Optical performance verification and calibration of the HST advanced camera for surveys

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ABSTRACT

The Advanced Camera for Surveys (ACS), scheduled for installation on the HST observatory in December 1999, is nearing completion at Ball Aerospace. This versatile camera, comprising 3 detector systems covering the wavelength range from the far UV through 1.1 micron, a large complement of filters, polarizers, prism and grism dispersers and a coronagraph, must be fully characterized before launch. We present plans for the instrument-level optical performance verification and calibration which will be performed later this year. Our intent is to perform a comprehensive characterization of the ACS to facilitate plans for its use aboard HST and to optimize the scientific usefulness of the immense data volume that ACS will provide. In order to comply with the aggressive delivery schedule and relatively restrictive budget, the calibration program will make use of much of the tools and apparatus developed at Ball for previous HST instruments and the data acquisition process will be improved, applying the lessons learned from those earlier programs.

Keywords : Hubble Space Telescope, HST Advanced Camera for Surveys, ACS, CCDs, filters, calibration

1. INTRODUCTION

The Advanced Camera for Surveys (ACS) is a third generation axial replacement science instrument currently under development for the HST Project by Ball Aerospace Systems Division in Boulder, Colorado. The ACS science objectives, set by its Investigation Definition Team (IDT) led by Principal Investigator Holland Ford at the Johns Hopkins University (JHU), range from wide area surveys in the near infrared to study the early universe and its large scale structure, to high resolution imagery and polarimetry of active galactic nuclei, coronagraphic studies of nearby stars in search of companions and far ultraviolet studies of planetary atmospheres.[1] The ACS design addresses these objectives with a novel optical design aimed at optimizing throughput while delivering well sampled, high quality images over a broad wavelength span.[2] A carefully specified filter complement and a set of dispersers for low spectral resolution survey studies enable a broad range of investigations.[3,4] Three channels are incorporated in the ACS layout, each optimized for specific wavelength coverage, field size and spatial resolution requirements of the ACS science programs. The wide field channel (WFC), intended for survey work in the visible and near IR, covers an area of the sky over 200 arcsec square with 50 milli-arcsec pixels on a pair of butted 4Kx2K CCDs.[5] This high efficiency detector, together with the excellent optical throughput provided by the 3 mirror optical design and enhanced silver coatings, and the wide sky coverage, yield an order of magnitude improvement in discovery efficiency over the current HST wide field camera. The high resolution channel (HRC) employs a 1K square CCD to cover a 25 arcsec field, from the near UV through near IR, with improved efficiency and includes an aberrated beam coronagraphic capability, which permits high contrast studies within about 1 arcsec of bright point sources. Finally, the solar blind channel (SBC) uses a spare detector from the Space Telescope Imaging Spectrograph (STIS) program[6,7] to provide far UV imaging capability over a field of about 26 arcsec. The ACS design and objectives are descibed in detail by Ford, *et al*.[1]

While the ACS is designed to provide a major improvement in the HST science capability, it is being built with a budget and schedule of approximately half that of the previous science instruments. This is possible only because the instrument and its development, verification and calibration programs were designed to make use of the design work, flight hardware spares, flight software and ground support equipment that were developed for the first and second generation HST instruments. The experience gained during those earlier programs has resulted in major cost and schedule savings throughout the ACS program, to date, and must be used effectively during the final stages of integration, verification and calibration, if the instrument is to be delivered on schedule and fully characterized. The completed ACS is expected to be shipped in December 1998 to the NASA Goddard Space Flight Center (GSFC), where it will undergo additional testing in preparation for its shuttle flight to the HST observatory a year later.

This paper describes the program by which the ACS optical performance is being verified and the current plans for ACS calibration prior to delivery to GSFC. (Verification of the ACS operational performance, including tests of the flight software and commanding, is described by Fike and Schoeneweis,[8] in this conference.) These programs have been strongly influenced by the availability of several pieces of test apparatus that were developed for previous instruments; these are described in the next section, followed by outlines of the optical verification program that is already well underway, and the calibration test plan, as currently formulated. Finally, we discuss our plans for optimizing the testing program operations.

2. AVAILABLE TEST APPARATUS

The Refractive Aberrated Simulator/Hubble Opto-Mechanical Simulator (RAS/HOMS) combines a full field optical stimulus closely matched to the HST optical telescope assembly with a high fidelity mechanical mock-up of two sets of axial science instrument latches.[9] This apparatus, originally built to verify the performance of the Corrective Optics Space Telescope Axial Replacement (COSTAR) in 1992-3, provides accurate measurements of image quality and field location/orientation. The RAS utilizes 6 lenses and a pupil mask to represent the OTA obscuration and is fed by an array of single mode optical fibers mounted in a source plate that may be articulated in 3 axes with a micrometer stage. The lenses are anti-reflection coated at 633 nm to minimize ghosting and the fibers are fed by a He-Ne laser via a system of beamsplitters and microscope objectives. The RAS matches the OTA wavefront to better than .05 waves RMS at 633 nm, over the field. RAS/HOMS has, itself, been extensively verified as an accurate representation of the HST observatory by several independent teams using different methods,[10] but the strongest testament to its accuracy comes from the very successful on-orbit performance of the COSTAR,[11,12] STIS[13] and NICMOS[14] instruments, which were tested and aligned using the RAS/HOMS. While RAS/HOMS provides an excellent, full-field match to the OTA beam and provides an accurate tool for image metrology, it is best used at a single wavelength (633 nm) in ambient environment and the instrument under test must be fully integrated into its enclosure, with latches.

The reflective aberrated simulator for calibration (RAS/Cal) was developed at NASA GSFC for the STIS thermal vacuum (T/V) calibration campaign, as a broadband (far UV to near IR) OTA simulator at the STIS field center. It has subsequently undergone modification at GSFC for use near either of the ACS field center locations and to eliminate susceptibility to vibration that hampered the STIS testing program. RAS/Cal uses two mirrors (a conic and an asphere) to mimic the OTA spherical aberration and astigmatism at these two field points only; two additional mirrors steer the beam. Its all-reflective design and use of vacuum compatible materials, along with a thermal control system, permit RAS/Cal to operate in the far UV in a thermal vacuum chamber. Motors allow the remote selection of entrance aperture size, focus, beam steering and insertion of several standard calibrated detectors into the output beam. The RAS/Cal image quality has been verified using the same techniques employed for RAS/HOMS evaluation and shown to properly match the OTA wavefront to better than .05 waves (633 nm) at the two design field points. In addition to its vacuum calibration duties, RAS/Cal is also being used for ACS optical alignment and verification in ambient conditions and under dry nitrogen purge to facilitate alignment of the SBC in the far UV.

When used in the vacuum chamber at Ball, the RAS/Cal entrance aperture is fed by the Calibration Delivery System (CDS) that was developed for STIS T/V calibration. CDS includes a monochromator, with full wavelength coverage using 3 turret-mounted gratings, a set of interchangeable continuum and emission line lamps, and several ganged wheels housing a selection of neutral density and bandpass filters. The CDS beam is collimated and sent through a MgF_2 window on a port in the vacuum chamber wall; inside the chamber the beam is folded and reimaged onto the RAS/Cal aperture. A beam selection mirror permits imaging of either the monochromator exit slit or the emitting volume of a lamp (attached to a separate appendage of the CDS vacuum enclosure) onto the RAS/Cal aperture. Because the main chamber is isolated by the window from the CDS, lamp configuration changes involve cycling of the CDS vacuum only, a process that typically takes less than an hour.

A number of additional test articles that were developed for COSTAR and STIS are being applied to the ACS verification program. Among these is the Ball image analyzer (BIA), which consists of a commercial Photometrics^{TM} CCD camera head mounted on precision-aligned 3-axis motorized stages. The BIA is used in the verification of the RAS/HOMS and RAS/Cal, providing image data that can be used for accurate determination of aberration content (using phase retrieval) and image location (chief ray) metrology. Another device, the aberrated beam analyzer (ABA),[10] was developed at the GSFC for independent verification of RAS/HOMS for COSTAR and has subsequently been used to align and check RAS/Cal for both STIS and ACS. Other key test equipment with heritage in the earlier HST programs include: a Zygo Mark IV interferometer, used for optical figure testing of the mirrors and filters, and verification of their mounts; the CCD test dewar, controller and illumination system; and the multi-anode microchannel array (MAMA) detector test apparatus, developed for STIS and used most recently to calibrate the STIS spare MAMA detector for the ACS SBC.

3. OPTICAL PERFORMANCE VERIFICATION

3.1 Objectives

There are two main objectives of the optical performance verification program: to assess progress of the instrument toward its completion during its subsystem construction and integration phases, and to characterize the final product in key areas against the contract end item (CEI) specifications and the expectations of the ACS user community. By closely monitoring the performance of the components as they are procured and the subsystems as they are assembled, problems can be avoided at later stages of development, when solutions are likely to become more costly and carry greater risk to both hardware and schedule. Furthermore, as parts or subsystems are shown to perform better than expected, specifications and tolerances for later stages of development may be relaxed correspondingly, with no risk to final performance while bringing potential cost and schedule savings to the program.

3.2 Component-level tests

Each of the ACS optical and detector components was carefully specified to assure that the instrument would meet its final performance requirements. Nearly all of those components are now delivered and most of their specifications have been directly verified by test at the vendor, at GSFC, and/or at Ball.

The reflectance of each of the mirrors was measured independently at Ball and at the vendor using witness articles with similar surface quality and coated with the flight mirrors. Figure was also measured interferometrically at Ball for the flats and spheres; figures of the more complex mirrors were assessed at the vendor only, as was surface roughness. The detector window transmissions were measured directly at Ball as well as their transmitted wavefront. These measurements were used to select the flight articles and to populate the preliminary end-to-end efficiency models that are used for calibration planning. Several of the witness mirrors are kept with the flight optics as they are integrated into the instrument and serve as contamination monitors.

A major effort has been underway to assure that the ACS filters are well characterized before delivery to Ball. The filters were all procured by GSFC and tested in special facilities set up there expressly for this purpose. Measured quantities include transmitted wavefront, spectral transmission, out of band blocking, and transmission uniformity, as well as polarization angle and efficiency for the polarizers and dispersion for the grism and prisms. The filter test program is detailed by Leviton, *et al*.[15] and Boucarut, *et al*.,[16] in this conference.

The mounts for both filters and mirrors were also carefully developed and tested to assure that no significant strain is imparted to the optic while maintaining positioning accuracy through launch. Interferometric measurements were obtained before and after vibration testing with dummy optics to verify effectiveness of the mounts.

Another primary focus of attention has been placed on testing and selection of the CCD devices to be incorporated in the flight detectors. Each device is tested first at the vendor (SITe, Inc.) and potential flight candidates are then packaged and subjected to a comprehensive set of measurements at Ball. Select devices are also being characterized at the Johns Hopkins University, the Lick Observatory and at the University of Arizona, where special backside treatment is being applied to some devices under the direction of Dr. M. Lesser.[17] The ACS CCDs and their characterization and selection programs are fully described by Clampin, *et al*.[5], in these proceedings.

3.3 Subsystem-level tests

Each of the three detector subsystems will undergo a rigorous verification program involving vibration and thermal/vacuum environmental tests interlaced with functional test sequences in ambient conditions. These tests and their associated apparatus were largely developed during the STIS program at Ball. The SBC MAMA (a STIS spare) has successfully passed through its full suite of tests and is ready, at the time of writing, for installation in the optical bench. Each of the CCD subsystems (at least two flight devices for each channel, in addition to an engineering model "pathfinder" for the unique WFC detector will be produced), will be mated with a test bench simulating the flight electronics for optimization of clocking pattern and bias voltages and functional testing. These tests will include dark rate, gain, read-noise, linearity and CTE measurements, as well as imaging verification with point source and flat field illumination.

A number of end-to-end checks of the optical alignment during the course of instrument integration are planned. The optical alignment is accomplished with a dedicated system of alignment telescopes, theodolites, and associated tooling for accurate placement of each element in 3-space and orientation. RAS/Cal will then be used to illuminate the instrument at the field center of each channel so that the alignment can be assessed in terms of image location, quality and focus. This is especially important for the SBC, since its further verification must await the T/V testing very late in the program. Early SBC testing will be achieved by enshrouding the optical bench, RAS/Cal and its illumination system with an air-tight enclosure and purging with pure, dry nitrogen, through which the far UV light to which the SBC is sensitive can pass.

An early test of the WFC optical train was afforded during the alignment program when RAS/Cal was used to produce a point source image on a surrogate detector (a Photometrics CCD camera head) after the three mirrors were installed and aligned on the flight optical bench. This test provided a key verification of the optical model, the as-built WFC mirrors (two of which have complex surface figures and were capably produced by Tinsley), and the alignment methods. The test also employed, for the first time, the corrector mechanism, which incorporates a unique nested eccentric cylinder design for angular adjustment in two axes. The mechanism performed well and the image quality was rapidly optimized to yield encircled energy measures easily meeting the specified goals (>80% within .25 arcsec diameter at 633nm).

Each of the ACS mechanisms, like the detector subsystems, will also be subjected to a series of functional and environmental tests to prove their spaceworthiness before integration into the optical bench. While many of the mechanisms have direct heritage in the STIS program, those that involved significant departure from the earlier design required engineering model unit construction and will be life-tested to beyond the expected on-orbit service. In addition to basic functionality verification, the subsystem test program also involves repeatability assessment, resolver and position transducer calibration, timing tests and interface testing with flight-like test bench electronics. The WFC and HRC shutters also require tuning of their acceleration/deceleration profiles and timing accuracy tests, and the corrector mechanisms must be carefully mapped to calibrate the relationship between resolver and motor step positions and mirror pointing.

3.4 Instrument level verification tests

After the instrument is fully integrated into its enclosure, a series of comprehensive test sequences, which exercise all of the primary ACS operational modes will be executed. These "functional tests" will bracket an acoustic vibration test and will be run multiple times through the T/V test program, as the instrument is thermally cycled through "hot" and "cold" environments that simulate the expected extremes that it may experience on-orbit. Further repetitions of the functional testing will be performed in ambient conditions while the ACS is prepared for launch at GSFC and KSC to assure that instrument integrity is maintained through transportation and handling.

In addition to the functional tests, a number of other verifications of key specifications will be made in ambient and/or T/V environments. The list presented below represents the plan at the time of this writing and may be modified as more becomes known about the instrument performance.

3.4.1 Detector performance parameters

Dark rate, read-out noise (CCDs only), dynamic range, and cosmetic defect fraction will be measured. While some of these measurements will be repeated often during the course of subsystem testing and instrument integration, definitive measurements must be made in the final configuration under realistic environmental conditions, in the T/V phase.

3.4.2 Image quality at field center

Encircled energy vs. radius and FWHM measurements will be made for each channel at a point near the center of the field only (this point will be offset from the WFC midline gap). For the WFC and HRC channels, these are best measured using RAS/HOMS at 633 nm, after adjusting the corrector mechanisms to optimize image quality. For the SBC, RAS/Cal measurements during T/V will be required, using Kr line lamp (124 nm) illumination through CDS, again after optimizing the image quality with the HRC/SBC corrector.

3.4.3 Radiometric throughput

RAS/Cal throughput measurements will be made during T/V, at the CEI-specified wavelengths for each channel, using the CDS monochromator and RAS/Cal radiometer, with illumination provided by continuum lamps; quartz tungsten halogen (QTH) will be used for visible wavelengths, deuterium for the UV. The measurements will be made near field center only. A large RAS/Cal aperture will be used to provide illumination over a substantial area of the detector.

3.4.4 Throughput stability monitoring

UV throughput will be monitored while ACS is under vacuum as a tracer of optical contamination or detector instability. Care will be taken to assure that the far UV response of the instrument is not impaired by outgassing contaminants and photopolymerization on the optical surfaces; the instrument will not be subjected to significant levels of UV illumination early in the vacuum cycle. Repeated measurements of the response near 122 nm (SBC) and 200 nm (HRC) will be made to assess stability.

3.4.5 SBC out-of-band rejection

The sensitivity of the SBC to radiation longward of its nominal passband will be assessed using the RAS/Cal with QTH lamp illumination in the T/V chamber. A bootstrapping approach utilizing neutral density filters will be required to reach the required dynamic range of 10^6.

3.4.6 Shutter linearity and repeatability

Tests will be made to assess the WFC and HRC shutter performance over their range of nominal open times. A series of images from the minimum exposure time (.1 s for HRC, .5 s for WFC) up to 100 s (at which any shutter variations should have negligible effect) will be obtained with flat field illumination using a large integrating sphere in the ambient environment. Multiple images will be obtained at the shorter exposures to assess repeatability. Neutral density filters or changes in lamp flux may be required to adequately cover the exposure range without saturation.

3.4.7 Flat field uniformity and stability

The 10% response uniformity requirement will be verified for a selection of optical modes, including at least 2 filters with each channel. A large integrating sphere situated directly in front of the ACS aperture, providing uniform illumination from its QTH lamp, will be used for WFC and HRC flats. The SBC will be measured in T/V with a diffusing screen installed in between the RAS/Cal output port and the ACS aperture. This reflective diffuser, made of the same material (Spectralon) used for the on-board calibration subsystem, will be directly illuminated by the CDS beam, requiring an optical configuration inside the vacuum chamber (hence a vacuum cycle). This configuration may also be used for WFC and HRC flats while ACS is in the chamber. Verification of the flat field stability requirement will be problematic during ground testing, since the instrument environment and test apparatus configuration will not likely be stable enough to make meaningful measurements over the specified 60 day span. However, flat field measurements in several modes will be repeated over shorter intervals to assess stability.

3.4.8 Verification of the internal calibration system

The internal calibration lamps will be used to make flat field images in order to demonstrate their utility for on-orbit calibration. Selection of the flight the spectral shaping and neutral density filters that are incorporated into the calibration optics train will be made to achieve the best compromise in flux level through the wide range of filters and dispersers. Repeated measurements using the on-board system may provide the most useful constraints on flat-field stability for the WFC and HRC. The onboard lamps are limited-life items so their use for ground testing must be restricted to measurements for which external illumination is impractical and a log must be kept of their cumulative operation time.

3.4.9 Instrumental (induced) polarization

This will be assessed for the WFC and HRC by illuminating ACS with a highly un-polarized source (the same large integrating sphere used for flat field illumination) and using the polarizer filters to measure the induced polarization at several wavelengths covering the HRC and WFC spectral ranges. This measurement assumes knowledge of the polarizer efficiencies, which are measured at the component level, and the relative angles between each of the 3 filters of each set, which is a calibration item.

3.4.10 Image stability

There are two image stability requirements, one regarding short-term jitter and the other referring to longer-term drift. The former will be assessed by obtaining rapid series of short (exposure time equal to minimum shutter open time), sub-array (to expedite readout) images of a simulated point source from RAS/Cal in the T/V chamber with both the WFC and HRC. Drift will be measured during thermal transitions induced by both detector cycling and by changes in the chamber environment, as well as during thermally quiescent periods. Repeated images of the RAS/Cal point source will be obtained for 2 hr periods with no intervening ACS mode changes.

3.4.11 Mechanism functionality and repeatability

Each of the mechanisms will be operated repeatedly as part of the functional test sequence. Positioning repeatability of the coronagraphic masks, HRC/SBC selector mirror, filter wheels, and corrector mechanisms will be assessed during the T/V campaign with sequences of repositionings during which the ACS is otherwise quiescent. The coronagraph mask repeatability will be measured using external diffuser screen illumination. The RAS/Cal point source will serve for the channel selector (M3) and corrector measurements. Filter wheel repeatability will be checked using ramp filters (in wheel 2) in combination with the grism (in wheel 1) while RAS/Cal reimages the monochromator exit slit, with the monochromator delivering broadband illumination (zero order, QTH lamp). The position of the resultant image indicates wheel repeatability; a sequence of wheel 1 repositionings (with wheel 2 stationary) will be followed by a series of wheel 2 repositionings (with wheel 1 stationary). Corrector repeatability will be assessed using RAS/Cal point source illumination while adjusting in angle and focus. It will be particularly important to ascertain the level of angular (tip/tilt) wander while the focus is adjusted, as this will bear on the on-orbit alignment operations plan.

4. CALIBRATION PLAN

4.1 Objectives

The calibration program is designed to extend the verification measurements beyond those needed to demonstrate compliance with the instrument specifications in order to more fully characterize the ACS performance. Detailed knowledge of ACS operating parameters is required by the STScI to develop optimal instrument commanding and scheduling software and to apprise the user community of ACS capabilities so that astronomers can develop appropriate proposals for its use and the scientific productivity of the instrument can be maximized. A major goal of the calibration program is to provide the reference data required to remove the instrumental signature from the science data, so that they can be properly reduced and analyzed. Reference files for use in the STScI routine science data processing "pipeline" must be developed from the calibration measurements and delivered to the STScI to populate the calibration data base in time to support ground systems testing prior to launch.

Other objectives of the calibration program are to accrue experience with the ACS while subjecting it to sufficient run time in all of its modes to assure that "infant mortality" issues are not of concern and potential operations problems which may occur only in rare circumstances are addressed. The program also provides an opportunity to test the validity of the adopted data reduction strategies and may identify shortcomings of the plans that were developed without detailed knowledge of actual ACS characteristics.

4.2 Calibration measurements

The suite of calibration measurements that is currently envisioned is presented in this section. Schedule and budgetary pressures are likely to affect the degree to which this plan can be completed, but with careful planning, scheduling and prioritization, a large majority of the planned goals should be achievable. This calibration program is likely to evolve as more becomes known about the as-built ACS characteristics.

4.2.1 Detector properties vs. temperature

As an extension of the verification measurements described above, the CCD dark current and charge transfer efficiency (CTE), using the extended pixel edge response (EPER) method, will be measured as functions of the CCD temperature. These measurements will be made while the temperature control setpoint is lowered incrementally, during T/V nominal environment testing, to characterize the behavior of the TEC control system and to determine the minimum stable CCD operating temperature for each detector. These measurements should be scheduled early in the T/V program and used to select the nominal setpoints for the remaining calibration activities. Flat field illumination is required for the CTE measurements; use of the onboard lamps may be required since the external flat field illumination configuration may not be available early in the T/V program. The SBC MAMA dark count rate should also be assessed as a function of detector temperature (which depends on length of operation time), since this detector has exhibited dark rate temperature sensitivity during subsystem testing.

4.2.2 Detector linearity

The photometric linearity of all 3 detectors will be established during component or subsystem testing, but will be measured again in the final flight instrument configuration. Measurements will be made with both flat field and spot illumination. SBC measurements will be performed in the T/V chamber using RAS/Cal for point source illumination and the external flat field configuration for wide area illumination. The CCD full well level can be assessed in ambient, using either RAS/HOMS or RAS/Cal for point source simulation and an integrating sphere for wide area illumination. The CCDs must be operated cold during these measurements.

4.2.3 Geometric calibration

Plate scale (arcsec/pixel) and detector orientation with respect to the vehicle (V2/V3) axes will be measured for the CCD channels in RAS/HOMS, as well as the mapping between detector and vehicle coordinates and the location of the coronagraph field masks. The RAS/HOMS source plate will be designed to project point source images at the nominal field center and corner locations for the WFC and HRC. The source plate can be accurately articulated to establish plate scale and actual field boundaries. These measurements will proceed after the image quality is optimized with the corrector mechanisms. SBC field location and scale can be determined by comparison between SBC and HRC images projected by RAS/Cal in T/V.

The geometric distortion of the ACS optical design is significant, with anamorphism on the order of 10% in all channels and additional higher-order distortion in the WFC due to the Schmidt plate correction of the large field. This distortion will be measured using RAS/HOMS with a special target plate comprising either a precision Ronchi ruling or a mask with a regular pinhole pattern backed by a transmissive diffuser and illuminated by an incandescent lamp. An iterative solution to the distortion over the field can be derived from a series of images obtained while the target plate is translated by precisely known amounts using its micrometer stage. An initial estimate of the SBC distortion will be produced by combining the HRC distortion map produced with the method described above with the map of the inherently large distortion of the MAMA that was obtained during subsystem testing.

4.2.4 PSF characterization

The instrumental PSF will be measured both in the core and wings as a function of field position. Encircled energy and FWHM characteristics will be measured at 633 nm only for the WFC and HRC in RAS/HOMS, which provides proper illumination over the field. Measurements of the PSF wings at other wavelengths, to measure the extent of the red halo effect,[18] will be performed with RAS/Cal, near field center only, during T/V. The SBC PSF characterization must also be performed with RAS/Cal during T/V; the CDS Kr and Xe line lamps will provide illumination at 124 and 147 nm, respectively. These point source images must be deep enough to characterize the full extent of the PSF wings; a range of exposure duration may be required to permit comparison of wing to core intensity without saturation. The residual PSF of point sources centered on the coronagraph masks and “Fastie finger” occulting bar in the HRC will also be measured at 633 nm in RAS/HOMS.

4.2.5 Throughput

The small set of throughput measurements included in the verification program will be extended to all optical modes (valid combinations of filter or disperser and channel). While a detailed mapping of the response profile of each filter would be prohibitively lengthy, measurements at nominal band center and at wavelengths of the nominal 20 and 80% of peak T will serve to provide sufficient verification of the throughput models developed from the extensive component characterization program. These measurements will be made near field center only using the RAS/Cal radiometric capability and the CDS monochromator channel with QTH, deuterium, or Kr continuum lamps. Radiometric calibration is extended over the full field by normalization of the flat field images obtained at the same wavelengths. The absolute accuracy of the throughput determinations should be better than 10%.

Two other aspects of filter throughput will also be investigated. The response of the UV filter modes of the HRC to red light is particularly important to quantify as any significant "red leak" can preclude use of these filters for studies of all but hot objects. Red blocking measurements will therefore be made of the filters with central wavelengths below 400 nm, using RAS/Cal with broad band illumination from a QTH lamp through a long pass filter. These measurements may be made in ambient or during the T/V testing. The second investigation concerns the utility of a small set of filter combinations for purposes of attenuating the signal from very bright targets during the autonomous acquisition of targets to locations centered behind the coronagraph masks. The throughput of these filter combinations, which nominally provide attenuation of up to 10^4, will be measured at several wavelengths covering the full spectral range of the HRC detector.

4.2.6 Flat fields

Flat field images with pixel-to-pixel noise of less than 1% RMS will be obtained for each valid filter or disperser and detector combination. For the CCD channels uniform illumination will be provided by a large integrating sphere situated directly in front of the ACS aperture and fed by a QTH lamp or a deuterium lamp for wavelengths below about 300nm. Sets of high signal-to-noise images will be obtained with broadband illumination and combined with cosmic ray rejection to produce the required flats. SBC flats will be obtained in the T/V chamber using the configuration described in sec. 3.4.5, above. Because of the MAMA global count rate limit, SBC flats will be time consuming, requiring of order 10 hr to accrue the desired signal-to-noise ratio. While care will be taken to produce illumination as uniform as possible with the Spectralon screen, it is anticipated that the chief utility of these flats is for correction of high spatial frequency (pixel-to-pixel) response variation; low frequency flats will be derived from on-orbit measurements.

Flat field variations in the WFC and HRC at wavelengths above 700 nm will be significantly affected by interference patterns ("fringing") in the thinned, backside-illuminated CCDs. This effect will be strongly dependent on the spectral bandwidth of the illumination. Flat field images will be obtained with the vacuum chamber flat field screen and the CDS monochromator set at a variety of passbands and wavelengths between 600 and 1100 nm to investigate the amplitude of this fringing effect.

The optimal strategy for flat-fielding ramp filter images remains unclear as of this writing. It will be prohibitively time-consuming to obtain flats for each possible wheel position (central wavelength setting), but the viability of interpolating between flats taken at several wheel positions is unknown. This interpolation approach will be investigated by obtaining sets of high signal-to-noise flats at 5 wheel positions, spanning the full range, for each ramp filter. If the variation with wavelength is more severe than anticipated, additional flats at intermediate wheel settings may be required.

Another aspect of the radiometric calibration over the field is the uniformity of the shutter open time. This shutter "shading" effect will be evaluated using the same data set used to evaluate shutter linearity and repeatability as described in sec. 3.4.5; comparison of the field dependence of the ratio of short and long exposures will yield the shading correction.

4.2.7 Dispersion

The dispersion (nm/pixel vs. wavelength) of the ACS grism and its 3 prisms will be directly measured at field center only. Dependence on field position, primarily in the dispersion direction, is expected since the chief ray angle through the disperser varies, but we will rely on model predictions of this effect, since no apparatus exists for its proper measurement. At the low resolving power of the ACS dispersers (R~100, degrading to R~10 at longer wavelengths for the prisms), the traditional use of spectral line lamps for this purpose becomes difficult due to line blending, necessitating a less efficient approach. The RAS/Cal and CDS monochromator will be used to select a series of approximately 10 wavelengths spanning the nominal range for each disperser, which will be imaged in turn without intervening configuration changes. This method relies on the monochromator wavelength calibration, which must be performed (using standard line lamps), prior to the T/V calibration campaign. The direction of the dispersion (nominally parallel to the CCD serial registers) will also be determined from these measurements.

4.2.8 Ramp filter calibration

The central wavelength of each ramp filter segment must be calibrated as a function of wheel position. The component testing to date indicates that the passband varies sufficiently smoothly (as specified) that the central wavelength at any position can be interpolated from 5 points over the range covered by the ramp segment. Nevertheless, mapping of the passband edges for each of the 100 configurations would be tedious and time consuming and the suite of calibration apparatus currently in hand does not support this approach. An alternative method would use an objective grism in the RAS/HOMS pupil plane to produce dispersed images at the focal plane; the position of the image passed through the ramp would indicate the central wavelength after calibration of the spectrum (wavelength vs. detector coordinate). A single image would be required for each ramp position, facilitating the calibration immensely, but an appropriate grism (similar to the flight grism, but on a substrate that passes wavelengths as low as 360 nm) would need to be procured.

4.2.9 Polarimetric efficiency, angle

Measurements will be made of the polarization angle of each polarizer filter and the efficiency, *i.e.*, the degree to which they modulate a fully polarized beam. The measurements will be made in ambient, using RAS/Cal with a QTH or deuterium lamp and a polarizing prism inserted into the beam path in front of the ACS. The prism will be mounted on a precision rotation stage from which the absolute angle about the beam axis can be read to within 1 degree. For the polarization angle measurements the prism will be rotated in 1 degree increments about the nominal filter angle while a series of images are obtained. The series will then be repeated at prism angles about 90 degrees from the nominal filter angle. Measurements will be obtained for all 6 polarizing filters, combined with broad bandpass filters at each end of their nominal wavelength range.

4.2.10 Straylight characterization

A series of measurements will be undertaken while the instrument is in RAS/HOMS, to detect and quantify image artifacts due to inadequate straylight rejection. Such artifacts include “ghosts” from detector window and filter reflections, glints from baffle or mask edges at the margins of the fields of view and other spurious light paths that produce undesired illumination of the detectors. While it is difficult to conceive of a straightforward test suite to discover all possible straylight paths, most significant artifacts will likely surface as the ACS progresses through the verification and calibration programs, with their sundry illumination schemes and use of all of the instrument optical modes. Nevertheless, special observations will be made to assess the level of straylight from sources just outside the fields of view using white light illumination of an inverse FOV mask on the RAS/HOMS target plate, and to detect undesirable scatter by placing a bright point source image on the edges of the “Fastie finger”, at the edges of the ribs between the ramp filter segments, and in the gap between the two halves of the WFC detector.

The ACS enclosure rejection of ambient light in the HST aft shroud must also be tested. This can be accomplished by a continuous series of exposures with the WFC and HRC, undertaken while a bright light source (a fiber light) is passed around the enclosure panel edges, vent ports and any other potential light leaks.

5. OPTIMIZATION OF TEST OPERATIONS

As described above, the currently envisioned ACS verification and calibration program comprises a very large number of observations to be obtained in many test configurations and under tight schedule constraints. All of the instrument level testing will ideally be accomplished in the 5 months currently scheduled between the completion of integration and final delivery from Ball to the GSFC, although additional ambient calibration at GSFC could be undertaken at additional expense while the instrument awaits shipment to KSC for launch. In order to maximize the probability of delivering an adequately characterized ACS to GSFC, the test planning and operations must be optimized and the program must be prioritized to assure that the measurements of primary importance are completed.

It is nearly certain that some of the investigations now planned will remain uncompleted, even with the most careful planning, due to unforeseen circumstances. Hence, the schedule of test activities must reflect the following priorities:

- Verify CEI specifications. These are the most fundamental benchmarks of instrument performance and contractual obligations require that they be verified.

- Assure that the instrument configurations required for the science program developed by the investigation definition team are fully characterized. Assign higher priority to measurements which support the most used ACS modes, and vice-versa.
- Assure that all data required for definition of the ACS commanding software is acquired in timely fashion so that development and testing of the ground software system may proceed according to schedule.
- Emphasize measurements that are difficult or impossible to perform on-orbit because of the need for special illumination or instrument control requirements.
- Use time in the thermal/vacuum chamber for those measurements that cannot be made in the ambient environment. The T/V test time is a precious resource and must be reserved for test that require the vacuum environment or the RAS/Cal and CDS test apparatus.

The most effective means of optimizing the test program is careful, detailed planning at all levels, from the broad ordering of test sequences so that interdependencies are properly handled, to scheduling work on both hardware and software tools required for test support so they are ready when needed, to accurately estimating the times required for individual exposures and their set-up overhead times. The experience accrued during the previous HST test programs will continue to prove invaluable in guiding the ACS planning process. It is essential that test details be fully developed, especially for the T/V program; ambient testing prior to the T/V campaign provides a relatively low cost opportunity to evaluate T/V verification and calibration plans and assures that major aspects of instrument operations are nominal before committing to T/V.

An important tool for detailed test definition is an exposure time calculator based on the most current estimates or measurements of individual component efficiencies. Several such calculators are in various stages of development by the IDT, GSFC and the STScI, ranging from simple spreadsheets to sophisticated packages capable of image simulation and including detector effects. The latter tool is intended for development of optimal science program specifications but may see its first use in assisting the ground calibration program planning.

The efficiency of the test program may also be strongly affected by the way in which the exposure sequences are carried out. Generally, the optimal use of time will be achieved with stored command sequences (SMSs) that operate the ACS in the same way as it will be used on-orbit. Early development of these SMSs permits review and verification by running against the ACS simulator test bench. Stored command operation avoids the risk of manual command errors and operator confusion that may result in substantial inefficiency, but the SMSs must be properly sized to avoid large losses of time when set-up errors occur. It is essential that sufficient personnel support be available (around the clock during T/V testing) to support rapid adjustment of SMS exposure specifications with revised and verified versions in order to keep the program flowing smoothly. Even with this support, some exposures are better executed with realtime command sequences, issued by the SITS operator according to written (and reviewed) specifications. These include investigations of proper exposure levels or adjustments of illumination pattern, etc., when new test apparatus is introduced. Whenever possible, test apparatus should be characterized and verified in advance, so that realtime commanding and its attendant risks can be avoided.

The test data must be rapidly analyzed and reviewed as they are produced to assure that test objectives are met and to detect any anomalies that will require further investigation. This process begins with conversion of the data packets from SITS into standard form (FITS) and inclusion, with the image data, of all information required to document the exposure parameters, ACS and stimulus configurations and any engineering data that may be useful for analysis. The data will then be archived and ingested into a database for future reference. This process will be automated to the extent possible to relieve the on-site personnel of some of the burden of realtime data logging and to improve its uniformity and accuracy, but some manual input will be required.

The near realtime data analysis needed to optimize the test flow will be achievable only if the required software tools are developed and verified in advance and sufficient trained personnel and computing resources are available. Several quick-look tools are already available and in use for the component and subsystem testing. Others can be readily adapted from those developed for STIS calibration, but some new capabilities, such as polarimetric analysis tools, will be required. The ACS science team, including members of the IDT as well as instrument scientists and data analysts from the STScI, will provide timely support both on-site at Ball, for test direction, data logging and rapid reduction, and at their home institutions, for data analysis. A system of workstations, printers and data storage media will be assembled at Ball to support the test program and data will be archived at the STScI for future reference.

Finally, it is essential that excellent communications be established among the test and analysis personnel, especially during the 24 hr/day T/V operations that will require multiple shifts. Shift leaders will be required to keep complete, accurate logs and overlap with preceding and following shifts. Daily assessments of the test progress and schedule priorities will likely also be required as the inevitable variances arise. Nevertheless, with careful planning, early preparation and the combined efforts of a dedicated ACS science and engineering team, a well characterized instrument will be delivered to the HST observatory to greatly improve our view of the universe at the start of the new millenium.

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