HST IMAGE RESTORATION: CURRENT CAPABILITIES AND FUTURE PROSPECTS

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Abstract. The spherical aberration in the primary mirror of the Hubble Space Telescope causes more than 80% of the light from a point source to be spread into a halo of radius of 2-3 arcsec. The point spread function (PSF) is both time variant (resulting from spacecraft jitter and desorption of the secondary mirror support structure) and space variant (owing to the Cassegrain repeater optics in the Wide Field / Planetary Camera). A variety of image restoration algorithms have been utilized on HST data with some success, although optimal restorations require better modeling of the PSF and the development of efficient restoration algorithms that accommodate a space-variant PSF. The first HST servicing mission (December 1993) will deploy a corrective optics system for the Faint Object Camera and the two spectrographs and a second generation WF/PC with internal corrective optics. As simulations demonstrate, however, the restoration algorithms developed now for aberrated images will be very useful for removing the remaining diffraction features and optimizing dynamic range in post-servicing mission data.

Key words: image restoration – deconvolution – Hubble Space Telescope

1. The HST Imaging Problem

The Hubble Space Telescope (HST) suffers from spherical aberration in the primary mirror (see, for example, Burrows et al. 1991). The aberration has been measured as -0.43 waves rms at $\lambda 633$ nm, which leads to a 4.6 μm optical path length error for marginal rays at paraxial focus. The error in the surface scales as (radius)^4. Marginal focus is 43 mm from paraxial focus. The aberration causes the point-spread function (PSF) to cover a region over 5 arcsec in diameter, with only about 15% of the light in a sharp core with radius $0\overset{''}{.}1$. Had the telescope performed at the design specification, 70-80% of the light would have been concentrated within the core. The core of the PSF is formed by the inner region of the mirror, and the halo (comprised of diffraction rings and tendrils) originates from aberrated rays from the outer region of the mirror and from obscurations in the optical telescope assembly (OTA).

There are a number of effects that need to be considered in doing HST image restoration work:

• Noise in the data makes this a classic "ill-posed" restoration problem. One of the major objectives in image restoration is to find techniques that restore the object structure without excessive noise amplification. Since noise in the PSF adds further instabilities to the restoration processing, it is important to be able to compute PSFs based on knowledge of the telescope optics. Computed PSFs are also required for wide-field restorations since observing time is generally not available to map the spatial dependence of the PSF adequately.

• The programs currently available for computing model PSFs do not produce results that match observed PSFs to the required degree of accuracy. Work is now in progress on improving the PSF models utilizing both phase retrieval techniques and more sophisticated PSF computations.

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• The modulation transfer function (Fourier transform of the PSF) may have points with zero or near zero amplitude. Restoration techniques will have difficulty restoring structures at the corresponding spatial frequencies even when the noise in the data is negligible. However, note that constraints on the image such as positivity can sometimes help to restore even these 'difficult' structures.

• PSFs are wavelength dependent. Images taken in broad-band filters will show different PSFs for red and blue objects.

• The PSF for the Wide Field/Planetary Camera (WF/PC) is strongly space-variant. At the edge of the field the internal Cassegrain repeater causes vignetting of the OTA pupil. Even well within the field, however, the WF/PC internal obscurations are offset from the OTA obscurations, and thus the PSF is formed by rays traveling over differing paths and having differing phase errors as a function of field position.

• The PSF for all instruments is time dependent. Spacecraft motion is induced by the solar array panels, especially as the telescope enters and exits from the earth's shadow. The resulting jitter (with typical frequency of about 0.1 Hz) degrades resolution. The secondary mirror support system is known to be shrinking with time from desorption, giving rise to changes in focus on time scales of months. There is also some evidence for focus changes on time scales comparable to the orbital period, suggesting that the secondary support system may be subject to thermal instabilities.

• Both the Faint Object Camera (FOC) and WF/PC produce data with low dynamic range. The WF/PC is limited by its 12-bit analog/digital converter and the associated read-out noise (13.5 e-) to a dynamic range of about 2000. The FOC response becomes strongly non-linear at count rates exceeding 1 $\sec^{-1}$pixel^{-1} (512×512 pixel format, $f/96$) yielding an optimum dynamic range of about 1700. In practice these values are rarely achieved because of the overlapping halos of bright objects and uncertainties in the PSF models.

• Some restoration algorithms require that bad pixel values (cosmic ray hits, data drop-outs, etc.), be repaired prior to deconvolution.

• WF/PC data suffers from undersampling in the spatial domain, especially in the UV part of the spectrum. Restoration techniques based on Fourier transforms have potential problems with aliasing.

• Aside from simply improving HST images qualitatively, astronomers are concerned with the photometric integrity of the data. Restoration techniques must conserve flux and the linearity of response, at least over some well-defined intensity range, or well-calibrated correction procedures must be available.

2. Current Studies

2.1. Jitter

Thermal expansion and contraction of HST's solar panels cause the entire spacecraft to wobble as it moves out of or into the earth's shadow. The spacecraft's guidance system attempts to compensate for the motion but cannot always react to the large magnitude of the resulting pointing error, resulting in a loss of lock on the guide

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stars. Revisions to the onboard software installed earlier this year have greatly improved HST's tracking performance from jitter with a magnitude of 20–50 milli-arcsec, a level which significantly blurs the PSF, to 7 milli-arcsec rms or less more than 90% of the time, where there is virtually no affect on the PSF or on image restoration. Restoration of archival data for which the pointing stability was poor, or for the small fraction of data that continues to be troubled with poor pointing, will need to utilize jitter functions generated from the engineering data. These can be convolved with model PSFs in order to generate a PSF suitable for restoration processing.

2.2. Secondary Mirror Motion

The desorption curve for the secondary mirror support structure has been monitored since launch. The position of the secondary mirror is known to within $\pm 5\ \mu$m given the best fit to the desorption measurements, although discrepancies as large as 11 μm have been seen. We have done numerical tests on simulated data in order to understand the effects on restoration of using a PSF model computed for an incorrect focus position. For focus errors of 5 μm or less the effects are negligible, at least for averaged brightness profiles, whereas errors at the level of 11 μm introduce systematic errors at a level of about 1 part in 3000. Thus, small focus errors can typically be ignored except in cases where detailed structures requiring high dynamic range are to be recovered.

2.3. Photometric Linearity

While several restoration techniques (such as Fourier inversion and Wiener filtering) are intrinsically linear, the techniques that are best suited to HST image restoration are inherently non-linear. This does not mean, however, that linearity is *necessarily* corrupted. Our tests of the Lucy-Richardson algorithm (Lucy 1974, Richardson 1972, Snyder 1990) indicate that the photometric response is linear over a dynamic range of at least 6 stellar magnitudes. The linearity of other restoration techniques has been investigated (Busko 1992), and modifications to the maximum entropy method that preserve linearity have been suggested (Weir 1991). In general, MEM techniques are notorious for corrupting photometry and must be used with caution.

2.4. PSF Modeling

PSF modeling programs such as TIM (Telescope Image Modeling software; Krist, Hasan, and Burrows 1992) and TinyTIM (Krist 1993) have, to date, been only partially successful in computing satisfactory PSFs for image restoration purposes (e.g., Krist and Hasan 1993). One of the primary problems with the PSF models is that they require a full specification of the telescope optical system, usually given in terms of the Zernike polynomial coefficients and a residual phase error map. This specification is a best overall fit to observed PSFs for a variety of wavelengths and filters, but frequently there are substantial mismatches between the models and real data. Our current efforts in this area utilize a non-parametric approach to solving for the residual phase errors. An initial guess for the phase distribution over the aperture which incorporates the known telescope optical characteristics is used as a starting point for an iterative method derived from the maximum likelihood equation for Poisson statistics. The resulting algorithm is similar to the Richardson-Lucy iteration: at each step of the iteration the phase map is adjusted by comparing the observed PSF with the computed PSF. After about 20 iterations a PSF is computed that is in much better agreement with the data (see Fig. 1). This approach works well when an approximate solution for the large-scale phase errors is already known, but tends not to converge properly if the initial guess is poor. We do not yet have enough experience with this new technique to determine how useful it will be in *predicting* PSFs as a function of wavelength or camera position, as opposed to simply *fitting* PSFs for a particular image.

A second potential problem with the approach used by TIM and TinyTIM is that they model the obscurations in the telescope as if they all occur in the same diffraction plane. For the WF/PC in particular, which uses a Cassegrain repeater system that introduces obscurations that are field-angle dependent, this assumption is incorrect and may lead to significant errors in the PSF model. This problem is now being investigated further by our collaborators D. Redding and M. Levine at the Jet Propulsion Laboratory.

2.5. Enhancements to the Lucy-Richardson Algorithm

The Lucy-Richardson algorithm (Lucy 1974, Richardson 1972) with modifications as suggested by Snyder (1990) has been the technique most frequently used to restore HST imaging data. The technique assures a non-negative result, recognizes the noise characteristics of HST data, and is fairly conservative in computational resource requirements (i.e., can easily be run on a desk-top workstation). Additional improvements to the algorithm include computing the restored image on a higher density pixel grid (possible because the model image is totally independent from the observed data and is compared to the observation only after convolution with the PSF and rebinning to the observed resolution) and increasing the rate of convergence by augmenting the correction made at each iteration. White (1993) has recently developed a further modification to the iteration in which the correction term is scaled according to the local S/N ratio. One problem with the Lucy-Richardson algorithm is that different regions of the image converge at different rates, with high S/N regions taking longer to converge and low S/N regions being iterated too far (causing correlated noise patterns to appear in the restored image). This 'adaptive' technique avoids amplifying noise in portions of the image where a smooth model adequately fits the data, but allows the iterations to continue sharpening the image in high S/N regions (see Fig. 2).

2.6. Restoration With a Space-Variant PSF

Perhaps the most difficult problem in HST image restoration is the space-variant PSF associated with the WF/PC. Assuming that the space variance of the PSF is known, in theory one could solve this problem by a brute-force approach in which each pixel has a separate PSF. The essence of the problem is to be able to convolve

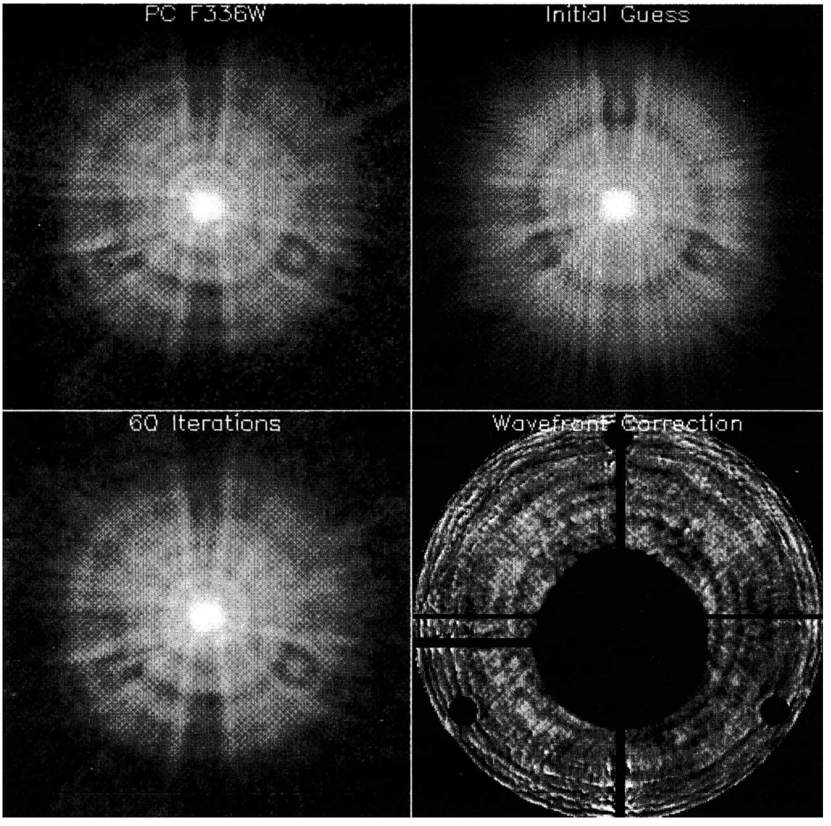

Fig. 1. **A non-parametric phase retrieval method has been used to improve the theoretical model for the HST PSF. *Upper left:* observed PSF. *Upper right:* PSF computed using low-order Zernike polynomial model for wavefront, which is used as an initial guess in the phase retrieval computation. *Lower left:* refined PSF model after 60 iterations. *Lower right:* corresponding phase correction map for the HST aperture (the large black region in the center is the obscuration of the secondary mirror combined with the secondary in the WF/PC Cassegrain repeater, the three small black circles are the primary mirror support pads; the spiders for the secondary mirror and the WF/PC Cassegrain repeater are also visible).**

a model image with the full set of space-variant PSFs, a step which is required for virtually all restoration techniques. If the convolution is done algebraicly we simply require a computer with vast amounts of memory and disk storage and an efficient I/O system. For example, the PSFs for a single 800×800 WF/PC frame would consume some 25 GB of disk storage (100×100 pixel PSF images), and different PSFs would be needed for each of the 8 CCDs and each of the 40 filters, yielding a total storage requirement of 8 TB. This PSF database would need to be recomputed each time the telescope is refocused. Although some efficiencies might

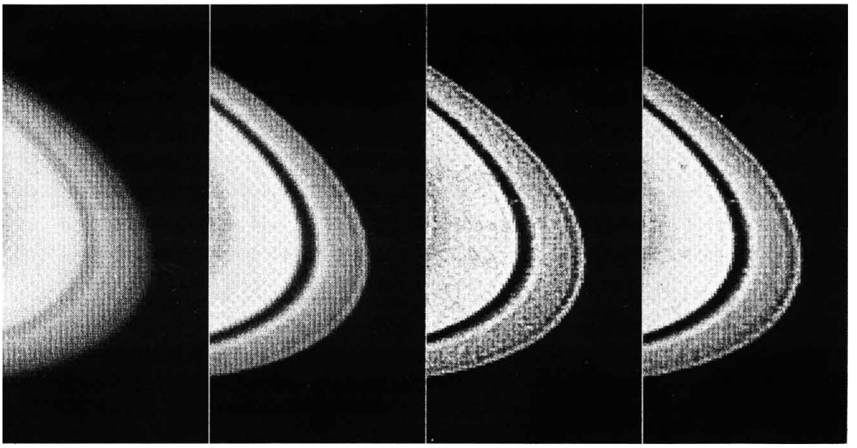

Fig. 2. Comparison of several results obtained with the Lucy-Richardson algorithm. The first panel shows the original data, which is a portion of Saturn's rings as observed with HST's Wide Field camera. The second panel shows a standard Lucy restoration using the improved noise model of Snyder (1990) after 70 iterations. The third panel shows the result of running the Lucy algorithm for 600 iterations; dynamic range is improved, but a very mottled appearance has been given to smooth areas of the brightness distribution. The final panel shows the results of the adaptive Lucy algorithm, which maintains sharpness of edges and high dynamic range but suppresses over-fitting of the data in smooth regions.

surely be attained, the scope of the computational problem is clearly beyond reach at this time.

A simplified version of this approach has been demonstrated by Cobb et al. (1990) using a Connection Machine. They segmented a 512×512 pixel WF/PC subimage into 32×32 pixel cells, and used a corresponding array of 256 (16×16) PSFs to restore each cell independently. Restorations were computed using the maximum entropy and Lucy-Richardson methods. A sustained computational throughput of 1.1 GFLOPS was required to complete the MEM restoration in approximately 90 seconds of elapsed time.

Stetson (1991) has shown that the space-variance of the WF/PC PSF can be modeled reasonably well by using a quadratic interpolation scheme (the PSF is fit to an analytic core plus a look-up table of corrections complete to second order), at least for the purposes of PSF fitting in the DAOPHOT II program. We have not yet tested whether the PSFs obtained in this manner are accurate enough for image restoration.

An alternative approach is to find an appropriate transformation or geometric distortion that would render the PSF spatially invariant. The image would be restored in this space-invariant domain, then transformed back into the normal image space. Our collaborators in this work, B. Hunt and S. McNown at the University of Arizona, will be investigating this technique in the coming year.

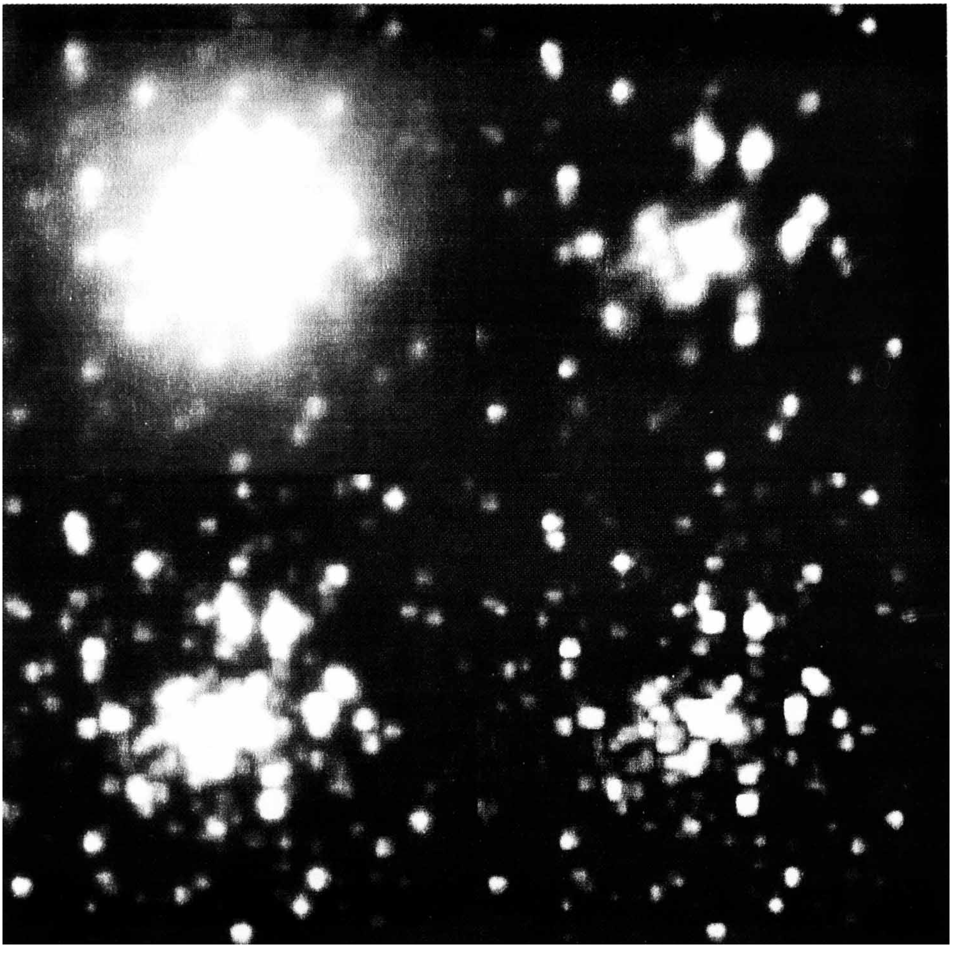

Fig. 3. HST simulated images of a star cluster. *Upper left:* current telescope performance. The model is convolved with the current PSF. Poisson noise and detector read-out noise have been added. The gray scale runs from 0 to 10% of peak flux. *Upper right:* Lucy restoration of frame at upper left. Gray scale for this and subsequent frames runs from 0-5% of peak flux. *Lower left:* WFPC-II performance. The model is convolved with the WFPC-II PSF assuming perfect correction for the aberration in the primary mirror, and Poisson noise and detector read-out noise have been added. Note added sensitivity to fainter stars. *Lower right:* WFPC-II after restoration. Resolution is improved by approximately 20-25% after restoration. Actual results from in-orbit data will depend on pointing behavior and the performance of the corrective optics in WFPC-II.

3. The HST Servicing Mission and Image Restoration

The first servicing mission for HST is currently scheduled for December 1993. The plan for this mission includes replacement of the solar panels, removal of the High-Speed Photometer and its replacement by COSTAR (Corrective Optics Space Telescope Axial Replacement instrument), removal of WF/PC and its replacement by WF/PC II (which has internal corrective optics), and repair of several other minor problems. COSTAR will correct the spherical aberration for the two spectrographs and the Faint Object Camera.

We have done simulations to compare current and post-servicing mission images and the benefits of applying the same restoration techniques to aberration-free data. Typical results are shown in Fig. 3. The simulations assume perfect correction for spherical aberration and perfect knowledge of the PSF, and thus represent a best-case scenario.

Application of restoration algorithms to post-servicing mission data will continue to have a major benefit. Substantial improvements in dynamic range and spatial resolution are achievable even in the ideal case we have simulated, and these techniques can help correct for any residual optical errors resulting from an incomplete prescription in COSTAR or WF/PC II. The corrective optics are necessary, of course, in order to recover absolute sensitivity and dynamic range, but restorations of high signal-to-noise data now achieve virtually the same spatial resolution as will be obtained for raw data after the servicing mission.

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References

Burrows, C. J., et al.: 1991, *Astrophys. J.* **369**, L21.

Busko, I.: 1992, submitted to *Pub. Astron. Soc. Pacific.*

Cobb, M., Hertz, P., Whaley, R., and Hoffman, E.: 1990, *Bull. Amer. Astron. Soc.* **22** (4), 1281.

Krist, J.E., Hasan, H., and Burrows, C.J.: 1992, in *Astronomical Data Analysis Software and Systems I*, D.M. Worrall, C. Biemesderfer, and J. Barnes, eds., ASP Conference Series **25**, 223.

Krist, J.E.: 1993, in *Astronomical Data Analysis Software and Systems II*, R.J. Hanisch, R.J. Brissenden, and J. Barnes, eds., in press.

Krist, J.E., and Hasan, H.: 1993, in *Astronomical Data Analysis Software and Systems II*, R.J. Hanisch, R.J. Brissenden, and J. Barnes, eds., in press.

Lucy, L.B.: 1974, *Astron. J.* **79**, 745.

Richardson, W.H.: 1972, *J. Opt. Soc. Am.* **62**, 55.

Snyder, D.: 1990, in *The Restoration of HST Images and Spectra*, R.L. White and R.J. Allen, eds., Space Telescope Science Institute, 56.

Stetson, P.B.: 1991, in *Proceedings, Third ESO/ST-ECF Data Analysis Workshop*, P.J. Grosbøl and R.H. Warmels, eds., European Southern Observatory Conference and Workshop Proceedings **38**, 187.

Weir, N.: 1991, in *Proceedings, Third ESO/ST-ECF Data Analysis Workshop*, P.J. Grosbøl and R.H. Warmels, eds., European Southern Observatory Conference and Workshop Proceedings **38**, 115.

White, R.L: 1993, in preparation.

Discussion:

Napier:
You have shown that, even after the spherical aberration is corrected, restoration algorithms will improve HST images. What are the remaining aberrations that are being corrected in this case?
Hanisch:
The simulations show the expected point spread function for HST's WFPC - II given the known obscurations in the pupil. Thus, one has the normal Airy pattern, with diffraction features associated with the spider supporting the secondary mirror, etc. The model also incorporates the known zonal errors in the primary mirror (which remain after correction for the spherical aberration).