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Facility Calibration Unit of the Hobby-Eberly Telescope* Wide Field Upgrade

Hanshin Lee [a,†], Gary J. Hill[a], Brian Vattiat[a], Michael Smith[b], Marco Häuser[c]

[a] McDonald Observatory, University of Texas at Austin, 2515 Speedway Stop 1402, Austin, TX 78712-0259, USA
[b] Department of Astronomy, University of Wisconsin – Madison, 475 N. Charter Street, Madison, WI 54706, USA
[c] University Observatory Munich, Physics Department, University of Munich, Scheinerstrasse 1, 81779 Muenchen, Germany

ABSTRACT

The Hobby-Eberly Telescope (HET) Wide-Field Upgrade (WFU) will be equipped with new Facility Calibration Unit (FCU). The FCU is in support of VIRUS and the facility instruments and consists of the head and source box. The FCU head, connected to the source box through two liquid light guides, is attached to the bottom of the WFU Wide-Field Corrector (WFC) and can be deployed into the beam to inject calibration light through the WFC whenever calibration is needed. A set of Fresnel lenses is used in the FCU head to mimic the caustics of M1 as much as possible to re-produce the telescope's focal plane illumination pattern. Various imaging/non-imaging optical components (e.g. Compound Parabolic Concentrators, cone reflectors, condenser lenses) are used for efficient coupling between different types of calibration lamps and light guides, covering wavelengths from 350nm to 1800nm. In addition, we developed an efficient and tunable Light-Emitting Diode (LED) based source and coupler for UV and Visible spectral flat field calibration. This paper presents the designs, prototypes, and as-built components / subsystems of the FCU.

Keywords: Facility Calibration Unit, Light sources, Hobby-Eberly Telescope, HETDEX

1. INTRODUCTION

Over the next year, the Hobby-Eberly Telescope (HET) will be upgraded with a 22 arc-minutes diameter field of view wide field corrector (WFC), a new tracker and prime focus instrument package (PFIP), and a new facility calibration unit (FCU) to support the Hobby-Eberly Telescope Dark Energy experiment (HETDEX) and other facility instruments (Figure 1)[1][2]. The new corrector has improved image quality and a 10-meter pupil diameter[3].

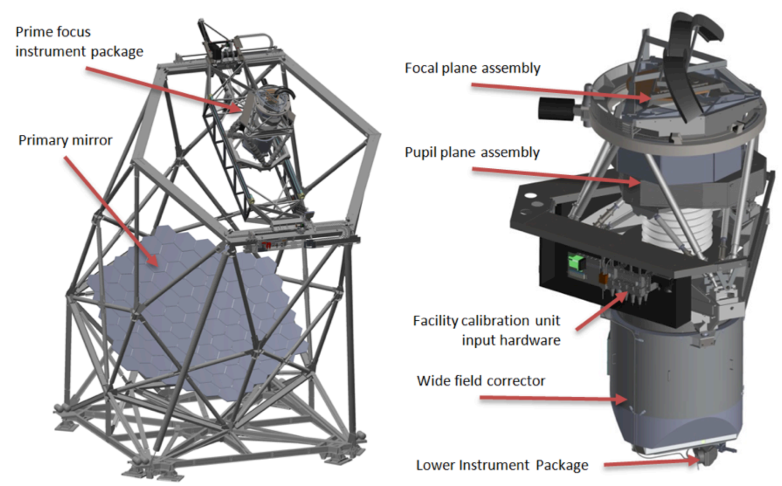

Figure 1 (Left) Solid models of the upgraded Hobby-Eberly Telescope and (Right) the Prime Focus Instrument Package

The PFIP consists of the focal plane assembly (FPA), the pupil plane assembly (PPA), the WFC, and the lower instrument package (LIP)[4]. At the half way between the FPA and LIP, there is a frame called the strong-back, which interfaces the PFIP with the hexapods in the tracker. To the side of the strong-back, an electronic box called the FCU source is attached, where all FCU calibration input hardware is located (e.g. line lamps, continuum sources, power supplies for the lamps, and lamp control hardware/electronics).

Depending on calibration modes, a certain set of lamps is selected, mixed, and then fed to a liquid light guide (LLG). The FCU source contains specially designed & arranged non-imaging optical components (e.g. Compound Parabolic Concentrators and Cone reflectors) for efficient coupling between different types of calibration lamps and light guides, covering wavelengths from 350nm to 1800nm. In addition, we developed an efficient and tunable Light-Emitting Diode (LED)

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† Hanshin Lee: E-mail: lee@astro.as.utexas.edu

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based source and coupler for UV and Visible spectral flat field calibration. The light is then transported through the LLG to the FCU head that is part of the LIP attached to the bottom of the PFIP. The FCU head is a relay optical system that projects a diffuser disk (illuminated by light from the LLG output) onto the focal plane of the WFC (i.e. in the FPA). The FCU head optical system has been designed based on Fresnel lenses to reproduce the optical caustic of the HET primary mirror as much as possible so that the projected illumination at the telescope exit pupil in the PPA and at the focal plane in the FPA mimics those given by the telescope when looking at the sky. The FCU head sits on a pneumatically deployable rail so that it can be inserted into the telescope beam whenever calibration is needed. This paper presents the designs, prototypes, and as-built components / subsystems of the FCU.

2. FCU SYSTEM

2.1. FCU Head Optical Design and Assembly

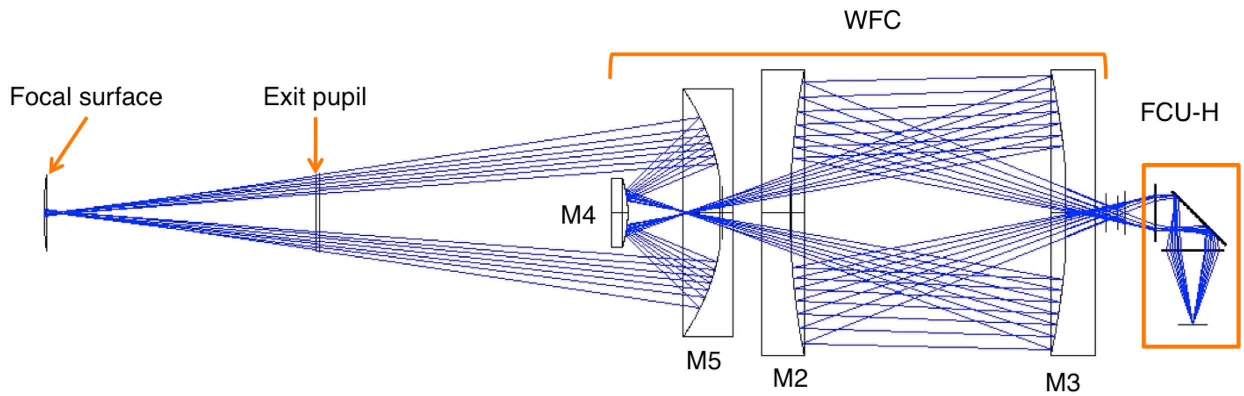

Figure 2 The optical layout of the WFC and FCU Head.

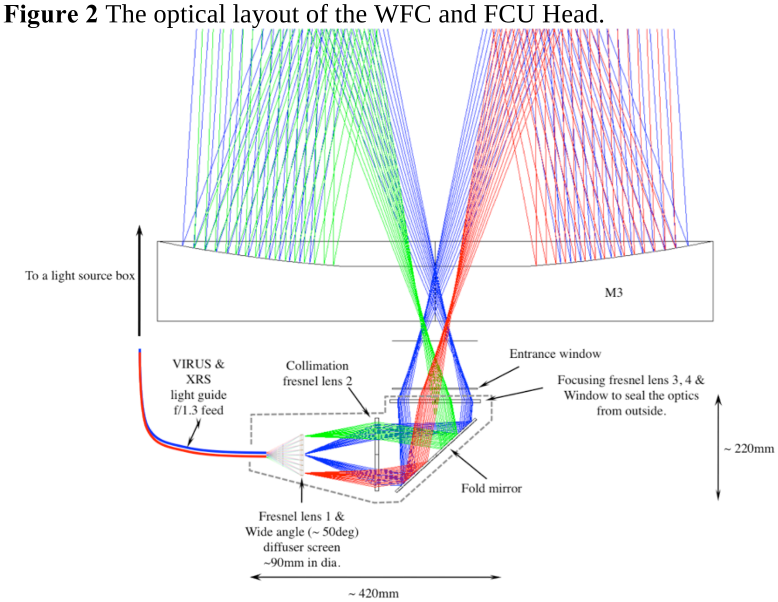

Figure 3 A Close up view of the FCU Head.

Figure 2 shows the optical layout of the WFC fed by the FCU head (indicated by the orange rectangle). The FCU head is a Fresnel-lens based relay optical system (Figure 3), similar to the SALT calibration system[5]. The LLG feeds the system with a f/1.3 output beam. The spherical beam is then collimated by the first fresnel lens (Fresnel lens 1). Immediately after Fresnel lens 1 follows a 90mm diameter engineered diffuser screen which is manufactured on a fused silica substrate to uniformly diffuse incoming (collimated) light into a cone with 25 degrees half angle. The diffuser screen then acts as an object that is subsequently projected by the rest of the FCU head (Frensle lens 2, 3, and 4) and the WFC onto the WFC focal surface. Immediately after Fresnel lens 2, there is a circular stop acting as the system entrance pupil and a stray-light baffle. There are two fold mirros to prevent the overall system from collision with surrounding strubtures. The fold mirror between Fresnel lens 1 and 2 is not shown in Figure 2 and Figure 3 to simplify the view of the beam path.

Fresnel lens 1 has a conic surface profile on a UV transmitting Acrylite polymer substrate and has been procured as an off-the-shelf item from Fresnel Tehcnology Inc. Fresnel lens 2 and 3 have even aspheric profiles and Fresnel lens 4 has spherical profile. These three lenses have been custom fabricated by diamond-turnning UV transmitting Acrylite polymer substrate (Evonik PLEXIGLAS® Solar 0Z370, Tabs > 90% from 350nm to 1800nm) from Eschenbach Optiks Gmbh in Germany. Due to the sensitivity of these polymers to humidity, the top end of the FCU head is sealed by a

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B270 window with a broadband AR coating. The window and the fold mirrors (as uncoated) have been custom fabricated by Sydor Optics. Spectrum Thin Films has coated the fold mirrors with UV Silver mirror coating (Tabs > 90% from 350nm to 1800nm).

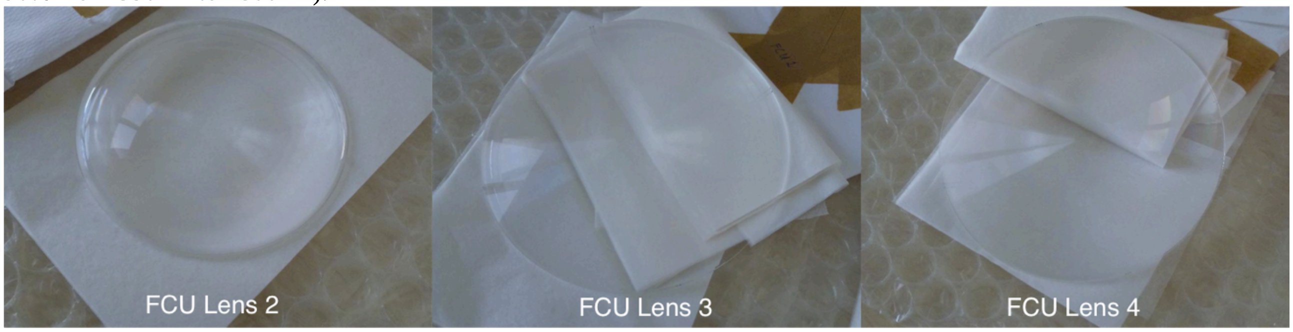

Figure 4 The FCU Fresnel Lens 2, 3, 4 as fabricated by Eschenbach Optik.

One of the challenges of the FCU head optical system design was to mimic the enormous caustic from the HET primary mirror within highly contrained space underneath the WFC. The natural choice of optical component was Fresnel lenses and we decided to use three Fresnel lenses since fewer lenses were insufficient to balance aberration while adding more lenses resulted in minimal improvement without requiring more space. One of our requirements of the design process was to allow the deviation of the FCU head illumination on the focal surface to be as large as 10% of the on-sky illumination on both surfaces. Another important requirement for the FCU head illumination is to have the beam speed at the WFC focal surface to be as close to the nominal f/3.65 as possible so that the beam going into individual fiber optics in each IFU can have correct numerical aperture. This requirement can be naturally met if the "simulated caustic" from the FCU head becomes the actual one. The design was started by assuming a disk diffuser as an object that has a uniform scatter cone angle of 45 degrees. We discovered that the extent, to which the caustic can be simulated by using the uniform disk scatter disk and the Fresnel lens design, was limited, but that using a Gaussian scatter profile ($y = \exp[-G\ r^2]$ where G is the Gaussian width parameter and r is the normalized pupil radius) in the diffuser disk instead of a uniform profile can further improve the approximation to the on-sky illumination patterns. The optimization suggests that the Gaussian parameter G = 0.45 (gives the optimum illumination.

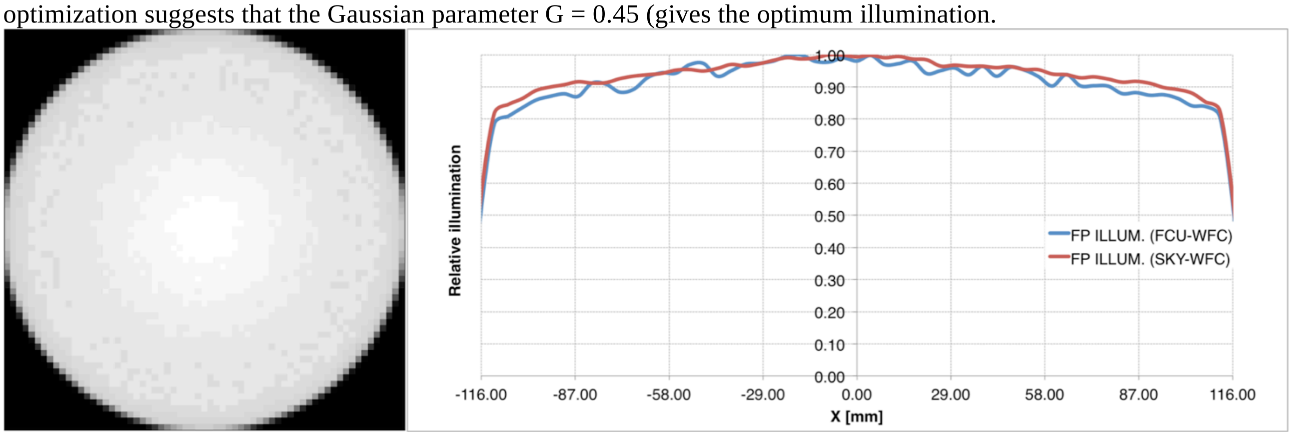

Figure 5 (Left) The illumination given by the FCU head design at the WFC focal surface. (Right) Horizontal cross sections of the illumination by the FCU head (blue line) and that by the uniformly scattering sky (red line). Note that radial position of 116mm corresponds to the edge of the field.

The left panel of Figure 5 shows the illumination at the WFC focal surface given by the FCU head design. The horizontal cross section of the illumination is shown as the blue curve in the plot on the right panel. Also plotted is the horizontal cross section of the illumination by the uniformly scattering sky. These were calculated from Zemax model. The RMS deviation of the FCU head illumination from the sky is 1.7% and the maximum deviation is 2.5%. The fluctuation in the curves are due to the finite number of rays used in the calculation. The calculation also indicates that, at each field location, more than 95% of incoming light is contained within a beam cone of ±7.9 degrees with respect to

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the local normal on the focal surface, which corresponds to f/3.65. Therefore the design satisfies the two most important optical requirements.

Fig. 6 shows the solid model of the FCU head. The top panel shows the FCU head in the Lower Instrument Package (LIP) that is mounted to the input end of the wide field corrector and is a platform for the entrance window assembly, tip-tilt camera. The figure is shown as up side down. The entrance window assembly can select between three 184mm diameter windows. The three windows are mounted to a rotary stage, which is designed to form a low-leak seal with the wide field corrector. A pneumatic cylinder deploys and retracts the FCU head at the entrance of the WFC. When deployed, the output head forms a light-tight seal with the corrector to enable calibration during the day or with dome lights on. At the input end of the FCU head, two liquid light guides are attached to a two-position pneumatically actuated selector for controlling which of the two light guides are used. The blue-optimized light guide is positioned such that the entire telescope field is covered. The red-optimized light guide includes an additional optic and is positioned to cover only the telescopes field occupied by the high, medium, and low spectrograph feeds, but not the VIRUS feeds.

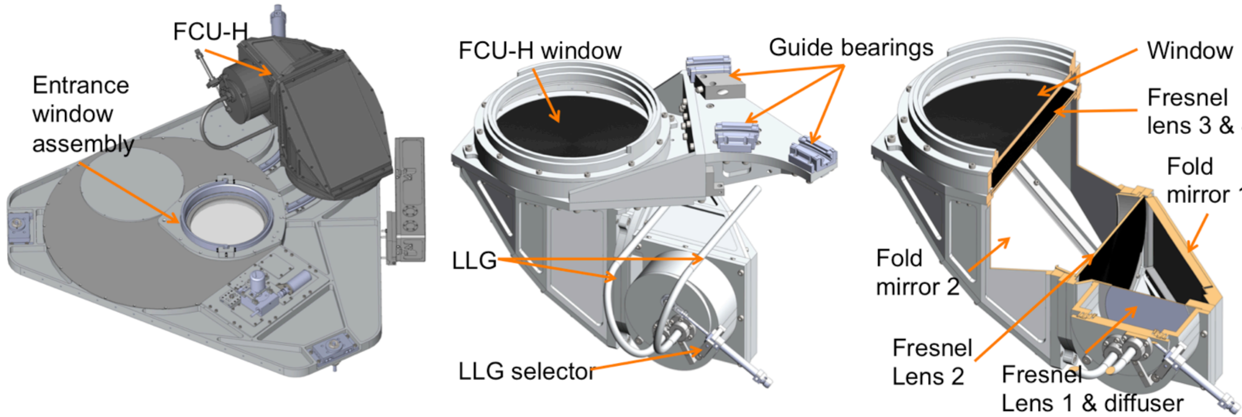

Figure 6 The solid model of the FCU head. (Left)The FCU head in the Lower Instrument Package (LIP). (Middle) The FCU head. (Right) a section view of the FCU head.

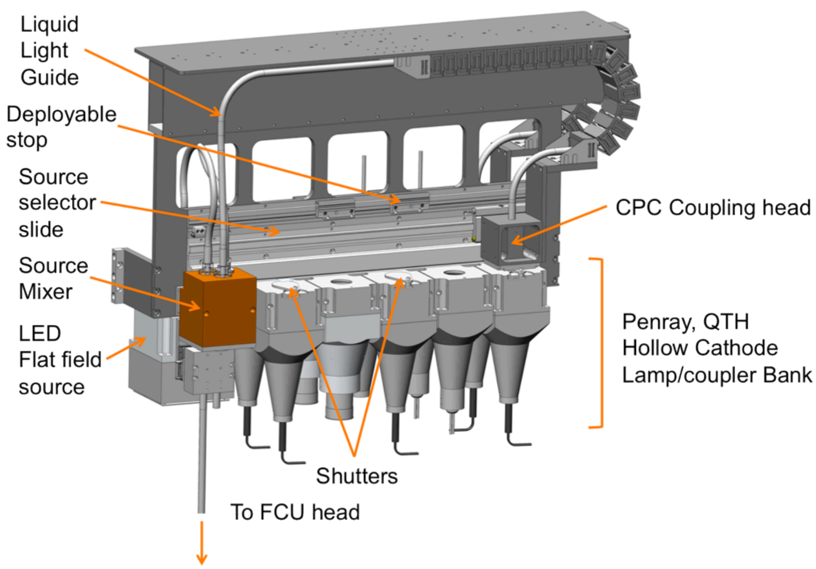

Figure 7 The solid model of the FCU Source assembly.

2.2. FCU Source Assembly

The FCU source assembly (Figure 7) contains a variety of reference emission line / continuum light sources fed into the FCU head. The FCU source assembly is located in a remote enclosure (see Figure 1). Two liquid light guides transmit the light from the FCU source assembly to the FCU head. The FCU source assembly can hold 10 penray, hollow cathode, or QTH lamps, separated into two banks of five lamps. A liquid light guide on each bank can be positioned to any of the five light sources. A third light guide is coupled to a LED-based light source. The three light guides transmit light from their respective sources to an optical mixing unit to combine the light from all three sources. The output of the optical mixing unit is fed into one of two liquid light guides, which feed directly to the FCU head. A Festo SLF-10 pneumatic stage is used to select between the two light guides, with one guide optimized for blue wavelengths and to other optimized for red. The source selector is a Festo SLG-12 pneumatic slide with integral ball guide a pneumatically deployed stops mounted mid-stroke. This off-

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the-shelf solution provides a way to position a source light guide over the multiple light sources with ball guide accuracy and the simplicity and reliability of a pneumatic actuator. Hall effect switches indicate the position of the source guide and the states of the deployable stops.

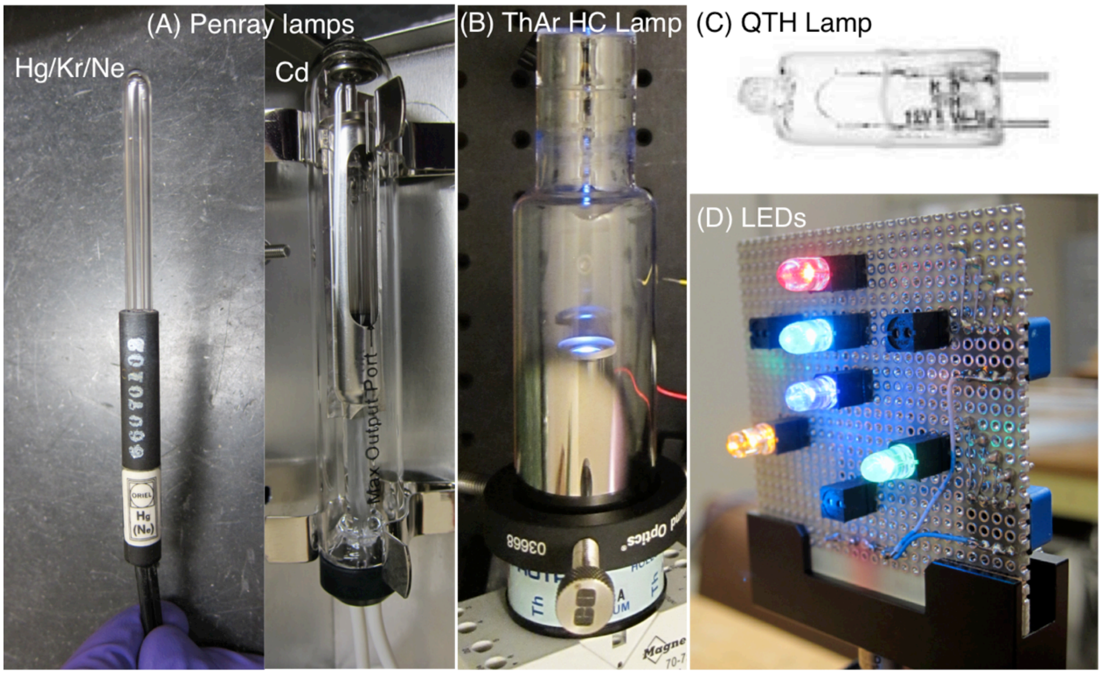

Figure 8 There are 5 different types of calibration lamps in the FCU Source assembly.

There are five different types of calibration lamps used in the FCU Source assembly (Figure 8). These lamps not only have different spectral properties, but also come in different physical packaging with distinctly different illumination source shapes and locations within the packaging. For example, the Mercury (Hg), Krypton (Kr), and Neon (Ne) penray lamps have a thin pen-like package with a 2inch-long illuminated quartz rod, while the Cadmium (Cd) penray lamp comes in a much thicker package with a short (< 1inch long) illuminated rod. The Thorium Argon (ThAr) Hollow Cathode lamp has its illuminated cathode plate inside a long thick quartz tube. In order to efficiently couple light from these different calibration lamps into the FCU head, we designed different couplers for the individual lamps. Except the LED coupler design, the rest of the couplers share one gross design feature that consists of a reflective cone followed by a pair of relay lenses.

The coupler design in Figure 9 is for the Hg / Kr / Ne penray lamps. These lamps have thin quartz light emitting rod. In the design, this illuminated rod is inserted into a reflective cone from behind. The emitted light from the rod is then reflected off the inner surface of the cone and guided toward the larger opening of the cone. The light escaped from the cone is then collimated by a condenser lens and then focused by another condenser lens into a compound parabolic concentrator (CPC). The CPC is optically coupled with the input end of a liquid light guide. The penray lamps are from UVP LLC. The condenser lenses are from Thorlabs and the CPC is from Edmund Optics. The reflective cone is custom made from aluminum in-house. Assuming bare aluminum surface, the estimated coupling efficiency is 20%.

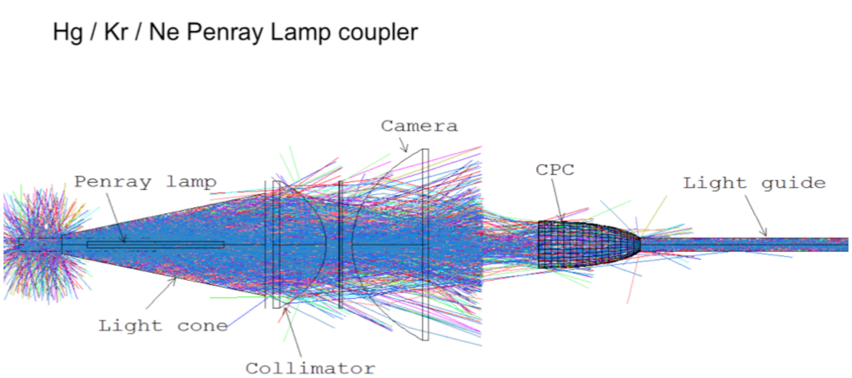

Figure 9 The coupler design for Hg / Kr / Ne penray lamps.

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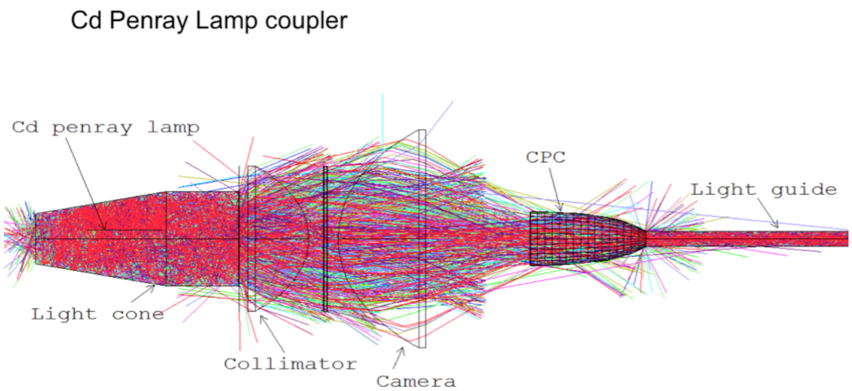

Figure 10 The coupler design for a Cd penray lamp.

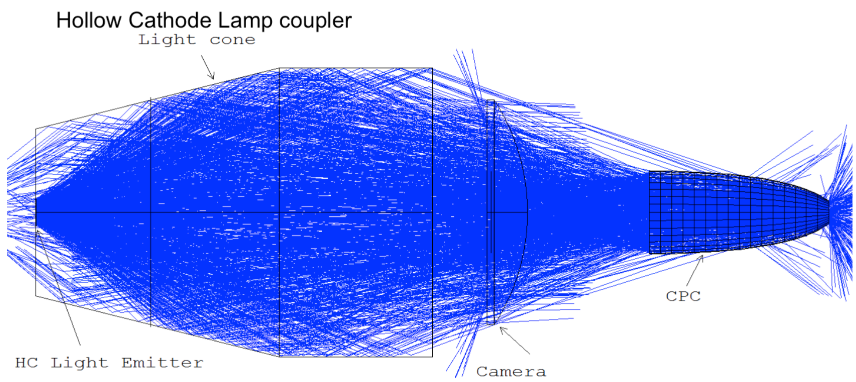

Figure 11 The coupler design for a Hollow Cathode lamp.

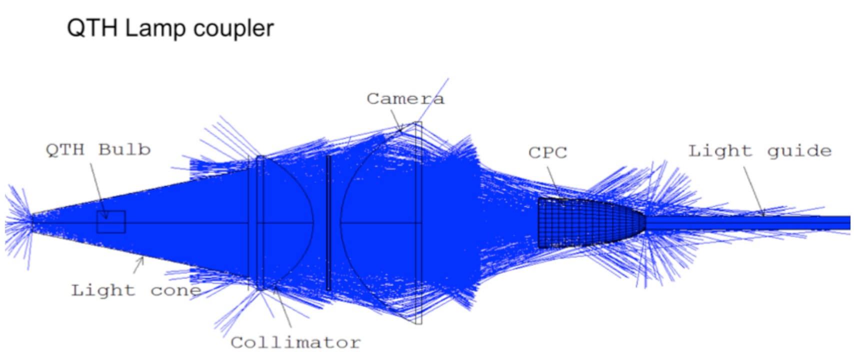

Figure 12 The coupler design for a QTH bulb.

The coupler design in Figure 10 is for the Cd penray lamp. This lamp has a shorter light emitting rod within a thicker quartz tube. Like the previous penray design, the tube is inserted into a reflective cone from behind. The left end opening of this cone is larger and the right end of the cone has an extended tube. The emitted light from the lamp is guided toward the right end of the tube extension. The light escaped is then collimated by a condenser lens and then focused by another condenser lens into a CPC coupled with a liquid light guide. The penray lamp is from UVP LLC. The condenser lenses are from Thorlabs and the CPC is from Edmund Optics. The reflective cone is custom made from aluminum in-house. Assuming bare aluminum surface, the estimated coupling efficiency is 20%.

Figure 11 shows the coupler design for a Hollow Cathode lamp. The lamp has a light emitting cathode plate within a long quartz tube. The tuber is inserted into a cone until the light emitting plate coincides with the left end opening of the cone. Like the Cd lamp coupler, the cone has a tube extension at the right end cone opening. The guided light is then focused by a camera lens into a CPC, which is again optically coupled with a liquid light guide. The camera lens is an off-the-shelf item from Edmund Optics. The estimated coupling efficiency is 25%.

Figure 12 shows the QTH lamp coupler design. The design is almost identical to the thin penray coupler design. The bulb is inserted into the cone. The pair of condenser lenses focus QTH light into the CPC.

For the VIRUS instrument, it is important to have sufficient light in the UV/Blue wavelengths (i.e. from 350nm to 550nm) for flat field calibration. A QTH lamp often used as a flat field source, but generally has weak intensity toward the blue end of the VIRUS spectrum while emitting strong IR radiation. Such strong IR radiation can act as a heat source and quite often reduces the lifetime of the lamp itself or damages coupling light guides or fiber optics. Therefore, we have been seeking an alternative UV/Blue flat field solution for the VIRUS instrument and came up with a LED-based flat field source.

LEDs are compact, bright, long-lifetime, and energy efficient (thus less heat generated) light sources and used in almost all modern lighting applications from traffic light to desktop stand lamps. Individual LEDs have distinct spectral profiles with different central wavelengths and widths. Each LED also comes in a different packaging (e.g. some have aspheric lenses attached to direct light while others have a LED chip without a lens). Unlike a QTH, a single LED can

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not be used for a flat field source across a broad spectral range. This means that one must mix and match multiple LEDs with different spectral responses in order to synthesize the desired flat field response. For the VIRUS flat field synthesis, we have selected 24 LEDs that are mixed by a custom-designed LED coupler (Figure 13). The LED coupler consists of a LED circuit board with 24 LEDs mounted along a ring of 35mm radius. We have chosen the LEDs with aspheric lenses attached so that the output beam divergence is less than 15 degrees in full-width at half-maximum. In front of each LED, a collimation singlet lens (9mm in diameter from Edmund Optics) is mounted to collimate the LED out beam. The collimated beams are focused by a Fresnel lens (from Fresnel Technology Inc.) in to a CPC coupled with a liquid light guide. The reason for having the LEDs arranged in a ring pattern on the PCB is due to the fact that the liquid light guide efficiently mixes input light in the azimuth direction in the beam angle space while the radial mixing is very poor. By arranging the LEDs in a ring pattern, each LED beam after the Fresnel lens propagates along the direction with the same radial angle and different azimuth in the beam angle space, thereby the beams are mixed very well. The mixed output beam at the end of the liquid light guide will have annulus pattern in the angle space, which can be further spread in the radial direction by subjecting the beam to a diffuser screen. We have prototyped this coupler design as shown in **Figure 14**. The LED board has one socket at the center, six sockets at a radius of 1inch, and one socket at a radius of 0.5 inch, so that we can measure the radial and angular mixing property of the liquid light guide (Lumatec Series 300). The CCD camera has an achromatic doublet attached to collimate the output beam from the light guide and form the pupil at a diffuser screen. A 1:1 relay system then re-images the pupil onto the CCD. The CCD chip covers f/1.3 pupil. The pupil image shows the output beam illumination in angle space. As shown in the first two of **Figure 15**, the mixing in the radial direction is very weak. The violet LED was at the center, and the blue LED was at the radius of 0.5 inch while the green, orange, and red LEDs were at the same radius of 1inch from the center of the board. Since the entire pupil (f/1) was much larger than the CCD chip, we had to laterally offset the CCD camera in order to see the outer part of the pupil illumination. The LEDs on the outer ring show very similar annular illumination. The violet LED shows an illumination

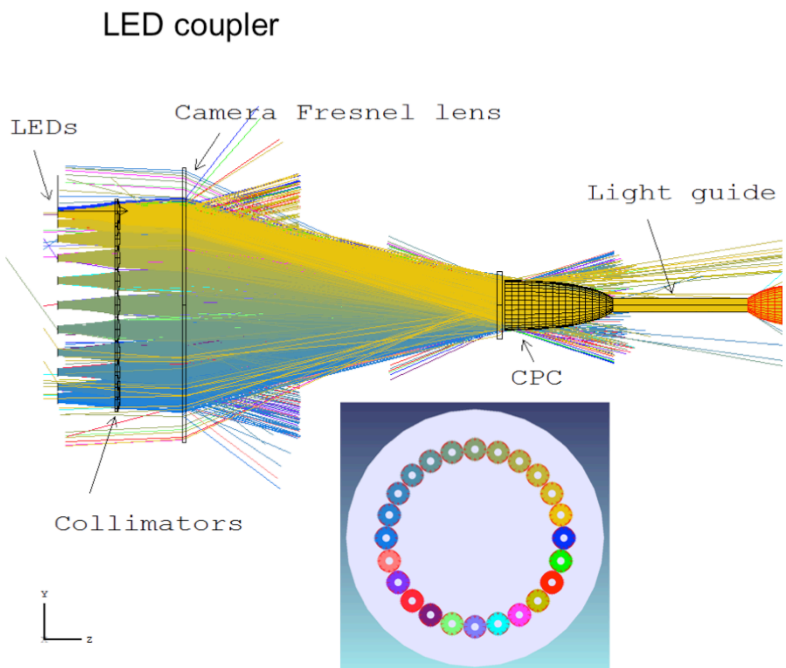

Figure 13 The LED flat field source coupler design.

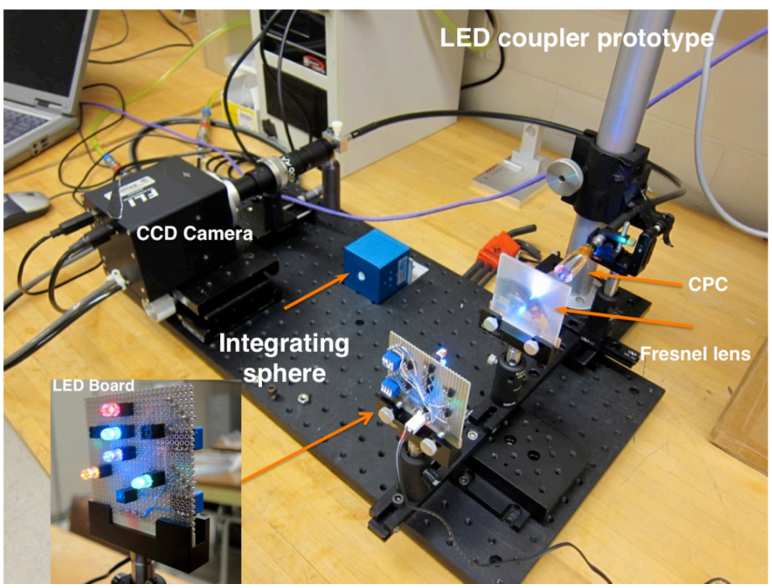

Figure 14 The LED coupler prototype. The collimation lens is not shown here.

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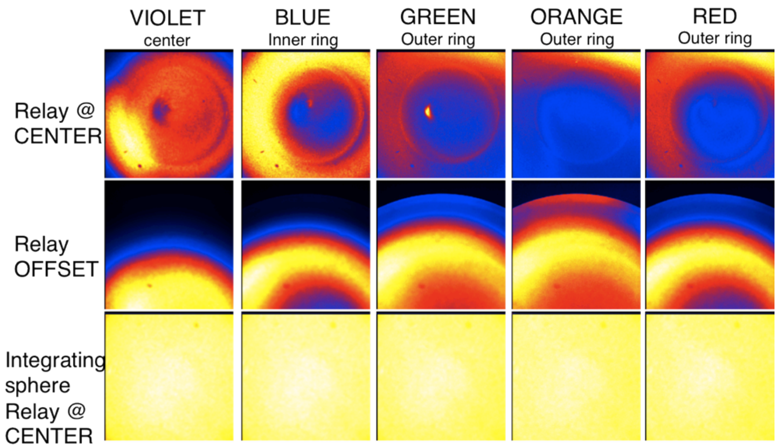

Figure 15 The liquid light guide mixing property measurement.

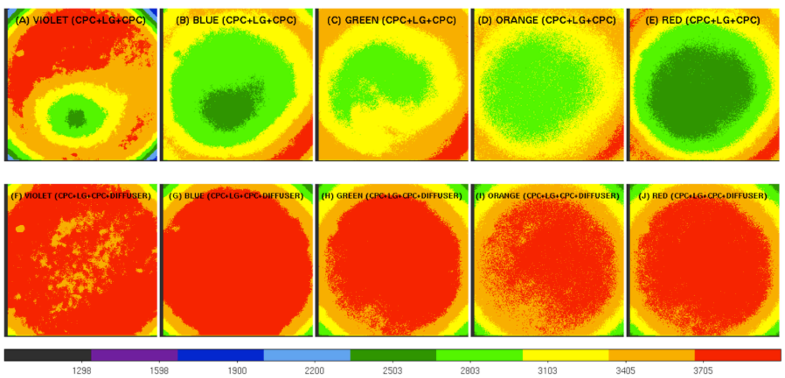

Figure 16 The radial mixing by using a diffuser screen.

that resembles a filled disk. The blue LED shows intermediate illumination pattern between the violet LED and the rest. We also tested the idea of using an integrating sphere for mixing and scrambling light and replaced the CPC with an integrating sphere from Ocean Optics. The purpose of this test was not to compare the flatness of the illumination (since the integrating sphere outputs very flat illumination as in the bottom row of **Figure 15**), but to check the efficiency of an integrating sphere. The estimated relative efficiency of the integrating sphere was 1.3% (i.e. only 1.3% of the input light made it to the light guide), which was what we anticipated.

We then tried to radially mix the LED light at the light guide output by using a 40 degrees FWHM uniform engineered diffuser screen (from Rochester Photonics) (**Figure 16**). The output illumination patterns show distinct structures depending on the radial positions of the LEDs (top row). When the diffuser screen was used at the output of the light guide, the illumination patterns become well scrambled and the structures pretty much disappeared. The measured relative efficiency was 90% or more, which proves that the use of a CPC and a diffuser for mixing and scrambling is much more efficient than using a integrating sphere.

In order to test the photon flux through these lamp couplers, we made a breadboard prototype coupler as shown in Figure 17. The middle panel shows a prototype cone reflector for the thin penray lamps. However, we were able to adapt the set up other lamps (i.e. a Hollow Cathode lamp or LEDs by using different relay lenses). At the time of this experiment, we did not have a cone reflector for a hollow cathode lamp. However, since the hollow cathode lamp's cathode plate emits diverging beam in the direction of the optical axis of the setup, we used the lamp to just see photon flux from the lamp without a cone reflector. A QTH was not tested since we had no change to do so. The Cd penray was not tested for the reason that this lamp has illuminated rod that emits light to the direction perpendicular to the optical axis and, without a cone reflector, it was not possible to capture light from this lamp.

Since the coupler set up tells us about the photon flux through the coupling system only, it was necessary to have an efficiency prediction for the rest of the systems from the output light guide through the FCU head and the WFC optics to the WFC focal surface. The following table (Table 1) shows this prediction at different wavelengths from 350nm to 1500nm based on the Zemax non-sequential polarization ray tracing models of the FCU head, the WFC, the fold mirror coating measurements, diffuser screen scattering efficiency (based on a fused silica diffuser scareen efficiency from Rochester Photonics) and the transmission curve of the liquid light guide (Lumatec Series 2000). For the photon flux measurement, we used a photo-diode from Thorlabs (PDA36AL).

Table 1 Net efficiency prediction of the combination of a output light guide (Lumatec Series 2000), FCU Head optics (Fresnel lenses, Fold mirrors, Diffuser screen, Window), WFC Optics, based on Zemax models and known quantities.

Wavelength [nm]	350	450	550	650	750	850	950	1000	1500	1800
Efficiency	6%	11%	11%	11%	11%	11%	11%	11%	10%	9%

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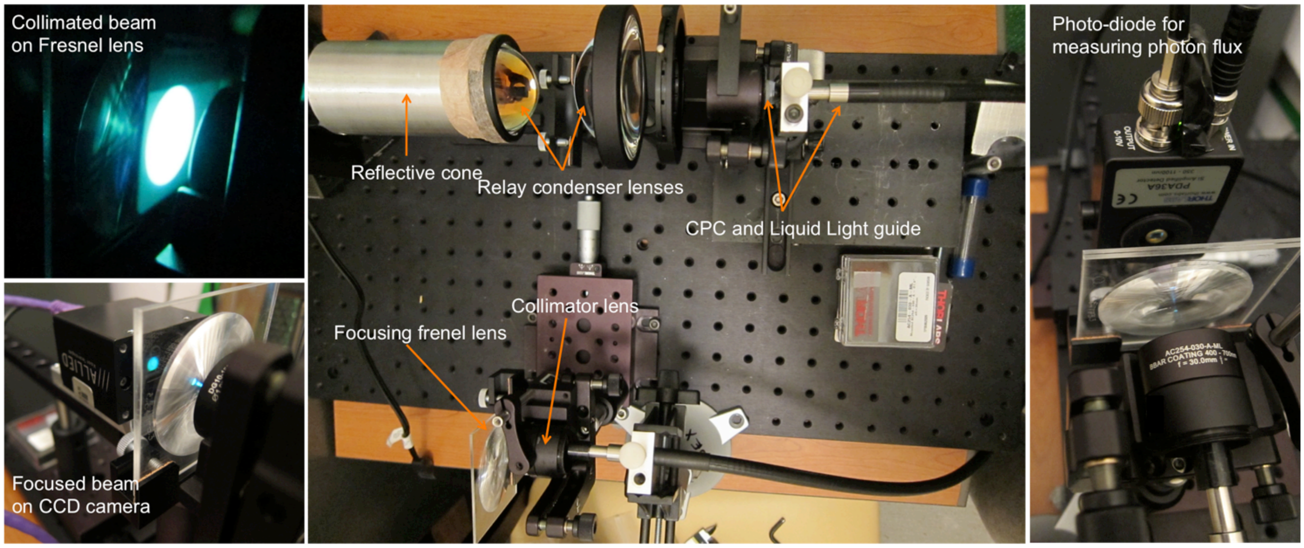

Figure 17 (Middle) Top view of the thin penray lamp coupler breadboard model (a Hg penray is inside the reflective cone). (Top left) Collimated beam on the focusing Fresnel lens. (Bottom left) Focused beam on a CCD camera that is now shown in the top-view picture. (Right) A Thorlabs photodiode (PDA36A) in place of the CCD camera for photon flux measurement.

Table 2 shows the photon flux measurement from the breadboard coupler setup. The photo-diode outputs a voltage value (Colum 3). This value is converted into a watt value (Column 5) by dividing the voltage by the effective responsivity of the photo-diode (Colum 4) at a reference wavelength (Column 6). The LEDs have well defined central wavelengths, thus we used these wavelengths in the responsivity calculation. Other lamps have many emission lines at different wavelengths. For these lamps, we used an average responsivity value across the spectrum of our interest, which happened to have the responsivity value at 500nm. We then converted the watt value to a photon flux value (Column 7) using photon energy equation at the reference wavelength (e.g. E=hc/! where h is the Plank's constant, c is the speed of light, and ! is the reference wavelength). The converted photon flux was then multiplied by the net efficiency in Table 1 to estimate the photon flux at the WFC focal surface (Column 8). Since the FCU head projects the photon flux across the WFC focal surface, we took its portion for a single fiber (Column 9). This value was then converted into an equivalent V magnitude value through a 10m telescope aperture (Column 10).

Table 2 The measured photon flux of the breadboard couplers for different lamps.

LIGHT SOURCE	Background [V]	Output[V]	Effective responsivity of Thorlabs PDS36AL photodiode [A/W]	Output [W]	Reference wavelength for responsivity calculation [m]	Phton flux of the breadboard coupler setup [Photons/sec]	Photons/sec through FCU+WFC	Photons/sec/ fiber	Equivalent V magnitude through 10m pupil per fiber
VIOLET LED	0.0146	11.1000	0.1800	1.964E-04	4.050E-07	4.005E+14	2.374E+13	3.12E+07	10.86
BLUE LED	0.0147	8.9800	0.2500	1.144E-04	4.700E-07	2.332E+14	2.505E+13	3.29E+07	10.80
GREEN LED	0.0148	10.1800	0.3000	1.081E-04	5.300E-07	2.203E+14	2.332E+13	3.07E+07	10.88
AMBER LED	0.0148	4.0400	0.3800	3.379E-05	5.900E-07	6.888E+13	7.291E+12	9.58E+06	12.14
RED LED	0.0145	6.9700	0.4000	5.546E-05	6.250E-07	1.131E+14	1.221E+13	1.60E+07	11.58
Hg(Ne) Penray	0.0146	8.0800	0.3500	7.350E-05	5.000E-07	1.499E+14	1.586E+13	2.09E+07	11.30
Krypton Penray	0.0145	4.0900	0.3500	3.714E-05	5.000E-07	7.572E+13	8.015E+12	1.05E+07	12.04
Hg(A) Penray	0.0145	6.4500	0.3500	5.865E-05	5.000E-07	1.196E+14	1.291E+13	1.70E+07	11.52
ThAr Hallow Cathode	0.0138	0.323	0.35	2.818E-06	5.00E-07	5.745E+12	6.244E+11	8.21E+05	14.81

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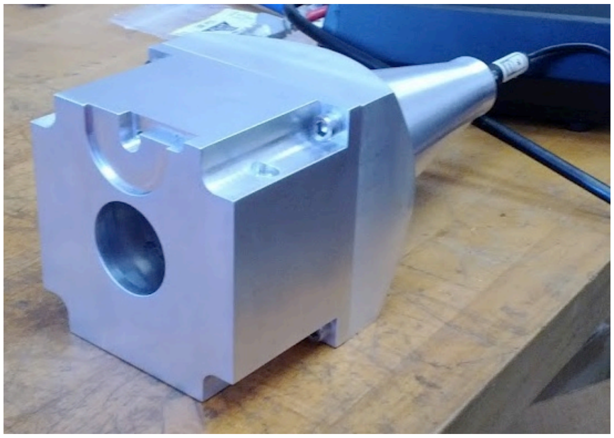

Figure 18 A photo of the penray lamp couplers.

As shown in the table, the lamps can be as bright as 11th magnitude per fiber, indicating sufficient photon flux for the calibration of the VIRUS instrument. For the other facility instruments (HRS, MRS, LRS2), the photon flux (of ThAr lamp in particular, but this can be improved when we start using a cone reflector for the lamp) may not be sufficient. Since the fiber feeds of these facility instruments are going to be located at the center of the WFC focal surface, we have a dedicated light guide feed for these instruments in the FCU head (see Figure 6 for description). Through this special feed, the FCU head projects all output onto a central section of the WFC focal surface (~11 arc-minutes diameter). We are in the process of prototyping the lamp couplers as appeared in Figure 6 (Figure 18) and further characterization of the coupling efficiency of the individual coupler is to be evaluated.

3. FCU SYSTEM CONTROL

The FCU includes a big variety of all kinds of actuators, lamps and sensors. All of the moving axes are driven by pneumatic-actuators, which are controlled by digital input solenoids. The lamps are also controlled via digital signals but needs to be driven by a higher current. So the controlling system needs be able to provide regular digital and high power digital outputs. On the other side the control system needs to deal with different kinds of sensors, like temperature-, humidity- and hall-effect-sensors. The temperatures are measured via special RTD-sensors and modules, which are optimized to highest reasonable 16-Bit accuracy and reliability within an industrial environment. In contrast to the temperatures is the humidity detected by an analog input module, which provides similar 16-Bit information about the values. The hall-effect-sensors provide the control system just with simple digital signals. A ILC 150 ETH of the brand *Phoenix Contact* control all these in- and outputs via specialized modules. All of them are arranged on a inline-bus system called IP20. This controller is able to communicate with a high level control computer called the PFIP-control-computer via Ethernet and reports periodic its status to a data-logger.

The code is designed to monitor all temperatures and the humidity within every cycle and categorize the value within a 3-level alarming logic. The first state represents a normal value, which allows a normal operation and is called green. If the value rises over an certain value, the system provides the operator via Ethernet with a notification, called yellow alarm but still keeps regular operations. All alarms are equipped with a hysteresis to avoid unstable states between green and yellow. If one value exceeds his red-value, the PLC will shutdown the whole FCU to a safe-mode until the problem has solved. After such a shutdown, the triggering value must get back to his green value before the PLC restarts the FCU. All of these actions are reported to the operator so they can react for example by an extended purge air flow rate to cool the FCU.

The more important task for the PLC-control system is to keep the thermal output of the FCU as small as possible. This is will be achieved by a smart logic that reduces the runtime of every lamp as much as possible. The total runtime per lamp will be exactly $t_{total}=t_{warm\text{-}up}+t_{exposure}$. So from the incoming information from the high-level software, the control system calculates the according time shifts for every lamp and triggers them just in time, so their spectra are stable enough.

Last but not least the FCU includes a module, which provides 24 LEDs, everyone with its own adjustable brightness. This module is specially developed and designed for the FCU but needs to be controlled by a special SPI. Sadly the PLC isn't able of connecting directly via a hardware module to this device, so the communication is implemented via regular digital in- and outputs and a according developed PLC-adapted software. Due to this the data transfer rate is way slower then it would usually be. Due to the estimated bit rate of roughly 1 kbit/s, a complete set of LED-brightnesses can be set within: $t_{message}=2\times(2\times96\text{Bit}+2\times192\text{Bit})/(1\ \text{kbit/s}) \approx 1.2$ seconds. This is compared to the usual use of these kinds of devices very slow, but still fast enough for this application. All these functionality is bundled within one PLC-station that is designed to run 24/7 during its whole lifetime without any maintenance, so the down time should not be influenced by this instrument part.

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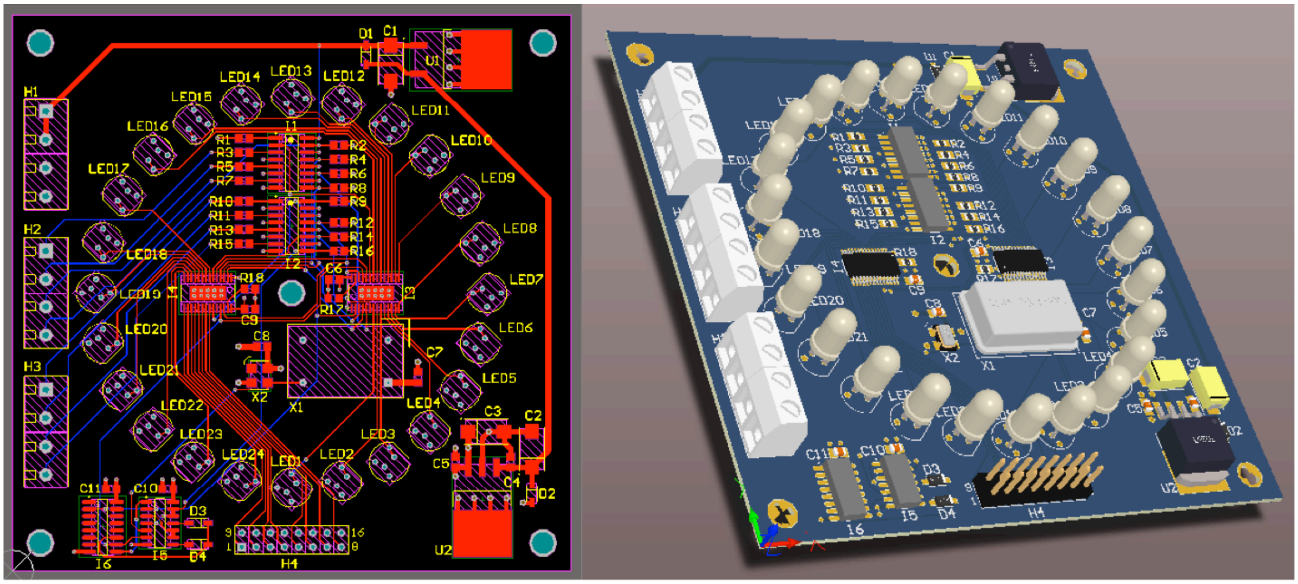

Figure 19 The LED PCB models.

Since 24 LEDs are used to produce the UV/Blue flat field source for the VIRUS instrument and individual LEDs have different spectral characteristics, it is necessary to have a library of the spectral response functions of the LEDs. Once the first production prototype of the LED board is completed, we plan to use a spectro-photometer from Ocean Optics to measure the spectral response function of each LED. This will provide the detailed profiles and central wavelengths of the LEDs. These data will be fed to an spectrum synthesizing program that will optimize the relative intensities of individual LEDs for a desired flat field output spectrum. One example is shown in Figure 20 where 24 LEDs' relative intensity values have been optimized (A) to synthesize a target flat continuum spectrum (D), based on LED vendor-supplied spectral response functions of the LEDs.

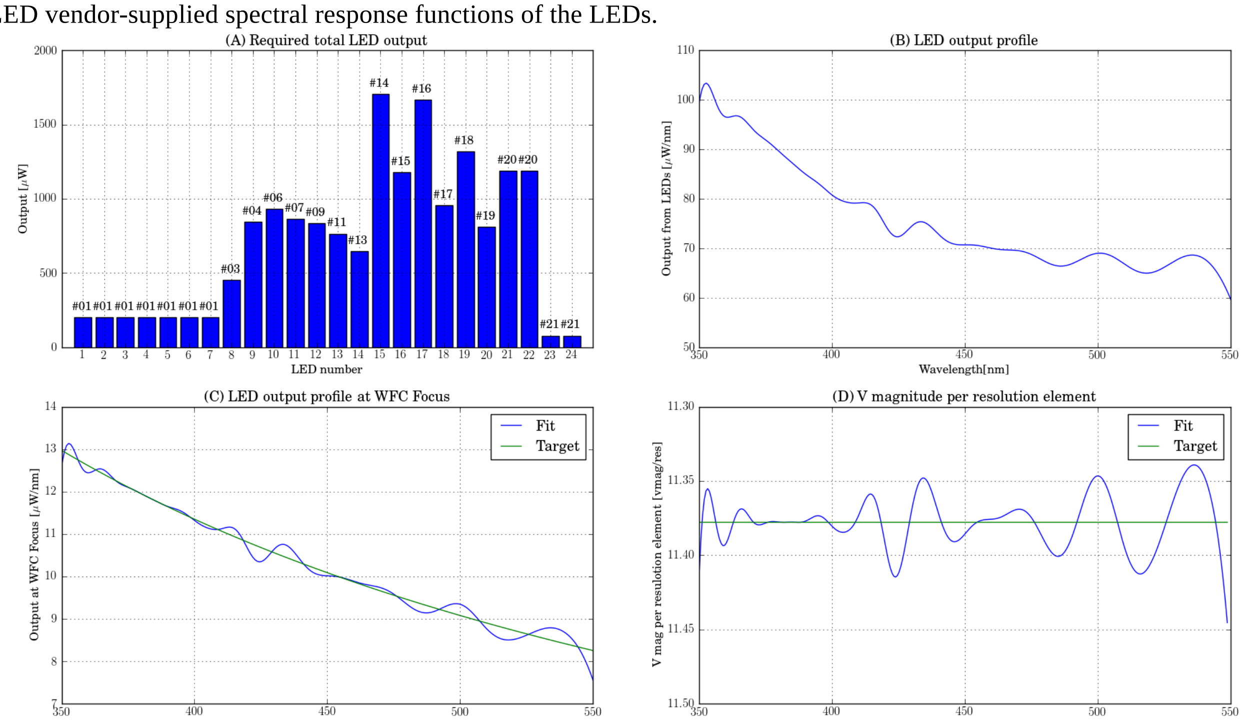

Figure 20 An example of VIRUS flat field spectrum synthesis based on the LED vendor supplied Gaussian spectral profiles and central wavelengths of 24 LEDs.

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The LED-PCB-schematic has been designed in a hierarchical structure, as it can be seen in the following picture, were the tasks are split in 4 different sub-sheets.

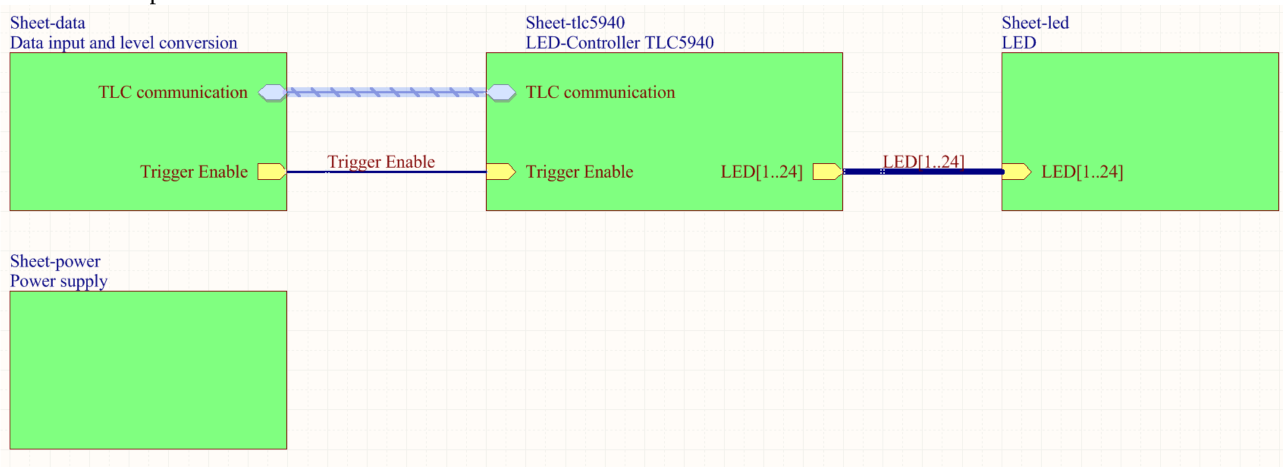

Figure 21 Top-sheet of the FCU LED-PLC which shows the 4 different sub-sheets and their according dependency's.

The only arbitrary sub-sheet is the power supply, were the incoming 24V DC is converted via 2 independent linear voltage regulators. The first regulator reduces the voltage from 24V to 8V and oppresses most of the external voltage ripples which should theoretical not arise, but still may occur in the final assembly by unpredictable bad mutual influence of the different subsystems within and without the FCU. The drop out voltage doesn't need to be considered here so a standard device like the *7808*-positive-linear-voltage-regulator (e.g. Motorola) can be used. It's designed to handle up to 2A and the according heat-production. Due to its D^2-Pack package it distributes the released energy efficient to the heat-tab-pin that is connected to a big cooling area on both sides of the PCB. The regulator is surrounded by an big entrance electrolytic capacitor and a 2 step exit filter circuit, which is build by an electrolytic capacitor of 4.7µm for the low frequency ripple and a standard ceramic 100nF block-capacitor. Out of this, more stable power source is the final 5V DC supply generated by a special low drop-out voltage regulator; in this case a *LM2940* of the branch *National Semiconductor*. The low drop-out is essential here, cause otherwise the voltage difference which needed to be covered would be bigger and the stability of the 5V DC supply would be worse. Last but not least is an other buffering and filtering circuit, like the first one, implemented to cover peak loads which may occur due to the following PWM-devices.

The second sub-sheet contains the data-input via PCB-mounted screw-terminals and the optoisolated level conversion from 24V PCL- to 5V device-logic. All channels are, according to their default values during boot time, equipped with a pull-up respectively a pull-down resistor.

After the data is converted to the 5V device-logic it can be directly entered in the *TLC5940* of *Texas Instruments*, which is basically a 16 channel LED driver with Doc-correction[‡] and Gray-scale[§] PWM control. This device needs to be feed with the a couple of state signals to determine the mode, which in this case should always be the combined Dot-correction and Gray-scale mode, and the according serial data.

After this transmissions the *TLC5940* resets its internal PWM-counter and starts to exercise a full PWM-cycle. Due to some applications it stops after this first run and waits for a trigger signal to start the next PWM-cycle without refreshed data. To avoid a jitter within the LEDs emission and the resulting spectra, the PWM-cycle defining crystal should be as close as reasonable possible to the maximum PWM-frequency of 30MHz, without provoking high-frequency issues. The FCU LED-PCB is going to be assembled with a 24MHz crystal which makes it impossible for the PLC to trigger this by it self. Therefore a special logic circuit of a 14-stage binary ripple counter[**] and a quad 2-input NAND gate[††] has been developed which enables the GSCLK (Grayscale-clock) for the PWM-cycle and counts the occurred clock-signals.

[‡] Dot-correction is the ability to determine the maximum current for every single channel within a 6Bit = 64 Steps range, which divides the, externally set maximum current in equidistant steps.

[§] Grayscale describes the ability to determine the runtime for every single channel within a 12 Bit = 4096 Steps range, which divides the, runtime within one PWM-cycle in equidistant steps.

[**] *74HCT4020* of the branch *NXP*

[††] *74HCT03* of the branch Philips

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This small circuit resets the *TLC5940* after an full cycle has been executed and triggers that way a endless loop as long this artificial enable signal is hold high by the PLC.

The FCU LED-PCB contains 2 cascade *TLC5940*-devices to control all 24 needed LED channels and provides additional 8 channels which can be accessed via a pin-header which is optional to populate. This feature might be useful for lab measurements prior to final assemble or during the systematic measurement of the LED spectra according to the set brightness and current.

Due to the required space the LEDs are placed on the last sub-sheet, which only contains the 24 multi-package-LEDs. This parts have been virtually designed to combine both occurring LED-packages within one overlapping PCB-library, so that the decision, which and how much LEDs of a certain type, can be felt during final assemble of the PCB and is easy to revoke.

4. SUMMARY

In this paper, we presented the designs of the FCU head and source system and described how the calibration lamps are coupled to the telescope. We also presented the LED-based UV/blue flat field source, its design principle, and mixing scheme. We have tested the LED mixing scheme in a prototype breadboard model. We also measured the photon efficiency of the lamp coupler designs in a breadboard model. The measurement suggests sufficient photon flux available for the calibration. At the moment, all FCU head Fresnel lenses (from Eschenbach Optik) and fold mirrors/window (Sydor and STF) have been procured. We have determined the Gaussian scattering value for the FCU head diffuser screen and the procurement has started. The fabrication drawings of the FCU head mechanical components are being produced. We are in the process of procuring 5 light guides from Lumatec (0.4m and 3m-long Series 300 UV/Blue light guides, 1.2m-long Series 380 Blue/Green light guides, 1.2m and 3m-long Series 2000 broadband light guides). We have been using Hg and Cd penray lamps and a QTH lamp in alignment test / image quality evaluation of our first production VIRUS unit. Other lamps will be procured. The lamp coupling optics and mechanical components are being produced or procured. We have selected a list of LEDs for the LED flat field source. The LED PCB board has been designed and the first production prototype is soon to be produced and tested by using the PLC control software.

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