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IN-ORBIT PERFORMANCE OF THE COSTAR-CORRECTED FAINT OBJECT CAMERA[1]

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ABSTRACT

The improvements due to the Corrective Optics Space Telescope Axial Replacement (COSTAR) on imaging with the Faint Object Camera on board the *Hubble Space Telescope* are presented. The encircled energy performance is dramatically improved, such that 85% of the total light in the PSF is now enclosed within a circle of radius 0″.1 at 486 nm wavelength, compared to 18% in the spherically aberrated PSF. This is equivalent to a sensitivity increase of 1.6 mag. The effective angular resolution is also improved from 66 to 43 mas at 486 nm. These improvements are slightly offset by a 20% lower total throughput at visible wavelengths. The plate scale is changed from 22.3 mas $pixel^{-1}$ to 14.35 mas $pixel^{-1}$, resulting in a decrease in the field of view from 11×11 $arcsec^2$ to 7.3×7.3 $arcsec^2$ for the workhorse 512×512 format.

Subject headings: instrumentation: detectors — space vehicles — ultraviolet: general

1. INTRODUCTION

In 1990 October, the *HST* strategy Panel (Brown & Ford 1991) identified the Corrective Optics Space Telescope Axial Replacement (COSTAR) concept as the most promising of a number of proposed means of correcting the spherical aberration of the *HST* primary mirror for three of the four axial instruments on board the observatory. Following a brief phase of more detailed technical study, the project won formal approval by NASA in 1991 October for inclusion in the First *HST* Maintenance and Refurbishment Mission which took place in 1993 December.

The COSTAR concept exploits the fact that the *HST* instruments are all designed to be exchangeable in orbit. COSTAR is particularly designed to replace the High Speed Photometer (HSP), and its single purpose is to position corrective optical reimaging systems in front of the entrance apertures of the Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), and the Goddard High Resolution Spectrograph (GHRS).

In this *Letter* we report on the initial performance of the COSTAR instrument in the case of the most demanding of the three instruments above, namely the FOC. Some early science results can be found in companion *Letters* in this issue (Macchetto et al. 1994; Jakobsen et al. 1994; Albrecht et al. 1994).

2. BRIEF DESCRIPTION OF THE COSTAR INSTRUMENT

Given the nature of the errors in the *HST* telescope, there are two fundamental considerations that need to be addressed by any scheme for correcting the resulting spherical aberration. First of all, since the fault arises at the primary mirror of the telescope (i.e., at the telescope entrance pupil), the error correction must take place at a pupil conjugate surface (i.e., on a surface on which a true image of the primary mirror is formed). In contrast to the situation in the Wide Field Planetary Camera (Burrows 1994), the internal FOC pupils do not coincide with any mirror surfaces, but are situated at the location of the internal filter wheels. This means that any internal correction device for the FOC would have had to be refractive, leading to an unacceptable loss in far-UV performance.

The second fundamental challenge concerns the alignment tolerance demanded of any type of *HST* corrective system. The placement of the pupil image on any corrective optical surface must be accomplished to very high accuracy; an error of more than 0.75 mm would introduce as much aberration (in the form of coma) as is generated by the misfigured *HST* primary. To make the COSTAR correction worthwhile, this centering error must be kept below the level of 10–20 μm, requiring on-orbit adjustment capability.

COSTAR addresses these two basic considerations in an economical and yet efficient manner. At the heart of the COSTAR concept is an external all-reflective corrective system, originally proposed and designed by the late Dr. Murk Bottema. In this elegant two-mirror solution, the lower (M1) mirror reflects a section of the *HST* focal plane to the upper (M2) mirror, which in turn sends the corrected image of the field back into the existing FOC entrance aperture, and also blocks the aberrated beam from the aperture. The focal length of the M1 mirror is set by the requirement that M2 be at a pupil conjugate, i.e., that M1 images the *HST* primary onto M2. The correction for the spherical aberration takes place on M2, whose focal length is set by its having to reimage to the existing *HST* focal plane. These constraints, together with the amount of space available between the back of the primary and the *HST* focal plane, basically set all system parameters—one consequence being that the corrected image received by the FOC is now f/37 instead of the original f/24, leading to a corresponding 156% magnification of the input image received by the FOC.

The second key feature of COSTAR is its use of the instrument bay and spacecraft resources relinquished by the HSP to both deliver and adjust the optical system described above. Positioning of the optics is done by means of a so-called Deployable Optical Bench (DOB) that can be extracted and retracted in increment steps through ground control. Mounted on the DOB are four sets of arms that swing into place and carry, respectively, the M1 mirrors of the FOC and the M2

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mirrors of the FOC, FOS, and GHRS (the M1 mirrors of the FOS and GHRS are located inside the base of the DOB). In order to limit the required number of mechanisms to an absolute minimum, the two sets of mirrors for the f/48 and f/96 cameras for the FOC are mounted on common upper and lower arms. On-orbit adjustment is limited to tip-tilt control of the lower FOC M1 arm (i.e., control of the location of the M1 image on the stationary M2 pupil corrector). Focus is controlled through bulk movement of the DOB. The two FOC channels are "ganged" in the sense that the two sets of FOC mirrors are fixed on each arm and cannot be controlled separately.

The off-axis aberrations of the COSTAR corrective system were minimized by giving the upper M2 mirrors a suitable anamorphic toroidal figure. Aside from alignment errors and possible errors in the prescription of the *HST* conic constant error and focus settings, the only significant residual aberrations expected of the system are caused by an unavoidable mismatch between the tilts of the original and corrected focal planes—which leads to modest amounts of astigmatism and defocus at the extreme corners of the zoomed FOC formats. The shift in the location of the entrance pupil also results in some vignetting at the outermost corners of the largest f/48 field of view.

Due to problems with the FOC f/48 camera, only the f/96 channel has been used with COSTAR correction so far. All of the performance details in this *Letter* refer to the f/96 relay only.

3. ALIGNMENT

The COSTAR DOB was successfully deployed on 1993 December 26, and the FOC mirror arms were deployed the following day. "First light" for the COSTAR-corrected FOC took place on December 28, when it was immediately realized that not only was the spherical aberration corrected, but the adjustment necessary to align the COSTAR mirrors was well within the mechanical range available.

Only a brief discussion of the alignment procedure is given; readers are referred to Jedrzejewski et al. (1994) for a more complete description. Full alignment is achieved by adjusting the COSTAR M1 tip-tilt mechanism to remove any residual coma that results from miscentering the reimaged telescope exit pupil on the COSTAR M2 mirror and by adjusting the DOB position to optimize the focus. This was done in two steps. First, an iterative series of image taking and COSTAR alignment updates removed most of the tip/tilt and focus errors. This was followed by a set of sweeps in both tip/tilt and focus that allowed interpolation of the best settings for COSTAR. Only a small fraction of the allowable range of adjustment was used in setting the tip/tilt mechanisms, while the optimum DOB setting was exactly in the middle of its travel.

4. THE "NEW" FAINT OBJECT CAMERA

The COSTAR-corrected Faint Object Camera differs from its uncorrected version (Greenfield et al. 1991) in several respects, such that it is appropriate to treat it as a "new" instrument.

4.1. *Imaging Performance*

After full alignment, the encircled energy was measured to be 85% within a circular aperture of radius 0".1 at 486 nm wavelength. The resulting PSF is compared to an FOC PSF taken before the installation of COSTAR in Figure 1 (Plate L1). Figure 2 shows a comparison of the PSF intensity profiles and encircled energy curves for the pre-COSTAR and COSTAR-corrected FOC images.

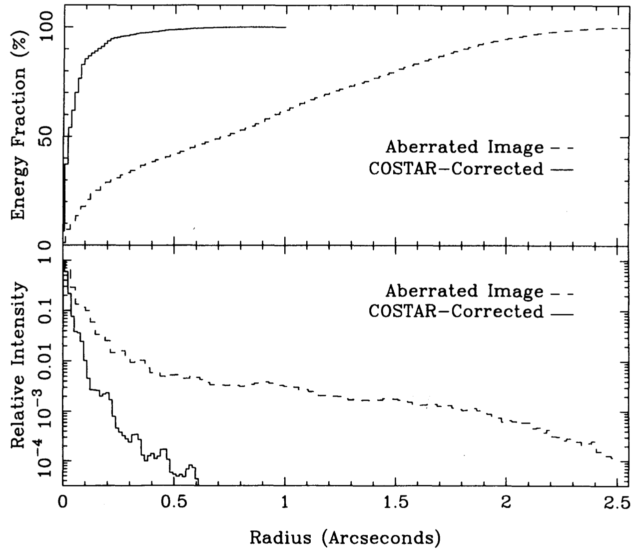

FIG. 2.—Comparison of PSF image profiles (*lower*) and encircled energy profiles (*upper*) before and after COSTAR. Pre-COSTAR is depicted by the dashed line, COSTAR-corrected is shown by the solid line.

It is of interest to compare the COSTAR-corrected FOC PSF with that which would be expected from a perfect diffraction-limited PSF from a 2.4 m telescope with a 0.33 central obscuration. Figure 3 is a plot of the comparison of the observed and theoretical encircled energy curves and of the core profile. It is seen that the encircled energy curve and the FWHM of the observed PSF are almost as good as the theoretical ideal. The FWHM is now 43 mas at 486 nm wavelength.

The primary effect of COSTAR is an increase in sensitivity, since most of the flux is now detected in a small area in contrast to the pre-COSTAR PSF, where most of the energy was spread out over a large area. A comparison of the sensitivities of the pre-COSTAR and COSTAR-corrected FOC is given in Table 1, which lists the time required to detect an A0V star of

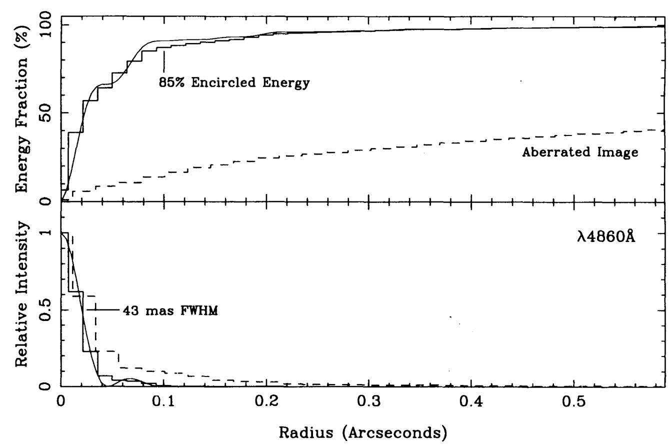

FIG. 3.—Comparison of the COSTAR-corrected PSF image profile with that of a perfect diffraction-limited PSF from a 2.4 m telescope with 0.33 central obscuration. The model is shown by the continuous curve, while the data is shown as a histogram-like plot.

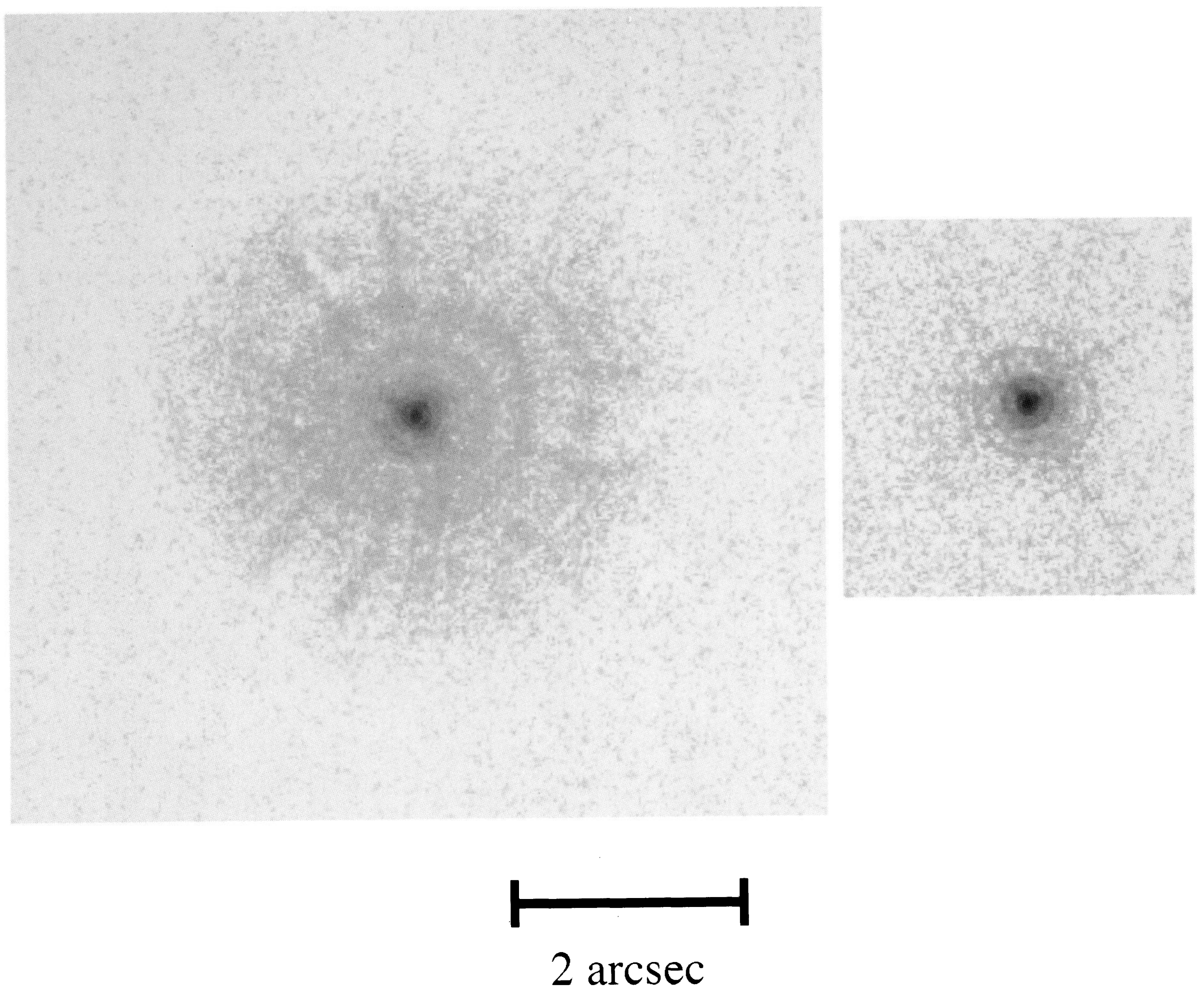

FIG. 1.—Comparison of PSF images taken before and after COSTAR installation. *Left:* the aberrated PSF. *Right:* the PSF after the alignment of COSTAR. The pre-COSTAR image was magnified to the same plate scale as the post-COSTAR image. The images are of the same star through the same filter (a narrowband filter centered on 486 nm wavelength) and with similar exposure times.

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TABLE 1

COMPARISON OF FOC SENSITIVITIES

Magnitude	$T_{f/96}$ (s)	$T_{f/151}$ (s)
22.0..........	22.6	9.5
23.0..........	82.6	27.1
24.0..........	358.3	83.6
25.0..........	1792	285.6
26.0..........	10004	1022
27.0..........	59840	4229
28.0..........	369338	19619

NOTES.—Exposure time required to reach a signal to noise ratio of 5 for observations of an A0 V star through the F430W filter for the pre-COSTAR and COSTAR-corrected FOC.

given magnitude to a signal-to-noise ratio of 5. In each case, the aperture size was chosen to minimize the exposure time required to reach the specified signal-to-noise ratio. A standard background value of $\sim 10^{-3}$ counts s^{-1} $pixel^{-1}$ was assumed. It can be seen that whereas even detecting a 27th mag star would have been prohibitively expensive in terms of telescope time for the pre-COSTAR FOC, a 28th mag star can now be detected in 5.5 hr. The net increase in sensitivity is 1.6 mag.

4.2. *Plate Scale*

The plate scale was measured on orbit by comparing star positions in an image of the globular cluster 47 Tucanae with the corresponding positions measured before COSTAR was installed. The plate scale is increased from an effective focal ratio of f/96 to f/151. This makes the FOC pixels 14.35 × 14.35 mas^2 in size when used in "normal" mode, and 28.70 × 14.35 mas^2 in "zoom" mode. The accuracy of this figure is determined by how well the geometric distortion is corrected; for most observational situations the uncertainty is $\pm 0.5\%$.

This makes the field of view of the workhorse 512 × 512 format 7.3 × 7.3 $arcsec^2$, while the 512z × 1024 format has a field of 14.6 × 14.6 $arcsec^2$. Users should be aware that for imaging formats of 256 × 256 or smaller, an interactive acquisition should be used to acquire the target since there is a significant probability that the combination of guide star and user coordinate errors could make the target appear outside the field of view.

The smaller field of view is compensated to some extent by improved sampling of the PSF down to wavelengths of 3300 Å (at this wavelength, $\lambda/D = 2$ pixels). The core of the PSF is also sharper than in the pre-COSTAR FOC; this is because the size of the PSF core was previously determined by the diameter of that part of the primary mirror that was in focus, somewhat less than the full 2.4 m aperture. The FWHM of the PSF core is still 3 FOC pixels, but whereas this corresponded to 67 mas in the pre-COSTAR case, the COSTAR-corrected PSF has an impressive 43 mas FWHM at 486 nm.

4.3. *Field Rotation*

Because COSTAR forms an intermediate image between the M1 and M2 mirrors, the field is rotated by 180° with respect to the pre-COSTAR situation. The parity of the images is not changed by COSTAR.

4.4. *Total Throughput*

Because of the two extra reflections at the COSTAR mirrors, the total throughput is reduced from the pre-COSTAR value.

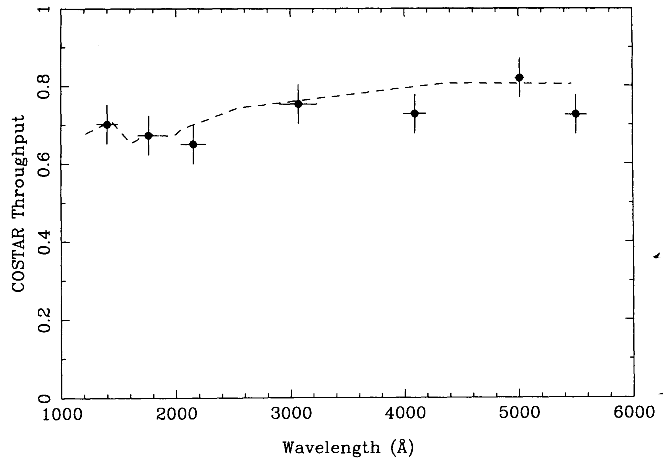

FIG. 4.—The throughput of the COSTAR mirrors as measured by observations of a spectrophotometric standard star compared to measurements of COSTAR witness mirrors. The vertical error bars are $\pm 5\%$, characteristic of comparative flux measurements with the FOC, while the horizontal error bars correspond to the FWHM of the filter used for measurement.

Images of the spectrophotometric standard star BPM 16274 before and after COSTAR was deployed show that the loss of throughput compared to the pre-COSTAR values amounts to $\sim 20\%$ longward of 3000 Å, and $\sim 33\%$ between 1200 and 2000 Å, which is close to the limit achievable with two reflections from Al + MgF_2 coatings. This also agrees very well with measurements of witness mirrors that were used to track the COSTAR mirror reflectivities, indicating that the activities of launch and the servicing mission did not add significant amounts of contaminants. Figure 4 shows the comparison of on-orbit measurements with the witness mirror reflectivity curve.

4.5. *Field-dependent PSF*

Whereas the PSF in the pre-COSTAR FOC was field-independent, the COSTAR corrective scheme is not able to maintain this characteristic. There are two effects that characterize the field dependence of the PSF. First, the COSTAR-corrected image plane is inclined with respect to the FOC object plane. This is an unavoidable consequence of the two-mirror design. The effect was minimized during the design by making the included angle between the M1 and M2 mirrors as small as possible. The effect is very small over the 512 × 512 imaging format, amounting to an effective defocus of 0.4 mm at the edges of the field, and with a linear dependence on field position.

Second, COSTAR introduces field-dependent astigmatism. This also is a consequence of the two-mirror correction. The tangential and sagittal focus planes produced by COSTAR are inclined with respect to each other. One can set the distance between these two planes to the value that the FOC corrects internally at one field point, but away from this field point the astigmatism increases linearly. Again, the effect is small over the 512 × 512 format, but is noticeable at the edge of the large imaging format, amounting to 0.06 waves rms at 486 nm there.

5. SUMMARY

COSTAR has fulfilled the promise of restoring the performance of the Faint Object Camera to nearly what had been hoped for before launch. The sensitivity has been increased by over 1.5 mag compared to the aberrated *HST*, with only a small price in terms of a smaller field and a slight field dependence in the PSF. The COSTAR-corrected Faint Object Camera is now able to fully exploit the imaging performance of the *HST* over the whole visible wavelength range and well into the ultraviolet.

The results reported in this paper owe their existence to the professionalism and dedication of the many individuals of NASA, ESA, STScI, and in US and European industry who worked together to make the First *HST* Servicing Mission—and the COSTAR instrument in particular—such an astounding success. P. J. is grateful to colleagues at the Department of Physics and Astronomy at Johns Hopkins University for their warm hospitality during the COSTAR/FOC commissioning campaign. R. J. acknowledges support from ESA through contract 6500/85/NL/SK.

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