SCIENCE WITH THE SECOND WIDE FIELD AND PLANETARY CAMERA

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ABSTRACT

With the commencement of Cycle 4 observations, the General Observer community will have access to the second Wide Field and Planetary Camera (WFPC-2), a replacement for the original WFPC instrument. WFPC-2, a wide-field photometric camera which covers the spectrum from 1200 to 10000 Ångstroms, will be installed in the Hubble radial bay during the currently manifested December 1992 Shuttle servicing mission. Besides optical correction for the aberrated Hubble primary mirror, the WFPC-2 incorporates evolutionary improvements in photometric imaging capabilities. The CCD sensors, signal chain electronics, filter set, FUV performance, internal calibrations, and operational efficiency have all been improved through new technologies and lessons learned from WFPC operations and Hubble experience since launch. Here we provide an overview of the new instrument, beginning with the assumption that the reader is already familiar with the original WFPC now in service[1].

1. WFPC-2 SCIENCE PERFORMANCE

Basic requirements. The WFPC-2 is now in the final stages of assembly, scheduled for completion in time for the commencement of system level testing at Jet Propulsion Laboratory in March 1993. The period between March and November 1993 is scheduled for comprehensive instrument tests at JPL, payload compatibility checks at Goddard Space Flight Center, and payload integration at Kennedy Space Center. At this time it is necessary to predict instrument performance, however we can predict with some confidence that the WFPC-2 will meet its engineering performance requirements on the basis of component and subassembly tests to date. Formally, the instrument performance requirements are set forth in a document called the Contract End Item Specification (CEIS). In brief, the WFPC-2 specifications call for accurate correction of the HST spherical aberration, a scientifically capable camera configured for reliable operation in space without maintenance, an instrument which can be calibrated and maintained without excessive operational overhead, and comprehensive ground testing and generation of a viable calibration database prior to instrument delivery. The WFPC-2 CEIS address the same science goals as WFPC-1, hence the WFPC-1 and -2 instrument specifications are substantially similar. The most notable change for WFPC-2 is the correction of the HST spherical aberration and substantially tighter optical alignment tolerances. In evaluating the science performance of WFPC-2 we consider not only its basic capabilities, but also the ability of the instrument to meet performance requirements in normal day-to-day operations. Years of experience with WFPC-1, both in laboratory testing and in science operations on-orbit, have given us additional insight into the practical aspects of operating a CCD camera in the HST environment, and this experience has allowed us to improve science capabilities and efficiency in many areas.

Reduction in scope. A reduction in scope of the WFPC-2 instrument was mandated in August 1991 due to budget and schedule exigencies. The primary result of this rescope was a reduction in the number of relay channels and CCDs. The WFPC-2 field of view is divided and distributed into four cameras by a four-faceted pyramid mirror near the HST focal plane. Three of these are f/12.9 (WFC) cameras, and the remaining one is an f/28.3 (PC) camera. There are four sets of relay optics and CCD sensors in WFPC-2, rather than the eight in WFPC-1. Consistent with this rescope, the pyramid rotation mechanism has been eliminated, and all four cameras are now located in 'WFC' locations. These positions are denoted PC1, WFC2, WFC3, and WFC4, and projection of their fields of view on the sky is illustrated in Figure 1. Each shutter opening provides a mosaic of three f/12.9 images and one f/28.3 image.

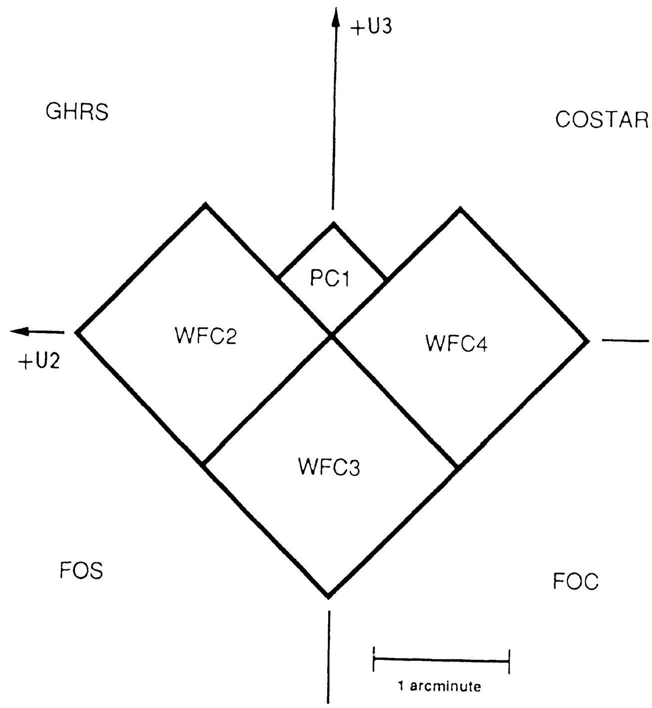

Figure 1. Projection of the WFPC-2 field of view into the sky.

Aberration correction. The strategy for correction of the Hubble aberration preserves the basic optical layout of WFPC-1, but with steep corrective figure on the relay secondary mirrors and substantially tighter optical alignment tolerances. The optical correction implemented for WFPC-2 will recover near-diffraction limited images over the entire CCD fields of view. We expect that the corrective optics will facilitate essentially all the scientific objectives of the original WFPC.

Through a number of independent analyses, based on investigations of star images obtained on-orbit and examination of fixtures used during the figuring of the primary mirror, the aberrations of the Hubble telescope optics is now considered well characterized[2]. The surface of the primary mirror was figured to an incorrect conic constant: -1.0139 ± 0.0005 rather than the -1.0023 design requirement, resulting in a large amount of spherical aberration. By design, WFPC-1 creates an image of the Hubble's exit pupil (essentially an image of the aberrated primary mirror) near the surfaces of its relay cassegrain secondaries for each of its four channels. The basic configuration is illustrated in Figure 2. This design was originally intended to minimize vignetting in the relay optics, but for WFPC-2 the superposition of the exit pupil image (complete with the wavefront aberration) on the relay secondary serves an additional purpose. The optical figure of the WFPC-2 secondary mirrors have been altered with the addition of a compensating 'error' in conic constant. Adopting the prescription and error bars above for Hubble's primary mirror, corrective secondary mirrors have been made with sufficient accuracy that we expect the residual spherical aberration in the WFPC-2 wavefront to be small compared to other tolerances in the WFPC-2 optical wavefront budget. On the other hand, new and stringent alignment requirements are created by the steep optical figure on the corrective secondary mirrors. The aberration presented in the exit pupil image must be accurately centered on the corrective mirror, and the image must appear with the correct magnification. In practice, centering is the difficult requirement, and failure to center accurately would create new aberrations in the form of coma, such that a misalignment by 7% of the pupil diameter would introduce as much RMS wavefront error as was present in the form of spherical aberration prior to the introduction of corrective optics. The new requirements for alignment accuracy and stability lead to an additional term in the CEIS specification of wavefront error, of magnitude $\lambda/25$ RMS at 633nm, in the overall instrument wavefront error budget. This is indicated in the following table.

Wavefront error budget

	WFC (f/12.9)	PC(f/28.3)
Design error	$\lambda/143$	$\lambda/50$
Fabrication and alignment error	$\lambda/14.7$	$\lambda/14.7$
Alignment stability error	$\lambda/25$	$\lambda/25$
Total wavefront error	$\lambda/12.6$	$\lambda/12.3$

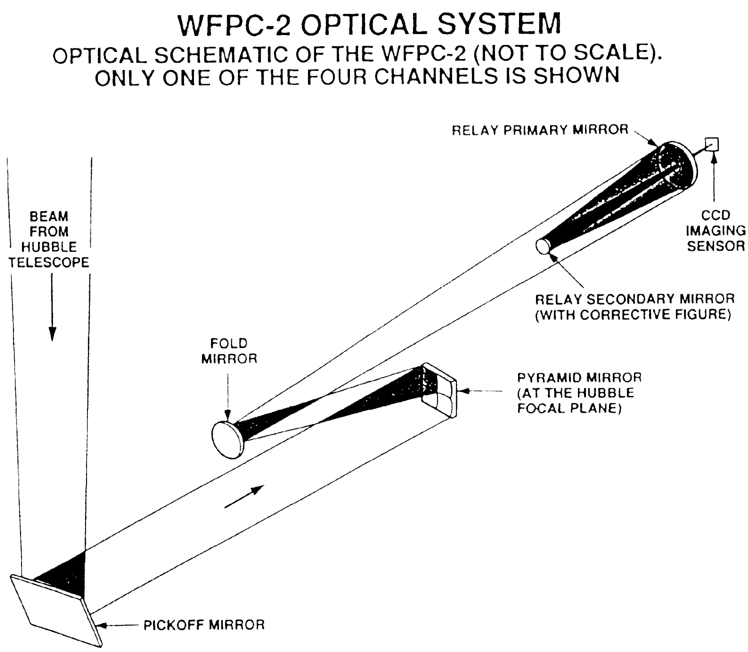

Figure 2. Sketch of one WFPC-2 camera.

The first two lines in the wavefront error budget are essentially identical to those for WFPC-1. 'Design error' refers to the aberrations inherent in the design itself, which would be seen if the optics conformed perfectly to their specifications. At this time all optics have been fabricated and integrated into the WFPC-2 optical bench, and it has been established on the basis of component tests and end-to-end optical interferometry that the WFPC-2 optical system is performing well within the stated tolerances for 'fabrication and alignment' in the current laboratory environment. What remains is to demonstrate the stability of the optical alignment during forthcoming instrument tests, launch vibrations, and in response to the thermal environment on-orbit. Inclusion of the 'stability' line anticipates these uncertainties, and must be verified during system tests and early science operations.

Two new mechanisms have been introduced in WFPC-2 to provide small amounts of alignment correction as may be required in the Hubble environment. The 47° pickoff mirror has two-axis tilt capabilities provided by stepper motors and flexure linkages, to compensate for uncertainties in our knowledge of Hubble's latch positions, ie. instrument tilt with respect to the Hubble optical axis. These latch uncertainties would be insignificant in an unaberrated telescope, but must be compensated in a corrective optical system. In addition, three of the four fold mirrors, internal to the WFPC-2 optical bench, have limited two- axis tilt motions provided by electrostrictive ceramic actuators and invar flexure mountings. Fold mirrors for the PC1, WFC3, and WFC4 cameras are articulated, while the WFC2 fold mirror has a fixed invar mounting identical to those in WFPC-1. This arrangement of mirror actuators allows compensation for potential pupil image misalignments in all four cameras, with the expectation that mirror adjustments will be infrequent following the initial on- orbit alignment.

Photometric imaging. WFPC-2 will meet or exceed the photometric performance requirements for WFPC-1. Nominally, this requirement is 1% photometric accuracy in all filters, which is essentially a requirement that the relative response in all 800^2 pixels per CCD be known to a precision of 1% in flatfield images taken through each of the 48 science filters. Success in this area is dependent on the stability of all elements in the optical train and availability of appropriate flatfield reference targets. Stability of the CCDs, filter characteristics, and an internal flatfield reference are foremost on the list. Photometry at wavelengths shortward of ~3000 Ångstroms will be improved through control of internal vapor contamination sources and the ability to put the CCDs through warmup cycles without loss of prior calibrations.

CCD technology. The CCD sensors for WFPC-2 were manufactured by Loral in 1991, processed and packaged for flight at JPL, and the technology is considerably more up to date than the Texas Instruments devices manufactured for WFPC-1 more than a decade ago. In their WFPC-2 setting these new CCDs will contribute to better photometry at all wavelengths due to quantum efficiency (QE) stability and inherent pixel-to-pixel uniformity, lower read noise and dark current, better residual image recovery, better charge transfer efficiency, and refinements in signal chain electronics. The WFPC-1 pixel format (800^2, 15×15 μm pixels) is copied in the new Loral CCDs. Here we compare the WFPC-1 TI and new WFPC-2 Loral devices.

WFPC-1 CCDs are thinned and 'back' illuminated, meaning that the active silicon layer is a free-standing membrane somewhat less than 10μm thick, with photons impinging directly on the silicon layer without attenuation in the polysilicon gate structure built on the other ('front') side of the device. The WFPC-1 devices are overcoated with coronene phosphor, which converts photons shortward of ~3600 Ångstroms to longer wavelengths where the CCD QE is high. The flatfield appearance of the WFPC-1 CCDs results from local variations in membrane thickness, and variations in thickness of residual inactive silicon and the electrostatic charge state at the back surface. A massive UV (2500 Ångstrom) flood followed by maintenance of a continuous cold temperature is required to stabilize the backside charge state and QE of the WFPC-1 CCDs. The QE instability is most pronounced in B images.

The Loral CCDs are illuminated from the 'front' surface, ie. the light passes through the polysilicon gate structure overlying the ~10μm thick active silicon layer. The front surface is overcoated with a lumogen phosphor, which serves as the primary detection medium for photons shortward of ~4800 Ångstroms, down-converting these to 51-5800 Ångstroms. The QE of the Loral devices is stable without maintenance, hence the UV flood is obviated. Their QE appears to be unaffected by normal temperature cycling. Laboratory tests find no evidence for QE hysteresis, ie. no measurable QE variations are induced by previous bright exposures. The QE curve representative of the WFPC-2 CCDs, including the effects of its MgF_2 window, is plotted in Figure 3. In a comparison of QEs between the WFPC-1 and -2 devices, we would expect comparable QEs longward of 7000Å due to similar thicknesses of the active silicon layer, somewhat lower QEs between 4800 and 6500Å due to attenuation in the frontside structures, and higher QEs shortward of 4800Å due to better phosphor efficiency. In an 'apples-to-apples' comparison, the observed QEs of WFPC-2 devices are somewhat higher than WFPC-1 at all wavelengths, based on direct comparisons between 1981 WFPC-1 laboratory data and recent measurements of both residual WFPC-1 and new WFPC-2 devices. Such comparisons are rendered uncertain due to the unknown backside charge state in the 1981 data. We expect that WFPC-2 exposure times will be similar to those experienced with WFPC-1.

The flatfield response is uniform within a few percent, with the exception of a manufacturing pattern defect which generates a ~3% reduction in QE in one out of every 34 rows. This pattern defect is identical in all CCDs, and also creates an astrometric offset of approximately 3% of the pixel height (0.003 arcsec in the WFCs) every 34^{th} row. The WFPC-1 (PC7) and WFPC-2 flatfields at 6000 Ångstroms are compared in Figure 4. WFPC-2 flatfields will also include instrument effects, such as vignetting and shadowing by dust particles, and will not be available until the completion of system tests.

Dark current is somewhat reduced, allowing CCD operations approximately 10°C warmer than WFPC-1 for comparable dark rates. Read noise has been measured to be ~7 electrons/pixel for the Loral CCDs in the WFPC-2 flight signal chain. Typical charge transfer efficiency is 0.99995 in flight devices. Linear full well

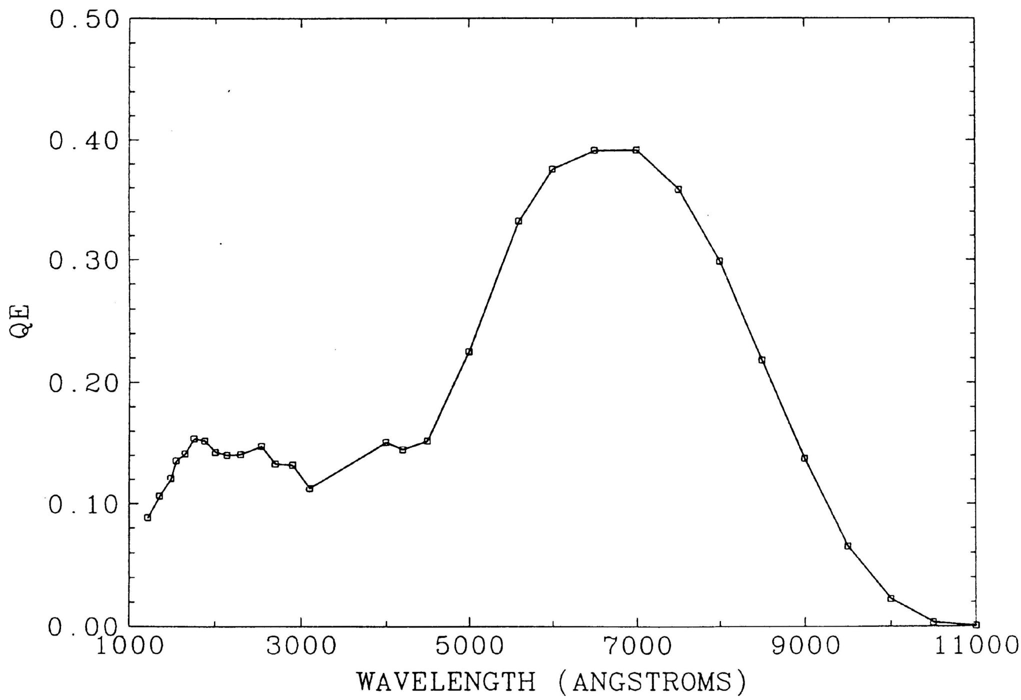

Figure 3. Average QE of the WFPC-2 CCDs, including MgF_2 window.

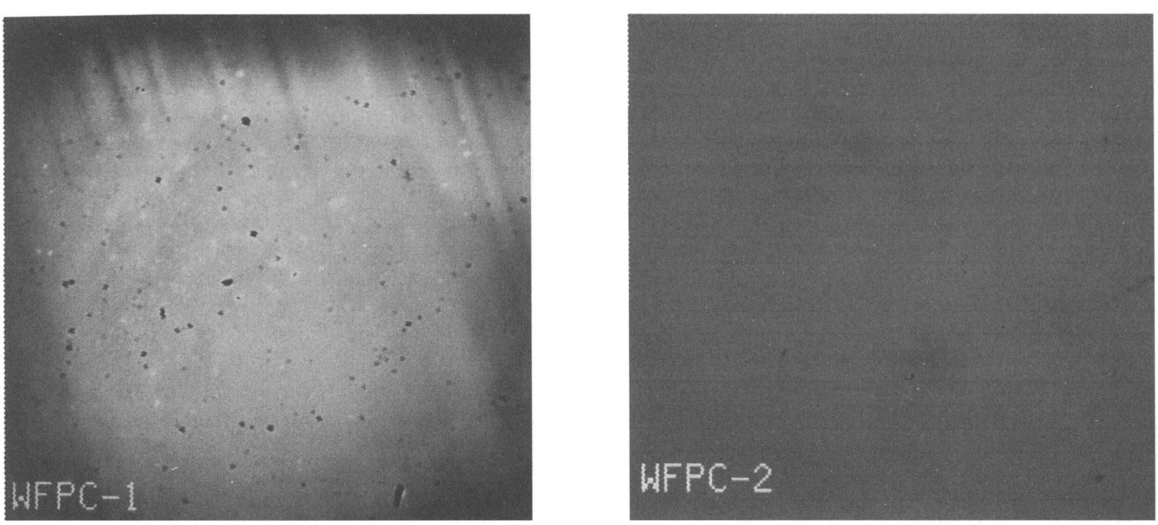

Figure 4. Comparison of WFPC-2 and WFPC-1 (PC7) flatfields.

capacity for these devices, clocked appropriately for the MPP mode, is approximately 70000 electrons/pixel. As driven by the WFPC-2 electronics, the CCDs recover quickly from a large overexposures (100 times full well or more), showing no measurable residual images a half hour after the overexposure. Because the devices are frontside illuminated and supported by a bulk silicon substrate, the CCD surface is flat, which is expected to reduce uncertainties in astrometric calibrations at about the 1/10 pixel level. The Hubble instruments are subjected to cosmic rays and protons from the earth's radiation belts, so it is important to note that the cosmic ray signature in the Loral CCDs is essentially the same as seen in the WFPC-1 devices. This is an indication that photoelectrons generated by cosmic rays (and infrared photons) are efficiently removed by recombination in the low resistivity substrate material.

Filters and spectral coverage. Revisions have been made to the set of 48 scientific filters, based on considerations of the science effectiveness of the WFPC-1 filter set, and as defined in a number of science workshops and technical reviews. The filter set preserves the WFPC 'UBVRI' and 'Wide UBVRI' sequences, while extending the sequence of wide filters into the far UV. The set now includes a Strömgren sequence. Wideband UV filters will provide better performance shortward of 2000 Ångstroms, working together with reductions in UV absorbing molecular vapor contamination by a factor between 10^{-3} and 10^{-4}, a capability to remove UV-absorbing accumulations on cold CCD windows without disrupting the CCD quantum efficiencies and flatfield calibrations, and an internal source of UV reference flatfield images. We expect substantial improvements in narrowband emission line photometry. All narrowband filters were specified to have the same passband profile (scaled in $\delta\lambda/\lambda$). Center wavelengths and profiles are accurately uniform over the filter clear apertures, and laboratory calibrations include profiles, blocking, and temperature shift coefficients. The narrowband set now includes a linear variable filter which provides a passband FWHM $\delta\lambda/\lambda = \sim 1\%$ over the 3700-9800 Ångstrom range. The filter set is illustrated in Figure 5.

Flatfield reference channel. An internal flatfield system will provide reference flatfield images over the spectral range of WFPC-2. The system contains tungsten incandescent lamps with spectrum shaping glass filters and a deuterium lamp. The flatfield illumination pattern will be uniform for wavelengths longward of about 1600Å, and small differences between the flatfield source and the OTA will be handled in terms of correction ratio calibration images. Shortward of 1600Å the flatfield is distorted due to refractive MgF_2 optics, and at these wavelenghs the channel will primarily serve as a monitor of changes in QE. This system physically takes the place of the WFPC-1 solar UV flood channel, which is unnecessary for WFPC-2 and has been eliminated.

2. INSTRUMENT CALIBRATION

Calibration is a process rooted in instrument design and testing. A database of laboratory characterizations of optical components, CCD sensors, filters, and the flatfield channel is needed to support instrument calibration. System-level thermal vacuum testing of the assembled instrument is a critical element in the 'thread-of-truth' leading to a calibrated instrument on-orbit. On-orbit calibration procedures generally require large amounts of HST observatory resources, distract from science observations, and must be generally minimized in practice. For WFPC-2, the inherent stability of the CCD sensors, well calibrated filters, internal flatfield calibration system, and calibration database populated with flatfield images prior to launch will minimize disruptions in science observations and improve science data analysis and productivity.

3. SERVICING MISSION

WFPC-2 science verification requirements are being developed by the science team, GSFC, and the STScI to include: verification of baseline instrument performance, demonstration of optical 'alignability' in the course of reaching best focus and minimizing coma, estimation of residual of wavefront errors from the analysis of star images, demonstration of photometric 'calibratability' with a core minimum set of filters (including visible and UV wavelengths, and consistent with anticipated early science observation requirements), evaluation of photometric accuracy with the core minimum filter set, and measurement of photon detection efficiencies with the core minimum filter set.

Following early alignment and calibrations, further instrument calibration will be interspersed with science observations over an extended period. Calibrations of new modes and filters will be coordinated with GTO and GO science program planning. Initial calibrations of new filters will be merged into the routine STScI maintenance and calibration time to support an increasing diversity of science programs. We expect that the nominal 10% of spacecraft time devoted to instrument maintenance and calibration will be increased in the first year following the servicing mission, in order to accommodate the timely calibration of all WFPC-2 filters.

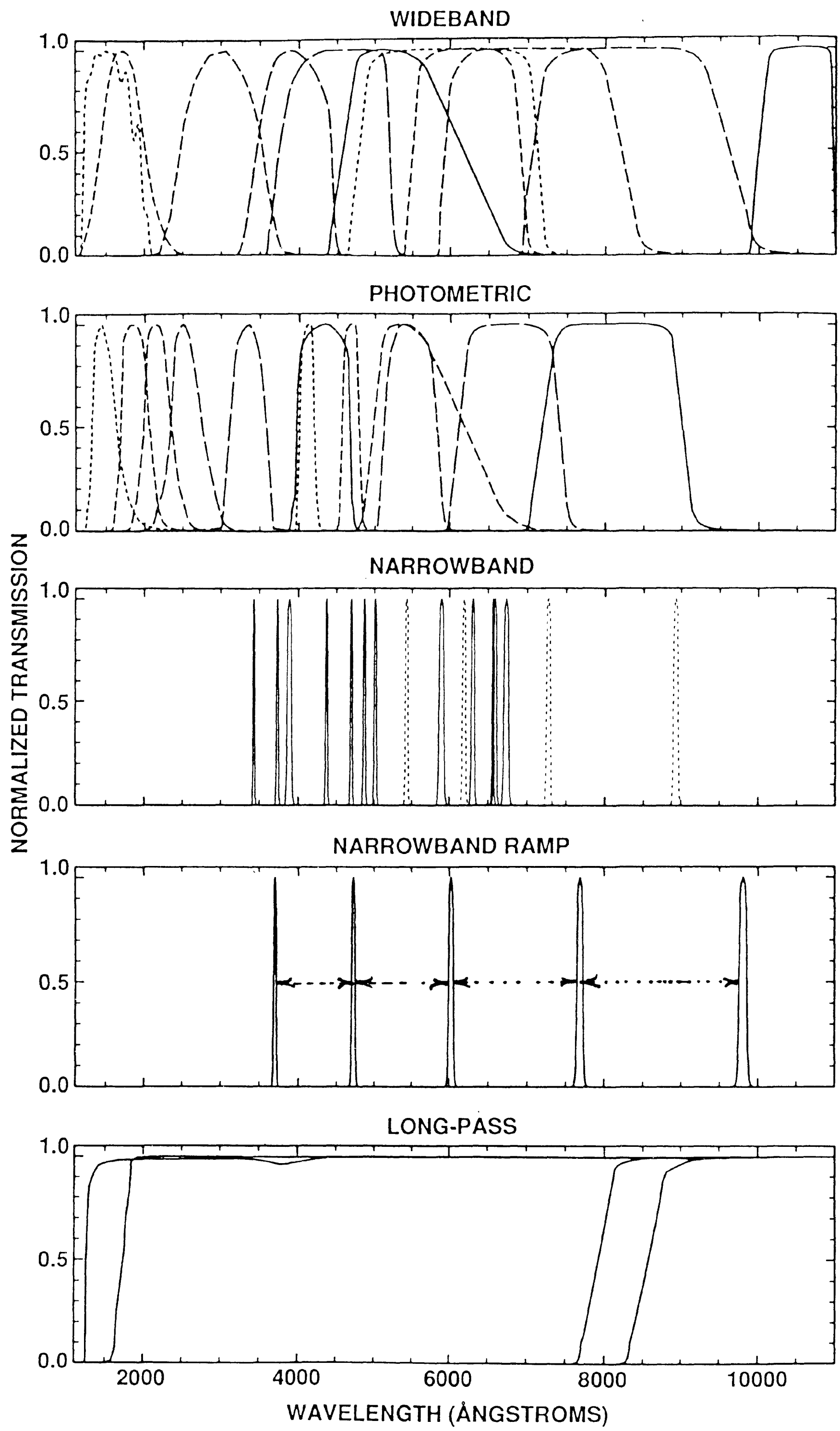

Figure 5. WFPC-2 set of 48 filters.

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