MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescope

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Studies on the mirrors configuration of MAGIC II reflector

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Abstract

The overall structure of the MAGIC II reflector can be considered a clone of the MAGIC I reflector: the mounting structure is the same, and the dimension and the paraboloid characteristic of focal distance around 17 m also remained unchanged. In the case of MAGIC I, the square mirrors have dimension of 495 mm along each side, and they are grouped in 3 or 4[1] onto panels which constitute a reflective unit. The four mirrors have a fixed orientation on the panel defined at the moment of assembly. At the center of each panel, a hole houses a laser for Active Mirror Control. MAGIC I has 248 panels with 964 mirrors in total. For the layout of the MAGIC II reflector, a simplification is being considered, particularly in mirror dimension. With today's technology, larger mirrors have become affordable.
This note provides simulation results for a reflector built entirely of $1m^2$ mirrors, using the `REFLECTOR` program and comparing to results with the old reflector.

Contents

[1] Inner panels are constituted by 4 mirrors, while some outermost panels house 3 mirrors in order to better resemble a roundish frame.

1 The characteristic of MAGIC reflector

A complete description and characterization of the reflector surface of the MAGIC I telescope is currently under edition and will be available as a separate note.

1.1 The parabolic shape

We want to report here the principal characteristic of a reflector of parabolic layout. The paraboloid shape ensures the best time coincidence of a light ray reflected into the camera, better than the Davies–Cotton layout for the spherical shape. This is very important for a fast Cherenkov flash due to a shower in the atmosphere, whose typical duration is 2–3 ns. The coincidence of the reflected light in the camera allows a detailed time reconstruction of the image. A reflector with spherical shape, focal length 17m and diameter 17m has an additional maximal time spread of 7.5 ns, which can be reduced to zero in the case of a parabolic shape.

1.2 Aberrations

Spherical aberrations

Such a huge reflector must of course deal with aberrations. A perfect paraboloid mirror imaging an object on-axis at an infinite distance would have no spherical aberration, i.e. the optical pathlengths object to focus will be equal, no matter where the light strikes the mirror. When imaging at a finite distance, this is not so, and there will be some spherical aberration present. Additionally, the real reflector is only an approximation of the perfect paraboloid surface.

Aberrations occurs when the diameter is large compared to the focal length, and thus the "paraxial beam" approximation is not valid. That implies that photons impinging on the reflector in the outermost region are not reflected in the focus but at a smaller distance. Figure 1 illustrates an example of spherical aberration in the case of a lens..

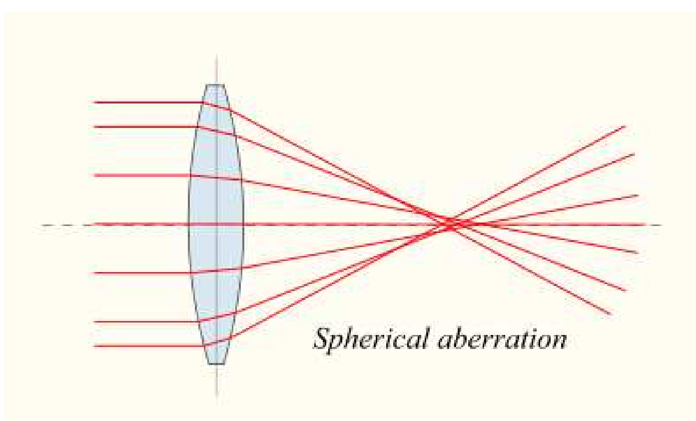

Figure 1: Spherical aberration in the case of a lens.

This aberration is always present and produces a smeared image with a non–zero point spread function (PSF). In case of non–vertical incidence of the photons onto the reflector, this aberration takes the name of *coma aberration*[2]. It creates a non–roundish image on the focal plane, more resembling a triangle. The triangle is in reality composed by many circles, each due to the photons at a certain distance from the beam center, with their center progressively moved in a direction. Figure 2 illustrates this case in the case of a lens..

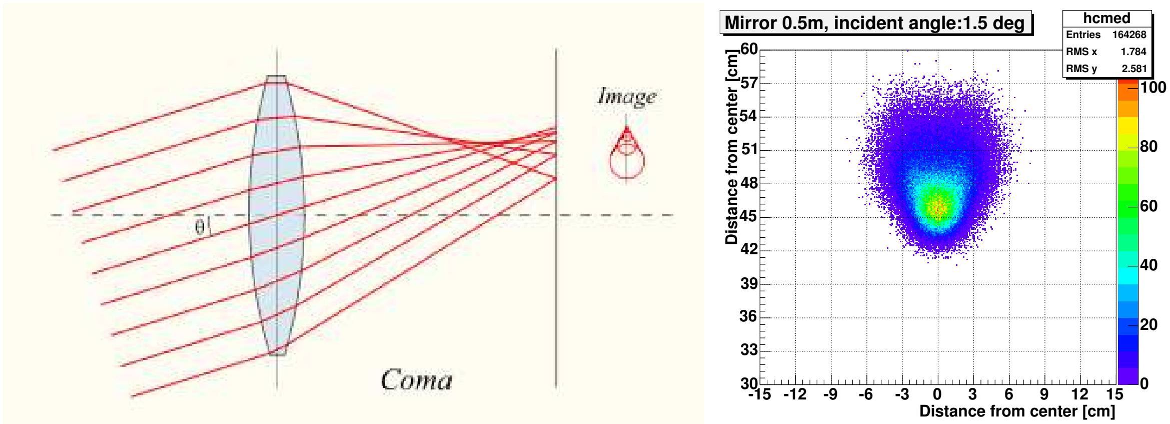

Figure 2: *(left)* The coma aberration.*(right)* Image of the spot on the camera of the MAGIC telescope produced by a beam of light impinging at an angle of 1.5 deg. The comet shape is clearly observable.

Tessellated mirrors aberrations

Another contribution to the aberration is given by the fact that each mirror unit within the reflector has not a parabolic shape but a spherical one, basically due to the complexity of the realization of a good parabolic reflective surface. This misbehavior with respect to the ideal parabolic surface smears the image in the focal plane, with a contribution increasing with the distance from the center of the reflector. There are basically two reasons for this: one, because the paraxial approximation worsens with increasing distance from the center, and second because with increasing distance the corresponding number of mirrors also increases.

Finite quality aberrations

Finally, two other phenomena determine a degradation of the reflected image: the finite precision in the optical quality of the reflective surface of the mirrors implies a non–point–like reflected spot at a focal distance, second, the finite precision in the orientation of the panel onto the camera of the telescope also contributes to a smearing of the spot. An estimation of these effects will be discussed further on in this document.

[2]The name comes from *comet*, the icy–structure showing a large tail of material as it passes between the Earth and the sun. The shape of the comet resembles the shape of the reflected image in the focal plane in the case of the non–vertical illumination.

2 The idea of introducing larger mirrors for the reflector of MAGIC II

In the case of MAGIC II telescope, some important modifications are expected to facilitate the construction of the reflector. Although the production of the MAGIC I mirrors (from here on called *small mirrors*), was a success, we believe there is an advantage in in realizing larger units doubling the side length, i.e. mirrors of 1 m^2 area. Some prototypes have been already realized by INFN–Padova group at the Legnaro laboratories and by the MPI group. Basically these new mirrors (from here on called *large mirrors*) resemble the small ones, although with some differences: The unit is composed of a 3mm–thickness aluminum slab constituting the reflective surface, mounted on an aluminum box, about 60mm high, with dimension few millimeters smaller than the reflective plane. They are glued together with a resistant glue and filled with a honeycomb aluminum structure which provides both low weight and robustness of the structure (A detailed description of the mirror will be found in future publications). This large dimension implies that mirrors are no longer grouped onto panels. Consequently, there is no need for a back supporting plane on which to assemble the mirrors. The hole accommodating the laser is now at the center of the mirror itself instead of on the panel for the laser housing. Thus the reasons for moving to such large unit are several:

- the number of mirrors to be realized would decrease by a factor of 4, from nearly a thousand down to 248. This will speed up the production, decrease shipping costs, and accelerate the installation on the telescope;
- the fact that the mirrors are no longer grouped supresses the need for the interalignment of the 4 mirrors installed in each panel;
- the structure will be lighter: a large mirror weighs 18 kg, to be compared with the weight of a panel plus four mirrors (at least 20+4x3=32 kg);
- in case of damaged units, the replacement is much easier.

Larger mirrors, of course, approximate a parabolic surface less accurately than smaller ones, so the optical quality of the reflector is a critical parameter to investigate. In order to understand and characterize the potential deterioration, we have invested some effort using ray tracing.

3 The simulation of the MAGIC reflector

The original idea was to simulate the reflective quality for three different layouts:

1. entire reflector made of 1m^2 mirrors
2. the innermost 6 rings made of large mirrors, the outermost 2 rings of panels of small mirrors
3. as the preceding case, but the outermost 2 rings made of aspherical 1m^2 mirrors, i.e. mirrors with a different radius of curvature along the vertical and the horizontal axis.

The results for the layout 1 above, that we show below – positive as we consider them – have obviated the necessity of simulating the latter cases, so in this document only the first reflector will be discussed.

3.1 Modification introduced in the `REFLECTOR` code

The `REFLECTOR` program is the second step of the Monte Carlo simulation of events for the MAGIC telescope, following CORSIKA which produces the Cherenkov light from the showers, and followed by CAMERA, which transform the photons in the focal plane of the reflector in events in the camera of the telescope. Minor changes had been applied in the `REFLECTOR` in order to introduce the 1m^2 mirrors. In the CVS version of Reflector 6.0,the size of the mirror element must be the same for all of the elements of the dish. For this work smaller modifications have been applied to allows a configuration with large mirror. The following files had been modified: `geometry.c`, `ph2cph.c` and `init.h`. The executive `writemagicdef.c` whose task is defining many mirror parameters including position, curvature and focus, has been modified to create the new layout for the MAGIC II 1m^2 reflector, called `magicII.def`. A new release of `REFLECTOR` had recently followed these changes and now this configuration can be already used for simulation.

3.2 Description of the analysis.

The simulation has been carried on for the two reflector layouts:

- All reflector composed by 964 0.5m x 0.5m mirrors
- All reflector composed by 249 1m^2 mirrors

For each of these, two telescope conditions have been investigated:

- Condition of *Perfect Reflector*
- Condition of *Real Reflector*

In the first case, the simulation takes into account only the spherical shape of the mirrors and the reflection of the photons onto the tessellated mirrors. The condition is defined *perfect* because it is not taken into account that the surface of the each mirror cannot be geometrically perfect and that also the alignment of each reflective unit can not be perfect. The inclusion of these conditions determines the so-called *real* case. Within the `REFLECTOR` code, these conditions are introduced with two parameters: in the `magic.def` file, a parameter called `point_spread` is the *"point spread function, sigma in x and y on camera [cm]"*. This means that artificially the photon impinging the camera at a given position x, y is artificially moved in a direction according to a 2-dim Gaussian of sigma 0.5 cm. This value has been decided after some considerations a posteriori of the real reflected spot in the MAGIC camera[3]. The second parameter is instead defined in the `axisdev.dat` file. This file gives information on the axis deviation for each mirror. For each mirror a pair of number is defined, giving *"the deviations in x and y of the spot of a single mirror on the camera plane. The numbers are*

[3] The smearing introduced artificially with `REFLECTOR` contributes for about 0.7 cm PSF. Usually at the `CAMERA` level another 1.4 cm PSF is added to reproduce the real working condition PSF of MAGIC

taken at random from a Gaussian distribution with sigma = 0.5 cm"[4]. So the case of perfect reflector is taken by setting to zero all these two deviations, thus remaining only with the mirror layout.

3.3 Composition of the reflected spot

The image on the camera due to a beam of parallel light even from an infinite distance is not a single point due to aberrations as described before. However, one must take into account the fact that not the entire reflector produces the same aberration, and in particular the further from the axis a mirror, the larger the effect. Just to be clearer, figure 3 illustrates the case.

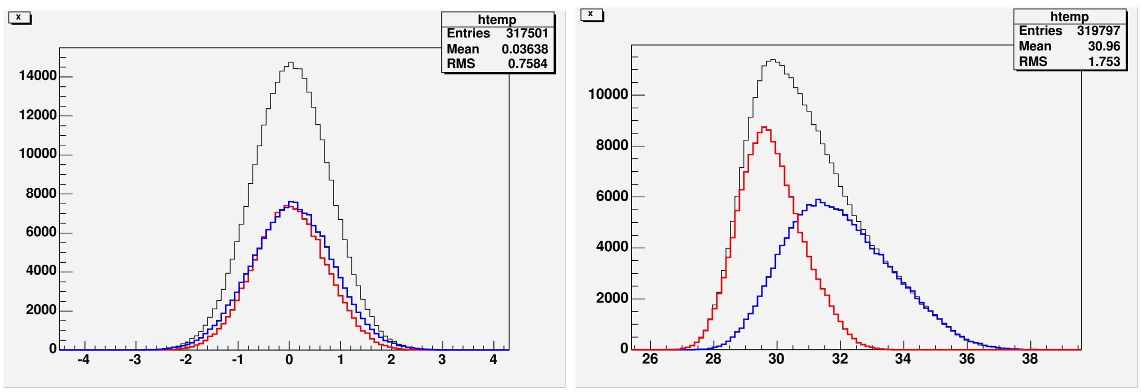

Figure 3: Contribution to the reflected spot by the inner part of the reflector (first 6 rings – red line) and the outer two rings (blue line). In the left plot, the incidence is vertical. In the right one, the incidence is 1 deg.

Following this argument one could argue that a better performing reflector should have the ratio focal length over diameter larger than 1: $F/D > 1$. Even if this statement is true, this solution would bring technical problem related to the increase of difficulties in substaining the camera at a larger distance, and the camera itself should also have a larger diameter to fulfill the correspondent larger FOV.

From figure 3 one can see how the outermost rings contributes differently in case of vertical and tilted incidence. In the case of vertical incidence, the contribution due to inner reflector and the outer two rings is almost the same: the width of the two distribution does not differ too much. This is not the case in the rightmost plot. Here one can clearly see how the outer rings produces a shift of the image towards larger radius. This aberration broadens the reflected spot[5]. This fact also foresees that at large angle of incidence, the principal effect on the spot size is due to the coma aberration.

To have an idea on how the spot size get modified as the incident angle change, figure 4 can be clarifying.

[4]The test in italics is taken directly from the cited files definition headers.

[5]It is anyhow clear how is the positive contribution in term of sensitivity of a larger reflector with respect to a small one

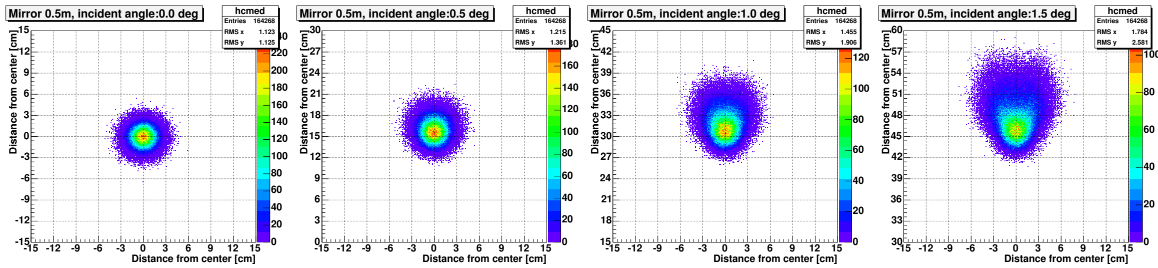

Figure 4: Images of the spot in the camera taken with different incidence angles: from left to right 0, 0.5, 1.0 and 1.5 deg. The images are done with the real smearing of the spot size.

3.4 Images of the reflected spot in the camera

The behavior of the reflected spot at the varying incident angle, for the two layouts and for the case of perfect and real reflector is given in figure 5.

Figures in figure 5 are basically intended to have a graphical impression. Anyway, some effects can be here underlined:

- In the case of the perfect reflector, the spot profile presents some irregular peaks. These are due to outermost part of each mirror, which is the part that is mostly different from the parabolic shape. In fact one can see how the number of the peaks is clearly equal to the number of the rings of mirror of that size. This effect is washed out in the real reflector by the finite quality aberrations.
- The appearance of the spot in the case of the real and perfect reflector is strongly different. The enlargement is substantials.
- In the case of the small mirrors perfect reflector, the spot size for vertical incidence is very narrow.

3.5 Comparison Perfect and Real reflector

As seen in figure 5, the spot characteristics are strongly modified by taking into account the optical quality of the mirror and the non-perfect alignment.

In figure 6 a comparison of the vertical and tilted incidence in the case of the real and perfect reflector is provided. Note that the vertical scale is different between the two figures, while the integral is almost the same, so in the case of the perfect small mirrors reflector the spot is really concentrated. Additionally, how can see estimate how the smearing due to the real reflector broaden the spot. One can also see that the difference is smaller when the light impinges inclined with respect to the telescope axis. Also, the first impression is that while the broadening of the spot due to the large mirrors in case of perfect reflector is high, this is not that much the case when the real reflector conditions apply.

3.6 Systematic studies

In table 1 a comparison of the spot characteristics is provided for different angles and in both case of real and perfect reflector.

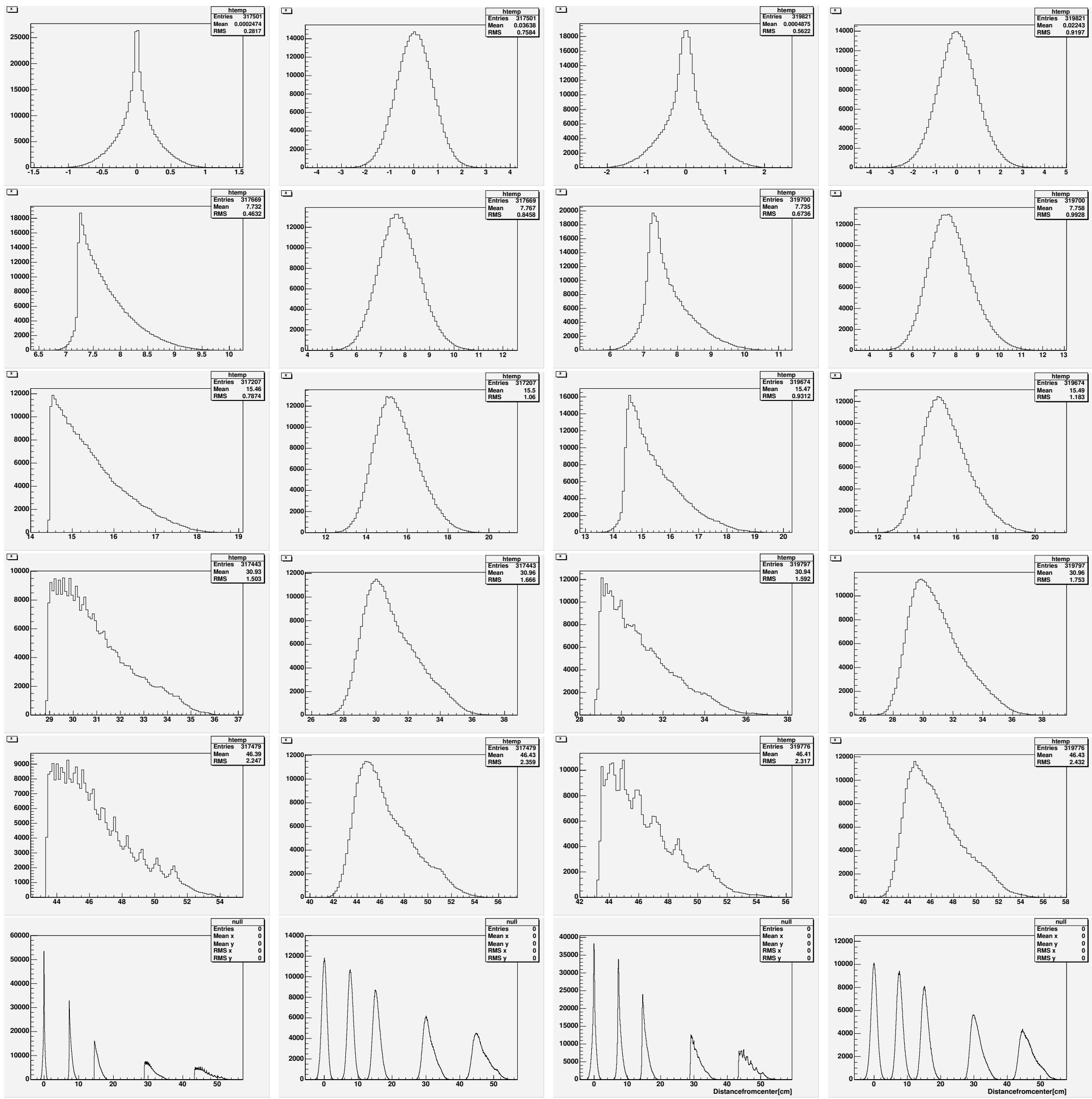

Figure 5: Results from the simulation of the spots in the camera. *leftmost column:* Perfect reflector with all small mirrors,*center-left column:* Real reflector with all small mirrors, *center-right column:* Perfect reflector with all large mirrors *rightmost column:* Real reflector with all large mirrors. From top to bottom the incident angles vary: 0, 0.25, 0.5, 1.0 and 1.5 deg. Bottommost plots show the profile of those same spots at the same different angles. Please take into account the different range in the vertical axis.

Next figures shows the contents of table 1.

Let us now analyze the deterioration of the image parameters between small and large mirrors. It is expressed as percentage of the new parameter with respect to the old one.

One can clearly see from figure 8 how fast the degradation is becoming smaller as the incident angle grows. If one wants to estimate an overall degradation parameter, one must take into account also how many times a light ray impinging on the reflector under a certain angle. This of course depends on the lateral distribution of the showers and the distribution

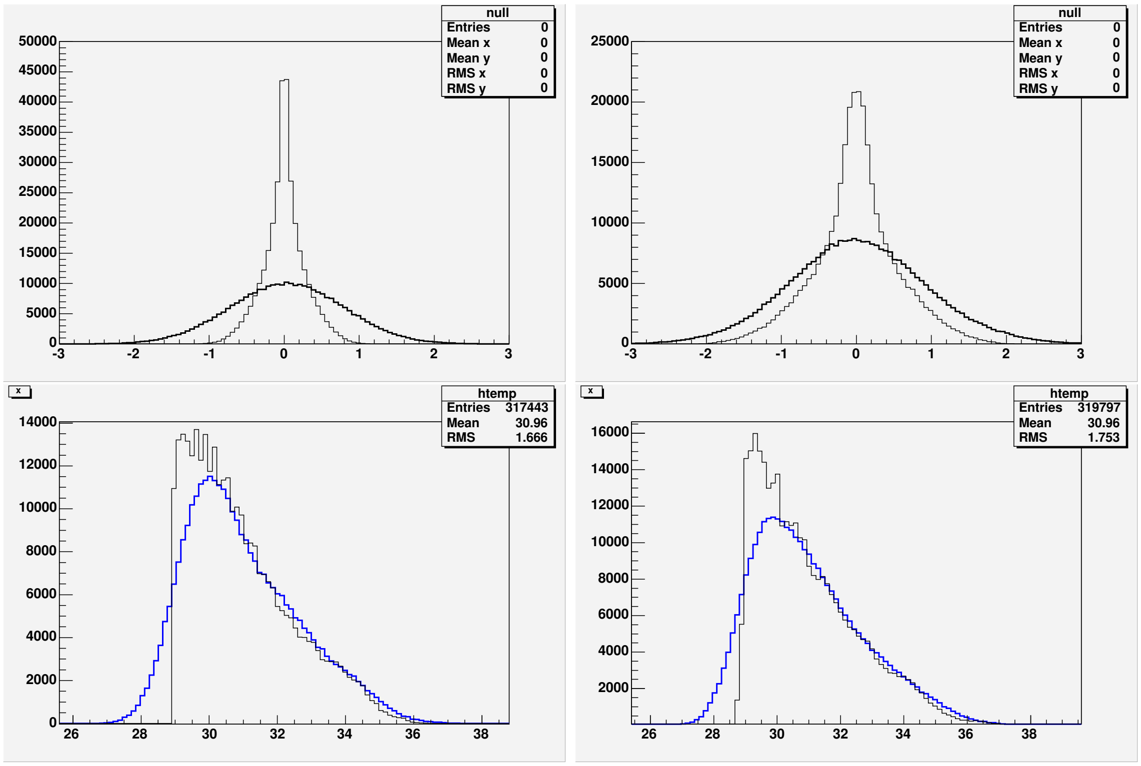

Figure 6: Vertical and 1deg incidence

		Real reflector				Perfect reflector			
Dim m	angle [deg]	rmsX [cm]	rmsY [cm]	r50 cm]	r90 [cm]	rmsX [cm]	rmsY [cm]	r50 [cm]	r90 [cm]
1	0.0	0.91	0.89	0.90	1.80	0.56	0.56	0.48	1.14
1	0.25	0.99	0.92	0.90	1.86	0.67	0.60	0.54	1.56
1	0.5	1.18	1.00	1.02	2.28	0.93	0.72	0.72	2.22
1	1.0	1.75	1.27	1.44	3.90	1.59	1.07	1.44	4.14
1	1.5	2.43	1.60	2.04	5.82	2.32	1.47	2.46	6.48
0.5	0.0	0.76	0.75	0.72	1.44	0.28	0.28	0.18	0.54
0.5	0.25	0.85	0.78	0.84	1.62	0.46	0.36	0.36	1.14
0.5	0.5	1.06	0.86	0.96	1.98	0.79	0.52	0.78	2.10
0.5	1.0	1.67	1.14	1.32	3.60	1.50	0.93	1.56	4.20
0.5	1.5	2.36	1.51	1.86	5.46	2.25	1.36	2.34	6.30

Table 1: Characteristics of the spot sizes for the both real and perfect reflector and for small and large mirrors configurations.

of the impact parameter, which differ from gammas to hadrons, and additionally it depends on the active trigger region in the camera. Thus the camera occupancy is not unique and could differ from MAGIC I to MAGIC II.

Only as an example, one can take the radial profile of the pixel usage. Figure 9 shows

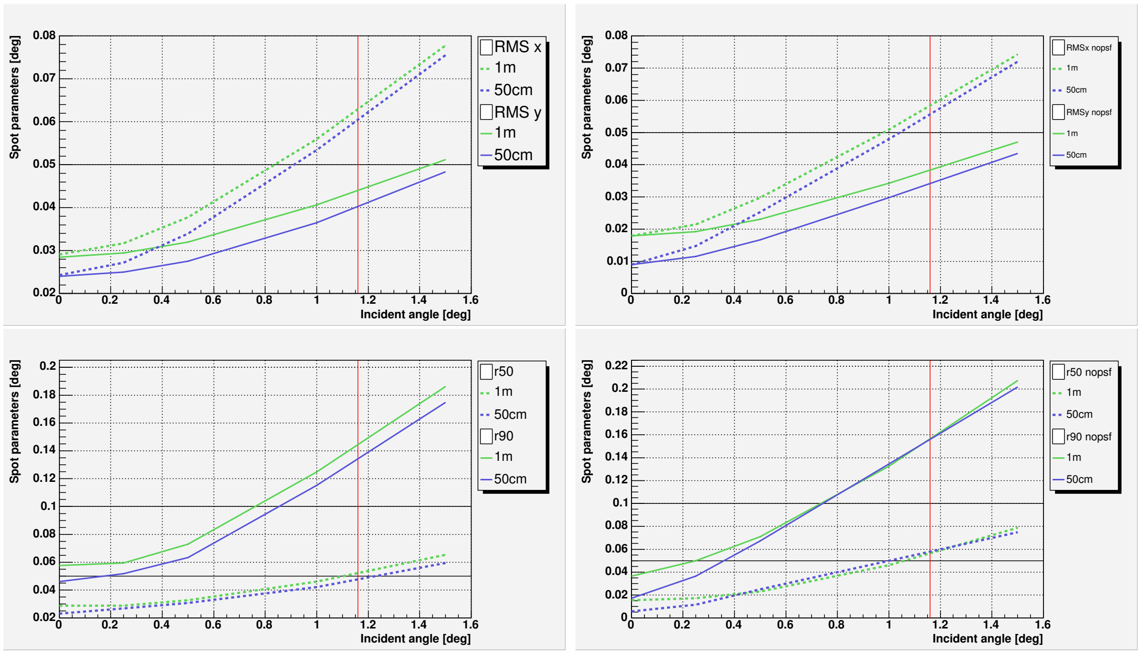

Figure 7: Behavior of spot parameters with incident angles and comparison between small and large mirrors configurations.

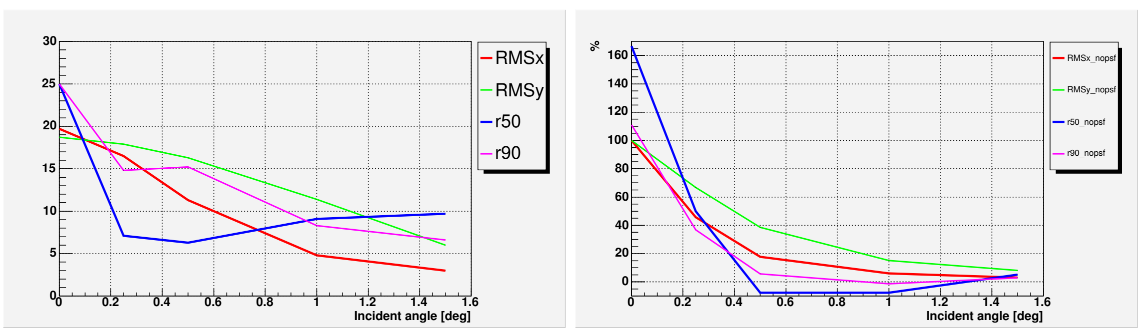

Figure 8: Percentage worsening of the characteristics of the spots.

the profile in the case of a normal MAGIC observation.

It is thus clear that the central camera is the most used, and this is even more valid in case of low energy showers, which tend to concentrate in the central pixels.
In this region, the performance of the new configuration remains good. This definitively a good sign to go for an homogeneous reflector all constituted by 1m^2 mirrors.

4 Conclusions

The spot on the camera changes with the incident angle. In particular the effect of the coma aberration is clearly observable from the simulation for tilted incidence.
A reflector made entirely of large (1m^2) mirrors has worse performances than a reflector made of small mirrors, for all parameters analyzed: RMSx, RMSy,r50 and r90. This deterioration, however, depends on the incident angle and decreases fast as the angle increases, from a value

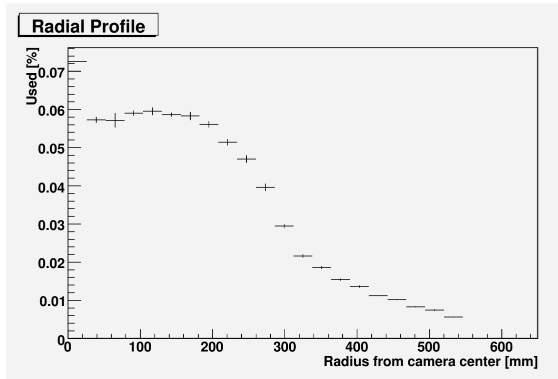

Figure 9: Radial profile of the pixel usage taken during a typical run of data.

of 20% at 0 degree to a value of 3% at 1.5deg.
The camera is mostly used in the central part, also where the lower-energy showers concentrate. In this region, a large mirror configuration does not alter strongly the quality of the spot.

We conclude that it is probably better to build a homogeneous reflector of 1m^2 mirrors, if one takes into account the advantages described in section 2 in terms of costs, production, mounting and care.
Additionally, as mentioned above, this simulation is performed by subestimating the real dimension of the PSF in the camera, as if the mirror quality were higher. So the idea to go for larger mirrors it even more valid if the quality of the new mirrors would not enhance with respect to the actual ones.

Acknowledgments

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References

[1] A. Moralejo, *The* ***REFLECTOR*** *Simulation Program v0.6*, TDAS 02-11