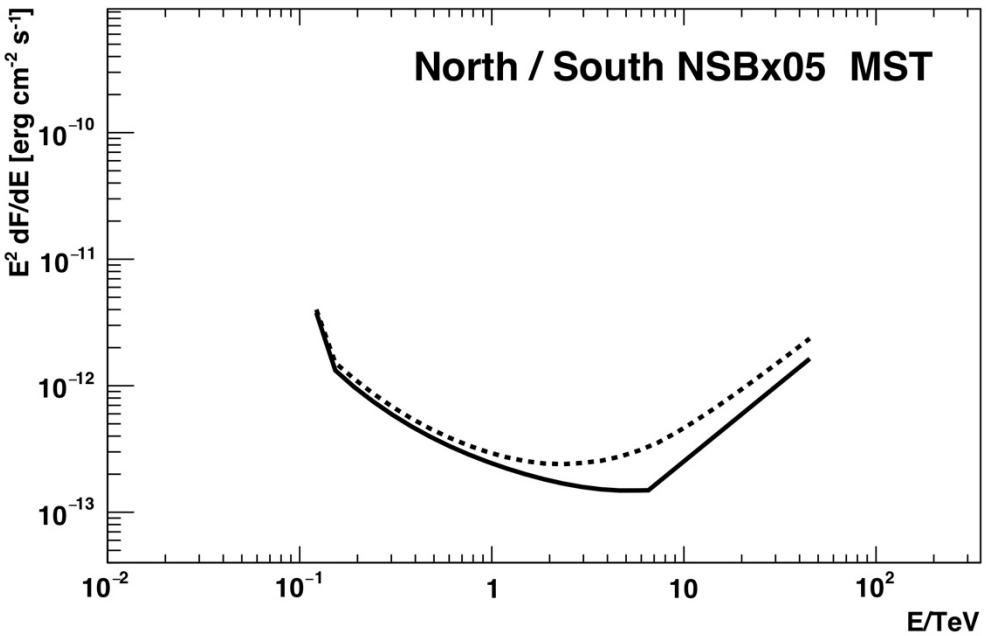
The MST sub-system at the southern site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached under *Reference Conditions* in the three specified observation timescales of 0.5, 5 and 50 hours. Sensitivity is required in the energy range 80 GeV - 50 TeV.

Black line: 50 h observation time. Red line: 5 h observation time. Green line: 30 min observation time.



A-PERF-1130 MST sub-system Sensitivity under Low Moonlight (N)
The MST sub-system at the Northern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached at a background illumination level of 0.9 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm following the Moonlight Reference Spectrum, in a time scale of 50 hours. Sensitivity is required in the energy range 125 GeV - 50 TeV.

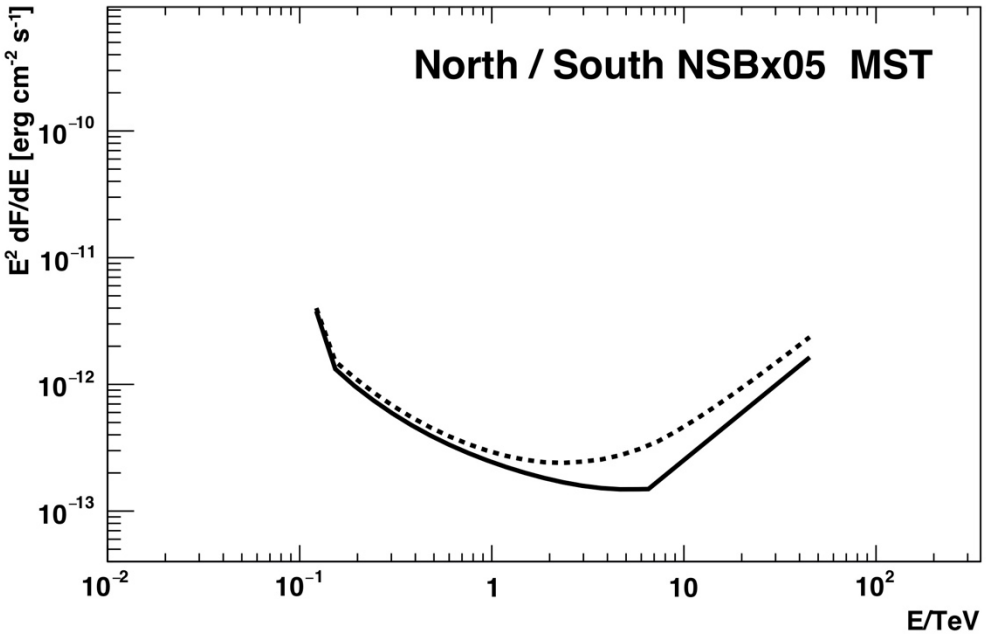
Dashed black line: 50 h observation differential sensitivity under Low Moonlight - North - MST



A-PERF-1140 MST sub-system Sensitivity under Low Moonlight (S)
The MST sub-system at the Southern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached at a background

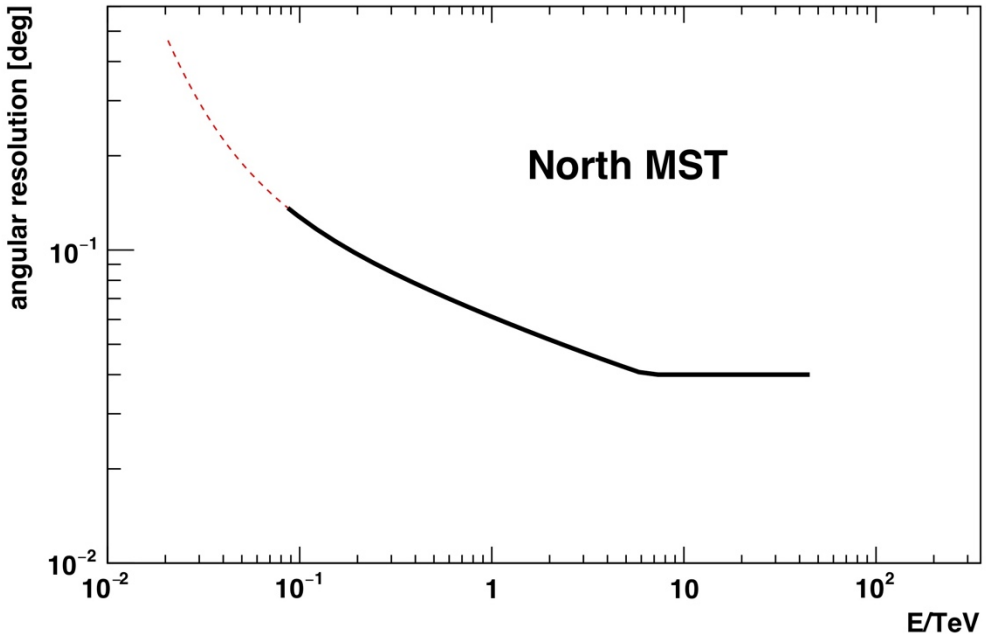
illumination level of 0.9 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm following the Moonlight Reference Spectrum, in a time scale of 50 hours. Sensitivity is required in the energy range 125 GeV - 50 TeV.

Solid black line: 50 hour observation differential sensitivity under Low Moonlight - South - MST



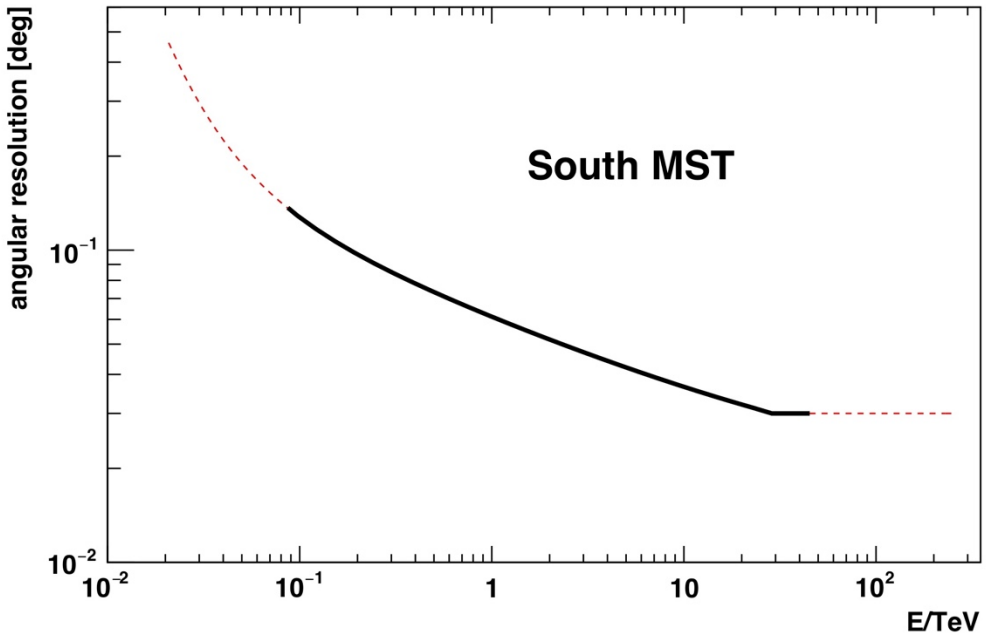
A-PERF-1150 MST sub-system Angular Resolution (N)

The MST sub-system at the northern site must meet the *Angular Resolution* given in the figure below and attached data files at 20 degrees zenith angle and for the gamma-ray selection corresponding to the 50 hour sub-system sensitivity requirement.



A-PERF-1160 MST sub-system Angular Resolution (S)

The MST sub-system at the southern site must meet the *Angular Resolution* given in the figure below and attached data files at 20 degrees zenith angle and for the gamma-ray selection corresponding to the 50 h sub-system sensitivity requirement.



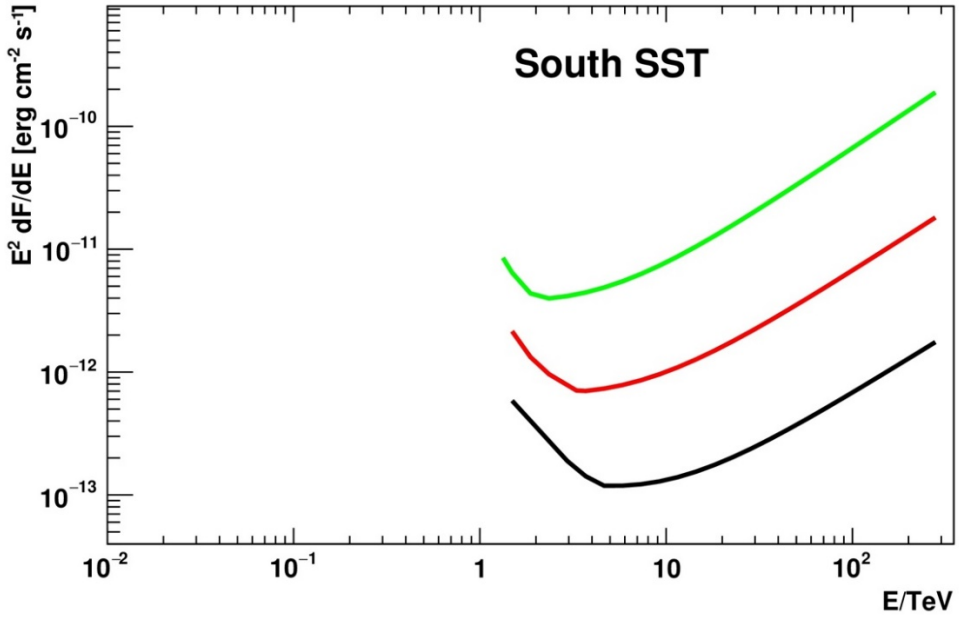
A-PERF-1200 SST sub-system Repositioning

The SST sub-system must be capable of changing target from and to any part of the *observable sky* within 90 s.

A-PERF-1210 SST sub-system Sensitivity

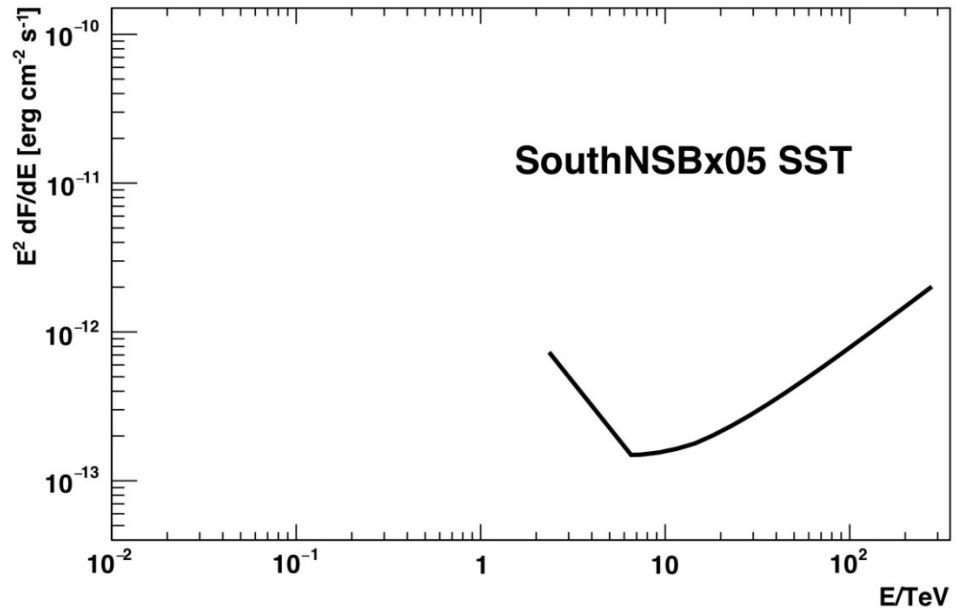
The SST sub-system at the southern site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached under *Reference Conditions* in the three specified observation timescales of 0.5, 5 and 50 hours. Sensitivity is required in the energy range 1 TeV - 300 TeV.

Black line: 50h observation time. Red line: 5 h observation time. Green line: 30 min observation time.



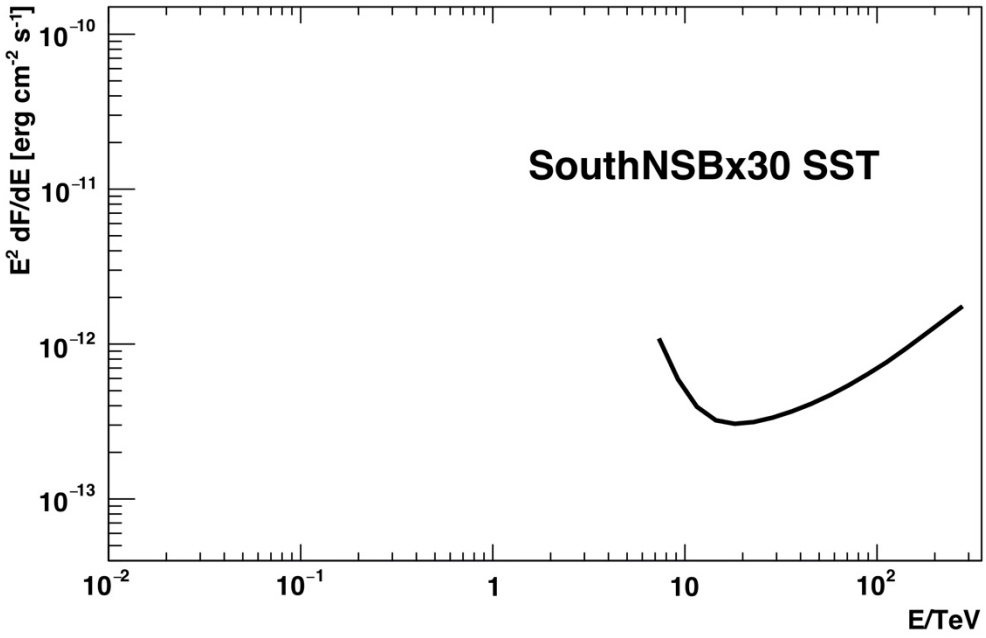
A-PERF-1230 SST sub-system Sensitivity under Low Moonlight

The SST sub-system at the Southern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached at a background illumination level of 0.9 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm following the Moonlight Reference Spectrum, in a time scale of 50 hours. Sensitivity is required in the energy range 2.5 TeV - 300 TeV.



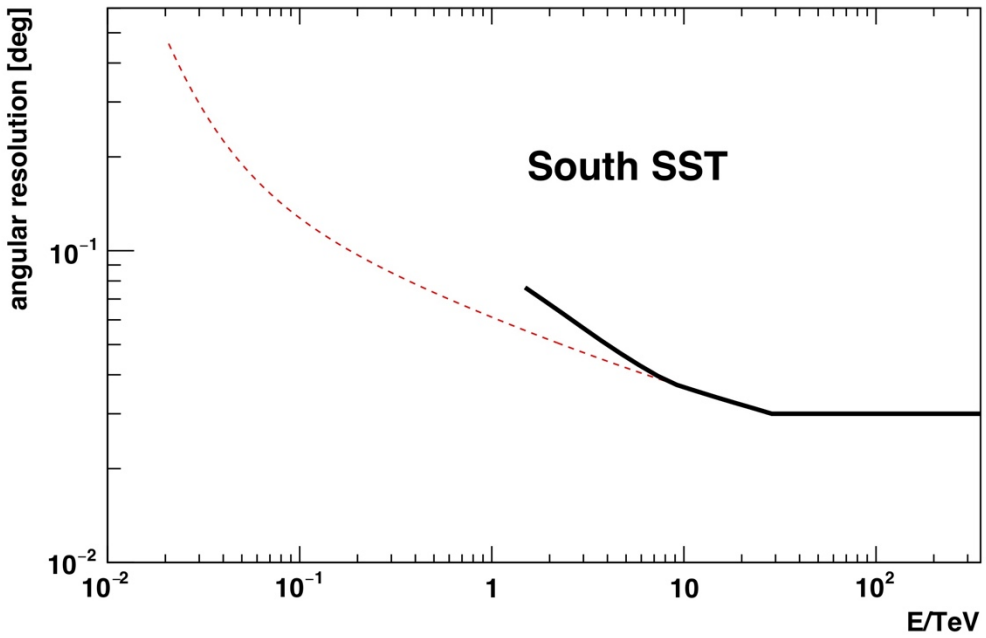
A-PERF-1240 SST sub-system Sensitivity under Moonlight

The SST sub-system at the Southern CTA site must allow the point-source *Differential Sensitivity* given in the figure below and attached data files to be reached at a background illumination level of 4.3 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm following the Moonlight Reference Spectrum, in a time scale of 50 hours. Sensitivity is required in the energy range 8 TeV - 300 TeV.



A-PERF-1250 SST sub-system Angular Resolution

The SST sub-system at both CTA sites must meet the *Angular Resolution* given in the figure below and attached data files at 20 degrees zenith angle and for the gamma-ray selection corresponding to the 50 hour sub-system sensitivity requirement.



A-PERF-2030 Field of View Centering

The *Field of View* of each telescope should be centred on the *Target* position with a precision sufficient that the gamma-ray acceptance change is less than 2% between the actual and nominal position.

A-PERF-2043 Transition Time: Off to Safe
It must be possible to bring the system as a whole from the *Off* to the *Safe* state in less than 5 minutes.

A-PERF-2044 Transition Time: Safe to Standby
It must be possible to bring the system as a whole from the *Safe* to the *Standby* state in less than 90 minutes. The opposite transition must be possible in 1 minute.

A-PERF-2045 Transition Time: Standby to Ready
It must be possible to bring the system as a whole from the *Standby* state to the *Ready* State within 5 minutes. The opposite transition should be possible within the same timescale.

A-PERF-2046 Transition Time: Ready to Observing
It must be possible to bring the system as a whole from the *Ready* State to the *Observing* State in 1 minute. The opposite transition must be possible on the same timescale.

A-PERF-2050 Absolute Throughput Error
The systematic error on the measurement of the absolute intensity (i.e. photons per square metre) of the Cherenkov light (post-calibration) at the position of each telescope must be <8 %.

A-PERF-2150 Optical PSF
In order to minimise the impact of telescope optics on performance, the optical point-spread-function (PSF) size must be smaller than the camera pixel size and/or the minimum angular scale on which shower information can be derived from typical images. The angular size of camera pixels must be less than the FWHM of gamma-ray images in the relevant energy range (see figure).

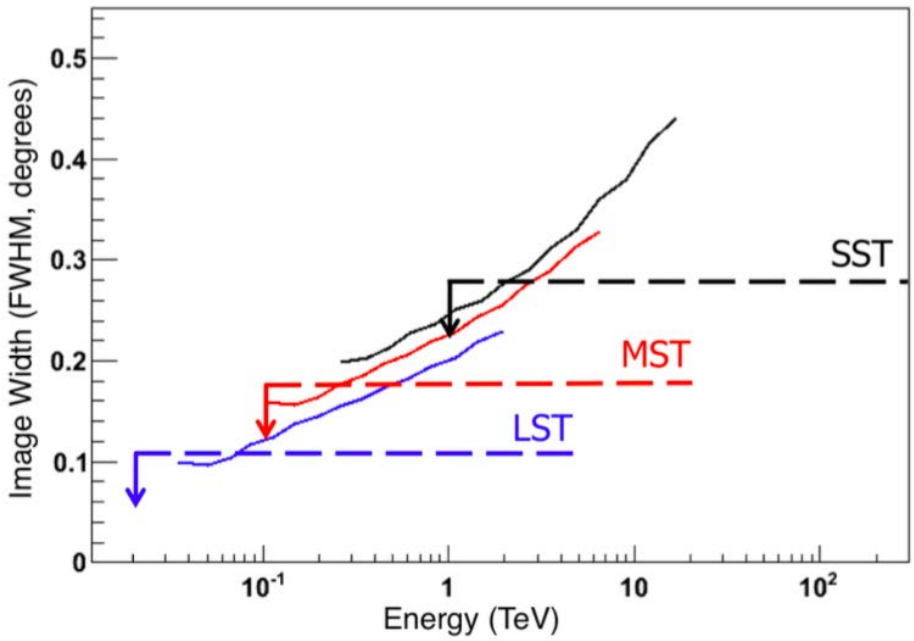


Figure: FWHM of *γ*-ray images, recorded with three of the different telescope types in the *Prod-1* simulations, versus energy. The energy ranges and required maximum pixel sizes of the LST, MST and SST telescope types are illustrated.

A-PERF-2250 Telescope Deadtime
The fraction of the time that it is not possible to generate, receive or process triggers and/or data from an individual Telescope whilst in the Observing state during observations must be <6 %.

A-PERF-3000 Sub-Array Operation
Operation of the telescope arrays at the CTA sites as up to 8 simultaneously and independently operating *Sub-arrays*, containing one or more different telescope types, must be possible.

A-PERF-3010 Cherenkov Light Simulation
Simulations used to produce instrument response information for CTA must model the atmosphere, air-shower development, and production and propagation of Cherenkov light from air showers to array level, with a precision high enough that the uncertainty on the Cherenkov density within 200 m of the axis of a gamma-ray initiated shower over the full energy range of CTA and for zenith angles up to 60 degrees, is less than 3%.

A-PERF-3020 Knowledge of Selection Efficiency
The contribution of the event triggering and selection process at the level of individual telescopes to the uncertainty on the *effective collection area* of the system must be less than 8%

A-PERF-3030 Background Model
Science Users of CTA must be provided with a model for the residual background in the field of view of every observation, which must be derived from existing CTA data during routine science operations. This model must be accurate at a level of +/-2% of the peak background at 99% confidence, for all energies between 50 GeV and 50 TeV, over at least the *Gamma-ray Field of View*.

A-PERF-3040 Atmospheric Monitoring
Residual uncertainties (after characterisation using on-site monitoring systems) in the models of the atmosphere above the two CTA sites must be such that the contribution of these uncertainties to the uncertainty in the reconstructed gamma-ray energy is less than 7% for the *Reference Gamma-ray Spectrum*.

A-PERF-3050 Analysis Energy Scale Uncertainty
The contribution of the array-level event selection and reconstruction process to the uncertainty on the energy scale of the system must be less than 4%.

A-PERF-3060 Monitoring of Data Processing
All steps in data processing must be subject to quality monitoring procedures. Problems with the potential to impact performance must be flagged for follow up.

A-PERF-3080 Science Alert Pipeline
Science alerts must be produced with a sensitivity degraded with respect to the sensitivity of the full processing pipeline by no worse than a factor of 2, (for a source with the *Reference Gamma-ray Spectrum*) for a total latency of 90 seconds.

A-PERF-3100 Processing Robustness
Data processing at all levels must be resilient against all data quality issues that can reasonably be anticipated.

4 References

[1] *Performance Requirements for CTA*, MAN-PO/121004

[2] *The Layouts of the CTA Arrays*, OBS-SCI/160420

[3] *The Standard Monte Carlo Simulation Framework for CTA*, CTA-PRO-SCI-00000-0001

[4] *Construction Proposal Overview and Plan*, MAN-TDR/150315 (section 4.10.2)