

A common mirror test facility for the Cherenkov Telescope Array

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My goal is simple. It is a complete understanding of the universe, why it is as it is and why it exists at all... . We see the universe the way it is because if it were different, we would not be here to observe it.

Stephen Hawking, former Lucasian Professor of Mathematics, Washington Post newspaper, 15 April 1988.

Eidesstattliche Erklärung

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A common mirror test facility for the Cherenkov Telescope Array

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Tübingen, den 26.10.2016

Stephanie Göggelmann

Abstract

Aims: Development and characterization of a new, common mirror test facility for the Cherenkov Telescope Array (CTA) in order to measure the reflectivity and the Point Spread Function (PSF) of the spherical telescope mirror files in a wavelength range from 310 - 525 nm.

Methods: The mirror is placed at a distance equal to twice its focal length away from a screen. First, a reference measurement is executed: The direct measurement of the amount of light emitted from a light source, i.e. in this case the flux through a predefined area, is done. Therefore, the light, which is emitted by the light source, impinges directly on a screen and causes a light spot, which is photographed by a CCD camera. Second, the light spot, which is reflected by the mirror, is measured. Thus, parts of the mirror test facility are turned around in such a way that the light from the light source falls onto the surface of the mirror, becomes reflected and then impinges on a screen. By doing so, the same screen is used and the setup camera to screen is kept stable. The resulting light spot on the screen is photographed by a CCD camera. This CCD image of the reflected light is used to calculate the PSF of the mirror. The reflectivity of the mirror is given by the ratio of the integral of the light intensity over the reference spot and the integral of the light intensity over the reflection spot.

Results: The new test facility provides a vast time saving in comparison to the old test facility built for H.E.S.S. mirrors: A measurement with the new facility takes about 10 minutes, while the same procedure with the old test facility lasts about 7-18 hours, depending of the mirror size. With the new test facility, a complete mirror measurement process, including mounting and (un)packing the mirror, can be done in about one hour. A user-friendly analysis software, which includes the latest CTA requirements and a reliable control software for both the light source and the CCD camera has been developed within this work and is now operative. Furthermore, the study of systematic errors like the reproduction scale of the CCD camera, has been investigated.

Conclusions: The new 2f measurement facility is working rapidly and efficiently in principle, but more analysis of some underlying systematics are required for an

overall-improvement of the facility. Additionally, further investigations concerning e.g. the light source, are necessary and some components of the facility should be improved, in order to ensure an inaccuracy of the measurements of less than 1%.

Zusammenfassung

Zielsetzung: Entwicklung und Charakterisierung eines neuen Spiegelteststandes für das Cherenkov Telescope Array (CTA), der es ermöglicht, die Reflektivität und die Punktabbildungsfunktion der sphärischen Teleskopspiegelteile in einem Wellenlängenbereich von 310 - 525 nm zu messen.

Methode: Der Spiegel wird in einem Abstand, der seiner doppelten Brennweite entspricht, vom Schirm entfernt aufgestellt. Zunächst wird eine Referenzmessung durchgeführt: Es wird die Gesamtmenge des von der Lichtquelle emittierten Lichts direkt gemessen, d.h. in diesem Fall der Fluss durch eine festgelegte Fläche. Dazu fällt das Licht, das die Lichtquelle verlässt, direkt auf einen Schirm und erzeugt dort einen Spot, der von einer CCD Kamera fotografiert wird. Für die darauffolgende Messung des von einem Spiegel reflektierten Lichts wird der Messstand nun derart gedreht, dass das aus der Lichtquelle austretende Licht auf den Spiegel trifft, dort reflektiert wird und wiederum auf einen Schirm trifft. Dort wird der reflektierte Lichtspot mittels einer CCD Kamera aufgenommen. Durch die Drehung des Messstandes kann der gleiche Schirm sowohl für Referenz- als auch für Spiegelmessung verwendet werden und der Aufbau von Kamera und Schirm kann stabil gehalten werden. Das erhaltene CCD Bild des Lichtspots wird dazu benutzt, die Punktabbildungsfunktion (PSF) des Spiegels zu bestimmen. Die Reflektivität des Spiegels ist gegeben durch den Quotienten des Integrals der Lichtintensitäten des Referenzspots und des Integrals der Lichtintensitäten des reflektierten Lichtspots.

Ergebnisse: Der neue Spiegelmessstand bietet eine enorme Zeitersparnis gegenüber dem alten Spiegelmessstand, der für Spiegel des H.E.S.S. Experiments gebaut wurde: Die Messdauer des neuen Messstandes beträgt etwa 10 Minuten, wohingegen dieselbe Messung mit dem alten Messstand etwa 7-18 Stunden dauert (abhängig von der Größe des zu messenden Spiegels). Ein kompletter Messprozess einschließlich Montage des Spiegels, Aus- und Einpacken kann mit dem neuen Messstand innerhalb einer Stunde vollzogen werden. Der neue Messstand ist ausgestattet mit einer benutzerfreundlichen Analysesoftware, die die bis dato aktuellsten Auflagen der CTA Kollaboration enthält, sowie einer zuverlässig funktionierenden Steuerungssoftware für die Lichtquelle und die CCD Kamera. Außerdem wurden systematische Fehler, wie z.B. der Abbildungsmaßstab der CCD Kamera, untersucht.

Fazit: Die neue 2f-Messmethode funktioniert im Prinzip schnell und zuverlässig, jedoch ist eine weiterführende Analyse einiger zugrundeliegender Systematiken ratsam, um ein komplettes Verständnis aller Komponenten des Messstandes zu erlangen. Zudem sollten weitere Untersuchungen einzelner Komponenten, z.B. der Lichtquelle, durchgeführt werden. Einige Komponenten sollten ausgetauscht oder verbessert werden, um eine Ungenauigkeit der Messungen von weniger als 1% garantieren zu können.

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1 Introduction

Astronomy has always been a part of the human culture and astronomical observations already started in the Stone Age ([20]). Out of the early observations of the moon, some planets and the stars, which were performed just by eye, the classical-geometrical astronomy evolved. A new window to modern astronomy was unbolted by Galileo Galilei, who performed observations with optical telescopes in 1609. In the same year, Johannes Kepler published in his work *Astronomia Nova* the fundamental laws of planetary movements. About three centuries moulded by big progresses and stunning inventions and observations followed, until 1912, driven by the discovery of cosmic rays by Victor Hess ([22]), for which he received the Nobel Prize in 1936, a new era in astronomy began: Astroparticle physics as a new field of research was born. Today, the energy spectrum of cosmic rays is, probably, one of the most famous diagram in modern physics. Including more than 12 orders of magnitudes, it has been called “*one of the seven world wonder of the world of physics*.”([23]).

1.1 Cosmic rays

Cosmic rays are charged and stable high-energy particles which propagate through the interstellar or even intergalactic medium. When they reach the Earth’s atmosphere, they produce showers of secondary particles. A large part, 85%, of the charged primary cosmic rays encountering the Earth’s atmosphere are protons, 12% are helium nuclei and 1% are nuclei of heavier elements up to uranium. The remaining 3% of the primary cosmic rays are electrons ([18]). Figure 1.1 shows the relative particle flux of incoming cosmic-ray particles as a function of their energy in the Earth’s lower atmosphere. The energy spectrum of cosmic rays can be described with a power law with an index varying with the energy range ([24]):

- $10^{10} \text{ eV} < E < 10^{15} \text{ eV}$: The index of this region, with the ‘knee’ at 10^{15} eV , is -2.7.

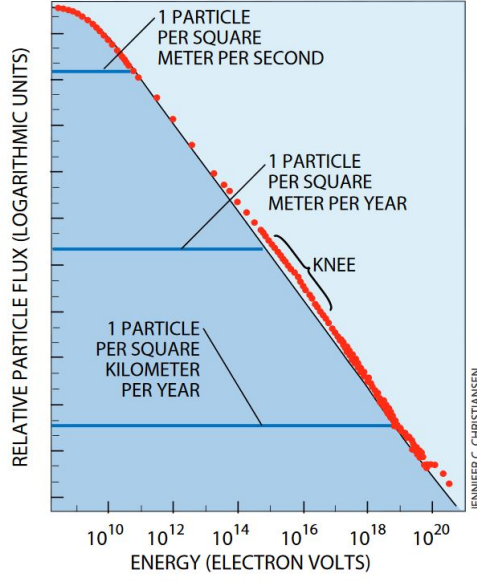


Figure 1.1: The relative particle flux of incoming cosmic-ray particles in logarithmic units as a function of their energy. Taken from [7].

- $10^{15} \text{ eV} < E < 10^{18} \text{ eV}$: The index of this region, with the 'ankle' at 10^{18} eV , is -3.
- $E > 10^{18} \text{ eV}$: The index of this region is again -2.7.

Almost all of the incoming cosmic-ray particles have higher energies than those which can be reached in thermal processes, also the power law is a hint to this. Thus, cosmic rays seem to originate from cosmic accelerators and are not produced in thermal processes ([24]). In a simplified picture, the cosmic-ray particles with energies below $\sim 10^{10} \text{ eV}$ can be considered to be of solar origin. Particles above the ankle are certainly extragalactic and particles above the knee are almost certainly still galactic. The transition must be in the region between 10^{15} eV and 10^{18} eV ([24] and [12]).

One theory for a non-thermal process, which is able to produce such high-energetic particles, is the diffuse shock acceleration or first order Fermi acceleration ([24]). The diffuse shock acceleration describes a strong shock, that propagates through the interstellar medium, e.g. shock waves propagating through the interstellar medium forwards the supersonic shells of SNRs. A flux of high energy particles, which have velocities close to the velocity of light, is assumed to exist in front of and also behind the shock front. Because of the high velocity of the particles, they propagate much faster than the shock wave. Scattering of the particles, which propagate through

the shock front, which is caused by streaming instabilities or turbulent motions on either side of the shock wave, leads to a velocity distribution of the particles, which is isotropic in the reference frame of the moving fluid on both sides of the shock front. When a particle passes through the shock front, it gains energy and there are no crossings which lead to a decreasing energy. In the up- and downstream region of the shock the particle can be reflected by turbulent magnetic fields. But the probability is not high and hence, the flux of the particles, which are accelerated by this process, can be described by a power law with the index -2. This is not in consistence with the above described power law of cosmic rays, but the difference can be explained by an escape of the cosmic rays, which depends on their energy which is able to change the index of the power law to -2.7. Once a particle is reflected away from the shock front, it is gone and can not pass through the same one again. The ankle and the knee in the spectrum of cosmic rays can then be explained by either a change in the type of the source or the production process or a change in the effectivity of the production of particles with exactly these energies.

The theory of diffuse shock acceleration presumes the existence of a shock front and a free charged particle. In high-energy astronomy, there are two common sources for shock fronts, supernova remnants (SNR) and active galactic nuclei (AGN). Data from the Fermi Space Telescope showed in 2013 that a significant fraction of cosmic rays have their origin in the shock fronts of supernova explosions (see [14]): There are two well-established ways for creating a supernova: Either a white dwarf in a binary system accretes mass from its companion star, until the Chandrasekhar limit, $M_{\text{Chandrasekhar}} = 1.4587 \cdot M_{\odot}$, is reached. After reaching this limit, a gravitational collapse occurs. Type Ia supernova explosions feature a thermonuclear runaway explosion and nothing is left. In the other case neutron star or black hole is left. The other way for creating a supernova is the end of the life of a massive star with $M > 8M_{\odot}$. Such stars die in supernovae explosions, in which the stars eject most of their mass into the space, while the inner parts of the star implode. The ejected material reaches velocities greater than the speed of sound, more than 10% of the speed of light, and forms supernova remnants with shock fronts. The shock slows down when it sweeps up in the interstellar medium, but the time scales are large. The brightest shell-type SNR of the TeV gamma-ray sky is RX J1713.7-3946 [13]. Besides SNRs, which are reserved for cases where the shocks of the expanding matter is producing the emission, there are also pulsar wind nebula (PWN). PWNs are one of the most extreme particle accelerators in galaxies, they are accepted as multi-TeV



Figure 1.2: Composite image of the Crab Nebula, based on data taken by the Karl G. Jansky Very Large Array, the Spitzer Space Telescope, the Hubble Space Telescope, the XMM-Newton Observatory, and the Chandra X-ray Observatory. Credit: NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires).

electron- and positron sources and they are one of the dominant classes of Galactic gamma-ray sources ([32]). A PWN is located inside of a shell of a SNR which is powered by pulsar winds of a central pulsar. Pulsar winds are a flux of high energetic particles. When high energetic particles enter the nebula, shock waves come into existence because of the slowdown of the particles. PWNs generate no shell structure, but become brighter and brighter towards the centre, in contrast to the conventional SNRs. PWNs are sources of high-energetic γ -rays, like AGNs or SNRs - but first cosmic rays are produced, which in terms produce gamma rays. It is known, that in PWNs this is mainly electrons. The most famous PWN is the Crab nebula, which is presented in figure 1.2.

Another source of cosmic rays are active galactic nuclei ([24]). In the centre of galaxies, there is usually a black hole, which can accrete matter from their local neighbourhood. This matter does not directly fall into the black hole, but forms a disk around it. Accelerated particles, which propagate on magnetic lines can form jets perpendicular to the disk of accreted matter. If the black holes produce jets

which are more luminous than all other stars in the respective galaxy, they are called AGNs. There are also shock fronts propagating through the jets, which allow diffuse shock acceleration of charged particles. Besides this, the decay of high-mass dark matter particles is supposed to be a mechanism for the production of high energy cosmic rays.

Note, that by now, the question of the origin of cosmic rays, can not finally be answered. However, the sources of cosmic rays are expected to be both galactic and extragalactic, but most of the cosmic rays have their origin outside the solar system. The charged high-energy particles, which are produced by a cosmic accelerator, become redirected by Lorentz forces just after their formation and therefore, they lose the information about their direction of origin. Furthermore, charged high-energy particles interact with the galactic magnetic field during their propagation through the space, which results in randomly distributed directions when these particles reach the Earth. This is why the high energy photons, which are also produced by the sources described above, are objects much more worthwhile to study: They do not interact with the galactic magnetic field and are also not influenced by the Lorentz forces. When the high-energy photons reach the Earth, they still carry the information about the directional information of their source. By measuring the spectra of gamma-rays, one can get information about the underlying particles.

1.2 Ground-based γ -ray astronomy

The energy range of γ -ray photons starts at about 100 keV. The energy ranges for the gamma-ray interaction mechanisms - Photoelectric effect, Compton scattering and Pair production - are shown in Figure 1.3.

- The **photoelectric effect**, i.e. the ejection of an electron from an atom (usually from the K or L shells), caused by a photon. This photon becomes completely absorbed and its energy is completely transmitted to the atomic electron. As a result, characteristic X-rays and Auger electrons are emitted when the atom de-excites. This effect dominates the energy range between 100 keV and 1 MeV.
- At higher energies, **Compton scattering** becomes dominant: A loosely bound electron is scattered off by a gamma ray. The electron loses only a part of its energy and recoils in a direction while the gamma is scattered in another direction with a smaller energy.

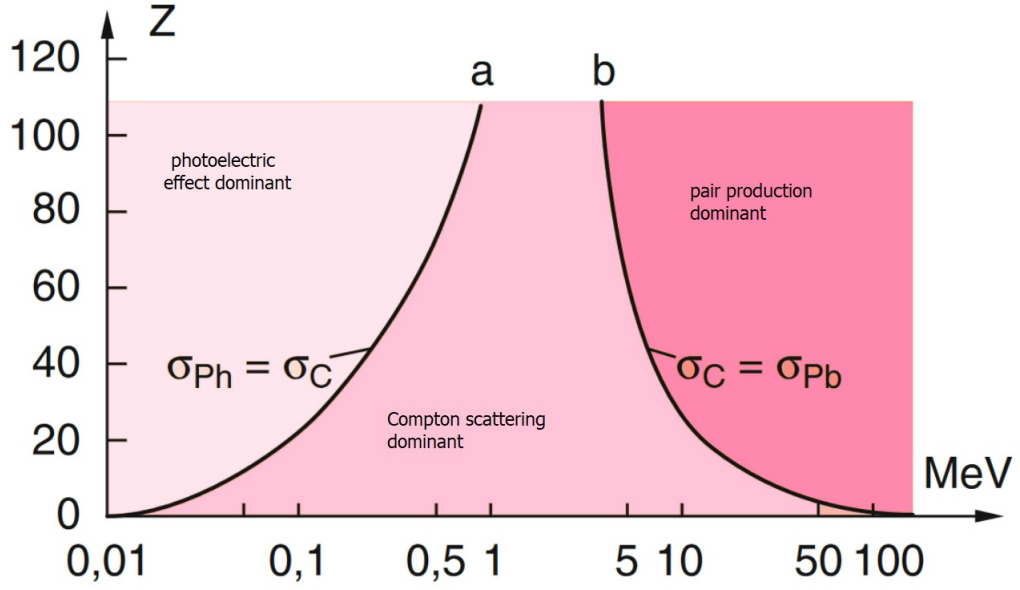


Figure 1.3: The dominant energy-loss mechanisms for electro-weak interacting particles in dependency on their energy and the atomic number Z of the absorber, based on [11] (modified).

- **Pair production** dominates the highest energies ($E > \sim 10$ MeV). Pair production means that a photon of $E_{\min} = 1022$ keV is annihilated and an electron-positron-pair is created. This process has to take place in the field of a nucleus of another electron, because conservation of energy and momentum would not be possible for a photon in a vacuum.
- **Inverse Compton Scattering:** A high-energetic charged particle is scattered on a low-energy photon. Energy is transferred from the charged particle to the photon.
- **Pion decay** The neutral pion π^0 decays via electromagnetic interactions into two photons, $\pi^0 \rightarrow \gamma + \gamma$. The charged pions underlie the weak interaction and decay into pairs of a lepton and a neutrino, as described below.

Cosmic rays will induce hadronic showers, when they interact with the Earth's atmosphere. Leptons will induce electron-photon showers in the upper atmosphere ([24]). While a simplified scheme of the development of hadronic showers caused by the collision of a primary cosmic-ray particle with a particle from the Earth's atmosphere (in the picture a nitrogen atom), Figure 1.5 shows the principle of origin of a Gamma shower in the Earth's atmosphere, induced by a high-energy cosmic-ray

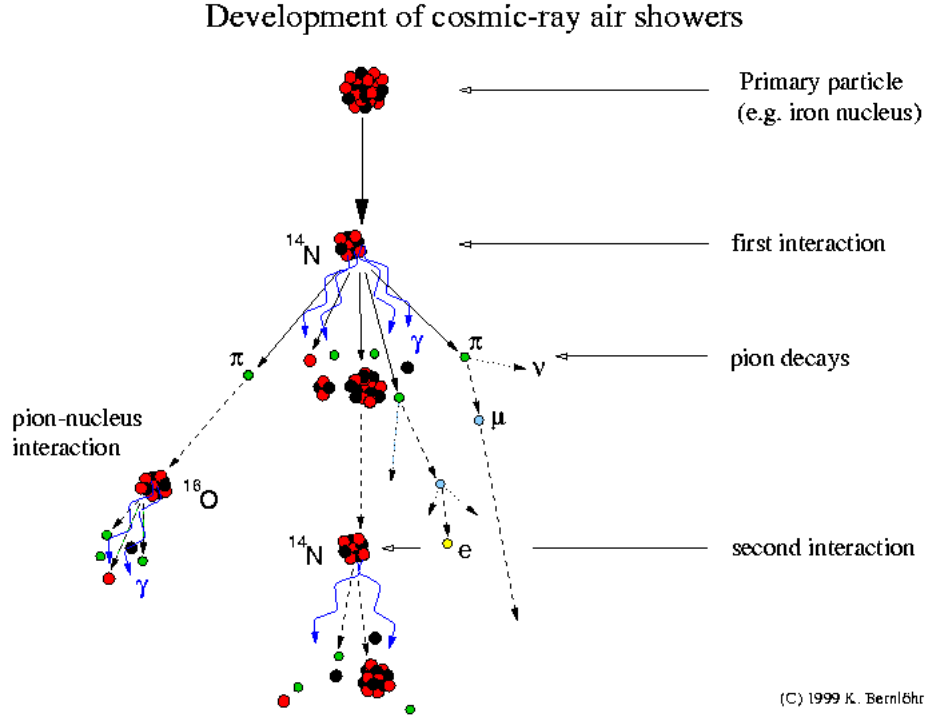


Figure 1.4: Simplified scheme of the development of hadronic showers caused by the collision of a primary cosmic-ray particle with a particle from the Earth's atmosphere. Credit: K.Bernlöhr, MPIK

particle as a mechanism for losing energy.

The high energy collisions in the upper atmosphere induce showers of lighter particles. Kaons and pions are produced, which cause muons by the following decay branches ([24]):

$$\begin{aligned}\Pi^+ &\longrightarrow \mu^+ + \nu_\mu \\ \Pi^- &\longrightarrow \mu^- + \bar{\nu}_\mu.\end{aligned}$$

K^+ can either produce directly muons or indirectly by decay into a pion. Note, that K^0 and $\bar{K}^0$ cannot decay directly into muons (branching ration $< 10^{-4}\%$, according to [4].)

More than 50% of the cosmic radiation - measured at sea level - are muons ([37]), the others are electrons, positrons and γ particles from cascade events. Due to the high energies of the originally incoming cosmic-ray particles, most of the charged particles produced by cascade events are ultra-relativistic, their velocities exceed the

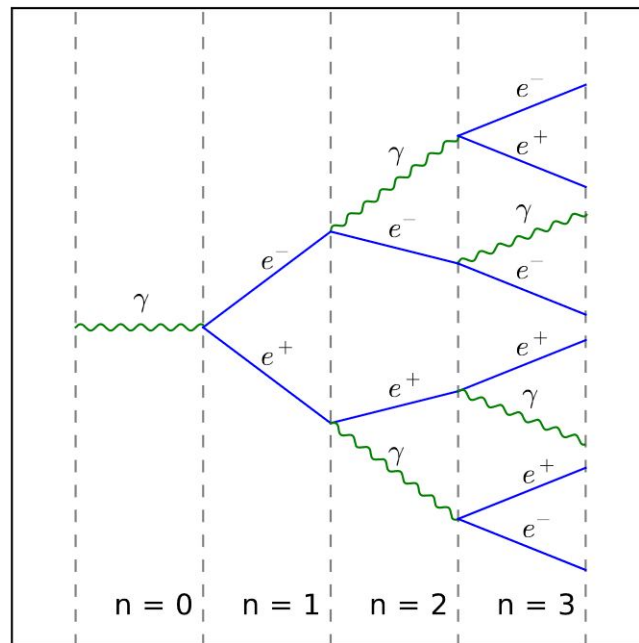


Figure 1.5: The principle of origin of an electromagnetic shower in the Earth's atmosphere, induced by a high-energy particle. A incoming high energy gamma performs pair production or emits bremsstrahlung. One single gamma induces a multitude of electromagnetic particles in a shower. Taken from [36].

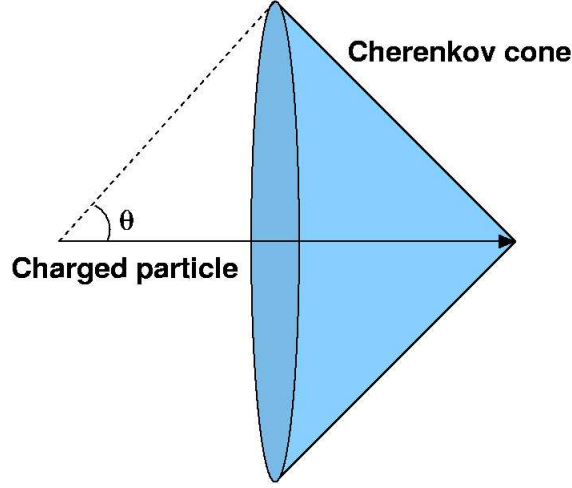


Figure 1.6: The geometry of the formation of a Cherenkov cone, taken from [26].

speed of light in air and so, Cherenkov radiation is emitted. The emission angle is

$$\Theta_C = \arccos\left(\frac{1}{n\beta}\right),$$

with n the refractive index of the medium and $\beta = \frac{v}{c}$ the velocity of the particle relative to the speed of light ([18]). The Cherenkov photons are emitted isotropically in azimuth, for relativistic particles the Cherenkov angle is 42° in water and 1.4° in air ([18]). The direction of the trajectory of the incident primary photon determines the axis of the resulting Cherenkov cone, whose geometry of the formation can be seen in Figure 1.6. A single charged particle produces about 220 photons per centimetre in water and 30 photons in the atmosphere ([18]). These photons can be detected either with water Cherenkov Telescopes, e.g. HAWC or Milagro, or with Imaging Air Cherenkov Telescopes, e.g. VERITAS, H.E.S.S., MAGIC. With IACTs, photon-induced electromagnetic showers can be detected and differentiated to the more numerous hadronic cascades. Hadronic showers show an isotropic behaviour (because of the above mentioned isotropic distribution of cosmic rays), while photons point back to their sources. Figure 1.7 shows characteristic Cherenkov patterns for both electromagnetic and hadronic cascades, which can be explained by the different interaction mechanisms. Identifying photon-induced electromagnetic showers is the big advantage of IACTs.

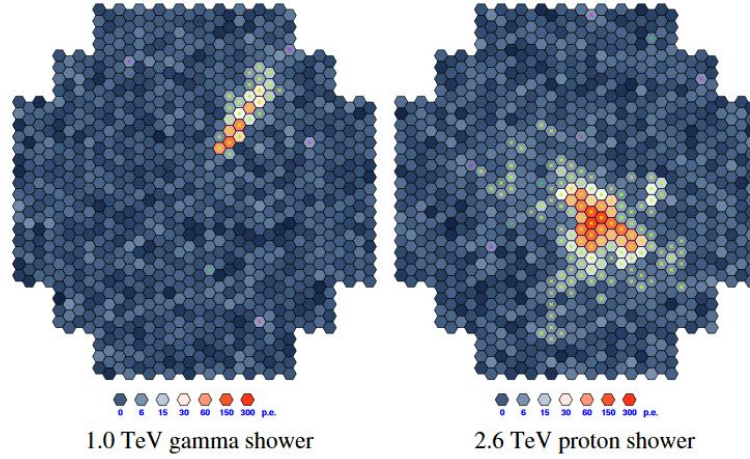


Figure 1.7: Characteristic Cherenkov patterns for both electromagnetic and hadronic cascades, taken from [33].

1.3 Imaging Air Cherenkov Telescopes

Figure 1.8 shows the Cherenkov spectrum and the Night Sky Background spectrum. The Cherenkov spectrum peaks at ~ 330 nm. The spectrum of Cherenkov light determines the wavelength range in which Imaging Air Cherenkov Telescopes (IACTs) operate. Because of the ~ 330 nm peak of the Cherenkov spectrum, the mirrors used for the Cherenkov telescopes should have a good reflectance and PSF at this wavelength. Therefore, with the new mirror test facility at IAAT, the mirrors are measured down to 310 nm.

Ground-based stereoscopic observations with two or more telescopes are an advanced observation method for air showers. The technique of IACT observations have been first used at the Whipple telescope in 1968 ([34]). Though the technique works also with one telescope, it is much more reliable to observe the sky with more than one telescope. With stereoscopic observations, each telescope can detect the Cherenkov light in the atmosphere from a different angle and this provides multiple pictures of the observed event. The schematic idea of stereoscopic observations of Cherenkov light with more than one telescope is illustrated in Figure 1.9. Evaluating the elliptical images of the electromagnetic cascades, the origin of the air shower is located where the extended major axes of the ellipses meet. For a detailed description of the image reconstruction, see [21]. The reconstruction of the air shower works with sufficient precision and the more telescopes are used, the more individual images of the source can be taken and the better is the reconstruction. At least two telescopes

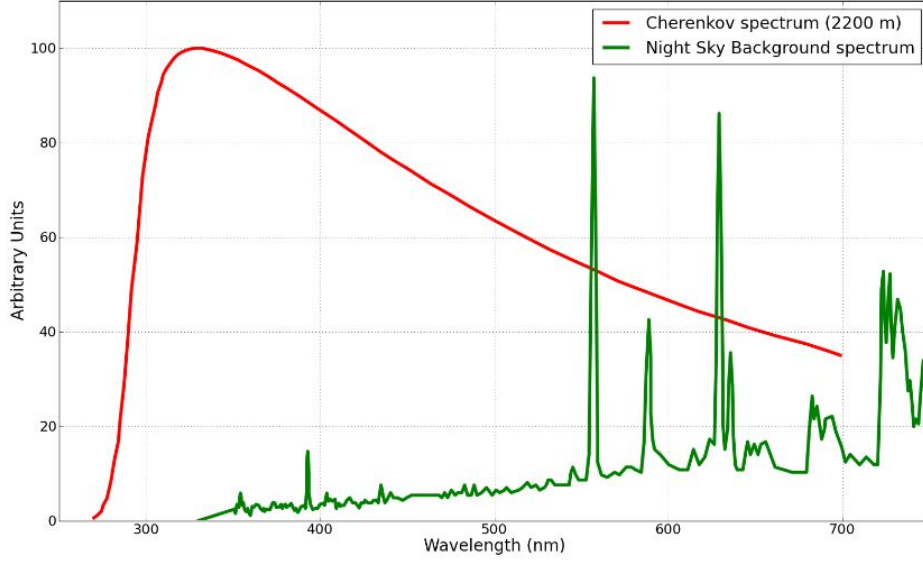


Figure 1.8: The spectrum of the Cherenkov light in comparison to the Night Sky Background spectrum, taken from [5].

have to observe the same shower.

Running major IACTs are VERITAS (Very Energetic Radiation Imaging Telescope Array System), MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes) and H.E.S.S. (High Energy Stereoscopic System). These telescope arrays consist of each 2-5 telescopes.

1.4 The Cherenkov Telescope Array - the next generation IACT

With the observational results of the currently existing IACT-experiments, new questions arose. It is indispensable to get more and better observational data of the respective areas. The Cherenkov Telescope Array (CTA) will be the most powerful system of IACT up to the present. Figure 1.10 shows the sensitivity of CTA in comparison to the sensitivity of current running IACTs.

CTA will likely consist of 19 telescopes on the northern hemisphere and 99 telescopes on the southern hemisphere and will provide full-sky coverage. Nevertheless, CTA will still do pointed observations and is not foreseen to do an all-sky survey, although galactic plane surveys and selected extragalactic field surveys will also be done.

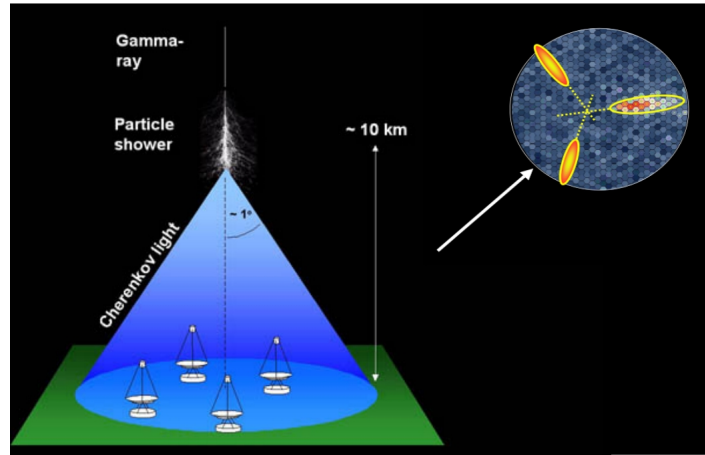


Figure 1.9: Schematic principle of stereoscopic observations of Cherenkov light with a multitude of telescopes, taken from <http://www.isdc.unige.ch/cta/outreach#Analysis?en>, 14.08.2017

There will be three telescope sizes included into the array ([1]):

- **Small Size Telescope (SST):**
 - $\sim 4 \text{ m}^2$ dish diameter
 - $\mathcal{O}(\sim 8 \text{ m}^2)$ effective mirror area
 - 8-10 deg field of view
 - covers the high energy range up to $\sim 300 \text{ TeV}$
- **Middle Size Telescope (MST):**
 - $\sim 12 \text{ m}^2$ dish diameter
 - $\mathcal{O}(\sim 100 \text{ m}^2)$ effective mirror area
 - 6-8 deg field of view
 - Energy range: $100 \text{ GeV} - 10 \text{ TeV}$
- **Large Size Telescope (LST):**
 - $\sim 23 \text{ m}^2$ dish diameter
 - $\mathcal{O}(\sim 400 \text{ m}^2)$ effective mirror area
 - 4-5 deg field of view
 - covers the low-energy range with an energy threshold of a few GeV.

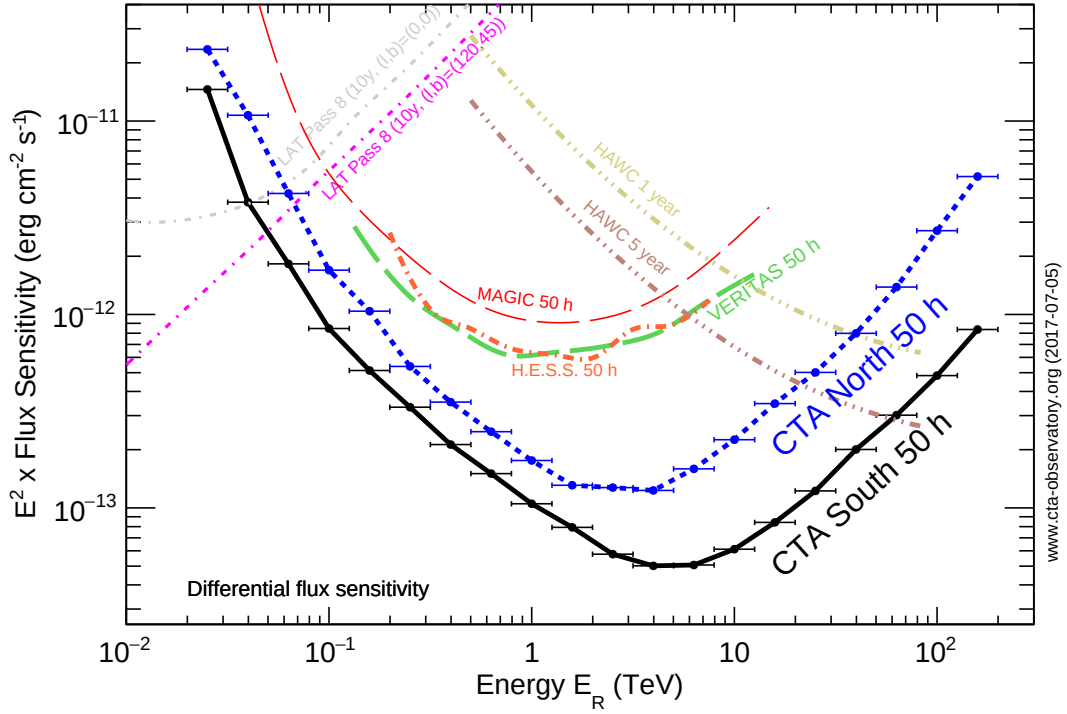


Figure 1.10: Sensitivity of the CTA experiment in comparison to the sensitivity of other gamma-ray observing instruments in the high-energy sector. Credit: Gernot Maier, DESY Zeuthen

While the LST comes with only one design, at this juncture there are two designs for MST and four designs for SST, including one dual-mirror Schwarzschild-Couder telescope design for MST and two for SST.

CTA will cover the energy range from ~ 20 GeV up to 300 TeV. For a full-sky coverage, CTA will be built at sites located both on the northern (La Palma, Spain) and on the southern hemisphere (ESO/Paranal, Chile). It is planned to build 4 LSTs and 15 MSTs on the northern site and 4 LSTs, 25 MSTs and 70 SSTs on the southern site. The whole project will cost approx. 200-300 M€. About 1350 members from 210 institutes in 32 countries are involved into the CTA project. Figure 1.11 shows a possible conceptual layout for CTA (not to scale).

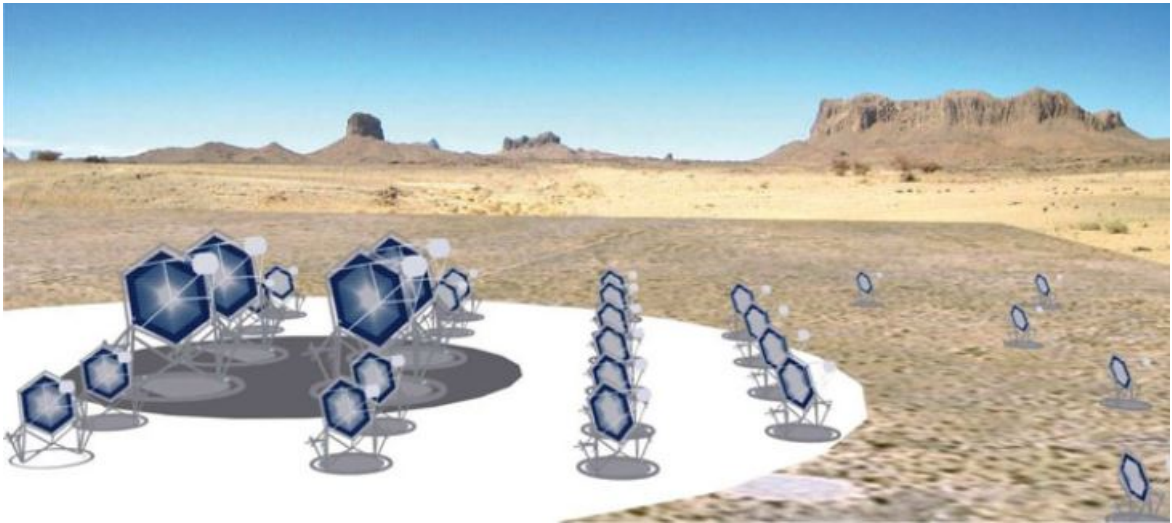


Figure 1.11: Not to scale conceptual layout for CTA, taken from [8].

1.5 The Common Technology Evaluation, Testing and Calibration project

CTA is subdivided into different projects. The Common Technology Evaluation, Testing and Calibration project (COM-project) is, in contrast to most of the other projects within CTA, a project that is not developing a common final product. The main goal of the COM-project group is to provide detailed calibration strategies and guidelines for the telescope array, developing supplementary instrumentation and supervising the central technology evaluation and quality control functions for as well the telescope mirrors as the telescope cameras. The COM-project group is split into four independent groups, as it can be seen in Figure 1.12.

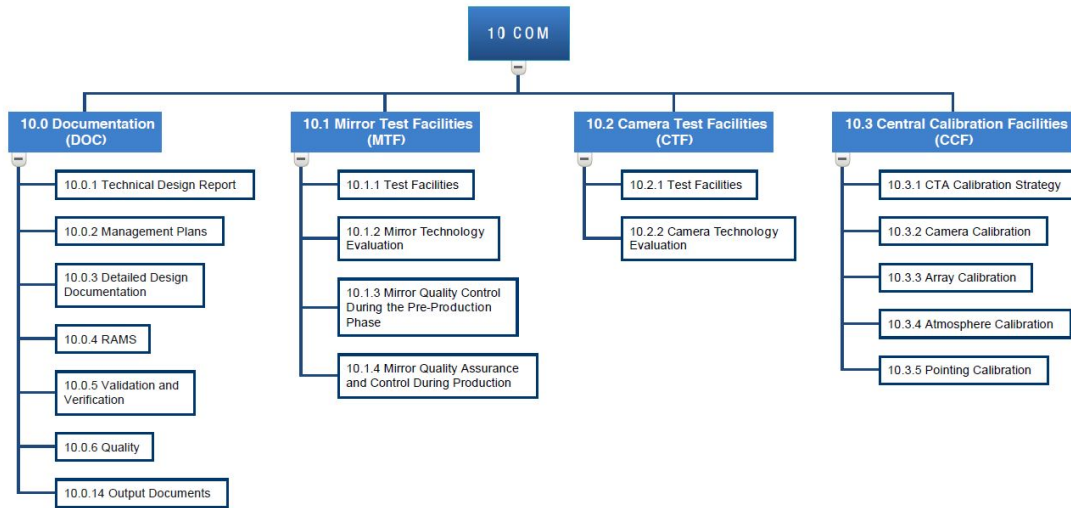


Figure 1.12: Schematic structure of the COM-project, taken from [6]

One of these concerns the Mirror Test Facility (MTF). The MTF group performs mirror tests, designs equipment for mirror testing and benchmarks the existing mirror technologies. Therefore, the MTF group is - as good as possible - independent from the mirror developing and manufacturing group, but the MTF group reports (during the pre-production phase of the mirrors) their results to the mirror developers, which try to improve the design of the mirrors on the basis of the MTF group reports. Once the pre-production phase is finished, the function of the MTF group will change to quality control. To evaluate the mirrors, the mirrors undergo the following tests:

- **2f measurements**
- **Phase Measurement Deflectometry Systems Measurements**
- **Local Reflectance and Scattering Measurements**
- **Mechanical and Environmental Testing**

Phase Measurement Deflectometry Systems take a CCD image of a well-defined test pattern. The curvature and slope of the surface are calculated from the photographed distortions and a ray-tracing script calculates the PSF of a mirror. Local reflectance measurements are executed with commercial spectrometers. Mechanical and Environmental Testing includes test concerning Coating Adhesion, Water Tightness Testing, Impact Testing, Temperature Testing, Solar Radiation Testing, Coating Adhesion, Abrasion Tests, Sand Blasting, Nanoindentation, Temperature and Humidity Cycling, Bird Faeces and Salt Fog. For a detailed description of these tests, see [6], the IAAT 2f measurements are described in Chapter 3.

2 CTA mirrors and specifications

2.1 MST mirror designs

Due to the different telescope sizes and designs in the CTA project, there are also different mirror sizes and designs. In this thesis only those mirrors are introduced, which were measured during the mirror measurement campaign (see Chapter 6), i.e. only MST mirrors.

The Institute of Nuclear Physics at the Polish Academy of Sciences in Krakow is developing the “IFJ_PAN”-design, whose details are presented in Figure 2.1. So far, there is a large series of the IFJ_PAN-mirrors: There are 8 mirrors with all-BOROFLOAT[®] 33 glass panels and 30 mirrors with all-soda lime glass panels. The Italian National Institute for Astrophysics has developed another design for MST-mirrors, which is called the “MLT”-design. It consists of an aluminium and quartz coating, the structure of these mirrors is shown in Figure 2.2.

The third mirror is developed at the Centre de Saclay and is called the “KPS”-design, its structure is shown in Figure 2.3. These mirrors consist of cold-slumped glass mirror and are generated in a two-step process: First, a core of G10 and aluminium honeycomb is shaped on mould. In a second step, front and back glass sheets are shaped to core on mould. Additional side walls improve the shape of the surface at the outer edges. So far, there are 20 MST prototypes within the KPS-design produced.

After extensive tests with these three mirror designs, the designs from Saclay and Krakow were collated and are now forming a new mirror project. The features of this new design, whose structure is presented in Figure 2.4, are:

- lighter weight of ~ 20 kg
- production technology does not use protective foils. The using of these foils can damage the mirrors
- significant cost decrease (one mirror is now well below €2000) by using a

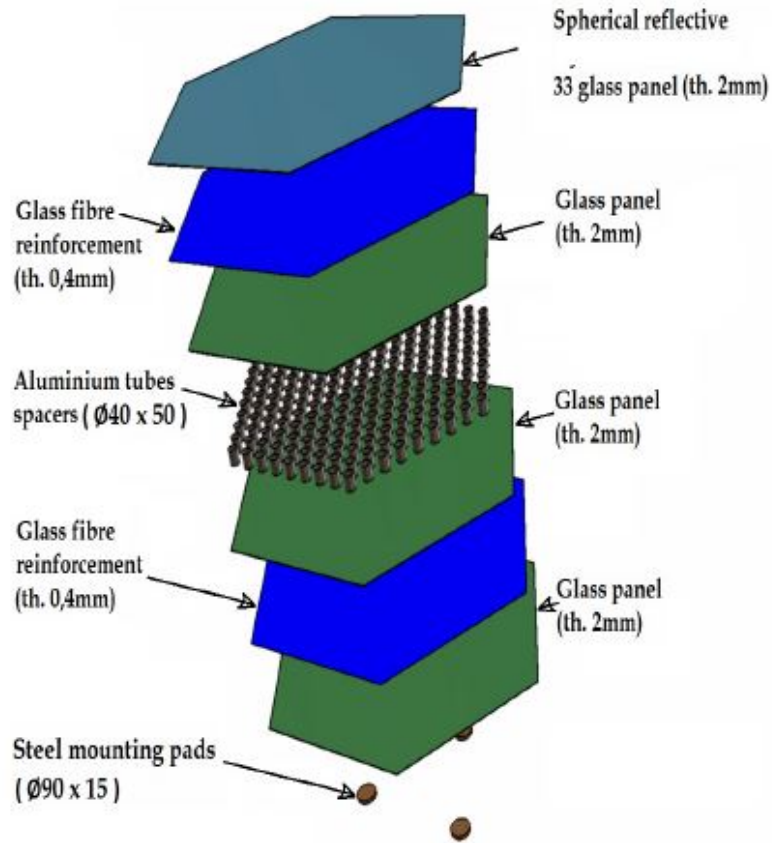


Figure 2.1: Set-up of the open-structure composite mirrors “IFJ_PAN”, taken from [27]

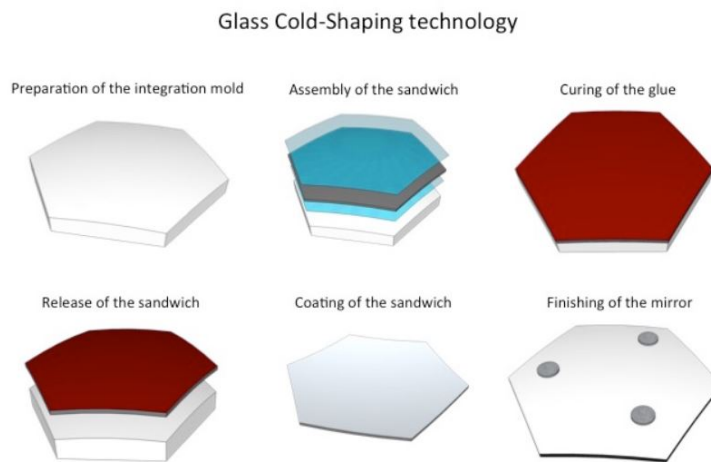


Figure 2.2: Set-up of the “MLT”-mirrors, taken from [27].

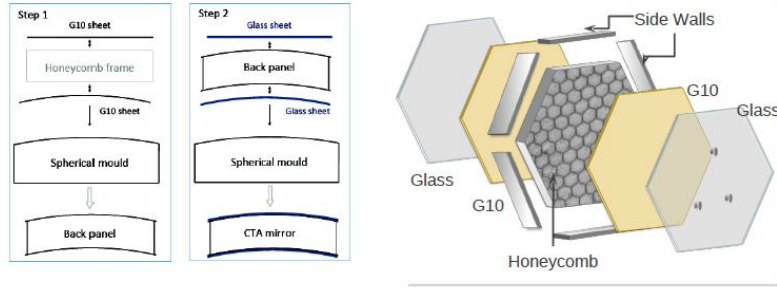


Figure 2.3: Set-up of the “KPS”-mirrors, taken from [9].

simplified production technology and equipment, which additionally needs less manpower

- closed structure based on honeycomb

The standard coatings for the CTA mirrors consist of a layer of aluminium for the reflectance and a thin layer of SiO_2 or Al_2O_3 for protection. There are still many coating-solutions under investigation., e.g. multilayer protective coatings, purely dielectric coating etc.

2.2 Mirror specifications

According to [6], the optical requirements for a MST and LST mirror file are defined as:

“85% of the incident light ¹ between 300 and 550 nm is reflected into a spot of $2/3$ of the pixel diameter², which corresponds to 33.4 mm for the MST and LST telescopes (pixel diameter 50 mm). 80% of this reflected light falls into a spot with a diameter of $1/3$ of the pixel size, i.e. 16.7 mm for MST and LST, - the so-called “D80” requirement.”

This definition is valid for a $2f$ geometry and not for far incident light from infinity. Please note, that the circles with diameters of $2/3$ respectively $1/3$ of the pixel size do not necessarily have to have the same centre. Unfortunately, not all of the institutes involved in mirror testing use this official definition for D80, which has to be considered when comparing the mirror measurement results (Section 6.3). Besides the official definition of D80, there are several more definitions of D80:

¹vertically incident, on-axis light

²pixel diameter of the telescope camera

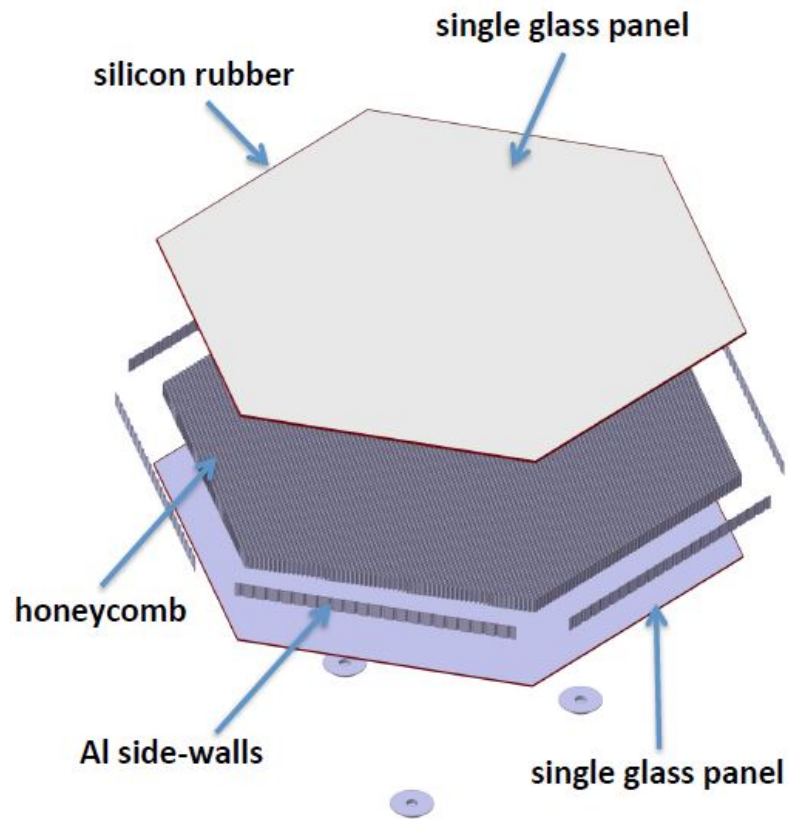


Figure 2.4: Set-up of the new mirrors, which collate characteristics from the IFJ_PAN- and the KPS-mirrors, taken from [27].

- **H.E.S.S. Definition:** A circle with a radius of $R = 1$ mrad equates to 100%. D80 is the diameter of the circle containing 80% of the incoming light. The radius of 1 mrad has only historic reasons.
- **Definition from DESY in Zeuthen:** This definition is based on a CTA MST requirements document from June 11, 2013. A circle with a radius of 1 degree equates to 100%.

3 2f mirror test setup

In order to determine the reflectivity and the Point Spread Function (PSF) of a mirror, the 2f setup is used for the IAAT mirror test facilities. Another possible, but very difficult method to get the requested results would be a combination of Phase Measurement Deflectometry Systems with a measurement of the roughness and the local reflectivity, for example. The problem here is obtaining the local reflectivity from all points of the mirror, which is far from being easy.

The measurement is an important step within the CTA quality control, because the reflectivity - especially at blue wavelengths - is critical, having in mind the Cherenkov spectrum vs. the night sky background, see Figure 1.8. Also the light should not be spread over too many PMT pixels. Currently, there are two mirror test facilities at IAAT, the “old” and the “new” setup, which will be both explained in the following.

The measurement is done at all available wavelengths in the relevant wavelength range between 300 nm and 550 nm. The available wavelengths are specified below and are different for the old and the new test facility due to technical constraints. The mirror is placed at a distance equal to twice the focal length f of the mirror from a light source. The size of the light source has to be much smaller than the expected PSF. The light source has to point exactly towards the centre of the mirror and the mirror has to be fully and isotropically illuminated. The reflected light is then focussed on a screen near the CCD camera and because of the chosen distance of 2f and principles of geometric optics, the image size of the mirror image has the same size as the original object size, only the orientation is rotated about 180° - acting on the assumption of a perfectly shaped spherical mirror. Due to the chosen size of the light source, which has to be much smaller than the PSF, the measurement is dominated by the point spread function of the mirror.

Note, that there is a difference between the spot size of a mirror between a light source at 2f distance and a light source at infinity ¹. The measured spot size in a

¹private communication with D. Gottschall.

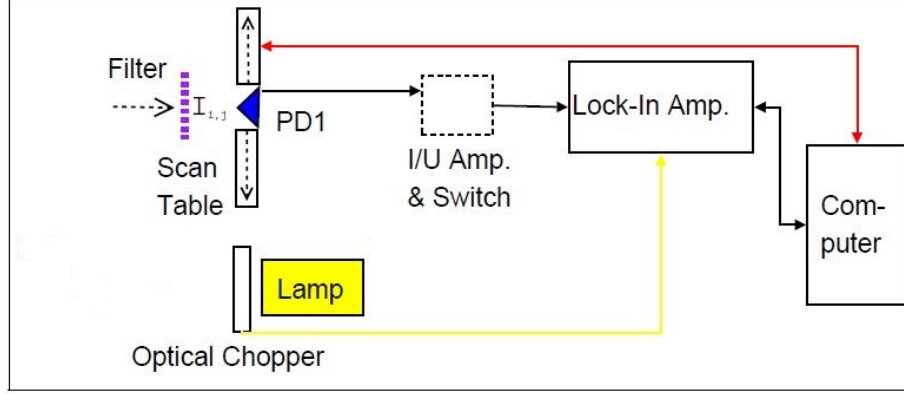


Figure 3.1: Working principle of the old mirror test facility, based on [17].

2f setup is twice the actual PSF, which is based on a light source at infinity. Up to now, the analysis script for the new 2f mirror test facility at IAAT calculates the PSF for the 2f case. The correction factor 2 for a source at infinity has not been implemented yet.

The spectral resolution can be achieved using many different techniques like filters, LEDs or a spectrometer. According to CTA requirements, at least four equidistant wavelengths in the relevant wavelength range between 300 nm and 550 nm with at least one measurement at $\lambda < 340$ nm are needed.

With the above described properties, the PSF of a mirror is measured. The reflectivity is given by the quotient of the amount of the reflected light by the mirror into a given area and the originally emitted light by the light source.

3.1 The old test facility

The so-called “old” test facility has been developed at the Max-Planck-Institut für Kernphysik in Heidelberg. Its working principle is illustrated in Figure 3.1. The measurement procedure of the old test facility also consists of a reference and a reflection measurement. A halogen lamp with an aperture of 3 mm diameter is used as light source. Additionally, there is a lock-in amplifier and a filter-wheel with available filters at 310 nm, 340 nm, 400 nm, 470 nm and 550 nm. A chopper wheel chops the light so the amplifier works. The amplifier and the filter-wheel are attached to the diode. The scan-table is moveable and scans the light spot, i.e. the reflected light by the mirror, in a scanning grid with grid “pixel” spacing of 5 mm or 2 mm, as a trade-off between resolution and time consumption. The problem is,

that the typical size of the PSF is in the order of ~ 20 mm, while the photo diode has an opening of 5 mm diameter. Therefore, the reflected light spot is rasterised. Furthermore, there is an additional high resolution measurement of the PSF, averaged over the wavelengths, with a non-UV-sensitive CCD camera using a screen at 2f. This setup is in use since 2008 at IAAT and well understood. A problem is the long measurement duration of ~ 10 hours for an MST mirror, up to 18 hours for an LST mirror.

Although this test facility is old and measuring is extremely time-consuming, it is used as a reference to compare the results of the new test setup, which is now under commissioning. For a detailed description of the old test setup and the measurement procedure, see [17].

The PSF measured with this setup is defective, because it is known, that the measured value for the PSF is $\sim 15\%$ bigger than the results from other institutes². Probably this is caused by a calibration problem, which is related to the fact, that the CCD camera and the screen are not located in the same plane.

3.2 The new test facility

It is planned to check the quality of about 10% of the utilized mirrors for the CTA project, which would last several years with the old test facility. Therefore, a new test facility, which requires significantly less time for the mirror measurement, is under construction.

Figure 3.2 shows the setup of the new test facility. The mirror is placed at a distance of 2f from the light source. In the light path between the light source and the mirror a screen is placed and an image of the screen is taken to measure the amount of light from the lamp (in the following: “Reference measurement” respectively “reference position”). In a second step, the same screen is placed next to the mirror. Now that the light path to the mirror is no longer blocked, the mirror reflects the light of the lamp onto the screen. With the same CCD camera as before an image of the reflected light is taken. This is called “reflection measurement” in the following. Comparing the amount of light in these two pictures, one gets information about the reflectivity of the mirror.

The most time consuming part of the old setup is rasterising the reflected light spot in a grid. So the general idea of the new test facility is to avoid this by detecting

²private communication with D. Gottschall

the whole reflected spot at once. Instead of using a halogen lamp with a chopper wheel and a lock-in-amplifier like the old test setup does, the new test facility uses monochrome LEDs with a collimator as light source. There are different LEDs for the different wavelengths: 310 nm, 365 nm, 405 nm, 490 nm and 525 nm. An UV-sensitive CCD camera is necessary, because normal CCD cameras, also for standard applications in astronomy, are not sensitive to wavelengths < 380 nm. Here, the model “1 Mpixel ALTA U47” from Apogee was chosen.

The light-source is aligned with the help of a laser rangefinder into the right position and points directly towards the centre of the mirror. The mirror has to be illuminated fully and isotropically. Both the reference spot and the mirror image of the light spot are projected on the same spectralon-like optical PTFE screen. Camera and screen are fixed on a rotatable mounting - hence, the measurement and the reference positions are reproducible. The rotatable design of the new test facility is a significant difference between the old and the new setup. Due to this design with the fixed setup between lamp and screen, there is no difference for this part of the measurement between reference and reflection measurement.

The PSF and reflectivity measurement is done wavelength after wavelength. Therefore, the PSF can be measured for each wavelength and not only wavelength-averaged. Indeed, the old test facility was also able to provide spectral resolved PSF measurements, but the quality is limited due to the low resolution of the grid scan. With the new setup, the whole measuring procedure for one mirror can be done within minutes and including unboxing and (un-)mounting, the complete measurement procedure lasts ~ 1 hour per mirror. For a detailed description of the new test setup, see [31].

3.2.1 The measurement procedure

In order to measure the reflectivity and PSF of a mirror, the following steps have to be executed:

- Mount the **mirror** on the mounting scheme (“H”-mounting scheme). The copped side of the mirror has to be placed towards the ceiling when the mirror is placed on the holding mechanism in the basement. In order to avoid mechanical tensions on the mirror, which can cause defective results (see Chapter 4.6), only the supreme screw should be tightened. The left and right sides have to be supported by wooden boards and bar clamps. This currently used mounting is only a intermediate solution, the final solution should be close to

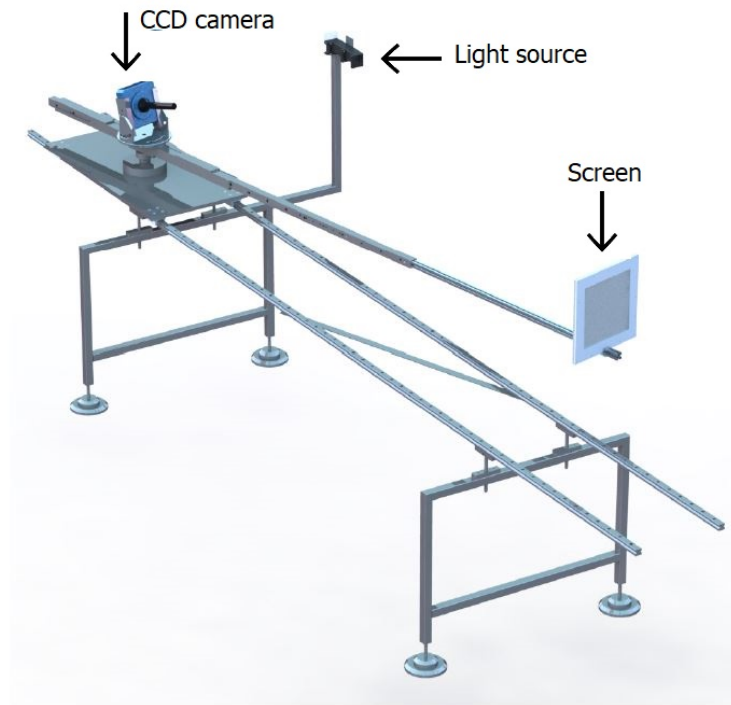


Figure 3.2: Setup of the new mirror test facility, based on [31]. Here, the new test facility is shown in the mode for the reference measurement: The emitted light from the LEDs inside the light source points directly onto the screen, where a light spot is created. This light spot is observed by the UV-sensitive CCD camera with a lens triplet in front of the CCD chip. In order to do measurements in the reflection mode, the metal arm where the screen and the CCD camera are located, can be rotated. Then the positions of the screen and the camera are swapped and the path of the emitted light, starting at the light source, goes to the mirror, which is placed in twice its focal length away from the light source. The light is reflected at the surface of the mirror and the light causes a spot on the screen of the test facility. This light spot is photographed by the CCD camera and saved as a .fits-file.

how the mirrors are actually mounted at the telescope.

The distance between the mirror and the light source has be adjusted at twice the nominal focal length of the mirror. Therefore, the laser distance meter is precisely put on the top of the light source. Then the laser and the light source have to be arranged in such a way that the laser points directly into the centre of the mirror.

- Mount of the **darkenings** on all windows in the basement. It should be checked if the darkenings are mounted in the right position, e.g. if they really emit no light. Concerning regulations of fire protection, all darkenings have to be unmounted after the measurement is finished.
- Place the **laptop** into the wooden box next to the test facility. Otherwise the stray light of the laptop screen could influence the measurement.
- The **camera** should be cooled down to -20°C . The measurement should not start before this value is reached.
- Do the **reference measurement**: Therefore, the metal arm of the test facility is turned around, so that the light source points directly to the screen. The adjusted distance between the light source and the screen has to be measured accurately. Later this distance will be used for the analysis procedure. Now turn on one of the LEDs and wait until the LED is stable. This can be checked with the help of the displayed voltage in the control software for the light source. When the initial appearing fluctuations of the voltage abate, then take an image of the light spot, but pay heed to the fact, that the centre of the spot and its dilatation can be seen on the image. Now turn off the LED and take an image of the background. These measurements have to be done for all of the LEDs. It is recommendable to measure each wavelength more than one time, all presented results in this thesis base on measurements with 5 runs per wavelength. This concerns also the measurement of the reflected spot.
- Do the **reflected spot measurement**: Turn around the arm of the test facility, so that the light from the LED is reflected by the mirror and the reflected spot is visible on the screen, as it can be seen in Figure 3.2. The light from the LED should cover the complete mirror. Now take an image of the reflected spot, then activate the shutter in front of the mirror and take an image with

the mirror covered. Leave the light during this step on. Do this measurements for all wavelengths. For an unobstructed analysis procedure it is advisable to take the same number of data files as in the reference measurement.

Note, that the reflection measurement can be done as well before and after the reference measurement, the order of the two measurements does not affect the result. The background for the reference measurement is taken with the LED off, while the background for the reflected spot measurement is taken with the LED on and a shutter in front of the mirror. The reason is, that the light source is not a perfect point-like light source and therefore, there is stray light in the basement, which is caused by the light source. One wants to measure this stray light and therefore, in the reflected spot measurement, the mirror is covered and the stray light can be measured. Covering the mirror while doing the reference measurement would not have any effect and therefore, the light source is turned off for this measurement.

4 Details on the new mirror test facility

4.1 Status of the new test facility at the beginning of my thesis

At the beginning of my work, the status of the new test facility was the following:

- Due to fire protection regulations, the former existing darkening for the windows in the basement had to be removed a short time before the beginning of my work. In consequence of this, there were no darkening when I started my work and therefore the signal-to-background-ratio was much too low for a sensible measurement. New darkening had to be designed and produced and afterwards, the resulting background had to be studied in order to find out if the background is limiting the accuracy of the measurement.
- To control the light source a text based serial interface had to be used which is not user-friendly and the used controlling software for the CCD camera, which was provided by the producer of the camera, was not satisfying. A new controlling software for the light source and the CCD camera had to be implemented.
- The analysis script for the calculation of the reflectivity and the PSF was based on some old H.E.S.S. definitions and was not longer compliant with the standards described in the TdR[6]. The script had to be revised and, in large parts, rewritten. Furthermore, there was no controlling file or GUI for a comfortable execution of the analysis.
- There was a problem with the mirror mounting. Since the mirrors have a spherical shape, they get deformed by mechanical tensions, which are caused

by the three mounting screws. The deformation ends in a significantly falsified result of the PSF and a slightly falsified result for the reflectivity. A new mounting, applying no pressure to the mirrors, had to be designed and installed. This problem was just detected during the measurements I did during the measurement campaign of the mirrors from DESY (see Chapter 5).

- While measuring mirrors, the distance between the CCD camera and the screen was not equal to the focal length of the lens triplet of the camera, so the measurements were done out of focus and therefore, an error of $\sim 5\%$ occurred in the measurement results. This issue of out-of-focus measurements was unknown until accidentally detected while performing measurements for this thesis. The correct focal length of the lens triplet had to be measured and furthermore, the mechanical framework of the test facility had to be slightly modified.
- The reproduction scale of the CCD camera was only known inaccurately, only a rough estimation of 6 pixels per mm was available. Since this parameter goes with the power of two into the analysis script, little changes cause huge variations of the results for the PSF. So the reproduction scale of the camera had to be determined as exactly as possible.

4.2 Design of new darkenings and resulting background

New darkenings for windows in the basement have been designed. Therefore, the reusable packaging from old H.E.S.S. actuators were agglutinated and cut in the right size. The basic idea was to attach them with hook-and-loop tape on the window frames. But because of the high humidity in the basement and because of the low temperatures in winter, the self-glueing hook-and-loop tape did not stick anymore on the plastic packaging. So for all of the darkenings a casing was made from fabric, and the hook-and-loop tape was fixed on the casing.

Determining the resulting background is of vast interest, because possible background contamination of the measurements was a concern. Therefore, the CCD background of a mirror characterization measurement was analysed. Figure 4.1 shows the average of five images at $\lambda = 405$ nm of the mirror uncovered minus five images with the mirror covered.

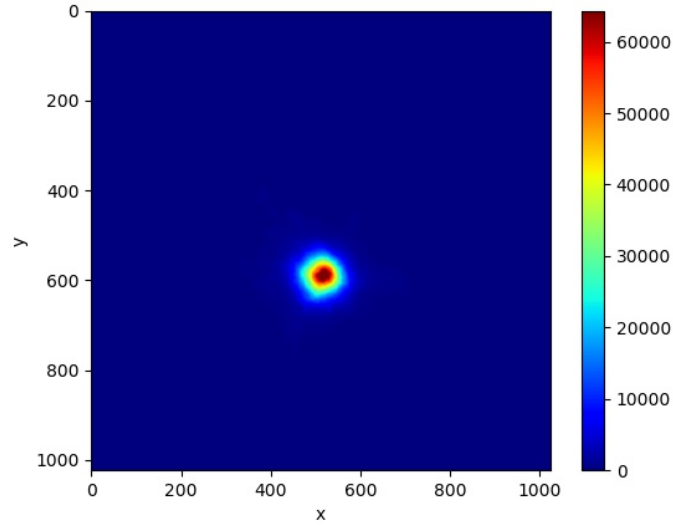


Figure 4.1: Image of the average of five images at $\lambda = 405$ nm of the mirror uncovered minus five images with the mirror covered.

In order to see background fluctuations, the scale was truncated. This is shown in Figure 4.2 for $\lambda = 405$ nm. In a next step, the mirror spot was masked, as it can be

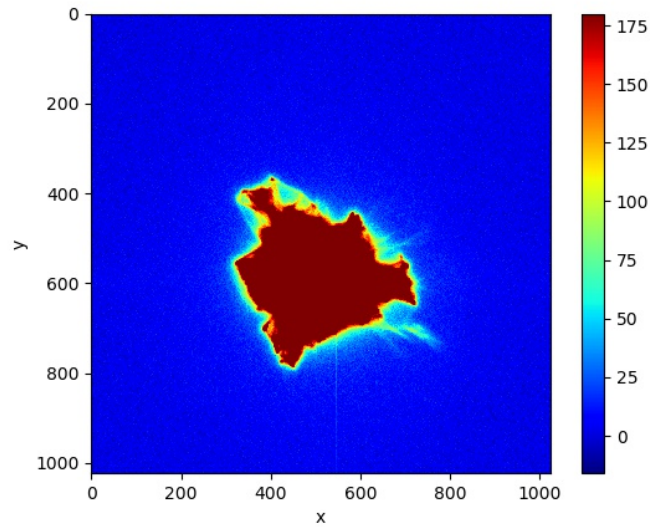


Figure 4.2: Truncated scale, in order to see background fluctuations, $\lambda = 405$ nm.

seen in Figure 4.3. The size of the mask is chosen slightly bigger than the real spot size.

The remaining data underwent a statistical analysis. A histogram can be seen in Figure 4.4. the signal-to-background- ratio is $\frac{I_{\max}}{\mu} = 23072$ for $\lambda = 405$ nm. This analysis has been executed for all LEDs. The signal-to-background-ratio is equal to 36810 for $\lambda = 310$ nm, 36434 for $\lambda = 365$ nm, 27012 for $\lambda = 490$ nm and 27499 for $\lambda = 525$ nm. So as a conclusion, the signal-to-background-ratio is big enough and does not limit the accuracy of the measurement.

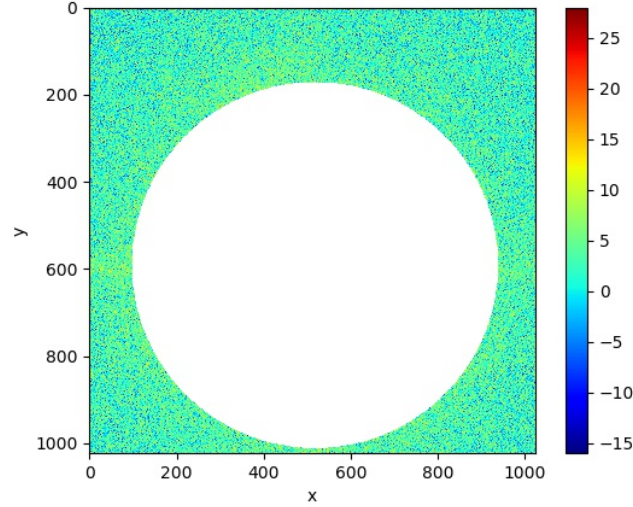


Figure 4.3: A mask was put on the mirror spot.

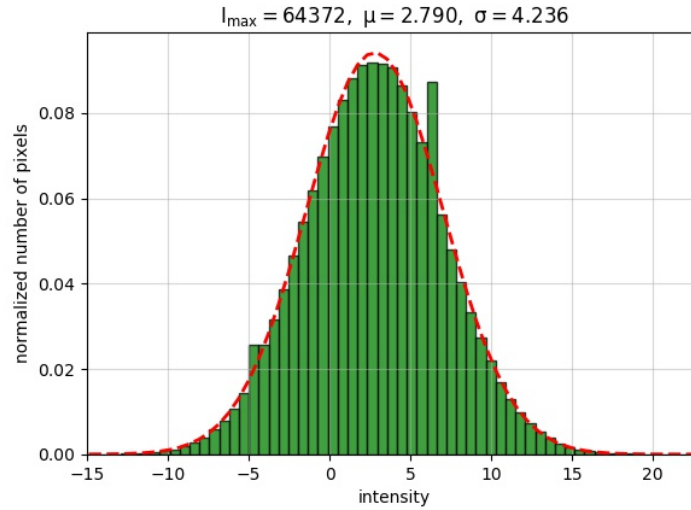


Figure 4.4: Histogram of the remaining data.

4.3 Analysis script

The analysis script for the new test facility is written in Python and is used for the evaluation of the reflectivity as well as for the PSF of the mirrors. It contains the most recent requirements from [6] at the release time of this thesis.

Each mirror measurement needs to be stored in a for this purpose established folder, where there is - besides the measurement data - a configuration-file, named “config.yml”. The analysis script can be started via typing "CTAMirrorAnalysis" into the terminal of the laptop belonging to the new test facility. Then the user has to enter the path of the data directory containing the measurement files and the YAML- configuration file, which has to include the name of the mirror, the type of the mirror (SST, MST, LST), the focal length of the mirror in metre and the nomenclature of the saved .fits-files for the reference measurement, the background measurement for the reflection measurement and the background measurement for the reference measurement. The nomenclature for the reflected data is intended to be left blank. With the use of a different nomenclature, the code of the analysis script has to be modified. Additionally, the distance between the camera and the screen at the reference measurement and the pixel coordinates of the centre of the light spot of the reference measurement, which has to be determined manually, have to be defined in the parameter YAML-file. Listing 4.1 shows an example for the configuration file.

Listing 4.1: Exemplary YAML- configuration file

```
mirror_name: KPS1_043

mirror_type: MST

# twice focal length of the mirror in m:
F2: 32.14

# nomenclature of saved the .fits-files:
ref_label: ref

bg_label: bg

refbg_label: refb

# distance between camera and screen at reference measurement:
ref_dist_in_m: 1.965
```

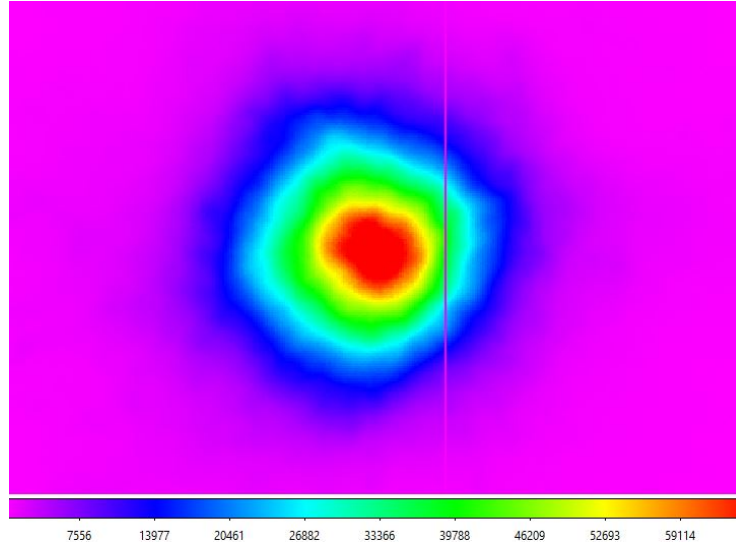


Figure 4.5: The vertical purple line at the right side of the light spot is caused by a row of broken pixel in the CCD camera. Here, a reflection spot from the mirror “KPS1_043”, at $\lambda = 405$ nm, is shown.

```
# center of light spot in pixels at reference measurement,  
# to be determined by eye:  
center_ref_x: 330  
  
center_ref_y: 704
```

In the following, the data of the reference measurement, i.e. the direct measurement of the light spot of the light source without the mirror, will be called “reference data”, while the data of the measurement concerning the reflected light spot, will be called “reflection data”.

In a first step, the parameters from the configuration file are read in. Some missing data, caused by a broken pixel row of the CCD camera, are filled with the arithmetic means of their neighbours. The broken pixel row can be seen in Figure 4.5 . After the correction of the broken pixel row, the background data are subtracted from their associated partner: The difference of the directly measured light spot and the background of the reference data (which is the reference measurement done with the light source turned off) is calculated, as well as the difference between the reflected light spot in the mirror and the background of the reflection data, which is gained by covering the mirror with a shutter. The reflectivity is calculated from these data in the following way:

1. First, the amount of reflected light is calculated. Therefore, the integral over a spot in a region of interest is calculated. The region of interest is set for now and for historic H.E.S.S. reasons to 1 mrad. The centre of the spot is equal to the centre of mass of the background-reduced reflection data.
2. The integral over a circle with a radius of 16.7 mm for MST and LST mirrors ¹ and a centre corresponding to the centre of mass of the values inside the above defined region of interest is calculated. The radius of 16.7 mm is equal to 2/3 of the pixel size of the telescope camera for MST and LST. The integration yields to the amount of reflected light at “2/3 PMT”.
3. The centre of mass of the data inside the circle with the radius equal to 2/3 of the PMT pixel size, similar to the description in the previous step, is calculated. This point is the centre for the next integration circle: The integral of a circle with a radius equal to “1/3 PMT”, i.e. 1/3 of the pixel size of the telescope camera, which is 8.35 mm for MST and LST, around the just described centre is calculated¹. This yields to the amount of reflected light at “1/3 PMT”.
4. Now the intensity of the reference measurement is calculated. Therefore, the virtual mirror size VMS, which is equal to the mirror size at the position of the reference screen is calculated by the theorem of intersecting lines. The virtual mirror size is defined by the real mirror size and the distance:

$$\text{VMS} = \frac{\text{ref_dist}}{2f} \cdot \text{mirror_size},$$

with ref_dist the distance between the light source and the CCD camera at the reference measurement, 2f is twice the focal length of the mirror and mirror_size is the side to side length of a hexagonal mirror.

Then, a circle with the same area as the virtual mirror is placed in the image. The centre is the centre of mass of the image. In the next step, the integral over the pixel inside the circle is calculated. In this process, the average is immediately taken by division by the number of pixel in the image which are inside the circle. With this average, the flux on the mirror is calculated by multiplying the value with the virtual mirror size in units of pixel². By doing

¹The radius for the SST mirrors are equal to the SST-Requirements and mirror specifications gathered from JAMA, the radii differ for the different SST mirror designs.

so, it is avoided to deal with sub pixels.

5. With the reference calculated in the previous step, the reflectivity can be calculated easily. The reflectivity is now defined as the quotient of the amount of reflected light and the reference value, which is the amount of light from the reference measurement. Listing 4.2 shows four values for the reflectivity: The reflectivity at “radius 1 mrad”, “2/3 PMT”, “1/3 PMT” and “1/3 PMT / 2/3 PMT”. The reflectivity at “radius 1 mrad” is the reflectivity, which is calculated with the amount of reflected light equal to the value calculated in the first step. The reflectivity at “2/3 PMT” is calculated with the amount of reflected light equal to the value calculated in the second step.
6. The reflectivity at “1/3 PMT” is calculated with the amount of reflected light equal to the value calculated in the second step. But now, the reference value is not the value calculated in step 1, but the intensity inside the circle with radius corresponding to “2/3 PMT” is now corresponding to 100% intensity.
7. The value for “1/3 PMT / 2/3 PMT” is given by the quotient of the reflectivities at “1/3 PMT” and “2/3 PMT”. Corresponding to the [6], the pass criteria for the mirrors can be expressed as this quotient of the reflectivities. If this value is greater 80, then the mirror has passed the criteria defined in [6].

The other characteristic value, which is calculated by the analysis script, is the peakiness of the spot. Therefore, the integrated light intensity described in step 1, is now set as 100% value. The radius, which contains 80% of this light, is now calculated and is called r80 (which is in consistence with the old H.E.S.S. definition of D80, $r80 = \frac{D80}{2}$). However, the analysis script calculates the output for the peakiness in the following way:

$$D80 = r \cdot 2 \cdot 1000, \tag{4.1}$$

The factor 1000 arises from the fact that the radius r is given in m and the output for D80 shall be given in mm.

In the CTA-TdR [6] the following statement can be found: The diameter of a circle that contains 80% of this light (D80), that is focussed into 2/3 of a pixel size, needs to be smaller than 1/3 of the pixel size. This means, 80% of the intensity of the light, which can be found inside a circle with the radius of 2/3 of the pixel size of the

telescope camera, has to be located in a spot with a radius of $1/3$ of the pixel size of the camera. Note, that both circles do not necessarily have to have the same centre, but the smaller circle has to be located completely inside the bigger one. Because of this, the centre of the circular mask describe above in step 3, was calculated by a calculation of the centre of mass of the data inside the circle from step 2.

All above described calculations are done for each wavelength individually. The results of the analysis can be found in the file “results.txt”, which is automatically created by the analysis script in the corresponding data directory (see Listing 4.2). It contains the name of the mirror, the centre of the reference spot, which was manually found, the reference distance and for each of the LED wavelengths the results of the calculation of the reflectivity and the PSF as well as information about the “centre”, which is the centre of the 1 mrad circle.

Listing 4.2: Exemplary Output file with the results, here shown for the mirror KPS1_043. The PSF is the measured one, not corrected for a light source in infinity.

```
KPS1_043
center_ref: (330, 704)
ref_dist: 1.965m

310nm
597 395 center @310nm
56.59% radius 1mrad@310nm
53.19% 2/3 PMT@310nm
38.06% 1/3 PMT@310nm
71.56% 1/3 PMT / 2/3 PMT@310nm
20.53mm D80 @310nm

365nm
597 395 center @310nm
24.08% radius 1mrad@365nm
22.70% 2/3 PMT@365nm
16.57% 1/3 PMT@365nm
72.98% 1/3 PMT / 2/3 PMT@365nm
20.20mm D80 @365nm

405nm
590 512 center @405nm
71.08% radius 1mrad@405nm
66.99% 2/3 PMT@405nm
48.25% 1/3 PMT@405nm
```

72.01%	1/3 PMT / 2/3 PMT@405nm
20.20mm	D80 @405nm
490nm	
653 457	center @490nm
54.34%	radius 1mrad @490nm
51.27%	2/3 PMT@490nm
36.89%	1/3 PMT@490nm
71.96%	1/3 PMT / 2/3 PMT@490nm
20.20mm	D80 @490nm
525nm	
593 453	center @525nm
50.25%	radius 1mrad@525nm
47.45%	2/3 PMT@525nm
34.24%	1/3 PMT@525nm
72.16%	1/3 PMT / 2/3 PMT@525nm
20.20mm	D80 @525nm

4.3.1 Effects of the variation of the reproduction scale of the CCD camera on the analysis script

The reproduction scale of the CCD camera goes as an area, i.e. with the power of two, into the analysis script and hence, small variations of the reproduction scale cause relatively big changes in the results of the analysis. This will be illustrated in the following. In doing so, the old definition for D80, i.e. a radius, is used. While the new definition separates the mirrors just into two categories - mirrors that pass the D80 criteria and mirrors that pass not the D80 criteria, the old definition allows to contemplate the distribution of the quality of the mirrors.

The results for the reflectivity at 365 nm has been removed, because the reflectivity measurement at this wavelength was not taken correctly. The underlying values for the reproduction scale - minimum = 0.156 mm per pixel, maximum = 0.179 mm per pixel and mean = 0.163 mm per pixel - and their identification are described in detail in Chapter 4.5.1.

Figure 4.6 shows the variation of the results for the detected PSF in dependency on different values for the reproduction scale, while Figure 4.7 shows the analogue for the reflectivity in the relevant wavelength range. The exact results are again shown in Table 4.3.1.

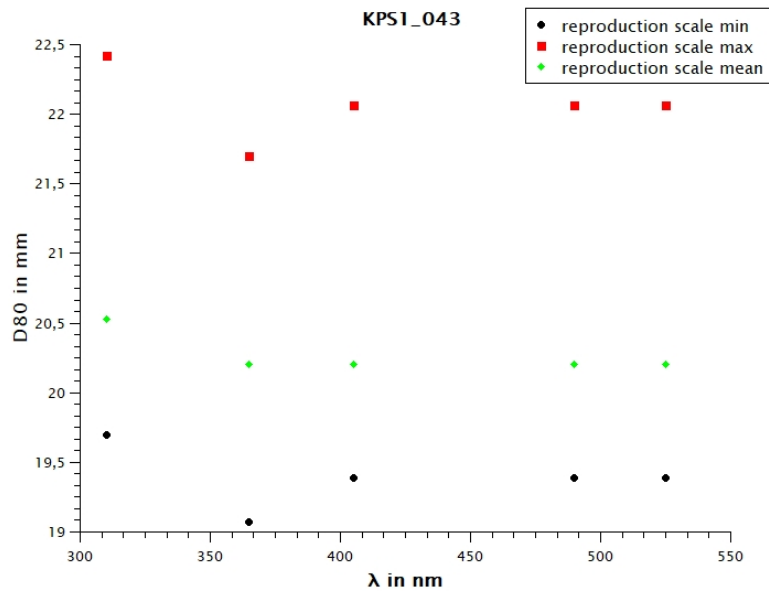


Figure 4.6: Determined results for the PSF in dependency on the reproduction scale. The used values are the minimum, the maximum and the mean value from the statistics, see Chapter 4.5.1 and especially Figure 4.35.

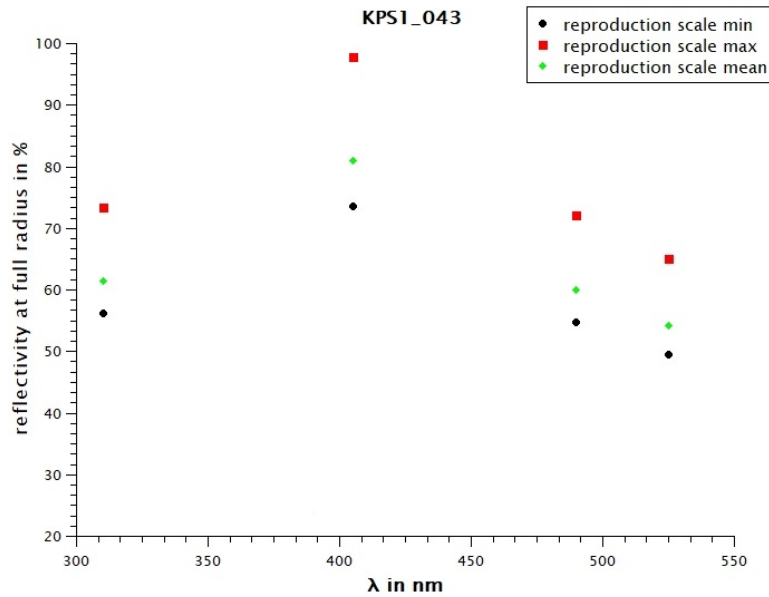


Figure 4.7: Determined results for the reflectivity in dependency on the reproduction scale. The used values are the minimum, the maximum and the mean value from the statistics, see Chapter 4.5.1 and especially Figure 4.35.

reproduction scale value	reflectivity in % at 310nm	reflectivity in % at 365nm	reflectivity in % at 405nm	reflectivity in % at 490nm	reflectivity in % at 525nm
min	56.12	-	73.57	54.70	49.52
max	73.48	-	97.94	72.15	65.02
mean	61.43	-	81.00	60.05	54.26

reproduction scale value	PSF in mm at 310nm	PSF in mm at 365nm	PSF in mm at 405nm	PSF in mm at 490nm	PSF in mm at 525nm
min	19.70	19.07	19.38	19.39	19.39
max	22.42	21.70	22.06	22.06	22.06
mean	20.53	20.20	20.20	20.20	20.20

Table 4.1: The reflectivity and the PSF of the mirror “KPS1_043” in dependency on the wavelength and the used value for the reproduction scale.

So, as a conclusion, the variation of the reproduction scale of the C CCD camera has a big influence on the measurement results. Therefore, the reproduction scale has to be determined as exactly as possible, which has been done during the work on this thesis. The measurement process is described in detail in Chapter 4.5.1.

4.3.2 Effects of the variation of the position of the centre of the reference spot on the analysis script

As mentioned above, the centre of the reference spot is identified manually with ds9 at the moment, so these pixel coordinates are probably defective. For this reason, the analysis script has to be non-sensitive to variations of the stated pixel coordinates of the centre of the reference spot.

In order to verify this non-sensitivity, various data sets have been analysed. In the following, only the results for the mirror KPS1_043 are shown, the analysis of the other mirrors are in consistence with the results presented here.

In a first step, the “real” centre, i.e. the centre which is - only for now - defined to be the real centre of the reference spot, is determined and the analysis script is executed with the pixel position of this centre. Varying the pixel position of the centre is subsequently done (illustrated in Figure 4.9), the distance in pixels to the real centre is calculated and the results are compared. Table 4.3.2 shows the results of the analysis for the reflectivity in percent for different wavelengths in dependency on the distance to the real centre in pixel. The same data are shown in Figure 4.8.

distance to centre in px	misspointing angle in mrad	310nm	365nm	405nm	490nm	525nm
0	0.00	61.44	26.20	77.6	59.18	54.63
11	0.92	60.41	26.03	76.4	58.50	54.02
28	2.35	61.85	26.30	78.09	59.37	54.90
57	4.79	62.48	26.42	78.81	59.71	55.30
85	7.14	63.35	26.35	79.75	60.19	55.84
154	12.99	64.29	26.76	80.54	60.49	56.42

Table 4.2: Reflectivity in % for different variations of the centre of the reference spot, this analysis is based on data of the mirror KPS1_043.

Having in mind the size of the whole .fits-dataset of 1024x1024 pixels and a typically spot-dilatation like in Figure 4.9, the here shown maximal deviation of 154 pixel is larger than the imprecision of the manually determined position of the centre of the spot. The centres of the reference spots differ slightly for the different wavelengths, but the analysis is enough non-sensitive to a variation of the centre of the reference spot, if one considers the possible accuracy of the manually finding of the centre of the spot.

The PSF is not affected by variations of the position of the reference spot.

4.3.3 Effects of the change of centre of the circles of the D80 definition on the analysis script

As described in Chapter 2.2, the centres of the circles used to calculate the PSF of the mirror, do not necessarily have to have the same coordinates. Therefore, this Chapter will show the effects of the change from the “concentric” to the “non-concentric” implementation. By chance, the effects have been determined with the data of the “KPS1_043” mirror. Note, that at the time when this analysis was done, the determination of the reproduction scale of the CCD camera has not been finished and because of this, an old value was used. This is the reason why the here shown results for D80 are slightly different from those shown in Chapter 5.

In a first step, it was tested how the centres really differ, when the analysis script shifts the positions of the inner, smaller circle with radius equal to 1/3 of the PMT pixel size. Thus, the analysis was done twice: In the first iteration the analysis script uses the fix coordinates for the inner circle, which were found for the outer circle before. In the second iteration, the analysis script shifts the centre of the inner circle

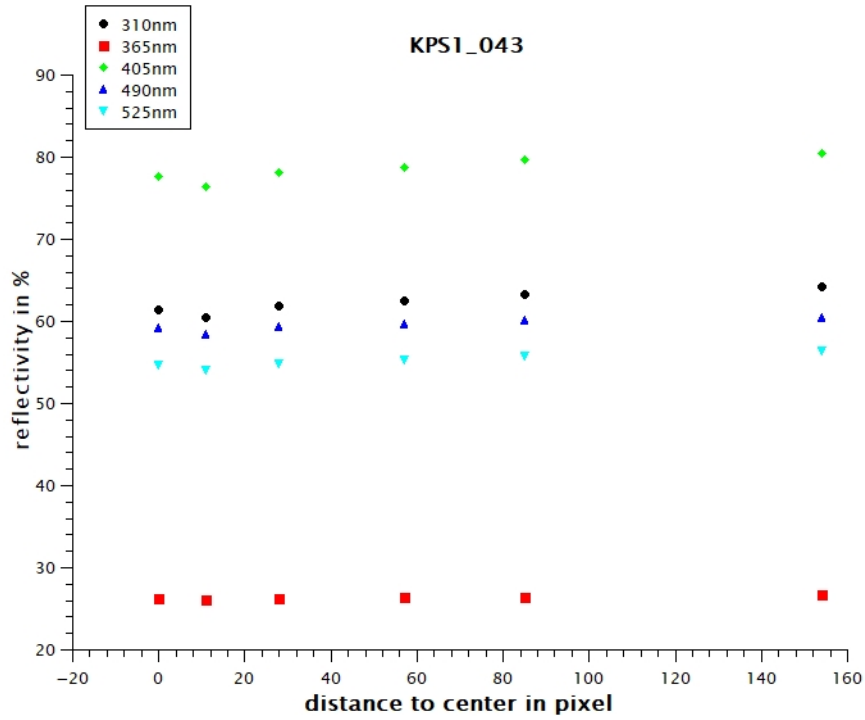
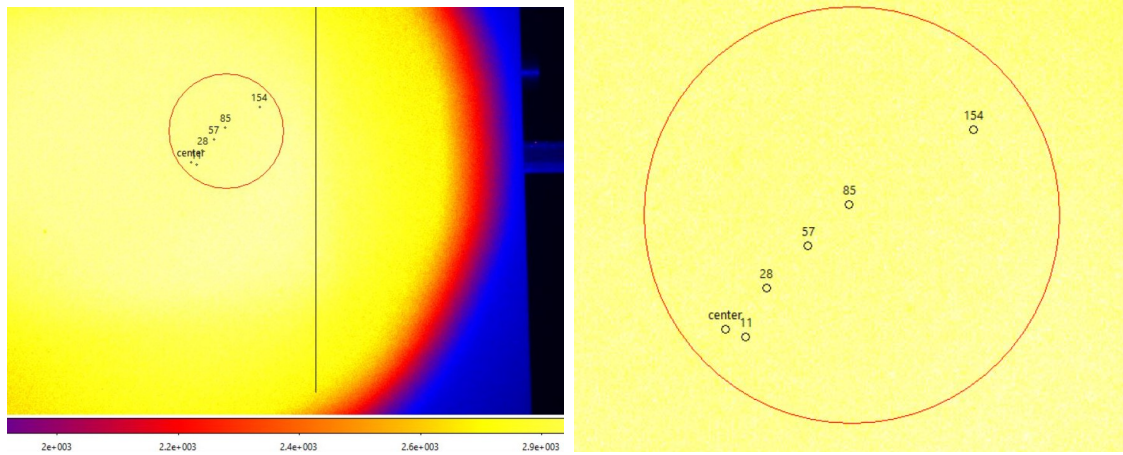


Figure 4.8: Reflectivity in % for different variations of the centre of the reference spot, this analysis is based on data of the mirror KPS1_043.



(a) Reference spot of KPS1_043, here at $\lambda = 405$ nm. The black line is caused by broken pixels of the CCD camera

(b) Zoom into the red bordered region

Figure 4.9: The pixel positions used for the analysis in order to get knowledge about the sensitivity of the script to variations of the centre of the reference spot.

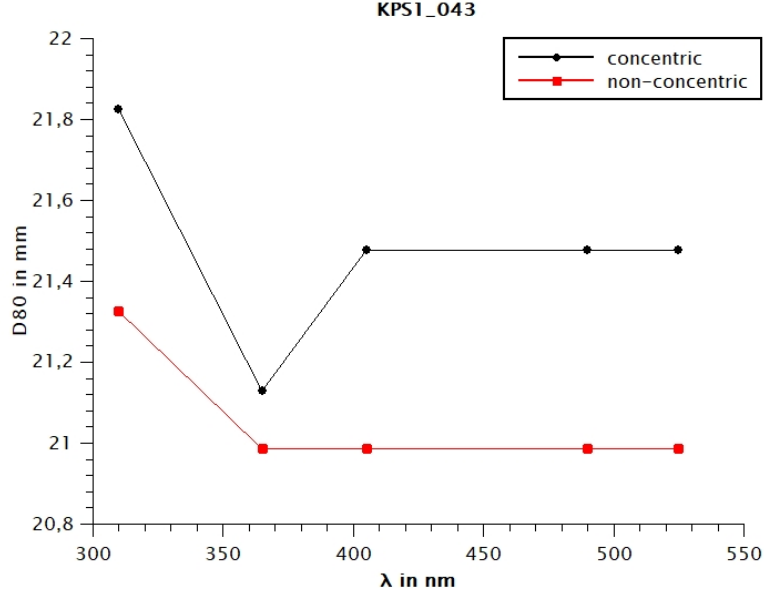


Figure 4.10: The PSF of the mirror “KPS1_043” in both the concentric and the non-concentric case.

successively into all possible coordinates, calculates the integral and searches then for the position, which is connected with the maximum value of intensity. Table 4.3 shows the results of this study.

λ in nm	position of inner circle in the concentric case	position of inner circle in the concentric case
310	(597, 395)	(597, 395)
365	(537, 451)	(538, 452)
405	(590, 512)	(591, 513)
490	(653, 457)	(654, 458)
525	(594, 453)	(595, 454)

Table 4.3: Positions of the centre of the inner circle in both the concentric and the non-concentric case in pixel coordinates.

One can see, that the effects of allowing the variation of the position of centre of the inner circle has only a marginal effect on the pixel position. However, it is of fundamental importance to check the effects of the variation of the centre of the inner circle on the reflectivity and the PSF of the mirror. The results of these investigations can be seen in Figures 4.10 and 4.11.

It is obvious, that the measurement data for the reflectivity are somehow defective,

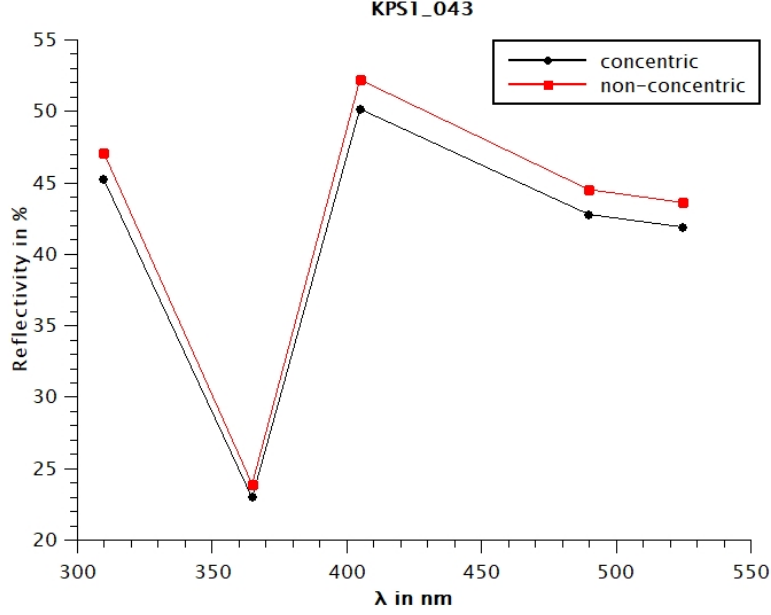


Figure 4.11: The reflectivity of the mirror “KPS1_043” in both the concentric and the non-concentric case.

because the values are too low and not in consistence with the data shown in Chapter 5. This may be caused by a deformation of the mirror during this measurement, probably due to the (old) mounting. But nevertheless, one can see, that the results for the PSF, at least for this mirror, in the non-concentric case are below the results in the concentric case. Besides, the non-concentric data are much more stable over the wavelength than the results of the concentric case for this mirror and the results of the reflectivity in the non-concentric case are a bit higher than the results in the concentric case.

4.4 Light source

In the optimal case, the intensity of the light illuminating the mirror is homogeneous. A perfect light source emits light with a radial profile with a circular plateau area of constant light intensity, which is able to illuminate the whole mirror. Outside the light cone there is no stray light. Considering the set-up of the light source of the new test facility, it is obvious that these claims cannot be fully reached. The behaviour of the light source of the new mirror test facility will be investigated in this chapter.

4.4.1 Cuts in x and y of the light spots

Figures 4.12 - 4.16 show pictures of the light spots at all available wavelengths. For each image of the light spot, an intensity profile can be seen at the bottom, concerning the x-axis, and at the right side of the picture, concerning the y-axis.

The LED at $\lambda = 525$ nm shows an absolutely unacceptable cut in x and y and should be changed as soon as possible. The other LEDs can be characterised by an less worse behaviour, but one can easily see, that the goal of a circular plateau area with ideally constant light intensity and steeply sloping edges could not be reached with the existing LEDs. Perhaps this is due to ageing effects of the LEDs. The behaviour of the LEDs should be tested with new LEDs of the same or another type. It has to mentioned, that one of the existing collimators, the middle-size-collimator, seem to be not suitable for the LED at $\lambda = 525$ nm, as it can be seen in Figure 4.17. The other wavelengths seem to be not affected, but at $\lambda = 525$ nm, this collimator is not operable.

4.4.2 Stability of the light source in dependency on the time

The intensity of the LEDs inside the light source is regulated by the input current provided by a constant current power supply. However, the intensity of a LED is not constant at a given current. During a short time scale after switching on the LED, the intensity of the emitted light varies because of temperature changes, which are caused by the passively cooling of the LEDs. Therefore, a mirror measurement should not start before the intensity of the LED is stable, otherwise the measurement results of the reflectivity will be defective. The behaviour of the LEDs after switching them on has been measured in order to find out the necessary waiting time. The LEDs at all available wavelengths have been measured both in February 2017 and in October 2017. Figures 4.18 - 4.22 show the results of this measurements at all available wavelengths. The intensity is given in arbitrary units, the different values are caused by different distances between the LEDs and the screen, the applied input current was the same for both measurements.

Table 4.4 shows the difference between minimum and maximum value, given in % for each wavelength, for both the measurement taken in 02/2017 and for the measurement taken in 10/2017. The maximum value equates to 100%. It has to be mentioned, that the duration of the measurement changed from 02/2017 to 10/2017. It should be investigated in future studies how the fluctuations of the stability of the

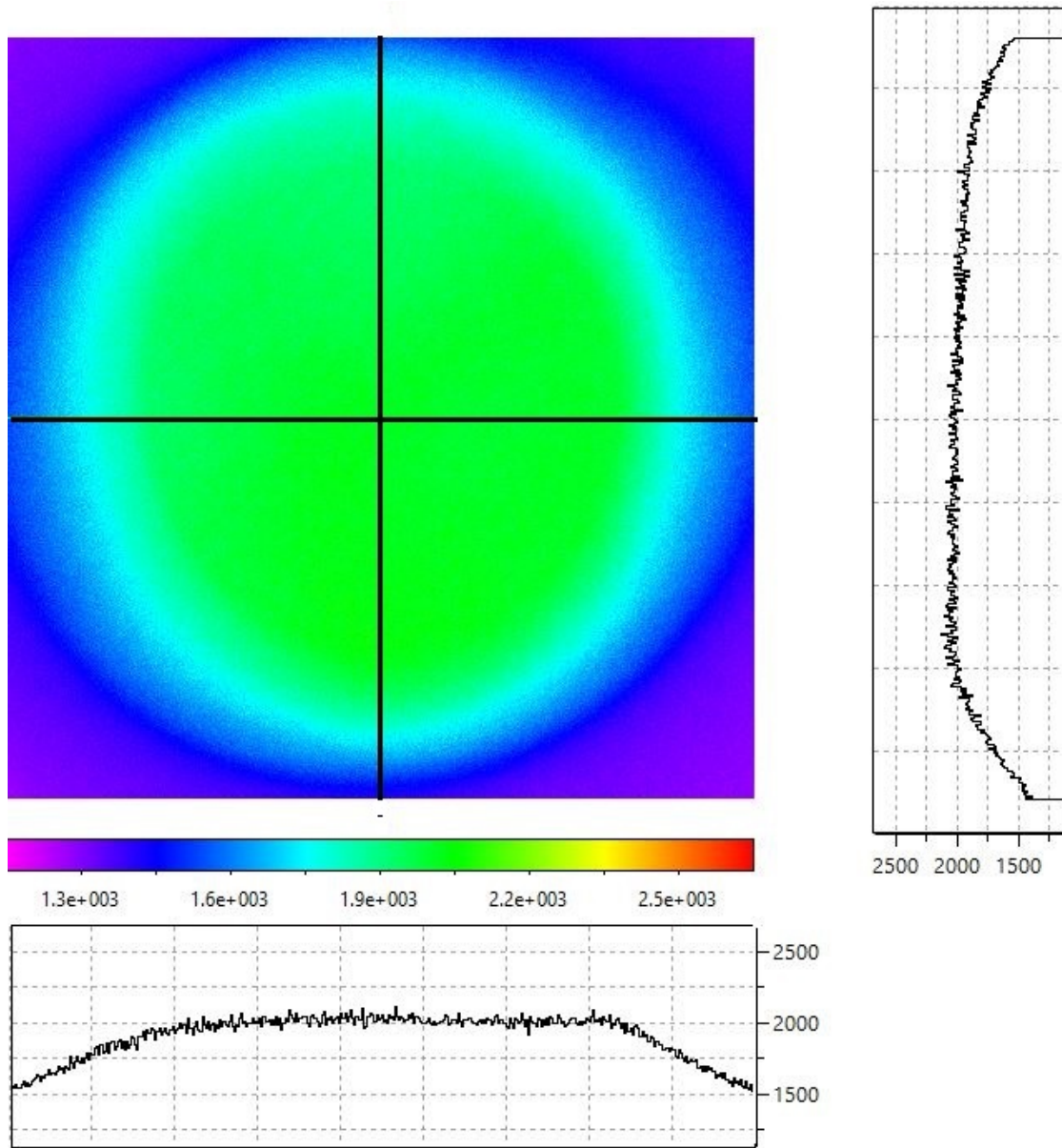


Figure 4.12: Image of the Spot of the LED at $\lambda = 310$ nm, taken in the reference mode of the new test facility. The graphs at the right and at the bottom show a cut of the light intensity in the vertical and horizontal plane, going through the centre of the light spot.

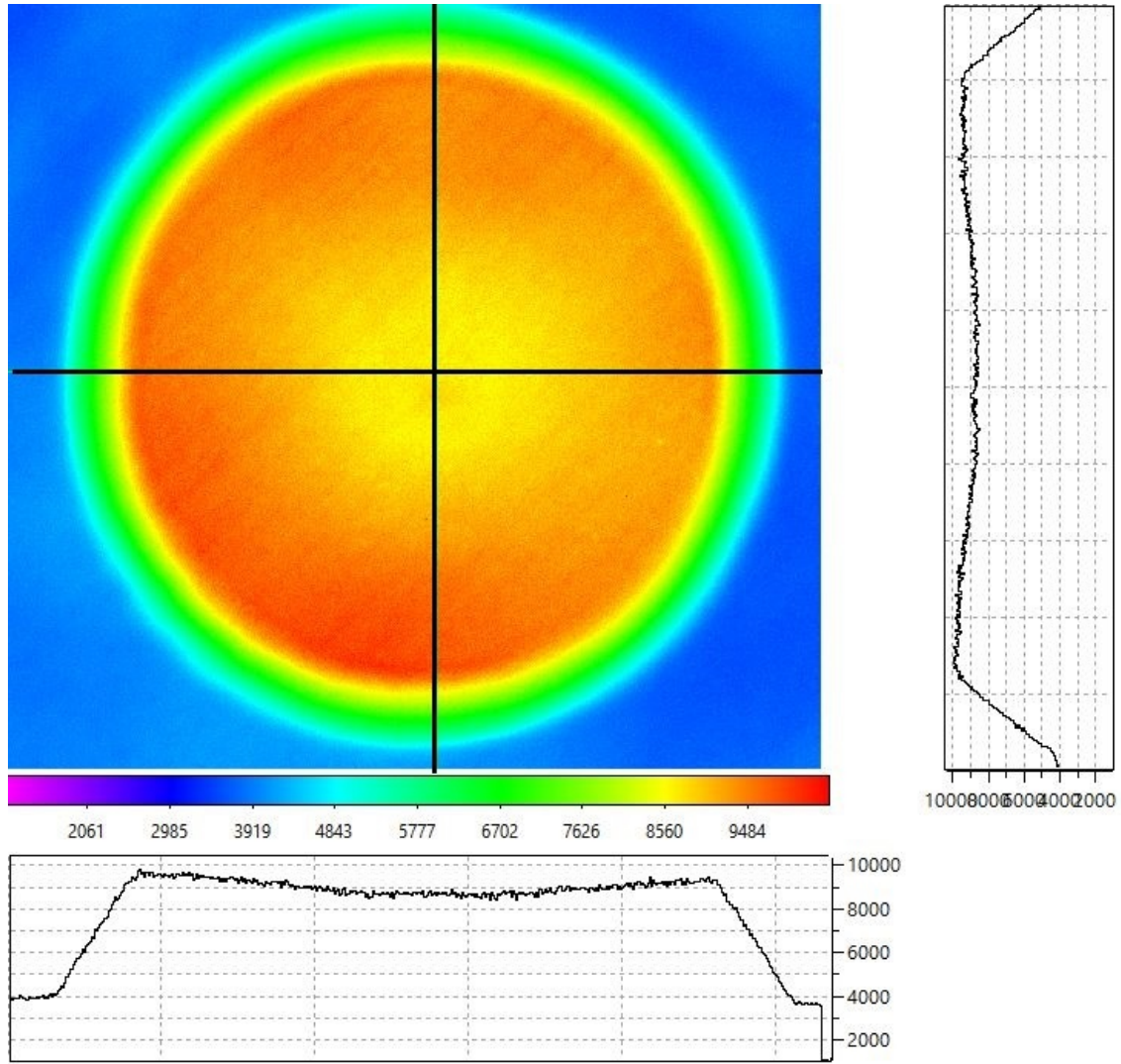


Figure 4.13: Image of the Spot of the LED at $\lambda = 365$ nm, taken in the reference mode of the new test facility. The graphs at the right and at the bottom show a cut of the light intensity in the vertical and horizontal plane, going through the centre of the light spot.

	02/2017	10/2017
$\lambda = 310$ nm	7.1%	1.6%
$\lambda = 365$ nm	0.8%	0.9%
$\lambda = 405$ nm	5.9%	1.1%
$\lambda = 490$ nm	0.8%	1.2%
$\lambda = 525$ nm	0.9%	0.8%

Table 4.4: Difference between minimum and maximum value, given in % for each wavelength, for both the measurement taken in 02/2017 and for the measurement taken in 10/2017. The maximum value equates to 100%.

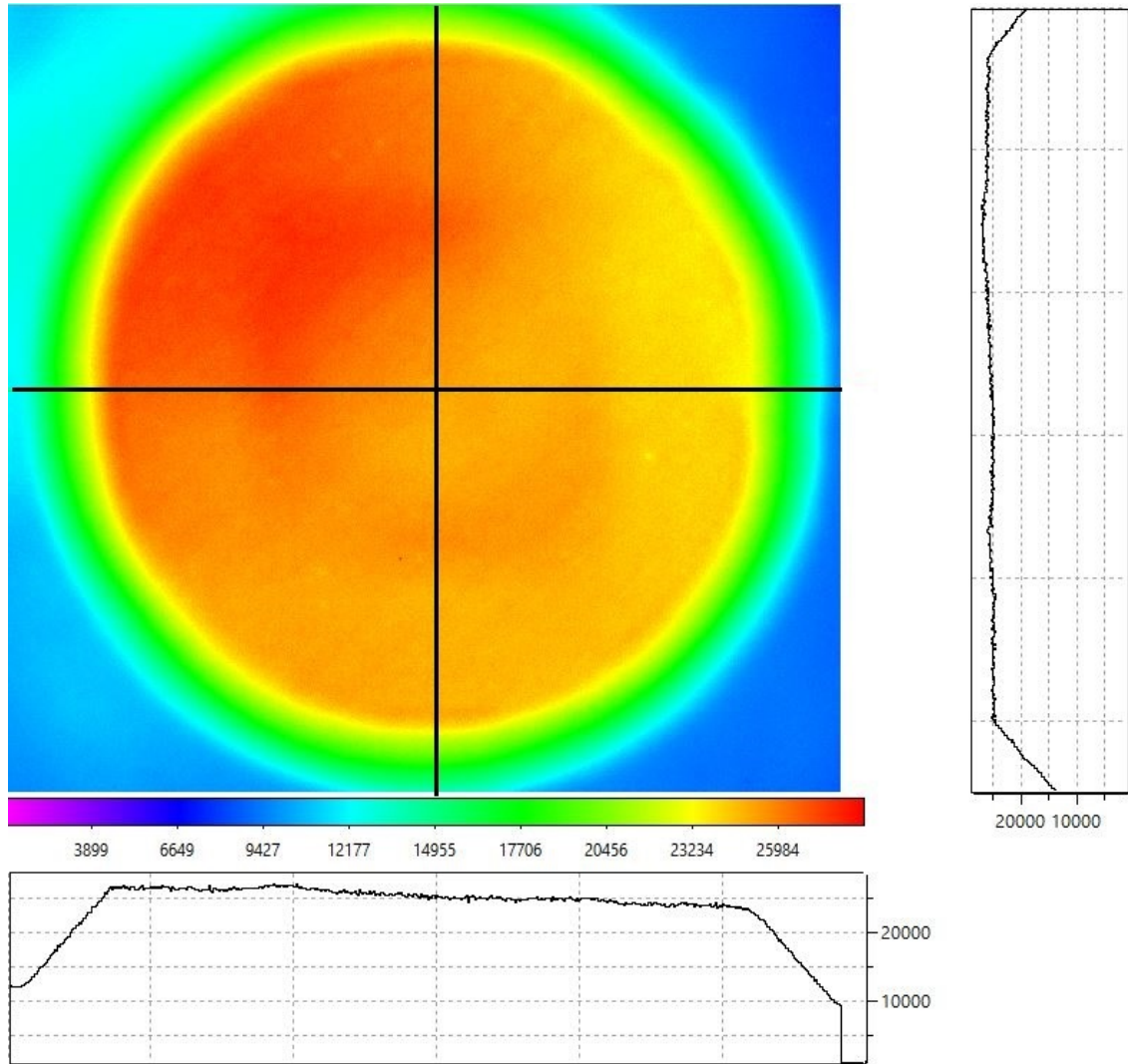


Figure 4.14: Image of the Spot of the LED at $\lambda = 405$ nm, taken in the reference mode of the new test facility. The graphs at the right and at the bottom show a cut of the light intensity in the vertical and horizontal plane, going through the centre of the light spot.

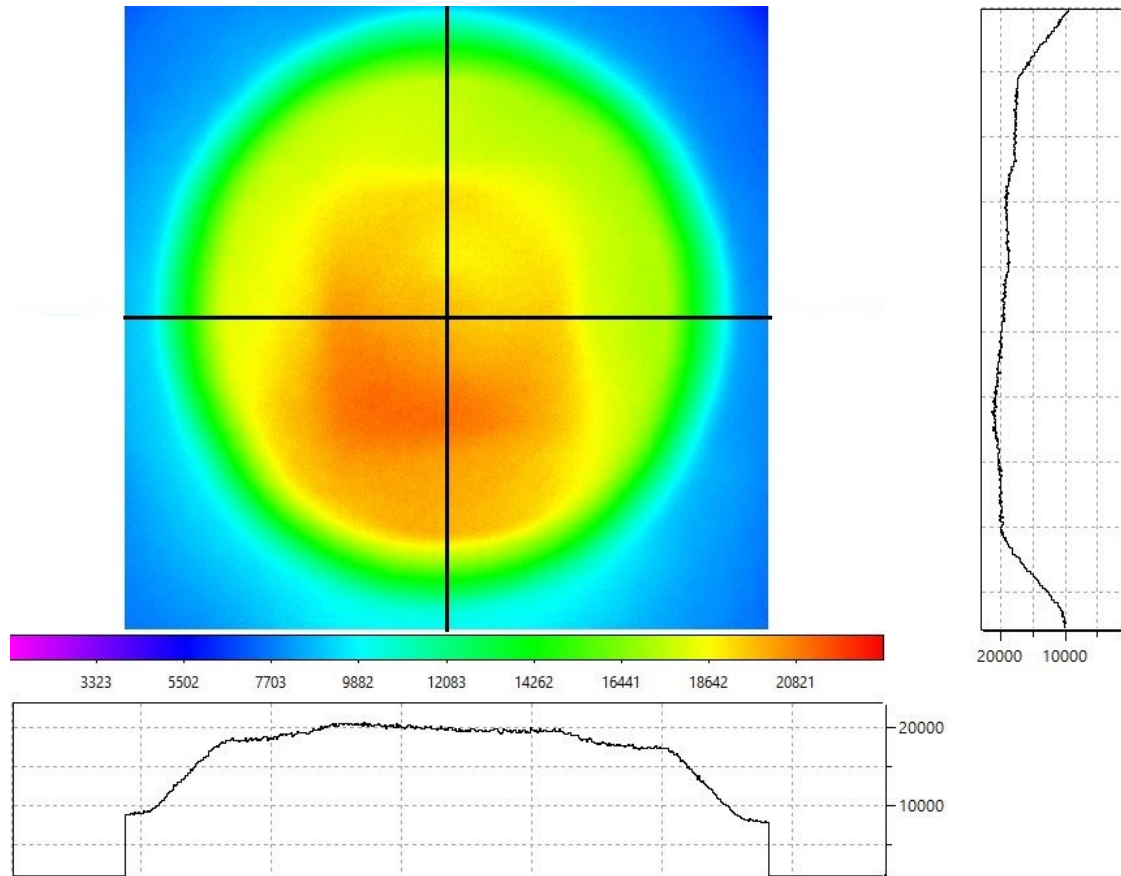


Figure 4.15: Image of the Spot of the LED at $\lambda = 490$ nm, taken in the reference mode of the new test facility. The graphs at the right and at the bottom show a cut of the light intensity in the vertical and horizontal plane, going through the centre of the light spot.

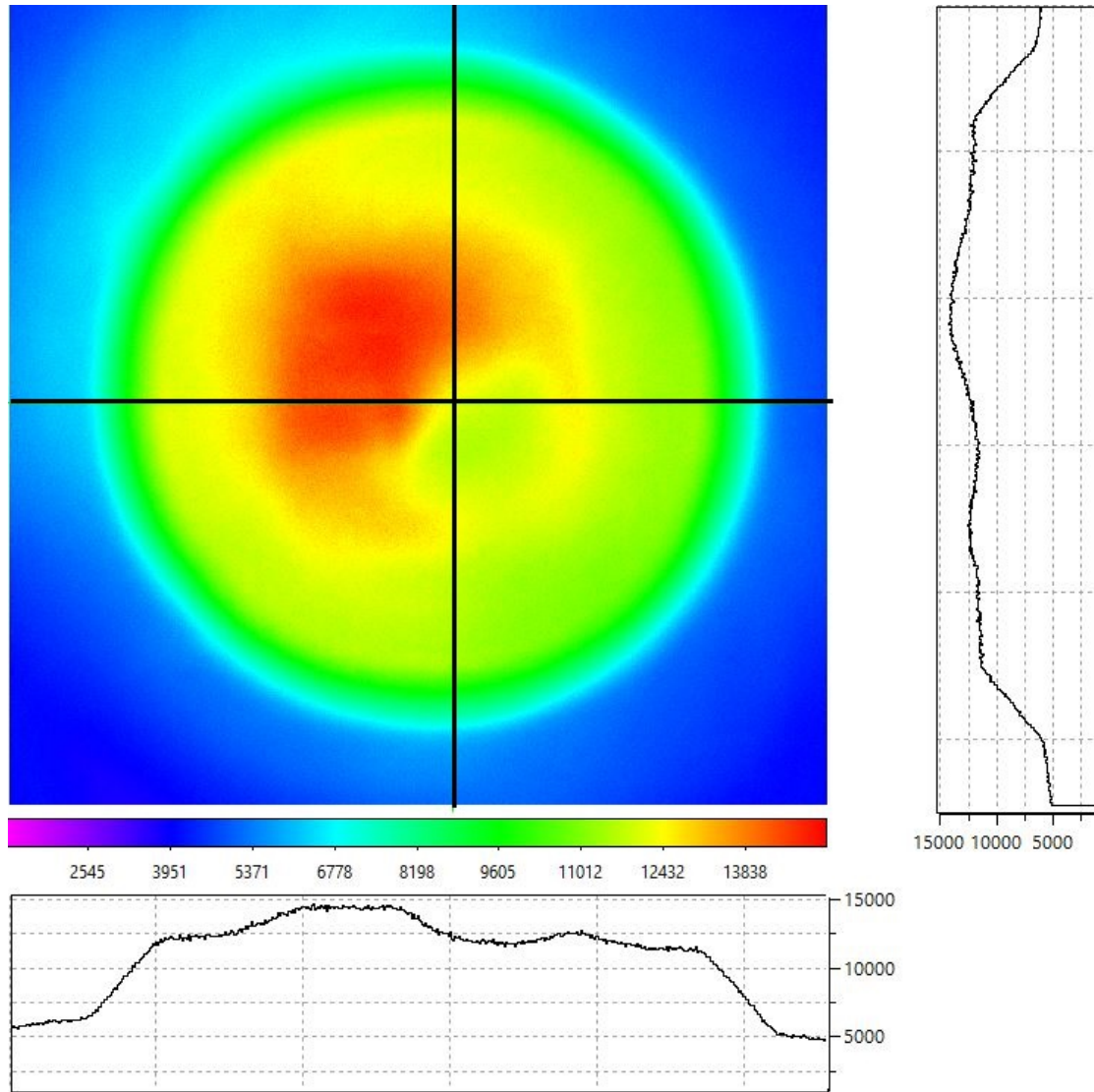


Figure 4.16: Image of the Spot of the LED at $\lambda = 525$ nm, taken in the reference mode of the new test facility. The graphs at the right and at the bottom show a cut of the light intensity in the vertical and horizontal plane, going through the centre of the light spot.

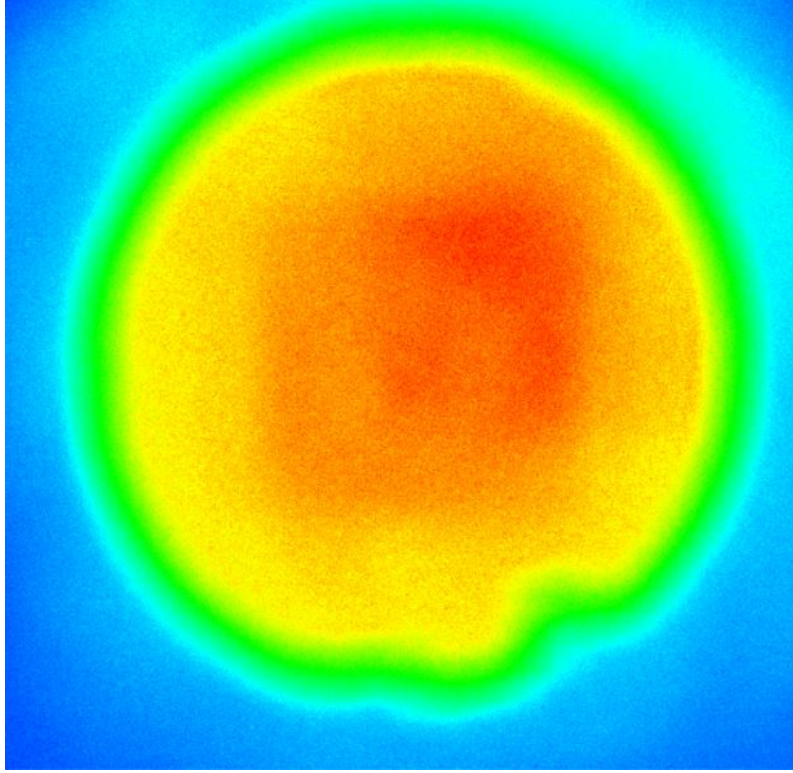
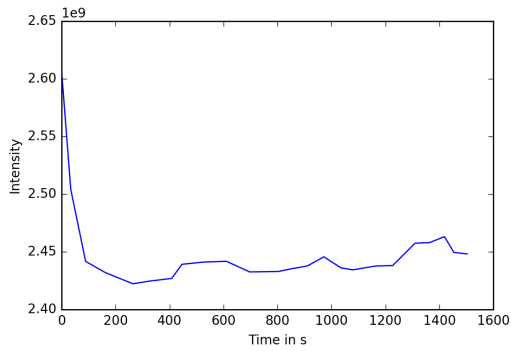
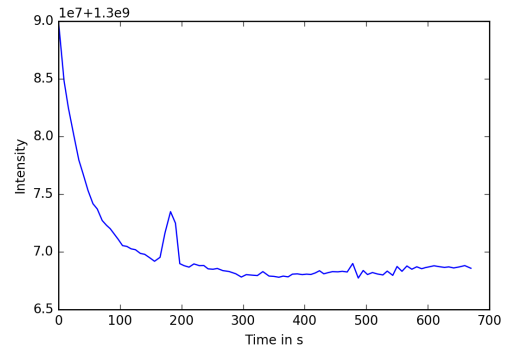


Figure 4.17: Image of the light spot at $\lambda = 525$ nm with the middle-size-collimator in use. One can easily see the deformation of the spot in the lower edge, caused by the collimator.

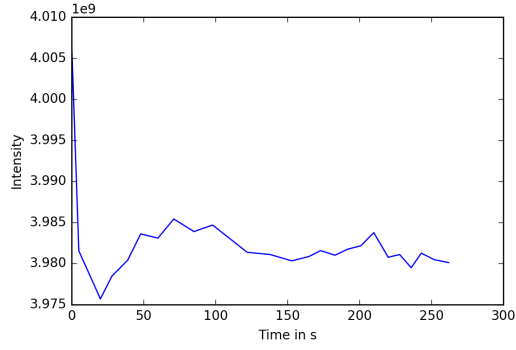


(a) Stability of 310 nm LED, 02/2017

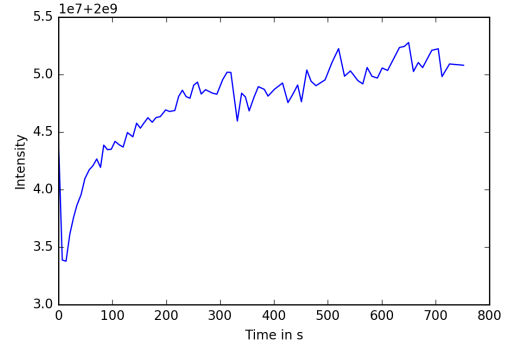


(b) Stability of 310 nm LED, 10/2017

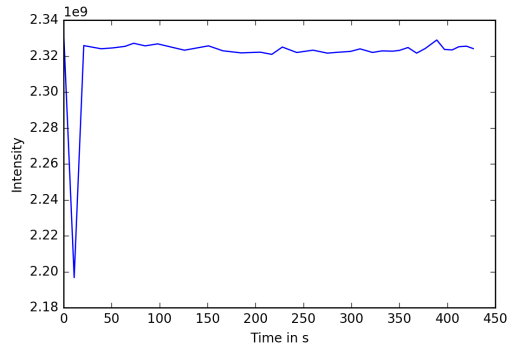
Figure 4.18: The stability of the LED at $\lambda = 310$ nm, measured in February 2017 (left side) and in October 2017 (right side).



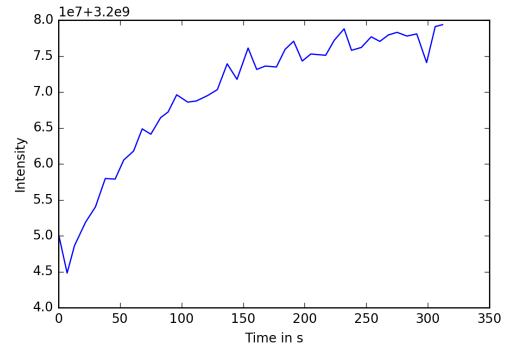
(a) Stability of 365 nm LED, 02/2017



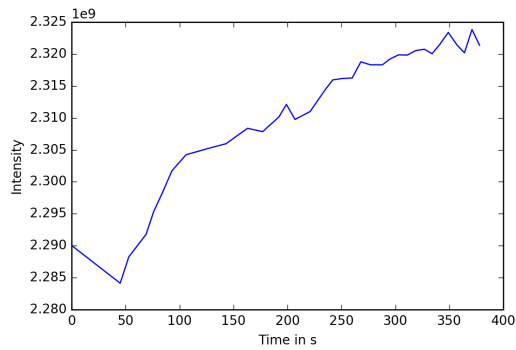
(b) Stability of 365 nm LED, 10/2017

 Figure 4.19: The stability of the LED at $\lambda = 365$ nm, measured in February 2017 (left side) and in October 2017 (right side).


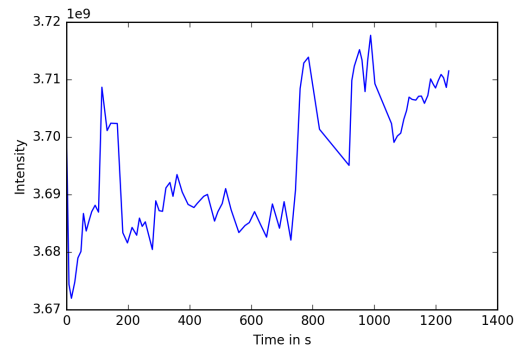
(a) Stability of 405 nm LED, 02/2017



(b) Stability of 405 nm LED, 10/2017

 Figure 4.20: The stability of the LED at $\lambda = 405$ nm, measured in February 2017 (left side) and in October 2017 (right side).


(a) Stability of 490 nm LED, 02/2017



(b) Stability of 490 nm LED, 10/2017

 Figure 4.21: The stability of the LED at $\lambda = 490$ nm, measured in February 2017 (left side) and in October 2017 (right side).

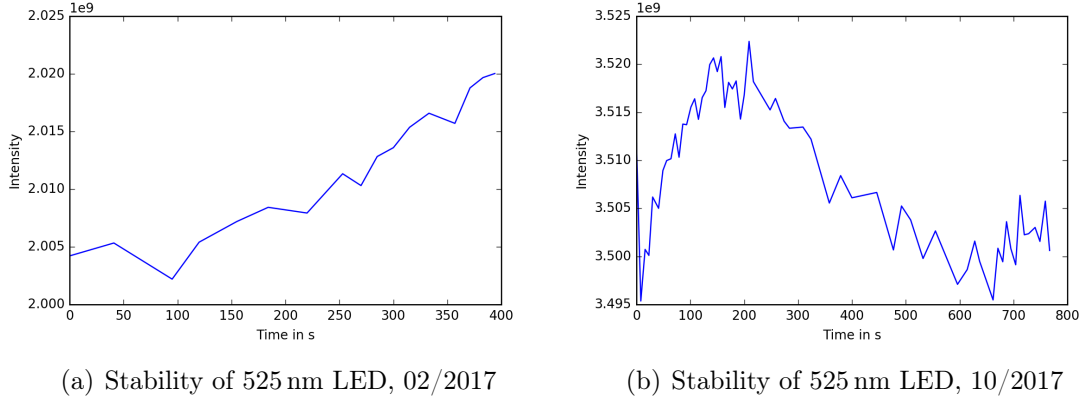


Figure 4.22: The stability of the LED at $\lambda = 525$ nm, measured in February 2017 (left side) and in October 2017 (right side).

LEDs influence the measurement result and if the currently used LEDs are stable enough and suitable for an overall-inaccuracy of smaller than 1%. If the initial waiting time for each LED extends 5 minutes, the goal of reducing the time for an measurement process to about 1 hour per mirror can not be reached.

4.4.3 Intensity of the emitted light in dependency of the distance

Using the inverse square law of physics, which says that any physical law concerning a given quantity or intensity is inversely proportional to the square of the distance from the source of the corresponding quantity, an analysis of the light source is worthwhile. According to the inverse square law, the behaviour of an ideal point-like light source can be described via

$$I \sim \frac{1}{r^2},$$

with the the distance r and the intensity I of the light source. But the light source of the new mirror test facility is, of course, not a perfect point-like light source and, more importantly, the 310 nm LED has a lens. Therefore, it has to be analysed in what extent the above described law can be applied on the light source.

In order to get knowledge about the behaviour of the intensity of the emitted light in dependency of the distance to the light source, the screen and the camera of the new test facility were put at different distances from the light source. The camera

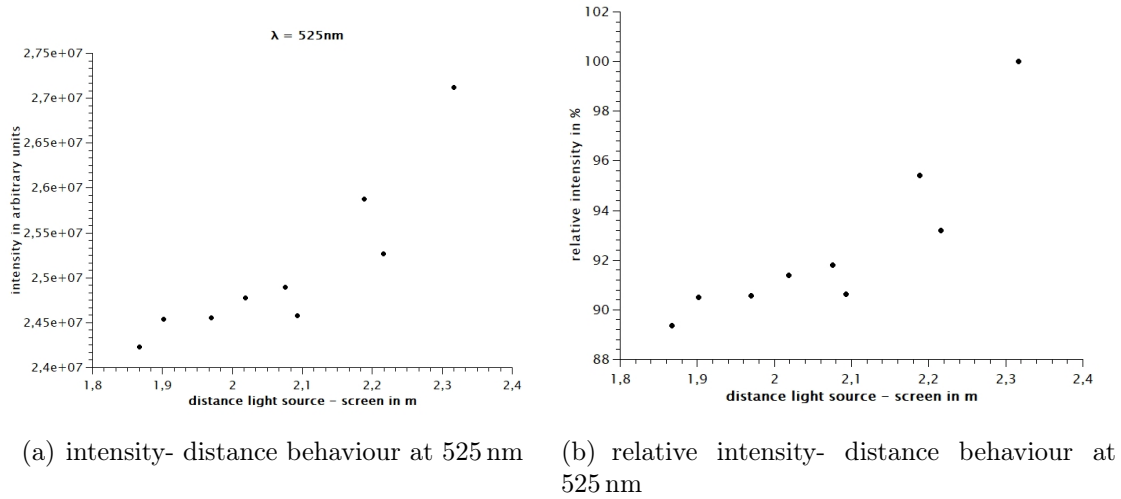


Figure 4.23: The intensity of the light emitted from the LED at 525 nm as a function of the distance. The left plot shows the absolute intensity in arbitrary units, while the right plot shows the relative intensity in %, referring 100% as the maximal intensity.

position was changed too, because the pictures should be taken with the screen at the focal distance of the camera lens system. For each distance between the screen and the light source, an image of the light spot on the screen was taken in the mode for the reference measurement and the intensity of the light spot was calculated by an integration over the spot. Therefore, the integration radius of the image taken at the closest distance was found manually and the radii for the other distances were calculated via the theorem of intersecting lines. For each distance, a mask with the corresponding radius was built and all values outside this mask were set to zero. Then the remaining light intensity over the whole image was integrated. In order to get the exact position of the centre of the light spot, which is equal to the position which reaches the highest value for the intensity integral, the mask was put at all reasonable positions, e.g. all positions which have a distance to the border of the image which is bigger than the radius of the mask, and the integral was calculated at each position. In the end, the maximum of the integrated intensity values was located and therefore, the intensity maxima could be compared, which leads to knowledge about the behaviour of the intensity of the light source as a function of the distance. This investigation was done for all available wavelengths.

Figures 4.23 - 4.27 show the results of these investigations. The left plots show each the absolute intensity in arbitrary units, while the right plots show the relative

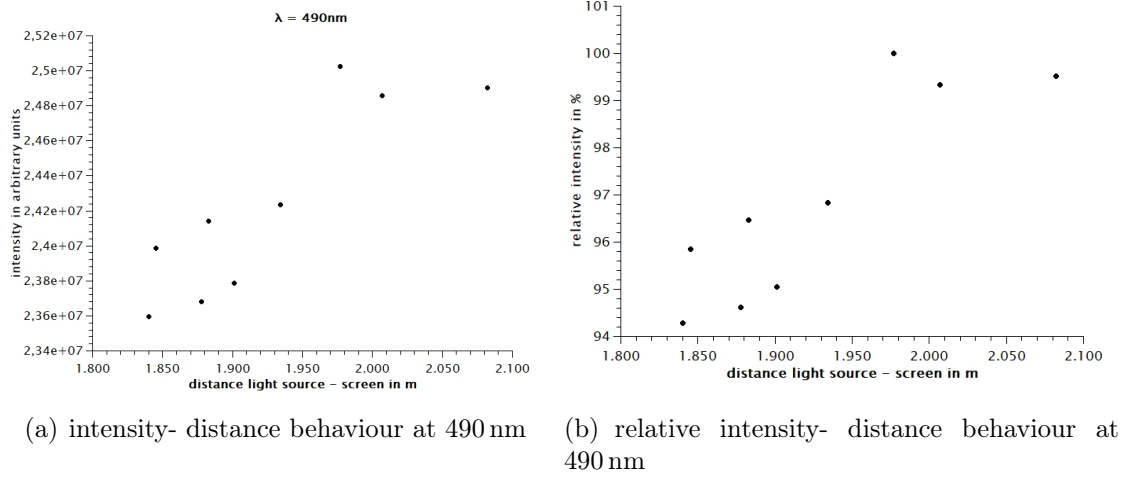


Figure 4.24: The intensity of the light emitted from the LED at 490 nm as a function of the distance. The left plot shows the absolute intensity in arbitrary units, while the right plot shows the relative intensity in %, referring 100% as the maximal intensity.

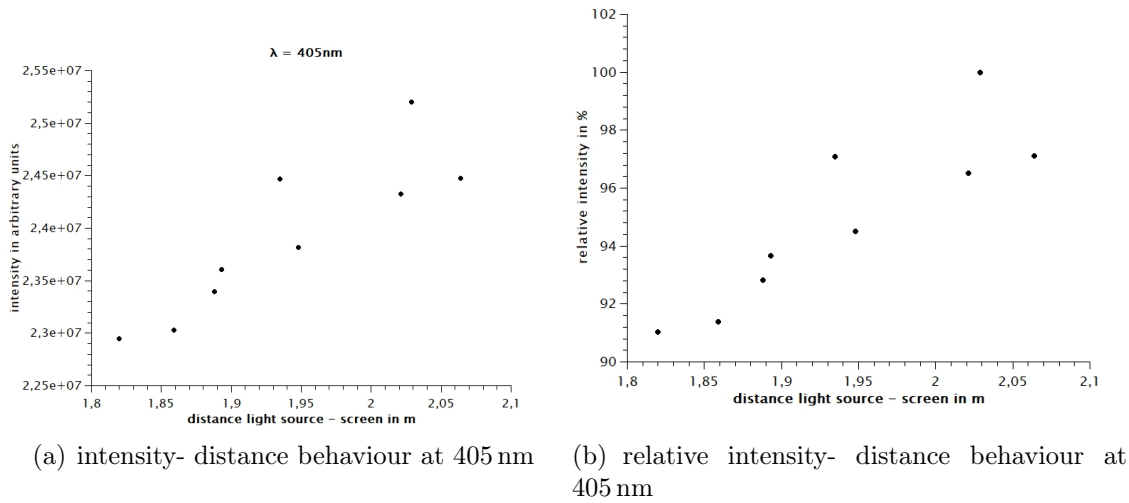


Figure 4.25: The intensity of the light emitted from the LED at 405 nm as a function of the distance. The left plot shows the absolute intensity in arbitrary units, while the right plot shows the relative intensity in %, referring 100% as the maximal intensity.

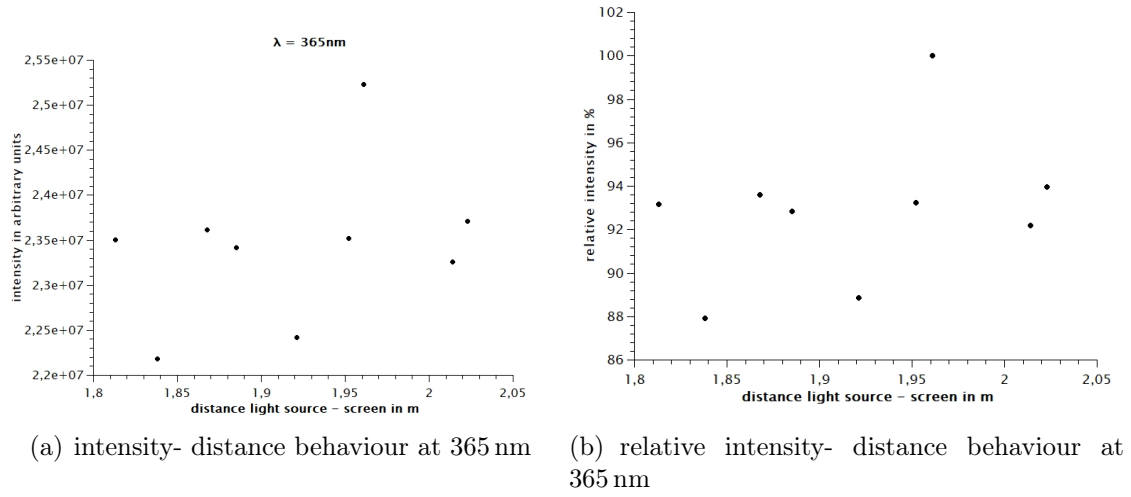


Figure 4.26: The intensity of the light emitted from the LED at 365 nm as a function of the distance. The left plot shows the absolute intensity in arbitrary units, while the right plot shows the relative intensity in %, referring 100% as the maximal intensity.

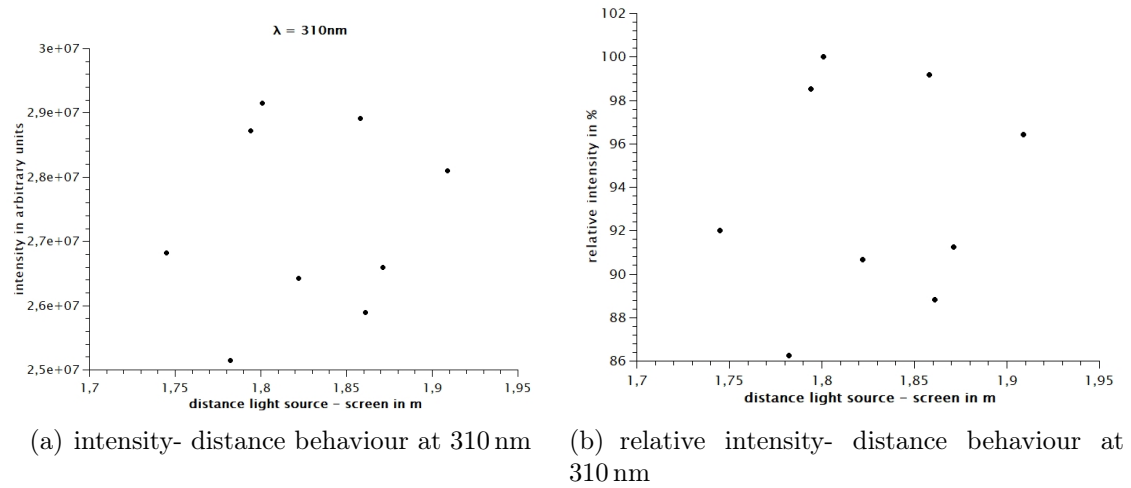


Figure 4.27: The intensity of the light emitted from the LED at 310 nm as a function of the distance. The left plot shows the absolute intensity in arbitrary units, while the right plot shows the relative intensity in %, referring 100% as the maximal intensity.

intensity in %, referring the maximal intensity as 100%. Because of the changing integration radius for each distance, a constant behaviour of the integrated value for the intensity is expected.

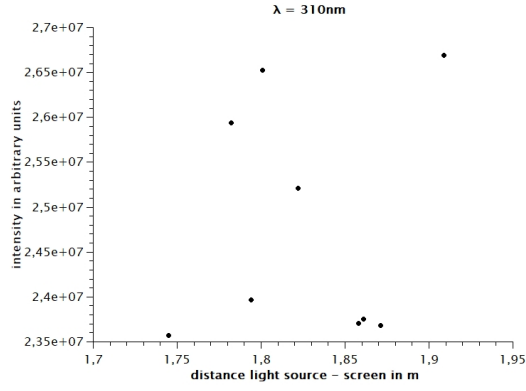
The intensities of the LEDs at $\lambda = 365\text{ nm}$ and $\lambda = 310\text{ nm}$ seem to be randomly scattered, while the LEDs at $\lambda = 525\text{ nm}$, $\lambda = 490\text{ nm}$ and $\lambda = 405\text{ nm}$ show a behaviour of increasing intensity with growing distance, which is not consistent with theory. So, apparently there is a linear increase additional to the quadratic behaviour at these wavelengths. The question is, if this is a second order effect: Does the quadratic behaviour dominate in first order and is there an additional increase in second order? To answer this question, a further analysis has been done: The size of the integration circle was now set constant for each wavelength and the circle was located at the centre of the light spot.

Figure 4.28 shows the results of this analysis. One can see, that the LEDs at 310 nm, 365 nm, 405 nm and 490 nm show not the behaviour expected from theory. Only the LED at 525 nm can be described by a quadratic decreasing behaviour. For this wavelength, a polynomial of degree two was fitted to the data.

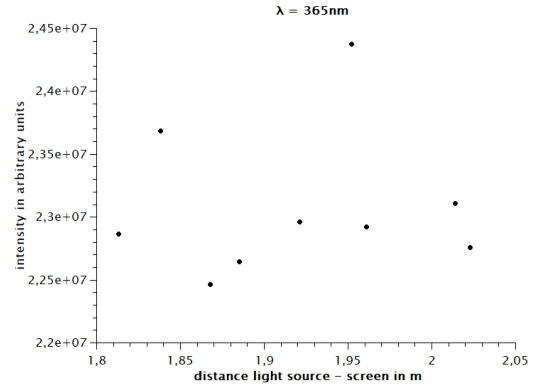
Because of the presented behaviour of the intensity of the light source as a function of the distance between light source and screen and because of the behaviour of the stability of the LEDs, which is discussed in the previous Chapter 4.4.2, it seems to be indispensable to replace the present used LEDs.

4.5 CCD camera

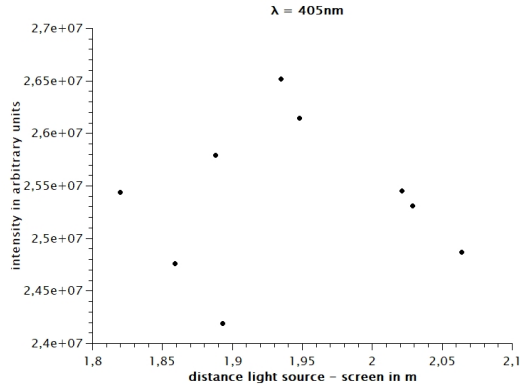
The camera used in the new test facility is the UV-sensitive Apogee Alta U47 CCD 1024x1024 Pixel CCD camera with an UV transparent objective. The data sheet for the camera and the associated achromatic lens triplet can be found in the annex, Chapter 7.2. The data sheet also includes a diagram of the sensitivity of the camera at different wavelengths. The camera is connected via USB cable to a laptop featuring a camera control software and the images are stored in the .fits-format.



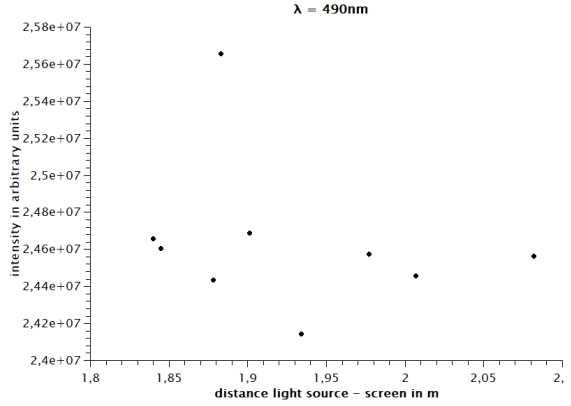
(a) intensity- distance behaviour at 310 nm, constant integration radius



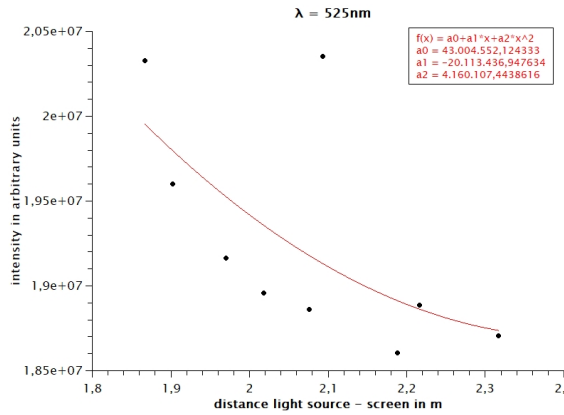
(b) intensity- distance behaviour at 365 nm, constant integration radius



(c) intensity- distance behaviour at 405 nm, constant integration radius



(d) intensity- distance behaviour at 490 nm, constant integration radius



(e) intensity- distance behaviour at 525 nm, constant integration radius

Figure 4.28: The intensity of the light emitted from the light source as a function of the distance, analysed with a constant integration radius.

4.5.1 Determination of the reproduction scale of the CCD camera

When the analysis script described in Chapter 4.3 was implemented, it was found out that a small variation of the reproduction scale of the CCD camera caused a big effect on the results of the analysis script, i.e. reflectivity and PSF of the mirrors, which is described in detail in Chapter 4.3.1. At the beginning of this thesis, the reproduction scale of the CCD camera was only very imprecisely identified: It was measured by eye, that the reproduction scale is about 6 pixel per mm. It is obvious, that this misrepresented value does not fit into the high claims to accuracy and hence, the reproduction scale had to be determined as precisely as possible. The reproduction scale β is defined as

$$\beta = \frac{\text{image size}}{\text{object size}}.$$

Unfortunately, the image distance b of the system is not known: The collimator is home-made by the IAAT workshop and the exact position of the lens triplet is unknown. Therefore, the lens equation

$$\frac{1}{b} + \frac{1}{g} = \frac{1}{f} \tag{4.2}$$

with the focal length f and the g the object distance, can not be used to calculate the reproduction scale. However, a precise measurement can solve this issue: The underlying idea is to take an image of a well-defined test pattern and use a script to determine the reproduction scale. Thus, after numerous experiments on different materials and test pictures, the following method was chosen: A grid with a center-to-center distance of 1 cm and a line width of 1 mm, was made of Trovidur[®] PVC-U: The red plate was varnished with black color, then the grid was milled with a CNC milling machine and the surface, except from the recesses for the grid, was ground down. The result is shown in Figure 4.29.

Then, the grid plate was photographed with the CCD camera under special conditions of illumination: A work light was pointed towards the wall and the ceiling and then the light spot was moved in such a way that the grid plate was illuminated as homogeneous as possible by the stray light. Under these conditions, the grid plate was photographed with the CCD camera. Figure 4.30 shows the resulting image. The two mounting screws of the grid plate are visible, because of their much higher

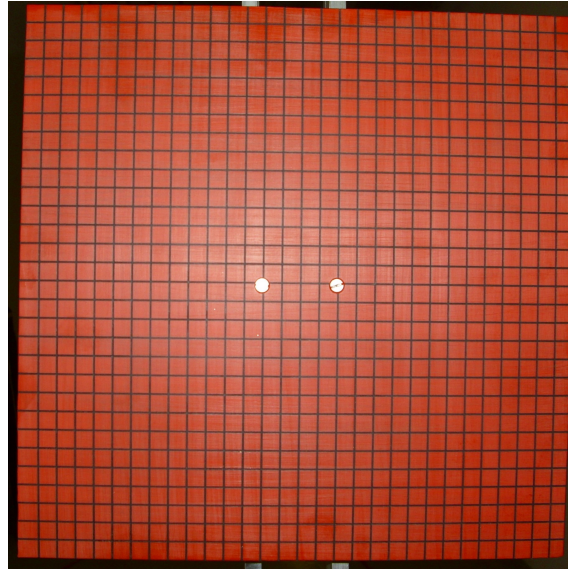


Figure 4.29: Plate made from Trovidur[®] PVC-U, containing a grid as a test pattern for the determination of the reproduction scale of the CCD camera.

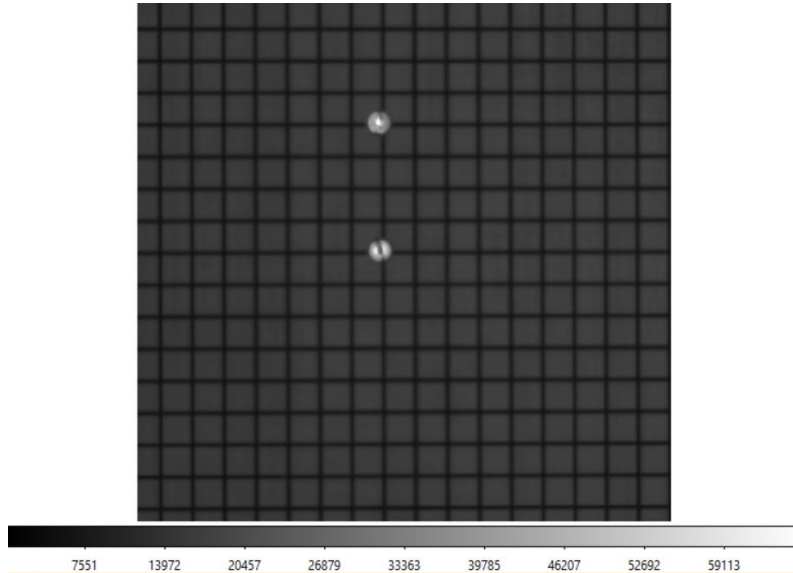


Figure 4.30: The CCD image of the grid plate. On the bottom, a scale for the intensities can be seen. The regions around the two screws, which are visible in the image, have been excluded from the following analysis.

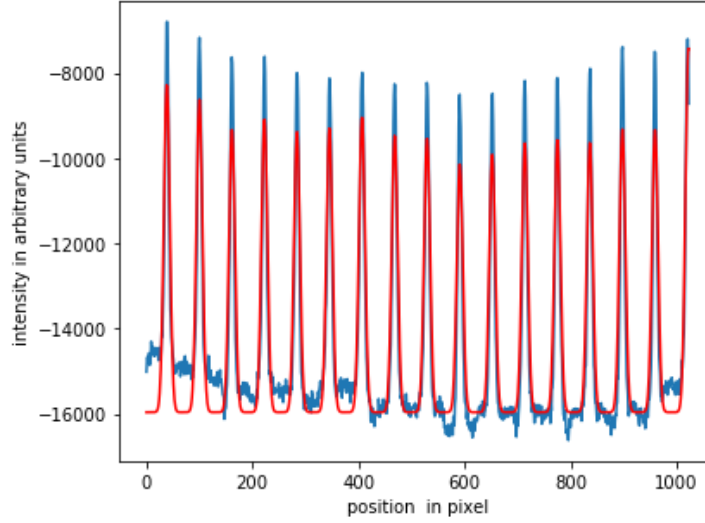


Figure 4.31: The analysed CCD picture of the test grid: The blue graph shows the maxima in intensity (measurement data), the red graph are the Gaussian fits. Here, an exemplary row of the whole data set is shown.

reflectivity. Therefore, the regions around the screws have been excluded from the analysis. The analysis is done with a python script and starts with the determination of the pixel position of the minima in intensity, which represent the lines of the grid. A change of the sign turns the minima into maxima in intensity, which can be seen in Figure 4.31 (blue graph). Gaussian fits are applied to these data and because only the positions of the maxima are relevant, the background and the amplitude do not have to be fitted satisfying.

In a next step, the peak positions of the Gaussian fits are identified in units of pixel. Due to the fact, that the center-to-center-distance of the grid on the Trovidur[®] plate is equal to 1 cm, one can calculate the number of pixels per cm from the peak positions. The results are illustrated in a scatter plot, see Figure 4.32.

This analysis is done for each row and column of the 1024x1024 pixels .fits-file, so in the end there are 2048 sets of data. Figures 4.31 and 4.32 show the maxima in intensity, fitted with Gaussian functions, and a scatter plot of the numbers per pixels per cm in dependency on the position on the screen for an exemplary row of the whole data set. Figures 4.33 and 4.34 exemplify the distribution of numbers of pixels per cm over the position on the screen for the rows, respectively columns on the top, bottom and the middle of the CCD image.

Hereupon, statistical analysis of all results, both rows and columns, are applied.

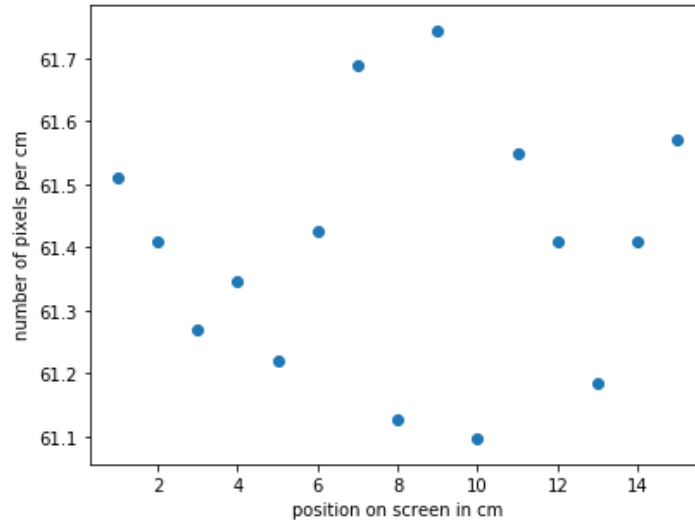


Figure 4.32: Scatter plot of the numbers of pixels per cm, in dependency on the position on the Trovidur[®] grid screen. Again, an exemplary row of the whole data set is shown.

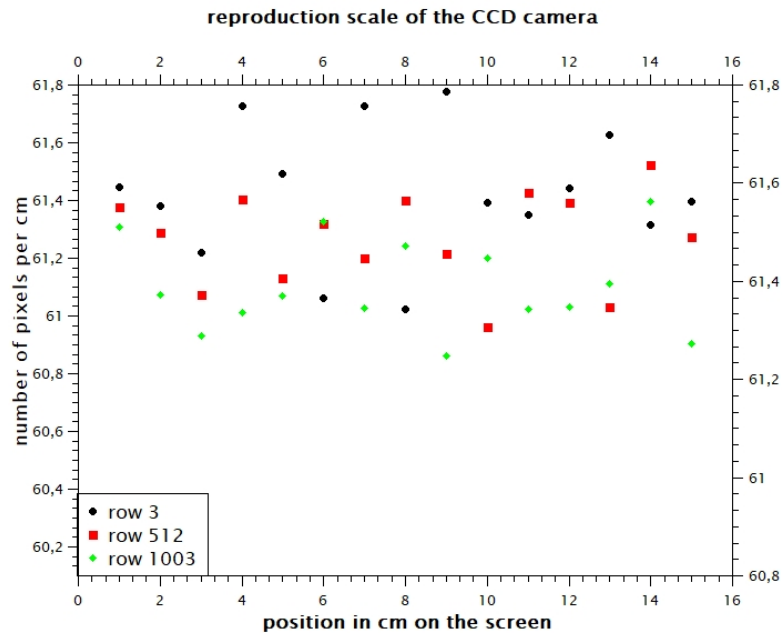


Figure 4.33: Distribution of numbers of pixels per cm over the position on the screen for the rows on the top, bottom and the middle.

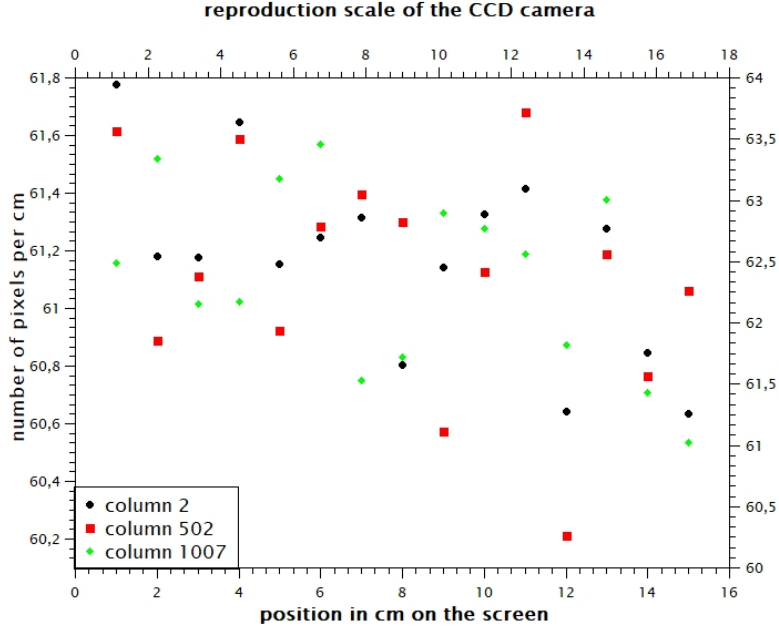


Figure 4.34: Distribution of numbers of pixels per cm over the position on the screen for the columns on the top, bottom and the middle.

Figure 4.35 shows the resulting histogram of the reproduction scale, i.e. the “pixel size”, so dilatation of a pixel in mm.

The characteristic statistic results are:

- Minimum: $\min = 0.1559 \text{ mm/pixel}$
- Maximum: $\max = 0.1789 \text{ mm/pixel}$
- Mean: $\text{mean} = 0.1632 \text{ mm/pixel}$
- Standard deviation: $\text{std_dev} = 0.0007 \text{ mm/pixel}$.

Beyond and with the help of these results, one can do some theoretical thoughts on the lens equation 4.2 in order to prove that the measurement results are consistent with the theory: Figure 4.36 shows the optical light path for thin lenses. Using the theorem of intercepting lines for the centre ray and the optical axis, one gets the reproduction scale A ,

$$A = \frac{B}{G} = \frac{b}{g}. \quad (4.3)$$

Therefore we get, by adding 1 on each side of the equation and calculating the inverse of the relation

$$\frac{b}{b+g} = \frac{B}{B+G}. \quad (4.4)$$

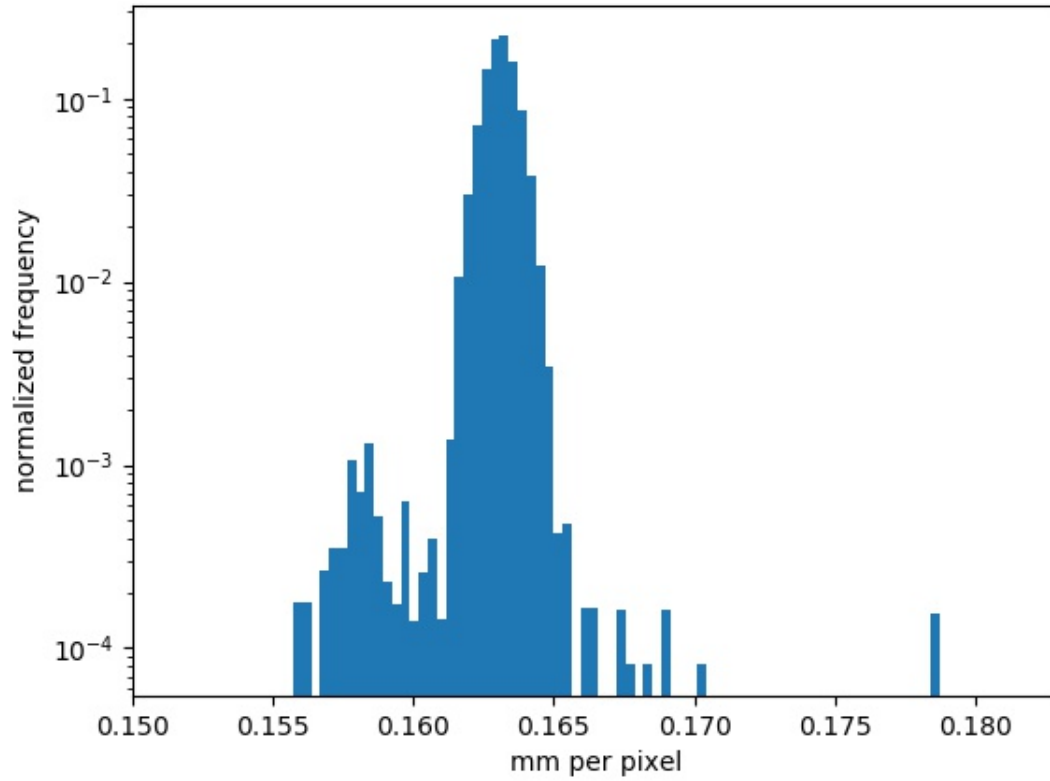


Figure 4.35: Normalized histogram of the size per pixel, i.e. the reproduction scale, over all analysis results for both rows and columns.

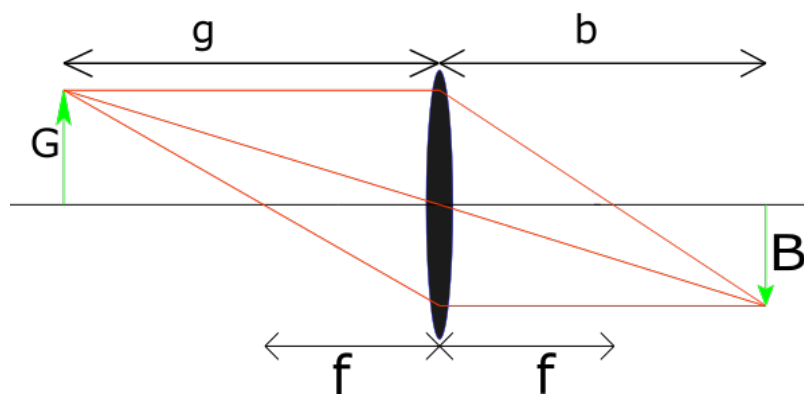


Figure 4.36: Scheme of the optical path at a thin lens with the focal length f , the object size G , the image size B , the object distance g and the image distance b .

Using the intercept theorem for the focal rays and the optical axis, one gets the relation

$$\frac{B}{G} = \frac{b-f}{f}, \quad (4.5)$$

which leads together with equation 4.3 to the lens equation 4.2. Transforming the lens equation equivalently leads to:

$$f = \frac{b \cdot g}{b + g}. \quad (4.6)$$

Inserting 4.4 into equation 4.6, one gets finally

$$f = \frac{B}{B + G} \cdot g. \quad (4.7)$$

This looks after some equivalently rearranging methods like

$$G = \left(\frac{g}{f} - 1 \right) \cdot B, \quad (4.8)$$

which can be used to try to get information about the position of the lens triplet inside the collimator. An imprecise measurement (a precise measurement is not possible because of the design of the hardware) of g is in the order of $g \approx 2.48\text{m}$. With the focal length of the lens triplet (taken from the data sheet, see annex, Chapter 7.2), $f = 17.462 \cdot 10^{-3}\text{m}$ and the physical pixel size of the CCD camera, also taken from the data sheet in the annex, $B = 13 \cdot 10^{-6}\text{m}$, G can be estimated with the help of relation 4.8:

$$G = \left(\frac{248 \cdot 10^{-3}\text{m}}{17.462 \cdot 10^{-3}\text{m}} - 1 \right) \cdot 13 \cdot 10^{-6}\text{m} = 17.1629 \cdot 10^{-5}\text{m} \pm 3.144 \cdot 10^{-6}\text{m}$$

which is in not consistence with the experimental detected values: The theoretical value is $\sim 3\%$ larger than the measured value. The errors are calculated by Gaussian error propagation, assuming a uncertainty for g of $2 \cdot 10^{-3}\text{m}$. Maybe the uncertainty for g is too small. Also, the distance between camera and screen for this measurement scale can be slightly off.

The major worry about the pixel size, respectively reproduction scale, worry was a distortion caused by the lens. With the study described in this Chapter, this could be excluded. Therefore, no correction function for the CCD lens triplet had to be implemented in the analysis script.

4.5.2 Determination of the focal length of the lens triplet

It was found by chance, that the camera was operating out of focus, i.e. the distance between the screen and the CCD camera was not equal to the focal length of the lens triplet belonging to the optical camera - collimator system and hence the pictures were blurry. Although the manufacturer indicated the focal length of the camera triplet (see annex, Chapter 7.2), this does not solve the issue: The collimator in use is home-made by the IAAT workshop and the exact position of the lens triplet is unknown and can not be measured. Therefore, the correct distance between the CCD camera and the screen has to be found out manually. The used method is the so-called variance of the Laplacian:

The following explanation is based on [29] and [30]. Firstly, a test pattern with well defined edges was generated with Inkscape and saved as vector graphics. This picture was printed out and photographed with the CCD camera from different distances. The basic idea is to calculate the Laplacian of the image by the relation

$$\Delta \text{img} = \frac{\partial^2 \text{img}}{\partial x^2} + \frac{\partial^2 \text{img}}{\partial y^2}$$

and convolve it with the kernel K,

$$K = \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}.$$

The variance of the response is calculated. If the value of the variance is below a defined threshold, then the image is blurry. Of course, a fixed threshold cannot be defined, because it highly depends on the motive and the lightning. For this investigation, a suitable threshold has been used. Fast intensity changes in the picture are pointed out by the Laplacian. An in-focus image shows a high variance, i.e. a wide spread of the resulting values from the method. Blurry images show tiny spreads of the results and therefore a low variance. The more an image shows blurryness, the less edges can be found by the Laplacian edge detection. So, in the end one gets a single float number, which illustrates the amount of blurry in an image.

This method was realized by several measurements of the picture shown in Figure 4.37, realized at a multitude of distances. In the measurement process, the motive and lightning was kept stable. A relative measurement was done, where only the

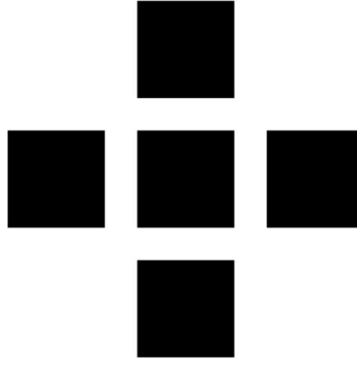


Figure 4.37: The test pattern which was used for the elimination of blurryness, caused by an out-of-focus distance between CCD camera and screen.

distance changed. The analysis of the received pictures was executed with a python script. Several measurements have been rendered. Figure 4.38 shows the results of the first test series. A peak in the variance can be seen at a distance around 1.63 m. The distance, which was used so far as focal distance, is 1.71 m.

Then, the measurement distance was curtailed. Figure 4.39 shows the results of the second test series. The variance values are different for each test series, because the test pattern on the screen was indirectly illuminated with a work light as used on construction sites. Different illumination intensities have been used for each test series.

The result of the second test series seems to reveal a hint at multiple focal lengths of the lens triplet. Finally, after several other test series, the established focal distance between camera and screen was found to be 1.623 m, but a second focal length could be at 1.619 m, as illustrated in Figure 4.40. However, the variance of the picture at this distance is slightly smaller than the variance at 1.623 m. Hence, the hardware of the test facility was modified to work with the ascertained focal distance.

4.6 Mirror mounting

The original mirror mounting at the time of the beginning of the work on this thesis consisted of three pads which were screwed onto the three mounting points on the mirrors, which are delineated in Figure 4.41. With these pads, the mirror was directly screwed onto the mounting framework, which caused mechanical tension on the spherical mirror. These tensions induce distortions of the spot of the reflected light on some mirror types. In order to avoid this, the mirrors are now mounted on

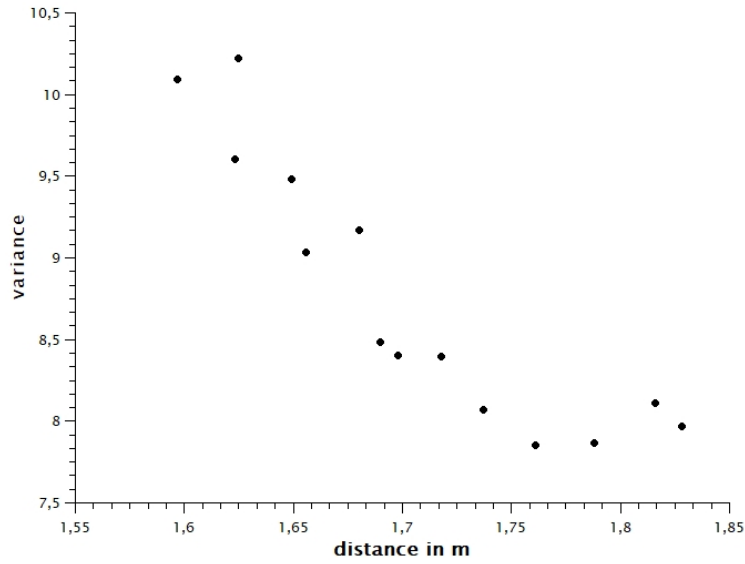


Figure 4.38: Determination of the focal distance of screen and CCD camera, here the results of the first test series. On the x-axis the distance of these two components is shown, the variance of the taken image (figured out by Laplacian edge detection) is applied on the y-axis.

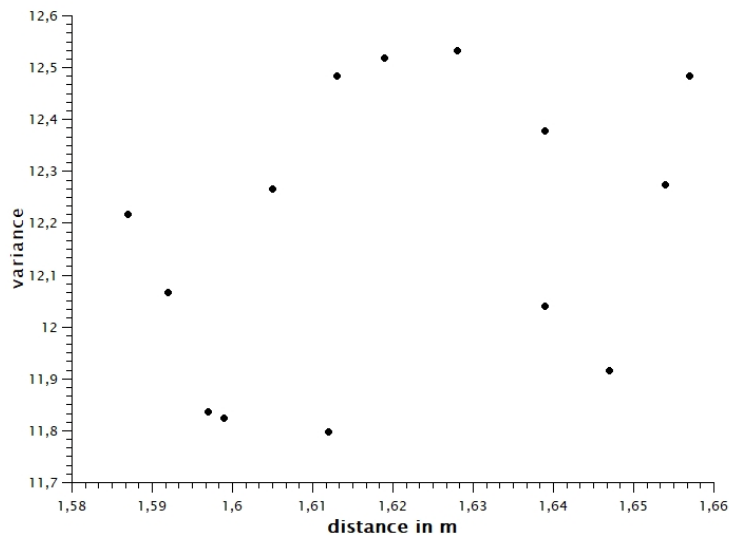


Figure 4.39: Determination of the focal distance of screen and CCD camera, here the results of the second test series. On the x-axis the distance of these two components is shown, the variance of the taken image (figured out by Laplacian edge detection) is applied on the y-axis.

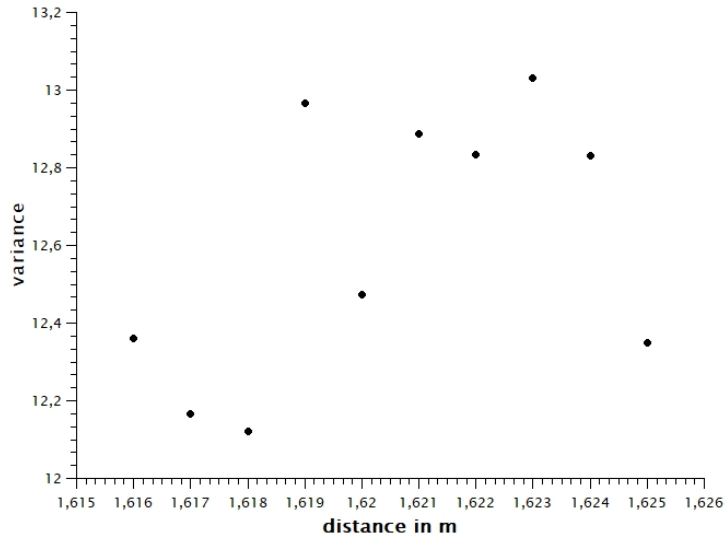


Figure 4.40: Determination of the focal distance of screen and CCD camera. On the x-axis the distance of these two components is shown, the variance of the taken image (figured out by Laplacian edge detection) is applied on the y-axis.

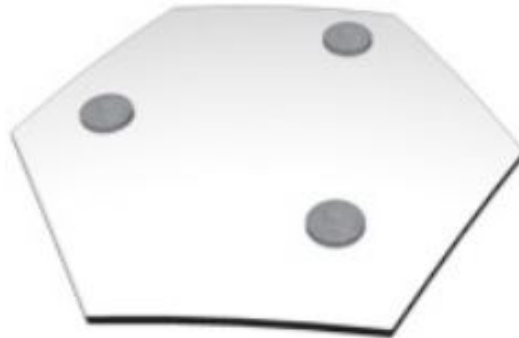


Figure 4.41: The mounting points on the MST mirrors. Credit: Giorgia Sironi, INAF-OA Brera

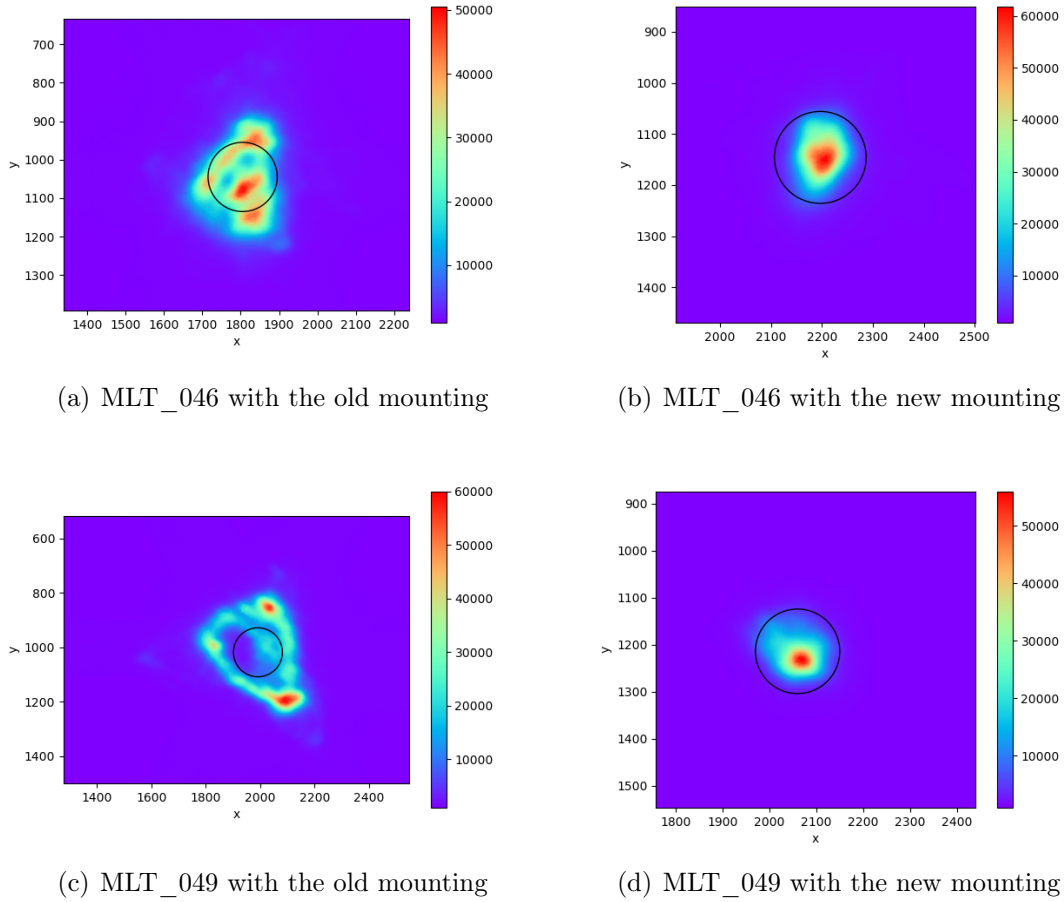


Figure 4.42: Comparison of the reflected light spots with the old and the new mirror mounting, here exemplified for the mirrors “MLT_046” and “MLT_049”.

only one pad (the mounting pad next to the top of the mirror-hexagon) and slightly supported by wooden boards on the lower side. The MLT-mirrors are strongly affected, while the IFJ_PAN-mirrors are not affected, which is presumably due to their heavy and stable honeycomb-structure. The KPS mirrors were not tested. Figure 4.42 shows exemplarily the difference between the reflected light spots of the mirrors “MLT_046” and “MLT_049” with the new and the old mounting. The black circle has a radius equal to 1 mrad

In Figures 4.43 and 4.44, the effect of the deformation of the light spots on the reflectivity are shown, while Figures 4.45 and 4.46 illustrate the effects on the behaviour of the PSF.

As a conclusion, D80 over all wavelengths changes from 26.2 mm to 14.6 mm for

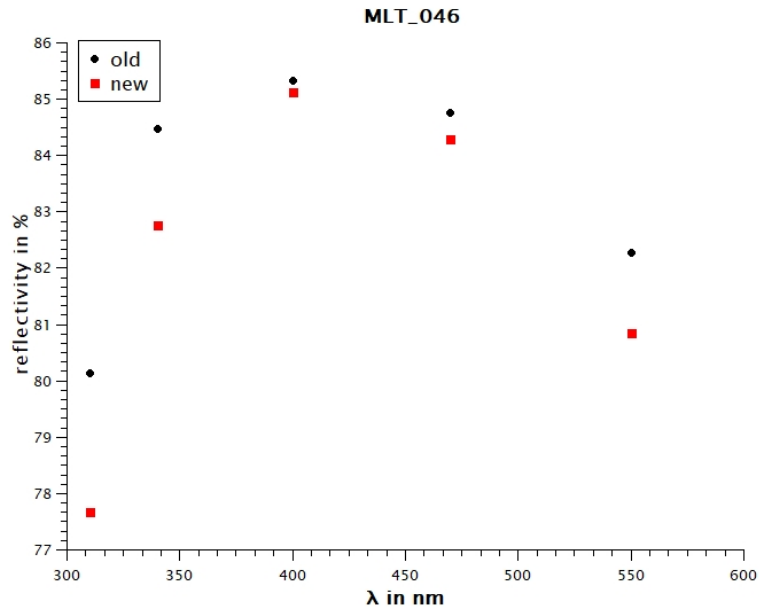


Figure 4.43: Reflectivity over wavelength for MLT_046, for both the old and the new mounting.

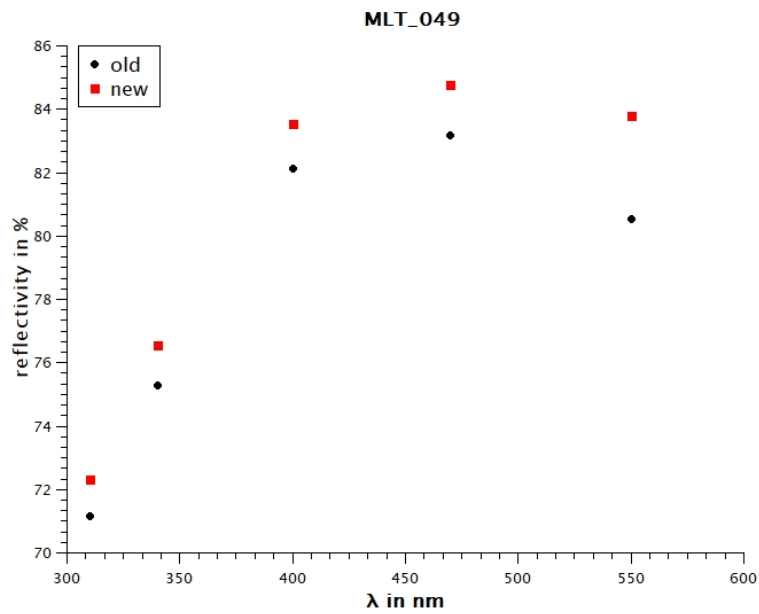


Figure 4.44: Reflectivity over wavelength for MLT_049, for both the old and the new mounting.

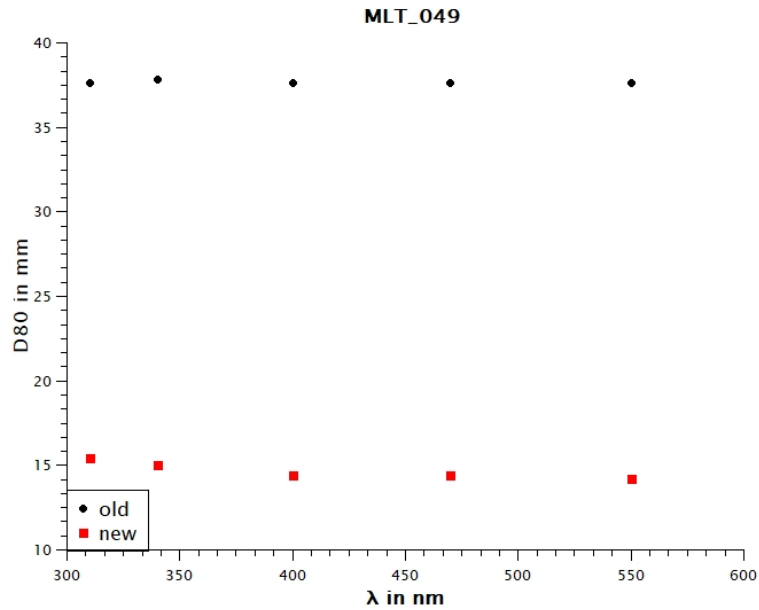


Figure 4.45: PSF over wavelength for MLT_049, for both the old and the new mounting.

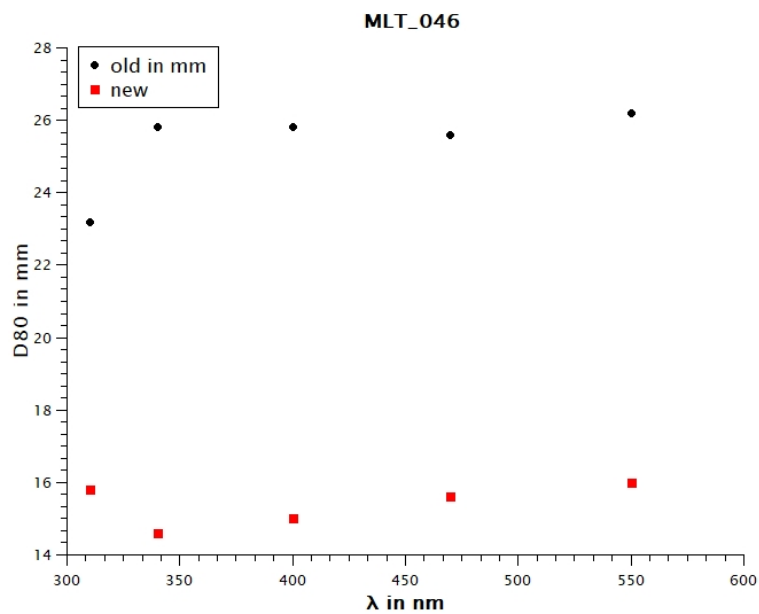


Figure 4.46: PSF over wavelength for MLT_046, for both the old and the new mounting.

MLT_046, respectively from 37.8 mm to 14.2 mm for MLT_049. Note, that these measurements were done with the old test setup and therefore are analysed with the old analysis script, which is based on the H.E.S.S. definitions for D80 instead of the CTA definitions.

5 DESY mirrors measurement campaign

5.1 Packaging and handling issues

When the mirrors arrived the IAAT in December 2016, most of them were significantly damaged and one of the two carrier boxes was broken at the edge. All damages have been documented in detail (see annex, Chapter 7.1) and the issue has been reported to DESY. Although getting no official explanation from DESY, at the CTA Consortium Meeting in Rio de Janeiro (May 2017), the producers of the Polish IFJ_PAN-mirrors presented a plausible explanation (according to [27]) for the little black dots on the reflecting surface of these mirrors (see Figure 5.1): The coating has degraded in the mirrors which were exposed to environmental conditions in the european winter, which is caused by the oxidation of the aluminium-coated layer. This is caused by the detaching of the protective foil, which is necessary to use in the technological process. The detaching generated micro-damages of the protective SiO_2 layer and therefore, the aluminium-coated layers are exposed. Nevertheless, a significant degradation of the PSF is unlikely due to these damages, but the reflectivity of the mirrors may be affected.

There are no explanations concerning the manufacturing of the other mirror types, so the damages are most probably caused by careless handling, packaging or transportation.

5.2 Results of the measurements

Be aware of the fact, that the measurement data received with the old test facility was analysed with the corresponding analysis script, which is based on the old H.E.S.S. definition for the PSF (see Chapter 2.2). The measurement data received with the new test facility was, in contrast, analysed with the new analysis script,

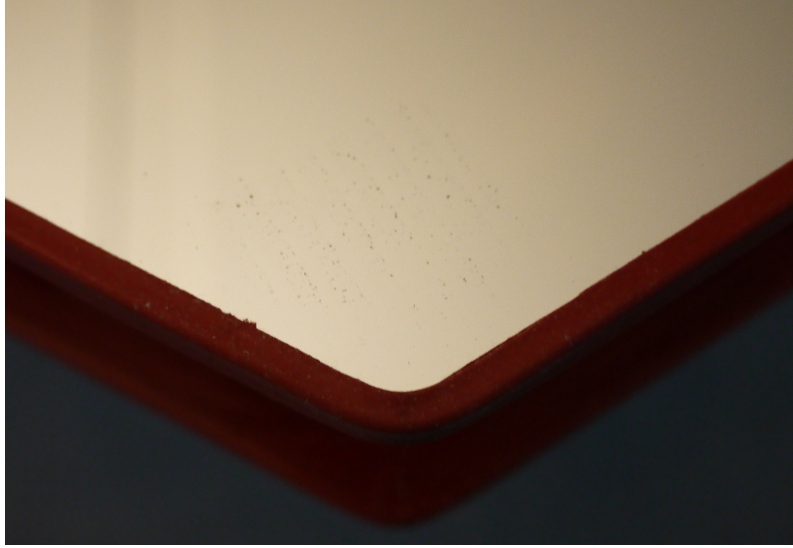


Figure 5.1: An example for the little black dots which can be seen on the polish mirrors, here IFJ_PAN_075 is shown.

which is based on the new PSF definition from [6]. So, the D80-values can only be compared with a lot of suspicion.

5.2.1 Measurement results of old test facility

All of the eight DESY-mirrors were measured during a measurement campaign in December, 2016. Table 5.1 shows the results for the reflectivity in dependency on the wavelength for all of the mirrors. The results for the PSF are shown in table 5.2 and the averaged results for the reflectivity and the PSF are illustrated in table 5.3. Note, that the averaged value for the PSF is based on the CCD measurement and includes calculations in the range of sub-pixels.

One can notice, that the PSF of the MLT mirrors is much better than those of the IFJ_PAN mirrors and the KPS mirror. However, the reflectivity of the MLT mirrors seems, by trend, to be worse than the reflectivity of the other mirrors.

5.2.2 new test facility

With the new test facility, only two of the DESY mirrors were measured: KPS1_043 and IFJ_PAN_077. The selection of these two mirrors was done by chance. The results from the measurement and their associated analysis are shown in Tables 5.4 and 5.5. Take note, that the wavelengths, which are used for the measurement, slightly differ from the ones of the old test facility.

mirror_name	310nm	340nm	400nm	470nm	550nm
IFJ_PAN_067	84.31	88.56	90.43	88.6	84.04
IFJ_PAN_071	81.21	86.79	88.50	88.89	85.18
IFJ_PAN_075	66.63	77.90	87.92	88.77	86.26
IFJ_PAN_077	88.48	91.97	92.70	90.87	85.84
KPS1_043	83.23	88.76	91.94	91.99	89.00
MLT_045	53.60	58.96	66.13	69.22	69.04
MLT_046	77.67	82.76	85.12	84.28	80.85
MLT_049	72.33	76.56	83.55	84.76	83.78

Table 5.1: Reflectivity in % for the DESY mirrors in dependency on the wavelength, measured with the old test facility.

mirror_name	310nm	340nm	400nm	470nm	550nm
IFJ_PAN_067	25.2	24.6	24.0	24.2	24.0
IFJ_PAN_071	27.0	26.0	25.8	26.0	26.0
IFJ_PAN_075	23.8	23.6	23.6	23.6	23.6
IFJ_PAN_077	23.6	23	22.8	22.6	22.6
KPS1_043	23.8	23.2	23.4	23.4	23.4
MLT_045	16.4	16	15.8	15.6	15.6
MLT_046	15.8	14.6	15.0	15.6	16.0
MLT_049	15.4	15	14.4	14.4	14.2

Table 5.2: D80 in mm for the DESY mirrors in dependency on the wavelength, measured with the old test facility.

mirror_name	averaged PSF in mm	averaged reflectivity in %
IFJ_PAN_067	23.8	87.19
IFJ_PAN_071	26.4	86.11
IFJ_PAN_075	23.2	81.50
IFJ_PAN_077	22.8	89.97
KPS1_043	22.8	88.98
MLT_045	15.6	63.39
MLT_046	15.0	82.14
MLT_049	15.0	80.20

Table 5.3: The wavelength-averaged results for the reflectivity and the PSF. The averaging of the PSF is based in the CCD measurement and contains sub-pixel.

All measurements have been executed with the usage of the new mounting, which is described in Chapter 4.6.

mirror_name	310nm	365nm	405nm	490nm	525nm
IFJ_PAN_077	87.47	57.13	93.87	84.72	77.47
KPS1_043	80.77	93.18	93.30	92.13	92.28

Table 5.4: Reflectivity in % for two of the DESY mirrors in dependency on the wavelength, measured with the new test facility.

mirror_name	310nm	365nm	405nm	490nm	525nm
IFJ_PAN_077	21.5	21.2	21.2	21.2	21.2
KPS1_043	21.4	20.8	21.1	21.1	21.1

Table 5.5: D80 in mm in % for two of the DESY mirrors in dependency on the wavelength, measured with the new test facility.

5.3 Comparison of the results received by the old and the new test facility

The results for the two mirrors, which were measured by both the old and the new test facility are shown in the Figures 5.2, 5.3, 5.4 and 5.5. Looking at the results for the KPS mirror, one can see that the results for the reflectivity gathered with the new test facility are below the results gathered with the old test facility for the smallest wavelengths. All other wavelengths show the contrary: Here, the reflectivity measured with the old facility is below the reflectivity determined with the new test facility. The PSF of the new test facility seems to be smaller than the one which was measured with the old test facility. Taking into consideration that the old test facility has a problem with its calibration, because the screen and the camera are not in the same plane, the offset of the results can be explained. The same can be observed at the results of the IFJ_PAN mirror, see Figure 5.5. Additionally, there is a clear trend visible in the old setup which seems to be some hidden systematic, it is not random fluctuations. Concerning the reflectivity of this mirror, one can say that obviously the reflectivity at 365nm seems to be highly defective. This is caused by a mistake during the measurement process. The waiting time for the stability of the light source was not long enough and probably the mirror was not fully illuminated. To avoid this in future measurements, the stability behaviour of the light source should be implemented into the measurement software and a better alignment system for the light source should be designed..

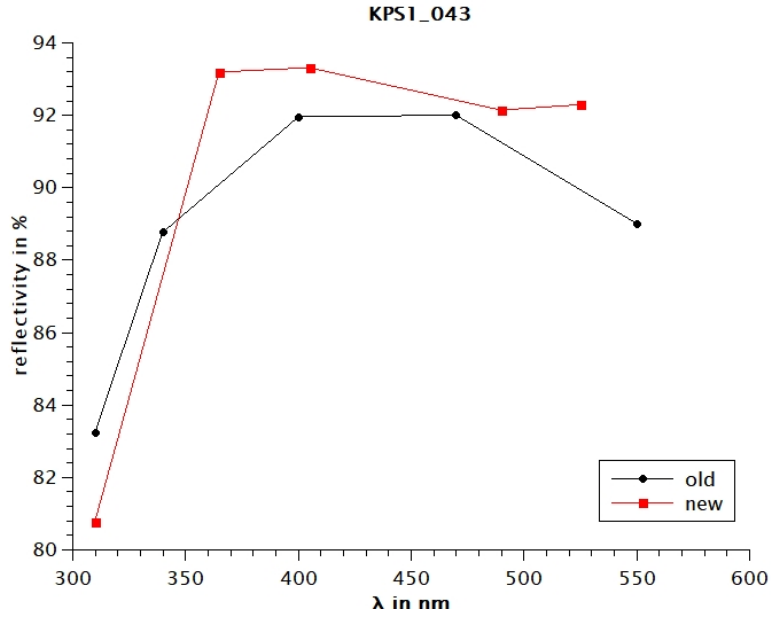


Figure 5.2: Comparison of the reflectivity of the mirror “KPS1_043”, determined with both the old and the new mirror test facility.

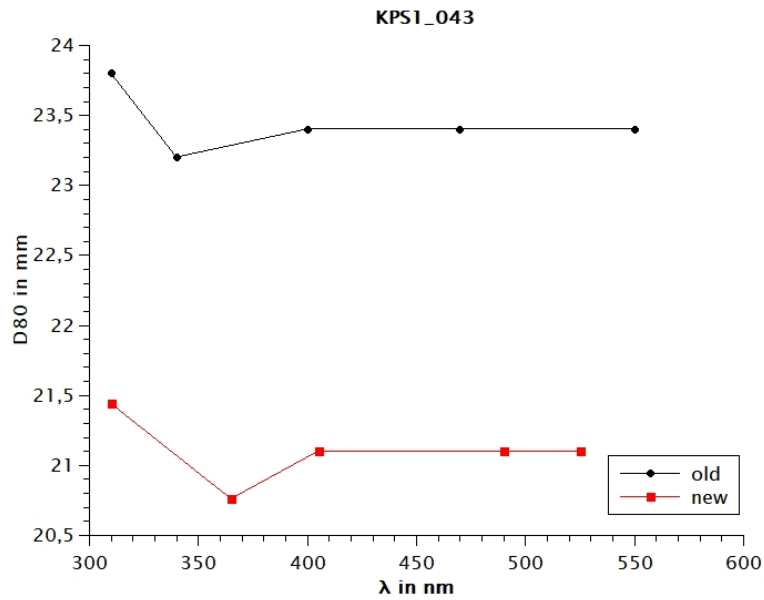


Figure 5.3: Comparison of the PSF of the mirror “KPS1_043”, determined with both the old and the new mirror test facility.

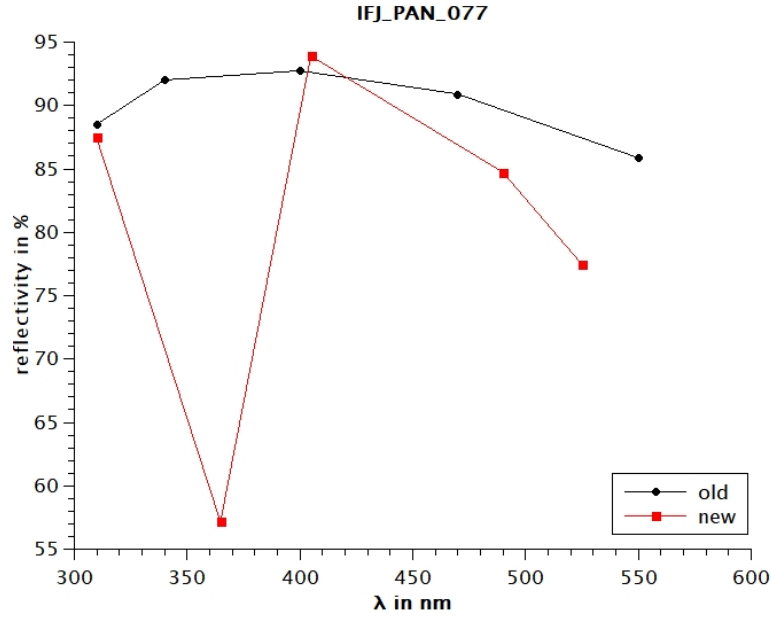


Figure 5.4: Comparison of the reflectivity of the mirror “IFJ_PAN_77”, determined with both the old and the new mirror test facility.

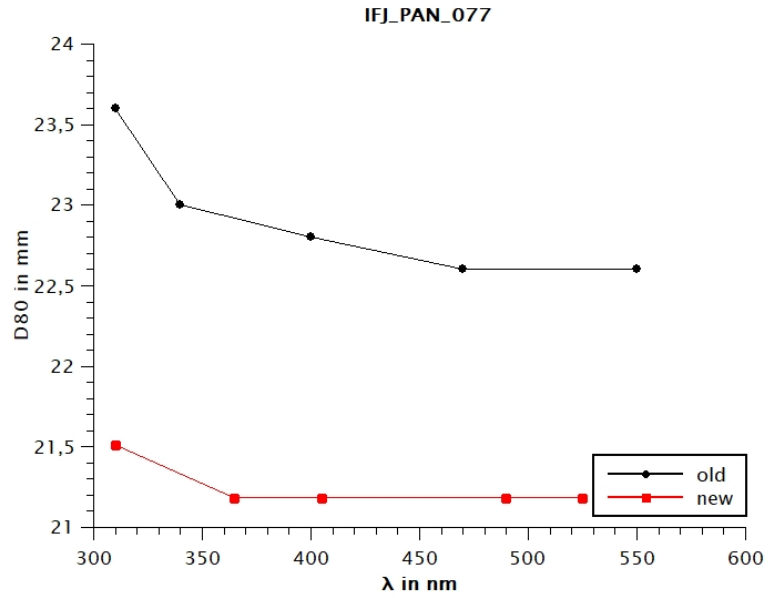


Figure 5.5: Comparison of the PSF of the mirror “IFJ_PAN_77”, determined with both the old and the new mirror test facility.

Analysis of the data received with the new test facility, determined with the old D80 definition

In order to compare the results for the PSF received by the old and the new mirror test facility, the analysis software of the old test facility was modified. Therefore, the definition for D80, which is used in the analysis script for the old test facility (see chapter 2.2), has been implemented in the analysis script of the new test facility. The following results have been received thereby:

mirror_name	310nm	365nm	405nm	490nm	525nm
IFJ_PAN_077	21.89	21.50	21.48	21.51	21.42
KPS1_043	20.88	20.45	20.67	20.63	20.50

Table 5.6: D80 in mm in % for two of the DESY mirrors in dependency on the wavelength, measured with the new test facility. The analysis based on the old H.E.S.S. definition for D80.

Figures 5.6 and 5.7 show the different PSF results for the analysis of the two measured mirrors. The “old” result is the result determined with the old test facility and the corresponding analysis software, while the “new” result is received with the measurement data of the new test facility, which were analysed with the modified analysis script of the new test setup, which contains the old H.E.S.S. definition for D80.

It is conspicuous that the data measured with the new test facility are well below the data measured with the old test facility. Furthermore, the data received by the new test facility seem to behave more constant over the wavelengths. To get the full information about the accuracy of the new test facility, a measurement of a calibrated mirror is inevitable. Such a calibrated mirror was unfortunately not available at the time of this thesis.

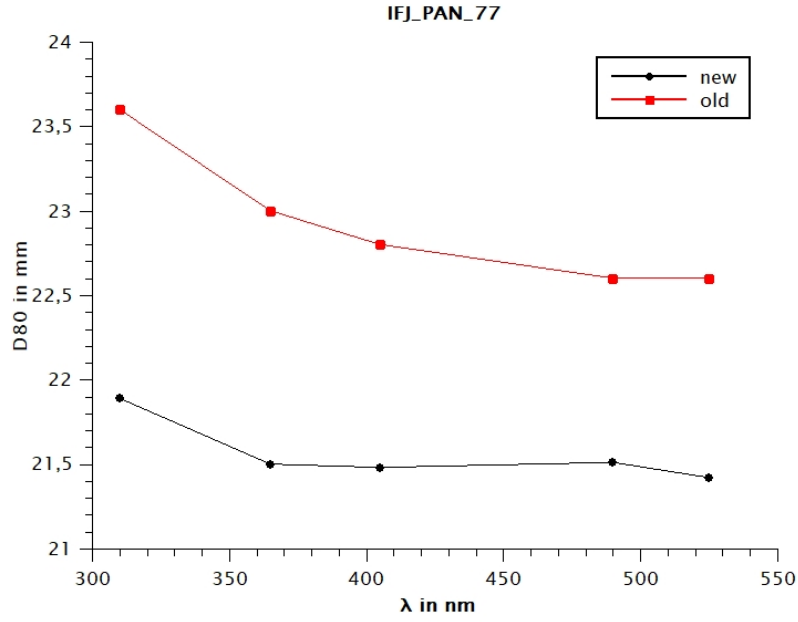


Figure 5.6: Comparison of the PSF of the mirror “IFJ_PAN_77”, determined with the old test facility and the new test facility plus an analysis script based on the old definition for D80.

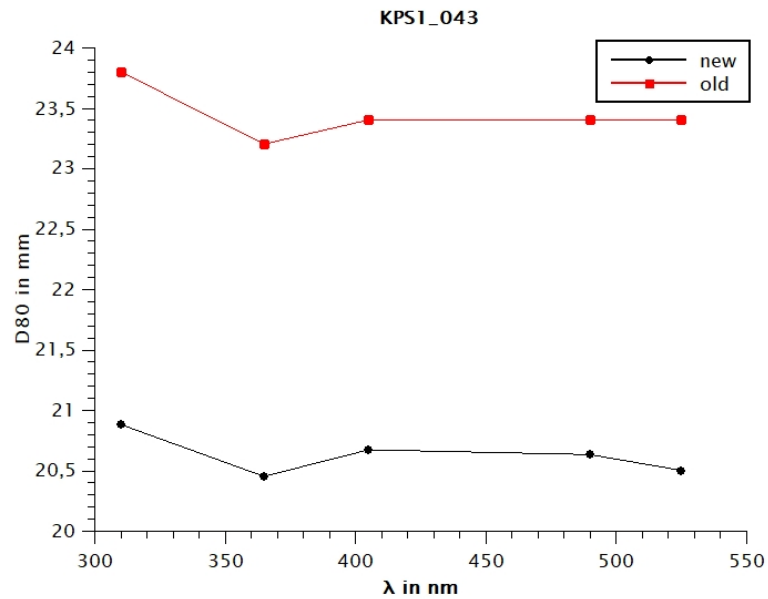


Figure 5.7: Comparison of the PSF of the mirror “KPS1_043”, determined with the old test facility and the new test facility plus an analysis script based on the old definition for D80.

6 Conclusion and Outlook

New darkenings for the windows in the basement have been successfully designed and built. The resulting background seems to be satisfying for a reliable measurement process. A dependable and more user-friendly controlling software for the light source and the CCD camera was built, also an analysis script including the latest CTA definitions for D80 and the reproduction scale of the CCD camera. It would be worthwhile to automate the measurement and analysis process, like it has been already done for the old test facility. Within this process, one could add the script analysing the blurriness of the CCD camera into the whole measurement process, in order to start the measurement only, when the screen is located at the focal distance of the CCD camera. A GUI for all components inclusive the analysis script could be developed. The mounting scheme of the mirrors has been successfully improved. Still, a new mounting scheme should be designed, which should be based on the same mounting scheme as used on the CTA telescopes.

The measurement of the cuts in x and y of the light source and the intensity of the LEDs as a function of the distance revealed, that the LEDs which are in use now are not optimal. They should be renewed, then the above described investigations should be repeated. It should be investigated in future measurements how the fluctuations in the intensity of the LEDs influence the results and if the LEDs underlie ageing effects. If this is the case, the LEDs should be changed from time to time. Then the exact time scale of the ageing effects should be investigated then. Furthermore, a characterisation of the behaviour of the CCD camera should be done, in order to find out the “stability” behaviour of the CCD camera. Furthermore, a detailed collimator study is needed, because it has been found out that at least one of the collimators affect the shape of the light spots. In addition to this, the test facility dangles a lot at the measurement procedure and it would be advisable to design some stabilisation equipment.

The rangefinder should be installed permanently on the test facility, in order to align the light source with a better precision to the centre of the mirror. Related to this, it should be investigated if the rangefinder and the LEDs of the light source

are actually parallel.

The DESY mirror measurement campaign has been successfully attended with the use of the old mirror test facility. At this opportunity, some of the mirrors have been also measured with the new test facility. Some results in the reflectivity can not be fully understood by now, e.g. see Figure 5.2. For the purpose of a better understanding, a calibrated mirror should be measured, after the LEDs are changed. This would be also extremely useful for the design of a new mounting scheme.

Also a detailed discussion of possible sources of error and a study of systematics for the new test facility has to be continued. Only with this discussion it can be found out, if the accuracy of the test facility is above the sought 1%. Moreover, a simulation with a ray-tracing-tool should be done for the understanding of the factor two difference between a light source at the distance of $2f$ and at infinity.

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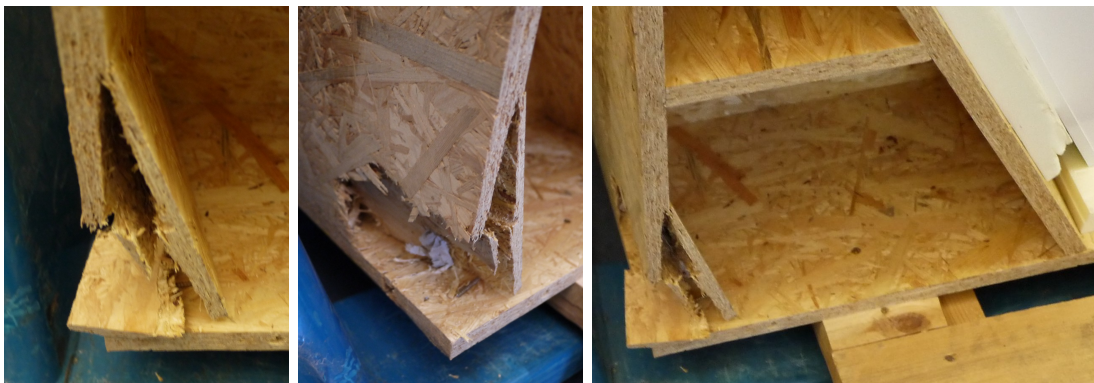
7 Appendix

7.1 Documentation on the damage of the CTA mirrors

This documents describes the defects the CTA MST mirrors have shown at their delivery in Tübingen at Dec 21, 2016. All described damages are located on the front side (i.e. the reflecting side) of the mirrors. In the following, the left-right-orientation is defined as viewed from the back of the mirror. The top-bottom-orientation is defined by the orientation the mirrors had in their carrier boxes at the arrival in Tübingen.

Carrier box

One of the two carrier boxes is damaged on the lower edge. It is the box intended staying in Europe containing the mirrors MLT-046, IFJ-PAN-071,IFJ-PAN-075 and MLT-049. The damage is located on the side where the first two mentioned mirrors are stored.



IFJ-PAN-067

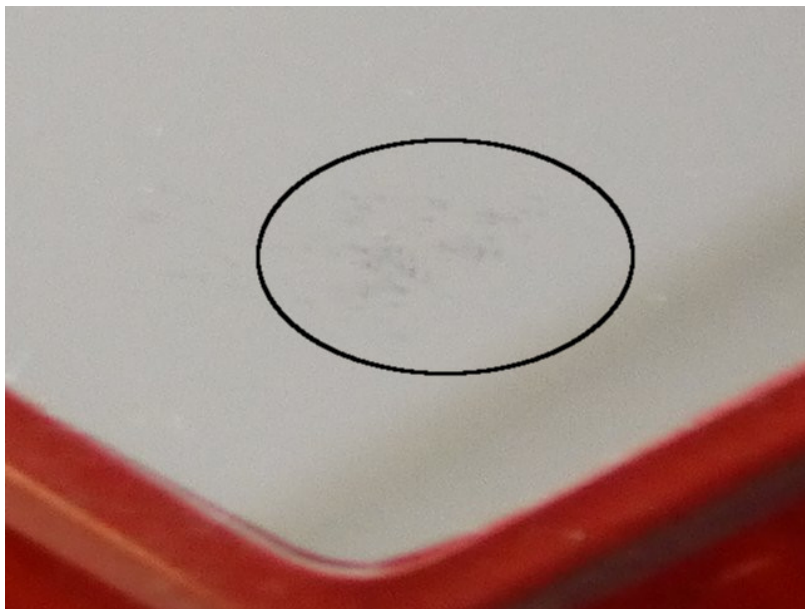
The mirror shows a moderate basic pollution (dust, dirt, ...)[1]. Looking from the back, there is on the left side a black spot with a length of approx. 10mm and a width of approx. 1mm, presumably a scratch [2]. Beyond this, there are black dotted patterns in the corner on the right side and in the corner on the right bottom [3]. These dotted patterns are potentially caused by abrasion of the reflecting surface.



[1]



[2]



[3]

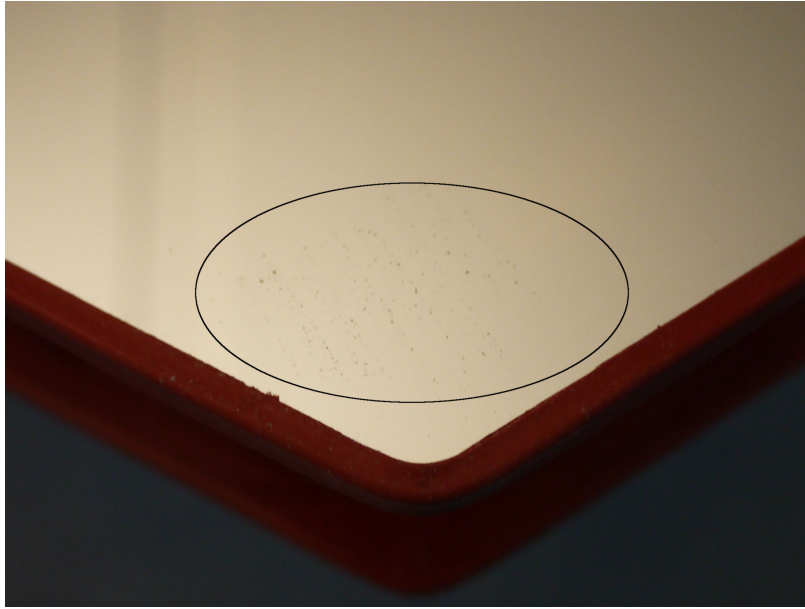
IFJ-PAN-071

The mirror shows a heavy pollution near the upper edge, potentially a leftover from an adhesive tape, which is hard to be taken in a picture.

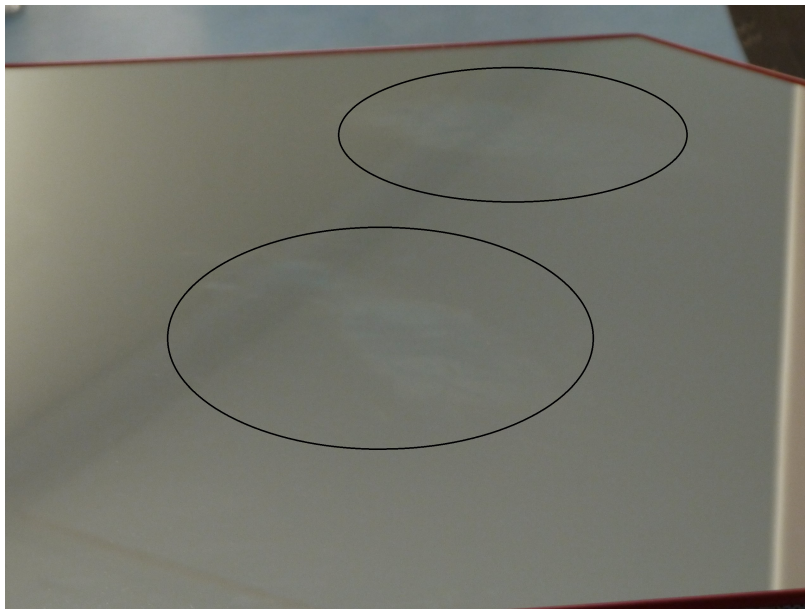


IFJ-PAN-075

The mirror shows black dotted patterns in all corners [1]. Furthermore, there are three huge polluted areas on the reflecting surface [2,3] and there is a scratch near the border [4].



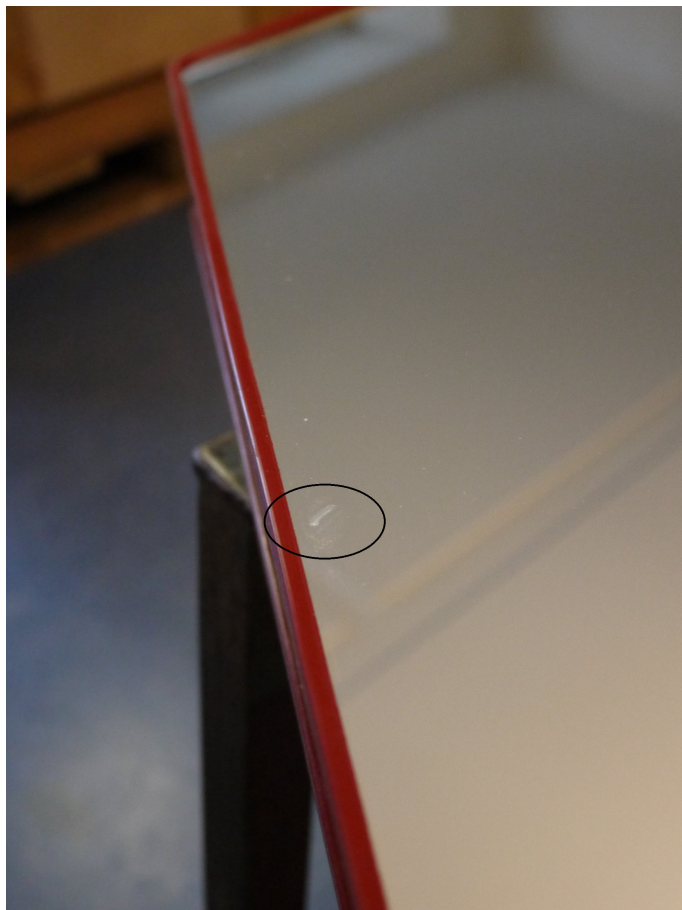
[1]



[2]



[3]



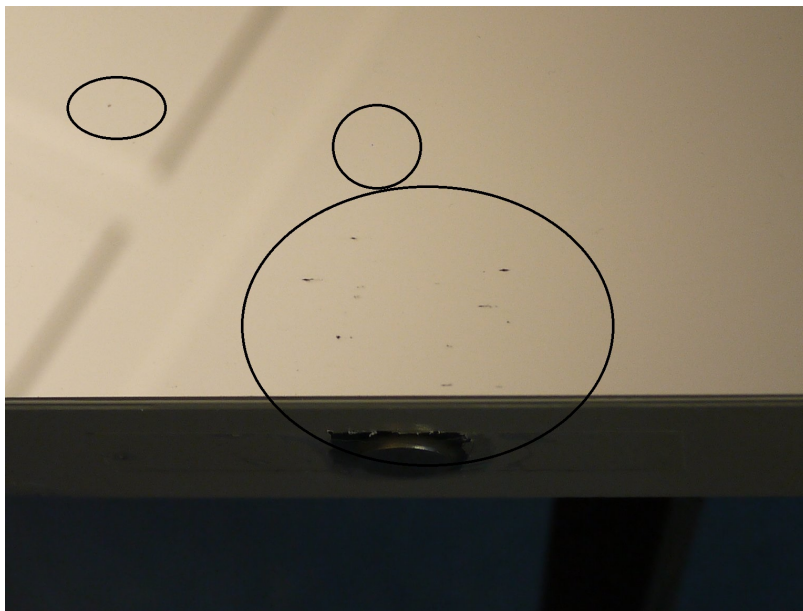
[4]

IFJ-PAN-077

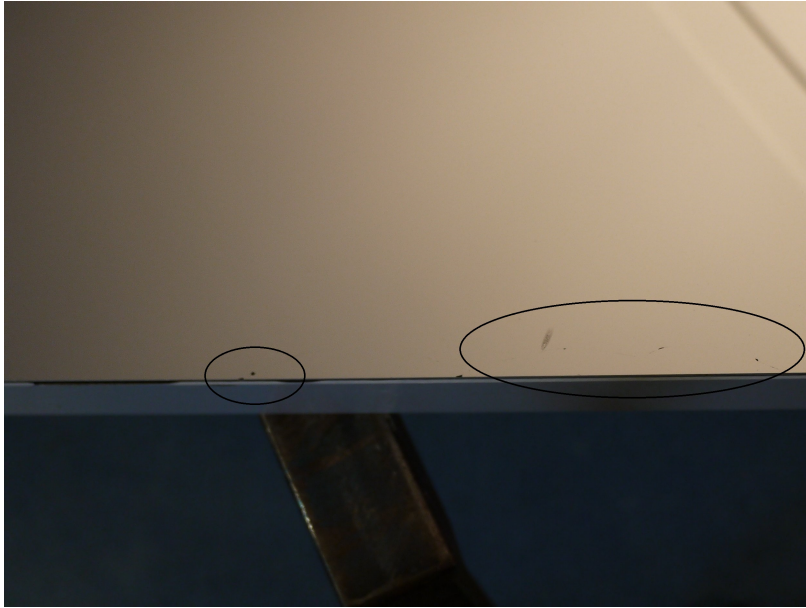
This mirror has no noteworthy damages.

KPS1-043

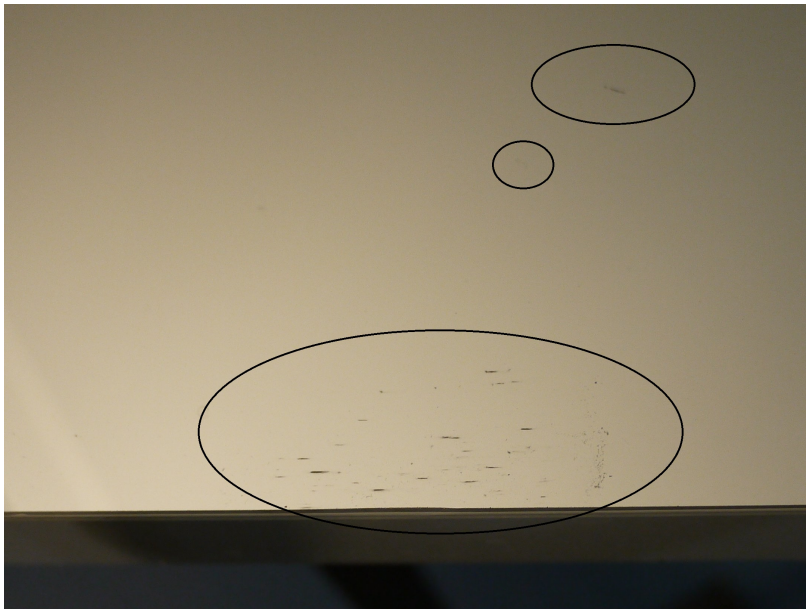
The mirror shows black dotted patterns in the corner on the right bottom [1] and at the left side between the center and the top [2]. Massive pollution and scratches are located at the right side near the corner [3] as well as at the edge on the left bottom [4]. In the corner on the left top, there are three damages [5]. There is a scratch of approx. 20mm length and 1mm width on the right side of the mirror [6].



[1]



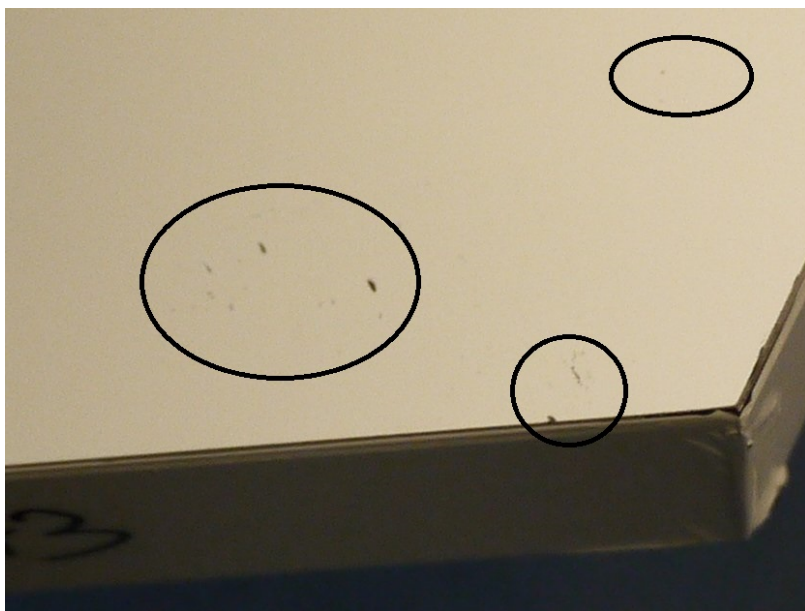
[2]



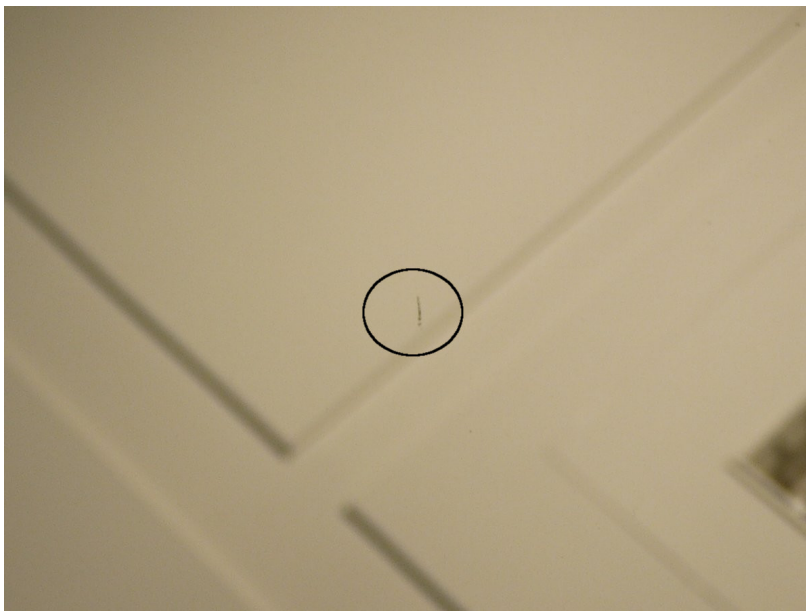
[3]



[4]



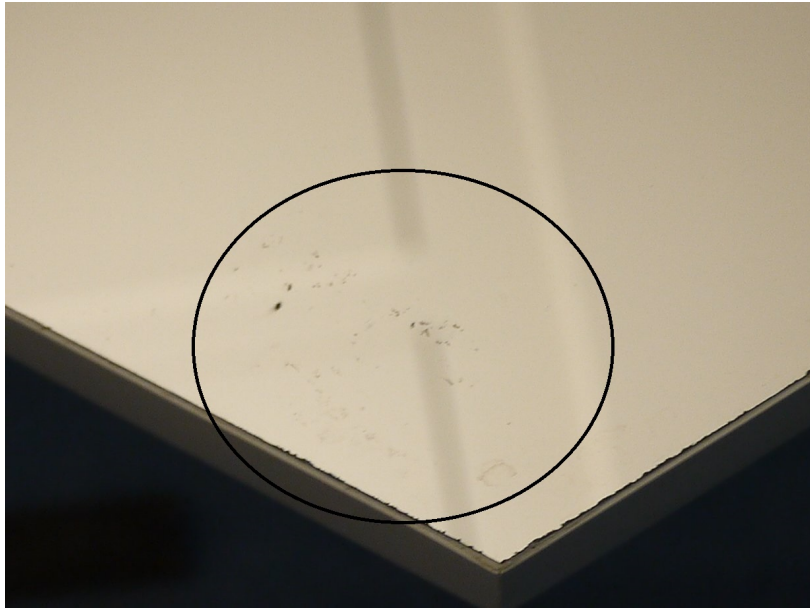
[5]



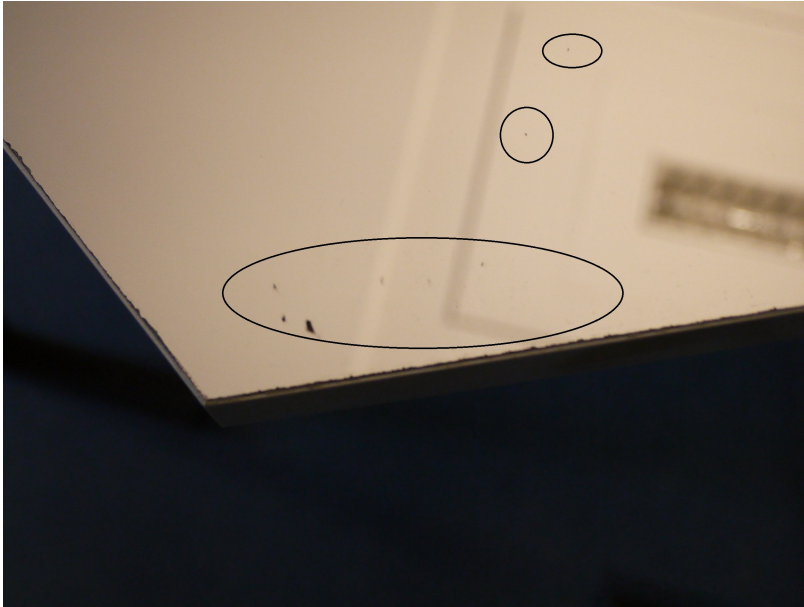
[6]

MLT-045

The mirror shows black dotted patterns in the corners [1,2], potentially caused by abrasion of the reflecting surface. One can find dried drops of water [3] and scratches[4], the biggest with dimensions of approx. 70mm length and 1mm width, on the reflecting surface [3]. In the center of the mirror, there is a bump with a diameter of approx. 30mm. In the picture, a reflection from a grid distorted by the bump, can be seen [5]. The mirror has a massive basic pollution.



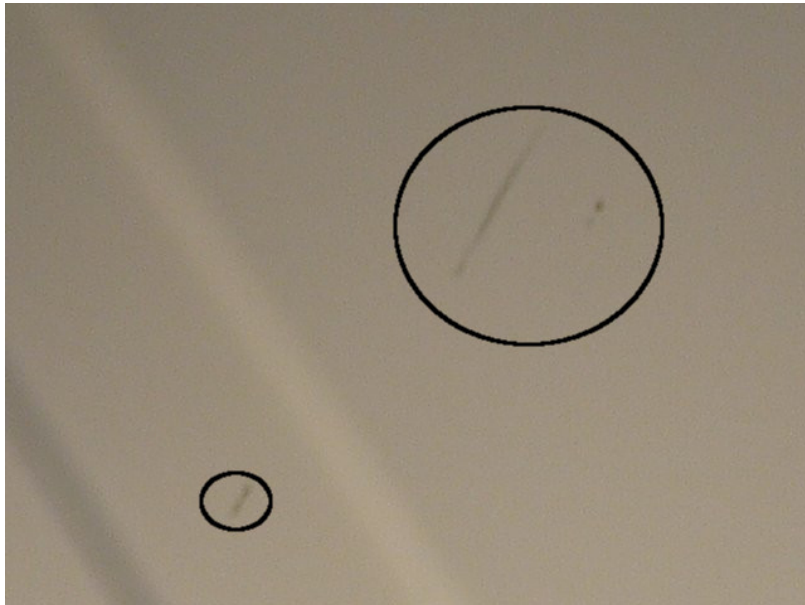
[1]



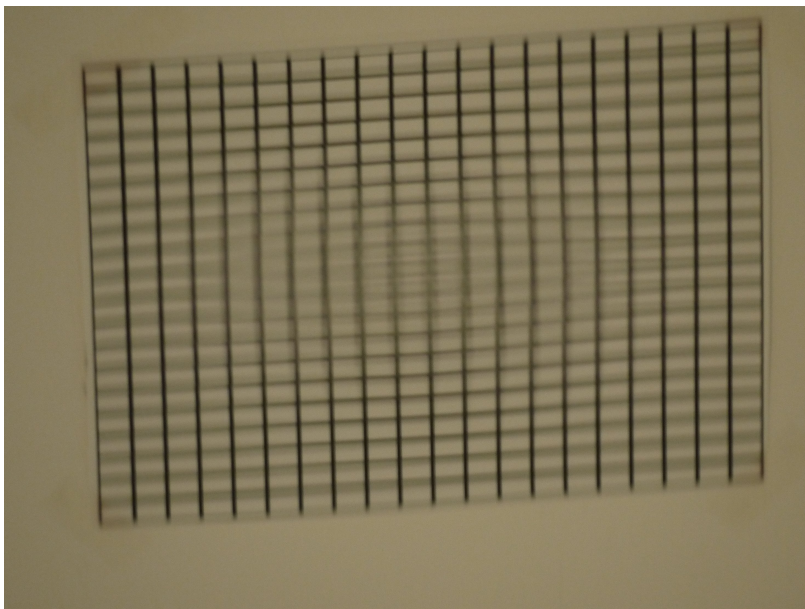
[2]



[3]



[4]



[5]

MLT-046

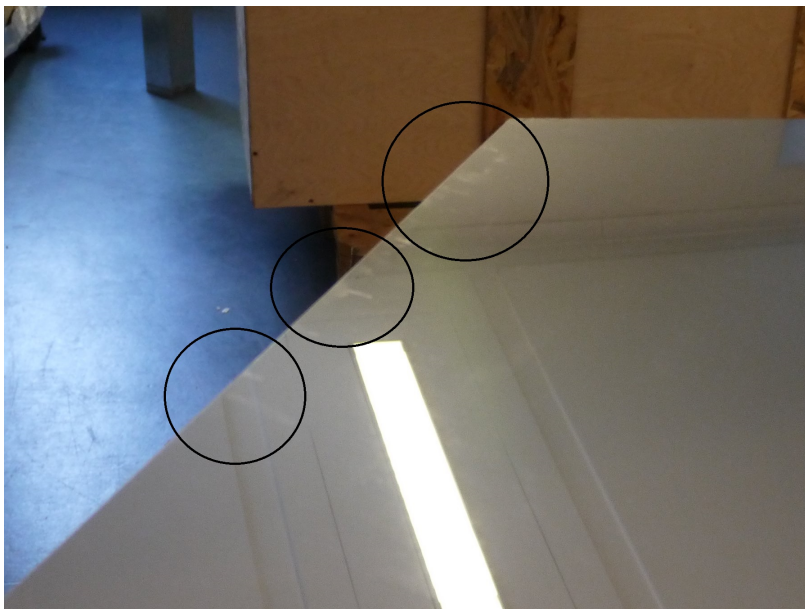
The mirror shows dirt on its edges [1,2,3,4] There is a bump [5] on the bottom side of the mirror. Furthermore, there is an extensive damage on the top edge [6] and scratches on the top left edge [7] and on the right bottom edge. The black spot in the lower right region of the reflecting surface [8] is possibly caused by the handling of the mirror in Tübingen. The mirror tilted while crating and slipped towards the back side of the mirror which was stored in the same box.



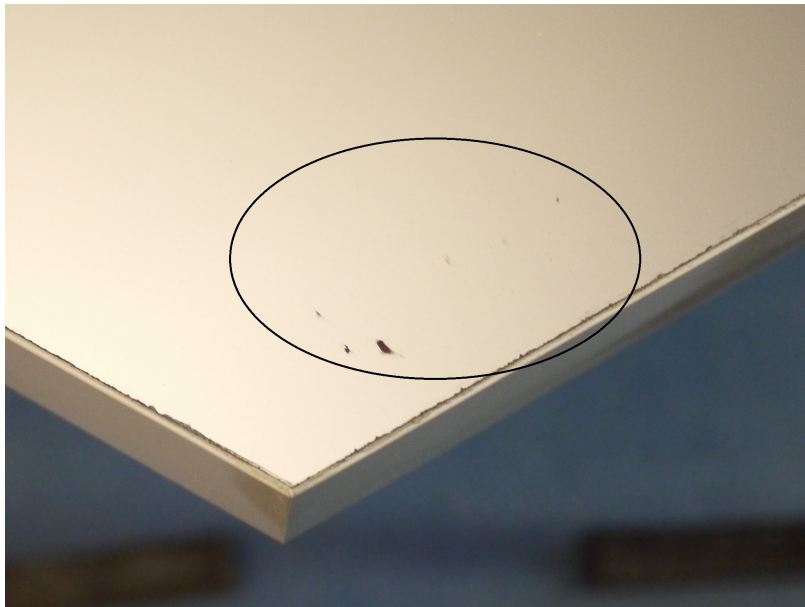
[1]



[2]



[3]



[4]



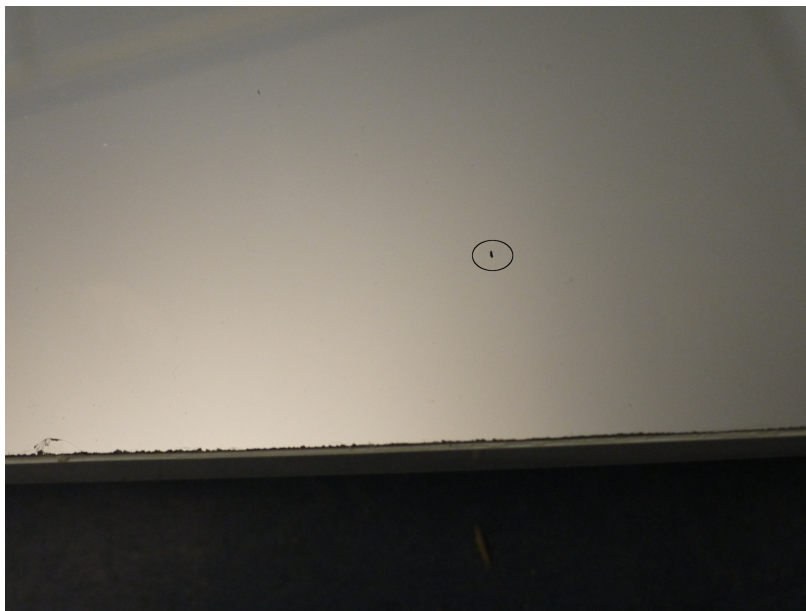
[5]



[6]



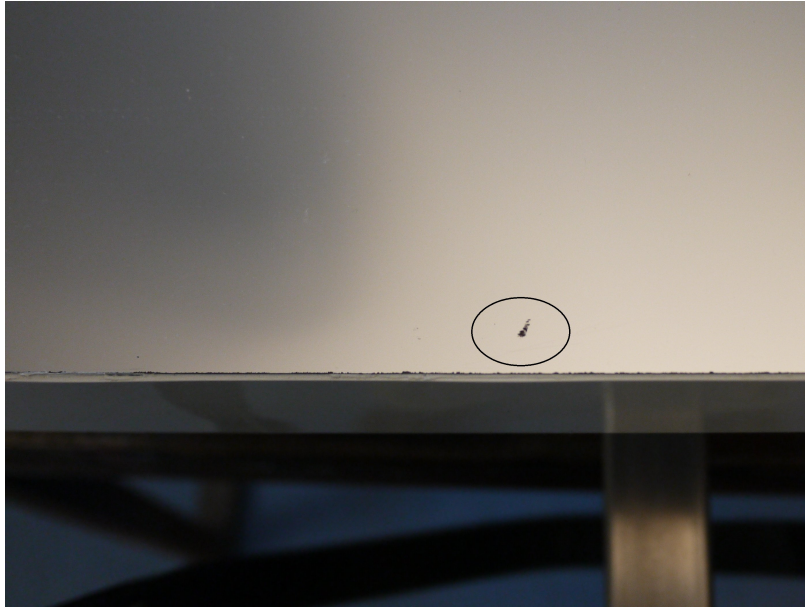
[7]



[8]

MLT-049

The mirror shows a black spot with a length of approx. 20mm and a width of approx. 1mm on the right bottom [1]. Dirt is located in the corners [2] and there is additionally a black dotted pattern at the right corner [3]. The center of the mirror is dirty [4].



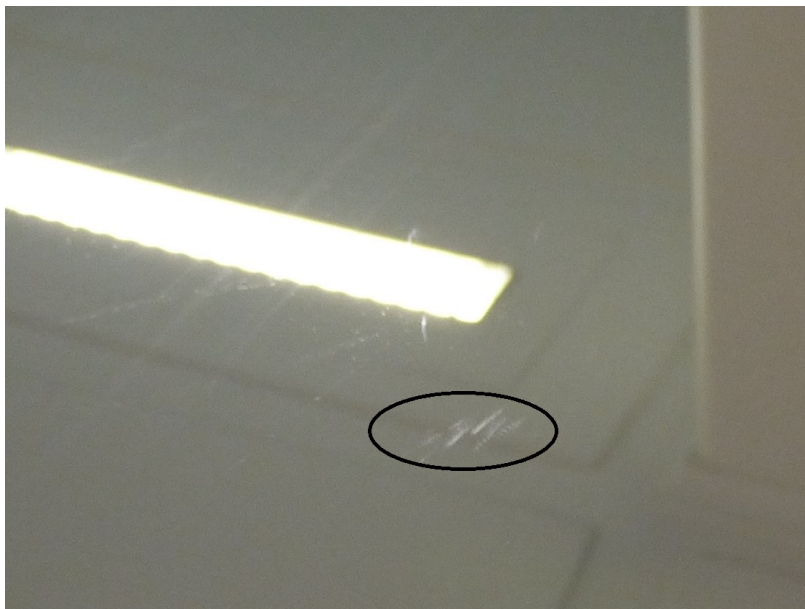
[1]



[2]



[3]



[4]

7.2 Data sheets of the CCD camera and the lens triplet



High Performance Cooled CCD Camera System ALTA U47

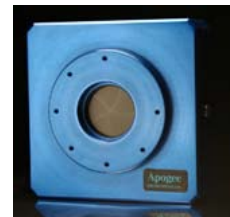
The Alta U47 has a back-illuminated full frame megapixel CCD with exceptionally high quantum efficiency. The standard midband coating (U47-MB) has the highest peak in the visible; the optional broadband coating (U47-BB) has somewhat higher QE in the near UV but lower QE across the visible. The UV-enhanced version (U47-UV) has the highest QE in the UV (See the quantum efficiency curve on page 2.)

Imaging Area of CCD



- 1024 x 1024 array, 13 x 13 micron pixels
- 2 MHz 12-bit and 700 kHz 16-bit digitization
- 32Mbyte camera memory
- USB 2.0 interface: no plug in cards or external controllers
- Programmable, intelligent cooling to 50-55°C below ambient (D02 housing)/ 70-75°C below ambient temperature (D09 housing).
- Binning up to 8 Horizontal x 1024 Vertical
- Subarray readout and fast sequencing modes
- Precision time delayed integration (TDI) and kinetics mode readout
- Programmable fan speed for low / zero vibration
- Two serial port outputs for control of peripheral devices
- General purpose programmable I/O port
- External triggering and strobe controls
- ActiveX drivers included with every system
- Field upgradeable firmware
- Fused silica windows
- Runs from single 12V supply with input voltage monitor
- Compact enclosure

- Astronomy
- Radiology
- Optical testing
- Non-destructive testing



CCD SPECIFICATIONS

CCD	E2V CCD47-10
Array Size (pixels)	1024 x 1024
Pixel Size	13 x 13 microns
Imaging Area	13.3 x 13.3 mm (177 mm ²)
Imaging Diagonal	18.8 mm
Video Imager Size	1.2"
Linear Full Well (typical)	100K electrons
Dynamic Range	83 dB
QE at 400 nm	52% (MB); 75% (BB); 57% (UV)
Peak QE	96% (MB); 86% (BB); 65% (UV)
Anti-blooming	none

For complete CCD specifications, including cosmetic grading, see data sheet from manufacturer.

©2009 Apogee Instruments Inc. Alta is a registered trademark of Apogee Instruments Inc. Specifications subject to change without notice.



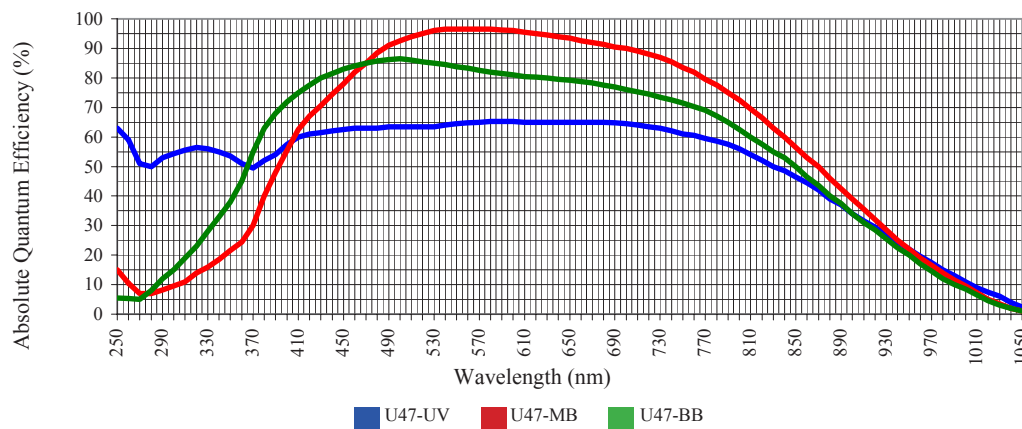
1020 Sundown Way, Ste 150
Roseville CA 95661 USA
tel 916-218-7450
fax 916-218-7451
<http://www.ccd.com>

ALTA U47 Camera System Performance



PC Interface	USB 2.0
Max. Cable Length	5 meters between hubs; 5 hubs maximum (max. total of 30m)
Digital Resolution	16 bits at 700 kHz and 12 bits at 2 MHz
System Noise (typical)	9 e ⁻ RMS at 700 kHz and 2 counts at 2 MHz
Pixel Binning	1x1 to 8 x 1024 on-chip
Exposure Time	30 milliseconds to 183 minutes (2.56 microsecond increments)
Image Sequencing	1 to 65535 image sequences under software control
Frame Sizes	Full frame, subframe, focus mode
Cooling (typical)	Thermoelectric cooler with forced air. Maximum cooling 50-55°C below ambient temperature (D02 housing); 70-75°C below ambient temperature (D09 housing).
Dark Current (typical)	0.2 e ⁻ /pixel/sec (-20°C). 0.02 eps for High Cooling D09 housing.
Temperature Stability	± 0.1°C
Camera Head Size	D02: Low profile: D06. Aluminum, hard blue anodized. 6" x 6" x 2.5" (15 x 15 x 6.35 cm) Weight: 3.1 lb. (1.4 kg). Wide Angle: D13. High Cooling: D09 (17.8 x 17.8 x 8.9 cm. 1.9 kg).
Mounting	3.5" bolt circle. 2" 24 tpi thread. Optional Nikon F-mount or Canon FD or EOS/EF mount.
Back Focal Distance	Standard: 1.025" (2.60cm). Low profile: 0.460" (1.17 cm). D09: 1.40" (3.56cm). [optical]
Operating Environment	-22° to 27°C. Relative humidity: 10 to 90% non-condensing.
Cable Length	Standard: 15 ft (4.5m)
Power	40W maximum power with shutter open and cooling maximum. AC/DC "brick" supply with int'l AC input plug (100-240V, 50-60 Hz). Alternate 12V input from user's source.
Shutter	Standard: Melles Griot 43mm. Low profile: no shutter. D09: Melles Griot 63mm.
Remote Triggering	LVTTL input allows exposure to start within 25 microseconds of rising edge of trigger

CCD SENSITIVITY



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TECHSPEC® 180mm EFL, unbeschichtet, UV bis NIR korrigiertes Triplet



Artikelnr. #47-313
€1,852.50
1 - 5 for €1,852.50 each.
6 - 10 for €1,759.88 each.

Verfügbarkeit: **ANFRAGE**

SPEZIFIKATIONEN

f/ #	8
Brennweite EFL (mm)	180.0
Brennweite EFL @ 248nm (mm)	180.00
Toleranz Brennweite (%)	±1.5 @ 248 nm
hintere Brennweite BFL (mm)	174.62
hintere Brennweite BFL ab Gehäuse (mm)	172.3
freie Apertur CA (mm)	22.5
Gehäusedurchmesser (mm)	30.00 ±0.05
Gehäuselänge (mm)	20.50 ±0.05
Oberflächenqualität	60-40
Substrat	CaF ₂ / Fused Silica / CaF ₂
Beschichtung	Uncoated
Typ	Achromatic Triplet Lens
Numerische Apertur NA	0.06
Wavelength Range (nm)	193 - 1000
RoHS	E

TECHNICAL INFORMATION

Effective Focal Length EFL	193 - 400nm		400 - 1000nm		193 - 1000nm	
	Chromatic Shift	RMS Spot Size	Chromatic Shift	RMS Spot Size	Chromatic Shift	RMS Spot Size
36mm	1.8mm	240µm	0.4mm	214µm	2.2mm	268µm
45mm	1.1mm	88µm	0.3mm	69µm	1.3mm	95µm
90mm	2.0mm	64µm	0.6mm	38µm	2.5mm	69µm
135mm	1.6mm	49µm	0.6mm	31µm	2.1mm	51µm
180mm	1.4mm	46µm	0.6mm	28µm	1.9mm	45µm

