Four-shooter: a large format charge-coupled-device camera for the Hale telescope

James E. Gunn
Princeton University
Astrophysical Sciences
Princeton, New Jersey 08544
and
Palomar Observatory
California Institute of Technology
Palomar Mountain, California 92060

Michael Carr
G. Edward Danielson
Ernest O. Lorenz
Richard Lucinio
Victor E. Nenow
J. Devere Smith
James A. Westphal
California Institute of Technology
Geological and Planetary Sciences
Pasadena, California 91125

Donald P. Schneider
Institute for Advanced Study
Princeton, New Jersey 08540

Barbara A. Zimmerman
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

Abstract. We describe an astronomical camera for the 200-in. Hale telescope using four 800×800 Texas Instruments CCDs in an optical arrangement that allows imaging of a contiguous 1600-pixel-square region of sky. The system employs reimaging optics to yield a scale of 0.33 arcsec per pixel, a good match to the best seeing conditions at Palomar Observatory. Modern high-efficiency coatings are used in the complex optical system to yield a throughput at peak efficiency of nearly 50% (including the losses in the telescope), corresponding to a quantum efficiency on the sky of about 30%. The system uses a fifth CCD in a spectroscopic channel, and it is possible to obtain simultaneous imaging and spectroscopic observations with the system. The camera may also be used in a scanning mode, in which the telescope tracking rate is offset, and the charge is clocked in the chips in such a manner as to keep the charge image aligned with the optical image. In this way, a survey for high-redshift quasars has been carried out over a large area of sky. The instrument has produced images for the most distant clusters of galaxies yet discovered as well as spectra of the most distant galaxies yet observed.

Subject terms: charge-coupled device imager; astronomical instrumentation; low-light-level imaging.

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CONTENTS

1. INTRODUCTION

The emergence of CCD detectors has, it is fair to say, revolutionized optical astronomy. CCDs have quantum efficiencies an order of magnitude better than photoemissive devices and more than two orders of magnitude better than the best photographic detectors, and they possess positional stability better than plates and gain stability better than other electronic detectors. They have thus opened up for investigation a vast range of problems too difficult to have been undertaken before with even the largest optical telescopes. The early history of the use of CCDs at Palomar Observatory has been described by Gunn and Westphal,[1] and further instrumentation has been described by Oke and Gunn.[2] All of the really successful instruments at Palomar have used the Texas Instruments 800×800 CCDs (TI3PCCD) developed for the Wide-Field/Planetary Camera (WF/PC) for the Hubble Space Telescope.[3,4] One of the instruments built early in the game was a device called, only somewhat facetiously, PFUEI (Prime Focus Universal Extragalactic Instrument). A reimaging instrument that combined a camera and a low-resolution spectrograph, PFUEI did several things that pointed the way to the much more ambitious instrument described in this paper:

(a) It reimaged the telescope focal plane onto the CCD to better match the images of stars, about 1 arcsec or 86 μm at the f/3.5 prime focus of the 200-in. telescope, to the 15-μm pixels of the Texas Instruments 800×800 CCDs. The reduction ratio chosen for PFUEI was 2.5:1, which gave 0.42-arcsec pixels, small enough for good sampling and still, with the 800×800-pixel array, a reasonable field size of 5 arcmin. This was done in the PFUEI with rather fancy lens optics, which did not have the wavelength range desired for quality imaging and whose coatings performed poorly at the ends of the wavelength region of interest (from 400 to 1100 nm).

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(b) It incorporated a spectrograph as an integral part of the instrument, to which the camera could be converted in such a way that a very faint object could be acquired with the camera and placed on the slit of the spectrograph-to-be without disturbing the alignment. This allowed one to obtain spectra of objects much too faint to be acquired by any conventional spectrograph.

(c) It was integrated with a minicomputer-controlled data acquisition system, which performed all normal bookkeeping functions and ran the instrument.

PFUEI's shortcomings were many. Its optical system, as mentioned above, was neither as good, in terms of image quality over a broad wavelength range, nor as efficient, in terms of throughput over a broad wavelength range, as one might desire. The spectroscopic mode, while enormously valuable, was cumbersome to use, and since, as we shall see, calibration of the spectrograph is critically dependent on its exact configuration, the calibration had to be repeated for each setup. Under conditions of excellent seeing (atmospheric-turbulence-limited image quality) the 0.42-arcsec pixels of PFUEI were a bit large for optimum sampling. To make them smaller, however, given the finite size of the detector, results in a smaller field of view, and for many problems one needs a larger total field of view. In addition, we were heavily involved in the development of the WF/PC, and thus it seemed wise to build a ground-based instrument that was optically similar to the WF/PC and that would produce data in the same format in order to test the concept and aid in the development of reduction software.

Thus we began development of the instrument described in this paper. As its name suggests, the WF/PC has two modes. Each mode uses four CCDs in an optical configuration that creates a contiguous square field, each quadrant of which is covered by one detector (the so-called "optical mosaicking" technique). The instrument by necessity reimages, and since there is a reflective image splitter in the focal plane (the optical layout is described in Sec. 2), the opportunity arises in its ground-based counterpart to place a slit in that optical element and use a permanently installed and aligned spectrograph as a fifth channel. The image-splitting arrangement does not work well except in very slow (high f/ratio) optical systems, so we were led to abandon the prime focus (at which there was certainly not room for such a machine in any case) and move to the Cassegrain focus, whose f/16 beam and much roomier environment seemed more suited to our purposes. There are, of course, losses from the extra mirror in the telescope, i.e., the Cassegrain secondary, which is so large that putting a fancy coating on it is out of the question, but we felt we could more than recoup that loss by careful selection of coatings on the optics of the instrument itself. We began the conceptual design in the spring of 1978. Four-and-a-half years later the instrument was first tried on the Hale telescope and a year later entered regular service. The spectrograph was finished about a year ago, at about the same time work on some of the more esoteric modes we describe below were implemented. It is now substantially complete and has already been used for a number of pioneering projects at the limit of what can be done with large telescopes from the ground.

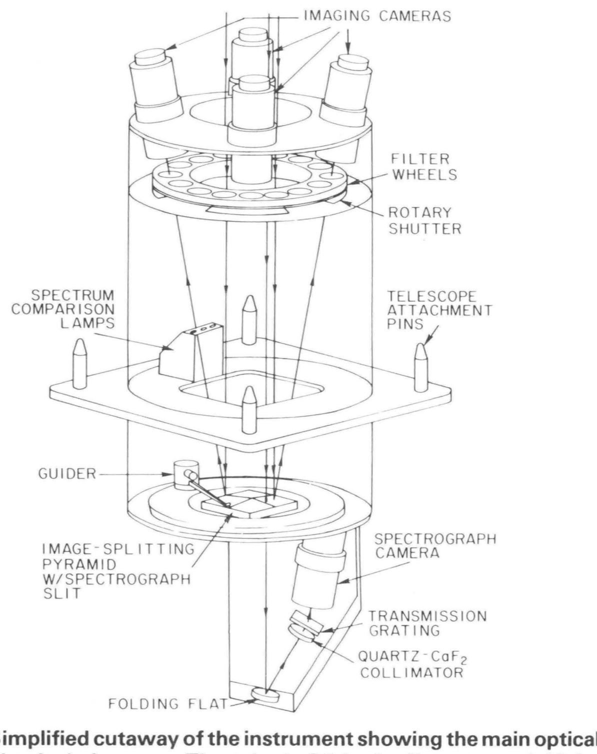

Fig. 1. Simplified cutaway of the instrument showing the main optical and mechanical elements. The tube is 30 in. in diameter and 48 in. long, and the instrument weighs about 1700 lb with the spectrograph installed. The four imaging Schmidt cameras are at the top, and the image-splitting pyramidal mirror is at the bottom, at the Cassegrain focal plane of the telescope. The spectrograph hangs below the tube and is fed by light passing through a slit in the pyramid.

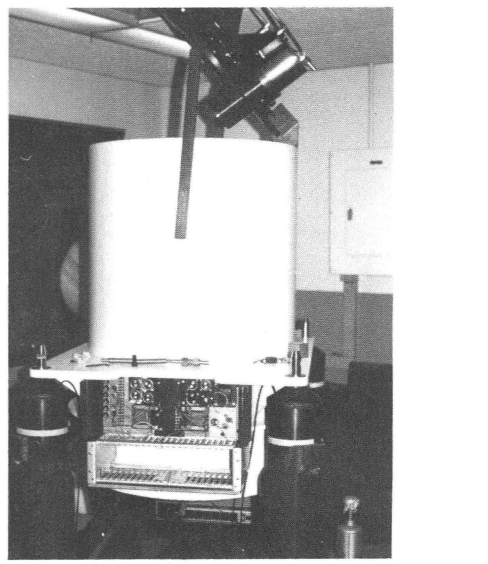

Fig. 2. Photograph of the instrument under construction in the laboratory. The hinge-and-support mechanism for gaining access to the filter wheels is shown, as are two of the cameras.

2. INSTRUMENT OVERVIEW

The general layout of the instrument is shown in Fig. 1. Figure 2 is a photograph of the system under construction. The main tube is rolled and welded of 1/4-in. steel and is 30 in. in diameter and 48 in. long. It is attached to the telescope by a standard arrangement of four tapered and slotted pins that allow fast attachment and removal without tools. The attachment plane is essentially at the bottom surface of the primary mirror cell of the telescope; thus, when installed, most of the instrument is out of sight inside the central hole in the 200-in. mirror. The mounting/location pins are mounted to a 1-in. steel plate, which also serves as a main stiffener and is welded with gussets to the main tube. The instrument's size and mounting peculiarities preclude its use on any telescope except the Hale. The top and bottom of the tube are reinforced with rings that are machined to provide precision mounting surfaces for the optical assemblies. These parts are mounted to machined aluminum plates, which are bolted to the top and bottom of the tube structure. The weight of the instrument without the spectrograph is about 1500 lb.

Figure 1 also shows the principal characteristics of the optical system. Light enters the top of the instrument through a 15-in.-diameter UBK7 window, whose sole function is to keep dust and debris out of the instrument and in particular off the pyramid, which is positioned at the bottom of the assembly and is the next element the light encounters. This is a four-faceted mirror, the faces of which are cut at such an angle that the light is pitched into the entrance windows of the four Schmidt reimaging cameras. The pyramid is in the focal plane of the Cassegrain f/16 beam of the telescope, and the angles are sufficiently small that there is little light loss along the edges of the facets. Just below the entrances to the four cameras is an assembly consisting of a four-bladed rotary shutter and two filter wheels, each with 16 openings: a clear position and three filter positions for each camera. The light then enters the cameras, which reimage the Cassegrain focal plane after a reduction of 8.6:1 onto four 800×800 TI3PCCDs. The resulting scale is 0.336 arcsec/pixel, and the field, after small overlaps along the pyramid edges are taken into account, is about 1570 pixels square, or 8.8 arcmin on the sky.

The spectrograph hangs below the main body of the instrument and is easily removable for testing and service. There are three pyramids; the one shown in Fig. 1 is for long-slit spectroscopy and has a slit 2 arcmin long and 1.5 arcsec wide cut in the quartz mirror blank, through which light enters the spectrograph. The beam is folded by the flat (just to make the spectrograph reasonably compact and mechanically stiff), is collimated by a quartz-fluorite triplet collimator, is dispersed by an interchangeable transmission grating, and passes through a shutter assembly (not shown) and into a camera different only in detail from the four imaging cameras. The camera is on a mounting that allows its angle with respect to the grating to be changed, in order to select the central wavelength of interest and accommodate a wide range of groove spacings on the grating.

The cameras are cooled by liquid nitrogen to about −140°C and are filled automatically from a 50-liter supply dewar mounted on the telescope. Since the four imaging cameras are inaccessible when the instrument is mounted, some such arrangement is necessary. The nitrogen is carried from the supply dewar in a flexible vacuum-jacketed line to the base of the main tube, where it enters another vacuum-jacketed tube through a swivel joint and is carried up to a plenum connecting all four cameras. Each camera has an insulated vent line that exhausts near the base of the instrument through a cryogenic solenoid valve. The system runs under a pressure of about 10 psi. The vents are normally closed, so the boiloff from the camera dewars goes back through the supply line, keeping it empty, and bubbles out of the supply dewar's pressure regulator/vent, which is responsible for regulating the system pressure. This boiloff is routed back into the main body of the instrument to keep it dry and

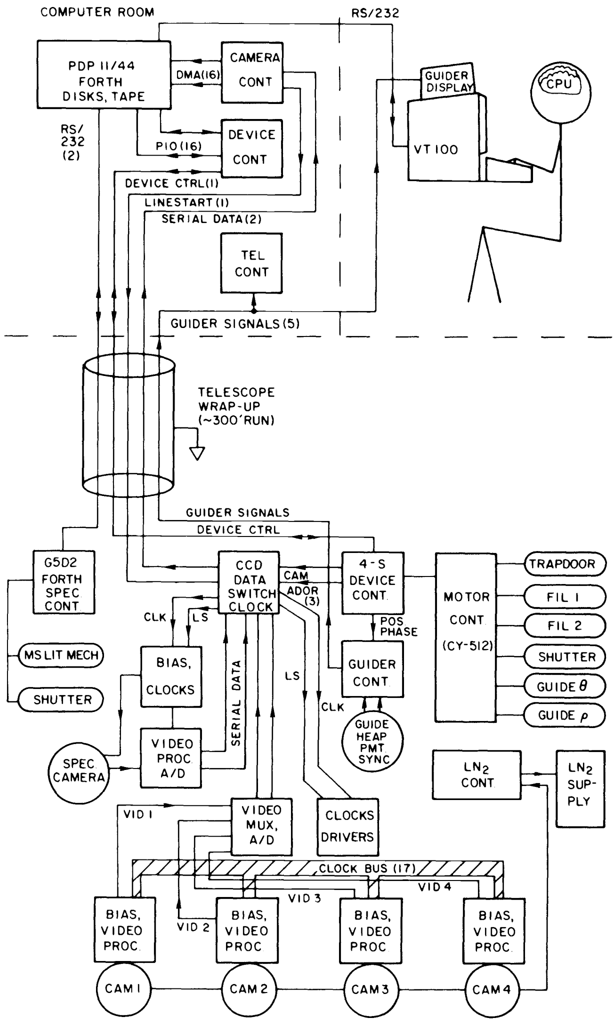

Fig. 3. Block control diagram for four-shooter. The items in the upper left box are physically isolated in a computer area in the dome, the operator and terminal are in the data/control room, and the rest (after the wrap-up) are on the instrument proper. The signals and boxes are described in the text.

clean. When any one of the four cameras is half full, as established by a simple carbon resistor bridge level sensor, all the vents are opened, allowing liquid to fill the line and flow into all cameras. The vents are closed one by one as each camera fills. The spectrograph system is similar but independent and uses its own supply dewar.

The four-shooter is entirely remote-controlled from a single terminal, through the aegis of a PDP 11/44, whose main function is to acquire, store, and keep track of the volumes of data the instrument produces (each 1600×1600 16-bit image is a bit more than 5 Mbytes, and with calibration frames it is not at all unusual to produce 50 frames a night; a four-night run can thus produce 1 Gbyte of data) and a flock of microprocessors to handle low-level mechanical functions. We discuss all of this in more detail in Sec. 4; an overall block diagram of the control system is shown in Fig. 3.

A device necessary for any remote-controlled instrument on a large ground-based telescope is a guider, i.e., a sensor that can produce signals to correct for small tracking errors that occur as the telescope moves to cancel the earth's rotation. The one on the four-shooter is shown in Fig. 1. It consists of a long thin arm with a tiny elliptical flat mirror on the end that moves just above the image-splitting pyramid; the light from the mirror goes through a small telescope, through a rotary chopper, and onto the photocathode of a miniature photomultiplier. In use, the mirror is moved to intercept the light from a star in the field. The star is imaged on the chopper, which is a knife-edge just cutting its axis of rotation, rotating at 5 Hz. When the star is exactly centered, the photomultiplier output is not modulated, but as the star drifts off center, a sinusoidal signal whose phase depends on the direction of drift is produced. This is phase-detected and sent back to the telescope fine-guidance circuitry. The motion to acquire the guide star is through two rotations, one about the axis of the guider housing, which swings the pickup mirror roughly along a radius through the center of the pyramid, and the other of the whole massive ring carrying the guider, whose center of rotation is the center of the pyramid. The 11/44 knows about the characteristics of this peculiar coordinate system and, given the x,y pixel coordinates of a star, sends the guide head thither.

3. OPTICAL SYSTEM AND CAMERAS

The experience with PFUEI led us to the conclusion that we should, insofar as possible, use reflecting optics in the new instrument, and this we have done in most instances. The pyramid is more complex than it looks; each facet is in fact a slightly concave field mirror with a focal length such as to image the telescope pupil on the secondary of the Schmidt-Cassegrain repeater camera.

Those cameras are shown, along with a schematic representation of the structure of the CCD dewar, in Fig. 4. The cameras are modifications of the classical Bowen semisolid Schmidt, which is widely used in fast spectroscopic applications. The original design was faster and was for a parallel incoming beam; these cameras, which reimage the pyramid, only a bit more than a meter away, onto the CCD, must be designed for finite conjugates from the outset. The only deviation in principle from the original design is the configuration of the secondary, which in this design is buried within the main block of the camera. This results in significantly smaller vignetting than in the original, at the expense of a couple of centimeters more of quartz in the optical path. The cameras, in fact all of the optics for the instrument, were constructed by Loomis Custom Optics (Tucson, Ariz.) and perform very well indeed.

All reflective coatings, both internal and external, are dielectric-and-silver coatings that reflect 99% or more above 420 nm and are still reasonably good down to 390 nm. The transmission elements have multilayer dielectric coatings that have maximum losses of 1.5% and average losses less than 1% over most of their 400 to 1100 nm band. The band from 310 to 400 nm was purposely ignored when the instrument was designed; to have reached it would have required aluminum mirror coatings and much less satisfactory antireflection coatings and with the large number of optical elements in the system (11 surfaces not counting the filter in the instrument plus two in the telescope) would have reduced the throughput by one-half or more. A large number of complex astronomical instruments have been crippled by the desire of a few users to gain access to this band; there is certainly data of interest there, but it seems silly to compromise every instrument to reach it. In any case, this one was not.

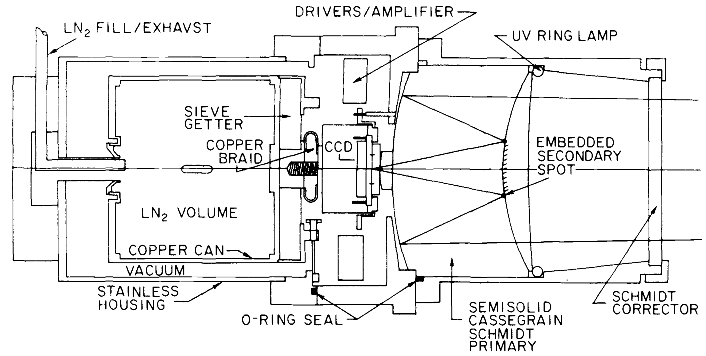

Fig. 4. Simplified cross section through one of the imaging camera/dewars showing the Schmidt optics and the CCD mounting and liquid nitrogen cooling system.

The primary block of the Schmidt camera forms the window to the dewar, as can be seen in Fig. 4. Atmospheric pressure over such a thick element causes negligible distortion, and since the back focal distance of the camera is only about 1 mm, a seal at the CCD itself would have been difficult or impossible. The CCDs, in round 40-pin packages about 40 mm in diameter, are cemented into aluminum cans to facilitate thermal contact with the liquid nitrogen reservoir. They are connected electrically with the preamp and drivers on a circuit board in the dewar through 5-mil constantan wires to minimize thermal loss. No CCD connection goes to the outside world directly; the incoming clock signals are on CMOS logic lines, and the only analog signal is the preamplifier output. The driver and amplifier circuitry are essentially those described in Gunn and Westphal,[1] with a few embellishments, which we describe in Sec. 4. The CCD can is connected to the dewar base by three thin-wall stainless tubes and is supported by opposing nuts on fine (1-72) screws to facilitate focusing and tilt adjustment.

Thermal contact with the cold reservoir is by a pressure pad that contacts the back of the can via a mica insulator and a thin film of Braycote cryogenic grease. This pressure pad is thermally connected to a coldfinger at liquid nitrogen temperature through two copper braid straps, whose lengths are trimmed so that the CCD can run at about −150°C. The operating temperature, about 10°C warmer (−140°C), is established by a resistive heater and regulated to about 0.2°C through a transistor sensor, whose base-emitter drop is monitored. The CCD charge-transfer performance is somewhat degraded at these very low temperatures compared to the preferred range of around −90 to −100°C, but the devices used are flight rejects from the WF/PC program and have dark current defects that are catastrophic at higher temperatures.

The vacuum is maintained and cleaned by a volume of molecular sieve getter, which communicates with the vacuum region through a fine-mesh perforated screen and is itself maintained at LN_2 temperature. The liquid nitrogen is contained in an electron-beam-welded copper can, which is welded to a stainless transition fitting that in turn is welded to a 1/2 in. thin-wall stainless tube to support the reservoir from the back and provide fill and vent space. The reservoir is supported at the front on a three-legged music wire spider.

It has been established by Janesick[5] that the quantum efficiency of the TI CCDs in the blue and green is enhanced and the stability of that quantum efficiency is greatly improved if the back (entrance) surface of the CCD membrane can be permanently negatively charged. This charge sets up an electric field in the device that sweeps carrier electrons away from the surface where the light is absorbed, where defects and traps abound, into the depletion region. This desideratum is met partway by flooding the entrance surface with ultraviolet radiation just prior to cooling. This UV flood is built into the four-shooter cameras; Fig. 4 shows the flood arrangement for the spectrograph camera, the one for the imaging cameras being a little different. A ring-shaped mercury discharge lamp just ahead of the primary block of the camera shines into an otherwise unused part of the camera aperture, past the secondary, and illuminates the CCD directly. This flood is operated for about 1/2 h before the cameras are cooled; the charge state thus induced lasts for as long as the cameras are kept cold.

The spectrograph camera is different in its detailed optical design from the imaging cameras since it does accept a parallel beam, but mechanically is essentially identical to them.

4. CONTROL SYSTEM

The instrument is designed to be operated by a single astronomer using a standard ASCII terminal. That terminal communicates directly with the PDP 11/44 control computer, which runs a stand-alone FORTH system, in which all the control software is written. The 11/44 communicates with the instrument through a DMA port for CCD data and a PIO port and an RS-232 port for control (see Fig. 3). The CCD data come from the instrument over a standard three-line serial system described in Gunn and Westphal[1]; the converter from the DMA port protocol of the DEC interface to that serial protocol is in a box adjacent to the computer; this box also converts the byte-wide input/output of the PIO port into a 64-bit high-speed single-conductor serial channel for instrument control. Two lines go directly (via driver-receivers) from an EIA serial port on the 11/44 to a microcomputer that controls the spectrograph, and five lines carry information from the guider to the telescope control computer (a PDP 11/23) and to the guider display. All together there are 11 coaxes that carry all the data and control information to and from the instrument. The run is about 300 ft through the building and telescope bearing wrap-ups. Since the power supplies are mounted permanently to the instrument and the 11 coaxes are in two seven-cable *coaxicon* bundles, the electrical installation of the instrument on the telescope is trivial.

The 64-bit control word basically runs the instrument. The word consists of one 16-bit data word and 48 assigned single-function control bits, which address the desired camera for reading, turn the high voltage on the guider photomultiplier on or off, select one of the six stepping-motor devices for motion, etc. The six devices are a protective trapdoor cover over the entrance window at the very top of the instrument (not shown in Fig. 1), the two filter wheels, the shutter, and the two guider coordinate motions. Each device is powered by a stepping motor and is controlled by a dedicated CY-512 stepper controller. The 16-bit data word embedded in the control word is relayed to the appropriate CY-512 as a stepping motor address, to select a particular filter, say, or to move the guider to a particular coordinate. The data word is also used to set the relative phase of the guider chopper, which changes as the instrument is rotated and as the guider moves from location to location in the field. Eight bits of the control word are for camera functions; there are three address bits, a master camera enable that must be active to perform any camera function (a preventive measure to keep glitches out during long integrations), and four erase bits, one for each camera (discussed later in this section).

The camera control electronics are more or less like those described by Gunn and Westphal but are multiplexed to handle the four cameras. Each CCD has individual bias requirements, and since the noise levels of the devices are at the level of about eight electrons, one does not wish to send low-level analog video over long distances. For these reasons the bias voltages and low-level video processing are handled by circuitry immediately adjacent to each of the four cameras. The video processing is by means of the classical double-correlated sampling technique and yields noise performance of eight electrons rms in this system; the older PFUEI system, with a CCD with a slightly different processing history, was slightly better at seven electrons rms. The video output of these processors is a 10-V signal; it is sent over a differential line to a central multiplexer and 16-bit A/D converter. The serial output of the A/D converter eventually goes back to the controller in the computer room for input into the DMA board and onto the disk and tape. The complex clock waveforms for the CCDs are generated in one place and drive a 100-Ω bus that connects all four cameras; the cameras attach to the bus one by one in a readout cycle, the video MUX selects the appropriate one, and the data are shipped to the computer. The readout time, which is set by the best noise performance of the on-chip CCD output FETs, is 25 μs per pixel; with overhead, each chip is read out in about 20 s, or about 80 s to recover a full image.

One problem with the PFUEI chip was residual images—badly saturated bright stars so upset the potential profiles in the CCD that charge leaked into the oxide, which then returned to the depletion region with a time scale of many hours at the operating temperature of the device. Janesick discovered some years ago that if the substrate of the CCD is run positive several volts so as to invert the channel, this charge is dumped back into the depletion region and can be read out. This erasure procedure is very effective and can be done on a chip-by-chip or all-together basis as required; it is done as a matter of course in the preparation cycle before each exposure is begun. Another problem with the TI chips has always been low-light-level charge-transfer efficiency through the transfer gate, the structure connecting the parallel array with the serial (horizontal) register. This is circumvented in this design by running the low level of the parallel clocks negative, shaping the transfer-gate transition, and clocking the transfer gate twice for each transfer; performance is an order of magnitude better than in the older design.

The system was originally designed so that the spectrograph camera was a fifth camera on the bus, but by the time the spectrograph was built it was decided that it should be an independent system with its own clock generators and A/D converter, mostly to facilitate testing. Thus, there is an additional switch to select whether the data system communicates with the multiplexed output of the imaging cameras or with the spectrograph; the original camera address scheme is used to control the switch.

The spectrograph control system is altogether more advanced than that for the imaging instrument. The control is via one serial link to a general-purpose microprocessor, in this case a Rockwell 6502 FORTH machine, which runs code in firmware. The spectrograph is simpler, to be sure, but the machine is more than sufficiently powerful to run the main instrument as well, and we will change the main control system in the near future. The mechanisms on the spectrograph are the shutter and a carousel and elevator associated with a multiobject spectroscopic mode, discussed in Sec. 5. All of these are essentially two-position devices and use permanent-magnet dc motors for power.

5. SPECTROGRAPH

The four-shooter spectrograph was designed with a single goal in mind—to produce an instrument with very high throughput for the recording of low-resolution spectra of the faintest possible objects, over a field large enough that many spectra can be recorded at once using multiple slits.

Low-dispersion transmission gratings are much more efficient than their reflective cousins, and thus a transmission-grating configuration was adopted; this and the desire for a wide input field led to a refracting collimator, the only substantial refracting element in the instrument. This lens is a triplet with a pair of fused quartz "flints" and a calcium fluoride "crown" sandwiched between and cemented. The triplet configuration was not chosen for optical reasons but simply to protect the fluorite element; also, coatings are much more efficient for quartz than for the very-low-index fluorite. The camera is essentially the same design as the imaging cameras but was redesigned for a somewhat faster focal ratio and, of course, for a parallel input beam.

To get all the light from a large input field into the spectrograph camera, a field lens must be placed immediately behind the slit (it plays the same role for the spectrograph as the figured facets of the splitting pyramid do for the imaging cameras). It is not shown in Fig. 1 but is built into the pyramid with the slit. There is, of course, also a pyramid with no slit, for the most "cosmetic" pictures, and one with a gaping hole for wide-field multislit work.

The implementation of the multislit mode proved to be a bit troublesome. The requirements are fairly severe: A picture must be taken in some mode in which the object of interest can be seen; the telescope must be maneuvered in such a way that the object will be placed where the desired slit *will be* when the slit is emplaced; and some way must be provided to ensure that the slit in fact went in correctly. With the long slit the problem is trivial, since the slit is fixed and the reflective pyramid surface is continuous up to the slit jaws. To arrange something similar with multislits would require that the multislits be cut or etched into a figured surface; since there must be a new multislit mask for each field one wishes to observe (cut to match the objects in that field) and one might do several fields per night, the complication and expense seemed excessive. The multislits used with PFUEI had been made photographically on graphic-arts emulsion from plots generated from PFUEI images on a dot-matrix printer; this technique was fast, simple, and inexpensive, and we wished if possible to use it on the four-shooter as well.

The solution was to build a mechanism that could place either the mask or a mirror in a highly reproducible kinematic mounting. The mirror takes the place of the missing part of the pyramid and allows images to be obtained of the part of the field that will be occupied by the multislit. An LED lamp behind the multislit can be used to illuminate the slits from the rear so as to allow a picture to be taken with the camera of the multislit mask. The procedure is thus to take a picture of the slit mask when it is mounted, usually in the afternoon before, and record the pixel locations of the slits that correspond to the objects in the field. Then a picture is taken of the field with the mirror in, and the telescope is maneuvered so as to place the target objects at those locations. The mirror is removed and the multislit emplaced, and another picture is taken of the slit mask using the LED to make sure it went in properly, and then the spectrum is taken. The changing is done by a carousel that holds the slit mask and the mirror and an elevator that moves the selected one into and out of position. This is done under the supervision of the 6502 FORTH machine with one RS-232 command from the operator via the 11/44.

6. SCANNING

For work at the very faintest levels, the limits are set by systematic effects that have to do with calibrating the sensors. The raw response of the CCDs is somewhat nonuniform, with amplitudes for these sensors (which are quite good) of about 20%. This nonuniformity is color dependent, which is a serious problem. The background in the pictures, of course, is the sky, and it is not possible to build a calibration lamp with a spectrum that mimics that of the sky sufficiently well to produce a "flat field" that removes the nonuniformities to better than 1/2% or so. The problems are worst in the near-infrared, where the chip is partially transparent, so one gets interference fringes from a monochromatic source, and, perversely, where the night sky spectrum is dominated by a forest of narrow emission lines of the OH radical. It is possible for some classes of problems to produce a flat field statistically from an ensemble of the pictures themselves, but the results are not completely satisfactory and the computational effort is very large indeed.

The technique we have adopted is one that has been used for some time in this and in other connections. If one offsets the drive rate of the telescope slightly, the image of the sky will move across the sensors. If one aligns the instrument very carefully so that that motion is exactly along the columns of the CCDs (and in our case, since there are four cameras, the cameras must also be aligned among themselves very precisely) and clocks the parallel register (the array itself) in such a way that the charge moves precisely as the image does, one can obtain a continuous tapestry, as it were, as the image of the sky moves across the sensors. The equivalent exposure time is the time required for a given star to completely traverse the device. The technique also has the advantage of great efficiency; the devices are being read continuously, so there is no overhead involved in reading the data, but the great advantage is that nonuniformities in response are averaged out along columns, and the flat-fielding exercise is now a one-dimensional problem. Statistical techniques here *are* very useful and not very expensive of computer time. This mode is most useful for surveys, where it is desirable to cover a relatively large area of sky as efficiently as possible. In one survey we have done, we have gone to the extreme of parking the telescope and letting the sky drift by at its diurnal rate; in this way we can look at more than 8 deg^2 of sky in a given night to a moderate but very-well-controlled depth. The object of this exercise was to map the distribution of the redshifts of quasars near the purported cutoff at about 3 (there are a few objects of

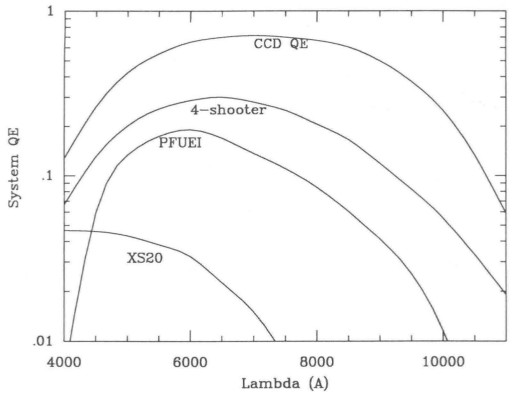

Fig. 5. The quantum efficiency of the four-shooter system compared with the QE of an ensemble of CCDs alone, the PFUEI system, and a hypothetical instrument with the throughput of the four-shooter but with a photoemissive detector with an extended S-20 photocathode.

TABLE I. Four-shooter limiting magnitude (5:1 S/N ratio) for various total integration times, for the median Palomar sky brightness and for 0.8 arcsec FWHM seeing. The magnitudes are monochromatic on the AB79 system of Oke and Gunn.[7]

Band	g	r	i	z
Time	500 nm	650 nm	780 nm	950 nm
60 s	24.1	24.3	24.2	23.6
5 min	25.1	25.3	25.2	24.6
20 min	26.0	26.2	26.1	25.4
4 h	27.2	27.5	27.3	26.7

higher redshift, but it would appear that the numbers decrease sharply beyond about 2.7). The preliminary results are encouraging.[6]

7. PERFORMANCE

Figure 5 shows the performance of the instrument in terms of quantum efficiency on the sky, in comparison with the QEs of bare CCDs, the measured performance of PFUEI, and that of a hypothetical instrument using an extended S-20 photoemissive detector.

This efficiency translates more or less directly into limiting magnitudes, given some information about image quality. The optical train of the four-shooter is of sufficient quality that the image quality is set by the atmospheric seeing in all but the very best conditions (less than about 0.5 arcsec) and by the telescope mirror then. Conditions on Palomar are often such that one has 0.8-arcsec images for reasonably extended periods, and under those conditions and with typical sky brightnesses one can obtain the limiting magnitudes listed in Table I in the four bands g, r, i, and z (approximately 15% bands centered at 500, 650, 780, and 950 nm).

We have included in this paper six images obtained with the four-shooter. In Figs. 6, 7, 8, and 9 we show full-field composites of familiar astronomical objects. The faintest stars in the globular cluster picture (Fig. 9) are about 26th r magnitude. This image was obtained as part of a study by Lupton and Gunn[8] of the very faintest stars in these systems, which are thought to be the oldest stellar systems in the galaxy. Figure 10 is a negative image of a distant cluster of galaxies found as part of a general deep survey for such objects[9] at a redshift of 0.756; the brightest galaxy in the cluster has an r magnitude of 23. The light we see now left this aggregate when the universe was only about 40% of its present age. Gunn and Dressler of the Mount Wilson and Las Campanas observatories have obtained spectra of about 20 galaxies in this cluster with the four-shooter spectrograph, and those spectra and others[10] in other not so distant clusters show convincingly that galaxies at these epochs were different from their present-day counterparts. Figure 11 is an image of a yet more distant cluster, at a redshift of 0.921. It is a 5-min four-shooter exposure shown for comparison with a limiting photographic exposure of the same field; the enormous gain in sensitivity is apparent.

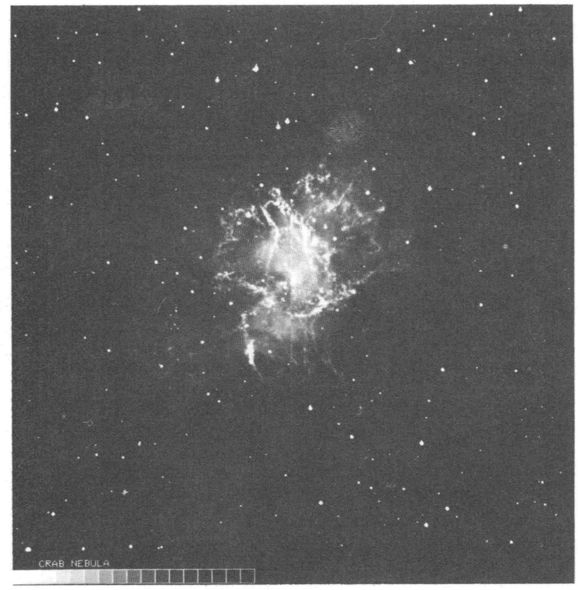

Fig. 6. The Crab Nebula, the remnant of the supernova of AD1054. This full-frame image was a 2-min exposure with the four-shooter in the red.

Fig. 7. The Horsehead Nebula, a region in Orion in which a dense cloud of cool gas and dust obscures the emission from stars and ionized gas beyond. Full-frame, 2-min. exposure in the red.

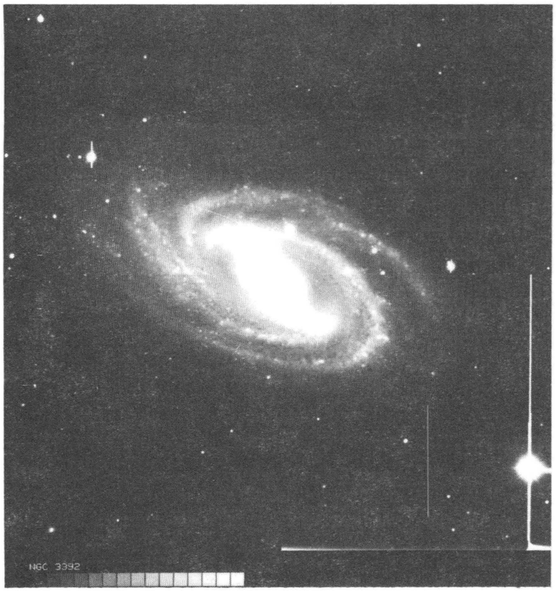

Fig. 8. The barred spiral galaxy NGC3392, a system likely very similar to our own. Full-frame, 2-min exposure in the red. The vertical bar through the bright star is the result of saturation; the phenomenon can be seen also in the Horsehead image (Fig. 7).

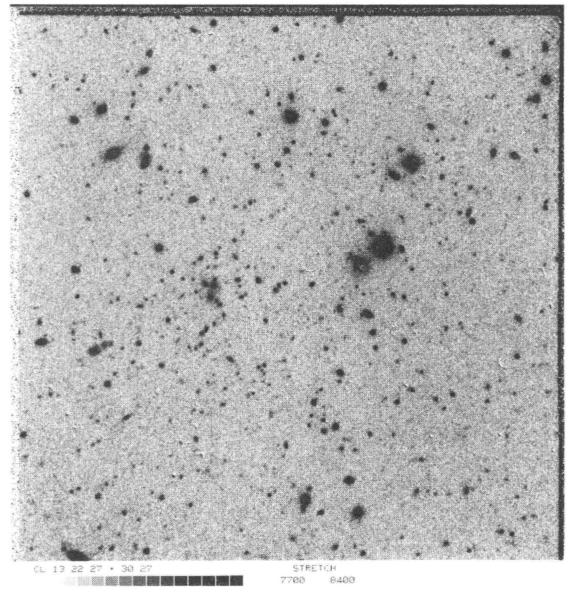

Fig. 10. Single-detector image of a cluster of galaxies at a redshift of 0.756; the two brightest galaxies in the cluster are just to the left of center, and most of the images in that region are cluster members. This is a 5-min exposure in the red.

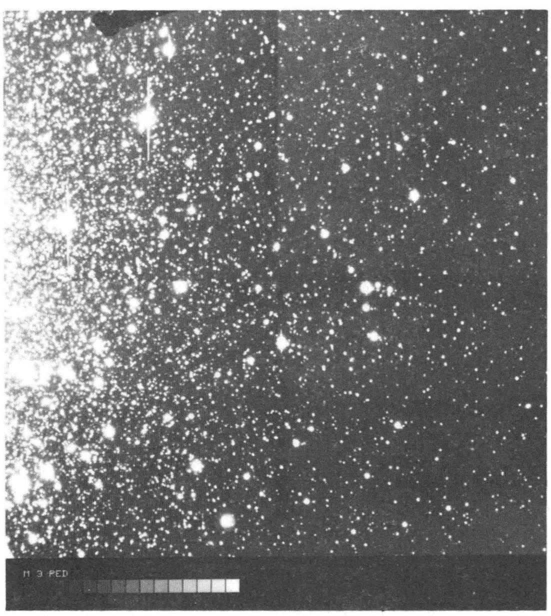

Fig. 9. The outskirts of the globular star cluster Messier 3. This 30-min exposure in the red, obtained in excellent seeing, reaches to a red magnitude of about 26.0. The guider arm and mirror can be seen in shadow in the upper left.

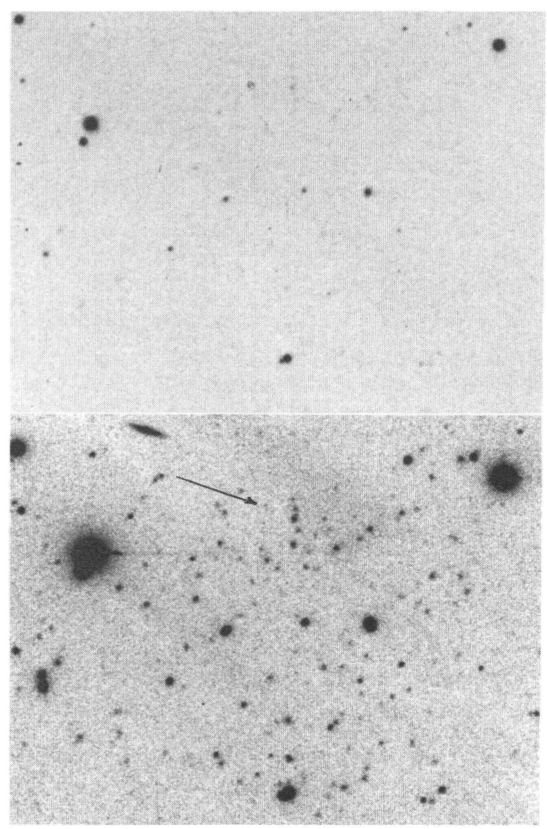

Fig. 11. Two images of the same region of the sky showing a cluster of galaxies at a redshift of 0.921. The upper image is a limiting photograph, 90-min exposure on a hypersensitized Kodak Spectroscopic Plate, type IIIa-F, obtained with the 4-m Mayall telescope on Kitt Peak. The lower image is the region as recorded with a 5-min four-shooter exposure; the arrow points to the cluster.

8. THE FUTURE

What next? A simple dewar and filter wheel and shutter arrangement at prime focus, with a Tektronics 2048-pixel square chip, when that device becomes available, will undoubtedly outperform this instrument for imaging; it will have higher throughput and marginally better images. Such an instrument cannot easily incorporate a spectrograph, however, and in any case the gains in sensitivity will not be large. The sad (happy?) fact is that today's detectors and coatings are so good that there is little margin to be gained, and for more light and so to go fainter there is essentially no choice but to build larger telescopes. But those larger telescopes will be severely crippled without larger and better CCDs. We have begun to look back far enough in time to see a universe significantly different than the one we live in today, but to pursue that study will require both bigger telescopes and bigger and better detectors than we have now.

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James E. Gunn, professor of astrophysics at Princeton University, cosmologist and designer of astronomical instrumentation at Palomar and elsewhere, did the conceptual, mechanical, optical, detector, and overall system design for the four-shooter.

Michael Carr, engineer, machinist, and instrument maker at Caltech, oversaw general construction and scheduling, kept Gunn's mechanical designs honest and doable, designed all the handling fixtures, and built a large portion of the machine with his own hands. He also fixes it when it breaks.

G. Edward Danielson, space scientist at Caltech, oversaw optical fabrication and filter design and fabrication and managed the construction budget in such a way that the machine actually got built.

Ernest O. Lorenz, senior technician at Caltech, did all the (many) things Gunn forgot until the last minute, did all the woodwork on the handling apparatus, did the photography on and made the PC cards, and did most of the machining that Carr did not do.

Richard Lucinio, digital engineer at Caltech, designed and largely built the digital part of the control and data system and computer interface and introduced us all to the wonders of dedicated microprocessors.

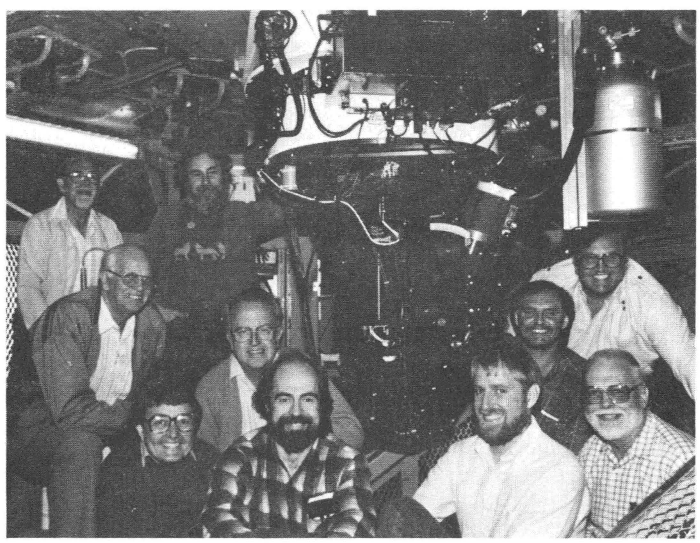
Victor E. Nenow, analog electronics and vacuum engineer at Caltech, designed and built most of the analog control circuitry, the precision power supplies, and (with Carr) the vacuum and liquid nitrogen cooling systems.

J. Devere Smith, senior technician at Caltech, did the lion's share of the wiring and testing and kept us *all* honest.

James A. Westphal, professor of planetary science at Caltech and principal investigator on the Wide-Field/Planetary Camera and cofather of the four-shooter, was active in all aspects of the design and implementation of the instrument, particularly in the areas of detectors, optics, and the vacuum and cooling systems.

Donald P. Schneider, astronomer at the Institute for Advanced Study, wrote essentially all of the data reduction software for both the cameras and spectrograph and did the software that makes the multislit masks for the spectrograph.

Barbara A. Zimmerman, software engineer at Jet Propulsion Laboratory, wrote all of the FORTH control software, including the very fast low-level device code that makes it possible to run the instrument efficiently with limited computer resources.



Left of four-shooter instrument: (top) E. Lorenz, R. Lucinio; (middle) J. Smith, V. Nenow; (bottom) B. Zimmerman, J. Gunn. Right of four-shooter: (top) G. Danielson; (middle) M. Carr; (bottom) D. Schneider, J. Westphal.