Initial Results from VIRUS Production Spectrographs

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ABSTRACT

The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) uses a novel technique of replicated spectrographs (VIRUS) to measure dark energy at intermediate redshifts ($2 < z < 4$). VIRUS contains over 30,000 fibers and over 160 independent and identical channels. Here we report on the construction and characterization of the initial batch of VIRUS spectrograph cameras. Assembly of the first batch of 16 is in progress. A brief overview of the assembly is presented, and where available performance is compared to specification.

Keywords: HETDEX, VIRUS, replication, spectrograph, fiber, multi-object spectroscopy

1. INTRODUCTION

VIRUS was originally conceived a decade ago as a new way to build a large instrument.[1–3] VIRUS is a replicated instrument, taking advantage of cost savings by working in large quantity and at smaller beam (and therefore optic) size. Since then, a VIRUS prototype unit was built (VIRUS-P, recently renamed the Mitchell Spectrograph), and become the most subscribed instrument used at the McDonald Observatory 2.7m.[4–6] The baseline VIRUS unit is composed of two identical channels contained in a single cryostat. The camera is a simple Schimidt camera. The exploded engineering diagram is seen in Figure 1. The camera, which is the main component discussed here, is seen in Figure 2. The current commissioning plan for VIRUS calls for 82 pairs, or 164 identical channels. Each pair is fed by a fiber cable which contains 446 fibers split into two identical entrance slits at the front of the collimator.

The building of a replicated instrument requires a different approach from more traditional astronomical instrumentation. By replicating a smaller scale instrument many times we remove much of the uncertainty

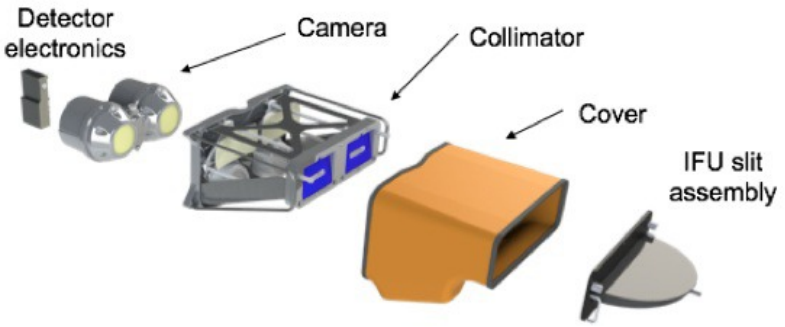

Figure 1. The components of the VIRUS spectrograph pairs. The pairs will be mounted in two cabinets mounted on either side of the Hobby-Eberly Telescope called the VIRUS support structure (VSS). The spectrographs require forced air to cool the detector electronics as well as a cryogenic system to cool the detectors within the cameras.

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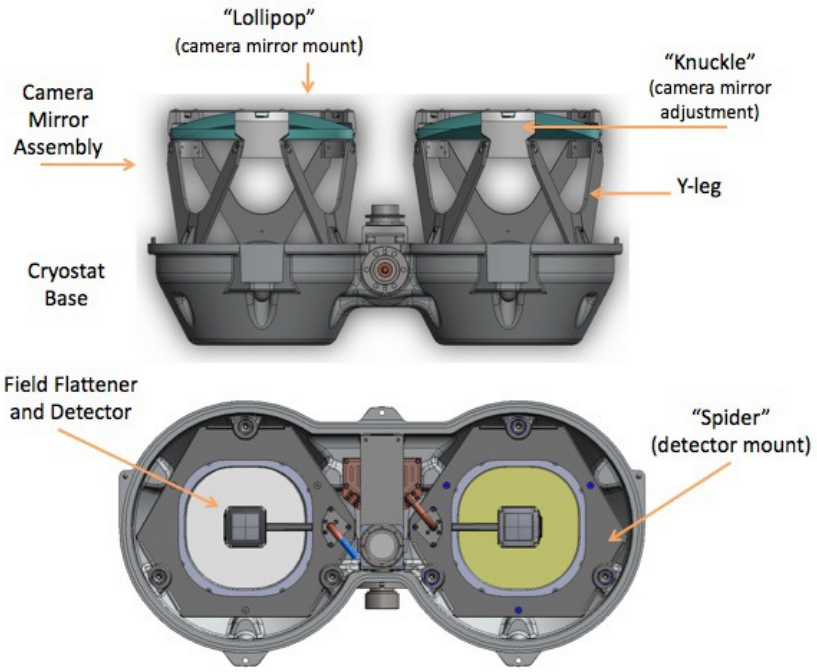

Figure 2. An edge on and face down view of a VIRUS camera pair. In both, the top section of the cryostat has been removed. The bottom of the cryostat base has a corrector plate. This aspheric vacuum window is where the beam enters from the collimator.

inherent in single build instruments. We acquire the ability to detect and correct mistakes during the prototyping stage, and can streamline assembly steps by reducing the number of parts and generalizing screw size and length. Repeated assembly and disassembly of test parts can reveal weak points in design or manufacturing. Replication also requires assembly which consistantly goes together within specification. Keeping this in mind, several compensation points have been built into the system to prevent the common instrumental approach of shimming until alignment is reached. Alignment via shimming would be very time intensive if used for all 164 channels.

2. ASSEMBLY

The mechanical design of VIRUS was driven by the goal of ease and repeatability of assembly.[7] It was also intended that at least some of the sub-assemblies could go together with limited expertise and student effort. We are currently in the process of training several students and technicians in assembling individual portions that require care but not necessarily accuracy. Parts were also designed to be assembled where variation between assembler would not unduly impact the final product. Figure 3 shows the sub-assemblies which make up the camera. The techniques used for each sub-assembly are described below. Relevant tolerances are also included to guide the reader in understanding which processes may be more difficult or require more accuracy.

2.1 Mechanical Parts and Preparation

The production parts are being built by several groups, including collaborators at Oxford University, Texas A&M, as well as commercial vendors. This has led to particular challenges in coordination of arrival of parts and integration. We've chosen to receive and assemble mechanical parts earlier to reduce issues with integration as well as schedule. By having the majority of the mechanical parts on hand we are able to focus on mounting and integrating the detectors into cameras as they are delivered.

All mechanical parts are cleaned first with an industrial degreaser (Brulin), then with isopropyl alcohol (IPA) - both of these are done with 5-15 minutes in a heated ultrasonic bath. Larger parts which intersect the light path are also painted with Alion MH-2200 black paint, designed specifically for absorbing optical wavelengths

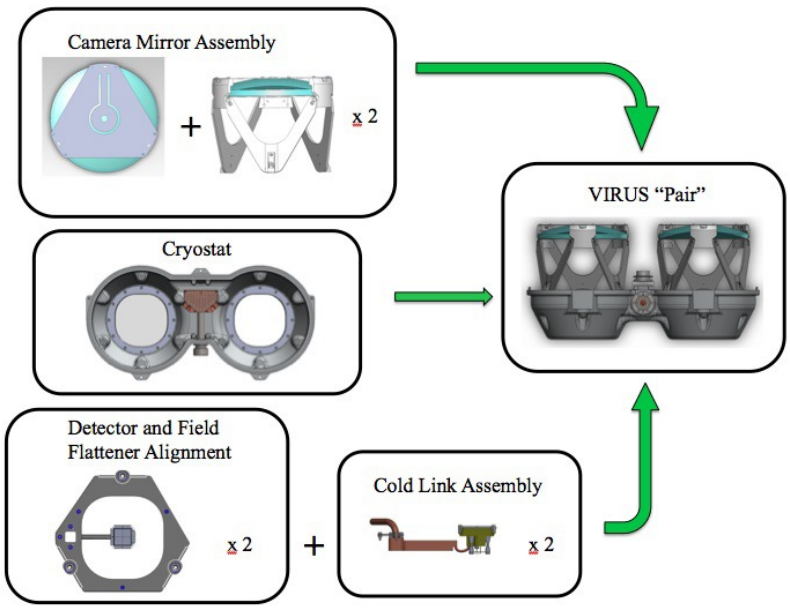

Figure 3. The work flow of the VIRUS camera assembly. Each of the sub-assemblies can be put together in a production line approach and then stored for later assembly into a pair. The details of the sub assemblies follows in the sections below.

to reduce scatter. They are then baked out in a vacuum oven (150° C for 4 hours).The cryostat (manufactured by MKS) is also painted with MH-2200 and baked out as above.

2.2 Cryostats

The camera cryostats are cast aluminum infused with Loctite Resinol RTC. We have found that these parts perform to specification contingent on both the cryostats and the Viton o-rings being baked out. In particular, a factor of roughly 2 in performance is gained when the o-rings are baked out. This is perhaps unsurprising, especially considering that there is a fairly large o-ring seal length compared to the volume of the vessel. We find that when the o-rings have been baked out, we are limited at room temperature by the Viton leak rate, which is the goal. Calculations for the rate are shown below. All o-rings are baked out at 150° C for 4 hours.[8]

$$R_{leak} = \frac{R_{Viton}}{V_{cryo}} * L_{Viton} = 6.46x10^{-8} \frac{torr}{sec}$$

$$V_{cryo} = V_{base} + V_{cover} = 30.971 liters$$

$$L_{Viton} = L_{cryoseal} + L_{bulkhead} + 3L_{KF25} = 2034.42mm$$

Once the cameras have been painted and baked out, the corrector plates are installed. These are vacuum windows of fused silica with a slight asphere. The light from the collimator passes through the grating and then enters the camera through the corrector plates. The plates sit sandwiched between two o-rings, and are centered by six teflon tubing rings that act as flexures. It is crucial to correctly orient the asphere, which can be done by inspecting the optic at grazing incidence. The aspheric side faces the air while the flat side is internal to the vacuum.

Finally, the female bayonet is installed to the base of the cryostat. This part is the mating part to the VIRUS cryogenic system, the closed liquid nitrogen system used to cool all the detectors in the camera pairs. At this stage the cryostat is closed using a temporary flex cable plug, and the system is pumped down to check for leaks and adequate vacuum pressure.

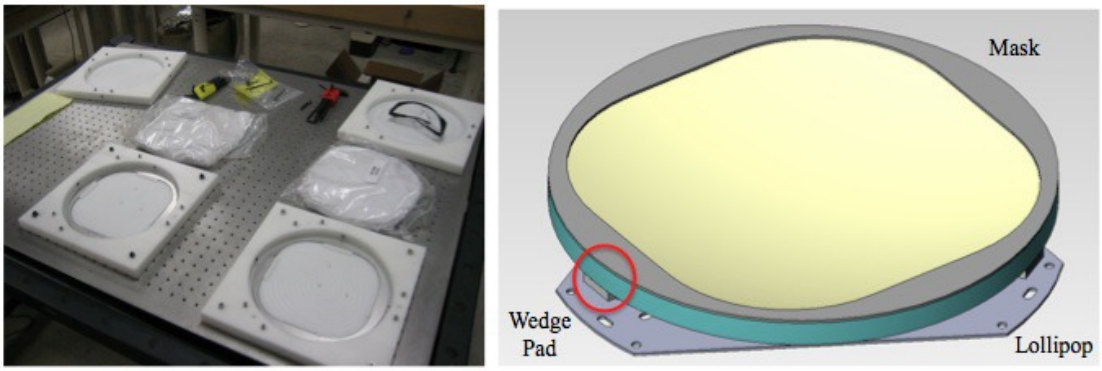

Figure 4. Left: The camera mirror jig is shown. Currently four jigs are available for use. The two at the bottom of the picture have camera masks installed. Right: The solid model of the camera mirror shows the wedge pad (circled in red), lollipop, and mask.

2.3 Camera Mirror Assembly

The camera mirror assembly (CMA) is the entire upper part of the camera, and consists of the camera mirror (and its associated mounts), the "knuckles" (the camera mirror adjusters), and the Y-legs (kinematic mounts to the spider).

The CMA is put together in two steps. The first uses Dow Corning 6-1104 CV sealant to adhere several features to the camera mirror. The camera mirror is spherical and used to focus and position the spectra onto the detector. A mask is attached to the mirror face and the "lollipop" (the centration and mounting surface) is adhered to the back. Each of these three parts (mask, mirror, and lollipop) is held in the correct location using the delrin locating jig seen in Figure 4. The mirror is held on four sides, two sides with spring plungers and two sides with soft-tipped set screws. Alignment is achieved within specifications ($\pm$ 200 microns)) by using a six-axis FARO arm to center the mirror, then placing the 6-1104 on the back of the mask and the back of the lollipop respectively. It is crucial to check the orientation of the lollipop, as the hole for access to the adjuster screws is slightly offset from the center. The setup is left to cure for at least 24 hours, although up to 72 hours is preferable to ensure sufficient cure before handling. The rate of cure is approximately .25 inches in 7 days, and this should be kept in mind when creating the bond line. The finished product is removed from the fixture to install the three wedge pads equally spaced around the back edge of the mirror. These are also attached with 6-1104. These wedges are used to distribute stress from the set screws used to adjust the camera mirror position through the knuckle.

Next, the setup is moved to the clean room for mechanical assembly. All parts have been cleaned as described in Section 2.1. Both the Y-legs and the knuckles are painted with MH-2200, as is the mirror mask. The assembly is put together from the mirror downwards. The knuckles are populated with the set screws (for adjusting the mirror) and the spring plunger (which provides resistance to the adjusters). Then the knuckles are mounted to the lollipop. Finally, the Y-legs are mounted to the knuckles. The Y-legs have their kinematic bracket which interfaces with the spider installed before assembly. All screws used on cleaned parts are installed with a small dab of Dupont Krytox LVP. Many of the parts described above are Invar, and the cleaned tapped holes are found to seize quite easily.

The CMA mounts off of the three bushings which have been epoxied into the spider during the detector alignment discussed in Section 2.4.

2.4 Detector and Field Flattener

The spider is the crux of the camera alignment, shown in Figure 5. The detector is mounted in the spider, and then aligned. Once aligned the relationship is locked by epoxying bushings into the large spider flexures. These then mount directly into the cryostat. The key is for the cryostat mount points to be precision machined, to limit the error stack up that needs to be adjusted for with the camera mirror (the camera compensation point).

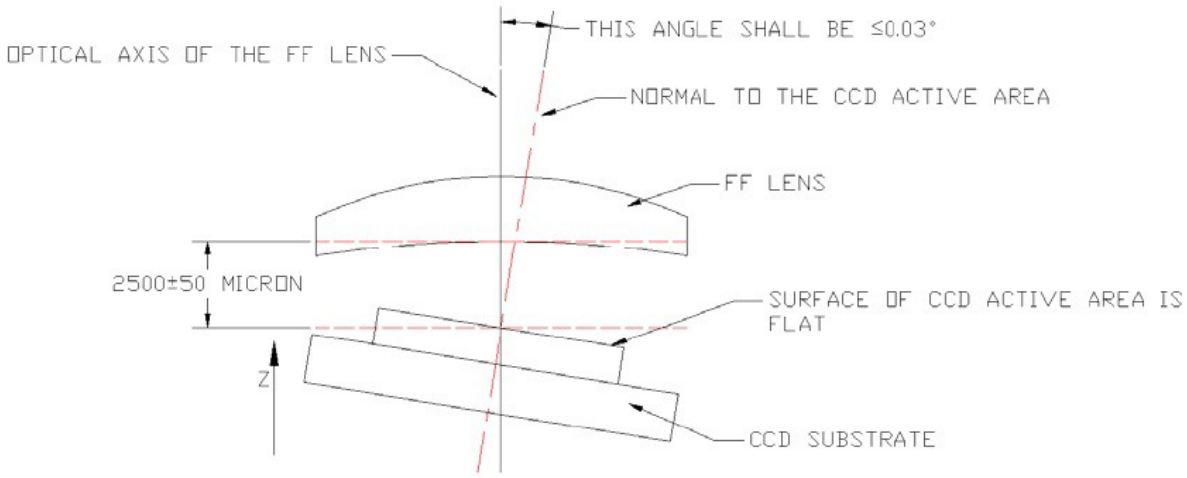

Figure 5. The alignment relationships constraining the field flattener/detector relationship.

The spiders are cleaned and painted as discussed in Section 2.1. The slot that interfaces the cold finger with the spider is checked to ensure no thermal contact is made between the mount and the cold link. The detector is mounted to the spider using three screws and Ultem standoffs to ensure thermal isolation. The spider is then mounted to an alignment plate that holds the spider while alignment occurs. The plate mounts kinematically to three sets of two stages which allow full adjustment of the detector surface with respect to the spider bushings. These bushings are held into a plate that mimics the mount within the cryostat. They have machined ridges to allow epoxy (Masterbond EP21TCHT-1) to flow and fill the mounting holes. The crucial alignments for this system are shown in Figure 5. These are achieved using the setup seen in Figure 6.

The alignment setup has two modes, one for alignment of the detector (done first) and the second for the alignment of the field flattener and installation of the detector mask. The first mode (not shown) proceeds as follows. Two cameras are used, one at the high point seen on the left, and the second mounted below it, above the ring light at the center of the photo. A HeNe laser is used (seen mounted at the top of the picture on the left) for centration. The laser is centered using a retroreflector which has been mounted in the correct location through a FARO measurement. Then tip/tilt is calibrated using a large flat. The machined test plate is installed and used to find the edges and the center. A micrometer is used mounted below the plate to set the zero height. The spider is then mounted on an alignment plate, with care taken not to have a collision between the bushings and the spider (these can be possible if the stages are in extreme positions or the outer flexures on the spider are quite collapsed. They can be shimmed outward for even spacing). A rough adjustment is made to the correct height, determined from vendor supplied metrology of the height and flatness of the detector. The tip and tilt are adjusted by maximizing the signal from the diffraction pattern imaged from the laser reflected off the detector. Then the X/Y position and rotation is set. A labview program was written to allow alignment using four dots supplied by the vendor on the detector front surface. Lines are interpolated between the two sets of points, and the center of the detector is found. Adjustment is made using the three X/Y stages until the deviation is minimized.

At this point, the Masterbond EP21TCHT-1 is mixed (an A:B epoxy mixed 100:60 parts by weight) and injected in between the spider and the bushings using foot-pedal dispensed nitrogen fed system. The aligned system cures for 24 hours.

A detector mask is glued to four Invar flexure clips that are mounted on the four corners of the detector mount. Then, the field flattener is mounted in a delrin jig seen on the right hand side of Figure 6. This holds the field flattener while the height and centration are set with respect to the detector using a modified version of the jig above, where one of the cameras moves down and is mounted beside the assembly (also seen in Figure

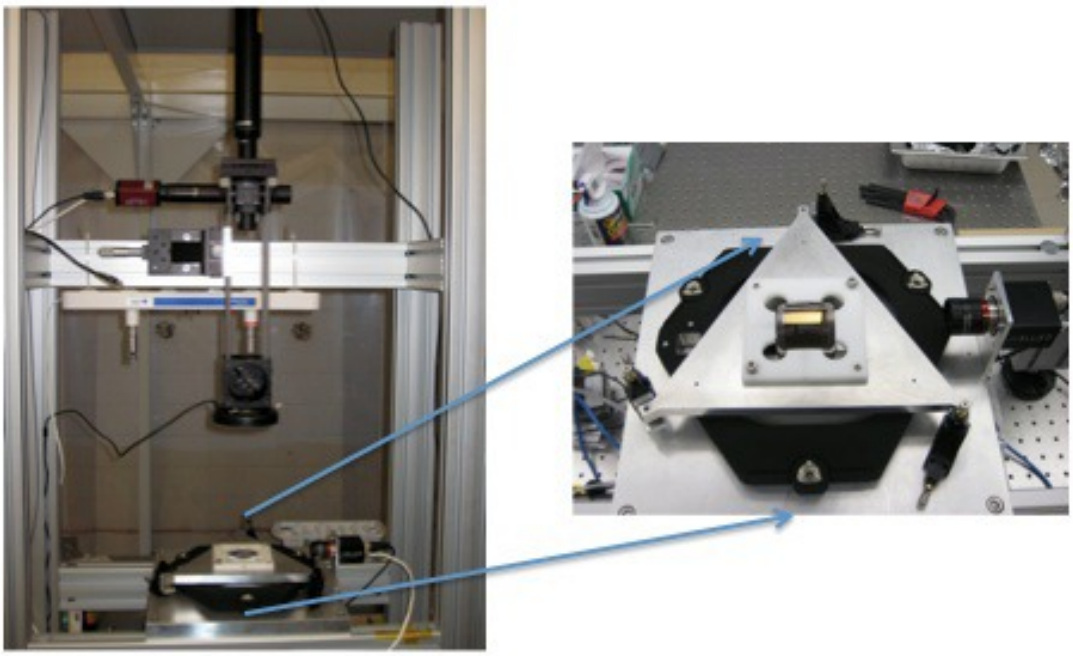

Figure 6. The detector and field flattener alignment is shown above. The demonstrated setup is for the field flattener (note the camera on the lower right hand side) which is used to measure the height of the optic. During detector alignment the camera is moved to the cage setup directly above the ring light in the center of the image.

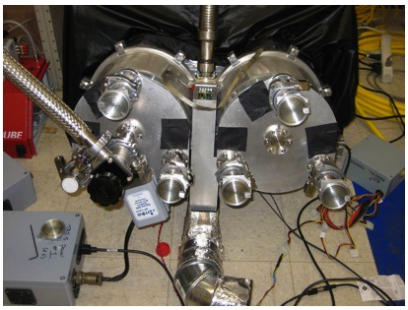

Figure 7. The adjuster back shown installed on a VIRUS camera. The adjuster back is a modified cryostat cover. The top portion has been cut away and refit with two caps which allow KF25 ports to bolt on, as well as vacuum windows to view each hex key. In this photo the windows are covered with black masks for imaging. The caps have been welded to the cryostat cover.

6). This is used to set the height of the field flattener, having been calibrated with a precision machined ball. Once the alignment is set, epoxy is placed on the second step of the Invar flexures to fasten the optic to them. This is again left to cure overnight.

The camera is aligned using an adjuster back with ferrofluidic feedthroughs which carry hex keys to the back of the camera mirror. These give three points of adjustment on each mirror as well as a locking screw to be engaged when alignment is complete. The adjuster back has a vacuum window for each point as seen in Figure 7. The alignment uses the analysis method described in during conference.[9] This method has been used to isolate individual wavefront errors and align the VIRUS cameras throughout our current testing phase.

2.5 Cold Link and Flex Cable

The cold link consists several copper parts connected by flexible copper cabling and isolated from the detector mounting system by several Ultem parts. The of the female bayonet seals the cryostat and mates with the VIRUS cryogenic system to cool the system. The bayonet connects directly to a copper getter filled with activated carbon (NORIT R1 Extra). Various sizes and shapes were tried for best fit and fill, as well as low dust content in the getter. From the getter, a large diameter (Druseidt PN 02863 with outer diameter = 7.5mm, wire diameter = 0.10mm) twisted copper braid connects to the cold finger. The cold finger is thermally isolated and mounted within the spider by an Ultem hub. From the cold finger a thinner copper braid connects to the cold block (Leoni 3.1mm OD twist with braided cover). The thick copper braid is clamped at both ends, while the thin copper cable is epoxied into place using a silver epoxy (a two part semiflexible epoxy, AIT EG8020). The thin braid is wetted on both ends, as are the receiving copper parts. The cold finger has a machined slot that is opened with needle nose pliers and clamped around the braid once epoxy is applied.

We have installed resistors in the back of the cold blocks (Caddock MK132-10.0-1%), which interface with the back of the Invar detector mounting block, that allow us to heat the detectors and control both sides to our target temperature (between $-110° > T > -115°$ C) to minimize dark current.

The temperature of the system is measured at several points using Heraeus C220-220 thin film RTDs (100 Ω). An RTD is placed on each cold block and wired in with the two resistors through a small daughter board, which then mates with the flex cable. An RTD is also placed on the getter and attached to the flex cable via a cable with a 2-pin header attached.

3. COMPONENT STATUS AND PERFORMANCE

We have begun production of the VIRUS cameras at McDonald, focusing initially on the 3 fiducial cameras to confirm compliance with specifications and complete development of the assembly line for each sub-assembly. We report here briefly on the parts received and their status with respect to initial specifications and requirements.

4. OPTICS

The camera mirrors are being manufactured and shaped by Corning Tropel. We have received 100 out of 160, with 40 of those coated by Cascade Optical Coatings. The aspheres (160 corrector plates and 160 field flatteners) have been received from Asphericon. The detectors are discussed below.

5. DETECTOR DATA

We have received the first 16 production detectors from ITL (M. Lesser). Here we present summary data of these parts. The parts generally meet specifications as expected. Although this data is provided by the vendor, we have tested pre-production devices and found the results to be similar. These devices will be tested again once they have been mounted into cameras.

The specifications were laid out in the Detector System Specification document (January 2010) which was initially provided for vendors, and has been modified over time as initial pre-production parts were received and studied. Figure 8 is a mirror of Table 1 from this document, listing the summary requirements for each VIRUS CCD. ITL has measured all parts at $-110°$ C, and all values reported here are from their test system. An ARC controller was used for these measurements, but not a VIRUS specific version. They are currently rewiring their dewar so all future production parts will be measured with the VIRUS specific control system.

Figure 9 shows the quantum efficiency of the first production batch of 16 detectors There is a slight dip in the middle of the wavelength range whose source is not currently known. The black dotted line shows the average of the ensemble.

The read noise is measured in each of the four possible read out amplifiers on each detector with the results seen in Figure 10. Two amplifiers are used at any given time. The flex cables which connect the detectors to the controllers are configured for a default pair of amplifiers. However, if a given amplifier is found to be below specification the alternate pair can be selected with a small modification to the flex cable. We have received one detector that requires alternate amplifier configuration out of the first 16.

Item	Parameter	Value
1	Number of Pixels	2064 x 2064
2	Pixel Size	15 µm x 15 µm
3	Fill Factor	100%
4	Image Area	30.72 mm x 30.72 mm
5	Device Type	Thinned backside illuminated
6	Quantum Efficiency	≥ 50% (wavelength dependent between 350 nm and 650 nm)
7	Anti-reflection Coating	Yes
8	Full Well Capacity	≥ 65,536 electrons
9	Dark Count	< 1 electron per pixel within a 600 second integration time
10	Charge Transfer Efficiency	> 0.99999
11	Readout Noise	≤ 4.2 electrons for any set of CCD and readout electronics
12	Flatness	Active area surface shall be flat to within ±10 µm with respect to the best fit plane that passes through this surface
13	Operating Temperature	Between -110°C and -90°C

Figure 8. A summary of the detector requirements. All requirements are met or exceeded.

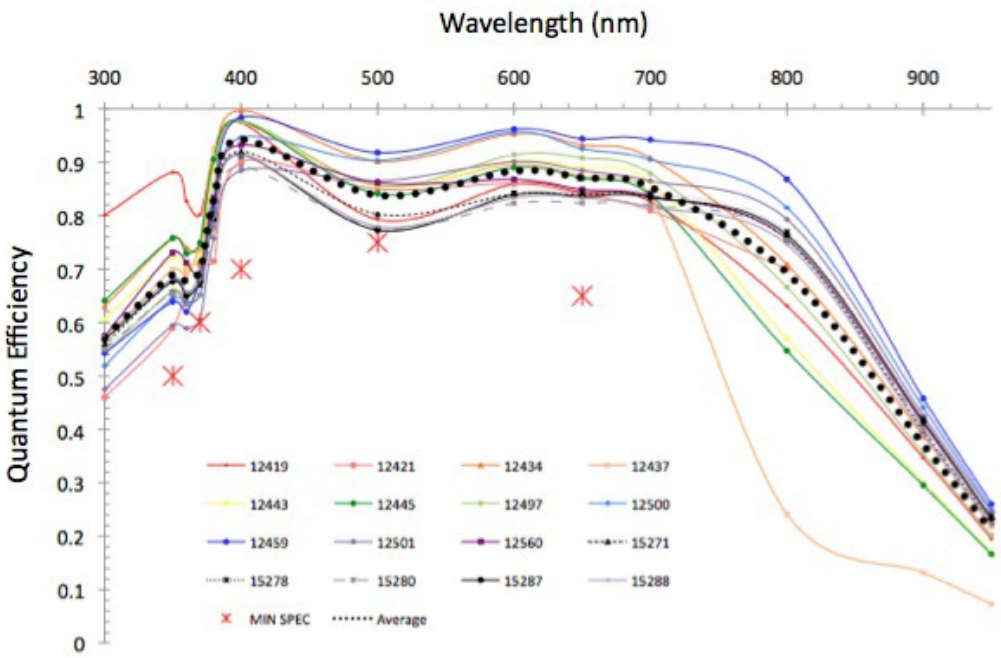

Figure 9. The quantum efficiency of all 16 CCDs from the first production batch of detectors, delivered between February and April of 2012. The minimum specification values are shown with large red stars.

Figure 10. Here we show the read noise for the first production batch of 16 devices. Each device has four amplifiers, for which the read noise has been measured separately. The value for each amplifier is shown in the histogram on the left side (64 total). On the right the best two amplifiers have been selected and plotted. The default is read the upper left and lower right amplifier, but if there is significant deviance of a high read noise amplifier, an alternative amp will be employed. All delivered devices fall below the requirement of less than 4.2 electrons, although this requirement is held over any combination of detector and controller combinations which has not yet been measured.

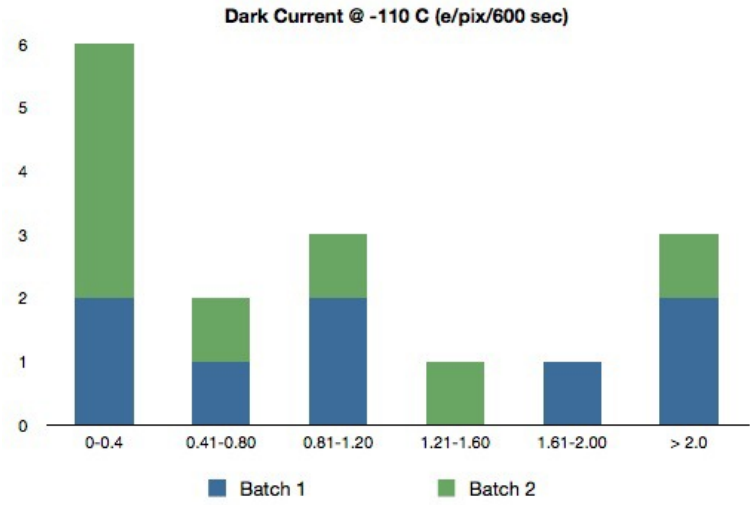

Figure 11. The distribution of dark current values is shown. The target is 1 electron per pixel per 600 seconds.

Item	Parameter	Value
1	Overscan	32 columns
2	Integration Period	1.0 to 3600 seconds in 0.1 second increments
3	Binning (Column x Row)	User selectable 1 x 1 and 2 x 1 (with 1 x 2 and 2 x 2 as a goal)
4	Number of CCDs	Each controller may service up to 2 CCDs
5	Controller Crosstalk	$< 10^{-5}$ of the signal
6	Dynamic Range	16 bits
7	Linearity	$\leq \pm 1\%$
8	Readout Time	≤ 20 seconds for 2 x 1 binning

Figure 12. A summary of the controller requirements. All controllers provided by ARC meet or exceed specifications.

The controller requirements are shown in Figure 12. One of the challenges for the large multiplexed system of VIRUS is to restrict crosstalk as seen in item 5, to an extremly low level of the signal. This test has been conducted and the specification met for CCDs within a single cryostat. We are currently preparing a larger test with two cooled cryostats (4 detectors) to confirm compliance with the multiplexed system.

6. DELIVERY SCHEDULE

Production deliveries have begun for the full complement of VIRUS camera parts. We expect to have the majority of parts in hand by Fall 2012. We have received full delivery of the cryogenic parts that interface with the camera, and selected a vendor for the external framework to store and deliver the nitrogen.

Our initial delivery is for three fiducial spectrographs with delivery expected by September 1st, 2012. These spectrographs will be distributed between McDonald Observatory (Camera), Texas A&M (Collimator), and AIP (IFU). Each of these groups is responsible for assembly and alignment of one component of the spectrograph, and the fiducial spectrographs will be used to ensure interchangeability and co-alignment throughout the completed systems.

7. INSTALLATION AND COMMISSIONING

VIRUS will be installed on the Hobby-Eberly Telescope (HET) at the conclusion of the Wide Field Upgrade (WFU) which increases the field of view from a diameter of 4 arcminutes to 22 arcminutes.[10] The reflectance of the new optics will also increase the overall throughput of the system. Installation of VIRUS requires several additions to the structure surrounding HET, including the VSS (VIRUS support structure), the cryogenic system to cool the cameras, and the enclosures that will protect the optics and cabling from incident. These will be installed alongside the WFU, which will allow initial fit checking and cabling runs to occur before completion of the WFU. The spectrographs will be staged at HET and stored in a climate controlled environment until installation begins. Installation and commissioning will be paced by the number of fiber bundles on hand. The current schedule predicts 60 fiber bundles in hand, which is an adequate number for commissioning operations.

Production of the VIRUS cameras is currently in full swing at McDonald Observatory labs in Austin. Our goal is to complete the first 8 cameras (using all batch 1 detectors) and fully test them by the end of the summer. We are also preparing the mechanical parts for the next detector delivery, with the intention to stay ahead of the detectors. Each camera after the first batch is expected to take roughly a week to assemble, although much of that is curing time for the detector and field flattener and will be filled with prep work for the next batch. This schedule, matching that of the detector deliveries, means we expect to have 60 cameras ready when the WFU is completed (Summer 2013) and VIRUS commissioning can begin at the Hobby-Eberly Telescope. The final 20 will be installed by the end of Spring 2014.

The first 8 cameras are being used for crosstalk measurements with two cooled cameras, as well as testing the robustness of the multiplexed detector controller system. This testing will go through the summer, and we will use the mixed elements to demonstrate the interchangeable nature of the cameras, controllers, and collimators. This will provide a new and exciting piece of knowledge about repeatability and control of both our process

and our parts. Since most instruments are only ever built once such information hasn't been tracked. We look forward to demonstrating the robustness of the system as we reach our goal of 82 cameras.

8. ACKNOWLEDGEMENTS

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