

Hubble Space Telescope Optical Performance

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ABSTRACT

The Hubble Space Telescope suffers from spherical aberration. Although much that is scientifically valuable can be done with the telescope in its present condition, we must install corrective optics on-orbit in order to enable many key programs. An analysis of imaging data obtained on-orbit gives the same results as measurements on the null lens used to fabricate and test the primary mirror, so such optics can be designed with confidence. The assumed conic constant on the primary mirror for all the corrective optics, $-1.0139(5)$, is consistent with measurements by four major independent methods. Aligning the new optics will be very demanding, because of the large slope of the wavefront to be corrected. If the images are to be diffraction limited, the pupil at the corrective element must be aligned to better than one percent of its diameter. Some other residual effects of the spherical aberration will remain after installation of the corrective optics, primarily in the pointing and collimation of the telescope. We summarize the present imaging performance of the observatory, and compare it with the expected performance when corrective optics (COSTAR and WFPC 2) are installed on-orbit.

2. INTRODUCTION

This is a general review of the status of and prospects for the Hubble Space Telescope (HST) optics, and the current and projected imaging performance of the observatory, written one year into the mission. Despite the spherical aberration, HST is now routinely producing high resolution images and spectra. Nevertheless its performance is seriously degraded relative to expectations. It has almost completed an extensive commissioning period, made more difficult by the spherical aberration, so now is a good time to review what we have learned, and where we are going. We concentrate here on the optical performance of the various observatory subsystems. The scientific results have been discussed extensively elsewhere,^{1,2} and in these proceedings. The present optical imaging performance, and pointing control system performance are generally well understood.³ We choose not to repeat information given in (3). Instead, we concentrate on giving the reader some additional background on the imaging performance and how it can be modelled. We concentrate here on understanding

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physically the current imaging performance and compare it with the expected performance which should be substantially attained after the planned servicing mission.

The HST will be serviced on orbit with a shuttle visit presently scheduled for November 1993. At that time, the bulk of the problems caused by the spherical aberration will be fixed. That mission will involve the most ambitious on orbit satellite repair ever undertaken. It will probably include replacement of the solar panels, gyros, the High Speed Photometer and the Wide Field/ Planetary camera (WFPC). The solar panels are affecting the pointing performance primarily during terminator transits because thermal gradients across the bistem array supports are causing them to rapidly bend and then oscillate. There are also impulsive torques on the spacecraft at other times due to stiction in the tensioning mechanisms. One of six rate gyro assemblies failed after nine months on orbit. A second gyro has failed, and a third has shown evidence of possible failure since the workshop. The Faint Object Camera (FOC), Faint Object Spectrograph and High Resolution Spectrograph will probably be largely corrected by a replacement for the High Speed Photometer, COSTAR. COSTAR is designed to deploy corrective optics in front of the scientific instrument apertures.⁴ Finally, but most critically, the Wide Field Planetary Camera (WFPC) which is the main scientific instrument of the observatory will be replaced by a similar instrument with internal correction.

3. MEASUREMENT OF SPHERICAL ABERRATION

In order for the corrective optical schemes to work, the spherical aberration must be precisely characterized. None of the schemes presently contemplated allows for on-orbit adjustment of the amount of compensating spherical aberration that they introduce. Measuring the amount of spherical aberration to the precision required has been a major challenge. It has been determined from historical optical test data, from recent measurements on the test equipment and from on orbit measurements with both the main cameras. Remarkably, these methods all agree to within about 1/45 wave, which is sufficient for the corrective optics. The loss of encircled energy in a 0.1 arcsecond radius resulting from such an error is only about 2%.

The on-orbit determination of the spherical aberration has evolved from low order phase aberration least squares fitting procedures (which were used to originally diagnose the spherical aberration), to involved procedures involving simultaneous solutions to the pupil phase map and pupil obscurations at three different focal settings as reported by Roddier in these proceedings. Many groups have developed such techniques but we only discuss our results here. The wavefront fitting procedure was first developed and applied within days of the WFPC first light images in May 1990. Since then it has evolved considerably by including the secondary mirror support spiders, primary mirror support pads and field dependent WFPC internal obscurations (which are misaligned in an unexpected but determined manner). The algorithm works best on well sampled out of focus images at long wavelengths with good pointing stability. Such images have been obtained in both the PC and FOC. Given the pupil

obscurations³, the image is determined in the Fraunhofer approximation once the distribution of phase errors on the wavefront in the exit pupil is fixed. These errors can be expanded in a series of orthogonal polynomials, and the coefficients deduced by a least squares fit to the observed data at various focus positions. The rms wavefront error expressed in waves at 632.8 nm is converted to a change in the conic constant on the primary mirror by dividing by 35.3. (This factor is correct rather than the 36.03 one naively deduces by doubling the sag on the mirror primarily because the reflected ray does not exactly retrace its path). Our result is that the conic constant on the primary mirror is 1.01410(45), from fifteen measurements in the planetary camera (PC6), after subtracting a correction of 0.0010 due to a manufacturing error in the camera. The FOC gives 1.01394(85) from four measurements and no significant camera aberrations are believed to contribute. Figure 1 shows a comparison of an observed star image in PC6 with filter F547M at a focus setting close to the telescope paraxial focus, with the results from phase retrieval. These same techniques are now being applied to the telescope collimation, and should be applied to generate theoretical point spread functions at the adopted focus position for use in deconvolution.

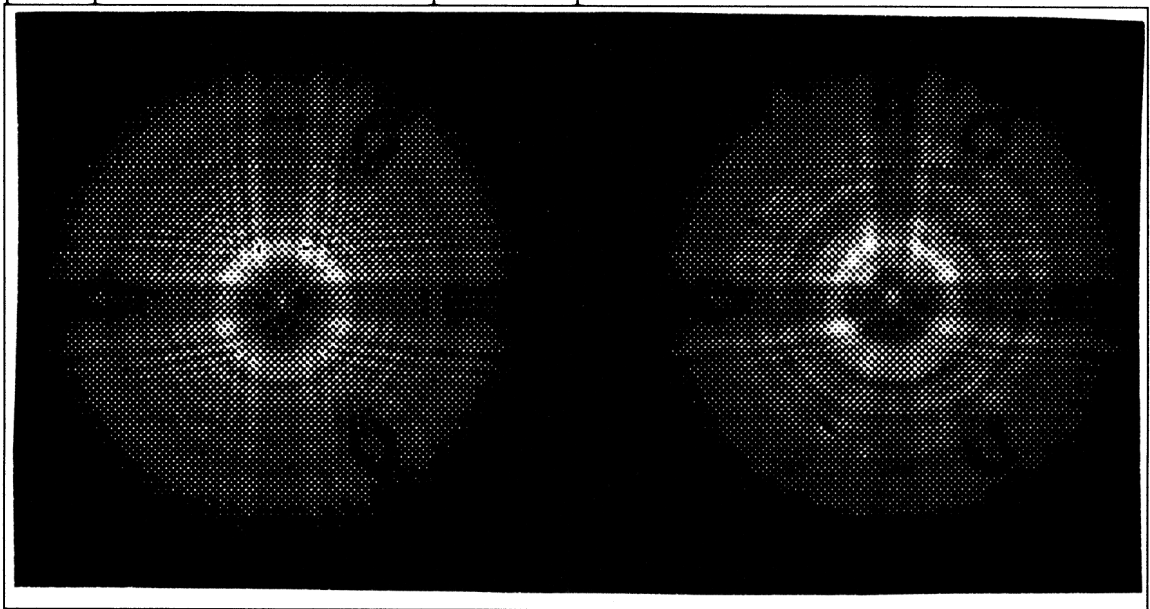


Figure 1 Comparison of fits to data for defocused images

The on-ground determination at Hughes, Danbury (formerly Perkin Elmer) has proceeded by recertifying the null lens used in their manufacture of the primary mirror. The combination of null lens and primary mirror was designed to reflect a spherical wave exactly back on itself as illustrated in Figure 2. The autocollimated wavefront from the assembly as built was measured with an interferometer, and changes were made to the figure of the primary mirror in order to get straight fringes. As a result errors in the construction of the null caused a corresponding error in the primary, and recertifying the null now comes close to a direct measurement of the primary mirror figure. The null consists of two spherical mirrors, which reimage the interferometer focus onto the center of curvature of the HST primary, and introduce

most of the required optical path changes, together with a refractive field lens that images the interferometer pupil onto the primary mirror

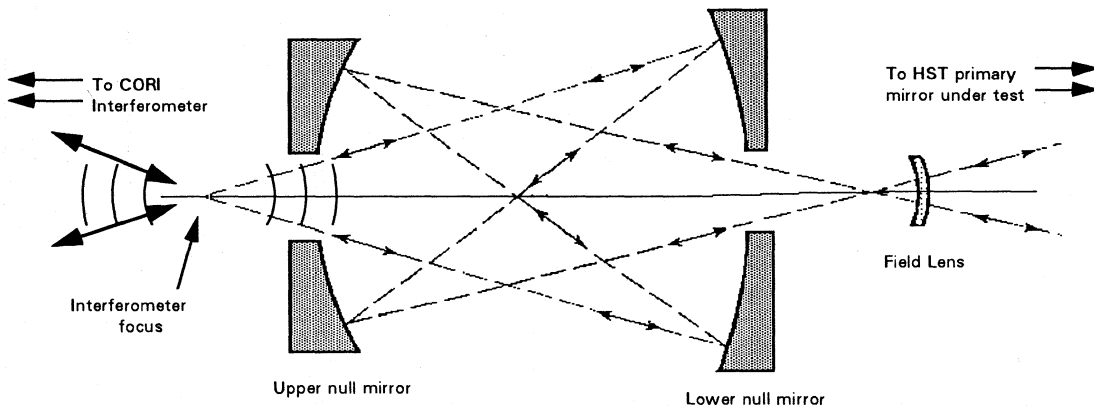


Figure 2. The null lens used in the manufacture of the HST primary mirror

The field lens positioning error primarily responsible for the spherical aberration in HST has now been measured as 1.305 mm and the cause of the error is believed to be understood⁵. In addition the two mirrors in the null lens have been remeasured as separated by an amount that differs from the design by 79 microns. This is also a significant error, and has recently been explained by measurements of the null mirror radii, which are in error by about the correct amount to explain the discrepancy, given the way they were positioned. The original spacing was set from the centers of curvature, while the recent measurement was from the surface vertices. After the remeasurement of the mirror radii, the reflective null lens data indicate that the conic constant on the primary is 1.01378(31).

Finally, a less precise (but more accurate!) refractive null lens was made that was used in place of the reflective null early in the testing. Archival interferograms from the period when the mirror was polished with this null indicate a conic constant of -1.01314(60). There is reason to believe that the secondary mirror was made correctly.

Figure 3 summarizes the status of all the above primary mirror conic constant estimates. All the measurements agree quite closely with the adopted value of 1.0139(5) which is being used in the design of the corrective optics. The nominal conic constant for the primary is -1.0022985. The difference between these values corresponds to an RMS wavefront error of -0.410 waves at 633 nm, and the edge of the primary is 2.2 microns too low. (which can be compared to its nominal sag relative to a sphere of 0.2mm)

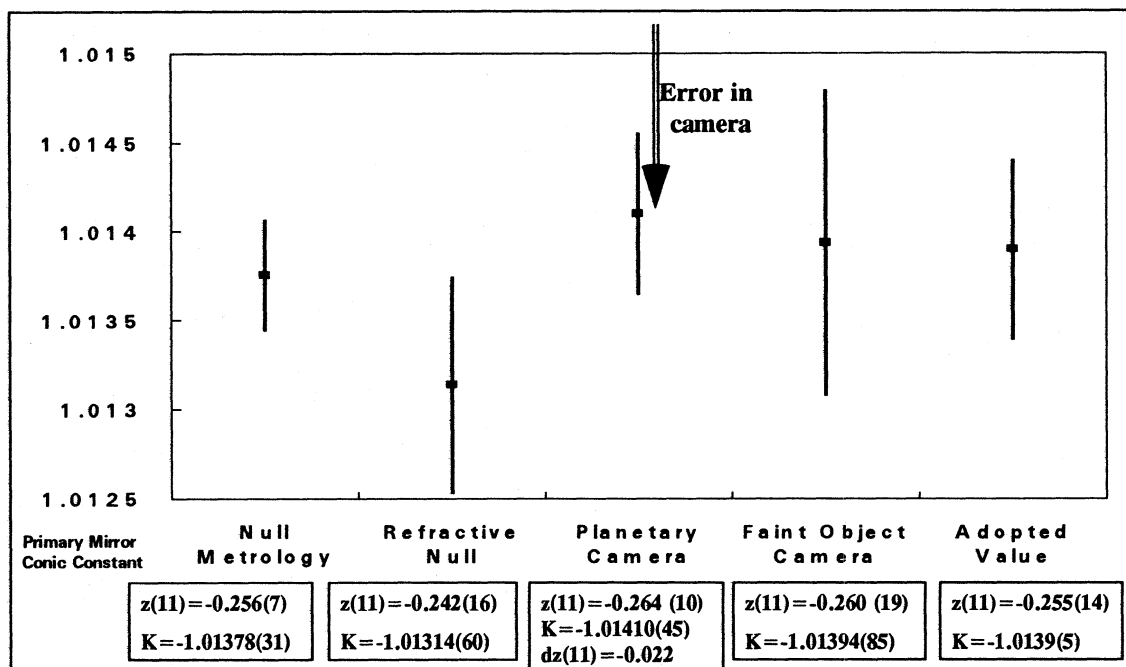


Figure 3. Estimates of the HST primary mirror conic constant.

4. CORRECTIVE OPTICS ERRORS

Because of the accuracy of our knowledge of the spherical aberration, on-orbit compensation for errors in the prescription is not planned. On the other hand, there are extremely tight positional tolerances for the corrective optics which will necessitate on-orbit centering adjustments. The reason for this is as follows. All the corrective schemes being pursued involve reimaging the primary mirror on to a corrective element which has exactly the opposite deformation to the primary mirror error. Thus the optical path delays at the edge of the pupil introduced by the primary mirror that presently cause marginal rays to focus 40 mm too far back are cancelled by compensating advances introduced by the corrective optic. The compensating term varies as the fourth power of the pupil radial position, and therefore changes rapidly near the edges. Slight misalignments then lead to large amounts of wavefront perturbation proportional to the derivative of the aberration (coma), and to the amount of misalignment. If the system is misaligned by as much as one percent, it will cease to be diffraction limited. A seven percent misalignment (which is about equal to the misalignments in the existing WFPC) would lead to as much RMS coma as we presently have in spherical aberration. Of course, the misalignments in the existing camera would not have significantly damaged the image quality, if the OTA wavefront had been nominal. Similarly, the scale of the pupil image must be right. If it is in error by 2 percent, we again fail to be diffraction limited. These issues are illustrated in Figure 4.

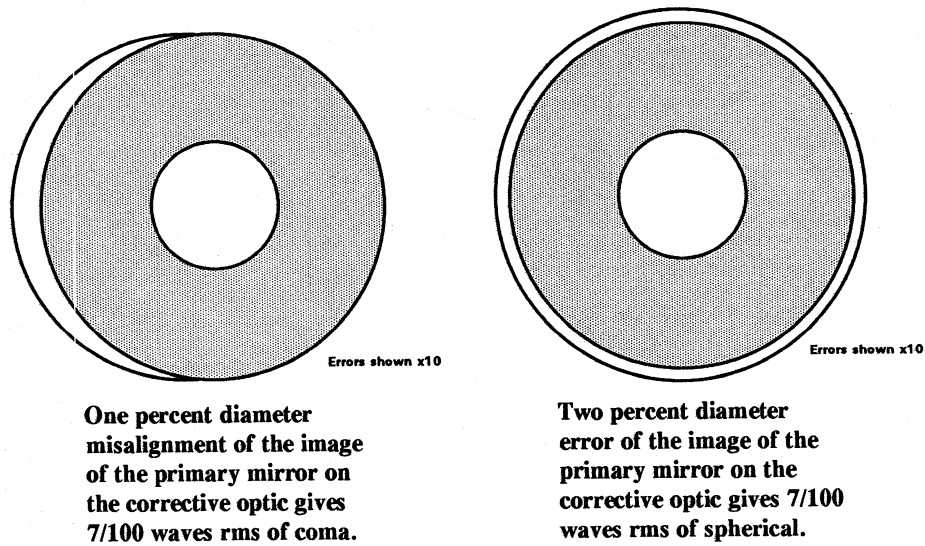


Figure 4. Sensitivity of corrective optics to misalignments and scale errors.

5. GUIDING PERFORMANCE

The servicing mission will probably not include changeout of the three Fine Guidance Sensors (FGS). These detectors are affected by the spherical aberration both in their coarse track and fine lock modes but for different reasons. Each FGS consists of a large pickoff mirror that takes a quadrant of the field between 10 and 14 arcminutes off axis and directs the beam onto an aspheric collimating element. The beam is then steered by two sets of moveable prisms onto a beamsplitter and thence to one of two orthogonal Koesters prism interferometers. The faces of the Koesters prisms are reimaged onto photomultiplier tubes with square 5 arcsecond field stops.

In coarse track the field of the four PMT in a given FGS is nutated around the star image, so that the system works somewhat like a quadrant detector. Performance is degraded because the star image is aberrated, so the image on the field stops is not sharp. The result is that the pointing performance is degraded by about 2 magnitudes. It still scales at the square root of the number of photons, but the rms jitter expected for 14.5 magnitude guidestars of 20 milliarcseconds is only realized for 12.5 magnitude guidestars.

In fine lock the performance is limited by the transfer function of the interferometers. Because of the presence of misalignments in the FGS, the beam is not exactly centered on the Koesters prism at interferometer null. This would not affect performance appreciably in the absence of spherical aberration from the OTA, but the fringe visibility is drastically reduced by the position dependent phase errors that result.

Operational changes to planning, scheduling and pointing control system control loop gains are being made to mitigate the degraded performance of the FGS, and solar array

induced jitter. For bright stars, we have excellent pointing stability in fine lock away from terminator transitions. The changes are making such performance possible on fainter (and therefore more common) guide stars, and avoiding loss of lock at the terminator. However, it is not expected that acceptable fine lock performance will be achieved on stars with visual magnitudes fainter than about 13.5, so coarse track (with its associated larger pointing errors) will continue to be the only available guiding mode over much of the sky.

6. TELESCOPE COLLIMATION

The Optical Control System (OCS), contains a set of three radial shearing interferometers (WFS), one in each FGS. They were designed to collimate the telescope (ensure that the optical axes of the hyperbolic primary and secondary mirrors coincide). They do not work because of the spherical aberration. There is always some zone on the primary mirror with such a rapid rate of change of the wavefront that the fringe separation in the instrument is smaller than the instantaneous field of view of the image dissector tubes, so the fringe visibility drops. In principle, they therefore can only accurately measure aberrations with significant angular dependence (such as astigmatism), but are poor when measuring aberrations that only have radial dependences (such as focus and spherical aberration), or that have angular dependences that look like wavefront tilt over any narrow annulus (such as coma). As a result the present collimation of the telescope was set by tilting the secondary mirror until the camera images were symmetrical and decentering it (with compensating tilts) until the OCS indicated zero astigmatism.

Hughes Danbury and Pierre Bely at STScI have independently modelled the FGS in fine lock, and are able to predict the effects of differing telescope collimation on the FGS transfer functions. The results to date indicate that the performance of the FGS can be significantly improved at least for FGS 1 and 3, but at the cost of the images in the WFPC and FOC. Now that the effects of collimation on FGS performance are better understood, and the effort to numerically understand the spherical aberration is completed, the collimation will be revisited with a view to improving the FGS performance while compromising the camera images as little as possible. To this end, a systematic study of the phase retrieval results at numerous secondary positions is underway, together with a sequence of dedicated HST observations to perform a 'coma sweep'. So far, results from both cameras seem consistent, and it is believed that the telescope has been operating with about 1/15 wave of coma. Improved knowledge of the collimation can be used to generate better theoretical point spread functions.

6. IMAGING PERFORMANCE

The Science Working Group (SWG) has defined the focus setting of the secondary mirror to be used for HST observations by requiring that it gives the maximum encircled energy in 0.1 arcseconds radius for the FOC at 486 nm. Figure 5 shows a series of theoretical encircled energy curves as a function of focus setting, assuming the nominal conic constant. In practice the encircled energy is lower than these curves

indicate primarily because of microroughness scatter from the mirror surfaces, but the shape of the curves seems to agree with observations.

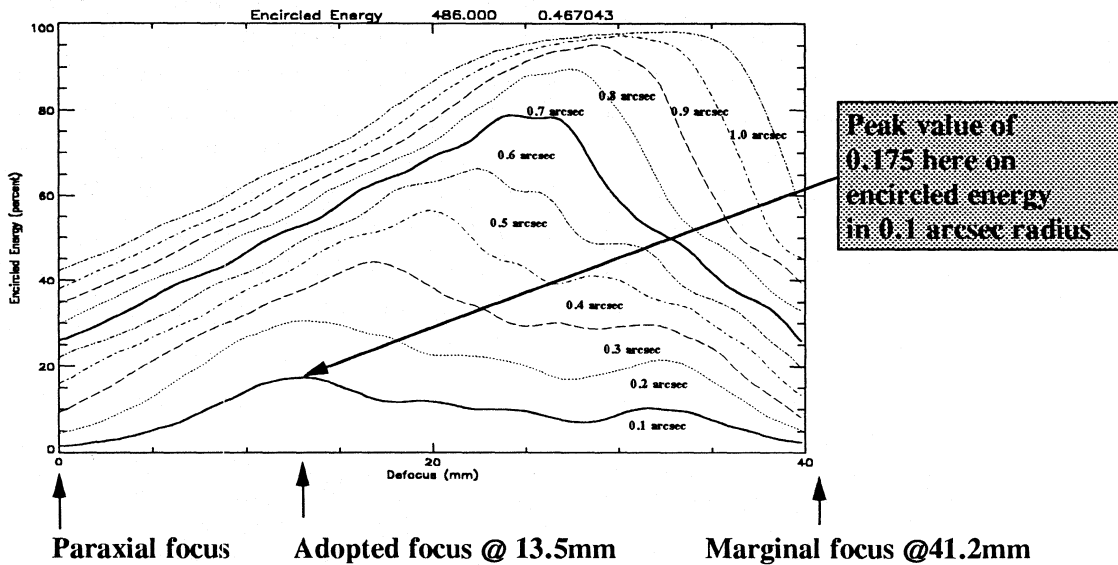


Figure 5. Predicted Encircled energy for the FOC as a function of focus position.

The peaks in the curves shift towards the paraxial focus as the wavelength is decreased. In the limit of short wavelengths, (neglecting microroughness), we get the ray trace limit which can be written in closed form, and is an adequate approximation for some purposes. The transverse aberration of a ray at fractional pupil coordinate x (with $0.33 < x < 1$) is then $T_m(x^3 - xd)$, where T_m is the transverse spherical aberration, of a marginal ray in the paraxial focal plane (about 3.07 arcseconds), and d is the defocus as a proportion of the longitudinal spherical aberration - d is 0.327 at the SWG focus. At this focus, the geometric image radius is obtained by setting $x=1$ and comes out as 2.07 arcseconds. Further it is easy to see that the zone of the mirror that geometrically is in focus is at $x = 0.572$. From the fact that the effective aperture contributing to the core is roughly $2/3$ the expected size, one might predict that the core would be about 50% broader than expected, and detailed diffraction calculations confirm this intuition. Specifically, the FWHM at 633 nm is 75 milliarcseconds, instead of 53 milliarcseconds, and it is proportional to wavelength to a reasonable approximation. (At longer wavelengths it oscillates somewhat about the linear trend due to interference phenomena, remaining constant between 850 and 950 nm for example.)

The WFPC differs slightly from the FOC in that the reimaging cameras contain secondary mirrors that obscure part of the center of the beam, and also contain about $1/30$ wave of extra spherical aberration. The result is that the encircled energy curve for a 0.1 arcseconds radius aperture is shifted by 3.7 mm further from the paraxial focus, and the encircled energy at the SWG focus is about 12% instead of a possible peak value of 17%. The central obscuration in the cameras moves in a predictable way from ray trace calculations, although it is not centered at the center of each chip as one

might expect from the optical design. The result is that star images change in a predictable way as one changes field position. An example is shown in Figure 6 which compares predicted and observed PSFs at several field positions in PC6 through filter F547M. The theoretical predictions are parameter free being based entirely on the known pupil function of the camera, the measured spherical aberration of the OTA and the SWG focus definition. Obviously one could improve the agreement further by introducing known misalignments in the telescope (primarily coma), and modelling the measured phase errors on the primary and secondary mirrors. This work is ongoing, and hopefully will lead to better simulated PSFs for deconvolution purposes. In the meantime, a library of PSFs with the above nominal parameters has been produced by at the STScI, using the TIM software. Both the library and the software are available to interested researchers on request.

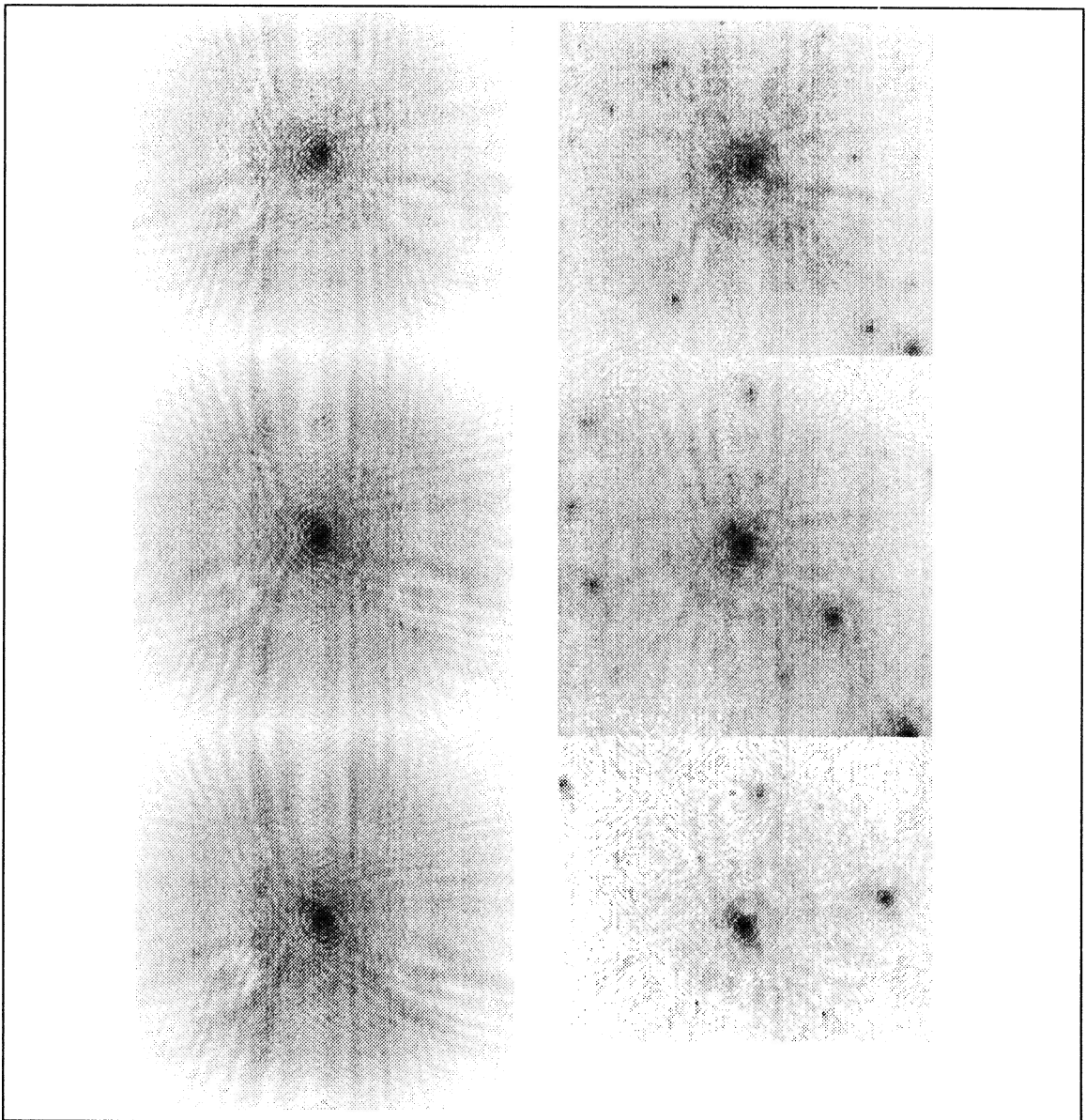


Figure 6 Comparison of predicted and observed PSFs at several field positions in PC6

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