A 64 Mpixel camera for the Wendelstein Fraunhofer telescope Nasmyth wide field port – WWFI

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ABSTRACT

Ludwig-Maximilians-Universität München operates an astrophysical observatory on the summit of Mt. Wendelstein[1] which will be equipped with a modern 2m-class, robotic telescope.[2] One Nasmyth port of the new *Fraunhofer* telescope is designed to sustain the excellent (< 0.8" median) seeing of the site [1, Fig. 1] over a FOV of 0.2 deg^2 utilizing three-element transmissive field corrector optics for optical wavebands. It will be equipped with a camera built around a customized 64 MPixel Mosaic (Spectral Instruments, $4 \times (4k)^2$ 15μm e2v CCDs). The **W**endelstein **W**ide **F**ield **I**mager has two filter wheels with eight slots each (SDSS[3] $[ugriz]'$ + eight still free) as well as two off-axis guiding units (two FLI Microline with 2k Fairchild CCDs on differential focus stages). A Bonn Shutter[4] ensures high precision photometric exposures. An option to either insert a low dispersion grating (for field spectroscopy) or support a wave front sensor probe allows for further expansion of the camera. EMI-safe housing has to overcome the emission of a close by 0.5 MW radio station. Special care has been taken to design a very low ghost budget of the overall system to allow for low-surface brightness applications (e.g. weak lensing surveys).

Keywords: CCD camera, wide field

1. INTRODUCTION

One may ask: Why build another wide field imaging system for optical wavebands with so many systems up and running (WFI@ESO/MPG 2.2 m, CFHT MegaCam, SUBARU Suprime-Cam, Pan-STARRS, Quest Large Area Camera) and even more to come (SkyMapper, VST / ΩCam, PanSTARRS 4, WIYN ODI, LSST)? For one, with Munich University Observatory being part of the HET consortium and also contributing to the VIRUS / HETDEX effort, it fits to build an imaging counterpart to the wide field spectroscopic capacity of the future HET. Also, it will enable us to further continue and advance in projects like M31 pixel-lensing studies.[5] Further, all existing and planned cameras are either community efforts for large public surveys and therefore follow strict schedules or are proprietary (or, even worse, are proprietary large surveys). While much science can be done from the archives of those surveys, the ability of carrying out follow-up observations can provide crucial additional information, e.g. by adding more filter bands and epochs or by providing better seeing quality. Moreover, such observations can be carried out in a timely manner avoiding the longer application cycles of public observatories. Another important aspect is to be able to carry out preparatory observations for projects at larger telescopes, which enable better focused applications for public facilities. Finally, one can also try out risky observing projects that would not easily be approved at other observatories.

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2. CAMERA LAYOUT

2.1 Design Goals

The new Wendelstein Fraunhofer telescope has been designed with a strong emphasis on its wide field capability as can be seen in the telescope's official call for tender, summarized as follows:

- The telescope shall provide a special wide field port with a unvignetted FOV of 0.71° diameter at least, aiming at 1° diameter.
- The plate scale has to be within the range of 0.17"/15 μm to 0.25"/15 μm and therefore yield a telescope f-ratio between $f/7$ and $f/8$.
- The telescope and wide field port optics have to deliver EE80% (EE=encircled energy) in 1.25 × the airy disk Ø and a polychromatic r.m.s. spot size of less than 5 μm, both, within a FOV radius of 15′, and, EE80% in 2 *times* the airy disk Ø and a polychromatic r.m.s. spot size of less than 10 μm, again both, within a FOV radius of 21.3′; these shall be true for a wavelength range of 350 nm to 1000 nm.
- Otherwise, the optical design shall aim at lowest image distortion and ghost image level feasible with a reasonable amount of effort.
- The unguided telescope track has to be no worse than 0.1"/600 s over the whole accessible hemisphere.
- In order to have room enough for large instrumentation the telescope instrument ports are required to give a free back focus distance of at least 550 mm within a tube of 1 m length along the principal axis and a diameter of 2 m.
- Every instrument port must be capable of carrying 350 kg co-rotating at least, aiming at 500 kg.
- They have to provide connection to standard support lines (power, network, cooling water, and pressurized air) as well as enough spare room in the cable wraps to allow for additional specialised instrument lines (relay control lines, cryogenic lines etc.).

Accordingly, the WWFI should reflect those requirements in as many respects as time and money allow for. The WWFI is also scheduled to be the prime of the first generation instruments for the telescope, if possible even its first light instrument.

Additionally, the WWFI should be a modern state-of-art astronomical camera, i.e.:

- The detector(s) shall be highly responsive and uniform, have a fast readout, low noise, and negligible dark current.
- The shutter has to enable high precision, photometrically stable exposures from 1/100 s to half an hour.
- The camera has to offer slots for ample sets of filters starting with (but not limited to) a SDSS[3] $[ugriz]'$ set.
- Of course, the camera mechanics shall not counter the efforts put into the telescope optics and mechanics.

Due to a nearby radio broadcast station all instruments on Mt. Wendelstein have to cope with radiation field strengths of 10 V/m in average with peaks up to 30 V/m. Finally, the WWFI shall have room left for later upgrades, i.e. an optional wavefront sensor or a slitless low dispersion wide field spectroscopy mode.

2.2 Design Approach

The amount of time for the whole project, from conceptual design to first light, has been limited to three years by the requirement that the instrument has to be available for telescope commissioning and evaluation. With a total of no more than eight people working on the four first generation instruments for the new Fraunhofer Telescope (and most of them only available part time for those projects) it was clear that existing solutions had to be used wherever possible. Therefore, we decided to build the camera based upon the largest commercially available CCD-Mosaics at that time which were offered by Spectral Instruments (Tucson). The only valid option for a high precision, large aperture shutter is a Bonn Shutter.[4] For the WWFI we purchased a $200 \times 200\,\mathrm{mm}^2$ model. The telescope (Alt.-Az., three mirror, Ritchey-Chrétien type) and the wide field corrector (three lenses, i.e. a doublet directly attached to the Nasmyth derotator plus an optically active dewar window) are procured through Kayser-Threde GmbH as part of the telescope contract. This left the frame and covers, as well as the filter change and off-field image analysis and guide probe mechanics to be designed.

3. CAMERA PERFORMANCE

3.1 Optical Performance

The optical performance of the camera with respect to image quality is almost exclusively determined by the telescope and its wide field corrector. Fig.1 gives the fraction of encircled energy, r.m.s. spot sizes, and spot diagrams for the two most extreme filter bands $[uz]'$. There are no surprises for intermediate wavelengths (i.e. SDSS[3] (gri)$'$), the transition in subsequent performance plots is more or less smoothly.

"Ghosting" is discussed in detail in Hopp et al.[2] The system grid distortion is largest for red wavelengths but even there has been limited to no more than 0.0027% which is about 0.1 ($15\,\mu$m) pixels on an absolute scale.

A standard set of thin film coated filters (SDSS[3] $[ugriz]'$) has been purchased through LASER Components from Omega Optical. The filters are $150 \times 150 \times 15\,\mathrm{mm}^3$ sized and designed to be put into the filter wheel which is closer to the detector mosaic. Fig.2 shows the performance of the individual filters, as well as the expected performance of the detector, the telescope, and all of them combined. Combining measured performance with conservative guesses we expect to have a total system throughput as shown in Tab.1, row Q.

3.2 Detector Performance

Our Spectral Instruments type 900 camera is a 2×2 array mosaic which employs e2v 231-84 backside illuminated $4\mathrm{k} \times 4\mathrm{k}$, 15μm pixel, deep depletion CCDs with an Astronomy broadband coating. These CCDs are mounted in the camera such that all chips are flat to 15μm in relation to one another. The CCDs are arranged such that there is at most a 7.5mm gap between vertically oriented CCDs, and a 1.5mm gap between horizontally oriented CCDs. Each CCD can be read from four ports. The CCDs will be cooled to an operational temperature of about 158 K by two closed cycle mechanical cryo coolers. The two cooler compressors will be placed off the telescope dome to limit the heat load on the telescope and instrument temperature controlling systems. The Bonn Shutter[4] can be directly controlled from the camera via TTL signal. The camera will be controlled and output its data through a 30 m fiber optic cable interfacing to a PCI card in the controlling computer. Two read speeds are provided, 100 and 500 kHz per port.

Dark current is about $0.0006\,e^-$/pixel/s. Minimum full well capacity (in 2×2 binning) is more than $245\,\mathrm{k}e^-$. Parallel and serial charge transfer efficiencies (CTE) are always better than $1 - 1e^{-5}$, for more than $3\mathrm{k}e^-$ always better than $1 - 1e^{-6}$. For 500 kHz and a gain of about $5.85\,e^-$/ADU the readout noise (RON) is $8.5\,e^-$ or better, For 100 kHz and a gain of about $0.73\,e^-$/ADU the RON is better than $2.6\,e^-$. Radiation tests by SI in the lab which tried to simulate the conditions we expect on Mt. Wendelstein* showed an increase in RON in the order of 10 to $27\,e^-$ when no additional shielding protects the camera.

For the detectors sensitivity see Fig.2.

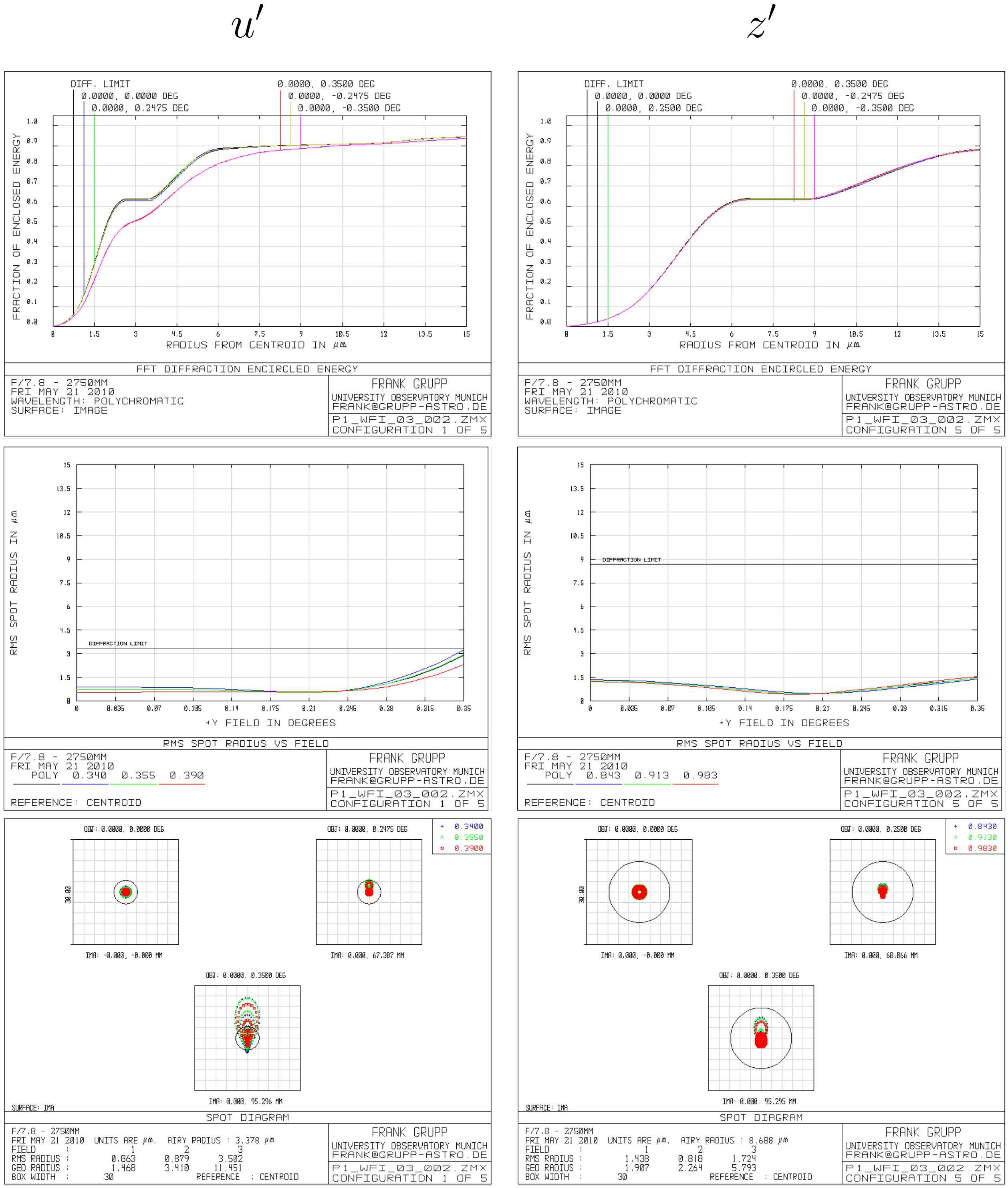

Figure 1. Top: Fraction of encircled energy vs. radius of respective distribution centroid for diffraction limit, chief ray, edge and corner of the realized field ($\sim 30' \times 30'$); center: R.m.s. spot sizes vs. distance of the chief ray; bottom: spot diagrams, boxes represent 2 × 2 detector pixels; left: SDSS[3] u' filter band; right: SDSS[3] z' filter band.

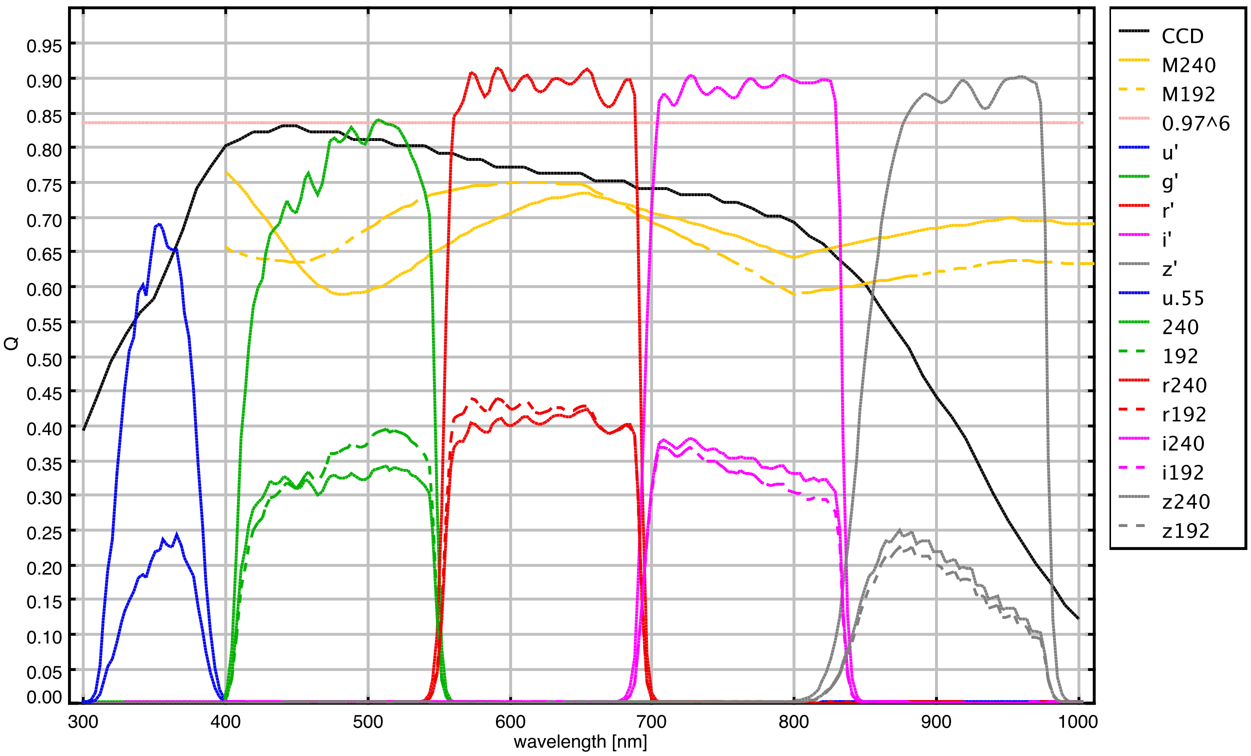

Figure 2. Individual and combined throughput of all WWFI and telescope components: A full set of SDSS[3] $[ugriz]'$ filters; the CCD performance of a prototype device (black, e2v 231-84 backside illuminated, deep depletion CCD with an Astronomy broadband coating); two options for the telescope mirror coating (aluminium with SiO/SiO_2 protective coating) from 400 nm to 1000 nm, the mirror performance for u' has been estimated to 0.65; a three-lens (six-surfaces) corrector with almost no anti-reflection coating would contribute transmission factor of $0.97^3 \approx 0.83$.

waveband	u'	g'	r'	i'	z'
Q	0.201	0.363	0.415	0.325	0.155
extinction	0.56	0.18	0.10	0.08	0.07
night sky AB	22.80	21.90	20.85	20.15	19.26
S/N	4.90	5.05	4.99	4.89	4.94
AB mag	24.90	25.45	25.00	24.45	23.55

Table 1. Signal-to-noise / limiting AB magnitude for the SDSS filter bands of the WWFI on the Fraunhofer telescope: Seeing 0.8", aperture 1.1", RON 2.6 e^-, 5 $\times$ 360 s exposures combined $\hat{=}$1800 s.

3.3 "On Sky" Performance

Aiming at a signal-to-noise ratio $S/N \approx 5$, taking into account all of the system parameters known, combining those with typical atmospheric extinction coefficients and night sky brightness, a seeing of 0.8", and unity airmass, one can reach limiting AB magnitudes in the range of $\sim 24.5 - 25.5$ with 1.1" apertures for half an hour exposures split into five individual exposures (see Tab.1).

4. MECHANICAL DESIGN

The camera has a modular design (see Fig.3): The first two lenses of the field flattening corrector in their steel housing are directly attached to the Nasmyth flange. The most massive part of the camera frame, an aluminium cone (Fig.3, top row), still also is directly attached to the Nasmyth port and covers the lens doublet. This cone ensures minimal flexure while growing from the ~ 0.4 m Nasmyth port diameter to about 1 m which, again, is needed to carry subsequent mechanics.

The next part of the frame, a half Serruier truss construction, is built as one part with the cone, again minimizes flexure, and connects to a circular mounting plate which separates the off-field image analysis, guiding probe, and shutter module (i.e. the observation support module, OSM) from the filter module (FM). The Bonn Shutter[4] directly sits on the mounting plate. Two guiding cameras (FLI Microline with 2k Fairchild CCDs) on motorized focus stages together with their fold mirrors reside on bridges over the shutter. Most of the guiding field is already vignetting. The cameras are tilted to compensate for the missing third field flattening lens. The option for a slider to insert either a fold mirror for an on-field wavefront probe or a low dispersion transmissive grating for slitless field spectroscopy has been elaborated but is deferred as a later upgrade.

The FM is confined by the already introduced and another, equally sized, circular mounting plate. They are separated by four thick poles, two of them serving as axes for the filter wheels. All four serve as feed through for support lines from the controller and detector compartment (CDC) to the OSM. Two identical ~ 1 m diameter filter wheels can carry up to eight filters each. The filters reside in removable cassettes for easier maintenance. The filters for the wheel closer to the CDC can be $150 \times 150 \times 15\,\mathrm{mm}^3$ without vignetting the beam, the wheel closer to the OSM requires $160 \times 160 \times 15\,\mathrm{mm}^3$ filters to avoid vignetting. We chose wheels over sliders or magazines as the latter two would have required complex counter balance mechanisms and despite their large size wheels were still in the "space budget". The wheels have lock notches for spring wheels to acquire highly reproducible filter positions.

The back end of the WWFI builds up on the backside of the second FM mounting plate. The CDC hosts the tip-tilt stage for our SI900 mosaic, the motors for the filter wheels, and all controllers, network and power adapters which may not be offloaded from the telescope because of the EMI issues of the site (see footnote$*$ in Sect.3.2). Any DC power, low voltage signal, or network lines have to be well shielded and as short as possible. The electronics altogether will produce about 1 kW of heat. Therefore, it was reasonable to gather most of the heat dissipating parts at the one place which has least impact on the structure. We plan to divert this heat load through simple heat exchangers which are often used in water cooled PCs.

The covers have to protect the camera from light and EMI. This is accomplished by fitting the cover sheets in tight gaps which are filled with special EMI proof gaskets. The OSM and the FM each have two part covers. The CDC has a "tub" cover fitting onto a ring which provides the feedthroughs for external support lines, i.e. one power line, fibre network lines, direct control relay lines (e.g. emergency shutdown), cooling water and refrigerant lines.

The telescope and field flattener optical design solutions set the limits for acceptable mechanical trade offs. The optical design shows that the alignment of the Dewar window with respect to the chief ray (lateral as well as tip-tilt) is least critical. Therefore, a simple tip-tilt stage for the detector (i.e. the image plane) will be sufficient for alignment at the back end. Finite elements analysis of our design gives a more or less constant absolute

[*] The average field strength at the future telescope location is about 10 V/m with peak values up to 30 V/m. Most energy is transmitted for FM radio broadcast (89.5, 93.7, 98.5, 102.3, 105.7 MHz). Other frequencies are from digital TV broadcast (578, 586, 690, 738, 754, 834 MHz). There are also some cellphone providers in the GSM 1800 band, but their transmitting power is just 50 Watts.

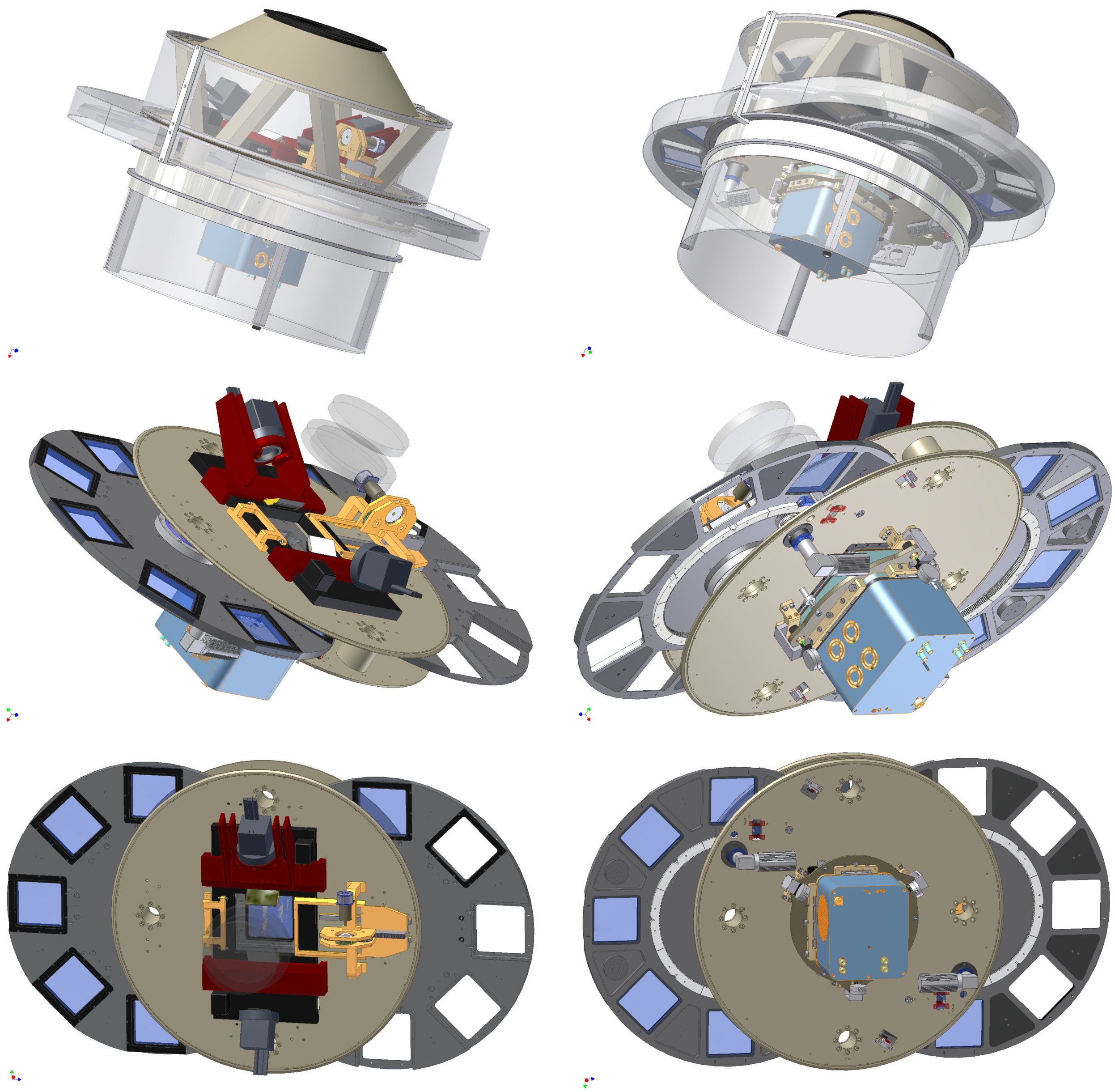

Figure 3. Top: The full WWFI without controllers, covers are transparent, cone and half Serruier frame shown; center and bottom: Covers, cone and half Serruier removed; corrector doublet transparent; Bonn Shutter, FLI guiding cameras, and filter cassettes black; filter wheels dark grey; main "frame" parts light grey; optional "add-on" slider beige; guiding camera mounts red; SI900 mosaic light blue with orange outline; left: front / side views; right: rear / side views. See main text for more detailed description.

lateral displacement of 70 μm at place of the image plane. This can be compensated by the pointing model of the telescope. The absolute tip-tilt at image plane is about $\pm 20\,\mu$m and will produce defocus in the image corners of less than 3 μm ($\sim$ 1/5 of a pixel).

The complete WWFI weighs less than 300 kg, i.e. well within the telescope's 350 kg limit.

5. ELECTRONICS & SOFTWARE

The electronic components of the WWFI show a multitude of interfaces in hardware and software. To standardize the interfaces we follow a simple well-tried but nevertheless hard to establish rule: Get everything to TCP/IP and "reasonably standardized" human readable command and status streams ASAP. TCP/IP allows to stick to Ethernet over fiber links which avoids the EMI issues, while human readable messaging speeds up deployment of software. For the most simple cases (e.g. motor controllers) this concept just means employing an Ethernet to serial converter and writing simple parser software running on some server for "decrypting" messages. For the more complex cases this involves either digging into (often enough not well written) software development kits, which usually come with many restrictions concerning operating systems and compilers (and even their versions), or living with existing, but functionally limited software interfaces, or even being forced to write your own low level driver software[†]. Sticking to software provided "as is" is simply no option when aiming at remote, robotic or even scheduled observations[‡]. All command and status streams will be combined as services in a bigger observatory control and status server. This server can be accessed either for human on-site or remote control via browser clients or even from robotic or scheduling clients.

6. STATUS – PROJECT TIMELINE

Detailed design of the camera has been finished. All critical parts besides the covers have been delivered or are at least ordered and due until July 2010. We expect to run component and assembly tests in summer and autumn 2010 and will have the camera ready in a test mode for preliminary telescope evaluation in early 2011. The WWFI is expected to be ready for science use in summer 2011.

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[†] Unfortunately this is the case for any commercially available CCD camera.

[‡] It is usually a very bad idea to force observers to operate on many logically dependent but not interconnected control interfaces, i.e. unless one delights in errors and frustration.