90prime: A prime focus imager for the Steward Observatory 90-inch telescope

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ABSTRACT

Steward Observatory is currently commissioning a prime focus wide-field imager for the 90-inch telescope located at Kitt Peak. The camera's focal plane array is populated with a mosaic of four thinned Lockheed 4096×4096 pixel CCDs. The f/2.98 system provides a plate scale of $0.45''$/pixel and a total field-of-view of $1.16^\circ \times 1.16^\circ$. The optical design includes a four element corrector and six position filter wheel. The first science run was conducted in November 2003. We will describe the design of the "90prime" instrument and results from the commissioning runs.

Keywords: Steward Observatory, 90prime, Bok, 90-inch, prime focus

1. INTRODUCTION

Steward Observatory shares a large number of major telescope facilities, namely, the MMT (45%), Magellan I and II (10%), and the soon-to-be-commissioned LBT (25%). Observatory personel are also involved with major surveys and related projects with SIRTF, 2MASS, and SDSS, all of which demand optical follow-up. Both the MMT and Magellan telescopes are equipped with instruments that allow wide-field spectroscopy. Yet, Steward's older telescopes, the Bok 2.3-m (90-inch) and the 1.5-m class telescopes, could not meet the demand for wide-field imaging in support of the newer facilities.

90prime, as described below, has increased the areal coverage of a single exposure at the Steward facilities by a factor of 150. When we couple this new ability with the capabilities of our 6.5-m telescopes, and with our space based projects, we allow science to be done that was impossible at Steward facilities in previous times. 90prime was envisioned as a workhorse facility instrument and was therefore designed to be a robust user friendly instrument.

The instrument consists of a "top" ring, an optics can, a topbox, and a CCD camera. A labeled mechanical drawing of the instrument is shown in Figure 1, and a picture of the completed instrument on the telescope is shown in Figure 2. The instrument is currently completing the commissioning phase and has been offered to astronomers for shared risk observing.

2. TOP RING

The prime focus position of the Steward 90-inch has never been used, and therefore, we were required to build a new "top" ring for the telescope. The top ring provides an interface between the telescope truss and the instrument. This called for retro-fitting a telescope built in 1968. The ring itself weighs 1300 pounds, far more than is required for mechanical stability. This weight is necessary to match the existing f/9 and f/45 rings so that instrument changes and subsequent balancing is made easier.

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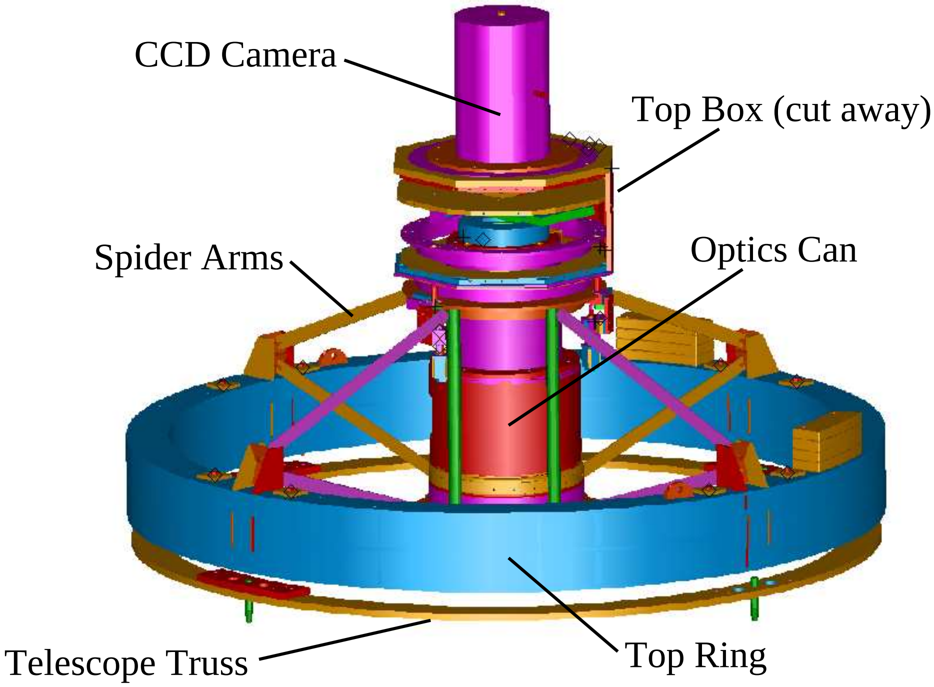

Figure 1. A mechanical drawing of the 90prime instrument.

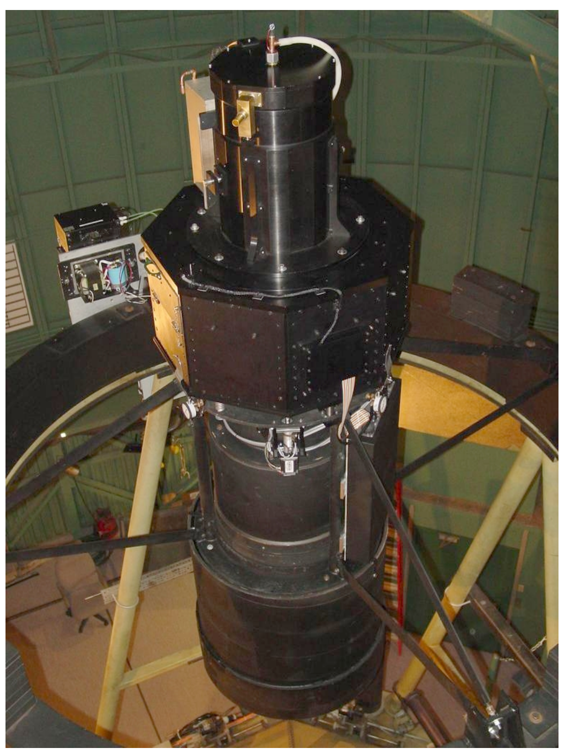

Figure 2. The 90prime instrument mounted on the telescope.

There are four pairs of spider arms which connect the ring to the “center hub”. The center hub is the mounting location of the optics can. The four spider arms are not precisely radial, they are slightly offset to reduce torsional frequencies.

Alignment of the lens can is achieved by manually adjusting the length of each spider arm. This is done by tightening or loosening nuts on a fine thread on the outer end of each arm. This alignment was performed at night so that extrafocal images could be obtained after each adjustment. These images were analyzed to determine the remaining wavefront error. The Zernike coefficients were compared with ray trace software to estimate the magnitude and orientation of the next adjustment. The alignment required the distance between the primary mirror and the lens can to be positioned to within ± 1.0 mm of nominal, the lens can to be centered to the primary axis to within 0.1 mm, and the the lens can to be aligned in rotation to 0.05 mrad about middle of the system. Although the initial alignment of the optics was relatively tedious, the system provides a stable alignment for an instrument which is mounted on the telescope many times per year.

The instrument top box is mounted to the center hub with three linear actuators. These actuators provide the mechanism for focusing and flattening the focal plane array. The actuators use stepper motors with a resolution 4800 steps per inch or 5.29 μm per step. The actuators are controlled with a Galil motion controller which is described in greater detail in Section 7. The actuators can move individually or in coordinated motion.

3. OPTICS

The Steward 90-inch telescope has historically delivered a median-seeing of approximately $1.3''$. Therefore, the prime focus optics were designed to match that level of seeing, but also to give modestly well-sampled images if the seeing improves to as good as $1.0''$. The goal of the optical design was to provide good image quality over one square degree with nearly no vignetting. This goal was achieved using a four-element design, three elements within the “lens can” and one used as the dewar window. The lens can provides baffling and properly spaces the three lens cells. The spacing between lens three and the CCDs (and thus the filter and the dewar window) is allowed to change for focusing. There is an additional baffle which extends below the optics can.

The design of the four-element optical corrector is shown in Figure 3. The corrector removes spherical aberration, coma, astigmatism, and field curvature to produce an RMS spot radius of less than 8.5 μm or $0.25''$. The best performance is on axis in the blue ($0.35 - 0.55$ μm) where the spot size is less than 2.9 μm or $0.09''$. In order to meet these requirements lens two of the corrector has one aspheric surface. Lens four, the dewar window, has only a small amount of power.

All the optics are made from fused silica which allows imaging down to the atmospheric UV cutoff. The optics were polished in the Steward Observatory Mirror Lab small optics facility. The hard broad-band anti-reflection coating was applied by the Los Angeles based company ZC&R. The reflectance is less than 2% from 300 nm to 950 nm.

The system was designed to use a filter between lens three (the top element of optics can) and lens four (the dewar window). This is not the most optically ideal location. However, this position was chosen to keep the filter size small and therefore affordable to allow individual astronomers to purchase custom filters required for their science. The filters are 6.0” square, slightly larger than the 5.75” NOAO mosaic filters. The design allowed a filter thickness in the range of 4–12 mm. We have now adopted a standard filter thickness of 12 mm to match the existing the NOAO mosaic filters.

The filters dominate the vignetting but only at the very edge of the field. A vignetting curve is shown in Figure 4. The baseline vignetting is the obscuration by the instrument, which is approximately the same as the amount of area in the Cassegrain hole. The fraction of unvignetted beam is approximately constant at 85% out to 65 mm and then drops to 60% at the very edge of the field. Since the filters are square the vignetting pattern is roughly square.

The current filter set consists of the “Bessell” prescription of the standard U, B, V, R, and I filters, the SDSS u’, g’, r’, i’, and z’ filters, and the Washington C, M, and DDO51 filters. In addition, R. Windhorst of Arizona State University has provided access to his BATC set of filters, a set of 15 medium-bandwidth filters (see `http://www.noao.edu/noao/mosaic/filters.html` for the BATC filter transmission curves).

As with all such cameras, ghost images are produced by multiple reflections of bright stars. An optical analysis indicates that the strongest ghost image is produced from reflections off the CCD onto the dewar window and back onto the CCD. In a simulation the result ghost had an RMS diameter of 1.91 mm. The number of photons from the ghost on any single pixel is 6×10^{-7} times smaller than the number of photons per pixel from the image itself. A highly overexposed image of one of the brightest stars in the sky shows all of the ghosting.

The bare 90" mirror has a focal ratio of f/2.67. The corrector optics modify the f-number slightly to f/2.98. This provides a plate scale of 30.2"/mm or a pixel scale of 0.45"/pixel. The edge-to-edge field-of-view is $1.16° \times 1.16°$ and the active field-of-view (area of the CCDs on the sky) is $1.03° \times 1.03°$.

4. SHUTTER

The 90prime instrument utilizes a 200 mm aperture Bonn[2] slit-type shutter, made by the Astronomical Institutes of the University of Bonn. Two carbon-fiber blades are driven by stepper motors and toothed belts and move on a pair of linear ball bearings. Uniform exposures are produced by moving one blade out of the beam for the start of the exposure and moving the other into the beam to end the exposure. For short exposures the two panels move simultaneously and a slit illuminates the focal plane. The exposure time is set by the distance between the two panels, i.e. the slit width. Exposure times as short as 10 ms are possible. The exposure homogeneity is better than 1.0% for a 100 ms exposure. The shutter is controlled with an external TTL signal from the CCD controller. Figure 5 shows picture of the 90prime shutter.

5. FILTER WHEEL

The size of the 90prime top box and therefore the vignetting due to the instrument was set by the size of the filter wheel. We chose a size that would accommodate six filters (e.g. U, B, V, R, I and clear). A classic offset filter wheel, typically used at the Cassegrain focus, would have required a relatively large top box. Therefore we designed a wheel in which the filters encircle the optical axis. The wheel rotates about the axis and at one position a filter can be translated into the optical beam.

Figure 6 shows a picture of the 90prime filter wheel. The outer ring rotates on an 18" diameter bearing. The wheel is driven by a stepper motor that advances a PIC2 cable ladder belt which encircles the circumference. Idler wheels assist in constraining the belt. Six aluminum tabs of differing lengths are mounted on the circumference of the wheel to provide indexing of the wheel. A Hall effect sensor is used to measure the length of each tab during rotation of the filter wheel.

Each of the filters is housed in a dedicated filter holder. There are eight holes on each holder which are populated with a unique combination of magnets. A filter is identified by its combination which is read by a set of Hall effect sensors mounted at the filter load position.

A filter is loaded into the beam with a stepper motor driven arm (not shown in the figure). A pin on the arm engages a slot in the filter holder as the wheel rotates into place. The stepper motor drives a threaded rod which draws the arm toward the optical axis. The arm slides the filter along wheels which guide the rails on the filter holder. A limit switch stops the arm as the holder begins to compress a spring loaded bar.

6. CCD MOSAIC AND DEWAR

The CCD camera was built at the University of Arizona's Imaging Technology Laboratory (ITL). The focal plane is populated with four Lockheed CCD485 devices. Each CCD contains 4096×4096 15μm pixels. There are four amplifiers on each device, one at each corner. The devices were backside thinned by ITL. An anti-reflection coating was applied to enhance the UV-to-blue response. A CCD quantum efficiency curve is shown in Figure 8. All four of the CCDs have been coated with a single 500$\AA$ layer of hafnium oxide (HfO_2) and two of the CCDs have an additional single layer of 900$\AA$ magnesium fluoride (MgF_2). The quatum efficiency curve for the devices with a MgF_2 coating are shown as the dashed curvie in Figure 8. The CCDs are not edge-buttable and are therefore mounted with a gap of approximately 15.8 mm between the CCDs. This gap corresponds to approximately 1060 pixels or $500''$ on the sky. Figure 9 shows the focal plane of the camera.

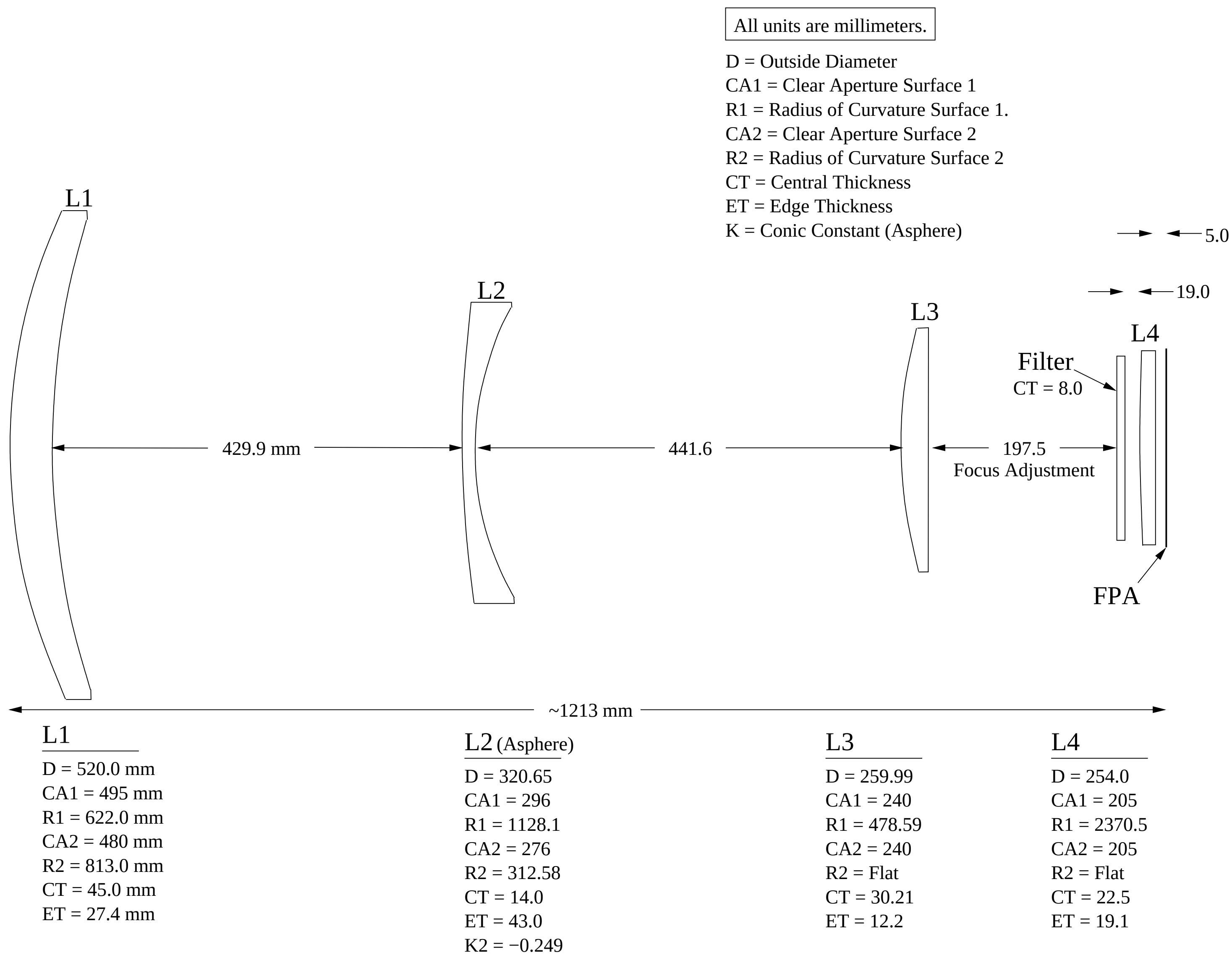

Figure 3. The 90prime corrector optics.

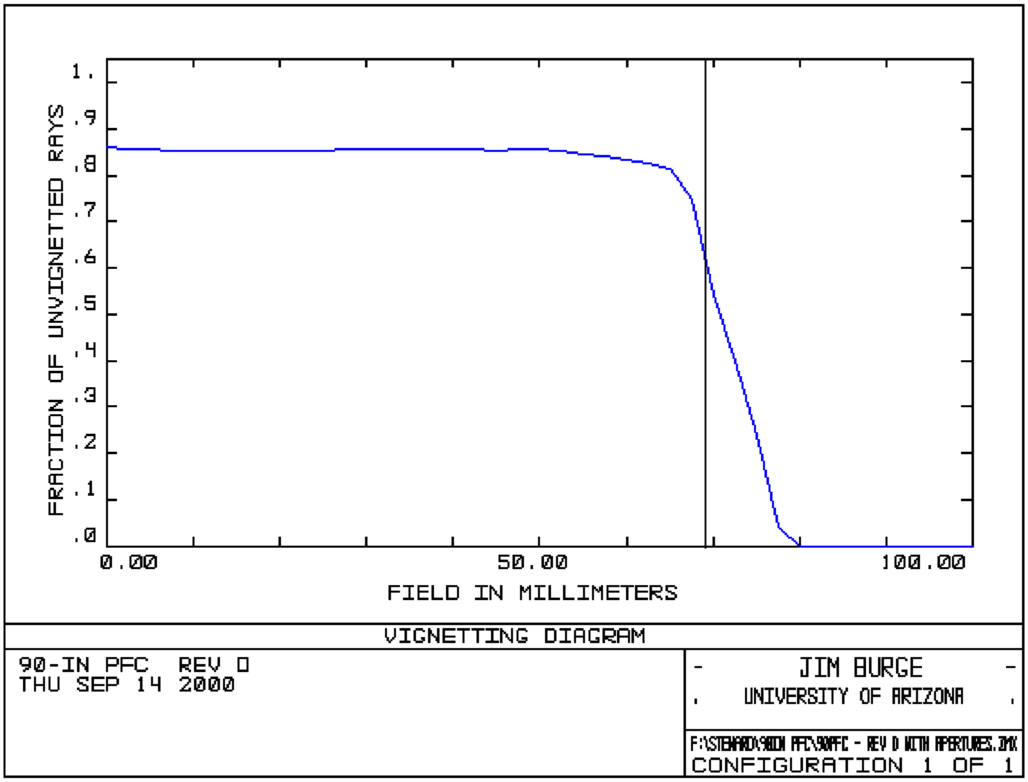

Figure 4. 90prime vignetting diagram. The dominant effect is from the clear aperture of the filter.

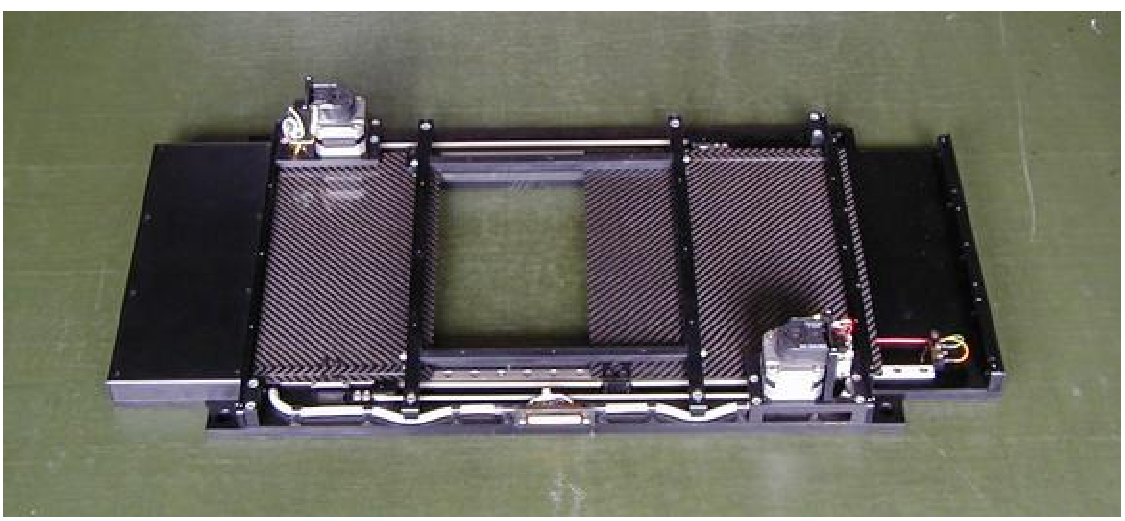

Figure 5. The 90prime 200 mm aperture Bonn^2 shutter.

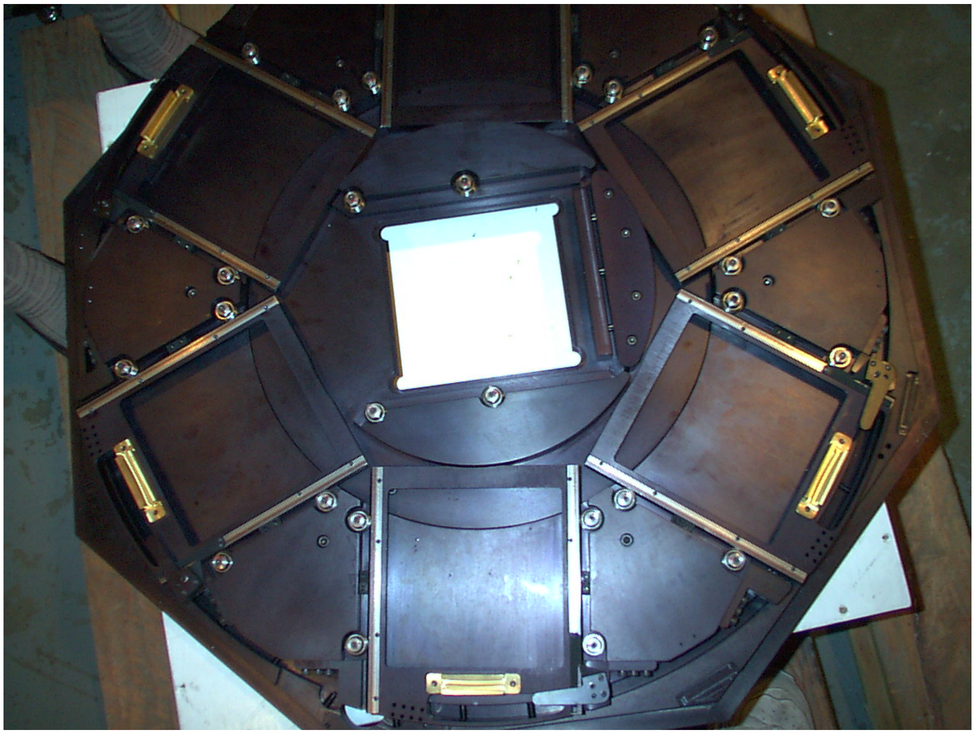

Figure 6. The 90prime filter wheel.

The dewar is a modified version of the standard ND-12 Infrared Laboratories liquid nitrogen (LN2) cooled dewar (see `http://www.irlabs.com`). The dewar has a 23 liter LN2 capacity and at an operating temperature of approximately $-100°$C has a hold time of greater than 48 hours. However, weight changes from boil off of the LN2 require filling once per day to avoid having to rebalance the telescope. An image of the dewar is shown in Figure 7. The controller mounts onto the side of the dewar at the two connectors near the mounting flange.

The 90prime instrument uses an ARC Generation III eight-channel CCD controller built by the San Diego State University (SDSU) CCD Laboratory. The camera is controlled with the AzCam software package (see Lesser et al. in these proceedings[1]). Each CCD is read out through two of its four amplifiers. Therefore, the camera is currently an 8 channel (4 video cards) system with provisions for adding the remaining 8 channels. A Windows-based PC runs the server (with the fiber optic interface card) and clients may connect from remote machines over ethernet. We typically operate with a local Windows client and a remote Linux client, all written in National Instrument's LabVIEW. A screenshot of the main camera control GUI is shown in Figure 10.

The CCD gain is approximately 2 electrons per data number. Clearing the array takes three seconds before each exposure and readout is complete in 50 seconds. The readout rate is about 170 kpixels/sec per amplifier, or 1.36 Mpixels/sec total. This speed produces a read noise of about 12 electrons, although it varies from 10 - 14 over the 8 amplifiers. Since our main use is broad-band imaging with fairly large pixels on the sky, we were able to tolerate a higher readnoise than one would like for spectroscopic applications, i.e. the camera is seldom read noise limited. The most significant issue of the CCD system is the limited full well of approximately 60k electrons per pixel in Multi Pinned Phase (MPP) mode, which may be due to our common clock driver. This limitation should be improved in the future.

The eight channels are read out simultaneously in 50 seconds and stored in the memory of the CCD controlling computer. The data are then de-interlaced (made into 8 appropriate images) and sent to the observer's computer. These deinterlacing and shipping tasks take an additional 35 seconds. The total time from end of exposure to being able to start a new exposure is thus 85 seconds for unbinned readout.

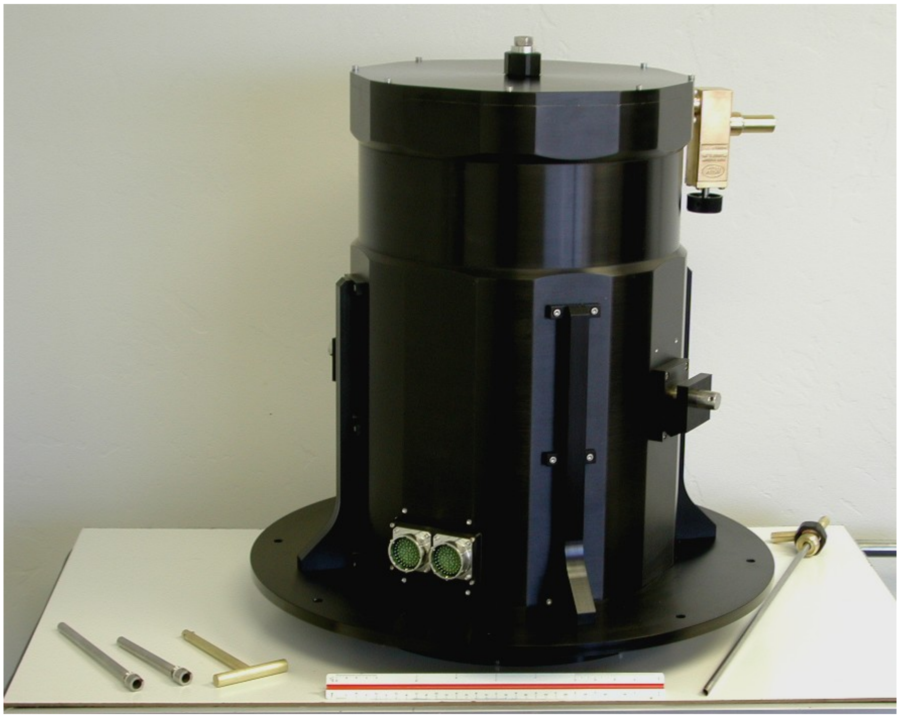

Figure 7. The 90prime dewar.

There is amplifier crosstalk at an as yet unmeasured level. Crosstalk is confined to the two amps on each individual CCD, not to other CCDs.

During operation of the science camera, the CCD-controlling computer prepares the image as a multi-extension FITS file with all headers required for display and analysis of the image by IRAF's and ds9's mosaic reduction routines. The image is then transfered across the network to the observer's computer, where it is received by a data server daemon that is listening on the appropriate TCP port. This daemon has the three functions: receiving the image data, writing it to disk, and producing an immediate 'quick look' by sending it (via the 'xpa' protocol) to a ds9 image display tool. The daemon runs under the high-priority real-time scheduler, using a graduated set of priorities to insure that the listener is always ready to receive data and also uses multiple threads to make effective use of both processors. The daemon runs suid root so that it can be started by a non-privileged user and still have the permissions required to make the scheduler system calls, but it is careful to drop root at all other times. An alternative design that used SAMBA to simply allow the CCD-controlling computer to write the data to a mapped linux drive was rejected as being less efficient, not allowing the fine control of process priorities, and not providing a direct method of generating the 'quick look' display.

Our original plans had a second computer which receives copies of the raw data from the CCD controller, for reduction and analysis. This second computer is probably necessary for optimal data reduction and archiving. We currently do not have an automatic archiving scheme; it is up to each individual observer.

7. INSTRUMENT CONTROL SOFTWARE

The 90prime observer's computer is a dual-processor machine using AMD Athon 2400+ cpus, 2 Gb memory and running linux. Approximately 280 Gb of primary data storage is provided by a software RAID 5 array containing 5 active and 1 spare 73 Gb 10,000 rpm SCSI disks. We can easily upgrade storage capacity by adding new disks. Matrox 450 graphics hardware supports dual 19" monitors which provide ample display area for the simultaneous use of the instrument control program, several analysis windows for IRAF, and the ds9 'quick look'

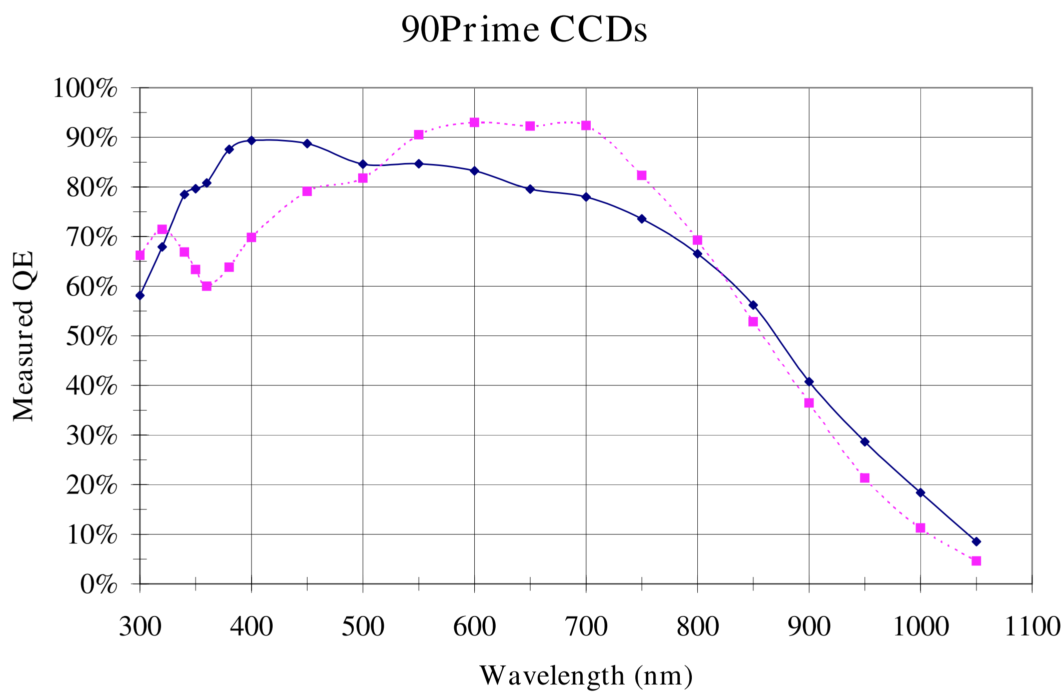

Figure 8. The measured quantum efficiency for the 90prime CCDs. All four of the CCDs have been coated with a single 500Å layer of hafnium oxide and two of the CCDs have an additional single 900Å layer of magnesium fluoride. The quantum efficiency for the devices with the the hafnium oxide only (hafnium oxide plus magnesium flouride) coating are shown as a solid (dashed) curve.

image. A DDS4 DAT drive and writable DVD device are available for backup and archiving of data. Gigabit ethernet connects the observer's computer to the CCD controlling computer.

The instrument motors are controlled with an ethernet based Galil model 2180 eight-axis motion controller. The filter wheel rotation motor, filter wheel translation motor, the focus actuators, the guide camera focus stage, and the guide camera filter wheel are all controlled with the Galil. A set of low level motion control application routines have been "burned" into the Galil's 4 Mb non-volatile EEPROM memory. These routines are comprised of a set of two letter Galil specific commands which specify the motion control. Higher level software is used only to send a set of variables, such as motion distance or speed, and a command that executes one of the Galil routines. This programming model prevents motor runaways if the communication is lost to the Galil during motion. The higher level software is written in LabVIEW but any scripting language could be used. Figure 11 shows a screenshot of the front panel of the 90prime main GUI.

8. GUIDER

The 90prime instrument utilizes a dedicated Steward Observatory CCD guide camera. These guide cameras are currently used at the 90", the Vatican Advance Technology Telescope, the 61", and the MMT. The guide camera dewar is a self contained unit which measures 4" in diameter by 2" thick. The CCD is a 1024×512 pixel, thermoelectrically-cooled, thinned, back-illuminated device operating in frame-transfer mode. The pixel size of 15 μm matches the science camera. The field-of-view of the camera is $4' \times 4'$.

The camera is fed by a pick-off mirror which is in a vignetted portion of the edge of the field. The vignetting is at the level of approximately 40% or one magnitude. In the optical path, the pick-off mirror is positioned before the science filter location. Therefore, an additional modified commercial Oriel filter wheel with colored glass filters is used to guide at approximately the same wavelength as the science camera. The guide camera and

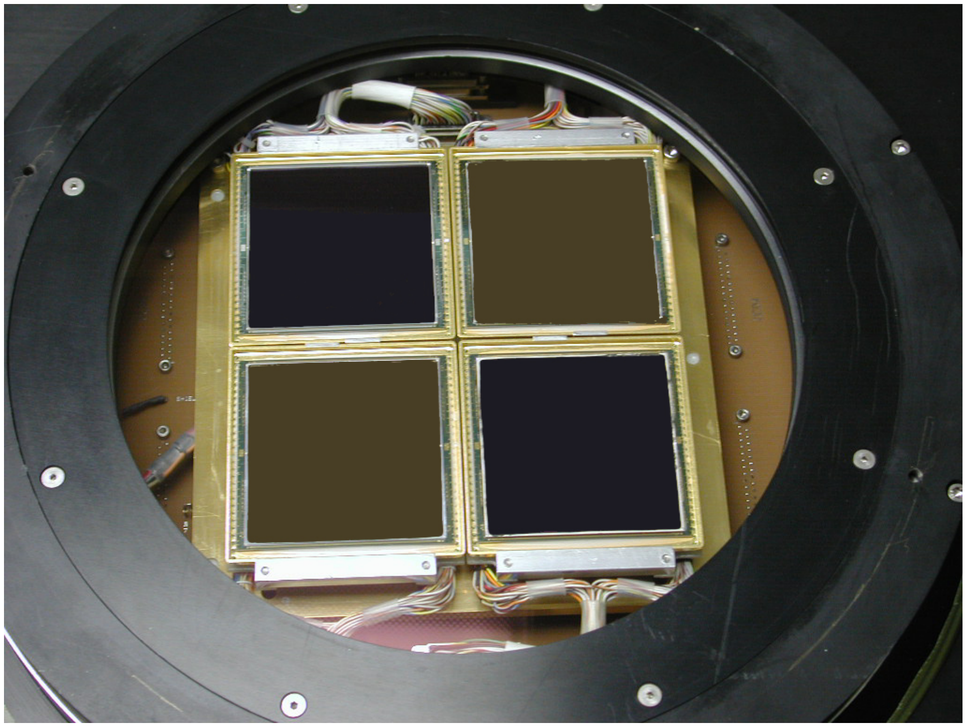

Figure 9. The 90prime focal plane array.

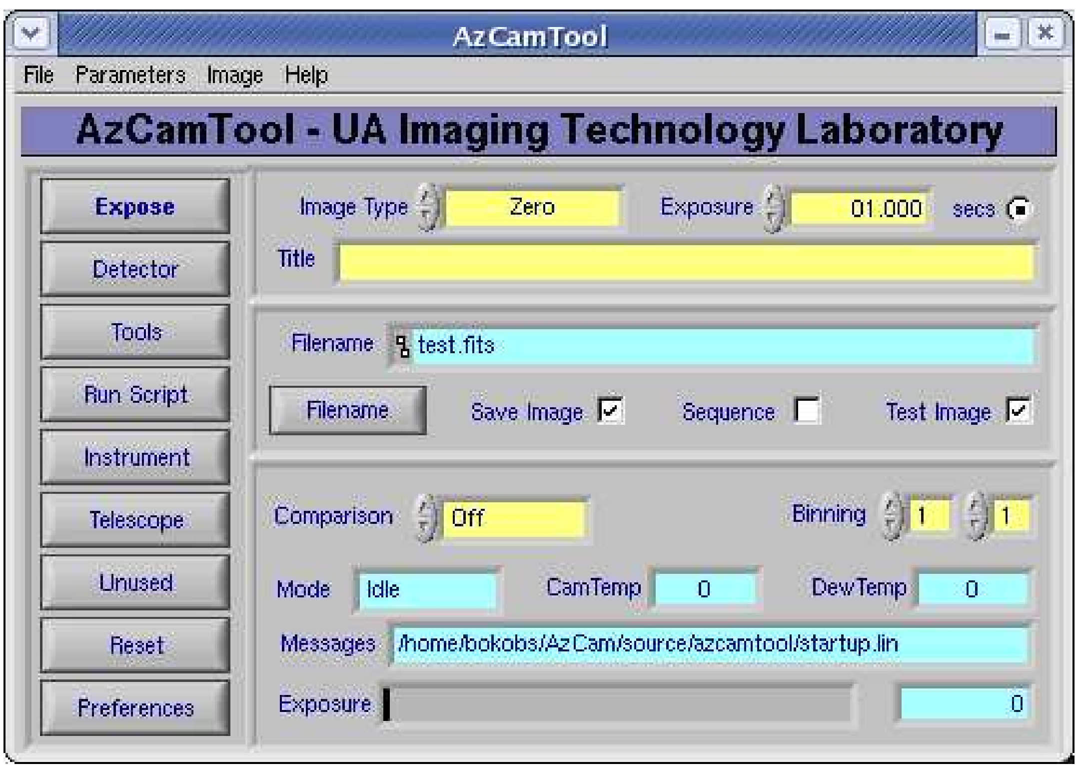

Figure 10. The main GUI for the AzCamTool software.

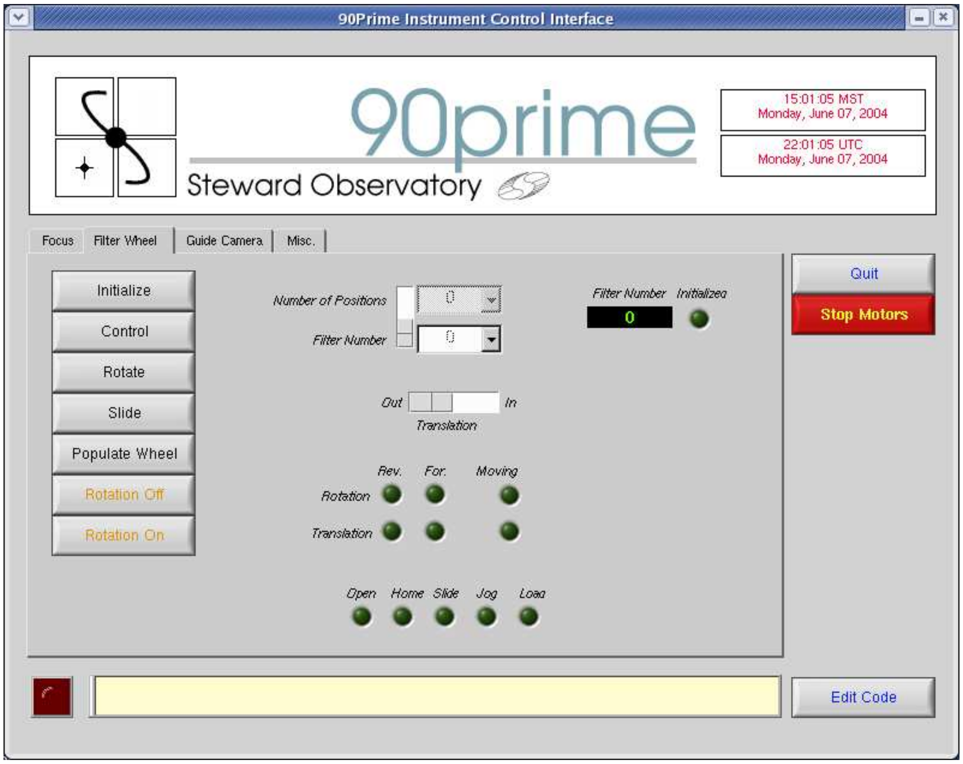

Figure 11. The main 90prime instrument control GUI.

filter wheel are mounted on a linear stage that allows focusing of the guide camera independent of the science camera.

The guide camera is controlled with an SDSU Generation I controller through a PCI controller to a Windows 2000 PC. The acquisition code is generalized through the use of network command/control interfacing. A complete user GUI for guiding written in Tcl/Tk and compiled C is provided. The camera is cooled with an alcohol water mixture.

The pick-off mirror and therefore the guider field is fixed relative to the science camera. The limiting magnitude of the camera is V = 19.0 for a 10 s integration under poor seeing conditions. However, good guiding requires stars brighter than V = 16.0. The combination of the camera sensitivity and its field-of-view usually provides several guide stars per field. It is occasionally necessary to dither the telescope slightly ($< 4'$) to obtain a bright enough guide star.

9. MOUNTING THE INSTRUMENT

We have paid special attention to ease of mounting the instrument. It is currently possible for two mountain staff personnel to remove the previous instrument, the f/9 or f/45 top end, and to mount the 90prime instrument in less than four hours. The mounting procedure is as follows: 1. The optics and cabling are inspected. 2. The instrument is lifted to the top of the zenith-pointing telescope with an overhead crane. 3. The instrument is bolted to the telescope. 4. The telescope is moved to a southern maintenance position approximately 10 degrees above the horizon. 5. A steel plate which weighs the same as the dewar is removed. 6. The dewar is installed and cabled, and the telescope is balanced. 7. The main baffle, shown in Figure 2 below the 90prime optics can, is installed. 8. The telescope is moved to a north maintenance position. 9. The communications cables and guide camera cables are installed and checked. 10. The computers are turned on and the science camera, guide camera, and communications to the top box checked. 11. The three focus actuators are set to their nominal relative positions, thus ensuring that the focal plane is aligned and flat.

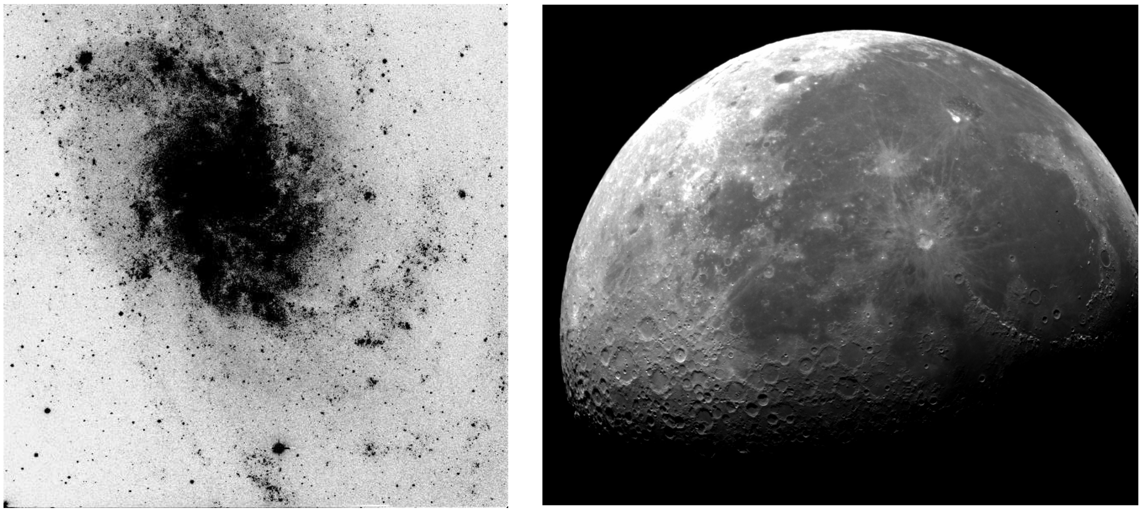

Figure 12. A B-band image of M33 and a U-Band image of the moon obtained with the 90prime instrument. The figures show targets which use only one of the four CCD chips in the mosaic. (Courtesy K. Gordon, Steward Observatory)

At this point the instrument is ready for science observations.

10. CURRENT USE

Shared risk observing with the 90prime instrument began in November 2003. Observers from Steward Observatory, the University of Arizona Planetary Sciences Department, Arizona State University, and Northern Arizona University have been awarded time. University of Arizona Observatories encompasses astronomers from all three Arizona Universities with more than 150 potential observers (including faculty, postdocs, and graduate students), and an equal number of collaborators from other institutions.

Figure 12 shows a B-band image of M33 and a U-Band image of the moon obtained with the instrument. Both images cover only one of the four CCDs, or 1/4 of the available area. The M33 image was used in Hinz et al. (2004)[2] to compare with Spitzer far infrared images. The instrument was scheduled for 49 nights between January and July 2004, and we expect more substantial use as the instrument commissioning continues.

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