Broadband interferometer for measuring transmitted wavefronts of optical band pass filters for Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS)

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ABSTRACT

The transmitted wavefronts of optical filters for the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) are characterized using the Wildly and Openly Modified Broadband Achromatic Twyman Green (WOMBAT) interferometer developed in the NASA/GSFC Optics Branch’s Diffraction Grating Evaluation Facility (DGEF). Because only four of thirty-three of ACS’s optical bandpass filters transmit the 633 nm light of most commercial interferometers, a broadband interferometer is required to verify specified transmitted wavefront of ACS filters. WOMBAT’s design is a hybrid of the BAT interferometer developed for JPL used for HST Wide Field and Planetary Camera II (WF/PC-2) filters and a WYKO 400 phase shifting interferometer. It includes a broadband light source, monochromator, off-axis, parabolic collimating and camera mirrors, an aluminum-coated fused silica beamsplitter, flat retroreflecting mirrors for the test and reference arms, and a UV-sensitive CCD camera. An outboarded, piezo-electric phase shifter holds the flat mirror in the interferometer’s reference arm. The interferometer is calibrated through interaction between the WYKO system’s software and WOMBAT hardware for the test wavelength of light entering the beamsplitter. Phase-shifted interferograms of the filter mounted in the test arm are analyzed using WYKO’s Vision for Optical Testing® software. Filters as large as 90 mm in diameter have been measured over a wavelength range from 200 to 1100 nm with a sensitivity of λ/200 rms at λ = 633 nm. Results of transmitted wavefront measurements are shown for ACS fixed bandpass and spatially-variable bandpass filters for a variety of wavelengths.

Keywords: Interferometry, Optical filters, Wavefront, Advanced Camera for Surveys

1. INTRODUCTION

The capabilities and science requirements of the ACS instrument place stringent requirements on not only spectral aspects for its filters but also on their allowable transmitted wavefront error. The ACS instrument wavefront error budget allocates λ/70 rms (λ = 633 nm) to filter transmitted wavefront for any 7 mm diameter area on the filter (roughly the size of a beam footprint at the filter from a point source on the sky). Most ACS filters (only a few of which transmit 633 nm) are nearly 90 mm diameter. In order to verify each filter’s suitability for flight in terms of transmitted wavefront, an interferometer would have to be brought to bear which would be able to measure wavefront error in transmission for filters having these collective attributes.

An interferometer system known as the Broadband Achromatic Twyman-Green interferometer (BAT) was developed for NASA/JPL to measure the transmitted wavefronts of HST Wide Field and Planetary Camera II (WF/PC-2) filters which are of order 50 mm square. This simple "tabletop" instrument is cost-effective, compact, portable, rugged, and suitable in construction for commercial application. However, as designed, it could not handle filters as large as those for ACS. We investigated purchasing an upgraded version of the BAT which would handle ACS-sized filters and would provide digital output, but cost, schedule, and the availability of its developer would not permit this. Since we already had some of the necessary hardware in our labs, and since we had no concerns for compactness, portability, or commercial application, we built the WOMBAT interferometer system with revised specifications based on lessons learned from the BAT, making improvements along the way with the luxury of the real estate afforded by a large optical table.

The BAT and WOMBAT interferometers are similar in that they both cover the wavelength range from 200 nm to 1100 nm using all reflective optics except for a fused silica beamsplitter. Other common features include a compact...
monochromator and UV sensitive CCD camera. The first main difference between WOMBAT and BAT are their optical arrangements used to collimate the monochromatic source light and to image the filter aperture onto the camera. The BAT used a single spherical mirror in an off-axis alignment to both collimate and re-image the beam. This arrangement makes the interferometer compact but at the expense of some distortion of the pupil image, even for filters the size of those for WF/PC-2. In contrast, WOMBAT uses two off-axis parabolic mirrors -- one for near-perfect collimation of the monochromated source and one just for re-imaging the pupil with negligible distortion even for large filters.

The next main differences between WOMBAT and BAT have to do with the outboarding or duplication of subsystems found in our commercially-available WYKO™ 400 interferometer system to get digitally-captured, phase-shifted interferograms with WOMBAT from which accurate phase information for each point within the aperture of the component in test can be computed. We use as WOMBAT’s imaging device a COHU™ CCD TV camera identical to the one inside the WYKO. This camera was ordered with its CCD socketed so that a UV-sensitive version of its original CCD could be retrofitted. We also outfitted WOMBAT with a phase-shifter for the flat, retro-reflecting mirror in its reference arm. To operate the system, we simply disconnect the camera and phase-shifter cables from the WYKO mainframe and connect them to their outboarded counterparts.

Therefore, WOMBAT can be thought of as a large-aperture hybrid of the BAT and our WYKO 400 interferometer. It is an automated, phase-shifting Twyman-Green interferometer calibrated through interaction between the WYKO Vision for Optical Testing software and the hybrid hardware for the test wavelength of light entering the beamsplitter. Interferograms are collected for some chosen wavelength but are analyzed in units of nanometers to obtain optical path difference (OPD). OPD results in nm can be converted to and reported in waves at 633 nm for comparison to specifications on transmitted wavefront for the ACS filters themselves. A reference interferogram is collected with no filter in test. The OPD from this interferogram is subtracted from the one for the filter in test. The result which pertains to the filter alone is scaled by 0.5 waves per fringe to account for the filter in test being double passed. A "difference" result is also collected by obtaining two interferograms of the filter in succession and subtracting their OPD’s. This result represents measurement repeatability and system noise. The differences are at the noise level of the WYKO interferometer system -- around 0.005 waves rms.

The complete ACS filter set consists of forty-eight different spectral filtration components, comprising bandpass, longpass, and ramp filters of various shapes and sizes, UV and visible polarizers, prisms, and a grism. All but one of the filters for ACS’s Solar Blind Channel (SBC) are far ultraviolet transmitting optical crystals which also transmit 633 nm light and so could be tested in transmission using the WYKO 400 interferometer. The polarizers, prisms, and grism also transmit 633 nm and could be evaluated similarly. Transmitted wavefront for each ramp filter, whose transmission varies as a function of position across the filter, had to be evaluated in WOMBAT at several wavelengths to cover the entire clear aperture of the filter. The passbands for the filter set vary from 5 nm to 300 nm. Of the forty-eight types of filter components, only the medium bandpass Lyman α filter (at 121.6 nm) for the SBC could not be evaluated for its transmitted wavefront. This filter is opaque in the visible due to aluminum layers in its bandshaping coatings. However, the uncoated substrate was measured for good transmitted wavefront before coatings were applied. This completed filter’s surfaces could easily have been measured for figure error in reflection, but, as the coatings are very environmentally sensitive, this test was foregone.

2. HARDWARE DETAILS OF WOMBAT

The basic approach used to obtain broadband transmitted wavefront measurements is to build a Twyman-Green interferometer using reflective optics wherever possible. By using large-aperture, fast, off-axis parabolic collimator and camera mirrors instead of lenses, a wide, achromatic collimated beam is created (figure 1). Any transmissive optical elements used, such as the beamsplitter, are made from fused silica. This construction enables ultraviolet to near infrared spectral coverage.

WOMBAT is built on a 1.5 x 2.4-m (5 x 8 ft) vibrationally-isolated optical table in the DGEF cleanroom which operates at the class 10,000 level. Transmitted wavefronts for ACS filters are measured in an environment that is stable, clean, and in close proximity to other filter metrology stations, thereby minimizing handling and transportation risks to the
Figure 1 -- optical layout of the Wildly and Openly Modified Broadband Achromatic Twyman Green (WOMBAT) Interferometer
filters. WOMBAT's entire optical bench is enclosed in a shroud or tent made from sheets of black, anti-static sheeting suspended over a metal frame. The tent minimizes air circulation in and around the sensitive interferometer cavity providing required fringe stability. The WYKO 400 interferometer is co-resident on this table and shares the same data acquisition system.

Two monochromators are used to achieve the required spectral coverage. The monochromators (Ealing™ models 27-5412 and 27-5214) are identical in size and mechanical configuration and are mounted on carriages for ease of interchange. While these units have motorized tuning, they are usually tuned manually with selection resolution of 0.2 nm. Four sets of interchangeable entrance and exit slits are available with the following widths: 100, 300, 600, and 1000 μm with corresponding bandpasses of 2, 6, 12, and 20 nm, respectively. Wider slits provide more flux for spectral regions where system throughput is low but at the expense of spatial coherence and therefore fringe contrast. 100 μm slits are used whenever possible. The model 27-5412 uses a ruled diffraction grating optimized for the 500 to 1200 nm wavelength range, while the 27-5214 uses a holographic grating optimized for 180 to 600 nm.

Several light sources are used to achieve broadband spectral coverage. A 150 watt fiber optic illuminator with a tungsten-halogen lamp illuminates the monochromator's entrance slit for coverage from 450 to 1000 nm. A 150 watt xenon arc lamp is substituted for the 200 to 450 nm region. Other sources are used for system alignment and monochromator spectral calibration. Initial alignment is accomplished using a HeNe laser. This laser remains in place should realignment become necessary. Diode lasers which have long coherence lengths and LED's can also be conveniently positioned at the monochromator’s entrance slit. The two-meter long, fiber optic light guide evenly illuminates the entrance slit and allows heat from the forced-air-cooled lamp housing to be dissipated remotely so that air turbulence does not disrupt the interferometer cavity. The power supply for the xenon arc lamp with its cooling fan is also kept isolated from beam paths.

WOMBAT's collimating and imaging mirrors are identical 150 mm diameter, f/3, off-axis parabolas. Two 100 mm diameter flat mirrors serve as return mirrors at the end of each arm of the Twyman-Green configuration. The mirrors are made from zerodur and are coated with bare aluminum. The surface figure quality of all mirrors and the beamsplitter is better than λ/20 PV at 633 nm.

The beamsplitter is 150 mm diameter by 25 mm thick fused silica and has a slowly-deposited, aluminum coating roughly 5 to 6 nm thick. In order to coat the beamsplitter with that thickness which provides comparable reflectance and transmittance over WOMBAT's operational wavelength range, we monitored its absolute reflectance and transmittance simultaneously during deposition at a wavelength derived by analysis where the target coating thickness would yield equal transmittance and reflectance. The first deposition was terminated when the transmittance and reflectance became equal. However, on venting the chamber, the aluminum film oxidized and became more transparent, causing the reflectance and transmittance curves to diverge once again. On subsequent deposition runs, the two curves were allowed to cross by an amount roughly equal to the change in transmittance for the initial run which occurred following the end of deposition proper. This "overshoot" produced reasonably well-balanced reflectance and transmittance across the whole band as measured from a coating witness slide after the coating had aged (oxidized) in the days following deposition. Having reflectance and transmittance of the beamsplitter mismatched primarily affects system throughput and not so much fringe contrast since the energy from each arm of the interferometer is still balanced. What one arm initially loses at the beamsplitter to the other's gain, the other loses on return and vice versa.

Both 150 mm diameter parabolic mirrors and the 100 mm diameter flat mirror in the test arm are mounted in correspondingly-sized gimbal mounts providing tip and rotation adjustments with resolution as fine as 0.03 arcsec. The 150 mm diameter beamsplitter is first mounted in an adapter ring which is in turn mounted in a 200 mm diameter gimbal mount also with 0.03 arcsec adjustability. The flat mirror in the reference arm is mounted in the previously-discussed, piezo-electric phase shifter which also has fine tip and rotation adjustments. To allow wide range, independent adjustments of length of the reference and test arms of the interferometer, the mounts for the flat return mirrors travel on manual, micrometer-driven, linear translation stages with 50 mm of travel and with resolution and knowledge of position of 1 μm. The latter resolution and knowledge of settings are essential to acquire and correctly manipulate interference fringes which are only visible for limited stroke of the flat mirrors from 20 to 50 μm.
An uncoated, fused silica compensator, equal in thickness to the beamsplitter, is optionally installed in WOMBAT’s reference arm to equalize the optical paths of the test and reference arms without regard to wavelength. Light from the test arm always traverses the thickness of the beamsplitter three times before reaching the camera. Without a compensator, light from the reference arm would traverse the beamsplitter only once. The optical path through the beamsplitter is a function of wavelength owing to spectral dispersion in fused silica (most pronounced at the UV end of the spectrum). In the absence of the compensator, the optical path difference (OPD) for the two arms can be nulled at some wavelength by axially adjusting the flat mirrors, however, in order to maintain coherence and thus adequate fringe contrast as wavelength is tuned, readjustment is required to maintain that null difference. Further, fringe contrast is reduced when losses in the test arm on each traverse of the beamsplitter are not balanced by similar losses in an uncompensated reference arm. The behaviour of required axial adjustments to the return flats for an uncompensated reference arm are well-understood both analytically and empirically, yet, in practice these adjustments but should be carefully tracked to avoid the inconvenience of losing knowledge of zero-OPD once it has been found.

As the light exiting the interferometer cavity is collimated, the parabolic camera mirror forms an image of the monochromator’s exit aperture at its focal point. The CCD camera is placed just beyond the focus of the camera mirror. The camera mirror and a fused silica field lens located near that mirror’s focus act together as a compound lens to image the interference fringe pattern corresponding to the filter pupil onto the CCD at the proper lateral magnification.

As supplied, the CCD’s short wavelength response limit is about 360 nm due to the glass cover over the chip. According to the CCD’s manufacturer, this CCD chip itself has appreciable quantum efficiency below 400 nm without the glass cover in place, and the glass is easily removed simply by laying the CCD (glass cover side down) for 30 seconds on a hot plate adjusted to about 200°C and carefully prying the glass off after the adhesive holding the glass to the ceramic package softens. After removing the cover glass from one device, we measured the device’s quantum efficiency to be of the order of 0.15 down to 200 nm, confirming the manufacturer’s assertions regarding this CCD’s short wavelength response. The chip was then assembled into the COHU camera.

3. CONFIGURING, QUALIFYING, AND OPERATING WOMBAT

3.1 Setup and alignment

The ability to make the most accurate transmitted wavefront measurements possible with WOMBAT depends on its initial setup and alignment. There are several important aspects to setup which allow efficient and repeatable subsequent use of this interferometer system. The recipe for proper alignment involves standard opto-mechanical and metrologic techniques. Initially, all components are set so that their optical centerlines are all at the same height off the optical table (nominally 200 mm) and at their appropriate locations with respect to the optical table’s grid of threaded holes.

The first optical alignment exercise for WOMBAT produces a collimated beam which is both parallel to the optical table and parallel to its rows of holes. Ordering each off-axis, parabolic mirror with its back surface polished flat and close to perpendicular to the mirror’s optical axis makes this process quite easy. First, an alignment telescope focused at infinity is set up so that it points backwards along the desired collimated beam’s chief ray. Next, an autocollimator is boresighted to the telescope. The off-axis, parabolic, collimating mirror is now interposed between the telescope and autocollimator and placed in its correct location on the table so that its back surface can be seen by the autocollimator. Tip and rotation of the mirror’s gimbal mount are adjusted until the mirror’s back surface is seen in exact autocollimation. The collimator is now correctly located with its axis very close to parallel to the desired collimated beam direction. The alignment telescope directly views the focal point of the collimator where a backlit, 5 µm diameter pinhole is precisely placed. Finally, a HeNe laser/spatial filter arrangement is set up using the pinhole to illuminate the collimating mirror thus creating a collimated beam. Minor adjustments of the collimator’s gimbal mount are made so that the collimated beam satisfies a shearing interferometer. Finally, the pinhole as viewed by the telescope is replaced by the exit slit of the monochromator whose body rotation is adjusted so that when light is injected into its entrance slit, light from the exit slit fills the collimator as uniformly as possible creating a well-collimated beam of uniform brightness.

Next, the flat mirror for the test arm is located at its nominal position on the table with its axial stage at center of travel. The center of this mirror is intentionally offset from the center of the collimated beam because the beamsplitter, once inserted, will laterally offset the beam to the test arm so that the collimated beam will then be centered on the flat. This flat mirror’s gimbal mount is adjusted to autocollimate the light from the monochromator, sending the collimated beam
back into the monochromator. The beamsplitter is now inserted into the collimated beam at its respective location and adjusted so that the center of the beam reflected towards the reference arm -- 90° separated from the test arm -- strikes the center coordinate of the reference arm's flat mirror. The transverse position of the beamsplitter is checked to make sure that it does not vignette the collimated beam for either arm. Next, the reference arm's flat mirror mounted in the phase-shifter is installed and adjusted similarly to the flat mirror for the test arm (now blocked) to autocollimate the beam from the monochromator. A gimbal mount to hold the filter in test is positioned just in front of the test arm's flat mirror. Finally, a HeNe laser is shone through the monochromator, and minor adjustments are made to the flat mirrors and the beamsplitter until fringes can be seen in the space where the beams from the two arms recombine past the beamsplitter. The camera mirror and fused silica lens are configured to relay an image of the filter pupil to the CCD camera which records the interference pattern therein.

The next challenge is finding the interferometer cavity's null OPD which is required when sources with low coherence (such as incandescents) are to be used. The HeNe laser has such coherence that fringes are easily observed with no care taken to null the OPD. A laser diode source was found whose coherence length is only a few cm which allowed us to make a transition from the HeNe laser to incoherent white light sources. First, we started by setting the two arms to nearly the same mechanical length so that we would still be able to see fringes when the laser diode was substituted for the HeNe laser. The axial positions of the arms' flat mirror's were adjusted to probe the space of usable fringe contrast. The axial positions giving maximum fringe contrast were set. On substituting a white light source for the laser diode, fringes were discovered within a short distance from that set point of maximum contrast by making the same type of adjustments over a smaller range and keeping track of what adjustments had been made. The range over which fringes with a white light source can be seen is of order 200 μm. Fine adjustments are made within this range to obtain maximum contrast.

Once satisfactory alignment is achieved, conscious efforts are made to preserve that alignment. All mount settings for translation stages and gimbal mounts are recorded and tracked as adjustments are made. Extreme caution is taken not to perturb the alignments of the beamsplitter and return mirrors when working around them. Alignment can be easily checked by injecting a HeNe laser into the entrance slit of the monochromator at any time.

The monochromator is manually tuned to select the measurement wavelength $\lambda$. If the compensator is not in place, the reference mirror position $I$ must be adjusted to maintain good fringe contrast. Typical behaviour for $\Delta l/\Delta \lambda$ is 2.5 μm/nm. The actual spectral dependence depends on thickness and dispersion of the beamsplitter, so that below about 400 nm, $\Delta l/\Delta \lambda$ begins to increase steadily as fused silica's dispersion increases. As wavelength is changed, the light level is adjusted for optimal fringe digitization. This is done either by selection of slit size or by adjusting lamp power or both. The light source is adjusted transversely behind the entrance slit to assure even illumination across the collimated beam. When the xenon arc lamp is used, a diffuser (made simply by roughening a thin fused silica window) is placed at the entrance slit to create even illumination of the monochromator's collimating mirror.

If fringes of peak contrast are observed with no filter in the test arm (zero OPD), inserting a filter adds double-pass optical path to that arm which is not compensated in the reference arm and causes the fringes to disappear. To once again see fringes, either the reference arm must be lengthened or the test arm shortened by an amount equal to a single-pass change in OPD or:

$$\Delta l = (n_1 - 1) \cdot t_1 + (n_2 - 1) \cdot t_2,$$

where $n_1$, $n_2$, $t_1$, and $t_2$ are substrate indices of refraction at the test wavelength and thicknesses, respectively. Typically, it is the test arm which is shortened to recover interference fringes after the insertion of a filter. The micrometer stage for the test arm's flat mirror is adjusted to drive the mirror toward the beamsplitter while keen attention is paid to the CCD camera's video monitor. Fringes will appear and disappear over a very short range of mirror travel. The operator must make adjustments slowly in order not to miss the fringes. The amount of adjustment turns out to be very nearly equal to the filter's focal shift times the average index of the glasses which make up the filter (roughly 1.5). Fortunately, the focal shifts of ACS filters have been very tightly controlled to a value of 2.436 ± 0.010 mm. This knowledge greatly facilitates reacquiring fringes on insertion of any ACS filter because adjustments to the test arm's flat mirror are essentially identical. (By coincidence, the adjustments -- roughly 3.5 mm -- are equal to the nominal thickness of a filter substrate because when 1.5 is substituted for $n_1$ in the expression above, the expression becomes approximately equal to
3.2 Qualifying WOMBAT

Four important aspects of any wavefront measuring interferometer are single measurement accuracy, measurement precision, measurement noise, and calibration of scale. Taken respectively or together, these aspects relate to the interferometer’s systematic error, measurement sensitivity, measurement repeatability and random error, and ability to assert absolute size of features found in any test wavefront. Before presenting results of transmitted wavefront for ACS filters, we first discuss how the set of measurements with WOMBAT is carried out for every filter such that these key aspects are addressed.

When we perform what we refer to as a reference measurement where the test arm is unoccupied, the OPD outcome is our instrument signature for an accompanying measurement with a filter in the test arm. It is also a direct measure of WOMBAT’s systematic error at that wavelength. (These statements are true for this interferometric configuration where an plano optic is measured in transmission with a plano wavefront, but they are not generally true for other test configurations.) Furthermore, if we obtain the same instrument signature in units of length without regard to wavelength, we not only get better knowledge of that systematic error, which is present in any single measurement of a test article, but we also demonstrate that the system correctly calibrates its own absolute scale for any wavelength. Average measured reference OPD is 0.013 waves rms at 633 nm across the entire spectral range of WOMBAT. The peak variation from that OPD has been 0.004 waves rms.

For a single measurement, precision and noise are closely related. An assessment of noise comes from making a measurement, then immediately repeating it and subtracting the two OPD outcomes. This difference is interpreted as the noise in either measurement as well as what could be referred to as best case single measurement sensitivity. Effectively, however, sensitivity can be improved by taking many measurements and averaging their resulting OPD outcomes. This is basically the familiar concept of beating down noise by increasing the number of samples.

Figure 2 -- OPD maps for SDSS r filter (85 mm diameter) for ACS WFC made using WYKO 400 (left) and WOMBAT (right). Measurements made at $\lambda = 633 \text{ nm}$ and following wavefront statistics are in waves at 633 nm: WYKO -- 0.151 $\lambda$ PV, 0.025 $\lambda$ rms; WOMBAT -- 0.141 $\lambda$ PV, 0.025 $\lambda$ rms

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Figure 2 is a convincing demonstration of the correctness of WOMBAT measurements. Here we chose an ACS Wide Field Channel (WFC) filter (SDSS r) which transmits 633 nm light and measured its transmitted wavefront using both WOMBAT and our WYKO 400 interferometer -- a commercially-available unit which produces highly accurate results. The measurements show nearly identical spatial features in the OPD maps along with the excellent agreement of OPD statistics. The wavelength-independent nature of absolute OPD measurement with WOMBAT is demonstrated in figure 3 where an ordinary glass window was measured at three well-separated wavelengths -- 500 nm, 700 nm, and 900 nm. The rms transmitted wavefront errors were 68 nm, 64 nm, and 62 nm respectively. Again, note that the OPD maps for widely different wavelengths are almost exactly the same in units of length which validates WOMBAT's ability to correctly calibrate itself with respect to wavelength.

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\begin{align*}
\lambda &= 500 \text{ nm} \\
\lambda &= 700 \text{ nm} \\
\lambda &= 900 \text{ nm}
\end{align*}
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Figure 3 -- transmitted wavefront measurements in WOMBAT for the same piece of glass at three widely-separated wavelengths -- 500 nm, 700 nm, and 900 nm

3.3 Measuring ACS filters with WOMBAT

The best WOMBAT measurements are collected with the flat mirrors in each arm adjusted to produce a null fringe with maximum contrast (minimizing tilt in the measurement). The OPD for each measurement is saved in a "wavefront file." The measurement control software allows averaging of multiple measurements. We typically average four measurements together when measuring ACS filters. The OPD scaling factor applied to all measurements is 0.5 waves per fringe appropriate for testing a transmissive optic in double pass. Each filter wavefront file has a corresponding reference wavefront file subtracted from it to yield the OPD of the filter itself. Reference wavefront files accumulated for different wavelengths over time can be analyzed to demonstrate the consistency of instrument signature.

The ACS ramp filters are constructed to have a spatially-variable passband whose peak wavelength behaves linearly with distance across the filter’s long dimension. For this reason, a monochromatic source within a ramp filter’s spectral coverage will be transmitted only by some subaperture of the filter, and therefore, transmitted wavefront for that wavelength can be measured only for that subaperture. Based on spectral design aspects (fractional wavelength coverage and fractional bandpass) of each ramp filter, transmitted wavefront measurements for 5 to 6 different wavelengths must be made to cover the entire aperture of each ramp filter. While using 1 mm slits on the monochromator to broaden its spectral content would allow more area on a ramp filter to be covered at once, this would be at the expense of monochromaticity. Since the phase-shifter modulates the length of the interferometer cavity in quadrature for only one wavelength, much of the monochromator’s spectral output would be modulated other than in quadrature which would confuse the measured pupil intensity levels, thereby defeating the purpose of phase-shifting.
4. APPLICATION OF WOMBAT / INTERFEROMETRIC RESULTS FOR ACS FILTERS

ACS filters have two free-standing substrates. The first substrate hosts complex, multilayer, interference coatings on its first surface and anti-reflection (AR) coatings on its second surface. The second substrate has identical AR coatings on both of its surfaces. The coating stacks on the first substrate can consist of as many as 120 layers. Generally, the transmitted wavefronts of these filters look excellent over their entire clear apertures. The most dominant features in some of the filters are slight edge-roll and a low-level, nearly axis-symmetric distortion of the wavefront attributable to power. This distortion is not seen in interferograms of uncoated substrates or filter second substrates which have the same coatings on both sides. Mechanical stresses in coatings are widely known to have the ability to deform thin optics to varying degrees. The effect can be astounding. We have been shown an example of a 1 mm thick, 250 mm diameter glass substrate, coated with complex multilayer stacks on one surface only, which was bowl-shaped with a sag in excess of 50 mm! Edge-roll is likely due to stress induced in the substrate when it is cut out from an oversize polished plate.

Depending on details of coating designs and substrate geometric aspect ratios, some curvature of filter substrates can be expected. This is generally not a problem as the substrate surfaces remain everywhere locally parallel and thus non-lensy. The effect on the filter substrate as a whole can be to turn it into an exceedingly weak lens. From measured wavefront data, we estimate the typical wavefront radius of curvature of filters to be of order 20 km. If we model a filter as a lens positioned in the filter wheel of the ACS instrument and having a focal length commensurate with this wavefront radius of curvature, we compute that the filter with greatest power would shift focus by 3 μm, which is completely negligible.

Figure 4 shows OPD maps over 84 mm diameter apertures for four WFC filters for ACS. Power has not been subtracted from these OPD maps. All four filters meet transmitted wavefront specifications. Note the properties described in the paragraphs above. The amount and direction of wavelength curvature seems to depend on substrate material and coating implementation. Figure 5 show OPD maps for four High Resolution Channel (HRC) filters. Figure 6 shows a photograph of a typical ramp filter segment mounted for test along with OPD maps for three subapertures on the part corresponding to different wavelengths transmitted by those respective subapertures.

In order to study wavefront distortions which would perturb the point-spread function (PSF) of any point source imaged by ACS, combinations of the first four Zernike polynomial terms corresponding to tilts, power, and piston are removed from OPD results. Considering full clear apertures for all ACS filters and removing only tilts and piston, wavefront errors range from 0.01 to 0.10 waves rms at 633 nm with the average being 0.04 ± 0.02 waves rms. As mentioned in preceding paragraphs, the power term is always sufficiently small to justify its removal. Removing power reduces the average wavefront error to 0.02 ± 0.01 waves rms. Compare these values to the full aperture goal of 0.033 waves rms. For completeness, to compare a filter’s measured transmitted wavefront error to actual specifications, we analyze full aperture OPD’s for various 7 mm diameter subapertures on each filter (top, bottom, left, right and center). Peak and average subaperture wavefront errors for all filters are 0.008 and 0.005 waves rms at 633 nm, respectively. Compare these values to the specification of 0.014 waves rms for any 7 mm diameter subaperture.

5. CONCLUSIONS

A broadband interferometer was developed and used to successfully measure the transmitted wavefront errors of optical bandpass filters for HST ACS. All filters exceeded their transmitted wavefront specifications. The noise level of the interferometer system was determined to be 0.005 waves rms at 633 nm with measurement repeatability at that noise level. Measurements of the same piece of glass at vastly different wavelengths gave consistent OPD results within 0.009 waves rms at 633 nm. Results for measurements of an ACS filter which transmits 633 nm using a conventional HeNe laser based interferometer and WOMBAT agreed to better than either interferometer’s noise level.

By combining a broadband Twyman-Green interferometer with the phase-shifting data acquisition capabilities of a commercial interferometer system, we were able to make automated measurements of transmitted wavefront errors of as-built flight filters for ACS to demonstrate that the filters met their wavefront specifications. To this end, we took advantage of a plethora of measurement control and data analysis and display facilities provided in the commercial system’s software. These included the ability to acquire calibrated phase-shifted fringe data and to remove certain low order aberration terms from measured OPD’s for a wavelength of choosing.
Figure 4 -- OPD maps over 84 mm diameter apertures for four ACS WFC filters measured in WOMBAT at the center wavelengths of each filter's passband; wavefront errors are reported in waves rms at 633 nm for each full aperture; OPD scale bar in nm applies to all four filters.

Figure 5 -- OPD maps over 36 mm diameter apertures for four ACS HRC filters measured in WOMBAT at the center wavelengths of each filter's passband; wavefront errors are reported in waves rms at 633 nm for each full aperture; OPD scale bar in nm applies to all four filters.
Figure 6 -- WOMBAT results for O III Outer Ramp Filter for ACS; Top: ramp filter mounted in its test cell showing clear aperture and spatially-variable wavelength characteristics; in person, one can easily see that the left end transmits green light, the center transmits yellow and orange light, and the right end transmits deep red light; Bottom: transmitted wavefront errors in waves at 633 nm for different wavelengths through the filter inset on outline of an outer ramp filter (middle and inner types have slightly different shapes).
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7. REFERENCES


