TELESCOPE CANADA-FRANCE-HAWAII TELESCOPE

CFH

INFORMATION BULLETIN D'INFORMATION

BULLETIN NO. 40 EDITORS: Pierre Martin - Christian Veillet 1999 SECOND SEMESTER

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M81

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A Word from the Editors ...

Here it is! This issue of the CFHT Information Bulletin was originally planned to appear at the beginning of the year. However, due to severe workload constraints on the CFHT science staff, the Bulletin could not be published on time. We apologize for this long delay and we hope that you will enjoy the content of the actual issue.

Following some discussions at CFHT and with several CFHT users, it has been decided that a printed version of the Bulletin will be re-introduced in parallel with the on-line version available on the CFHT Web site. This version will be distributed to astronomical institutions around the World but NOT to the individual CFHT users. We hope that this policy will increase the visibility of CFHT worldwide and catch the eye of the astronomical community on the quality of the science resulting from observations at our facility. Individuals willing to obtain a printed copy of the Bulletin for their personal use will be able to do so by downloading the issue, available under different formats, from our Web site.

Quite a lot has happened at CFHT since the last publication of the Information Bulletin! As described in this issue, exciting science results have been obtained, new projects are still being developed, many people have left while others have joined our staff, and,... a new Executive Director has taken office! We would like to take this occasion to acknowledge the previous editor of the Bulletin, Tim Abbott, who left last November and who did a terrific job with the Bulletin for several years! Thanks Tim and we'll try as hard as we can to fill your shoes...

Happy Reading!

Pierre Martin & Christian Veillet - Editors

CFH12K on the sky !

CFH12K: The new CFHT wide field CCD mosaic camera[1]

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Abstract

CFH12K, the new CFHT wide field CCD camera, a 12,288 by 8,192 pixel mosaic covering 42 by 28 square arcminutes (1/3 of a square degree) with 0.2 arcsecond per pixel, saw first light on the sky at prime focus early January 1999. This instrument, a collaboration between University of Hawaii and CFHT, benefits from a number of major technological improvements. These include twelve 2k x 4k pixel back-side illuminated CCDs providing significant increases in quantum efficiency, in particular in the B band. In addition to improved CCDs, a new generation of data acquisition system has been developed. It is optimized for mosaics and reduces the readout time and data delivery to less than a minute. To facilitate observations, a new modular software user interface has been implemented. This system allows the observer to interact with the camera and the telescope through either a graphical or a command line based interface. Significant features include the support of scripting, a set of tools to prepare and assist observations in order to optimize the use of telescope time. The CFH12K is scheduled for a very high fraction of the telescope time available. The instrument is also physically located in a relatively remote location in the prime focus cage atop the telescope. To facilitate efficient handling by the CFHT technical staff and to optimize on sky reliability, steps have been taken to provide remote monitoring and control of the entire system including the prime focus environment. In support of overall system performance, the 20 year old prime focus was revisited to improve sensitivity and baffling. This article includes the following sections: camera description, data acquisition system, prime focus upgrade, how to observe with the CFH12K, and finally the performance of the camera.

The Camera

The CFH12K camera was primarily designed and built by Gerry Luppino (Principal Investigator of the project) from the Institute for Astronomy, University of Hawaii, with substantial assistance of CFHT staff. Such collaboration was not new since both parties have been working on several CCD mosaic projects for CFHT over the past years (see Luppino et al. 1998 for a review of CCD mosaics built around the world in the last decade). Barry Starr from CFHT (Project Manager/ Project Engineer), handled the design of auxiliary control electronics unit (ACE) which controls the filter wheel, the shutter, the temperature regulation and various remote sensors.

a) CCDs and Focal Plane

The CCDs used in the CFH12K focal plane originate from the CCD consortium led by G. Luppino, grouping several facilities (ESO, UH, Keck, CFHT, Subaru, AAO) to fund the development of devices by the MIT/Lincoln Laboratory (MIT/LL) (Burke et al. 1998). CCID20 is a thinned 4096x2048 15 micron square pixel CCD that can be organized in a “2 x N” mosaic since is abuttable along 3 sides (Figure 1). There are two types of CCDID20 devices: those made out of high resistivity bulk silicon (HiRo) and those made out of the standard resistivity epitaxial silicon (Epi), and the CFH12K contains both types. The HiRo devices have a higher quantum efficiency in the red part of the spectrum (Figure 2) and a bit less fringing in the near-infrared than epitaxial devices.

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[1] *Front cover:* Messier 81 with the CFH12K. This image, made of three images taken in the B, V and R filters (four 5 minutes dithered exposures for each filter), only shows half of the total field covered by the CFH12K (28’x 21’ here versus 42’x 28’).

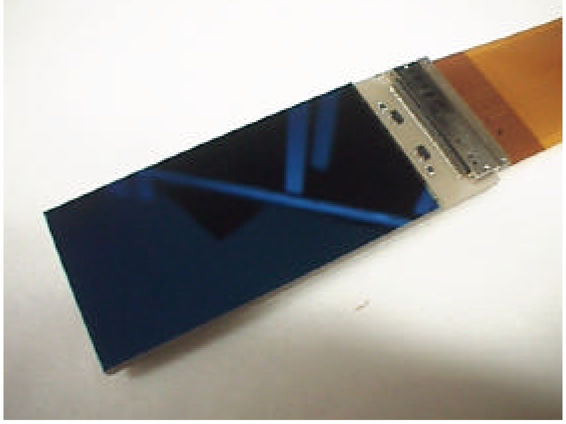

Figure 1: The CCID20 CCD from MIT Lincoln Laboratories, a 2048 x 4096 15 micron pixel thinned device (3.5 by 7 square centimeters). Twelve of this model form the CFH12K mosaic.

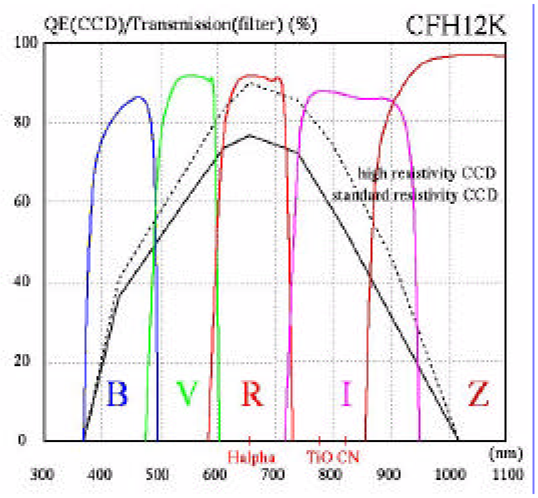

Figure 2: Quantum efficiency of high resistivity bulk silicon CCDs (dashed line) and standard resistivity epitaxial silicon CCDs (solid line). Optical transmission of broad-band filters available for CFH12K observations are also illustrated. The cut-off of the Z filter is set by the fall of the CCD quantum efficiency. Narrow band filters are mentioned on the horizontal axis.

The CFH12K houses twelve devices arranged in a 2 x 6 mosaic (Figure 3), giving a total of 12,288 by 8,192 pixels: more than 100 million pixels! The CCDs, which are flat to within 20 microns, are mounted on a custom package with three shims which were machined to within 2 microns. When mounting the twelve CCDs+package on the extremely rigid focal plane plate, the overall flatness of the mosaic was kept within 40 microns. This flatness is well within the depth of field at CFHT prime focus: 60 microns at f/4 with a 0.2”/pixel sampling. Flatness was the first priority to ensure the best image quality over the whole field. No guarantee was given to a perfect alignment between the devices along the lines and columns due to increased complexity. However, as described in the “Performance” section, the devices are well aligned thanks to a careful focal plane manual assembly.

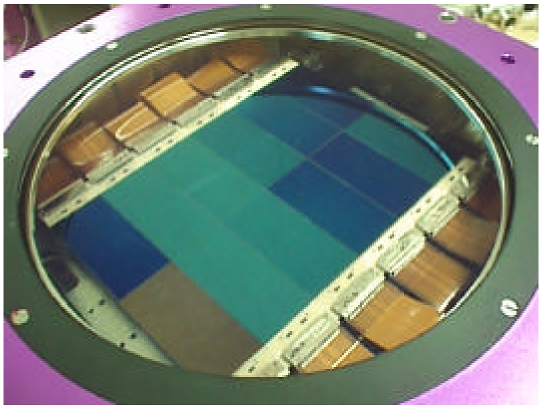

Figure 3: The CFH12K focal plane: 12,2888 x 8,192 pixels, over 100,000,000 pixels! The whole surface (21 by 14 square centimeters) is flat within 40 microns.

b) Cryostat

The focal plane is kept cold at –85 degrees Celsius using liquid nitrogen. The 8 liters nitrogen tank keeps the CCDs cold for more than 20 hours in a “down looking configuration” (Figure 4) with a typical vacuum in the cryostat better than 5. 10^{-6} Torr. The CFH12K has successfully been run for weeks while preserving its vacuum integrity. The diagram on figure 4 shows the CFH12K mounted in the prime focus cage, the ring on top of the cryostat provides multiple attachment points for the various cables connecting to the camera and the prime focus bonnette (power supplies, control cables, fiber optic cables,...).

c) Shutter

The shutter, a double blade system, designed and fabricated by G. Luppino and refined by the CFHT mechanical group is an evolution of the UH8K shutter. It is far more reliable and more compact. The opening and closing blades are made of two parts sliding on top of each other. The overall dimension is 17 by 14 inches, for a open area of 9 by 8 inches. The whole unit is removable from the CFH12K stack (filter wheel, cryostat) in a matter of seconds, improving the maintenance/check of this very critical part of the camera. A second “back-up” shutter is under development and is scheduled to be completed before the end of the year. Since the shutter is such a key part of the system and historically has proven to be one of the most unreliable, efforts have been taken to improve performance, reliability and diagnostics. A set of hall sensors monitored by the ACE allows the system to constantly check the shutter’s status and report failures if the opening/closing/recocking sequence fails at any point. In the case of failure, it is the responsibility of the master CCD controller to report the failure to the acquisition host which takes action based on standard failure scenarios (e.g. reset opening blade if shutter did not close at the end of the exposure). These efforts are taken to preserve integrity of data still on the detectors, since certain known failure modes may allow us to preserve science data. Since the opening blade travels across the focal plane at an increasing speed, the closing blade has to travel the same direction at the same speed to ensure uniform illumination. Two independent springs pull the titanium blades out/in the beam. Hence the ballistic of

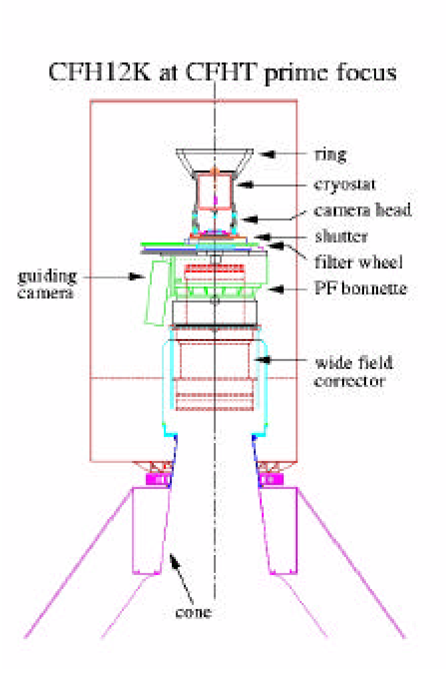

Figure 4: Configuration of the CFH12K at prime focus. The prime focus cage stands atop the telescope at 20 meters above the floor. This drawing does not show any of the electronic and cabling.

the blade is slightly nonuniform. The time delay (difference in exposure timing across the focal plane) is approximately 50 milliseconds (gravity influences this timing depending on the telescope position); for exposures of 5 seconds, the effect is only 1 part for a thousand, totally negligible for the type of photometry precision one can hope getting from such camera (standard photometry precision is approximately one percent). The opening and closing times of each exposure are measured by the ACE/CCD controller and saved in the file FITS header.

d) Filter wheel

The filter wheel, based on a Geneva mechanism, hosts four filters at once. The ACE controls the wheel motion and monitor its different states (moving, on position, ...) through hall effect sensors. It takes less than 4 seconds to move from one position to the nearest one, each position being secured by a pin ensuring a positioning repeatability of approximately 10 microns: good enough to ensure that flat-fielding patterns due to the filters (dust) will repeat themselves in the course of the nights through various filter changes. See below in the “Observing with the CFH12K” section for information on filters.

e) Auxiliary Control Electronic

This complex unit based around two FPGAs (Field Programmable Gate Array) handles the shutter control, filter wheel control, focal plane temperature regulation, and the monitoring of various sensors distributed in the CFH12K system.

The ACE not only controls actions from these different elements, its behavior is based around a state machine where any evolution from one state to another is conditioned by given values for a set of variables defining the system. In particular, this allows effective handling of unexpected events in a normal sequence to raise a flag.

The ACE receives simple orders from the CCD controllers through a reduced number of lines (high and low level), these orders being the interpretation of the commands received by the CCD controller from the data acquisition host (e.g. “FLT 1”). In return, the ACE sets input lines for the CCD controller that get interpreted to identify the current state of the system. The ACE can also be controlled manually from a well furnished front panel easily accessible in the prime focus cage. This allows control and check of the auxiliary functions without the use of the whole data acquisition system.

Data acquisition system

The CFH12K data acquisition system was a complete in-house CFHT development effort led by S. Isani (data acquisition software, global software architecture) and J.-C. Cuillandre (observing session & tools, CCD controllers & CCDs optimization, also camera characterization) with system engineering support from B. Starr. The archiving was handled by the CFHT software group.

a) CCD controllers

A new controller generation was needed to match the performance of the MIT/LL CCDs: two separate Generation II SDSU CCD controllers (Leach et al. 1998) handle the CFH12K mosaic, each reading a bank of six CCDs. The SDSUII system was still under development at the time the CFH12K project started. This resulted in some extra effort from the CFHT side to setup properly two controllers, each of them dealing with six channels running in parallel and both controllers synchronized from a similar 50 Mhz clock. DSP code development and system analysis eventually led to a readout time of 58 seconds for the whole mosaic with the two controllers synchronized within 6 nanoseconds over the whole duration of the readout (essential to avoid pickup noise from one controller to the other, a problem that forced for instance the two UH8K controllers to be read out sequentially, hence multiplying the readout time by a factor of two). A 58 seconds readout time results in a data rate of 1.8 megabytes per second per channel, both along the fiber optic cables leading to the IfA custom serial to parallel boards that connect to SBUS interface cards into a single computer, a Sparc20. The system could run faster but some CCDs require low serial transfer rates to ensure better charge transfer efficiency.

The CCD controllers are also in charge of sequencing the exposures (timing, readout) and also interpret the filter wheel and shutter commands to set orders for the ACE. In the course of an exposure, the state of the system is checked every millisecond to see if the ACE raised an error flag. In that case a message is sent down to the acquisition host which reacts based on foreseen scenarios.

b) Acquisition host

A Sparc20 hosts the program called “12kcom”, the main element for taking data with the CFH12K. It is a client running inside a wrapper called “director” providing extensive features to ease interaction between a human being and a piece of software (commands/status/feedback). “12kcom” incorporates a set of features already extensively used by DetI (used on KIR and EEV).

A great feature of “12kcom” is its ability to handle several tasks in parallel in order to reduce the overhead when taking data on the sky and hence maximizing the time spent collecting photons. Reading data from the detectors down to memory takes 58 seconds and then the write to disk still has 40 seconds to go, but the next exposure is actually already starting (shutter open). With typical exposure times of 5 to 10 minutes, the CFH12K routinely reaches an efficiency on the sky of more than 90% over the whole night! The observing session with "director" runs on a Sun Ultra2 equipped with 100 gigabytes of disk space. DLT (35 gigabytes) and DDS3 (12 gigabytes) tape drives are available to the observer to save their data.

"Director" can wrap several clients: they all run in parallel with "12kcom". One handles the connection (through an RS232 link) to a set of power supplies placed in the prime focus cage to power the ACE, for example. A remote 110 volts AC power strip can also be turned on and off to power, for instance, the SDSU switching power supplies and provides a "hard way" to reset the system. Extreme care is taken to protect the devices, however, since the DSP code is setup to always gently set on and off the CCD voltages, and an internal power control board inside each CCD controller takes care of switching off the voltages if the input voltages enter a forbidden range.

c) Archiving Data

The CFHT archiving system needed an upgrade to handle the flow of 200 megabytes files, each night of observing producing typically 20 gigabytes of data. The archiving support is now DLT tapes with a 35 gigabytes capacity. Fortunately, CFHT now has a DS3 link between its headquarters and the summit, able to handle a data rate of 5.6 megabytes/s. Images actually get to be archived as fast as they get acquired since the writing data rate for DLT tapes is 4.7 megabytes/s! A duplicate of the tapes is then sent to CADC for the official data archiving.

Prime focus upgrade

The 20 year old prime focus which had been designed for the photographic plates (total field of view available is 1 square degree), showed its limitation for high sensitivity cameras used for deep imaging observations as outlined in Cuillandre et al. (1996). Scattered lights in particular from light reflections from nearby bright stars were a real concern as well as overall scattering. The issues make the flat-fielding of the large mosaic images a real challenge (MOCAM, UH8K). The prime focus upgrade conducted by the CFHT optic and mechanical groups now makes this focus a very clean and efficient light collector for the CFH12K.

a) Reducing scattered lights

Light scattering reduction was achieved using simple techniques such as implementing a special black velvet in the entry cone and on all the metallic internal surfaces in the prime focus bonnette and the wide field corrector (see Figure 4).

b) Improving optical transmission

The central lens of the wide field corrector (made of 3 lenses) was removed and sent to the Dominion Astrophysical Observatory (Canada) to get a special anti-reflection coating applied on its surfaces, providing an improvement of 8% of the transmission over the whole optical spectrum. The total efficiency of the primary mirror and the wide field corrector is now 73%.

c) Bonnette rotation

Bonnette rotation is disabled for the CFH12K: the camera occupies so much room in the cage that only +/- 20 degrees rotation is supported (XY axis aligned with the WE/SN axis). Analysis was conducted by the TCSIV group to efficiently map the guide star area to improve pointing efficiency and be able to obtain a guide star right at the first pointing (the guide camera pick-up mirror catches a part of the beam close from the edge of field to avoid vignetting the CFH12K field, hence it is suffering from the wide field corrector non linear distortion).

Observing with the CFH12K

Piloting the CFH12K is straightforward since the instrument complexity is totally hidden to the user. But observing, even for such direct imaging camera, can be specially tricky when the goal is to be the most efficient possible on the sky. For that purpose, a versatile user's interface was developed as well as tools to prepare and assist the observations. Refer to the "CFH12K Observer User's Guide" document for further information about observing with the CFH12K.

a) User's interface

The CFH12K can be controlled either from a Graphical User Interface (GUI), a Command Line Interface (CLI) or from scripts (any shell). The central element of the CFH12K session is the director window which acts both as a CLI and a status window. The main GUI window serves as both the camera status display and the control interface. This GUI reproduces only a reduced set of information, elements such as progress bars and detector temperature are indeed only appearing in the director window.

The elementary set of commands one gets to use when observing with the CFH12K at the CLI, all of them accessible also from a GUI, are given in Table 1. These commands can be combined in a script (on top of these, commands such as "abort", "stop", "break", "stopscript" can be entered when exposures are running).

Table 1: Basic set of commands for CFH12K observations

Command	*Action*
go n	take "n" exp. ("go" for a single exp.)
snap	quicklook exp. with current parameters
flux	exp. (small raster) for sky background
etype t	set exp. type (o=object, f=flat, d=dark, b=bias)
etime n	set exp. time to "n" seconds
raster full	set raster readout mode (full, full bin2, full bin4)
filter 0 B	select filter 0 (here, the B filter)
fits observer CFHobs	set the FITS OBSERVER header for the next exposures
fits object NGC3486 B	set the FITS OBJECT header for the next exposures
fits comment skyphoto	set the FITS COMMENT header for the next exposures
offset a b	offset the telescope by a" East and b" North
pfocus Z	set the Z of the bonnette (-1.0 < Z < +6.0)

b) Observing tools

The following tools are available either from the GUI, the CLI or from scripts:

- Focus: Take automatically a sequence of several exposures at different Z values on the same frame and offsetting the telescope between each position (only one readout). The image can then be quickly analyzed with standard tools to find out the best position.
- Telescope offsets: Small telescope offsets (< 400 arcseconds, depends on the initial position of the guide star in the guiding field though).
- Dithering patterns: A set of dithering patterns are proposed from 2 to 8 positions. The patterns are set so that none exposure has a similar X and Y coordinates value to allow removing detectors artifacts during data reduction. With such patterns, the CFH12K can run for hours without any human intervention. The observer can also build his own set of scripts if he/she isn't satisfied with the ones made available.
- Taking twilight flat-fields automatically: Twilight flat-fields appear to be extremely efficient to flatten CFH12K scientific data both at large- and small-scales. Hence it is important to acquire the maximum number of such frames. With the limited time to take flat-fields at twilights, an automatic tool has been developed to set up properly the exposure time from one exposure to another to keep the flux constant on the images while the sky brightness is changing rapidly. The input from the user is the initial exposure time (defined with the use of a "check flux" exposure), the number of exposures to acquire, the day period and the current filter.

c) Filters

Characteristics of the available filters available for the CFH12K are detailed in Table 2 (where λ_c = central wavelength, λ_l,λ_u= lower and upper wavelength at 50%). Transmission curves are displayed on Figure 2. An automatic focus adjustment will be provided soon, as well as a focus adjustment between exposures based on dome temperature changes.

Table 2: Filter characteristics for CFH12K

Filter	λ_c [nm]	λ_l[nm]	λ_u [nm]	T (%)	$\Delta\lambda$ [nm]
B	431.2	380	475	85	95
V	537.4	501	595	90	94
R	658.1	590	720	85	130
I	822.3	725	930	80	205
Z	---	850	---	95	Open
Hα OFF	645.3	---	---	92	9
Hα	658.4	---	---	95	7
TiO	777.7	---	---	90	18
CN	812.0	---	---	---	180

d) File format

Two file formats are proposed to the users at the moment: the Multi-Extension FITS format (MEF) where all 12 CCD images get stacked into a single FITS file, and the SPLIT format where the 12 CCD images are saved in individual standard FITS files in a dedicated subdirectory. For both modes, an independent binned by 8, overscan and relative gain corrected image is generated to allow quick and efficient display of the whole field of view. This quicklook (automatic display) allows the observer to check in one eye blink if something is wrong in the image (guide probe vignetting, scattered lights,...).

Performance

The CFH12K was on the telescope for five dark-time periods out of the first seven months of the year 1999. This is by any measure heavy use, especially for a new instrument. Prior to the first light on the sky in January, an in depth characterization of the camera had taken place in CFHT's CCD laboratory in Waimea. The amount of information collected is enormous and shortly reported here. Since an upgrade of the focal plane will take place in August 1999 to replace two defective CCDs (early draft engineering grade arrays), it is pointless to provide precise information on the current mosaic, hence only general values valid for the whole mosaic are given. When the revised focal plane will see its first light in September 1999, a complete report will be posted on the CFH12K web page. Still, apart better cosmetics for the new CCDs, the general performance will be very similar as mentioned hereafter.

a) Mosaic organization

Figure 5 provides a complete mapping of the CCDs within the mosaic.

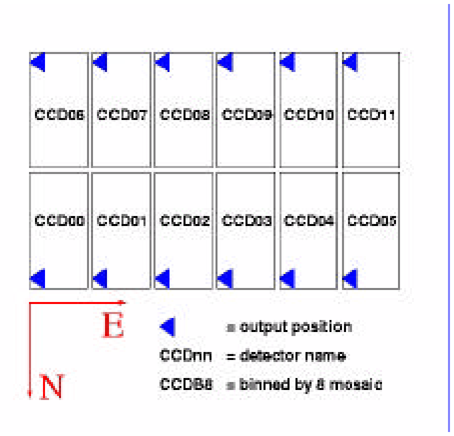

Figure 5: Geometric configuration of the mosaic and naming convention.

b) Optimization and characterization in laboratory

The CCD consortium provided a set of characteristic precise enough to assert the quality of each device (CTE, cosmetics, QE), but it was by no means supposed to deliver optimized running parameters. This optimization work had to be conducted for the CFH12K in the particular case of a direct imaging application. Priority was given to linearity over the whole range of the converters and charge transfer efficiency (CTE), then quantum efficiency, then the full well capacity, then readout noise (usually quickly dominated by the sky background photon noise, in particular with broad-band filters), and finally dark current. All CCDs were tested together within the CFH12K cryostat. A special optical bench was set up to accommodate the illumination of the very large focal plane (21 x 14 square centimeters) and special automatic softwares developed to handle multiple detectors at once in order to be the most efficient and parallelize the optimization.

- Linearity, gain and readout noise: Linearity was measured and optimized using the photon transfer curve procedure allowing also a measure of the conversion gain and the readout noise with a reasonable accuracy. The CCDs voltages were delicately tuned to get a linearity better than +/− 0.5% over the whole range of the 16 bits analog-to-digital converters, which for the gain of 1.5 electron per ADU gives a digital saturation at 100,000 electrons. The gain is set so that readout noise gets sampled on at least 2 to 3 ADUs: for most of the devices the noise is close to 4 electrons (at 150 kilopixels per second).
- Full well capacity and anti-blooming: Dithering anti-blooming was investigated in depth but was abandoned for an on-sky use due to the large generation of pocket pumping sites (see Tonry & Burke 1998 about pocket pumping). Fortunately the very high full well capacity of the CCID20 devices, typically around 400,000 electrons (Wei & Stover 1998), limits efficiently blooming from bright stars to a reduced number of pixels.
- Charge transfer efficiency: CTE was measured on all CCDs using a Fe55 source illuminating the devices through a custom beryllium window. Particular care was given to tune the serial register transfer speed to ensure at least a 0.99999 CTE, which is good enough for our direct imaging sky background limited, application with a 0.2 arcsecond/pixel sampling and a typical image quality (seeing) of 0.7 arcsecond. Parallel CTE is at least 0.999999.
- Quantum efficiency, brick wall pattern and dark current: The quantum efficiency (QE) is an intrinsic property of each device depending on the building process (thinning, coatings). However, the sensitivity in the red part of the spectrum can be increased (up to 20%!) by running the CCDs warmer than usual, say −90 C versus −120 C. Running the CCDs warmer also presents the great advantage of reducing the amplitude of the brick wall pattern (there are actually two types of BWP as shown on Figure 6), a feature from early type CCID20 devices that has been corrected in the later versions (only half of the CFH12K CCDs suffer from this effect). This pattern is corrected with proper flat-fielding but since the peak to valley amplitude can be up to 20% in the B band (less important at longer wavelengths, i.e. R band), this means a substantial change in sensitivity across the devices (physical scale is approximately 150 pixels). Reducing it as much as possible is a major concern and the CFH12K now runs at −85 C, high enough to maximize the QE and minimize the amplitude of the brick wall pattern, even to the cost of a potential dark current requiring an image processing correction. The dark current appears to be very low even at −85 C and can be neglected in broad-band filters applications. In the other case, since the dark current appears uniform over the whole devices, a simple constant subtraction takes care of removing this additive signal.
- Residual image: Residual image is a major concern for the CCID20 devices (Wei & Stover 1998) specially when observing with narrow band filters. The signal generated from the release of charges trapped in the Si-SiO2 interface is a function of time and varies from one device to another. In sky background limited observations, this extra signal gets lost within the photon noise though. Special cleaning schemes have been investigated to eliminate as many trapped electrons as possible in the short amount of time available between two exposures. Dithering anti-blooming mode (with shutter closed) was actually found to be an efficient way to reduce the residual image effect by massively bringing up holes from the substrate up to the Si-SiO2 interface where they recombine with trapped electrons.
- Crosstalk: Crosstalk between the video channels is negligible (8.10^{-5}) within a common video board (hosting 2 channels) and not detectable from one board to another.
- Cosmetics: Several CCDs from the mosaic can be qualified as “perfect” with only a fraction of a bad column. These CCDs appear also to be the ones with the best QE, low BWP and low readout noise. These are positioned at the center of the mosaic.

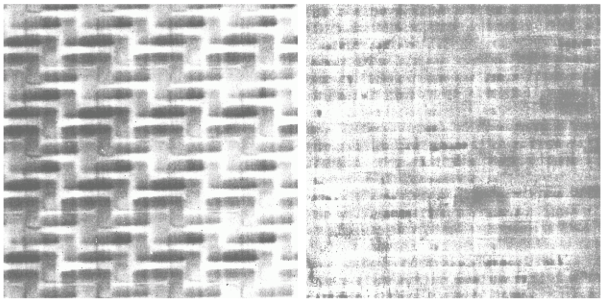

Figure 6: Illustration of the brick wall pattern: the areas shown are 2048 by 2048 pixel large and illustrate the two types of pattern encountered on different CCDs (but half of the mosaic does not exhibit any of these structures).

c) Characterization on the sky

- Mosaic alignment: The long axis of the mosaic can be precisely aligned along the East-West axis to within 0.1 degree by drifting the telescope for a few minutes to let stars crossing the whole mosaic (iterative process once at the beginning of an observing period). A mechanical pin should be installed soon to facilitate the bonnette alignment.
- Mosaic geometry: Astrometric measurements were conducted on the current mosaic, the largest tilt angle between two CCDs within the whole mosaic is 0.4 degree. The gap between the CCDs both along the X and Y axis is close to 6 arcseconds (~30 pixels or 450 microns).
- Image quality: We were blessed with a few nights of 0.5 arcsecond seeing during the first light (spatial sampling is 0.2 arcsecond per pixel) and were able to determine immediately that image quality is uniform over the whole field, with only a 0.05 arcsecond degradation from the center to the edge, most certainly the result of an optical aberration rather than a tilt of the focal plane since the same effect is present in all directions. Since then, 0.45 arcsecond seeing images have been obtained several times (R, I and Z bands)!
- Photometric performance:

Photometric zero points. The CFH12K is an extremely sensitive camera, the zero points surpassing all the previous detectors ever mounted at any CFHT foci (except for RCA4 in the B band back in the late 80s, but it was “only” a 320 by 512 pixel CCD). This is the result of the wide field corrector upgrade (coating) with the combination of higher efficiency filters (interference filters) and thinned CCDs.

The parameters for the photometric equation are:

magnitude = −2.5log[counts(e-/sec)] − a*X + b*Col + Co

with “a” the airmass term, “b” the color term (%) and “Co” the photometric zero point at zero airmass (e-/sec) (Table 3).

Table 3: Photometric zero points for CFH12K

Filter	a	b	Co
B	0.17	+5.7%	26.07
V	0.10	+0.5%	26.60
R	0.07	+4.0%	26.57
I	0.05	−0.1%	26.15

Sky brightness. Sky brightness (in magnitude per square arcsecond) was measured at zenith in photometric dark time (Table 4).

Table 4: Sky brightness measured with CFH12K

	B	V	R	I
Sky Brightness	22.5	21.6	21.2	19.8

Brick wall pattern impact. There were some concerns about photometric accuracy for objects on peaks versus valleys of the brick wall pattern. This was carefully tested by moving a set of objects across the detector and checking for color evolution (the data having been flat-fielded). No color effect could be detected at a level of a fraction of a percent (i.e. the QE curve shape in the peaks is similar to the one in the valleys). Flat-fielding corrects properly the brick wall pattern.

Short exposure time. As mentioned in the “Shutter” section, exposure times less than 5 seconds are not recommended if a contribution from the shutter ballistic in the photometric error budget of no more than one part over a thousand is required.

- Flat-fielding, brick wall pattern and fringing: With the prime focus optical upgrade, flat-fielding became much easier than for UH8K thanks to the overall reduction of scattered lights. Twilight flat-fields appear to work very well and provide easily a flattening close to the percent over the whole field. Building superflats is also much easier. Dome flat-fields work poorly due to the mismatch of the lamp spectrum and the dome paint with the night sky spectrum. CFHT will soon evaluate the use of a special screen and more appropriate lamps. Fringes appear in the frames when observing in the I and the Z bands. One needs to acquire twilight flat-fields in the given filter to flatten the scientific images from which a fringe frame can be extracted. This fringe frame needs then to be properly scaled for each exposure and then subtracted.
- Miscellaneous:

Cosmic rays. About five hits per minute per square centimeter (around 100 events per minute per CCD). Cosmic rays hits are much more punctual on thinned CCDs compared to thick CCDs and are much easier to identify.

Telescope noise. To optimize the telescope time, some operations on the telescope can be conducted while the camera is reading out: - pointing to a new field - setting a new Z for the bonnette - rotating the dome What must not be done (pickup noise would result): - activating the prime focus guide probe

d) First light

The first light took place on the 9th of January. The first field observed was the Horsehead nebulae. In the course of the following nights, a huge amount of calibration data was obtained along with scientific data and other objects for the promotion of this new CFHT instrument. The picture on the cover of this bulletin is Messier 81, observed in B, V and R. The data have been reduced with the FLIPS package. Twilight flat-fields were used to process the images (four dithered 5 mn exposures in each filter). Other images will be presented soon in the CFHT image galleries.

Conclusion

The CFHT community now has a new visible wide field camera available at prime focus. The CFH12K covers one third of a square degree with high sensitivity CCDs providing a spectral range access from the B band up to the near infrared. The 12K by 8K pixel mosaic provides excellent image quality over the whole field with a 0.2 arcsecond per pixel sampling. Images down to 0.5 arcsecond are now common beyond 600 nm. Readout time is less than a minute, resulting in very high observing efficiency (up to 90%). The observer can interact with the camera and the telescope from a graphical interface or a command line interface, scripting is also fully supported. A set of observing tools, such as automatic twilight flat-field sequencer and a variety of dithering patterns, is available from any of the user’s interfaces. Broad-band filters (B, V, R, I, Z) and narrow-band filters (Hα, Hα-OFF, TiO, CN) are available. The upgrade of the prime focus ensemble greatly improved flat-fielding efficiency by reducing the amount of scattered lights. Photometric performances are impressive: never CFHT has had such a sensitive instrument at one of its foci. Remote system control, reset and diagnostic functions serve to provide the most reliable system possible.

In only five observing runs, the CFH12K has covered tens of square degrees on the sky and stacked more than one *tera*byte of data. The CFH12K is scheduled for more than 70 nights for semester 1999II, 40% of that period, and the user’s community pressure on this instrument still keeps building.

Likely developments closely related to the camera include a dome flat-fielding facility and a dedicated data processing pipeline to support the user’s community by providing optimal calibration frames. In the near future, queue scheduling mode will be implemented for the first time at CFHT for use with this instrument.

Acknowledgments

The authors, who have worked on this project for more than 2 years, wish to greatly thank the CFHT staff for its giant effort during the Christmas and New Year’s day period to allow the CFH12K getting its first light on the sky early January 1999, and its contribution to make this instrument at CFHT prime focus this outstanding scientific tool now available to the entire CFH community. We wish to thank John Tonry from IfA for his constructive discussions, criticisms and advice provided all along the instrument integration.

Note

Visit the CFH12K web page at: http://www.cfht.hawaii.edu/Instruments/Imaging/CFH12K/ Comments and requests are welcome; you can contact the author at: jcc@cfht.hawaii.edu

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SCIENCE

Observations of the globular cluster M15 with the AOB and a Fabry-Perot

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Since 1994 we have been using the good seeing of the CFHT to probe the stellar kinematics and distribution of mass near the centers of globular clusters, particularly those with collapsed cores (Gebhardt et al. 1997). We use the Rutgers Fabry-Perot narrow etalon to take a sequence of images stepped in wavelength across a strong absorption line. Stellar photometry of these images with DAOPHOT (Stetson 1987, 1994) allows us to build up a short section of spectrum for every resolved star. Fitting a line profile to each spectrum yields the radial velocity.

In the centers of dense clusters our sample sizes have been limited by crowding rather than photons. With the ready availability of bright guide stars, this program is well-suited to the CFHT AOB. The only potential problem is that we need good photometry – about 2% – to obtain accurate velocities and some published reports suggest that this is difficult to obtain with adaptive optics systems (Roberts et al. 1997, Esslinger & Edmunds 1998). A further difficulty is the low Strehl ratio achievable at the wavelengths where our etalon works – we obtained 0.01 to 0.06 in excellent conditions – which complicates the estimation of the point-spread function (PSF). We focus in this article on our experience performing stellar photometry in images with small Strehl ratios and argue that photometry accurate to a few percent is possible.

In consultation with the CFHT staff, we chose to place our etalon in the f/40 converging beam behind the AOB focal expander. The STIS2 CCD yielded 0.031 arcsec pixels and a 63 arcsec field of view. However, the wavelength resolution of the etalon was degraded by the tilting of the converging beams away from the center of the field (i.e., the AOB optics are not telecentric) and this limited us to a region about 20 arcsec across. Because our primary targets were the centers of clusters, this limited field did not significantly compromise our scientific goals. At the center of the field, the converging beam caused a negligible degradation of the 2.0 Angstrom wavelength resolution.

The coatings of the Rutgers etalon allowed us to work at the 8542 Angstrom Ca triplet line. Choosing a line as far to the red as possible maximized the gain in angular resolution from the adaptive optics. We employed our own filter with a 30 Angstrom FWHM to isolate the correct etalon order. A dichroic in the AOB sent the I band light to the CCD and all other wavelengths to the wavefront sensor.

Our four night run in June 1998 was preceded by an engineering night. Hard work by the CFHT staff meant that we were observing by midnight of the engineering night. That was fortunate, as that night yielded our best seeing, with some of the 15 minute exposures of M15 having stars with a full width at half maximum (FWHM) of 0.1 arcsec. This night and the next were clear, while the following three had varying amounts of cirrus. Stellar FWHMs were around 0.1 arcsec on the engineering night, 0.1-0.2 arcsec on the second and fifth nights and 0.3-0.4 arcsec on the third and fourth nights. We obtained 24 15-minute exposures of M15, our primary target, and 13-14 exposures each for M13, M80, and M30. The data for M15 and a radial velocity standard observed in twilight are reduced and discussed here. For more details, see Gebhardt et al. (1999).

Figure 1 compares the average of our four best M15 frames with the U+B+V color composite Hubble Space Telescope image of Guhathakurta et al. (1996). Both images show the central 9x9 arcsec of the cluster and are displayed using a logarithmic mapping of intensity values to show both bright and faint stars. Our image has been rotated to the same orientation as that from the HST and the diagonal dark line is a bad column. The cores of the stars in the AOB image are nearly as sharp as those in the HST image. The AOB image does not goes as deep, at least in part because the 2 Angstrom bandpass meant that we collected about five times fewer photons despite using a longer exposure time and a larger telescope.

The star used for the wavefront correction of the M15 images was AC3, with V=13.5 and B-V=1.1 (Auriere & Cordoni 1981). It is 6.7 arcsec from the cluster center and out of the field of figure 1 to the right. Figure 2 shows the radial profile of this star in the M15 images, plotted with both linear-linear and log-linear axes. These profiles have all been normalized to the same arbitrary central intensity. Also shown as dashed lines are the diffraction-limited and uncorrected stellar profiles (with FWHMs of 0.05 and 0.5 arcsec, respectively). The wide range in the profile shapes reflects the 0.01 to 0.06 range in Strehl ratios for these images. However, this plot and a similar one for images of a bright radial velocity standard star suggest that the corrected stellar profiles have a sharp, nearly diffraction limited core surrounded by an envelope resembling the uncorrected stellar profile. Only about 10% of the light is in the sharp core even for the images with the highest Strehl ratio. Clearly, one challenge for obtaining accurate photometry is measuring the extended PSF profile with sufficient accuracy to determine the aperture correction between the amount of light in the inner, high signal-to-noise (S/N), portion of the profile and the total amount of light.

We determine both the aperture corrections and our photometric uncertainties by fitting line profiles to our stellar spectra. The fitted profiles are based on our knowledge of the instrumental profile. Stars with previously-measured velocities provide the information to determine a