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Different concepts of next generation IACT arrays

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Abstract. Having matured over a few decades, the IACT technique is now ready to widen its energy domain as well as to increase sensitivity in its core region (0.1–50 TeV) by as much as one order of magnitude as compared to existing facilities. This will allow to use γ astronomy to search for dark matter, probe intergalactic space and quantum gravity as well as to make efficient observations of extended sources.

The design of a new-generation IACT array is motivated by the key science questions to be addressed and constrained by the cost of the experiment. A number of performance characteristics impact the scientific capabilities, not just point-source sensitivity, but also field-of-view, angular resolution, energy threshold and others, and the optimization of the parameters at fixed cost defines the approach to simulation studies.

In this paper, I will highlight IACT array design studies carried through to optimize the array configuration, optical and mechanical designs as well as possible designs for telescope cameras.

1 Introduction

The idea of using the Earth's atmosphere as part of a γ-ray detector is the basis of the Atmospheric Cherenkov Technique. The Atmospheric Cherenkov Technique with an imaging focal plane detector brought the first solid detection of VHE γ-ray emission in 1989 (Weekes et al., 1989). With the addition of stereoscopic imaging (Daum et al., 1997), the Imaging Atmospheric Cherenkov Telescopes (IACT) have proved to be the experimental technique of choice to study sub-TeV and TeV γ-ray emission from galactic objects like pulsars, pulsar-wind nebulae, SNRs, binary systems and OB associations, as well as to study extragalactic objects like AGNs and starburst galaxies. The number of detected VHE γ-ray sources now numbers $\sim$100, with the source count roughly doubling in a time scales of $\simeq$3 years (Colin and LeBohec, 2009). Most importantly, many of these 100 sources have been studied in great detail with detailed imaging-spectrometry information or with light curves and energy spectra on minute time scales.

The sensitivity of current experiments like VERITAS, H.E.S.S. and MAGIC is $\sim$1% of the flux of the Crab Nebula, angular resolution for single γ-rays of $\sim 5'$ above 1 TeV, energy resolution of $\approx$15%, and the ability to locate sources with precision down to $10''$. In comparison to air-shower experiments like MILAGRO, the IACT technique offers a superior sensitivity, angular and energy resolution, but a limited field-of-view (FoV) ($\sim 5^\circ$) and a relatively poor duty cycle (with about 1000 hours of useful observations obtainable per year).

The collected experience from the current experiments guides us in the identification of common instrument parameters for the next-generation IACT array.

The following sections discuss the science drivers for the next-generation IACT instrument and their relations to the technical specifications of the telescopes including the telescope optical system, the focal plane instrumentation, and the array configuration, in particular, being studied for the CTA.[1]

2 Science drivers of the next generation IACT array

The design optimization of a telescope array depends on the astrophysical objects and the processes to be studied with the array. The problems that can be addressed with the next-generation IACT array can be organized by the energies of the detected gamma rays (Aharonian et al., 2008).

[1]Cherenkov Telescope Array, http://www.cta-observatory.org

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($E \lesssim 100$ GeV) At very low energies intrinsic fluctuations limit the technique. However this energy domain may provide the only means to study extragalactic sources (AGN, GRBs) at large cosmological distances ($z > 1$), or to detect the emission from the inner magnetosphere of pulsars. An array operating in this range has the potential of probing cosmic reionization models through gamma-ray absorption in high-z GRBs. To be able to reach such low energies, the telescopes should either form a very high density array or be equipped with large size reflectors (>20 m) perhaps located at high altitudes to further reduce threshold.

(100 GeV – 1 TeV) Above 100 GeV, angular and energy resolution should be good enough to move beyond the capabilities of Fermi, providing the most sensitive technique for searches for dark matter, galaxy clusters, pair halos, AGN and gamma ray bursts at intermediate redshifts and other sources.

($\sim$100 GeV) At this energies, the Cherenkov pulse width can be quite narrow ($\lesssim 3$ ns), and instruments with isochronous optics and fast electronics can reduce the telescope aperture required for achieving a certain energy threshold and can thus reduce the cost per telescope.

Looking for dark matter and pair halos requires a wider telescope FoV ($\gtrsim 8°$). The effect of e^{+-} pair formation in extragalactic magnetic fields along the path from distant AGNs to the Earth can be seen through energy-dependent time-delays of VHE flares. Temporal resolution down to sub-minute time scales is required to detect the effect. An improved temporal resolution would also help to test Lorentz invariance, as well as to detect variability of the brightest blazar flares on the time scales of a few seconds.

(>1 TeV) This is the energy range to study nearby galaxies, nearby AGN and their flaring states, IR absorption features in the energy spectra of galactic and extragalactic sources, the detailed morphology of extended galactic sources, galactic diffuse emission. The angular resolution of the instrument in this energy range is as important as is its sensitivity. A high-sensitivity, spatially resolved measurement of the gamma-ray emission of galactic sources would lead to the experimental determination of the local diffusion coefficient and/or of the local injection spectrum of cosmic rays. With an angular resolution of the order of $\leq 1'$ one could resolve the inner part of molecular clouds and measure the degree of penetration of cosmic rays. A next-generation IACT observatory should also be able to spatially resolve the outer and inner jet structures in radiogalaxies.

An array tuned to operate in this energy regime may potentially consist of telescopes with secondary optics equipped with fine pixelated cameras or/and have sub-arrays with smaller inter-telescope distances providing higher trigger multiplicities to provide higher angular resolutions.

(>30 TeV) An array providing larger detection areas, most likely consisting of small telescopes with a wider FoV, with separation $\gtrsim 200$ m (example configurations can be found in Plyasheshnikov et al., 2000; Rowell et al., 2008), would look for cosmic ray PeVatrons, the origin of galactic cosmic rays, and would explore the high-energy cut-offs of galactic accelerators. An array consisting of 50 $\sim$6 m diameter telescopes each, with a FoV of 8° could yield 100 TeV collection areas, exceeding those of VERITAS and HESS by a factor of $\sim$50 (Rowell et al., 2008). An array of telescopes with a conventional FoV ($\sim$5°) is considered in Colin and LeBohec (2009).

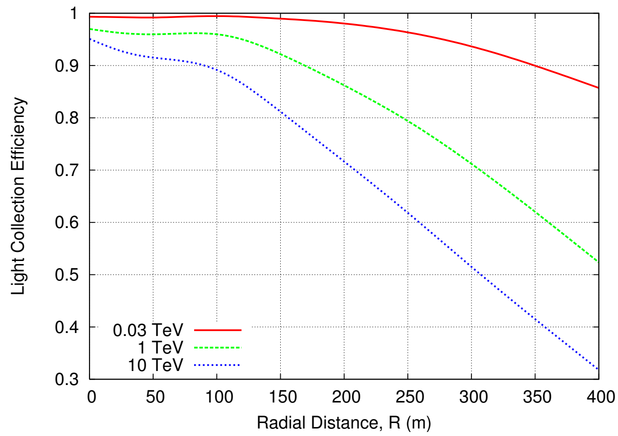

Fig. 1. Ratio of Cherenkov light detected with a telescope with a finite FoV (8° diameter) to that detected with a telescope with an infinite FoV plotted versus the distance of the telescope to the shower axis.

In this regime, air shower arrays like HAWC, Tibet or ARGO can also make important contributions given their very large FoVs and the long exposure times, surpassing the sensitivity of IACT arrays for VHE steady sources.

The main target specifications for Next Generation IACT Array can be summarized in the following list:

- High sensitivity, down to $\lesssim mCrab$. Simulations (for example, Bernlöhr (2008)) show the possibility to reach one order of magnitude better sensitivity than for existing IACT arrays with less than 100 telescopes.
- Broader spectral coverage (a few 10 GeV to above 100 TeV).
- Improved angular resolution down to $\lesssim$ arc-minutes.
- Temporal resolutions down to sub-minute time scales.
- Widened Field Of View (up to $(8-10)°$ diameters).

3 Design of a next generation telescope

3.1 Field of view

A next-generation IACT array will likely have a subarray consisting of telescopes with FoV$\geq 8°$. The motivations for increase of FoV fall into two categories.

The scientific motivation for a wide FoV is to provide a sensitive Galactic plane survey, a better background characterization for extended sources, and to provide a better match for prompt GRB positions and a higher probability for serendipitous discoveries. An 8° FoV would increase the exposure by a factor of $\sim$4 compared to HESS/VERITAS.

The technical motivation is to provide a better sensitivity and angular resolution. Figure 1 shows how a FoV$=$8° compares to a perfect instrument with a 2π steradian FoV. A large FoV improves the amount of information available for identifying the primary particle (γ-ray or cosmic ray) and also significantly improves the angular resolution by increasing the number of telescopes participating in the event reconstruction (see, for example, Maier, 2009). Furthermore, a large FoV results in more telescopes seeing showers with larger impact distance. As a consequence, the telescopes can be spaced further apart to achieve larger detection areas, and can obtain higher fractions of complete images, possibly leading to a better angular resolution. A larger telescope spacing itself may also result in an improved angular resolution due to a higher elongation of images. This effect is probably seen in Colin and LeBohec (2009). For 175 m spacing considered in the paper, an angular resolution better than 3′ is achieved for relatively large pixels (0.32°) for showers falling inside the array. At the same time, as it was pointed out, for example in Funk and Hinton (2008b), the angular resolution is deteriorating for very large distances ($\sim$500 m) between telescopes, so that the decision about the FoV should not be based on the targeted detection area alone.

The spectral reconstruction may also be improved for wider FoV due to the reduced fluctuations of the detected Cherenkov light intensity.

3.2 Pixel size

The size of focal plane pixels is tightly connected to the FoV and requires careful optimization. The benefit of small pixel sizes needs to be balanced against the growing number of pixels $\propto 1/PS^2$, where PS is the pixel size. Analysis techniques which extract the information contained in the narrow head of the image, as compared to its more diffuse tail, show that smaller pixel sizes lead to improved angular resolutions (see Fig. 2). In case of a classical second-moment analysis, the advantage of smaller pixels is more pronounced for telescopes with large ($>$ 20 m) reflectors, when one needs to resolve the structure of the compact images of low-energy events and to suppress the night sky background. Simulations carried through for CTA favour pixel sizes of 0.1° for the large telescopes, 0.18° for the medium size telescopes, and 0.25° for the pixels in wide-field telescopes in the halo of the array (CTA Consortium, 2010). The latter use the advantage of seeing extended images with large impact parameters. The CTA study based on standard analysis techniques finds no significant sensitivity improvements when using 0.07° pixels rather than 0.1° pixels (CTA Consortium, 2010). The sensitivity to point-like sources is not the only important characteristic, though. Improved angular resolution is one of the main science drivers for building a next-generation IACT array. It may happen that among two candidate array configurations with similar sensitivity curves, one of the configurations has a better potential to improve the angular resolution when using harder analysis cuts. For example, selecting only gamma rays with shower cores inside the footprint of an array would improve angular resolution, but would remove showers detected close to the "edges" of the array. Studies of infinite arrays showed some evidence for improved angular resolutions achieved with $<0.1°$ pixels even when standard analysis techniques were used (Bugaev, 2009). At the same time, Funk and Hinton (2008a) see only a slight improvement in the angular resolution for $PS < 0.1°$, even when using advanced image analysis techniques. The two results are not in contradiction since the approximation of an infinite array is equivalent to "hard" cut, described above, while Funk and Hinton (2008a) do not apply such a cut.

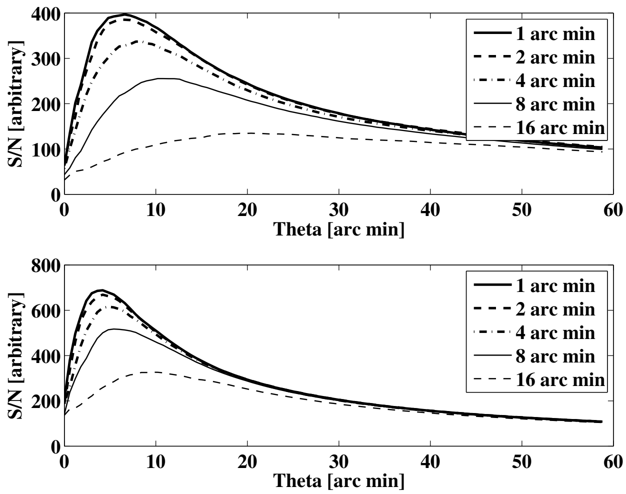

Fig. 2. A figure from Vassiliev et al. (2007). Ratio of the number of gamma ray events reconstructed within angular distance θ of the source to the square root of the number of isotropic background events in the same region. The two figures show the results of simulations for 40 and 100 GeV photons for an array of 75 m^2 telescopes with separation of 80 m. With 8 arc minute pixels, slightly smaller than those of current-generation instruments such as VERITAS (8.9′), the ratio reaches a maximum value which is $\sim$40% lower than the maximum for 1 arc minute pixels.

3.3 Optical system

Traditionally, the optical system (OS) of an ACT is either a Davies-Cotton (DC) mirror design or a paraboloid, approximated by spherical segments with varying radius of curvature adjusted in 2–3 steps, to provide a good approximation of the surface of a paraboloid.

The desire to increase the telescope FoV and to reduce the plate scale of the camera (hence, to dramatically decrease the camera cost) led to the search for new two-mirror OS designs. 2-mirror designs may be more economical than DC designs for small (<6 m) telescopes, which costs are dominated by their cameras.

3.3.1 Single mirror telescopes

In the past, the decision whether to use a DC design or a parabolic design was determined by tradeoffs in the collection area of the reflectors, FoV of a telescope and the time-resolution.

DC layouts with large f/D ($\gtrsim$1.4) provide good imaging over wide FoVs with a nearly circular point spread function (PSF), but introduce time dispersion (Mirzoyan et al., 1996). Tessellated designs with elliptic envelop shapes can yield even wider FoVs but at the expense of the timing accuracy. The distribution of photon arrival times for a DC telescope is flat, with an RMS spread proportional to the diameter of the reflector. The yardstick for the timing requirement is the intrinsic width of the Cherenkov pulse from a gamma-ray shower (a few nanoseconds for <100 GeV events). As a rule of thumb, the time dispersion introduced by a mirror should not exceed this value. For larger DC dishes the light pulse broadens. At the same time, the width of the time distribution of a parabolic dish (even with spherical mirror tiles) is negligible. Therefore, a parabolic shape may be preferred for very large telescopes to reduce trigger threshold, although this design suffers from large off-axis distortions (dominated by coma), not only degrading angular resolution but stretching the PSF by a factor of $\sim$1.7 along the radial direction in the FoV (CTA Consortium, 2010).

For small size telescopes (SST) and mid-size telescopes (MST), large f/D designs provide the best imaging over a large FoV. The showers with higher energies detected by a SST, are seen from well outside the Cherenkov light pool and there is a strong time gradient along the image major axis, so the time spread resulting from the dish shape is of lower relevance. In fact, longer electronic integration widths are necessary to record such large impact parameter images, given the substantial time gradient along the image.

Other alternative dish shapes face the same general trade-off between time dispersion and imaging quality (Schliesser and Mirzoyan, 2005).

3.3.2 Optical systems with more than one optical element

The desire to significantly improve the angular resolution, simultaneously increase the FoV, and reduce the focal plane scale of the telescopes (for compatibility with highly integrated, multi-pixel photon detectors) (see Fig. 3), motivates research of designs for optical systems of IACTs having more than one optical element.

With the two-mirror system, both spherical aberrations and coma can be corrected (Schwarzschild theorem). In optical telescope applications the secondary mirror is configured to magnify the image and increase the optical system focal length. In contrast, in ACTs it is desirable to use a demagnifying secondary mirror to decrease focal length, thus reducing the size of the telescope camera. Schwarzschild-Couder (SC) is such an isochronous optical system, free from spherical and coma aberrations . An analytic solution for both aspheric mirrors exists for all arbitrary two-mirror systems and was described in Lynden-Bell (2002). A SC telescope with primary and secondary mirrors separated by 3/2 of the OS focal length and with the distance between the secondary and the focal plane equal to 1/3 of the OS focal length, provides an excellent PSF and an almost constant effective light collecting area. At a field angle of 4°, the PSF $=\max\{\sigma_x,\sigma_y\}$ of such system is smaller than 2 arcmin. Even for a Davies-Cotton telescope with f/D=1.5, the PSF is $\simeq$4.5 arcmin. With a 9.6 m diameter primary mirror, such a system would provide $\simeq$50 m^2 of light collection area. One of the major disadvantages of two-mirror designs is that non-spherical mirrors are needed which are more difficult to fabricate. The tolerances on the relative alignment of optical elements are also rather tight. The systems for mirror alignment control may significantly contribute to the telescope costs.

While one-mirror and two-mirror mirror designs are considered as competing alternatives, a concept of the Schmidt telescope may also find its application in IACTs. With the Schmidt telescope design, it is possible to widen the FoV up to 15° by placing a thin Fresnel corrector element in front of a mirror composed of small (<60 cm) spherical segments (Mirzoyan and Andersen, 2009). The tolerance for the alignment of the element is not strict. For a 7 m telescope, the diameter of the camera would be less than 1.5 m, the resolution is $1'$ anywhere in the 15° FoV, and the isochronous distortions are smaller than 0.03 ns.

3.4 Focal plane instrumentation

Along with an improved optical performance of 2-mirror systems come lower wavefront distortions with a nearly isochronous time response to Cherenkov pulses. Most importantly, such systems provide small focal lengths dramatically reducing the plate scale of the camera. New designs of IACT cameras may also lead to an improvement in sensitivity, angular resolution and energy range of the detected gamma-rays. A compact design based on multipixel sensors might also improve the maintainability of telescopes improving the prospects for operating a large array of telescopes. Improvement in the sensitivity will partially come from the improvement in the collection efficiency of the Cherenkov photons and the efficiency of its conversion to photoelectrons in the photon sensors. Widening the energy range requires cameras with a larger dynamic range. But the camera dynamic range is not determined by the effective number of bits in the analogue-to-digital converters, but also by the dynamic range of the sensors, the pixel size, the telescope spacing, the sampling rate and other factors. Sensors should be able to detect single photons, and provide a dynamic range up to $\gtrsim$1000 photo electrons, with linearity deviations below a few percent. The signal distortion and power consumption, as well as the costs of the experiment, can be minimized by using highly integrated Application Specific Integrated Circuits (ASICs) in the front-end electronics.

Despite being based on vacuum-tube technology, photomultipliers (PMT) are still the most commonly used photon sensors for IACTs. VERITAS, H.E.S.S. and MAGIC currently use PMTs with peak quantum efficiencies of $\sim$25% and are unsurpassed as low-noise, high-speed single-photon counting detectors. The baseline for a new generation Cherenkov array is to use PMTs with enhanced quantum efficiency, resulting in 50% higher photon detection efficiency.

Currently favored pixel sizes for single-mirror OS for CTA are 0.1°, 0.18° and 0.25° for LST, MST and SST, correspondingly. These sizes roughly correspond to the same 1.5″ diameter. The active area of the sensors, however, can be reduced by a factor of up to $\sim 3-4$ by using light-collecting Winston cones. In a sense, two-mirror optics designs take the place of light cones reducing the pixel size down to 6 mm both for SST and MST. Unlike lightcones, however, the overall plate scale is reduced by a similar factor $\sim$3 allowing the use of multipixel devices (e.g. Multi-Anode PMTs (MAPMTs)) with a substantial reduction of per-pixel costs. MAPMTs provide multiple pixels in a compact package, with properties similar to monolithic PMTs. Their small individual pixels ($\sim$6 mm) are suitable for secondary-optics schemes. A camera design considered for two-mirror telescopes of CTA is shown in Fig. 3. Dead spaces between MAPMTs result in some gaps in the images - a half-pixel gap for every 8 pixels for the MAPMTs of the Hamamatsu H8500 series.

An alternative to MAPMTs in case of two-mirror telescope designs are Silicon Photomultipliers (SiPMs). These devices use a silicon chip containing up to thousands microcells coupled to a common signal output terminal. Each micro-cell is operated in Geiger mode. Photons can trigger a cell, while leaving the surrounding cells ready to collect other photons. The dynamic range for photon-counting is determined by the density of microcells. However, with increasing density comes reduced photon detection efficiency. There is the promise that silicon photosensors could provide higher photon detection efficiencies than the latest PMTs at lower cost and without the requirement for high voltage supplies. However, current devices peak at $\sim$30% PDE, lack the required UV-blue sensitivity of PMTs. These devices also require cooling to reduce the dark count to a manageable level, suffer from optical cross-talk and are not as well matched to the Cherenkov light spectrum as PMTs. Cross-talk may also be an issue for Silicon Photomultipliers or Multi-Anode Photomultipliers.

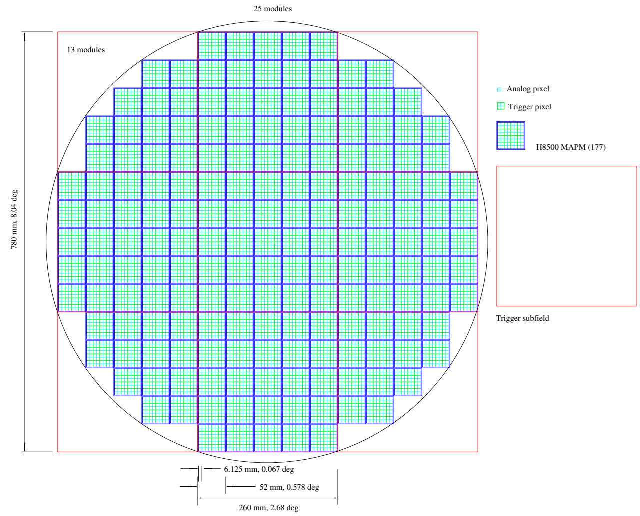

Fig. 3. A modular camera using MAPMTs. The camera is made of 177 MAPMTs with 64 pixels each. Some characteristic dimensions are given in mm, and in degree - assuming an effective focal length of $f = 5.5$ m

Two techniques for signal recording and processing are currently in use in existing IACT arrays and can be implemented in next-generation telescopes: Flash Analogue-to-Digital Converters (FADCs) digitize the photon-sensor signals at rates up to a few GSample/s. Waveform digitizers like FADCs allow implementation of sophisticated Cherenkov image analysis techniques using timing information to reject hadronic background and increase signal-to-noise ratio (Daniel et al., 2007). The large memory depth of FADC electronics allows time for sophisticated trigger logic without introducing dead time, and continuous instantaneous digitization could even provide a fast, all-digital trigger when combined with modern Field Programmable Gate Arrays (FPGAs). Development of low-power, low-cost FADCs could keep them a more viable option to implement in future telescopes. Modest-speed (250 MSample/s) FADCs being developed for the FlashCam concept for CTA are still in contention as a cost-effective alternative to other readout electronics (CTA Consortium, 2010).

3.4.1 Conventional gated QADCs.

To minimize per-channel cost and power, a number of groups are developing multichannel ASICs that make use of switched capacitor arrays for analogue memory. These offer high sampling rates and good dynamic range, but with slower digital conversion that only occurs after trigger. Current devices have limited memory depth, but recent developments may provide sufficient depth, double-buffering and fast readout that will allow effectively deadtime-free operation.

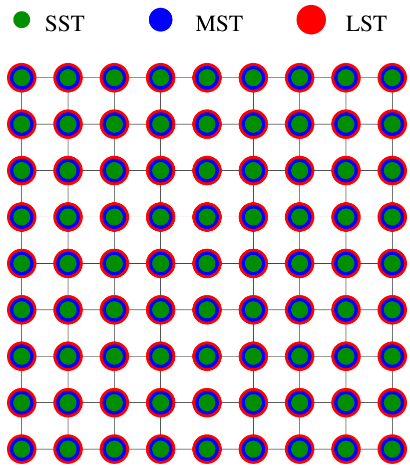

Fig. 4. A telescope layout for generic MC simulations

4 Telescope array configuration

Given the wide energy range of operation of the next-generation IACT observatories, the idea of a hybrid array consisting of telescopes with different reflector sizes and camera characteristics seems to be a natural idea. Ideally, optimization of a telescope array consisting of a few types of telescopes would start from detailed simulations of a generic array like the one in Fig. 4. Each node of a grid with a small spacing would contain every type of candidate telescopes in a future array. Later, candidate array configurations would be tested one by one by switching off all but one telescope in any given node. Practically, the described scheme requires immense computing power and data storage and hence is not practical. It is more practical to test a number of judiciously chosen candidate configurations which account for the limitations imposed by the geometry of the layout, for the properties of Cherenkov showers and for properties of homogeneous arrays derived from detailed MC simulations. A sub-array of some telescope type in a candidate configuration may be extracted from the array. In this case, general considerations about homogeneous arrays can be used to arrange telescopes of that type. For example, the study of Colin and LeBohec (2009) considers the trade-offs between having many middle-size telescopes versus a few large-size telescopes. Using Cherenkov light density profiles, and assuming that telescopes can be triggered only by showers with cores within the radius $D_{\max}$, it was concluded that the targeted energy threshold required impact parameters smaller than $D_{\max}\simeq 150$ m. The requirement of a three-fold telescope multiplicity leads to the conclusion that a hexagonal grid with inter-telescope distance $\Delta T\simeq 175$ m minimizes the cost per unit detection area. In the case of a two-telescope multiplicity, the optimal design is square grid with $\Delta T\simeq 200$ m. It is interesting that an array targeted at lower energies ($E\lesssim 100$ GeV) can be an exception from the above prescriptions. In this case, an increased reflector area makes it possible to detect light beyond the Cherenkov pool and to reduce the costs per detection area.

5 Summary

A next-generation IACT array operating over the energy range from a few ten GeVs to a few hundreds of TeV has the potential to improve on the sensitivity of the current IACT arrays by one order of magnitude while achieving an energy resolution of $\sim$1 arcmin at a few TeV. While there is a variety of ways to approach the target specifications, designs are converging towards using a hybrid array with different telescope sizes ranging from $\sim$5 m to $\sim$25 m and with variable telescope spacings, pixel sizes, and FoVs for each type of telescopes. The actual values for the spacings, the FoVs and the pixel sizes are subject to an optimization procedure for a given total cost of the experiment. A successful optimization should include a balanced combination of conventional proven technologies and new technologies.

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