[Photo: Miguel Claro, http://www.miguelclaro.com/]

FACT – the First G-APD Cherenkov Telescope

Novel Bokeh & NAMOD alignment for FACT

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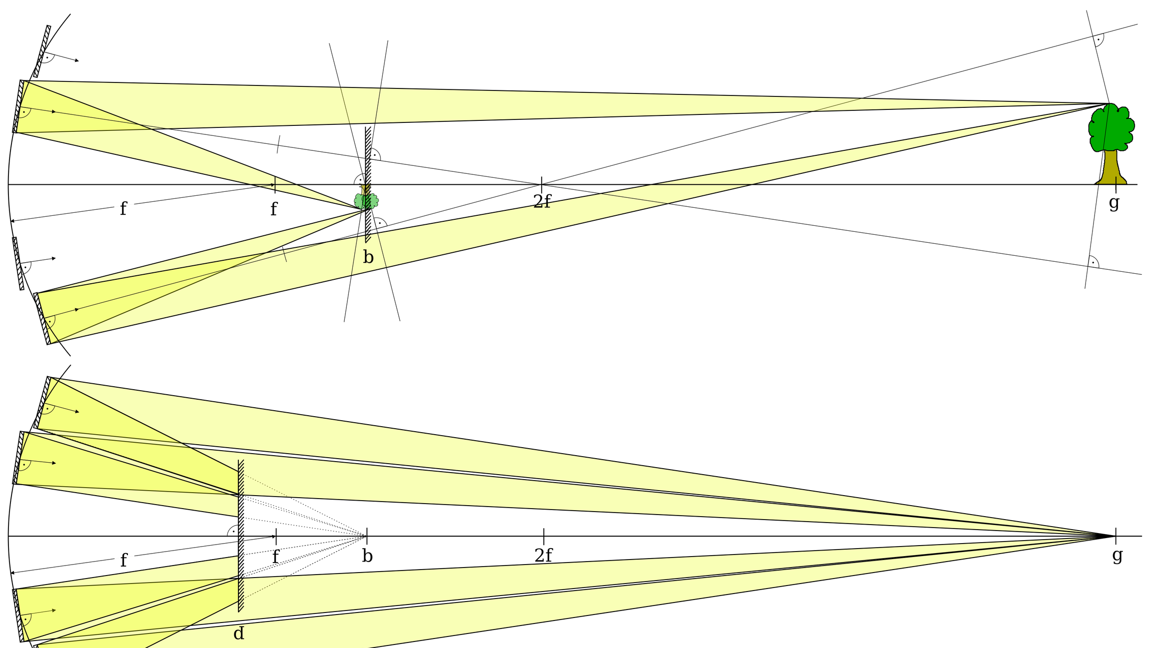
Imaging Air Cherenkov Telescopes, including the First G-APD Cherenkov Telescope (FACT), use segmented reflectors [1]. These offer large and fast apertures for little resources. However, one challenge of segmented reflectors is the alignment of the single mirrors to gain a sharp image. For Cherenkov telescopes, high spatial and temporal resolution is crucial to reconstruct air shower events induced by cosmic rays. Therefore one has to align the individual mirror positions and orientations precisely. Alignment is difficult due to the large number of degrees of freedom and because most techniques involve a star. Most current methods are limited, because they have to be done during good weather nights which overlaps with observation time. In this contribution, we present the mirror alignment of FACT, done using two methods. Firstly, we show a new method which we call Bokeh alignment. This method is simple, cheap and can even be done during daytime. Secondly, we demonstrate an enhancement of the SCCAN method by F. Arqueros et al., and first implemented by the McGill VERITAS group. Using a second camera, our enhanced SCCAN is optimized for changing weather, changing zenith distance, and changing reference stars. We call it NAMOD. Developed off site in the lab on a 1/10th scale model of FACT, both our alignment methods resulted in a highly telescope independent procedure, e.g. both our methods run without communication to the telescope's drive. We compare alignment results by using the point spread function of star images, ray tracing simulations, and muon ring widths before and after the alignment.

Bokeh Alignment

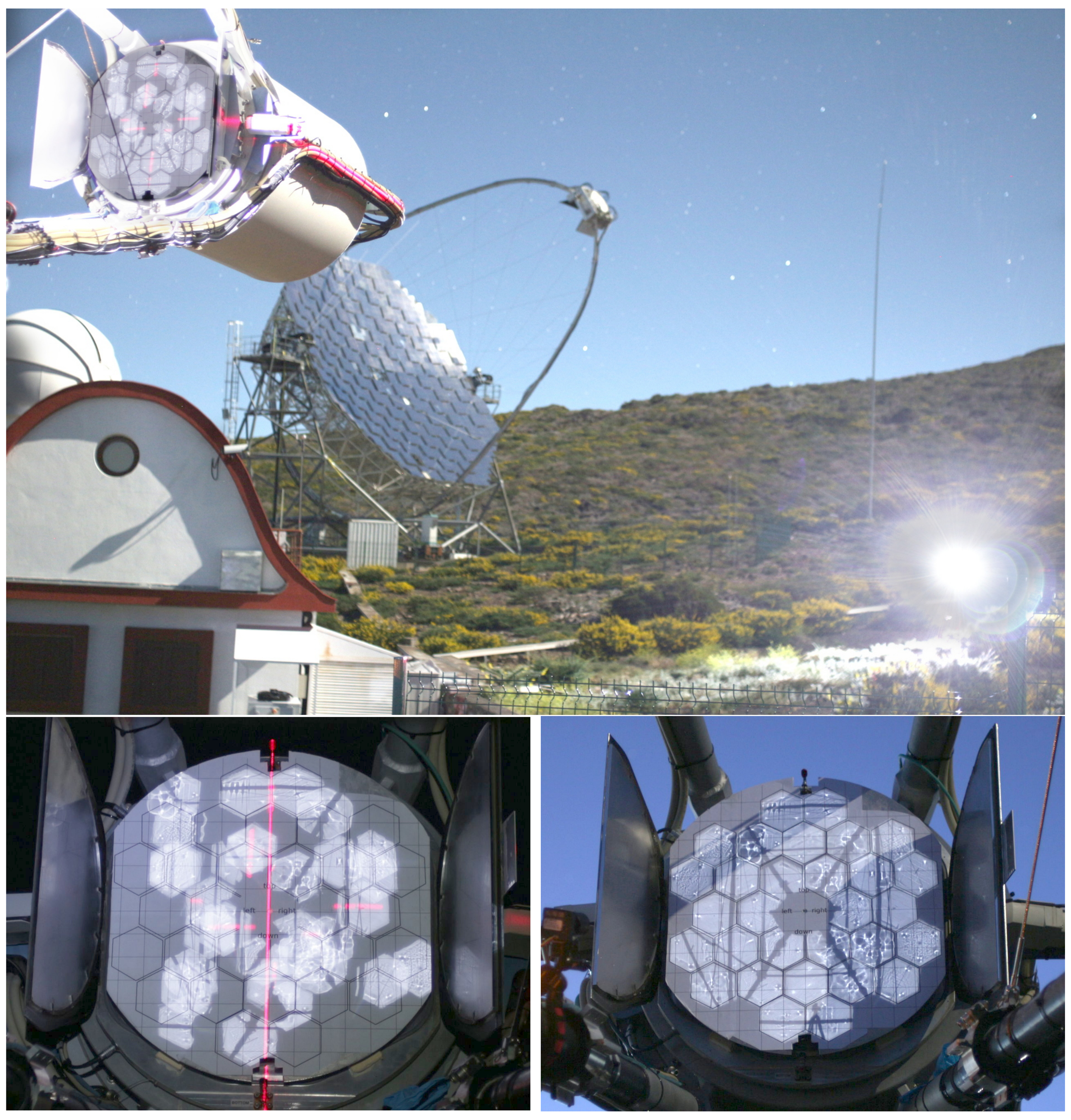
If the Bokeh of a segmented reflector is equal to its aperture up to a scale factor, then the mirrors are aligned.



Upper: A segmented reflector with focal length f maps a tree in g onto its image sensor in b. Two of the four mirror rays are highlighted in yellow.
Lower: The same segmented reflector facing a bulb in g during Bokeh alignment. The bulb is mapped on the Bokeh template screen in d. Both reflectors depicted are aligned.

Bokeh alignment was developed on Mini FACT. Needing only a light bulb, a consumer photo camera, a desktop printer, and a level, Bokeh alignment is cheaper and faster compared to computer vision based solutions. Bokeh alignment can be done during daytime when the light source is powerful enough, e.g. a consumer photo speedlight. Watch our Bokeh demonstration **video** showing the alignment of Mini FACT.

http://fact-project.org/qr/ICRC2015/Bokeh.mp4

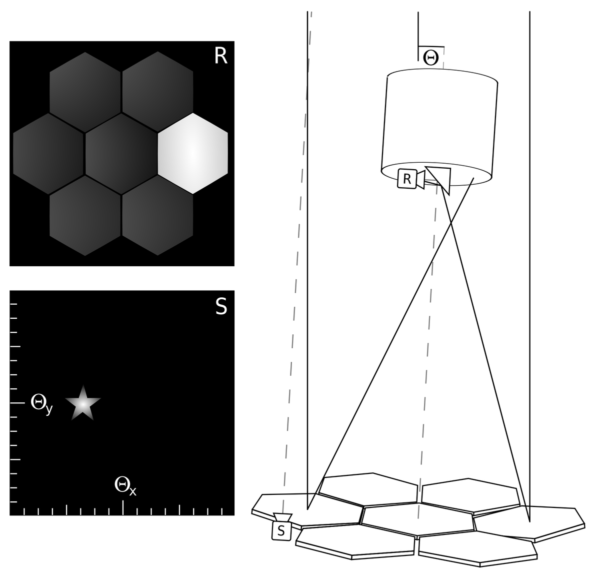


In May 2014 FACT was pre aligned using the Bokeh technique which gave good results. In daylight, we took a picture of the aperture function and printed it onto a template screen which was mounted in b, in front of FACT's image sensor. A bulb placed in $g \approx 50\,$m shined into the freshly reworked and non adjusted FACT reflector. A PSF size of $\approx 250\%$ of the size of the lower limit found in ray tracing simulations was achieved [2]. While climbing the back of the reflector, Bokeh corrections have been applied manually with a wrench based on eye hand feedback.

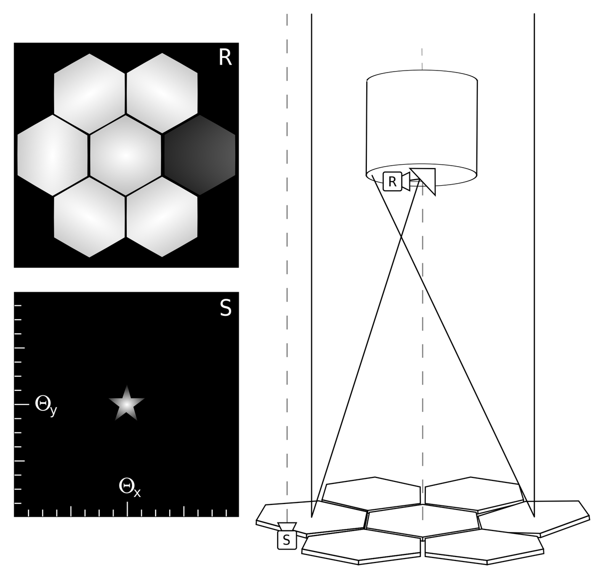
Bokeh alignment is easy and cheap, gives sufficient results, and can be done during the day.

NAMOD Alignment

NAMOD **N**ormalizes the mirror responses and records **A**synchronusly from the pointing of the telescope drive to do the **M**irror **O**rientation **D**etermination.



NAMOD reconstucts the mirror facet orientation by recording the facet's normalized response for various telescope pointing directions while wobbling the telescope close to a bright star in the night sky. Two cameras, a star **S** and a reflector **R** camera, are recording the telescope's field of view and the reflector facets simultaneously, see figure 1.



For each record, we reconstruct the telescope pointing, the star's light flux and the flux of the facet's response in the focal point. Several hundred records are taken while wobbling close to the bright star. Both camera's radiometric properties are known to estimate and compare the light fluxes [3, 4]. Our star camera, geometrically calibrated, obtains the telescope's pointing with respect to the bright star. To correct for atmospheric effects and to enable switching the reference star during recording, we normalize the facet response, see figure 2. There is no communication needed with the telescope drive.

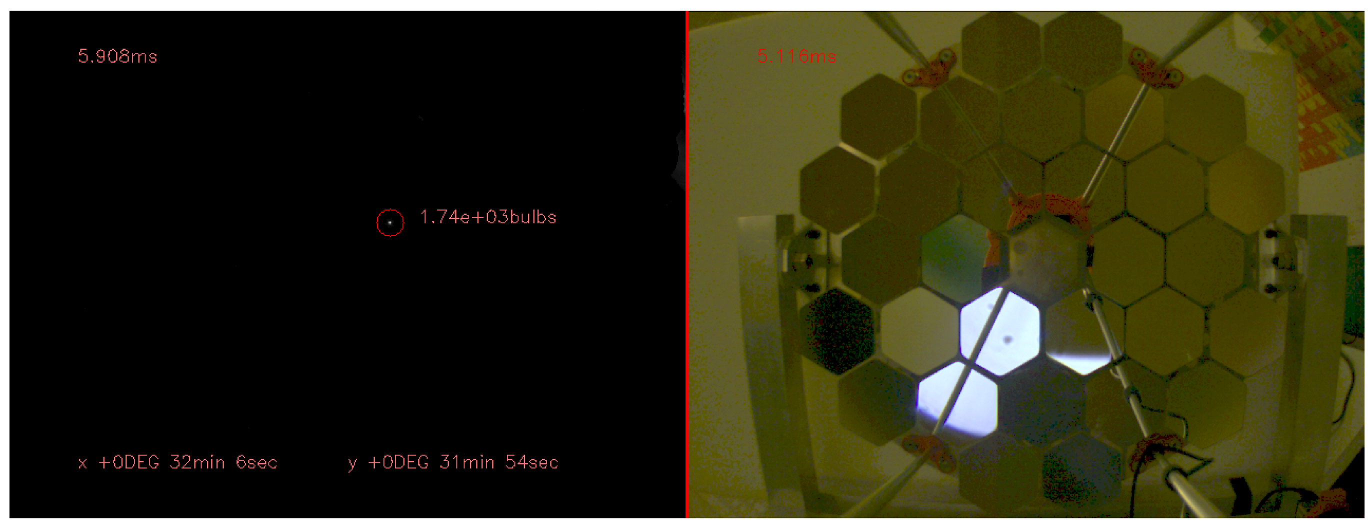


Figure 1: NAMOD GUI during alignment. Left star and right reflector camera.

http://fact-project.org/qr/ICRC2015/NAMOD_reflector.mp4

Whatch the reflector camera's view during the alignment of FACT.

Our NAMOD program controlls the cameras and records the telescope's pointing relative to the bright object and the facet responses for each facet and pointing. The NAMOD program shows where pointings are missing or where they are already dense enough. FACT was wobbled by either manual joy stick control or by scripting some wobbling. After 1 h of acquisition, NAMOD took $\approx 1\,$k records. Corrections are applied manually to the reflector during daytime using a goniometer and a wrench, see figure 3. NAMOD reduced the PSF from $\approx 250\%$ down to 142% of its lower limit, see figures 4 and 5. Reconstructions of muon events show a reduction of the muon ring width in muon event images caused by the alignment, see [5].

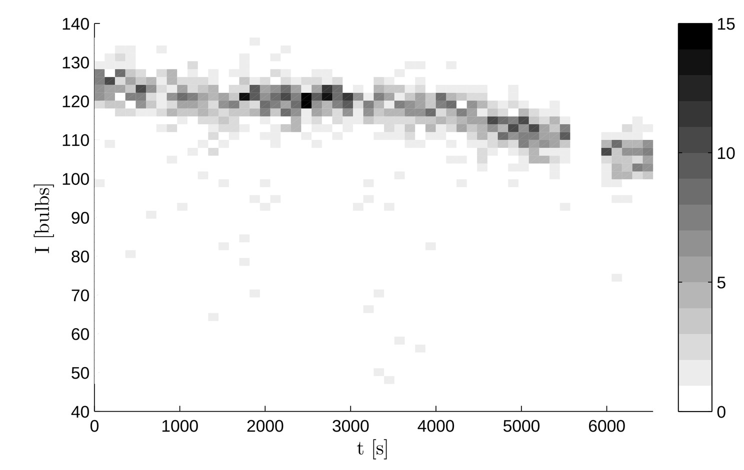


Figure 2: The star's light flux during alignment on FACT recorded by NAMOD's star camera. All variations are corrected for.

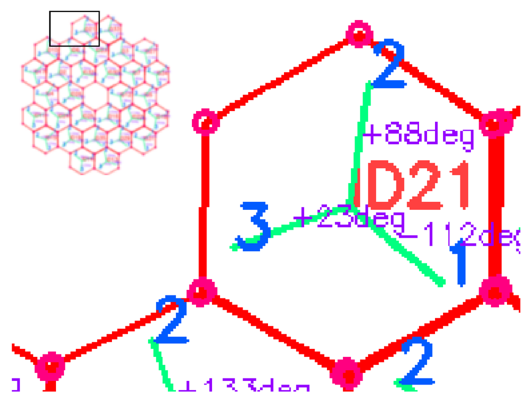


Figure 3: Instructions provided by NAMOD.

NAMOD is easy to install on various telescopes, accepts a wide range of night sky scenarios, and gives sublime alignment results.

PSF Recording

Figure 4: Before alignment

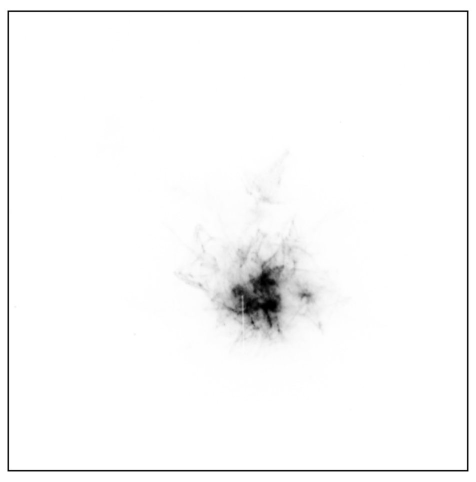


Figure 5: After alignment

We made direct PSF recordings before and after every alignment run using our $6 \times 6\,\text{cm}^2$ digital image sensor placed in FACT's pseudo focal point. This way, we obtained $0.42\,$Mpixel images of the overall reflector PSF. High dynamic range exposure time series are compared to ray tracing simulation results. Figures 4 and 5 show the PSF before and afer Bokeh and NAMOD alignment on FACT. The FoV is $0.7^\circ \times 0.7^\circ$, PSF images are in inverted color. On FACT we reached a PSF size as low as $\approx 142\,\%$ of the smallest PSF found in simulations.

Figure 6: $0.42\,$Mpixel, $0.7^\circ \times 0.7^\circ$ PSF sensor

Mini FACT

The development on a test bench like Mini FACT dramatically reduced overlap with observation time, total costs, and debugging time of the NAMOD system.

http://fact-project.org/qr/ICRC2015/Mini_FACT_docu.pdf

References

[1] FACT collaboration. *Design and operation of FACT - the first G-APD Cherenkov telescope.* JINST, 2013. [2] Sebastian Müller. *Clear Sight in Cherenkov Astronomy – Investigations of Reflector Geometry and Mirror Alignment for the FACT Telescope.* MA thesis. TU Dortmund, 2013/2014. [3] D. A. Forsyth and J. Ponce. *Computer Vision – A Modern Approach.* Pearson Education Inc., New Jersey U.S.A., 2003. [4] Prof. Christian Whoeler et al. *Presentation of early NAMOD in the group for Image Signal Processing.* TU Dortmund, 2013/2014. [5] Maximilian Nöthe and others. *FACT – Calibration of Imaging Atmospheric Cerenkov Telescopes with Muon Rings.* In: *these proceedings.* 298. 2015.

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