Comparative study of the performances in surveys of several CTA arrays

DESY Summer Student Programme, 2014

Rafael Mestre Castillo
University of Granada, Spain

Supervisors
Gernot Maier
Lucie Gerard

5th of September 2014

Abstract

The Cherenkov Telescope Array (CTA), still under developtment, will be the next generation of Imaging Atmospheric Cherenkov Telescopes (IACTs). There exists many possible telescope layouts, but the final configuration has not been decided yet. All-sky surveys are one of the main operations that CTA will carry out and allow the discovery of new gamma-ray sources, hence an study of the most suitable array is of high importance. In this report, the performance of the Medium Size Telescopes is analysed for galactic and extragalactic surveys, taking into account different parameters, such as the number of telescopes, their average separation or their covered area. Likewise, the effects of the addition of Small Size Telescopes are investigated. Finally, an argumentation of the best array is given, as well as the best procedure to carry out each kind of survey.

Contents

1 Introduction

The development of imaging air Cherenkov telescopes (IACT) has recently open a new window for the study of very high-energy (VHE) electromagnetic radiation that reaches Earth from different parts of the Universe. The study of radio sources in the middle of the past century suggested that observing phenomena under different energy ranges could lead to new detections which remain invisible for lower energies and help answer to some questions about the Cosmos [1]. Observations of VHE gamma-rays using telescopes orbiting Earth, such as the Fermi Large Area Telescope, which can detect radiation from about 30 MeV to 200 GeV, has several implementation and cost problems, since the flux of incoming particles becomes fainter at very high energies (about 1 particle per m^2 per year) [2]. Our atmosphere protects us from this radiation, thus making imposible direct detection with ground-based telescopes. The interaction with the atmosphere produces, however, extensive particle showers that can be easily detected from Earth. Gamma-rays, in particular, originate electromagnetic cascades, which can be simultaed via Monte Carlo methods. Created charged particles (e.g. electrons and positrons) can have extreme kinetical energies, overcoming the speed of light in the medium and producing secondary photons, named Cherenkov radiation, iluminating an area on the ground of about 150 m of radius, usually called the "light pool".

Current IACT instruments, such as H.E.S.S. in the Republic of Namibia, MAGIC in the Canary Islands and VERITAS in the United States of America work in the TeV energy band and are capable of observing not only point-like sources, but also extended objects. This has lead, in the past decades, to the discovery and exhaustive study of several VHE gamma-ray sources, like young Supernova Remnants (SNRs), Star Forming Regions (SFRs), Giant Molecular Clouds (GMCs), Pulsar Wind Nebulae (PWNe) and Active Galactic Nuclei (AGNs), amongst others. Furthermore, it has provided an extensive amount of information about particle acceleration mechanisms in these astronomical objects (still not well understood) and has helped in the search of Dark Matter and tests of Quantum Gravity theories. Due to the low flux of VHE photons, larger detections areas are needed in orderd to achieve enough statistics to discover a new source. The current IACT arrays do not possess enough sensitiviy and effective area to have access to some of the yet unknown sources.

CTA (Cherenkov Telescope Array) will be the new generation of ground-based IACTs for the study of very-high energy gamma-rays. CTA is expected to cover both low and ultra high energy ranges, from about some tens of GeV to hundreds of TeV with an improvement in angular resolution, energy resolution and sensitivity [3]. These goals can be achieved thanks to the implementation of about 100 telescopes, distributed between both hemispheres of the planet, in order to provide a full-sky coverage. After being initially proposed in 2006 with an estimated cost of around 150M€, the CTA consortium was formed in order to study its possible implementation and design. CTA has currently become a huge project, with more than 1000 members from 27 different countries and an estimated budget of 200M€. Despite being based on the imaging air Cherenkov reconstruction technique, CTA will be different from current IACT arrays, since its goals go far beyond what could be achieved with an improvement or upgrade of the current generation of telescopes.

In order to have access to such a wide range of energy (of four orders of magnitude, with an improvement of one order of magnitude compared to current instruments), CTA will consist of three types of telescopes: Small Size Telescopes (SSTs), Medium Size Telescopes (MSTs) and Large Size Telescopes (LSTs). The SSTs will be optimised to observe the ultra-high-energy range (>10 TeV) and, due to the low flux of ultra-energetic photons, a great number convering an area of several square kilometers will be necessary in order to be able to detect as many showers as possible. Several configurations of the telescopes are being studied, as well as two different optical systems, so as to find the best cost/efficiency performance. The arrays of MSTs wil be mainly used to study the central energy range, with mirrors of about 12 m of diameter. Finally, large-size telescopes will be used to study the low energy range (<100 GeV). Due to the high flux of low energy photons, enough gamma-rays can be detected and only 3 or 4 of these telescopes will be eventually established. The full configuration of telescopes will allow to improve the sensivity by a factor of 10, compared to any current instruments, as well as to obtain better angular resolution due to the simulatenous detection

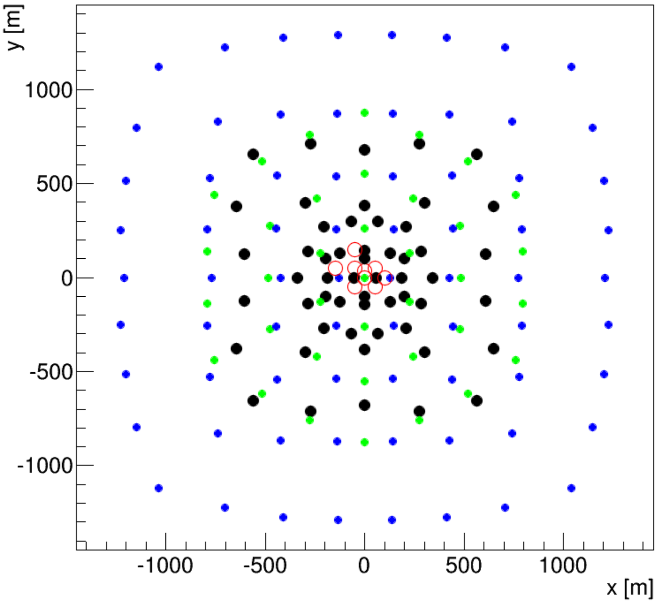

Figure 1: Sketch of the southern hyperarray under study by the CTA Collaboration. The black circles are MSTs, the red circumferences represent LSTs and the green and blue dots illustrate SSTs with Davies-Cotton and Schwarzschild-Couder optical designs, respectively.

of cascades by several of its many telescopes.

It is clear thtat CTA will be an enormously powerful instrument for discovering new sources of VHE gamma-rays, therefore a good performance in all-sky blind surveys will be compulsory. In this report, the sensitivity performance of different kinds of arrays in extragalactic and galactic surveys is studied. A brief discussion of the procedure, sites and array details is presented in Section §2. In Section §3 the influence of certain parameters in arrays containing only MSTs, such as the number of telescopes or their density, is studied for the case of extragalactic surveys and in Section §4 an analogous analysis is carried out for galactic surveys. Finally, Section §5 is devoted to the analysis of the impact of the addition of certain number of SSTs to formerly studied arrays. Two supplemental appendices can be found in the last pages. Appendix A shows a similar study that the one carried out in Section §4 for a higher threshold energy of 500 GeV and Appendix B contains all the array layouts that could be useful to inspect in order to have a achieve understanding of the results.

2 Procedure

Surveys are one of the many operations that CTA will carry out after its installation. It is foreseen an approximate total amount of 600 hours of observation for an extragalactic survey of 1/4 of the sky (a region of about 40x40 degrees) and 250 hours for a survey of 120 degrees of the galactic plane. Considering the average of 1000 hours of actual observation per year, these are meaningful amounts of time and an understanding of the performance of different arrays and diverse approaches to these surveys is of extreme importance. Surveys provide and excellent channel for the discovery of yet unknown sources or for the acquisition of datasets for further analysis in different energy ranges [4]. CTA will be able to detect fainter sources than its counterparts HESS or VERITAS, amongst others, with an improved angular and energy resolution

The atmosphere protects Earth from high energy particles coming from different parts of the

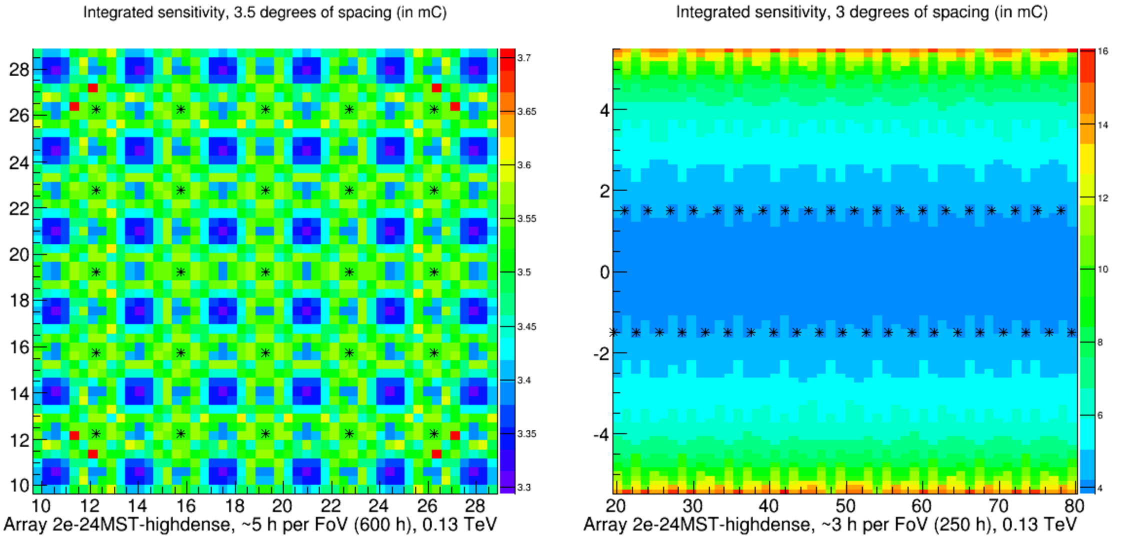

Figure 2: Example of two sensitivity surveys achieved by computer simulations. In both images, the stars represent observation points and the axis are given in degrees. The FoV used was of 8.5 degrees of diameter. The left picture illustrates an extragalactic survey with a linear pointing of 3.5 degrees of spacing. The borders were zoomed out of the image, in order to have a better appreciation of the inhomogeneities. The figure of the right represents a galactic survey with an equilateral triangular pointing of 3 degrees of spacing. The central line represents our galactic plane and the total longitude was of 120 degrees, from which a small part was chosen for a close-up.

Universe. When an incoming particle hits another one in the upper part of the atmosphere, more of them are produced, which in turn decay or collide with many more particles, producing an extensive shower that gets atenuated with distance and reaches the ground as radiation with a much lower energy. This radiation contains Cherenkov photons, produced when charged particles overcome the speed of light in the atmosphere. As already mentioned, IACTs are designed to detect these Cherenkov photons produced by electrons and positrons in electromagnetic cascades generated by VHE gamma-rays and, thanks to the stereoscopic imaging technique, the energy and the direction of the incident ray can be calculated. Nevertheless, other particles, such as protons, electrons or heavy nucleai, also reach the atmosphere as part of the so called cosmic rays, generating secondary particle showers that may obscure a gamma-ray signal.

The wide variety of possible arrays for both the north and south hemisphere was reduced by the CTA Collaboration after the selection of two hyperarrays, one for each site, which contain a great number of telescopes in different locations. The two final configurations will be sub-arrays of these hyperarrays. Electromagnetic showers produced by gamma-rays, as well as hadronic showers generated by other kinds of particles, are simulated via Monte Carlo methods. Other effects, such as moonlight or night-sky background are introduced following random distributions [5]. Next, the performance of each telescope of the hyperarray is simulated, taking into account the uncertainties related to the mirrors, the PMTs, etcetera. When one specific subarray is going to be studied, the response of each one of its telescopes is put together and, after some separation of events, cuts and different analyses, one obtains the final response of the array in the presence of a shower, called the Instrument Response Function (IRF). The number of signals triggered by two telescopes, the number of background light that misses the cutoffs, and other parameters are criterions that determine the final sensitivity of the whole array.

For the simulations carried out in this report, the IRFs of the hyperarray situated in the south-american site have been used. A depiction of this array can be visualised in Fig. 1. The obtained

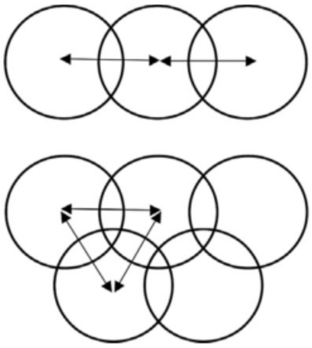

Figure 3: The two different pointings or tilings used in this report: linear pointing (top) or equilateral triangular pointing (bottom). Source: [4].

results could also be suggestive for the second possible settlement, in Namibia. Important parameters, such as the geomagnetic field, site height or atmospheric conditions, play an important role in shower simulations, and the aftermaths could differ. Nevertheless, the overall performance of an array in both sites is expected to be similar. The hyperarrays used for the south and north hemispheres are rather disparate and, together with the very different environmental conditions, the results presented in this report could not be considered definitive for a northern array study, but only as an aid for understanding the general behavior of the telescopes itself.

Differential sensitivities have not been studied in this report, since the main interest was the study of the perfomance over a whole range of energy. Therefore, only integrated sensitivities were evaluated using a threshold energy of 130 GeV for both extragalactic and galactic surveys. In extralagactic surveys, sources with a pretty steep energy spectrum are mainly observed, since higher energies are suppressed due to the interaction of VHE photons with low-energetic Extragalactic Background Light (EBL). For galactic surveys, the performances over an energy range starting at 500 GeV was also studied, since the EBL effect is not present for close sources and observations over a more energetic range can be fulfilled. The results of this study and some brief comments can be found in Appendix A of this report.

The energy spectrum of high-energy photons reaching Earth (and also cosmic rays) follows a power law of the form $E^{-\alpha}$ where α is the spectral index. The Crab nebula, whose energy spectrum has an index of about 2.6 is used as the standard candle in TeV astronomy to express the brightness or the flux of incoming particles. Therefore, in any analysis, the energy range should be always given, since the particle flux of the Crab nebula is energy-dependent. An instrument with an integrated sensitivity of 0.01 Crab or 10 mCrab at a certain energy threshold would be able to detect a source which has the same spectral index of the Crab nebula and is 100 times fainter. Thus, a lower sensitivity is always desirable, since it represents the minimum flux that an instrument can detect. For a general analysis of perfomance without a preferred spectral index, general flux units should be adopted (erg cm^{-2} s^{-1}). In this report, the measurement of the Crab nebula gamma-ray flux carried out by the HEGRA Collaboration has been used: $\mathrm{d}N/\mathrm{d}E = (2.83 \cdot 10^{-11} \pm 0.04 \cdot 10^{-11})\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ \mathrm{TeV}^{-1} \times \mathrm{E}^{-2.62 \pm 0.02}$ [6].

Finally, two different ways of accomplishing a survey were analysed in this report. The simplest one is a linear pointing, which goes over the sky with observation points differing a distance d, forming squares, and the second choice is a triangular pointing, using equilateral triangles to cover the whole region. For a galactic survey, however, a linear tiling only consists of a single row of observation points in the galactic plane or a row of triangles centered in the same plane. The off-axis performance, that is, the efficiency of the telescopes when the observed source is not in the center but at the edge of the Field of View (FoV), is not generally as good as the on-source performance. Therefore, the sensitivity in the outer parts of FoV of the telescope, plays an important role in the analyses, as it could produce an inhomogeneous coverage of the sky. In Fig. 3 the two tilings are depicted.

One way to compare on-source (that is, in the center of the FoV) observations with off-axis observations is the use of the effective observing time. Given a sensitivity on-source achieved after a certain time t, the effective observing time of a point of the FoV is defined as the total amount of time that would need to be spent in an observation on-soure on that point in order to reach the same sensitivity as before. Generally, the effective time increases when one moves away from the center of the observation point, that is, the sensitivity achieved in the edges is always poor compared to the sensitivity on-source. Namely, the best observation is always accomplished in the center of the FoV, worsening at the edges of it. In the simulations of this study, a FoV of 8.5° of diameter was assumed.

The effetive time (or effective total observation time) is also used as a more practical way to compare performances of different arrays. All the mean sensitivity values are obtained for a total observing time of 600 hours in extralactic surveys (250 hours in the galactic case). Therefore, fixing this value of observing time for the array with the best perfomance, the effective total observation time of any other array is defined as the total time that would need to be spent to achieve the same sensitivity as the best array. Since the observation time of 600 hours (250 hours) is fixed to the array with the best sensitivity, all the other observation times will be higher, as they will have worse sensitivities. In this way, we can obtain an useful comparison between different arrays based on the logistics of the project.

3 Study of MST arrays in extragalactic surveys

The Medium-Size Telescopes of CTA will be optimized for the study of the central energy range, that is, 0.1-10 TeV, also called the core range [3]. Each telescope will posess a Davis-Cotton optics design with 84 mirror facets in a dish of 12 m of diameter [7]. A 1:1 scale prototype has already been set and its mechanical properties are currently being studied at the DESY site in Berlin (Fig. 4). The total number of MSTs still remains undecided, as well as the final configuration and the distances between the telescopes. Simulations of the perfomance of these telescopes yield a differential sensitivity of the order of mCrab after 50 hours of observation in the central region of the energy spectrum. The sensitivity improvement in contrast with current IACT instruments is due to the increase of the number of telescopes and a larger covered area. In the stererostopic image reconstruction tecnique, a trigger of at least two telescopes is required (that is, two telescopes should detect the same signal in a specified time window). Events with a detection of a larger number of telescopes will result in improved resolution and reduced background. A larger covered area of telescopes would also increase the number of events recorded, positively affecting the performance of the array. Nevertheless, a large

Figure 4: Prototype of the MST located in Adlershof (Berlin). Some of the facets are real, but most of them are dummy mirrors and the camera is a concrete box of approximately the same weight as the real one. This prototype's only purpose was to study the mechanical properties of the instrument.

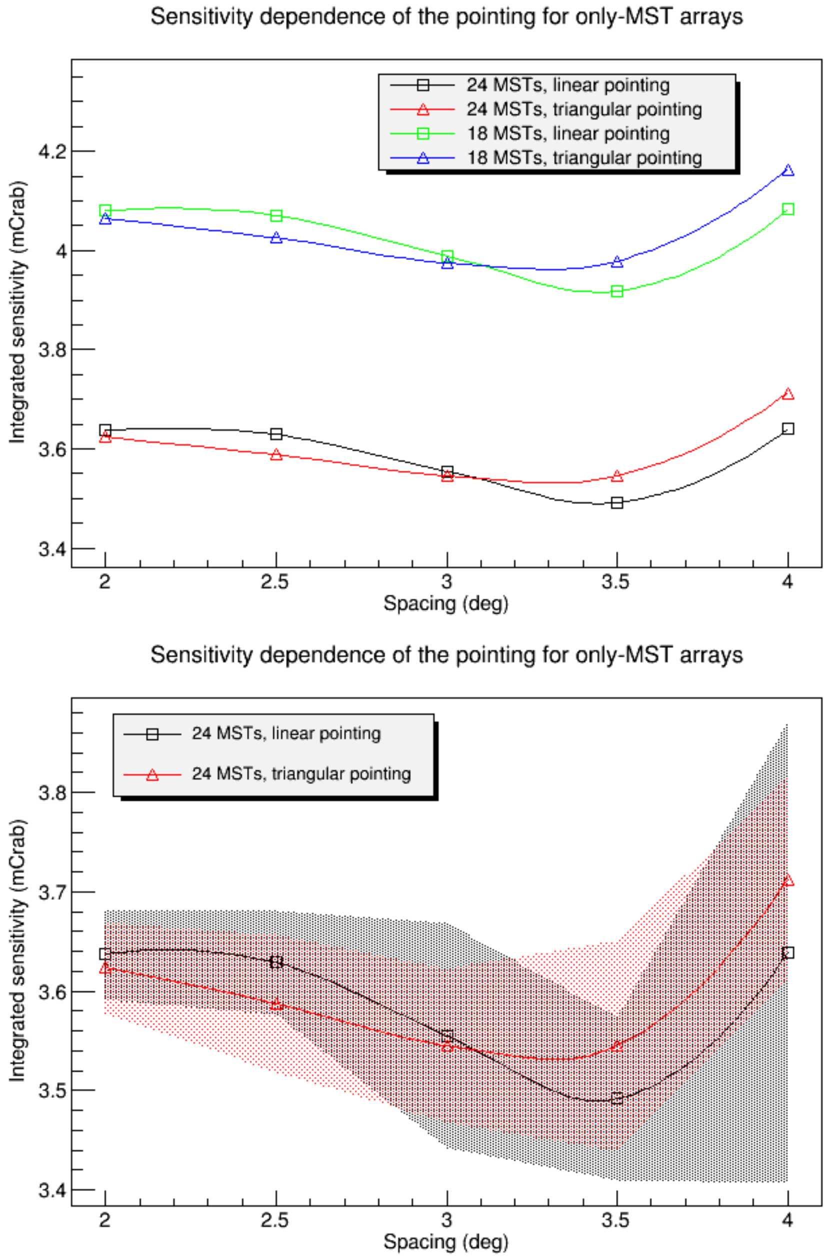

Figure 5: Top: Integrated sensitivity in mCrab for two different arrays of MSTs and two different kinds of pointings: linear and triangular. Bottom: Integrated sensitivity in mCrab for the array of 24 MSTs, including error bars. Both simulations were calculated for an energy threshold of 130 GeV and for a total observing time of 600 h.

area coverage with not enough number of telescopes would increase the telescope distances and, taking into account the average light pool diameter of 150 m, the senstivitiy of the array could turn out to be worsened, since detections with ≥ 2 telescopes would be supressed.

The choice of a type of pointing (linear or triangular) and separation between observations is an important matter that needs to be studied for the final array. The selection between one or another kind of tiling might be dependent of the off-axis performance of the array - a configuration with a good differential sensitivity but a poor off-axis performance could lead to the rising of gaps of lower

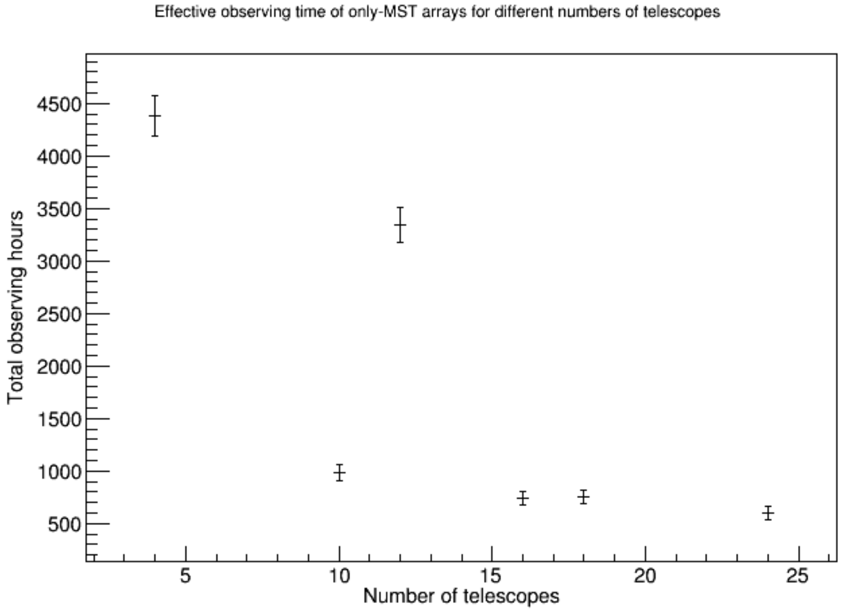

Figure 6: Total effective time in terms of the number of MSTs of the array. The hours of observing time have been normalised with respect to the time spent by the 24 MST array (600 h of observation in extragalactic surveys).

sensitivity at some points of the survey. Fig. 5 shows the mean integrated sensitivitiy for different arrays and types of pointing, excluding the border effects at the edges of the observed sky. The error bands, only represented in the bottom figure for clarity's purposes, are the standard deviation of the integrated sensitivity. Another way of considering the irregularities of the survey would be to represent the maximum and minimum values of sensitivity as error bars of the mean. Nevertheless, it was found that the error bars were only increased a value between a few percent and about 20% of the standard deviation, not being of great significance, and the standard deviation approach was maitained. For both arrays, and also for the other only-MST arrays analysed but not shown in the figures[1], the pointings show a clear tendency. Larger spacings present, as expected, higher standard deviations, since the off-axis performance plays an important role. For shorter spacings, the triangular pointing yields better, but roughly similar, sensitivity, which tends to get worse as the spacing increases. All of the extragalactic surveys studied from this point onwards will have been obtained using a linear pointing of 3.5 degrees of separation, since it is the one that generates better results with an acceptable standard deviation, and a quadratic propagation of uncertainties will be assumed.

Several simulations of extragalactic surveys were done for different parameters of arrays containing only MSTs. Fig. 6 shows the dependence of the number of MSTs on the effective observing time. All the data is normalised to the time spent by the array containing 24 MSTs in a typical extragalactic survey of 1/4 of the sky (approximately 600 hours). The Y-axis, thus, represents the time that would need to be spent in a survey of the same characteristics by any of the other arrays in order to reach the same integrated sensitivity as the 24 MST array. The integrated sentivities attained by the last three arrays are within the range 3.5-4 mCrab with a threshold energy of 130 GeV and the effective observing times are 756 h and 742 h for 18 and 16 MSTs, respectively. The aparent deviation from the trend can be easily understood taking a close look at each individual configuration of the 10 and 12 MST arrays (see Appendix B). Despite having aproximately the same number of telescopes, the distances between each one of them are fairly different. The array consisting on 12 telescopes has distances of more than 200 meters, therefore making rather difficult the stereostopic reconstruction of

---

[1] Specifically, arrays of 4, 10, 12 and 16 MSTs were also studied, yielding a similar trend. For clarity, only the arrays with the best results in terms of sensitivity have been shown

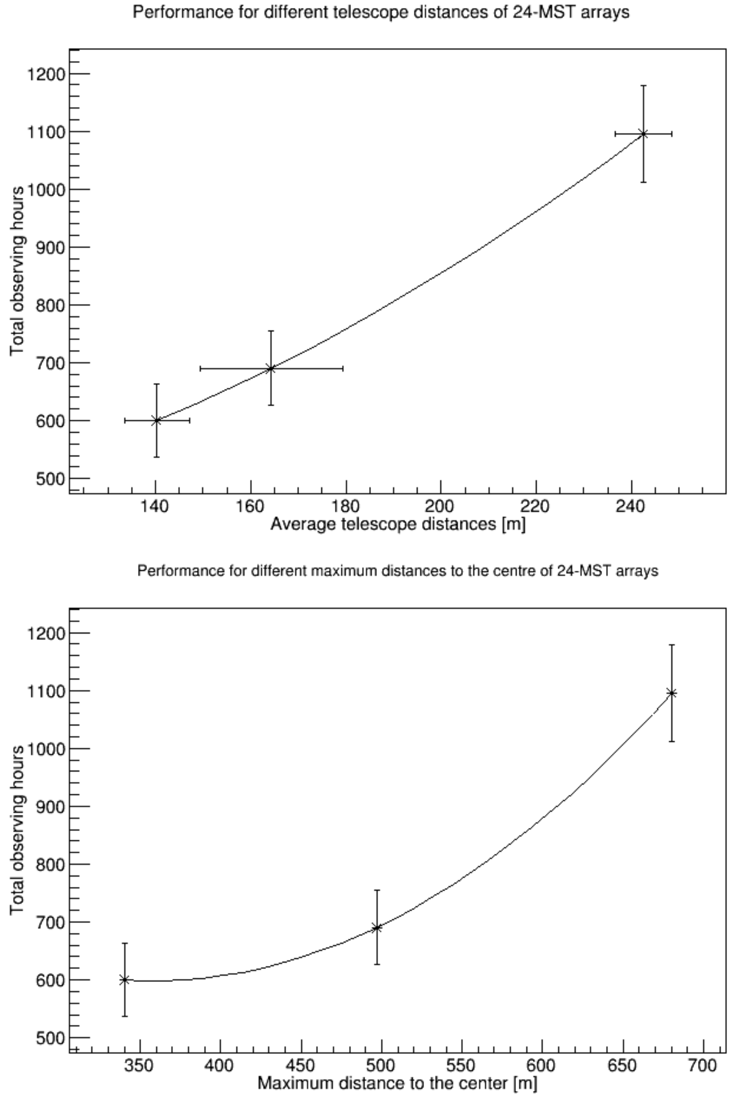

Figure 7: Top: Total observation time for different average distances between telescopes The horizontal error bars represent the uncertainty of the mean distance. Bottom: Total observation time for the same arrays in terms of the distance to the center of the further telescope.

events. The other array, however, has several telescopes within the range of 150 meters, considerably increasing the integrated senstivitiy with respect to the other configuration.

This effect really highlights the importance of a wise and compromised selection of the final array for the CTA. An increased number of telescopes without a proper separation between all of them could lead to unexpected and undesirable results. Nonetheless, these adjustments could be weakened by the outcome of the addition of other kinds of telescopes between the blanks spaces, like SSTs. The inclusion of these smaller and copious telescopes will be studied later on in Section §5.

Fig. 7 shows the performance dependence on the density of the array considering two different parameters: the distance of the further telescope to the center of the array and the average distance between neighboring telescopes. Both parameters provide a similar estimation of the density of the array since they manifest an analogous behavior and reveal the formerly mentioned effect related to the distances between telescopes. Both simulations were done for an energy threshold of 130 GeV

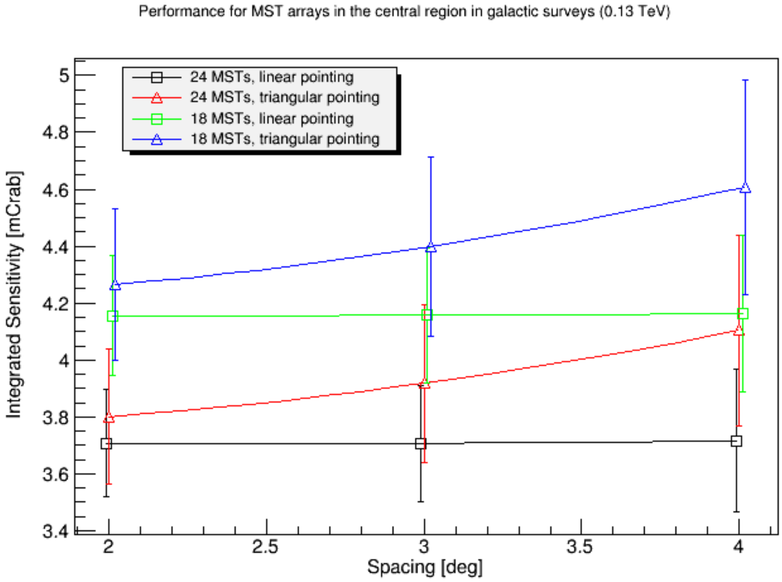

Figure 8: Mean integrated sensitivity for different arrays and different kinds of pointing in the first region of the galactic plane. All the points are situated at 2, 3 and 4 degrees. The off-set of the points was added in order to distinguish different error bars.

and quadratic propagation of the standard deviation is assumed for the error bands. In addition, two arrays of 10 MSTs with different densities were also evaluated. Similarly, the low density array, with an average separation between telescopes of about 347 m gave pretty bad results, as expected, since that separation is too large to apply a stereoscopic reconstruction tecnique. The array of high density, with an average distance between telescopes of 140 m, granted quite good results in comparison to its counterpart but still not as good as the 24 MST array, as can be seen in Fig. 6.

4 Study of MST arrays in galactic surveys

The study of a galactic survey, although it is based in the same procedure as an extragalactic one, needs to be looked at from a different point of view due to several and important border effects. In the analysis carried out in last section, the border effects were completely overlooked, since the larger central region, where the best sensitivity is achieved, holds the most interest. In a galactic survey, nevertheless, the obsevation is done around an exclusive plane in the sky, the galactic plane, where many of the VHE gamma-rays sources of our galaxy are visible, and the border effects can no longer be neglected. The central plane of the observation field will presumably have a fairly constant sensitivity but, due to the lack of observation points above and below, together with a poor off-axis performance, the sensitivity in the borders might not be the one desired at all. In general, it is useful to have a good sensitivity in the regions of latitude ±4°, and therefore it is advantageous to optimize the chosen array with the appropieate pointing, in order to achieve the best senstivitiy in the whole observation plane.

For the analysis, the galactic plane has been divided into four regions of interest, depending on the latitude. The first region is the central one, in the range ±1° of latitude. The second region is formed by the intervals [1°,2°] and [-2°,-1°]. Regions 3 and 4 are analogously constructed. In Fig. 8 and 9 the integrated sensitivities (at a 130 GeV threshold) for two different arrays in regions 1 and 4 of the galactic plane are illustrated. It can be easily noted that, for both arrays, the sensitivity in the central region remains constant for all linear pointings, although the standard deviation of the mean increases with the spacing. For the fourth region, it is almost stable. The triangular survey was

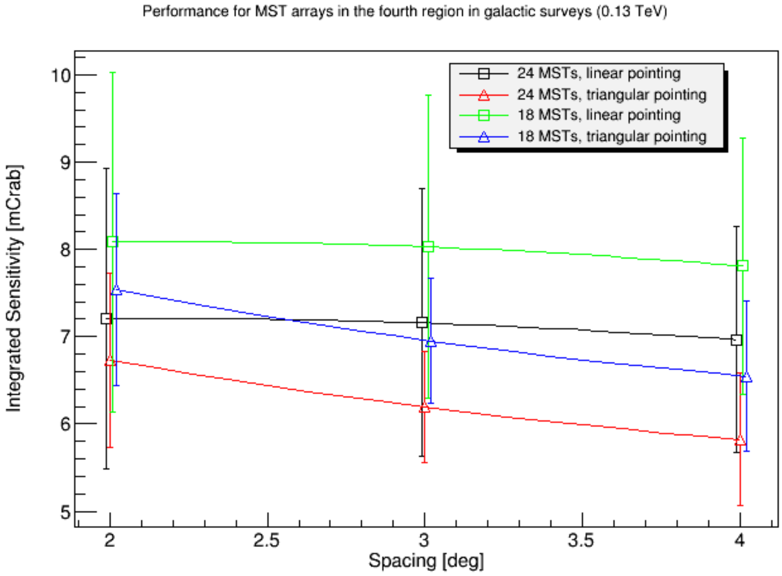

Figure 9: Mean integrated sensitivity for different arrays and different kinds of pointing in the fourth region of the galactic plane. All the points are situated at 2, 3 and 4 degrees. The off-set of the points was added in order to distinguish different error bars.

constructed using equilateral triangles forming a single row right in the center of the galactic plane, hence it is not surprising that the integrated sensitivitiy in the first region increases at the same time that the spacing does, meanwhile the sensitivity in the fourth region correspondingly decreases.

The static behaviour of the linear pointing in the galactic survey is present throughout the whole observing plane, as can be seen in Fig. 10. The mean sensitivities accross the whole region remain basically constant, with only a small decline in the fourth region. It is also noticeable the increment of the standard deviation in the further regions, which can result in differences of more than 800 hours of observation in the most extreme cases[2]. A linear pointing, consequently, would grant an excellent approach for examining the centrality of the galactic plane, provided that the border effects were neglected. An example of the fast increase of the sensitivity with latitude can be found in Fig. 11.

If a reasonable integrated sensitivity wants to be achieved in the outer regions formerly defined, the adoption of a triangular pointing is compulsory. For Fig. 8 and 9, equilateral triangles forming a single row were used, that is, the vertical separation from the galactic plane to any point above or below it was $\frac{\sqrt{3}d}{4}$, where d is the spacing. Several simulations were done in order to study the integrated sensitivity of the array offering the best performance (24 MST of high density) for different kinds of vertical separations and longitudinal spacings. The results for the four regions are exposed in Fig. 12. The variation of the average sensitivity in the outer region is stronger compared to the variation in the first region. Moreover, the choice of longitudinal spacing is not determining in any of the regions, since all of them turn out to yield very similar mean sensitivities. The standard deviation, nevertheless, does not remain constant, but increases for larger spacings, and more irregularities in the survey would be expected. This effect can be observed in Fig. 13, where two longitudinal profiles of the galactic plane are shown, for 2 and 4 degrees of linear spacing, respectively. Notice also the importance of the border effects in the left and right parts of the longitudinal plane, that can increase the sensitivity by 1 mCrab.

---

[2] Note that the effective hours of observation is a quantity that depends on the array of reference, since it is normalised to a certain value of the integrated sensitivity. This needs to be bear in mind when comparing effective times from different figures, as they will probably have different normalisations.

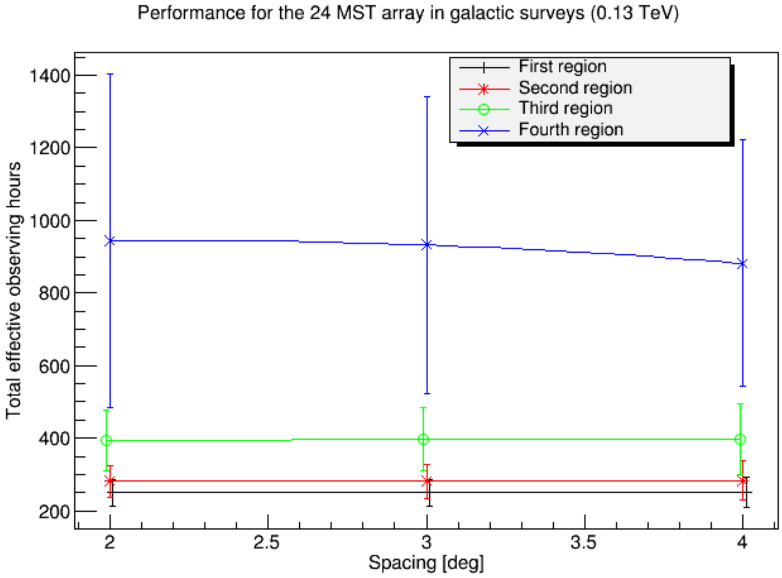

Figure 10: Performance of the 24 MST array with linear pointing for different spacings. All the points are situated at 2, 3 and 4 degrees. The off-set of the points was added in order to distinguish different error bars.

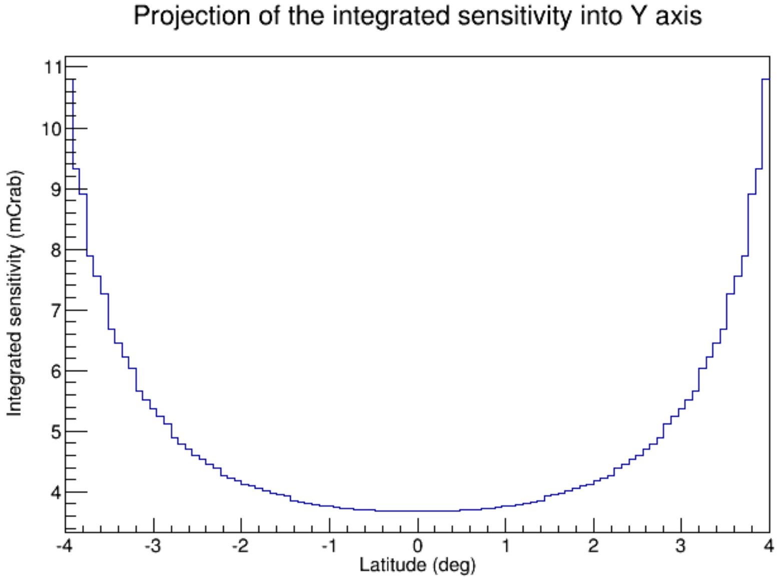

Figure 11: Transversal profile of the 24 MST array showing the mean integrated sensitivity found in each longitudinal plane for different latitudes. Linear pointing of 2 degrees was used.

5 Study of arrays containing both MSTs and SSTs

So far, performances of arrays containing only MSTs had been studied. The addition of SSTs, which will represent a higher fraction of the total southern array, can be crucial in surveys at high energies, but can also be of importance at more discreet energies in the range of the medium size telescopes. The LSTs will not be considered in this study, since they are devoted to the low energy range (≤100 GeV) and we are interested in the medium-high energy range, since MSTs and SSTs do

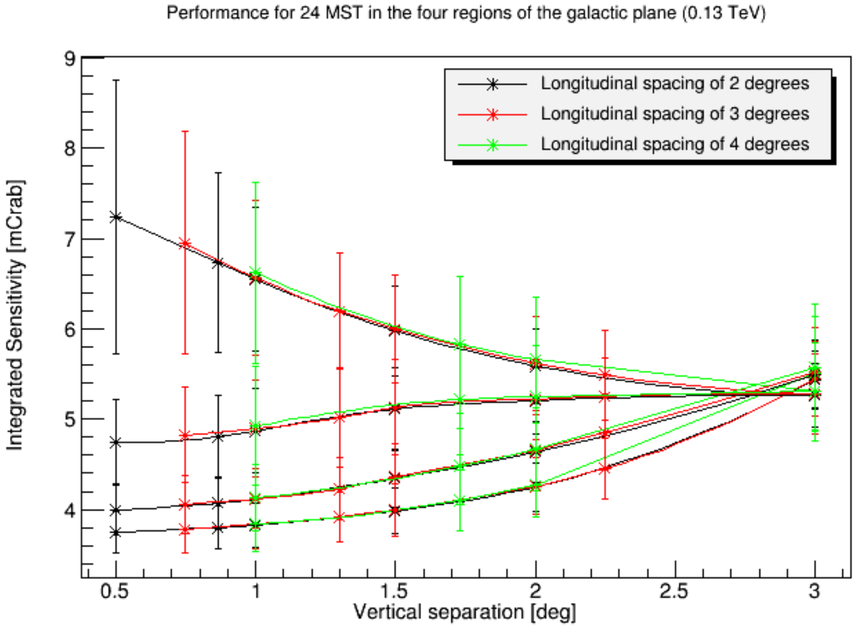

Figure 12: Mean integrated sensitivity of different regions for different longitudinal spacings (colors) and vertical separation (x-axis). The regions are, from top to bottom: region 4, region 3, region 2 and region 1.

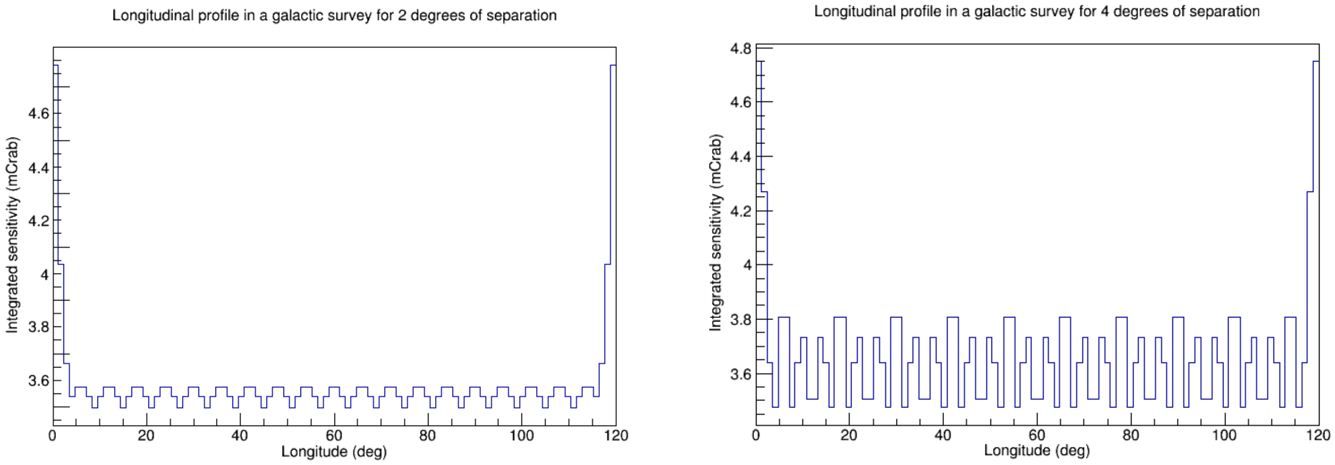

Figure 13: Left: Longitudinal profile in the center of the galactic plane for a linear spacing of 2 degrees. Right: Longitudinal profile in the center of the galactic plane for a linear spacing of 4 degrees. The mean sensitivity is practically the same, but the coverage of the 2 degree spacing is more homogeneous.

not have, generally, enough sensitivity to record events at such low energies. Two possible optical designs for the SST are being considered at the moment. One of them will possess a Davies-Cotton mirror composed of 18 hexagonal facets of about 4 meters of diameter, in contrast to the 12 meter diameter of the medium size telescope's mirror. A new dual-mirror telescope design (Schwarzschild-Couder design), which will reduce the dimensions, weigth and cost of the camera, is currently under study, and will result in an improvement in the angular resolution. An aproximate number of 24 Schwarzschild-Couder dual-mirror telescopes, together with 50-70 Davies-Cotton desgin telescopes

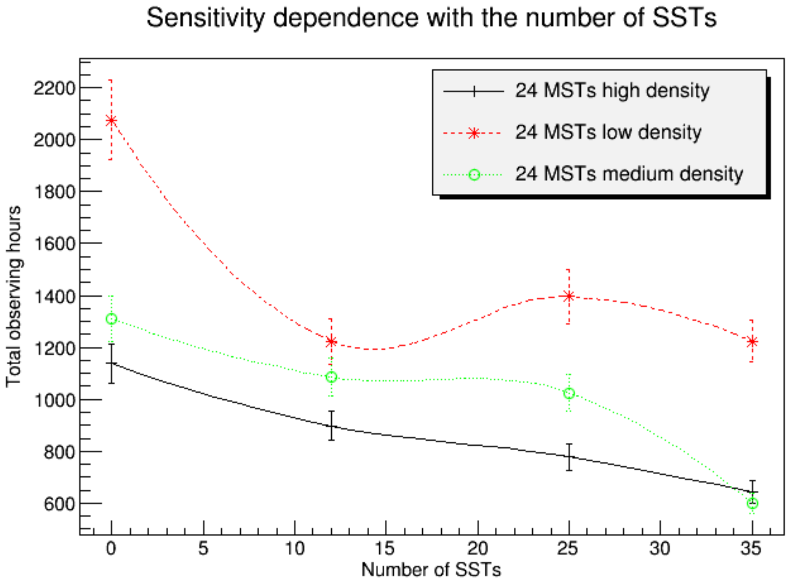

Figure 14: Effects on the total observing time of the 24 MST arrays with the inclusion of different numbers of SSTs. The arrangement of the additional telescopes is the same for the same MST arrays.

are expected to be installed in the southern site [8]. In the northern site, however, the installation of SSTs is still not guaranteed. For this study, only the influence of the Davies-Cotton SST has been evaluated.

Fig. 14 gathers the changes in total effective time with the addition of SSTs for the already studied arrays of 24 MSTs with different densities. The inclusion of small size telescopes has a relevant impact on the performance of every array. The array of higher density, which yielded the best mean sensitivity in extra- and galactic surveys, experiences an improvement of approximately 180 hours of observation. The array of medium density, which had a difference in observing time of around 50 hours with the high density array, improves by about 230 hours, reaching the same values of sensitivity that the higher density array with the same number of SSTs. Finally, the lower density array, whose separation between telescopes was not enough to detect many events suffers a gain of almost 300 hours of observation in some cases. The small wiggles in the data are not surprising given the large distances between telescopes and the low energy threshold. The distances are just too large for such a threshold and not enough events can be detected. With so little statistics, fluctuations in the simulations of low density arrays are not unexpected.

The effects on the performance of the arrays with the addition of the small size telescopes for the most important arrays considered before can be found in Fig. 15. Again, the repercusion of the "filling" of the blanks between MSTs is present in the array of 10 telescopes with low density. Adding 35 SSTs can decrease the total observing time by a huge factor. In other arrays, such as the 10 MSTs of high density or the 18 MSTs the difference is not so extreme. This can be easily understood again looking at the configuration of the arrays, found in Appendix B. In the 18 MST array, the telescope distances are comparable to the radius of the light pool of the Cherenkov photons and some of the SSTs were added between these telescopes. Relativistic muons generated in hadron showers also produce Cherenkov photons with a light pool of small radius. Having telescopes too close together can produce double triggers of muon showers, hence making harder the separation gamma/hadron showers. An increase of not distinguished background increases the minimum sensitivity achievable. Besides, the total area of the array did not increase significantly and the number of detectable showers did not grow. It is preferable, therefore, to have MSTs within a distance comparable to the radius of the light pool and no SSTs between them, in order to take advantage of a greater coverage.

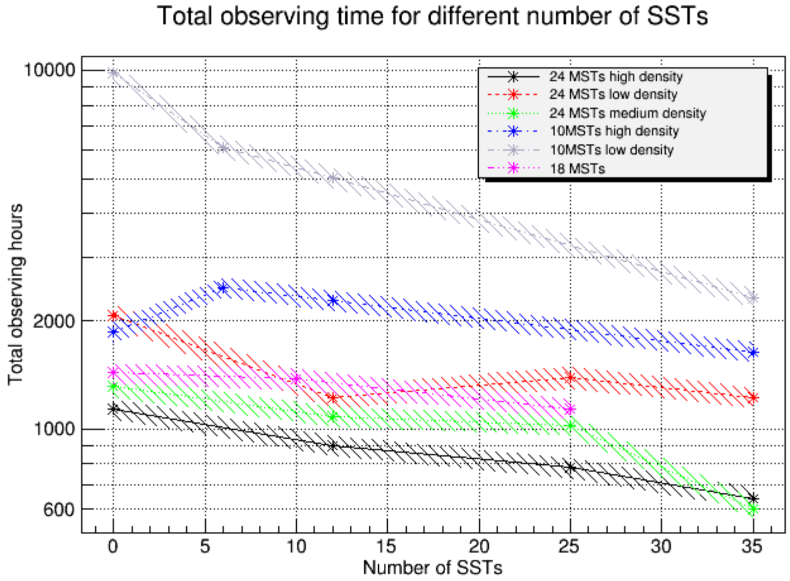

Figure 15: Effects on the total observing time of the most important MST arrays with the inclusion of different numbers of SSTs.

In galactic surveys, the addition of SSTs granted similar results. The arrays with the best perfomances were the arrays of 24 MSTs of high and medium density plus 35 SSTs around them. The performances in the four regions of the galactic plane followed the same trend, with a quite uniform coverage of the central plane and a very inhomogeneous one in the outer regions. The differences between tilings remained the same, with a similar tendency to suggest the linear pointing of 3.5 degrees as the best one for extragalactic surveys and a triangular pointing for galactic surveys.

6 Conclusions

The performed analysis of extra- and galactic surveys has demonstrated that CTA can actually achieve the goals that it was designed to. Even if only MSTs were established, the integrated sensitivity at medium-high energies (above 130 GeV) would be of some mCrab, overcoming by one order of magnitude the values of current IACT instruments. It has been shown how the separation between telescopes in the array is a crucial matter, as large distances can greatly deteriorate the performance of the whole array. An aboundant number of telescopes, can achieve sensitivities that would need about 4500 hours of observation with an array of 4 MSTs, similiar to the ones currently operational. An array of 16 MSTs, however, would need about 750 hours of observation to reach the same sensitivity that an array of 24 MSTs in 600 hours, saving 150 hours of observation that, taking into accout the average 1000 hours of yearly observation time, could translate into several days of work.

The choice of pointing does not seem to cause extremely crucial consequences. Nevertheless, for lower spacings between observations, a triangular tiling seems to reach smaller sensitivities, whereas for larger spacings the linear pointing yields better results. The standard deviation, an estimate of the sensitivity irregularities in the survey, increases for larger spacings, hence making preferable the choice of a smaller one. The best compromise seems to be a linear pointing of about 3.5 degrees of separation, since it has the lowest mean integrated sensitivity, and its standard deviation is acceptable compared to the rest of the pointings. For the array of 24 MSTs and high density, a linear pointing of 3.5 degrees achieves 3.5 mCrab of mean integrated sensitivity in an observation time of 600 hours, with a standard deviation of ±0.16 mCrab, approximately. Slight changes in the mean or standard deviation, alghouth not determining, might be expected due to computations errors related to the bining of the simulated sky. Moreover, uncertainties associated to the IRFs of previous simulations were not taken into account, and it could be useful to consider them in further studies.

In galactic surveys, the decision of a pointing is of higher importance. Due to the uniform coverage of the galactic plane with one row of linear or triangular observation points, the sensitivities achieved in the outer regions are greater and more inhomogeneous. If a good performance in those areas is desirable, a linear pointing is not recommendable. The sensitivity in the outer region shows a stronger dependence on the vertical separation of the observation points than the sensitivity in the central region, when using a triangular tiling. That is the reason why the best compromise could be found for a triangular pointing with vertical spacing of about 2 degrees of latitude, and a small longitudinal spacing of 2 degrees, also appropiate in order to achieve a more uniform coverage.

For both extra- and galactic surveys, an array with the highest number of medium size telescopes and telescope distances comparable to the light pool radius is preferable. The 24 MST array of high density (with an average separation of 140 m) can achieve, in a galactic survey, a mean integrated sensitivity in the central region of about 3.7 mCrab using a linear pointing, whereas in the borders the sensitivity would be of about 7.2 mCrab. With an equilateral triangular tiling of 4 degrees of spacing, the minimum integrated sensitivity attained are 4.1 mCrab and 5.8 mCrab in the central and outer regions, respectively. With the pointing described in last paragraph (in order to obtain the best mean performance in the whole area), the sensitivity in the central region reaches about 4.2 mCrab, meanwhile in the borders the value decreases down to approximately 5.6 mCrab.

Finally, the addition of small size telescopes can have significative consequences in some cases. Both 24 MST arrays of high and medium density considerably decreased their achievable mean sensitivity with the addition of 35 SSTs, saving between 500 and 700 hours of observation. All the other arrays of medium size telescopes also suffered an improvement. It was also proven how the configuration of the additional small size telescopes is important in order to take the best advantage of them, since adding telescopes between MSTs that already have a convenient separation does not really upgrade the perfomance by a great amount, and it can even worsen it in some cases.

Acknowledgements

First of all I would like to thank the DESY Summer Student Program organisers for giving me the opportunity to have a first contact with physics research, in special to Karl Jansen for his work and attention to us. This program would not have been the same without your organization and your activities. To my supervisors, Gernot and Lucie, I'm really grateful for your patience - I have truly learnt a lot. Thank both of you, and also Anna, Henrike and Maria for always trying to solve all my doubts, specially the first days when everything was so confusing, and for being so friendly and invite me to your group day out. Finally, a special thanks to the rest of the summies, for the great times and laughs - and the italian lessons. The seagulls are going to miss us.

A Study of galactic surveys at an energy threshold of 500 GeV

The best sensitivity of the MSTs is found at central energies, from several hundreds of GeV up to a few tens of TeV. Unfortunately, almost no high energetic gamma-rays can reach Earth from extralagalactic sources. The Extragalactic Background Light is a very important open question in cosmology. It is believed to have been produced by the very first stars in our Universe and they provide useful information about star and galaxy formation. However, they interact with the more energetic gamma-rays via eletron-positron pair production, difficulting their detection on Earth. Despite this setback, CTA will be an useful tool for the study of EBL, since it may help distinguish absorption of gamma-rays produced within the source and in the interestellar medium by EBL interaction.

However, in a galactic survey, the Electromagnetic Background Light plays no role and extremely high energetic sources are completely visible on Earth. That is the reason why the sensitivity of different arrays of CTA in galactic surveys was also analysed for a higher threshold energy, of 500 GeV, where one can take full advantage of the performances of MSTs and SSTs. It was found that every array, as expected, yielded a better sensitivity than for the 130 GeV case. With the best linear tiling and 250 hours of observation, fluxes of 2.7 mCrab in the central region could be detected with the 24 MST high density array, in contrast to the 3.7 mCrab flux at a lower energy. Using the same kind of linear tiling, the mean sensitivity in the borders is decreased from 7.2 mCrab at 130 GeV to 5 mCrab at 500 GeV. With an equilateral triangular pointing of 4 degrees of spacing, the sensitivity in the edges goes from 5.8 mCrab to 4.2 mCrab, and in the central region it runs from 4.1 mCrab to 2.9 mCrab. Fig. 16 and 17 show the dependence, which is basically the same as for the case of 130 GeV, but the sensitivities attained are lower.

The standard deviation, a measure of the inhomogeneity of the survey, also suffers an improvement. This is a cosequence of an enhancement of the off-axis performances of the arrays at higher energy threshold. This is obvious, since the telescopes used have a better performance at higher energies. Fig. 18 shows two longitudinal profiles in the center of the galactic plane for two different linear spacings at this threshold energy. For a spacing of 2 degrees the standard deviation is about the same, but for 4 degrees an improvement is visible, compared to Fig. 13. The transversal profile,

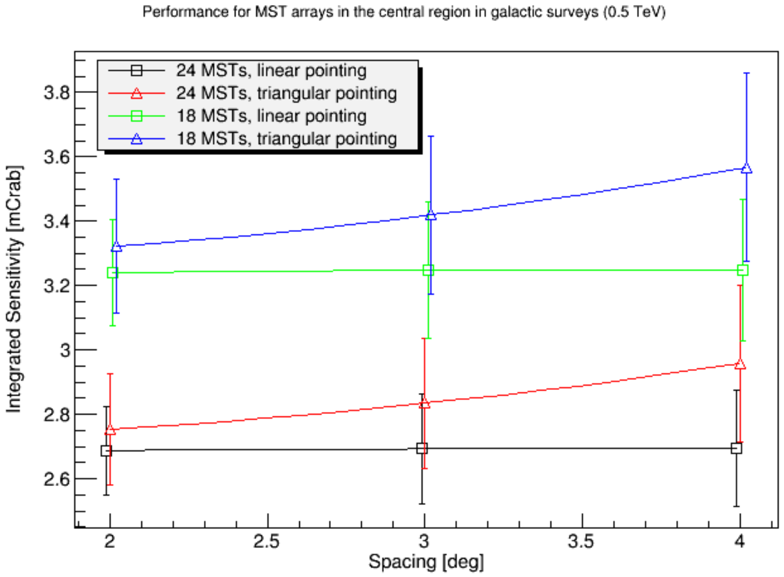

Figure 16: Mean integrated sensitivity for different arrays and different kinds of pointing in the first region of the galactic plane at 500 GeV. All the points are situated at 2, 3 and 4 degrees. The off-set of the points was added in order to distinguish different error bars.

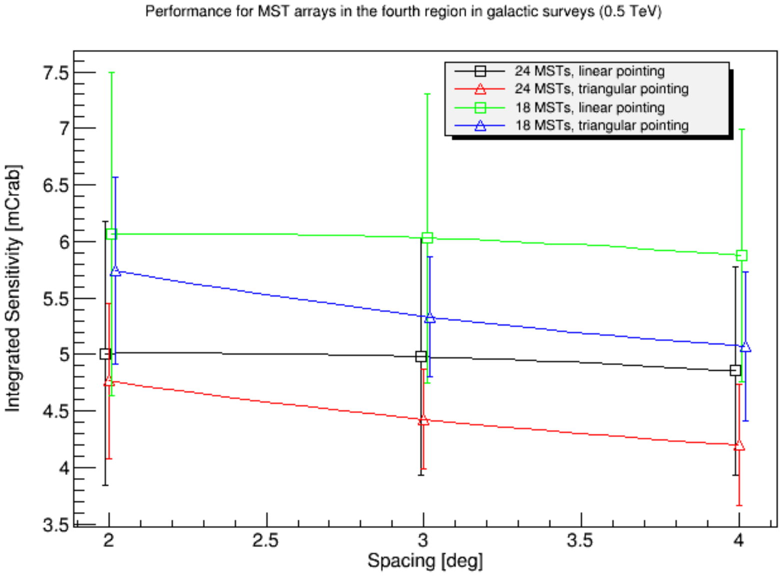

Figure 17: Mean integrated sensitivity for different arrays and different kinds of pointing in the fourth region of the galactic plane at 500 GeV. All the points are situated at 2, 3 and 4 degrees. The off-set of the points was added in order to distinguish different error bars.

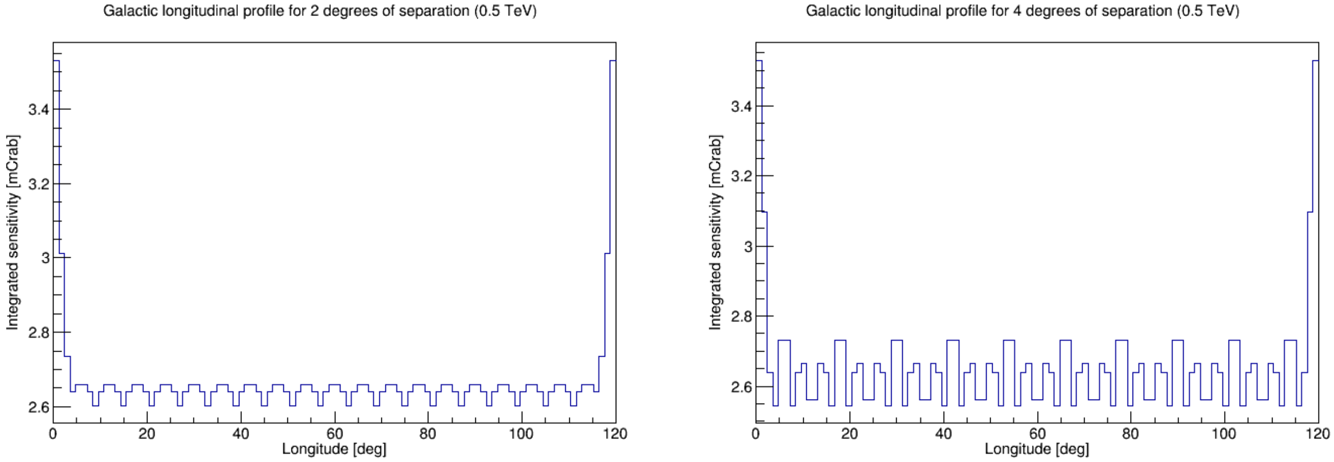

Figure 18: Left: Longitudinal profile in the center of the galactic plane for a linear spacing of 2 degrees. Right: Longitudinal profile in the center of the galactic plane for a linear spacing of 4 degrees. The mean sensitivity is practically the same, but the coverage of the 2 degree spacing is more homogeneous.

which shows the variation of the sensitivity with latitude, maintains the shape of Fig. 11, but shifted to lower sensitivities.

All the formerly analysed dependences remain unaltered for this new energy threshold. The pointing offering the best compromise between sensitivity in the galactic plane and at the edges is still a triangular tiling with 2 degrees of longitudinal spacing and 2 degrees of separation from the center. With this pointing, the sensitivities in the midpoint and the borders are 3 mCrab and 4 mCrab, respectively, which compared to the previous result of 4.2 mCrab and 5.6 mCrab at 130 GeV, turns out to be a prominent improvement.

B Array layouts

The following figures are the layouts of the arrays analysed in this report. Many of the phenomena mentioned beforehand can be easily understood by looking at the array configurations. Black circles represent MSTs, meanwhile green and blue dots are SSTs with a Davies-Cotton and Schwarzschild-Couder optical design, respectively. The numbers in red are just ID labels that are assigned to each telescope.

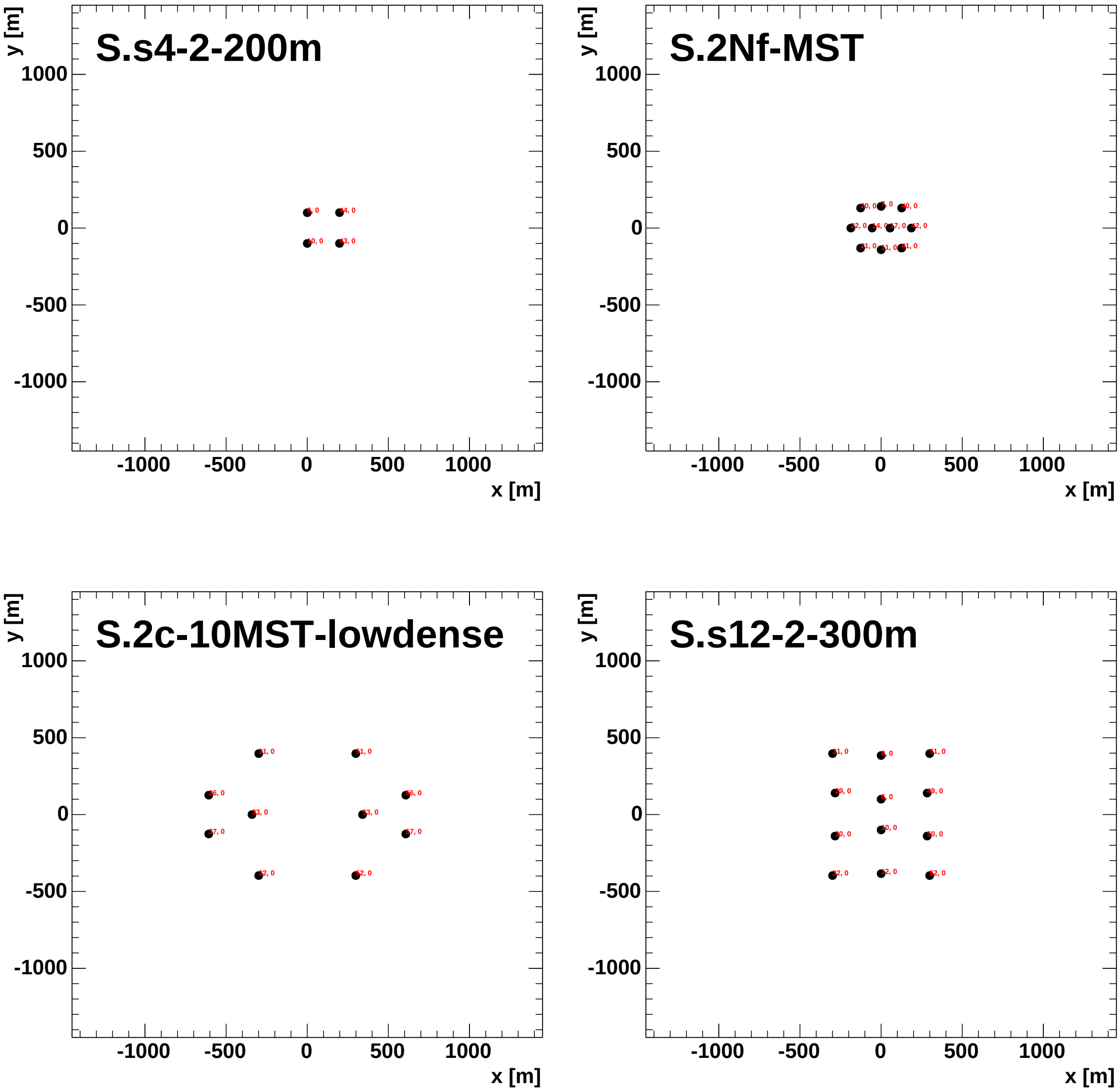

Figure 19: From left to right, top to bottom: a) 4 MSTs, b) 10 MSTs high density, c) 10 MSTs low density, and d) 12 MSTs.

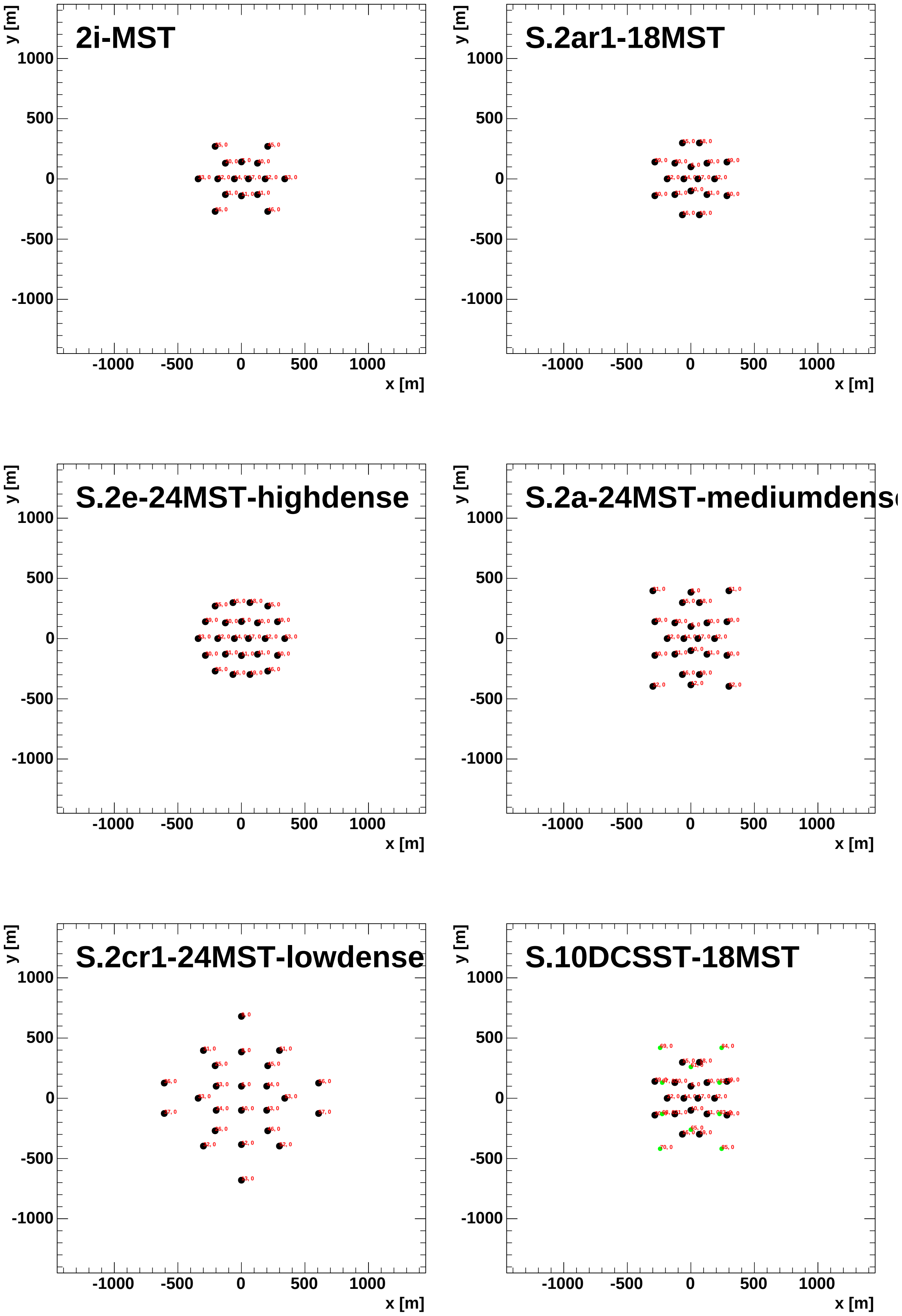

Figure 20: From left to right, top to bottom: a) 16 MSTs, b) 18 MSTs, c) 24 MSTs high density, d) 24 MSTs medium density, e) 24 MSTs low density, and f) 18 MSTs + 10 SSTs.

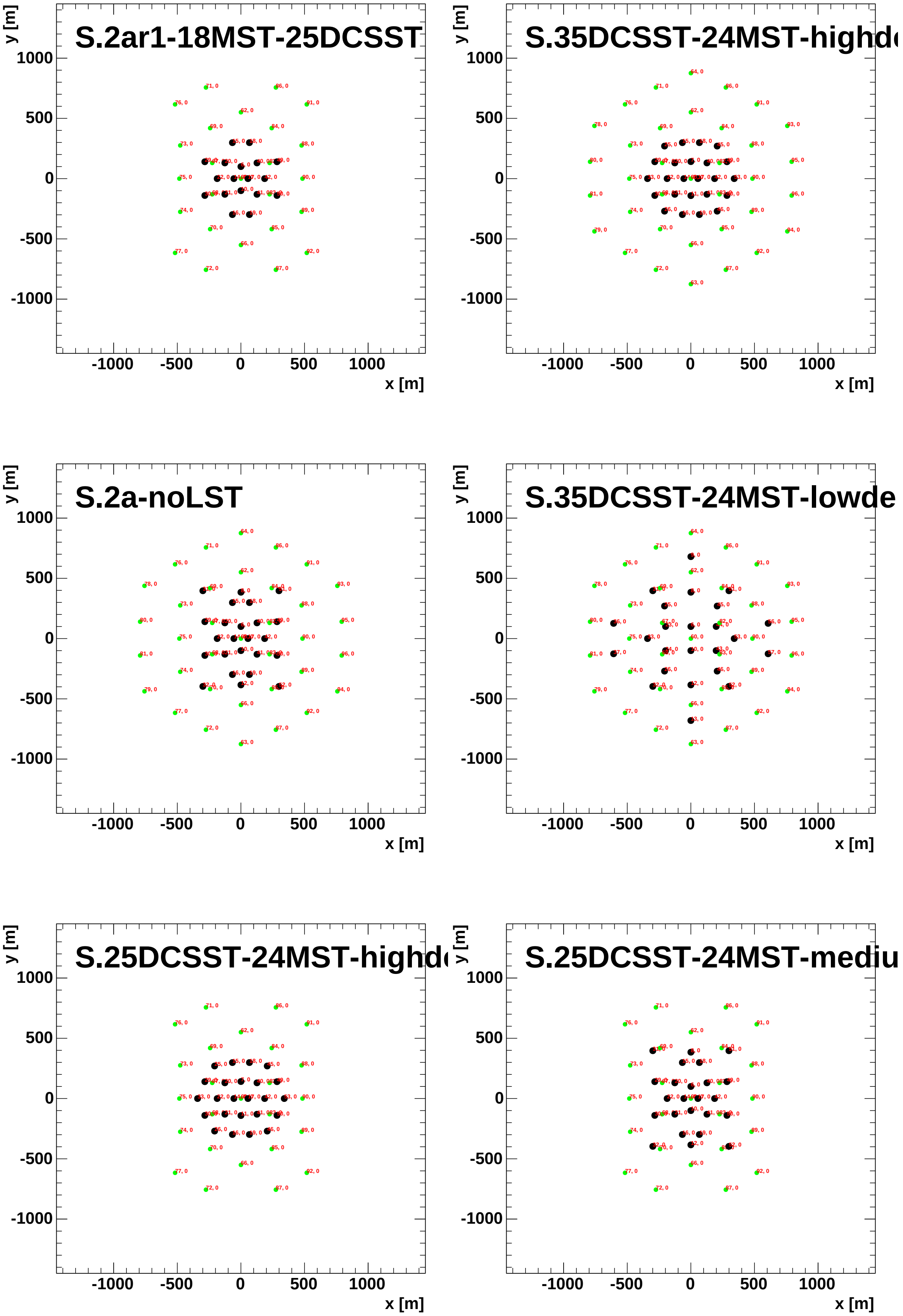

Figure 21: From left to right, top to bottom: a) 18 MSTs + 25 SSTs, b) 24 MSTs high density + 35 SSTs, c) 24 MSTs medium denstiy + 35 SSTs, d) 24 MSTs low density + 35 SSTs, e) 24 MSTs high density + 25 SSTs, and f) 24 MSTs medium density + 25 SSTs.

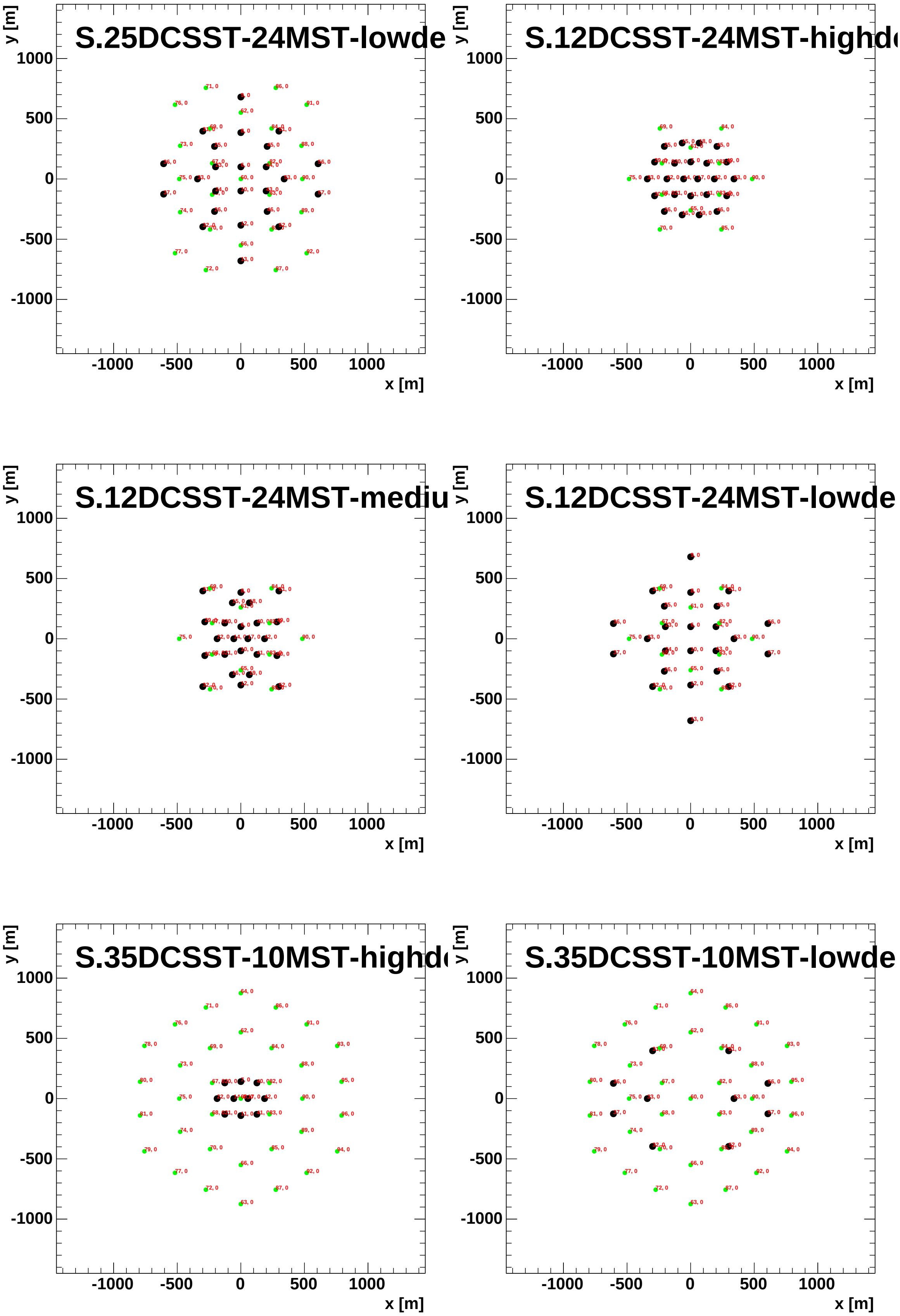

Figure 22: From left to right, top to bottom: a) 24 MSTs low density + 25 SSTs, b) 24 MSTs high density + 12 SSTs, c) 24 MSTs medium density + 12 SSTs, d) 24 MSTs low density + 12 SSTs, e) 10 MSTs high density + 35 SSTs, and f) 10 MSTs low density + 35 MSTs.

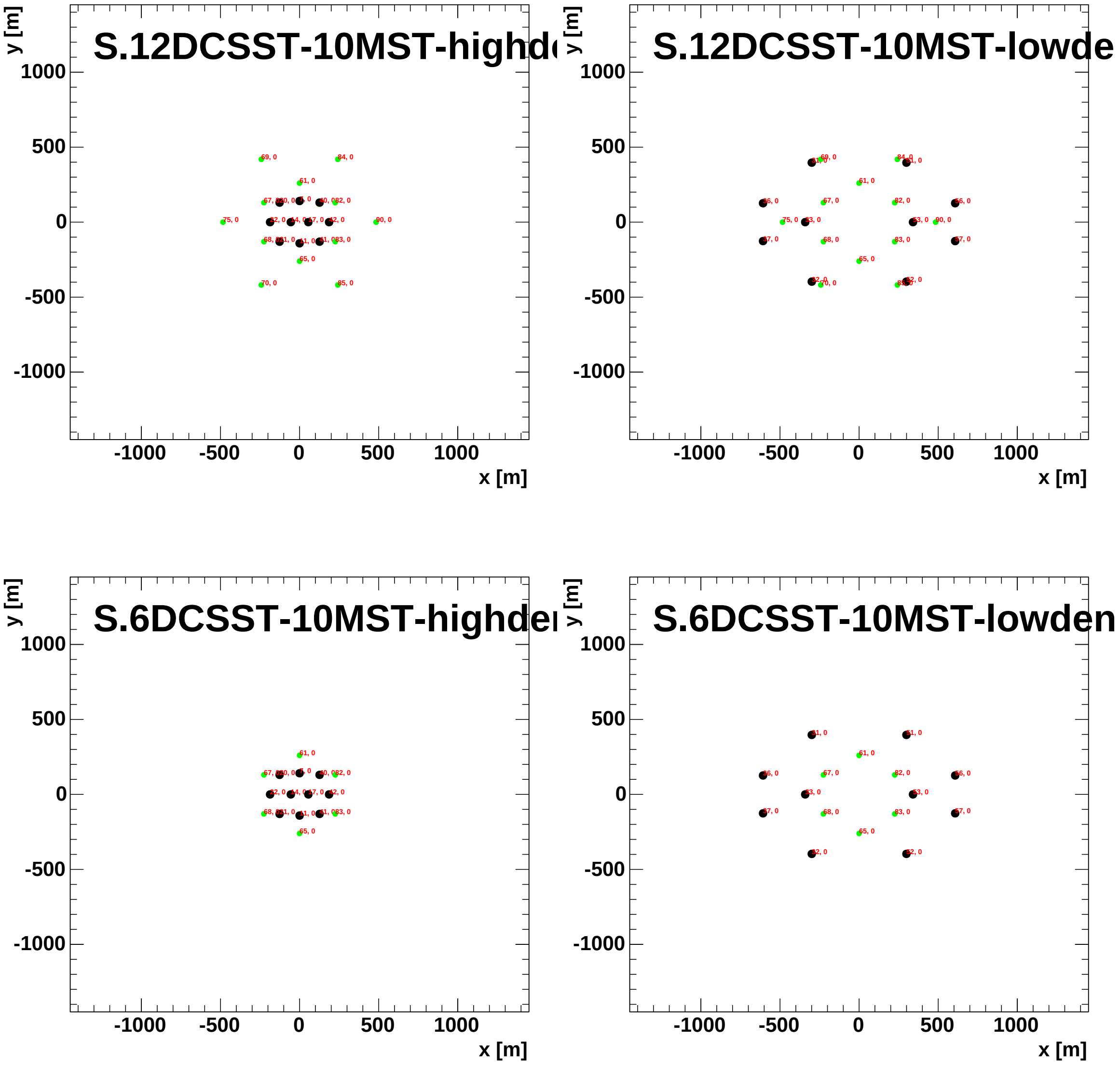

Figure 23: From left to right, top to bottom: a) 10 MSTs high density + 12 SSTs, b) 10 MSTs low density + 12 SSTs, c) 10 MSTs high density + 6 SSTs, and f) 10 MSTs low density + 6 SSTs.

References

[1] A.M., Hillas. *“Evolution of ground-based gamma-ray astronomy from the early days to the Cherenkov Telescope Arrays”*. Astroparticle Physics Journal, **42**, 19-43 (2013).

[2] Rieger, F., Oña-Wilhelmi, E., Aharonian, F. *“TeV Astronomy”*. Frontiers of Physics, **8**(6), 714-747 (2013).

[3] Acharya, B., Actis, M., Aghajani, T., *et al.* *“Introducing the CTA concept”‘*. Astroparticle Physics Journal, **43**, 3-18 (2013).

[4] Dubus, G., Contreras, J., Funk, S., *et al.* *“Surveys with the Cherenkov Telescope Array”*. Astroparticle Physics Journal, **43**, 317-330 (2013).

[5] K. Bernlöhr *et al.* *“Monte carlo design studies for the cherenkov telescope array.”* Astroparticle Physics, **43:171** (2013).

[6] HEGRA Collaboration. Aharonian *et al.* *“ The Crab Nebula and Pulsar between 500 GeV and 80 TeV: Observations with the HEGRA Stereoscopic Air Cerenkov Telescopes”*. **ApJ 614:897**, (2004).

[7] Baehr, J. *“Status of the CTA medium size telescope prototype”*. Instrumentation and Methods for Astrophysics. **arXiv:1212.3110 [astro-ph.IM]**.

[8] Vercellone, S. *“The next generation Cherenkov Telescope Array observatory: CTA”*. Nuclear instruments and Methods in Physics Research (2014).