PROCEEDINGS OF SCIENCE

MACHETE: A transit Imaging Atmospheric Cherenkov Telescope to survey half of the Very High Energy γ-ray sky

Juan Cortina*, **Rubén López-Coto, Abelardo Moralejo**
Institut de Fisica d'Altes Energies, Cerdanyola del Valles, E-08193, Spain
E-mail: cortina@ifae.es

Current Cherenkov Telescopes for VHE gamma ray astrophysics are pointing instruments with a field of view up to a few tens of sq.deg. We propose to build an array of two non-steerable telescopes with a FOV of 5×60 sq.deg. oriented along the meridian. Roughly half of the sky drifts through this FOV in a year. We have performed a MC simulation to estimate the performance of this instrument, which we dub MACHETE. The sensitivity that MACHETE would achieve after 5 years of operation for every source in this half of the sky is comparable to the sensitivity that a current IACT achieves for a specific source after a 50 h devoted observation. The analysis energy threshold would be 150 GeV and the angular resolution 0.1 deg. For astronomical objects that transit over MACHETE for a specific night, it would achieve an integral sensitivity of 11% of crab in a night. This makes MACHETE a powerful tool to trigger observations of variable sources at VHE or any other wavelengths.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

*Speaker.

PoS(ICRC2015)936

Very High Energy γ-rays are detected using space-based or ground-based detectors. From space *Fermi*-LAT is performing the deepest survey to date of the γ-ray sky from 20 MeV up to energies in excess of 100 GeV, although with limited sensitivity above 10 GeV due to its relatively small collection area (0.8 m^2).

From the ground IACTs, such as the MAGIC, H.E.S.S. or VERITAS arrays, detect γ-rays with energies above 50 GeV and have collection areas of more than 10^5 m^2. They are pointing instruments with a Field of View (FOV) on the order of tens of sq deg. The 12 m diameter Medium-Sized Telescopes in the Cherenkov Telescope Array (CTA), currently under design, have a FOV of around 60 sq deg.

On the other hand air-shower instruments such as Milagro, Tibet and HAWC detect γ-rays at higher energies, have a comparable collection area of $\sim$80000 m^2, but with a much larger FOV of $\sim$5000 sq deg and high duty cycle. They are non-tracking instruments. Unfortunately they are not as efficient as IACTs in eliminating the cosmic ray background, so they suffer from a lower sensitivity and they have poorer angular or spectral resolutions.

We propose to build an array of two non-steerable IACTs with a wide FOV of 300 sq deg. We call this array Meridian Atmospheric CHErenkov TElescope (MACHETE). The reader may find a detailed description of the instrument, its performance and its physics goals in [1]. Here we focus mainly in the optics, review the performance that is estimated using a full Montecarlo simulation and go through some of its possible applications.

1. A wide FOV IACT array

A Schmidt telescope is a well-known solution to achieve a large FOV with a small focal ratio. The optical components are an easy-to-manufacture spherical primary mirror, and an aspherical correcting lens, known as a Schmidt corrector plate, located at the center of curvature of the primary mirror. The corrector plate reduces optical aberrations and at the same time acts as a "stop" which defines the aperture of the telescope.

Our concept is inspired by a Schmidt telescope, but we have aimed at simplifying it so that it is easy and cheap to implement:

- Like in the original Schmidt telescope, the shape of the primary mirror is spherical. The nominal focal length is half of the radius of curvature.
- Also like a Schmidt telescope, the shape of the focal plane is spherical and concentric with the mirror.
- An IACT is not as stringent as an optical telescope in terms of mirror Point Spread Function (PSF). A PSF on the order of 0.05° is good enough. We shall remove the corrector plate and achieve an acceptable PSF by increasing the focal ratio.
- However if we eliminate the corrector plate we are not only worsening the optical performance of the instrument, but also eliminating the stop. We must find an alternative way to limit the aperture. Compared to optical telescopes IACTs are in fact peculiar because each pixel is typically implemented as a light concentrator followed by the actual photodetector.

In a natural way light concentrators can be used to define the section of the mirror which is viewed by each pixel and effectively the aperture.

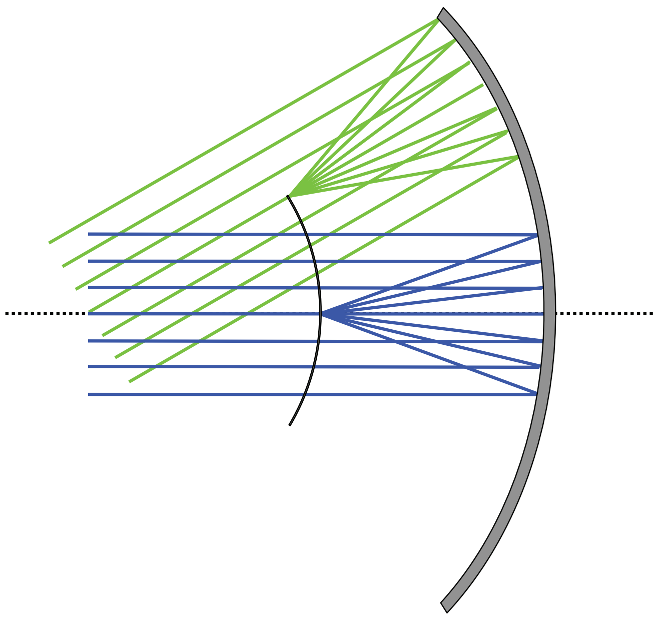

Figure 1: Layout of the optical elements of MACHETE. The dotted line represents the optical axis. Both mirror (outer grey arc) and focal plane (inner black arc) are concentric. Rays coming parallel to the optical axis and 30° off-axis are represented with correspondingly blue and green lines. Fig. from [1].

Fig. 1 illustrates the concept. We have drawn the optical path of a fan of rays coming parallel to the optical axis and of a fan of rays with a large 30° off-axis angle. The central ray of each of the fans goes through the center of curvature of the mirror and focal plane. As such it arrives perpendicular to both surfaces. The light concentrators limit the extension of the ray fans in Fig. 1 and the effective diameter of the mirror that collects light for every point in the camera.

For MACHETE we adopt the following optical parameters. The radius of curvature of the mirror is 34 m. We choose an acceptance angle of 20° in the light concentrators. The light concentrators at the camera front follow the curvature of the focal plane. The focal plane is at roughly half of the radius of curvature (17 m), so each point of the camera views a section of the mirror that is circular and has a diameter D=12 m.

We have used Zemax (OpticStudio 14.2) to optimize the optical layout of the design. We set the radius of curvature of the mirror to 34 m. We have not simulated the light concentrators. Instead we have defined a 12 m diameter circular stop perpendicular to the incident ray fan and centered at the center of the curvature of both mirror and focal plane. Both scenarios are optically interchangeable if the light concentrators have a ideally sharp cutoff. The distance from the mirror to the camera front has been optimized to obtain the smallest possible spot size. More specifically

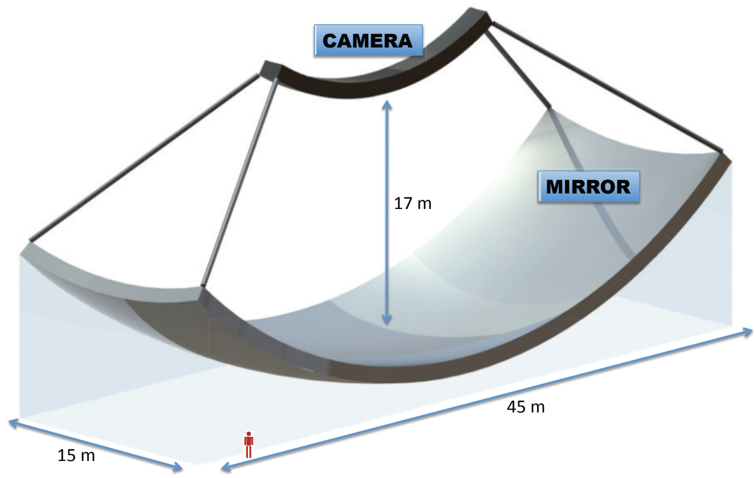

Figure 2: Conceptual design of one of the two telescopes. The mirror is a rectangular section of a spherical mirror, is fixed to the ground and its long axis is oriented north to south. The camera has a spherical curvature, is concentric with the mirror and has about half of its radius of curvature. Its FOV is a rectangle of $5^\circ \times 60^\circ$. A human figure has been added as a size reference. Taken from [1].

we have defined r_{80} as the radius around the centroid of the light spot that encloses 80% of the light and we have minimized r_{80} on-axis. The resulting distance from mirror to camera front is 16.84 m and the radius of curvature of the camera is correspondingly 17.16 m. The resulting r_{80} is 17.5 mm

With a camera as large as in Fig. 1 all rays coming parallel to the optical axis are blocked if we assume that the system is symmetric. The rest of the FOV would also suffer from significant shadowing. We can however restrict our FOV to a strip of $5^\circ \times 60^\circ$. Assuming that the camera is flat enough and ignoring the focal plane support structure, the shadowing is 16% for most of the FOV and only significantly smaller at the edges of the long arc (at the very edge it is about 8%). In this way we can still achieve a large FOV of 300 sq deg with a very simple optical design.

IACTs are usually steerable. This allows to observe a source for many hours in a night and up to hundreds of hours in a year. Since our aim is to survey a significant fraction of the sky, there is no need to track sources. We can point the telescope to an arbitrary direction and wait for sources to drift through the FOV.

We propose to place our optical axis vertical and align the FOV with the meridian. In this way the telescope will only have access to astronomical objects in the declination range of $\pm 30^\circ$ around the geographical latitude where it is located and only for about 20 minutes every night as they culminate for that specific geographical longitude.

We will extend the mirror so that all points in the FOV view a circular fraction of the total reflector with a diameter of 12 m. For the above-mentioned focal length, this corresponds to a total reflective surface of 620 m^2. From north to south the reflector has a length of about 45 m, from east to west it has a width of about 14 m. The physical size of the focal plane is about 27 m^2. It has a width of 1.5 m and a length (along the arc) of 18 m. Figure 2 is a conceptual view of such an IACT.

In order to benefit from stereoscopic reconstruction of atmospheric showers we need to work with at least two telescopes. We propose to build two identical telescopes with the above-described optical design and orientation at a distance of ∼100 m in the east-west direction.

We have not designed the focal plane instrumentation and readout system of MACHETE. We assume that the performance of these hardware components is similar to those in the MAGIC array[2]. Progress in photodetectors has been significant during the last years, especially in the case of SiPM. We will assume that the photodetectors of MACHETE have a PDE 1.5 times larger than the PMTs in operation in MAGIC but the same performance in terms of noise, spectral dependence of QE and time response.

2. Expected γ-ray detection performance

We have performed a Monte Carlo simulation of the MACHETE system to evaluate its performance. Here we will only describe its results. We refer the reader to [1] for details of the simulation setup.

After analysis cuts the energy distribution of the simulated gamma rays peaks around 150 GeV for a simulated power-law with photon index Γ=2.6.

The energy resolution is defined as the σ of the gaussian fitted around the peak of the $(E_{estimated} - E_{true})/E_{true}$ distribution. The energy resolution is similar for MAGIC and MACHETE, generally better than 20%, and reaching 15% above 1 TeV.

Let us consider the 2-dimensional distribution of reconstructed arrival directions. We define the angular resolution as the angle that encloses 68% of the events. The angular resolution is similar to that of MAGIC as well.

The sensitivity has been calculated using formula 17 of Li and Ma, which is the standard method in VHE γ-ray astronomy for the calculation of the significance, for 5σ in 50 h of effective observation time.

However, the operation of MACHETE would be different to that of existing IACTs. Similar to Milagro or HAWC, MACHETE is not a pointing instrument; sources in the accessible range of declinations simply transit through the MACHETE FOV every day. If MACHETE were located at the equator it could observe sources in the declination range from -30° to +30°. This corresponds to 50% of the sky. We will assume however that MACHETE is located at a geographical latitude of 30°, similar to the absolute latitude of all the existing IACTs.

The annual effective observation time of an IACT system like MAGIC during moonless nights is of around 1000 hours (after technical and bad weather losses). The total transit time of a source is 14 hours at 0° declination, 16 hours at 30° declination and 28 hours at 60° declination per year.

We have taken into account the change of acceptance as a function of position of the source in the FOV. For this goal we have considered only the time a given source actually spends within the *optical* FOV of MACHETE. Fig. 3 shows the MACHETE sensitivity calculated in this way for a source at an intermediate declination of 30° after 1 and 5 years of operation. It is compared to that of HAWC[3] and that of MAGIC for a dedicated 50 h observation. The same definition of

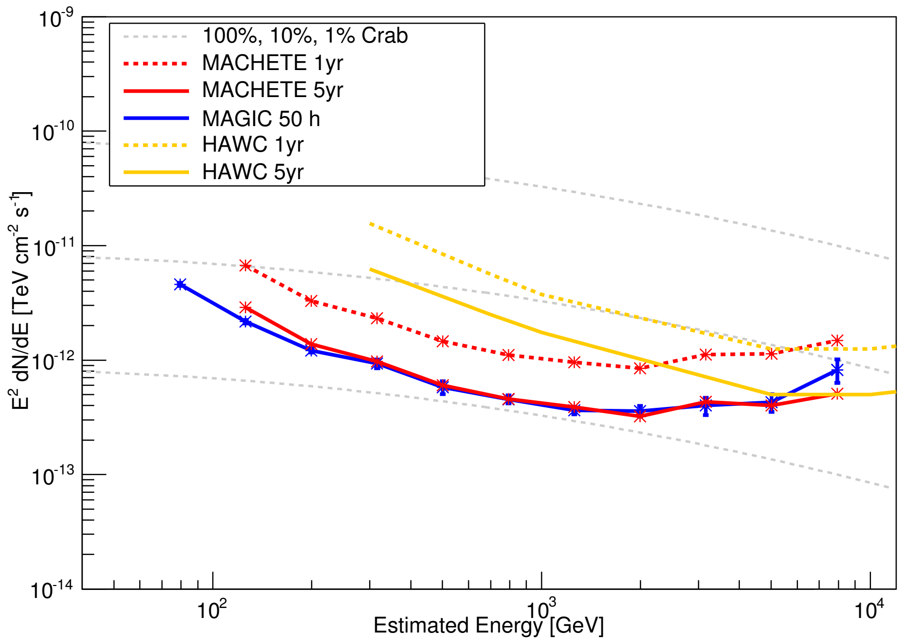

Figure 3: Differential sensitivity of MACHETE for a source at 30° declination after 1 and 5 years of operation. It is compared to the sensitivity of HAWC for the same operation time and with that of MAGIC for a dedicated 50 h observation. Taken from [1].

sensitivity was used. The best integral sensitivity of MACHETE is reached at 500 GeV and it is 0.77% of the Crab flux at 30° declination after 5 years of operation.

The sensitivity of MACHETE is significantly better than the sensitivity of HAWC for the same observation time and energies below 5 TeV. It must be stressed that HAWC has recently come online whilst it may take more than five years to build MACHETE, but even one year of MACHETE has better sensitivity than 5 years of HAWC below 2 TeV. In addition, the angular and spectral resolution would be significantly better than those of HAWC.

The sensitivity of MACHETE can also be compared to the sensitivity of the planned extra-galactic scan of CTA. For the full CTA-South array and an observation of half of the sky for 1000 hours, the expected integral sensitivity of the survey is ∼0.6% of the Crab flux above 125 GeV. MACHETE achieves a similar sensitivity in 5 years of operation at a slightly higher energy but for the same fraction of the sky.

MACHETE would achieve an integral sensitivity of ∼12% of the Crab flux in a single night for all sources in the fraction of the sky that is observable in that specific night. The fraction of the sky covered in a night ranges from around 15% in Summer to around 20% in Winter assuming a New Moon night.

3. Some words on the cost of MACHETE

MACHETE has features that make the operation and construction easier and less expensive than those of a steerable IACT. Let us go through some of them.

To begin with, camera and reflector do not move. This has numerous advantages:

- The alignment of the mirror facets is simplified. Considering that the reflector does not move and that it can be shielded from the wind, once the facets are aligned they are probably stable for years. There is no need for an active mirror adjustment as implemented in MAGIC. We may also consider aligning the facets using screws (as it is already done in VERITAS) and not mechanical actuators as it is done in many of the IACTs. We also require a much less demanding system to monitor the optical PSF and telescope pointing.

- In steerable IACTs the weight of mirrors and focal plane instrumentation must be strongly limited to reduce the demands on the steering system and to reduce deformations of the mechanical structure. In our design these limits can be relaxed. The cost of the mirrors can be correspondingly reduced. The camera may get heavier as well and may be afford more efficient cooling systems, which maybe necessary in case we used SiPMs.

- Mechanics are more simple. There is no need for azimuth or zenith steering: no motors, gears etc. In turn the peak power consumption demands of the telescope, which are typically dominated by fast repositioning, are much lower.

- Steerable IACTs are parked looking away from the Sun during the day or whenever they are not operating, so that the plane of the reflector is essentially vertical. This makes them especially sensitive to the wind and imposes extra requirements to mechanical supports and foundations. In our instrument the reflector points vertical and it can be shielded from the wind by walls.

Secondly, even if a camera is equipped with 15000 pixels, we only need to store data for a RoI of about 500 pixels around the shower image. The cost reduction factor depends on the actual technical solution implemented.

Finally it is worth to mention that all mirror facets have exactly the same curvature in this optical design. This facilitates production, installation and alignment.

More relevant is the cost of the telescope cameras. Each of them needs to be equipped with 15000 photodetectors. As of today IACT cameras are equipped with photomultipliers and the resulting cost would by far dominate over the cost of the rest of the instrument. Using SiPMs as photodetectors will foreseeably bring the cost down in the near future, maybe to as low as 1 US$/mm^2. As mentioned above each pixel must be equipped with a light concentrator to effectively limit the mirror diameter. Each concentrator has a hexagonal entrance window of 45 mm side to side and a circular exit window of around 15 mm diameter. This means that only one ninth of the focal plane total area must be instrumented with photodetectors. Even so the total cost of the photodetectors for one telescope would be on the order of 2.5 million US$.

4. Physics goals

Most of the extragalactic sky remains unexplored at energies above 100 GeV. MACHETE would allow to survey almost half of the sky with a sensitivity of ∼0.77% of the Crab flux in five years of continuous operation.

New AGNs will foreseably be discovered. Estimates for the number of actual objects that MACHETE could discover in five years differ from a handful to several tens.

Typically AGNs are observed by IACTs only during bright states in optical, X-rays or VHE. Instead MACHETE would produce light curves for known and unknown AGNs which are not biased by the state of the source. This allows to make correlations with other wavelengths and searches for periodicity and delays in VHE emission depending on energy.

Similar unbiased light curves can be produced for galactic sources. Good examples are the gamma ray binaries LSI +61 303 or LS 5039, which exhibit a wealth of periodic and sporadic variability. Such light curves could be used to define data sets with potential signal in neutrinos or even gravitational wave experiments.

MACHETE could prove essential to monitor variable VHE sources for flares and provide triggers to instruments at VHE and other wavelengths. The results of an online analysis of the data of MACHETE can be available in a matter of a few minutes, allowing steerable IACTs like those in CTA to repoint and observe the source. Current IACTs strongly benefit from alerts released by *Fermi*-LAT, but this detector will probably not be available by the time CTA starts to take data.

As mentioned above other surveys have detected a significant amount of sources that do not have a clear counterpart at other wavelengths. The survey may identify VHE sources other than the already known classes of VHE-emitting AGNs. This may include other active galaxies and other extragalactic or galactic objects in general. Some of them may not emit or emit only weakly at longer wavelengths ("dark sources").

Among other dark sources MACHETE may be able to spot γ-rays produced by annihilation of dark matter in clumps or sub-haloes. In general the data collected in the survey may allow to stack the signal produced in a variety of dark matter γ-ray-emitting candidates such as dwarf spheroidals or clusters of galaxies.

Some of these physics goals are tied to the location of the instrument. Galactic sources are more numerous in the south, so a survey would detect more sources and light curves of more sources could be produced. Yet, MACHETE may add little to the survey that CTA will most probably complete in its years of operation. Triggers from extragalactic transients will be as frequent in both hemispheres. In general it is probably a good idea to locate MACHETE at the same location of any of the CTA arrays, in order to follow as many MACHETE triggers as possible with CTA.

Acknowledgments

We gratefully acknowledge the MAGIC collaboration for allowing us to use their Montecarlo and data analysis software. This work is partially funded by the ERDF under the Spanish MINECO grant FPA2012-39502.

References

[1] J. Cortina, R. López-Coto, A. Moralejo, *MACHETE: A transit Imaging Atmospheric Cherenkov Telescope to survey half of the Very High Energy γ-ray sky*, accepted for publication in Astrop. Phys.

[2] J. Aleksić et al., *The major upgrade of the MAGIC telescopes, Part I: The hardware improvements and the commissioning of the system*, submitted to Astroparticle Physics and arXiv:1409.6073.

[3] A.U. Abeysekara et al., Sensitivity of the high altitude water Cherenkov detector to sources of multi-TeV gamma rays, Astrop. Phys., 50âĂŞ52 (2013) 26.