PROCEEDINGS OF SCIENCE

FACT – Novel mirror alignment using Bokeh and enhancement of the VERITAS SCCAN alignment method

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Imaging Air Cherenkov Telescopes, including the First G-APD Cherenkov Telescope (FACT), use segmented reflectors. These offer large and fast apertures for little resources. However, one challenge is the alignment of the mirrors to gain a sharp image. For Cherenkov telescopes, high spatial and temporal resolution is crucial to reconstruct air shower events. 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, has to be done during good weather nights which overlaps with observation time. 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. Developed off site in the lab on a 1/10th scale model of FACT, both our 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 overall muon rates before and after the alignment.

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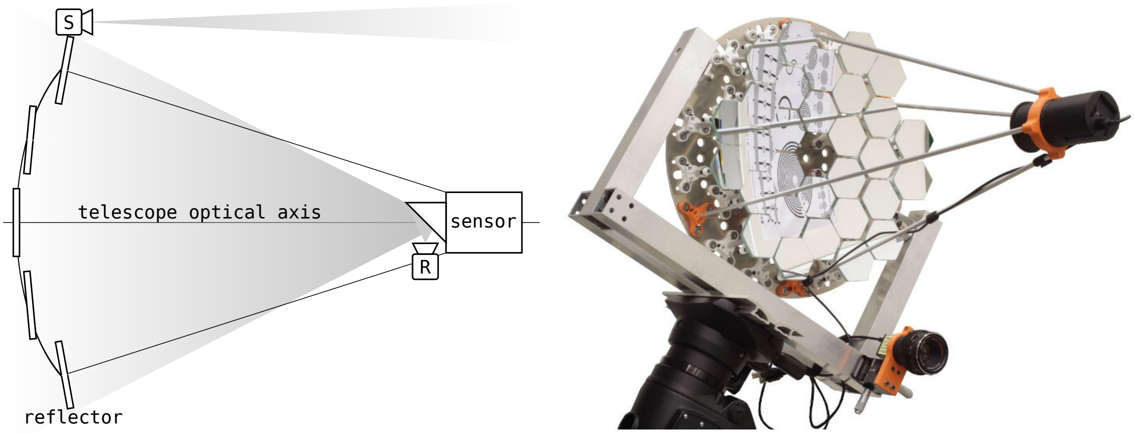

Figure 1: Our NAMOD [S]tar camera, [R]eflector camera, and their field of view on a telescope. Left: schematics with pseudo focal point. Right: NAMOD on the 1/10th scale Mini FACT test bench.

1. Introduction

Imaging Atmospheric Cherenkov Telescopes (IACT)s have brought the TeV photon sky to astronomy. Reconstructing the geometry of the Cherenkov light flashes, induced by γ-rays entering the Earth's atmosphere, IACTs need imaging systems with fast apertures and reasonable high mapping quality. Segmented reflectors give huge apertures and are built for little costs using mass production techniques. However, segmented reflectors can only provide the needed performance when the individual mirror facets are well positioned and oriented. To align the facet orientations on the 4 m class IACT FACT [1], we developed two Mirror Orientation Determination (MOD) systems. Our first method, called NAMOD, is based on the VERITAS raster alignment [2], which adopted SCCAN by Aqueros et al. [3]. On our test bench telescope Mini FACT, we enhanced the VERITAS method to deal with a wider range of night sky conditions and increased interchangeability to other telescopes. Orientations are reconstructed by recording the individual facet responses to the reflectors focal point while wobbling close to a bright star in the night sky. In our second and novel method, we use the reflector's Bokeh to determine the facet orientations. Bokeh alignment is very promising since it can be used during the day. Both methods have been performed on our 1/10 th scale test bench Mini FACT and on FACT on Canary Island La Palma, Spain.

2. Normalized and Asynchronous Mirror Orientation Determination (NAMOD)

NAMOD reconstructs the $j-$th mirror facet orientation φ_j by recording the facet's normalized response $N_{j,i}$ for various telescope pointing directions Θ_i while wobbling the telescope close to a bright star in the night sky. Two cameras, a star and a reflector camera, are recording the telescope's field of view and the reflector facets simultaneously, see figure 1. For each record i, we reconstruct the telescope pointing Θ_i, the star's light flux S_i and the flux of the facet's response in the focal point R_i. 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 R_i and S_i [4, 5]. Our star camera, geometrically calibrated, obtains the telescope's pointing Θ_i with respect to the bright star.

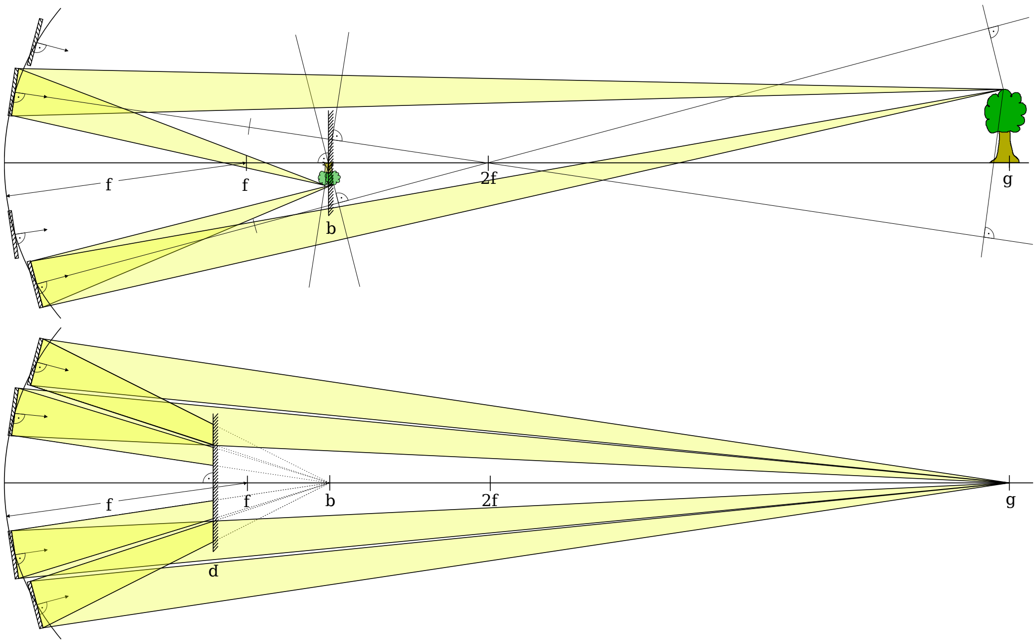

Figure 2: Upper: A segmented reflector with focal length f maps a tree in g onto its image sensor in b. Two of the four mirror rays are highlighted in yellow. Lower: The same segmented reflector facing a bulb in g during Bokeh alignment. The bulb is mapped on the Bokeh template screen in d. Both reflectors depicted are aligned.

To correct for atmospheric effects and to enable switching the reference star during recording, we normalize the facet response $N_{j,i} = R_{j,i}/S_i$. PSF histograms H^j_{PSF} are filled for each facet j with the normalized response $N_{j,i}$ according to the pointing Θ_i. From the reconstructed point spread maps H^j_{PSF}, the facet orientations φ_j are calculated using the reflection law and the telescope orientation Θ_j associated with the center of the response distribution found in H^j_{PSF}. Human and machine readable instructions are created to align the facets based on the reconstructed orientations φ_j. We call it NAMOD, since it **N**ormalizes the mirror responses and records **A**synchronously from the pointing of the telescope drive to do the **M**irror **O**rientation **D**etermination.

3. Bokeh Mirror Orientation Determination

As in every non zero aperture imaging system, segmented reflectors do have non trivial Bokeh. The concept of Bokeh functions of imaging apertures is well known in photography [6]. We make use of the very special aperture function of segmented reflectors which leads to special constraints for the reflector's Bokeh function. Using the thin lens equation and the intercept theorem, it turns out that the Bokeh function has to be a linear scaling of the aperture function when the facets are aligned [7]. Figure 2 shows a segmented reflector and the rays during normal mapping and during Bokeh alignment. To align a telescope using Bokeh, the aperture function of the reflector is acquired, scaled down and printed onto a template screen which is placed near the telescope's image sensor. The template screen can be placed in front of the sensor, e.g. on a closed sensor lid. While facing a light bulb, the heavily blurred image of the bulb on the template screen, i.e. the reflector's Bokeh, is observed. The mirror facets are now reoriented until the reflector's Bokeh matches

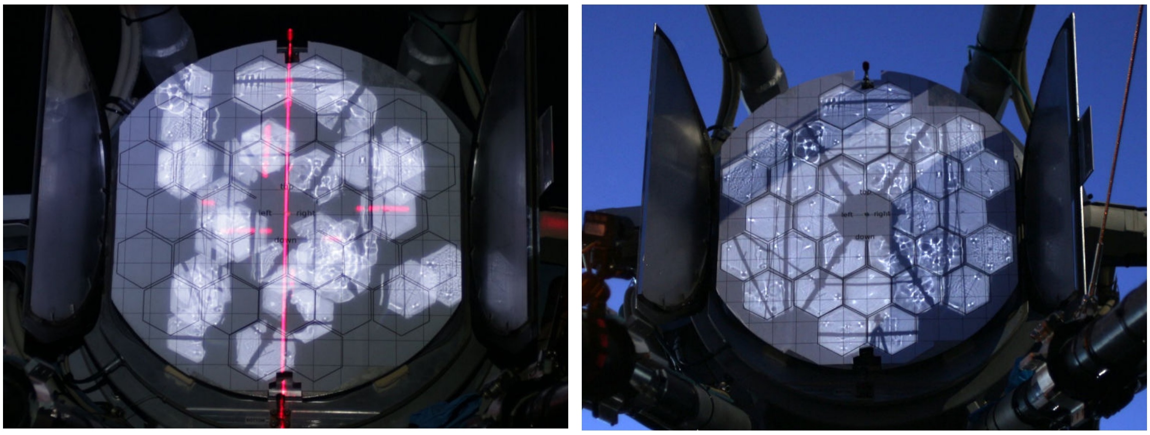

Figure 3: The not adjusted mirror facets (left) are pre-aligned to make the Bokeh fit the scaled aperture template (right).

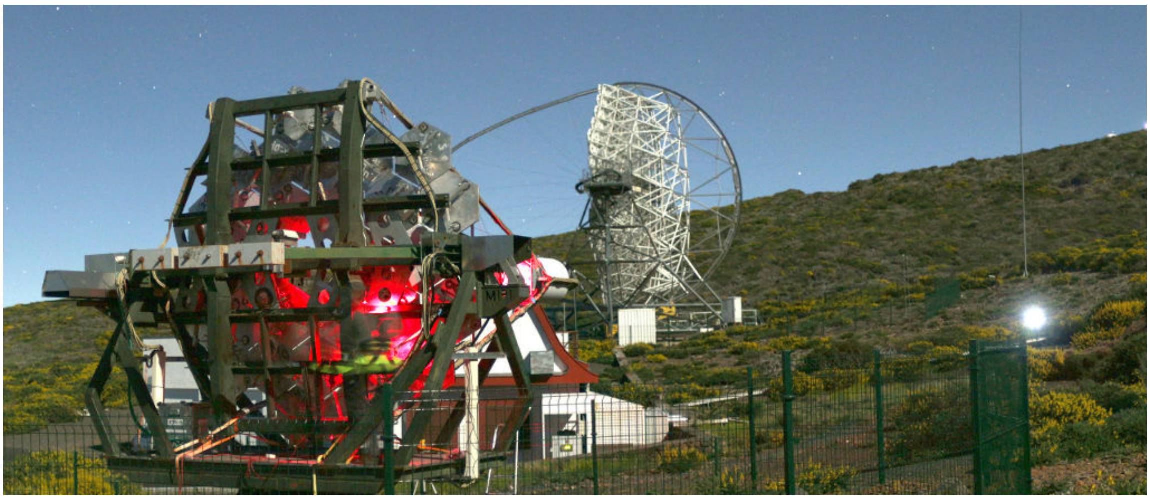

Figure 4: FACT is facing a light bulb during Bokeh alignment in dawn.

the aperture template printed onto the screen. Depending only on the power of the bulb, Bokeh alignment can be done during daytime. Although the theory assumes thin imaging systems, tests on Mini FACT and FACT gave sufficient results on Davies Cotton [8] and Paraboloid segmented reflector geometries, too.

4. Alignment of FACT in May 2014

4.1 Bokeh pre alignment

For the prealignment of FACT, we used the new Bokeh method and started with a fully non adjusted reflector after repositioning all facets. In daylight, we took a picture of the aperture function and printed it onto a template screen which was mounted in front of FACT's image sensor. Later at night, a 2.5 W LED at a distance of $\approx 50\,$m shined straight into FACT. We started the alignment during the night and finished just before sunrise with a PSF of $\approx 250\%$ the diameter of the lower limit found in ray tracing simulations [7]. While climbing the back of the reflector, Bokeh correc-

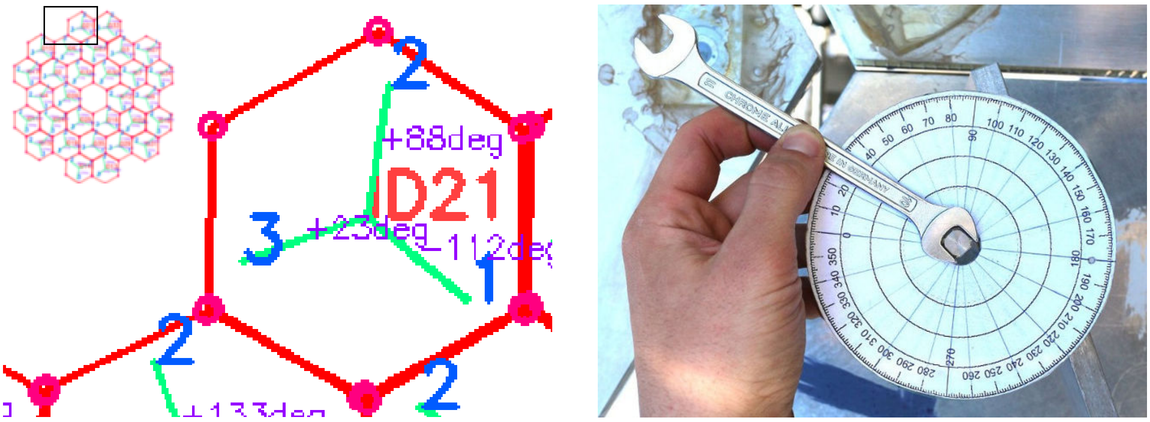

Figure 5: Detail of the instructions provided by our NAMOD and manual correction with a wrench and a goniometer. In violet: The correction rotations for the tripod mount bolts.

tions have been applied manually with a wrench based on eye hand feedback. Figure 3 shows the Bokeh template screen on FACT before and after Bokeh alignment. Two operators worked on two separate mirror facets simultaneously.

4.2 NAMOD fine alignment

For the fine alignment of FACT, we installed our NAMOD system as shown in figure 1. The star camera was mounted on the reflector structure with a screw clamp and the reflector camera was put into FACT's pseudo focal point provided by a 45° mirror. After choosing a bright object in the night sky by eye, FACT pointed and wobbled close to this object. On the small size FACT, we do not struggle with gravitational slump [7] and therefore chose the brightest planets or stars, regardless of their elevation. Our NAMOD program controlled the cameras and recorded the telescope's pointing relative to the bright object and the facet responses for each facet and pointing. The NAMOD program showed us where pointings are missing or where they are already dense enough. FACT wobbled by either manual joy stick control or by scripting some wobbling. After 1 h of acquisition, NAMOD took ≈ 1 k records. Fed the tripod geometry of FACT, NAMOD was not only able to provide the facet orientations, but also provides the corrections needed for the joints of each tripod. Corrections are applied manually to the reflector during daytime using a goniometer and a wrench, see figure 5. Starting with the pre aligned reflector using Bokeh alignment, our NAMOD further reduced the PSF from $\approx 250\%$ down to 142% of its lower limit. Figure 6 shows the overall PSF before and after the alignment together with the reflector camera view.

We did direct PSF recordings before and after every alignment run using our $6 \times 6\,\mathrm{cm}^2$ digital image sensor placed in FACT's pseudo focal point. This way we obtained 0.42 Mpixel images of the overall reflector PSF. By taking exposure time series with our dedicated PSF sensor, we have been able to acquire the overall PSF with high dynamic range to compare it with ray tracing results.

Additional recordings with NAMOD are done before and after alignment to feed the reflector status from before and after the alignment to the FACT Monte Carlo simulation. Reconstructions of muon events show a reduction of the muon ring width in muon event images caused by the Bokeh and NAMOD alignment, see [9].

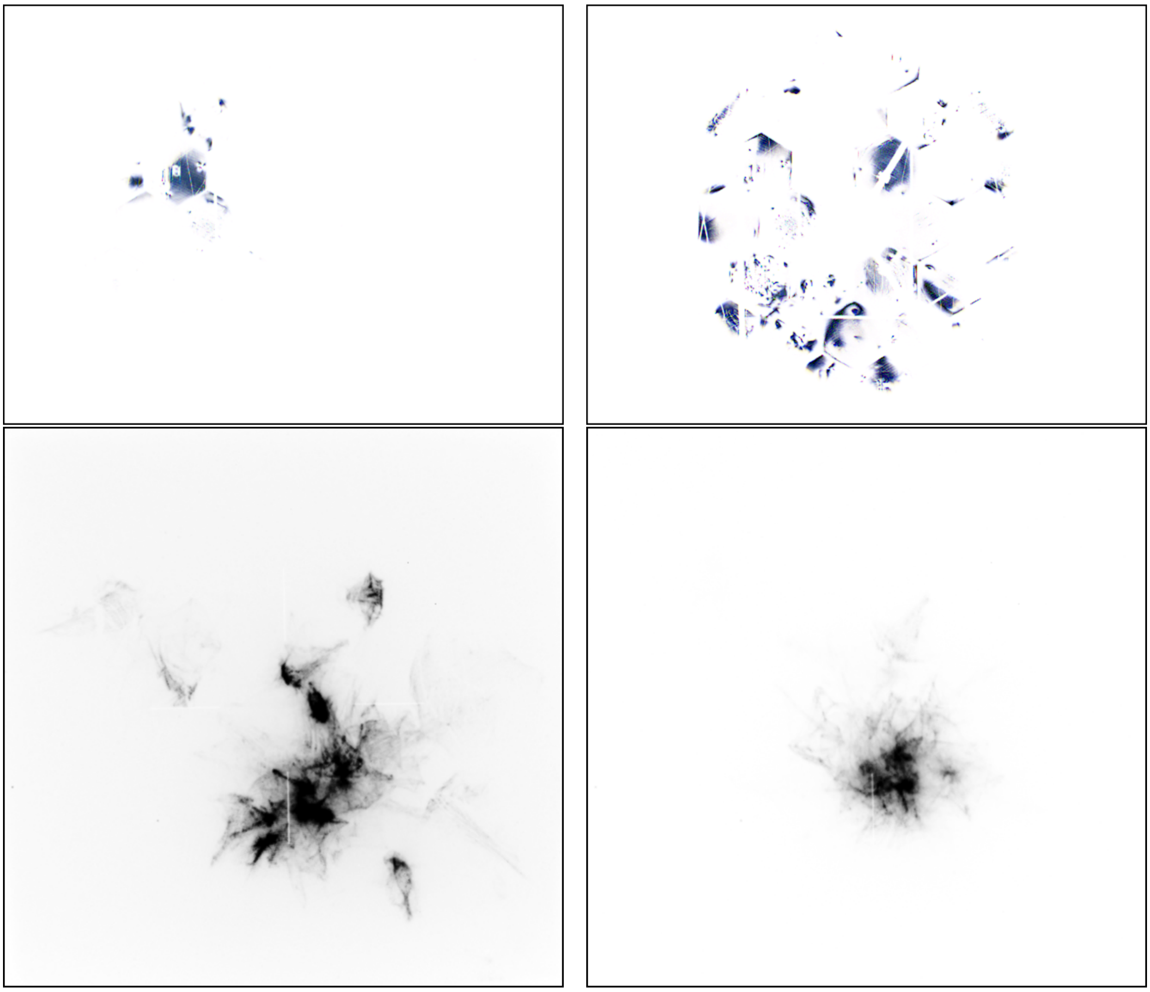

Figure 6: Reflector camera view on top, overall PSF below. Left: before Bokeh and NAMOD alignment. Right: 142% PSF after alignment. All images in inverted color. PSF image taken with our dedicated $6 \times 6\,\mathrm{cm}^2$ sensor, i.e. FoV is $0.7^\circ \times 0.7^\circ$.

5. Discussion

Our NAMOD system was successful during its initial run on FACT, La Palma, Spain. The overall PSF of FACT is now closer to its lower limit then ever before and limitations of previous alignment methods have been overcome [10]. The preparations on Mini FACT payed off well during the work at night on FACT. No unexpected situations have been encountered during NAMOD's first run on FACT. The feedback of our NAMOD, crucial to keep track of the recorded field of view, proved to work during recording on FACT. The stars light flux S recorded by NAMOD is shown in figure 7. We see vanishing flux S with rising zenith distance as well as a jitter, far higher then during lab calibration, which is caused by the atmosphere. Both variations motivate the normalization done by NAMOD. A single hour of recording with our NAMOD was enough to fine align FACT. A second 2.3 h run with over 5 k records was taken one year later in 2015 and showed noticeable higher resolution which can be used to inspect the individual facet PSFs in more detail.

The new Bokeh alignment was also successful on FACT. We achieved an overall PSF good

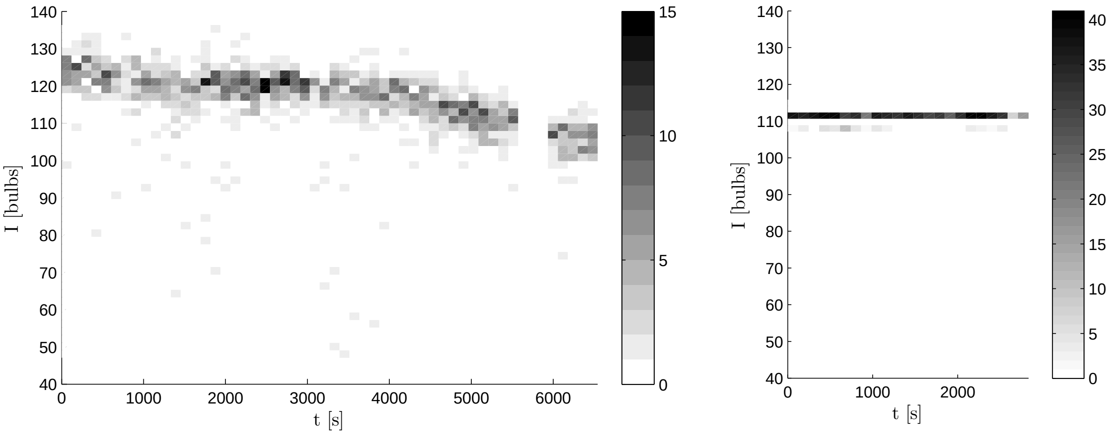

Figure 7: Left: Star light flux *S* in calibration units of bulbs taken during a NAMOD recording on a setting star on La Palma, Spain. Right: The steady flux of a bulb observed on Mini FACT in the lab.

enough to operate FACT after starting with totally non-adjusted facets from a freshly reworked reflector. With no preparation, the Bokeh lamp and the Bokeh template screen have been crafted on site. The fully manual Bokeh alignment of FACT was more challenging then the one on Mini FACT, since we had to climb on the reflector's back and had to watch on the template screen in over 5 m distance. Needing only a bulb, a consumer photo camera, a desktop printer, and a level, Bokeh alignment was cheaper and faster compared to computer vision based solutions like our NAMOD. The NAMOD gave the better result but the development time of our Bokeh system was only about 1% of the time needed to develop the NAMOD system.

Bokeh alignment in direct sunshine was performed on Mini FACT and worked well. Using a consumer photo speedlight, we observed the Bokeh on FACT with direct sunlight on the template screen, too. This shows that it is possible to align a segmented reflector during the day using Bokeh MOD to not overlap with astronomical observations. We already demonstrated Bokeh MOD on the full scale IACT FACT during dusk and dawn.

A drawback to Bokeh alignment is the need to face a light bulb with the telescope which makes it hard to check the alignment at various elevations. Bigger telescopes might have significant bending which needs to be taken into account.

Of course both our methods NAMOD and Bokeh MOD can also be combined with segmented reflectors which have computer based Active Mirror Control (AMC).

6. Conclusion

Our computer vision based NAMOD system, inspired by the VERITAS alignment system, fine aligned two very different telescopes pushing both close to their maximum performance found in ray tracing simulations.

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

Bokeh alignment showed acceptable alignment performance on FACT in its first use on an IACT ever. Future autonomous Bokeh systems, which observes the reflector's Bokeh using a camera and a speedlight during daytime, are in range now and the next step to go for.

Acknowledgements

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