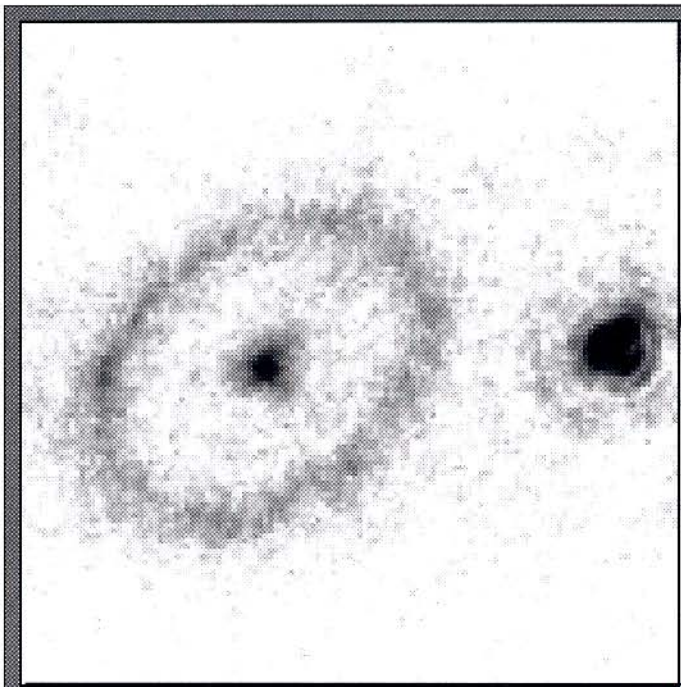
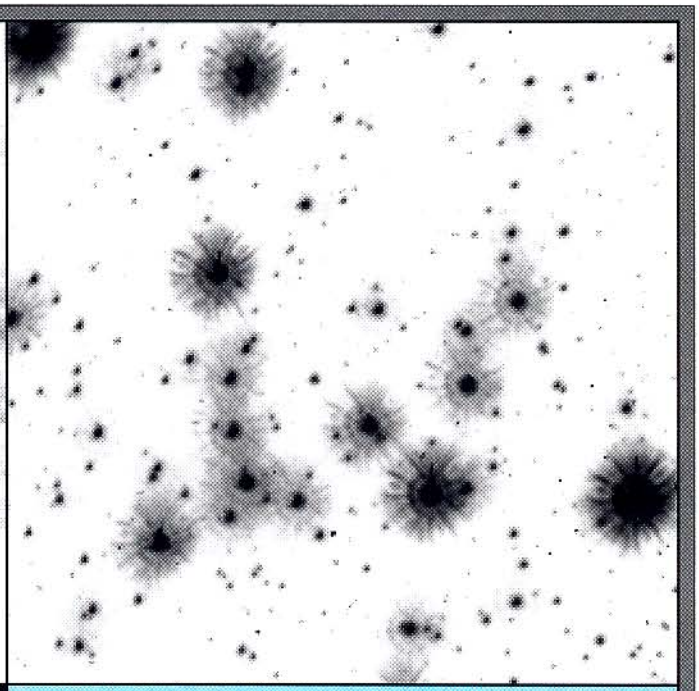
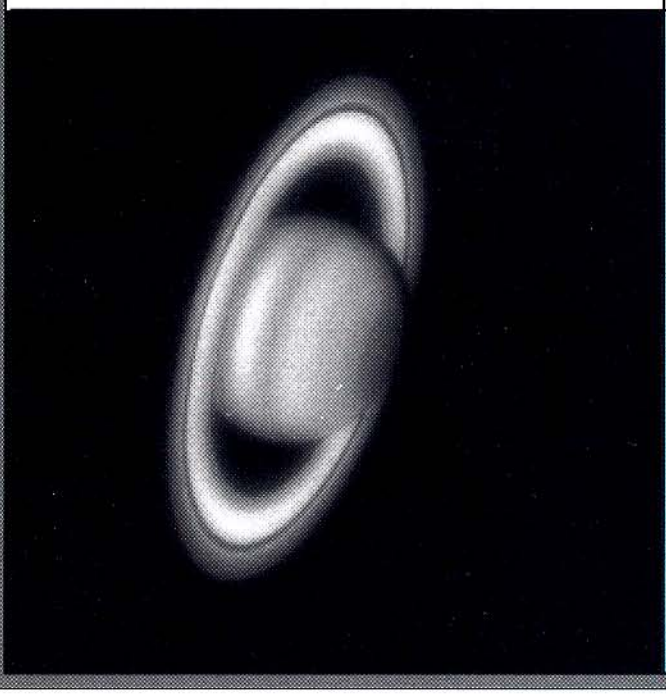
Number 14 October 1990

ST–ECF Newsletter

Space Telescope — European Coordinating Facility







Contents

HST in orbit—five months on

The HST is now an operating observatory in space with the first scientific data already obtained. All instruments are working well. The discovery that the telescope suffers from significant spherical aberration will, however, have a profound influence on the kind of observations which will be performed before an optical correction can be implemented.

Robert Fosbury

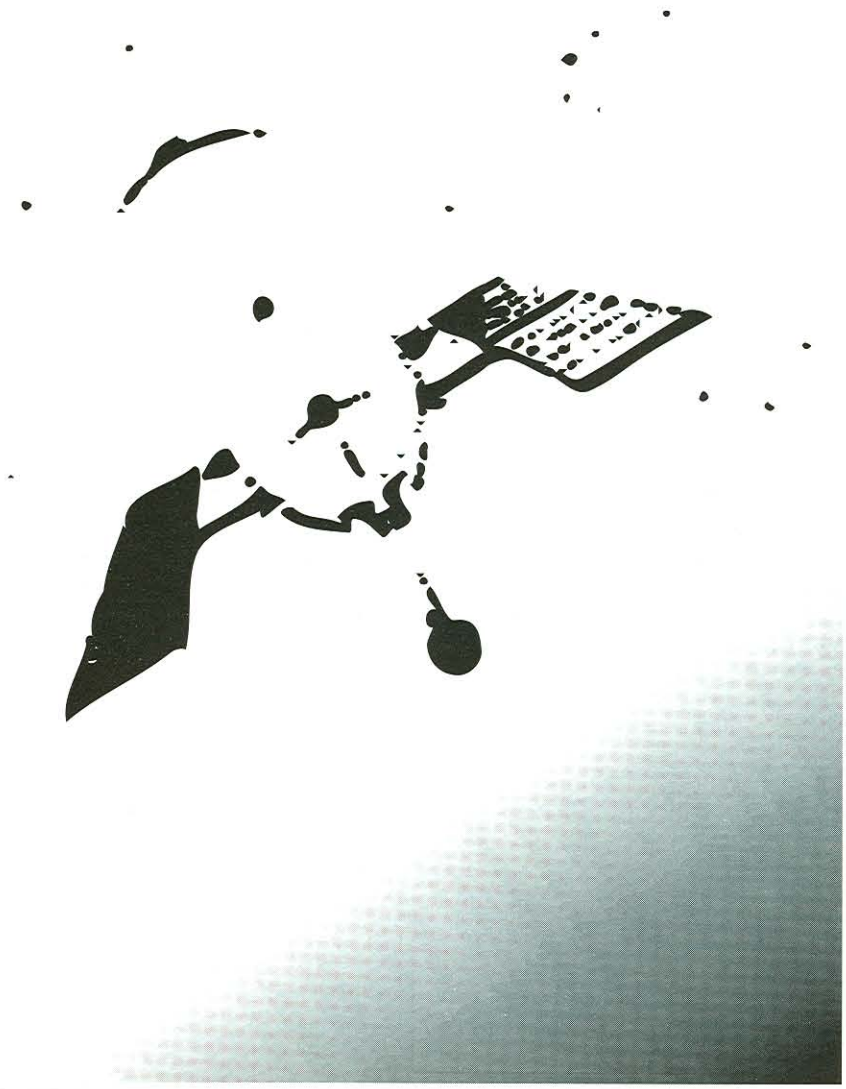
A little after five months from launch, the Hubble Space Telescope has taken its first scientifically interesting images and is just beginning to obtain spectrographic data of astronomical sources. Much has happened, however, in the period since our last Newsletter and it is worth glancing back over the stream of events—not all of them so pleasant—to see what we can say about the current state of the observatory.

Those of you who have access to the electronic bulletin boards at both the STScI and the ST–ECF will have been able to follow events in detail. For this we must acknowledge the labours of Ron Polidan at the Goddard Space Flight Center who, whilst initially writing reports destined solely for the Science Working Group and Users Committee members, was finally forced to acknowledge that his name, like that of famous newscasters, appeared regularly on the lips of thousands of astronomers around the world.

Much attention has been and is being devoted to the Pointing Control System or PCS, an acronym which soon became familiar. This is a hierarchical system consisting of reaction wheels, magnetic sensors, coarse sun sensors, fixed head star trackers, gyroscopes and, finally, the interferometric focal-plane star trackers known as the FGS. This is a complex system with a very high demand on pointing and tracking accuracy and precision. A number of problems were revealed as the Orbital Verification programme proceeded. Some of these have been solved, eg, poor star catalogues for the star trackers, software errors etc. A mechanical oscillation originating in the solar arrays and induced by thermal shock as the spacecraft passes the terminator is thought to be amenable to solution by adjusting the control software and a modification should have been implemented by our publication date.

The level of performance achieved by the three FGSs is crucial both to the operation of the observatory as it is now and for making the best choice amongst the various optical correction options which are being discussed by the 'Strategy Panel' (see P. Benvenuti's note in this Newsletter). These devices operate in both 'coarse' and 'fine' lock modes. Coarse-lock makes use of an error signal generated by a simulated 'four-quadrant detector' looking at the image of a guide-star and so is sensitive to any spherical aberration since it reduces the modulation. The fine-lock mode—necessary for the ultimate pointing stability—uses a pair of Köster prism interferometers which detect wavefront tilt when the star is off-axis and should, in principle, be insensitive to symmetric aberrations in the image. It is clear that these are not working on stars quite as faint as intended and the reasons for this are under very intensive study.

The performance of the HST Optical Telescope Assembly (OTA) has, of course, received considerable attention from astronomers, the media and the US Congress. Before the presence of significant spherical aberration was announced by NASA at the end of June, there had been a number of references to a 'core-halo' structure in the stellar images and some concern that the images were not reacting to secondary mirror movements in the expected manner. The symptoms of the aberration were (for most of us only in retrospect!) clear. The inability to correct it using the 24 primary mirror actuators, apparently, was not. A Presidential Commission was formed—headed by the recently retired director of JPL, General Lew Allen—to identify the origin of the error. This, it appears, has been done with the culprit being a 'reflective null-corrector' used to test the figure of the primary mirror. Fortunately, the test setup remained untouched since the mirror figuring was performed in the early '80s and it was possible to discover that a field lens in the corrector had been mis-located by about 1.3mm—enough to cause the problem.



The reason that no test was made at the time to detect a 'matching error' between primary and secondary will, no doubt, form an interesting chapter in the next volume of the project history.

The nature of the aberration is now rather well understood and there is good reason to expect that, given the measurements of the test setup on the ground and series of measurements of the image in orbit, the OTA performance will be characterised with sufficient accuracy to design corrective optics. Also, we hope it will be possible to compute the noise-free Point Spread Functions (PSF) which will be of such value in image restoration computations. The effect of the aberrated PSF on observations is discussed in some detail in this Newsletter: its major consequence for imaging is, in fact, to decrease contrast rather than spatial resolution—the diffraction limited core of the PSF can still be utilised to great effect. For the instruments with focal-plane apertures, the principal effect is to reduce throughput although there will generally be some effect on spectral resolution as well when the larger apertures are used. The performance of the OTA in the ultraviolet appears encouraging with the mirror reflectivity and microroughness being well up to the expected level of performance.

The instrument verification process has continued right through the period with extremely encouraging results. Each instrument has performed almost flawlessly, the cameras being used extensively in support of the OTA investigations as well as obtaining the first observations for the scientific assessment of the observatory. The ESA provided Faint Object Camera (FOC) was the first instrument to complete its orbital verification phase and, with its good sampling of the PSF (a great advantage for the application of image reconstruction algorithms) and high sensitivity in the ultraviolet, is all set to produce spectacular results.

The major spacecraft communication, thermal and power systems are in an excellent state: the power consumption is substantially lower than expected—due to thermal behaviour—and the ESA supplied solar arrays are producing an abundant supply of electricity.

The observatory hardware is, of course, not the only system to be exercised during the verification phase. The ground system and the whole operations philosophy has had to work and, indeed, has been required to react to changing circumstances far more frequently than is to be expected during routine observations. The generation of Science Mission Schedules (SMS) at the STScI, often needing revisions with little warning, has demanded unrelenting effort by a dedicated team.

The necessary investigation of the OTA has meant, inevitably, some disruption of the planned Orbital and Science Verification (OV and SV) programmes but it is anticipated that SV will start very soon and that Cycle 1 General Observer programmes will begin in the first half of 1991. Plans for the modification of accepted GTO and GO programmes have been communicated to the principal investigators.

In order to better understand the actual performance of the instruments, it was decided to obtain a series of Science Assessment Observations (SAO) and to distribute these as soon as possible to the scientists involved in the programme. The first of these have been obtained with the cameras and have already been distrubuted. The second set, containing some spectrographic observations, should follow shortly. In addition the acquisition of a a set of Early Release Observations (ERO), designed at least partly for publicity, is also underway.

Correcting the optics—the Strategy Panel

A panel has been appointed by the director of the STScI to advise on options for recovering the full HST optical performance. After a series of meetings in the USA and in Europe, it is due to report by the end of October. Proposals range from full-aperture solutions through to individual instrument correctors.

Piero Benvenuti

Shortly after the initial assessment of the problem affecting the optics of HST, the director of the ST Science Institute, Riccardo Giacconi, appointed a panel to identify and evaluate strategies for recovering the telescope capabilities (see the *STScI Newsletter*, Vol. 7, No 2, August 1990). The Panel, which is co-chaired by Holland Ford and Robert Brown of the STScI, is composed of a small number of astronomers and engineers and it is working on a tight schedule: the panel has already met three times (August 17–18 in Baltimore, September 3–4 in Garching and October 1–2 again in Baltimore). The final report will be discussed and presented to the director of STScI at the end of October.

The panel was charged with the task of exploring a wide range of corrective options and indeed more than thirty different ideas were tabled and discussed during the first meetings. The proposed solutions can be classified according to the nature of the correction they provide. A first group aims to correct the whole field of the telescope by acting on its full aperture, a second and third group consider the correction of the individual instruments, either before or after the focal plane. A slightly different group deals with the effects of masking the aperture and finally, the last group discusses the pros and cons of radical solutions like retrieving and re-launching HST.

Some of the ideas may seem rather weird but several appear quite promising from both the optical and engineering standpoint. All of them will appear, together with their assessment, in the final report in order to illustrate the broad range of options which have been explored by the enthusiastic and imaginative panel members.

Independently of the work of the Strategy Panel, but in close coordination with it, ESA has initiated a study on specific corrective options for the Faint Object Camera. The study is directed by the FOC Project Manager, Robin Laurance, and should be completed in a few months.

Hopefully, these activities will help NASA and ESA to choose the best strategy for restoring, as fully as possible, the design performance of HST. Preliminary results from these studies will be presented at the HST Workshop at ESTEC (see the notice in this *Newsletter*).

The HST point spread function

The spherical aberration produced by the HST primary mirror results in a PSF which is far from Gaussian and rich in high spatial frequencies. This article describes the implications for both the cameras and the spectrographs.

Sperello di Serego Alighieri & Jeremy Walsh

Description of the PSF

The characterization of the Point Spread Function (PSF) is the first and probably the most important step in understanding the implication of the spherical aberration present in the HST optics on scientific observations. The PSF depends on how the HST optics are adjusted, the spectral characteristics of the source and filters and, for the WFPC at least, the position in the field of view. We describe here the PSF as measured at the optical settings close to those fixed for the Early Release/ Science Assessment Observations (ERO/ SAO). Although focus may still be changed by some small amount, the PSFs described here are certainly representative of the final ones. Earlier accounts of the HST PSF have been given in the August 1990 issues of the *STScI Newsletter* and *ESA AstroNews* and on the HST bulletin boards.

Figure 1 shows the well exposed image of an isolated star taken with the FOC at *f*/96 and the F501N filter (a narrow-band filter centred at 501nm), while figure 2 shows an azimuthally averaged surface brightness profile. The encircled energy distribution derived from the same image is presented in figure 3. The bright central core is close to being diffraction limited: It has a FWHM of 0.055arcsec, the first diffraction rings are seen around the core and the radius of the first dark ring is about 0.06 arcsec (for an unobscured circular aperture of 2.4m the first dark Airy ring at 501nm is at a radius of 1.22 λ/D, ie, 0.052 arcsec). Clearly the FOC *f*/96 pixel is just about small enough to sufficiently sample this core at 501nm. The effect of the spherical aberration is to remove considerable energy from this core and to spread it over a large halo extending up to a radius of 2.5arcsec. In fact the core contains only about 12% of the energy within the first dark ring, while it was expected to contain 60% with the nominal PSF. The triangular structure visible both out in the wings and close to the core is due to the 3 pads holding the primary mirror, an effect which is rendered prominent by the spherical aberration.

Figures 2 and 3 also show the characteristics of the PSF derived from the first ultraviolet light FOC image taken with the F120M filter around 120nm. The very central core of the PSF has about the same fraction of light and the same size as at 501nm, although it is not entirely diffraction limited at this shorter wavelength. At larger radii more energy is spread out in the wings of the PSF in the UV than in the visible. A substantial degradation of the PSF in the UV was expected before launch due to microroughness in the primary mirror (see the nominal curves in figure 3). It appears, however, that microroughness does not degrade the PSF in the UV beyond what is already caused by spherical aberration.

The Fourier transform of the PSF at 501nm (see figure 4) has 3 clearly distinct components which can be traced back to 3 separate features of the PSF. The broad nearly flat plateau (region 3 in figure 4), extending up to a frequency of about 0.3pixel^{-1}, is the transform of the diffraction pattern which is present in the inner parts of the PSF and includes the core and the diffraction rings. It demonstrates that the PSF has substantial power at frequencies exceeding 10arcsec^{-1} and therefore some of the expected resolution of 0.1arcsec is still achieved. The central sharp peak (region 1) is the result of the broad wings of the PSF: its sharpness reflects the width of the wings. The struc-

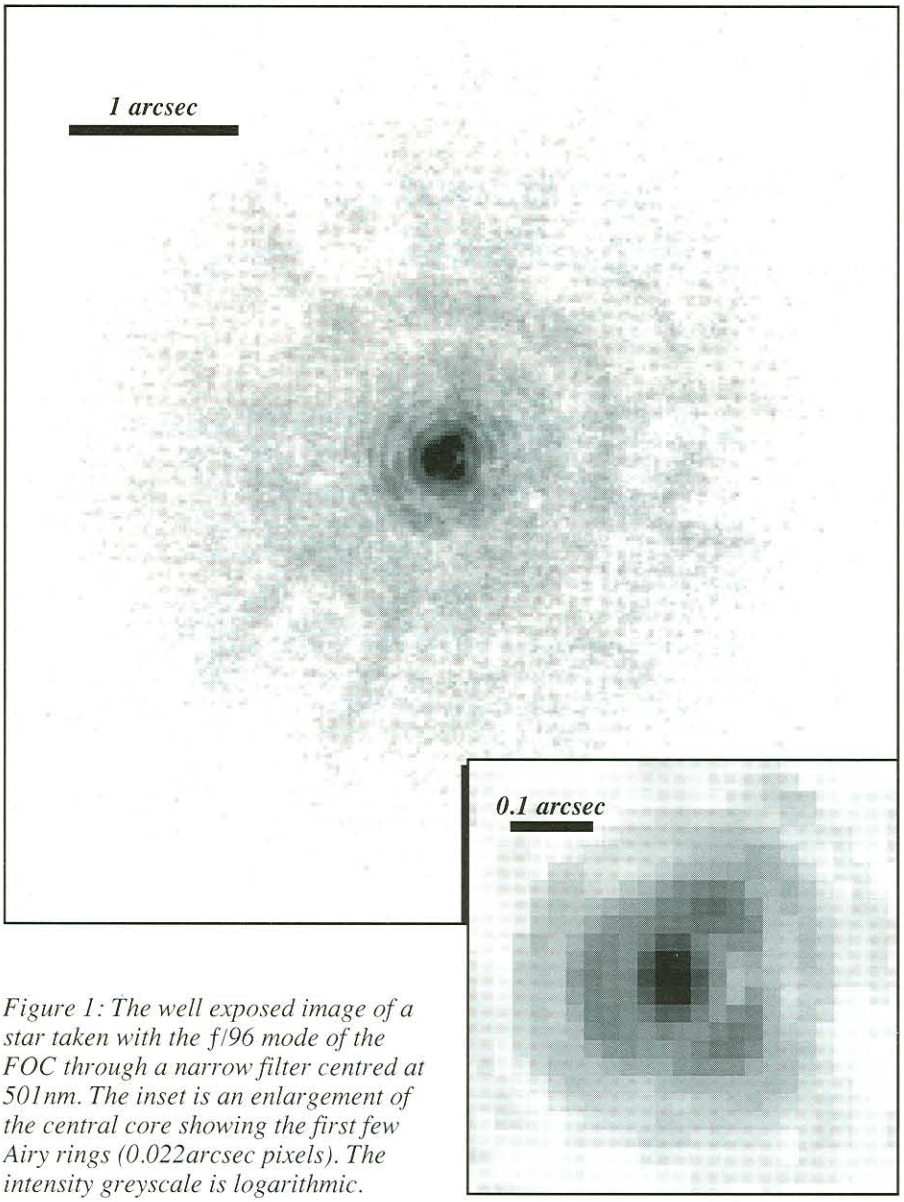


Figure 1: The well exposed image of a star taken with the f/96 mode of the FOC through a narrow filter centred at 501nm. The inset is an enlargement of the central core showing the first few Airy rings (0.022arcsec pixels). The intensity greyscale is logarithmic.

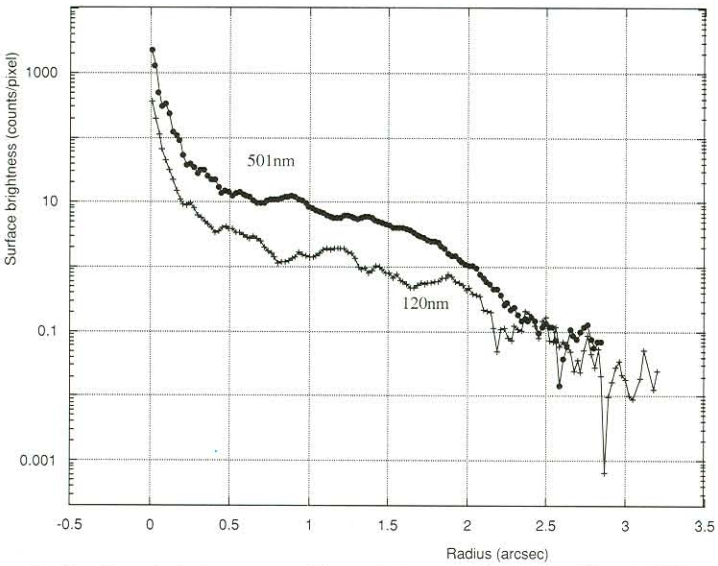


Figure 2: Surface brightness profiles of the star shown in Fig. 1 (501nm) and also of a star from a UV image taken through a medium bandwidth filter at 120nm with the FOC at f/96.

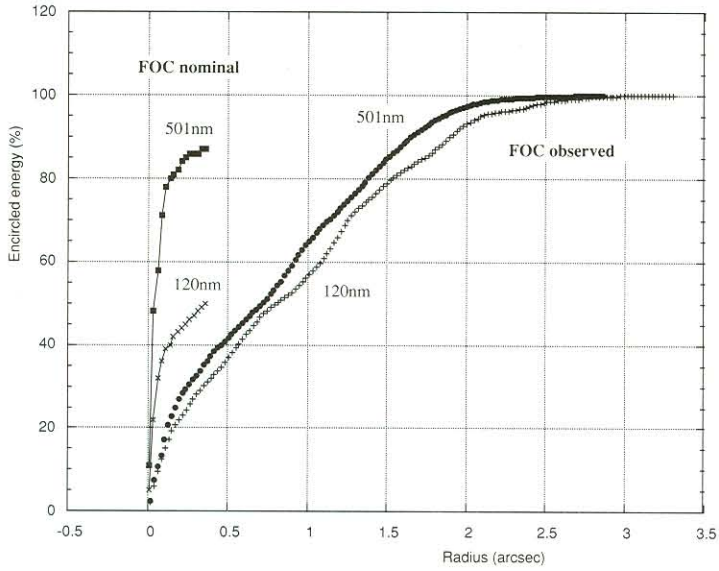
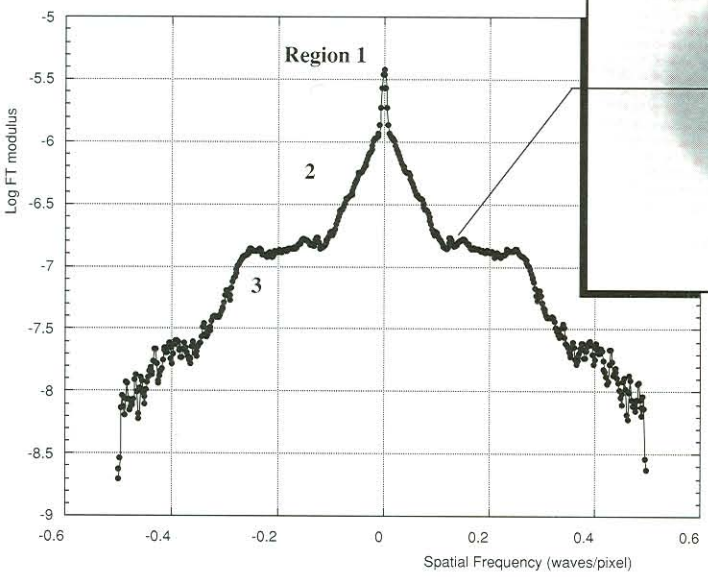


Figure 3: Encircled energy profiles derived from the stars imaged at 501 and 120nm. Shown also are the nominal profiles at the same wavelengths given in the FOC Instrument Handbook.



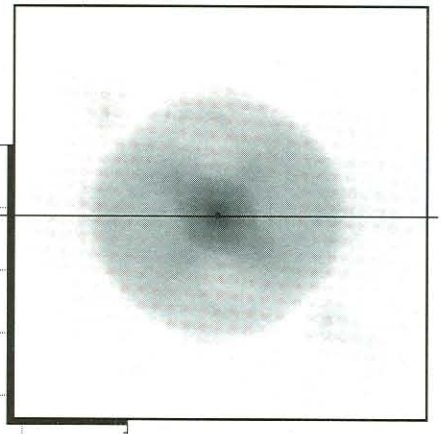


Figure 4: A slice through the modulus of the Fourier transform of the 501nm PSF (shown in the inset). The three distinct regions are discussed in the text.

ture in the Fourier transform joining the peak to the plateau (the triangular region 2 in the logarithmic plot of figure 4) contains the intermediate frequencies resulting from the rings and the spikes that are seen out in the wings of the PSF. The Fourier transform of the nominal HST PSF would be dominated by the broad plateau: regions 1 and 2 are largely the result of the spherical aberration.

Effects on Imaging

The HST PSF is complicated and its effects on imaging science depend strongly on the application. We shall consider only a few simple cases here and defer a more complete discussion until the results of the ERO/SAO programme have been examined in detail.

The first HST images show that only the central core is visible for faint point sources, the wings being lost in other sources of background. This is due to the high contrast between the surface brightness of the core and that of the wings of the PSF (figure 2). Since this core contains only one fifth of the nominal energy, for the detection of faint and isolated point sources about two magnitudes are lost with respect to the expectations with nominal optical performance. An increase by a factor of five in the exposure time would not recover fully the nominal sensitivity, since the background is also increased in this way. If one aims at a low signal-to-noise ratio (s/n < 15) on faint isolated point sources, approximate exposure times can be re-evaluated considering only the core and neglecting the wings of the PSF. In crowded fields of even faint point sources the wings of the combined PSFs add a non-negligible contribution to the background and exposure times have to be estimated by modelling each individual case.

Simple aperture photometry is of little or no use for photometric measurements and even in simple cases it is necessary to use PSF fitting techniques as is done with the photometric packages like DAOPHOT and ROMAFOT. The photometric accuracy to be achieved with these software packages is decreased by the fact that the fit of the PSF has to be made on a much larger number of pixels and therefore with a larger sensitivity to inaccuracies in the background subtraction and to readout noise in the WFPC. Moreover the photometric packages are likely to find spurious objects due to the structure in the wings of the PSF of bright objects. One way to solve this problem is to first apply an image reconstruction algorithm to the data

(see the article on the subject in this issue) to help in finding the objects in the field. The object positions can then be fed to a photometric package working on the raw data to avoid possible adverse effects of the reconstruction algorithm on the photometric measurements. Image reconstruction can also help to disentangle the structure of extended objects, but good angular resolution can be achieved only on very high contrast regions.

Effect on the spectrographs

Since the two spectrographs, the Faint Object Spectrograph (FOS) and the Goddard High Resolution Spectrograph (GHRS) have apertures of fixed sizes, the principal effect of the spherical aberration of the HST telescope optics is a loss of throughput, the amount depending on the aperture size. A secondary effect is loss of spectral resolution for observations of a point source with the larger apertures. In addition, smearing of light from celestial sources outside the aperture, within ~2arcsec, will contaminate the spectrum. Spectral point-by-point mapping of extended sources with large surface brightness gradients will become very difficult. The on-board target acquisition techniques may also be compromised, particularly in crowded fields and for small apertures. The long slit mode of the Faint Object Camera, with its fixed 0.1arcsec wide slit, is also badly affected by throughput loss as well as contamination by the extended wings of the PSF.

The GHRS has two apertures, 0.25arcsec square (called the Small Science Aperture, SSA) and 2.0arcsec square (Large Science Aperture, LSA) and the nominal throughput was 80% and 100%. The SAO/ERO observations are planned for early October but until the real throughput has been measured it is useful to predict it from the PSF measured with one of the imaging instruments.

The stellar image taken with the FOC at 120nm (the same as that discussed above) was analysed and throughput values of 15% for the SSA and 61% for the LSA found. Since the FOC is at a similar off-axis distance as both spectrographs, the PSF's for these instruments should be similar. However this image, the first light UV image, still had some coma and the focus position differs slightly from that adopted for the SAO/ERO observations and will not necessarily be the final focus position. These figures should therefore be regarded as estimates and fractional changes of 10–20% may occur. It is anticipated that the final focus will optimize the fraction of radiation in the core thus giving maximum throughput for small spectrograph apertures.

The resulting spectral resolution for observations of a point source with both apertures is illustrated in figure 5; for the SSA there is a slight loss in resolution of about 10% over the nominal value (1 diode FWHM); for the LSA things are much worse (upper curve in figure 5) with a broader peak and extended line wings. Clearly if the large aperture is to be contemplated for spectroscopy on account of its higher throughput, the wings will be particularly damaging for study of faint absorption lines or faint emission lines near bright ones. Deconvolution of a large aperture spectrum will help but experiments by Ron Gilliland at STScI show that the best resolution cannot be regained. Therefore consideration of the scientific aims and the desired spectral resolution must enter into decisions of large versus small aperture. Figure 6 shows the results of a simulation of the effects of the large and small aperture on spectra of an emission line source, shown at the top: the poorer resolution of the LSA and lower throughput of the SSA are obvious.

Broadly the same considerations apply to FOS. The small apertures suffer a large loss of throughput, the large apertures less but with degradation of spectral resolution for a point source. However if the source is extended and spatial resolution is not a consideration then there is no degradation of either throughput or spectral resolution over the nominal values.

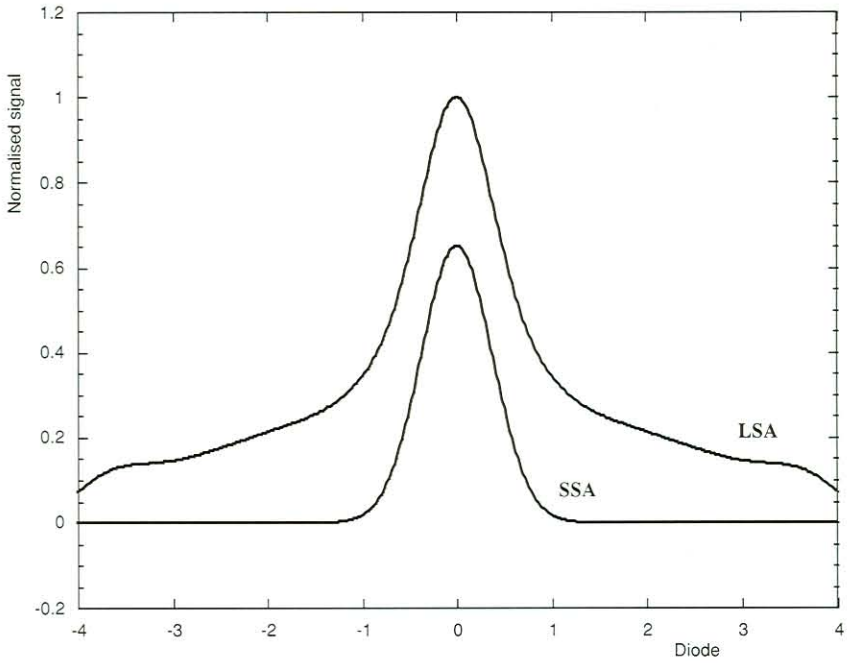


Figure 5: Line Spread Functions for the large and Small Science Apertures (LSA, SSA) of the Goddard High Resolution Spectrograph.

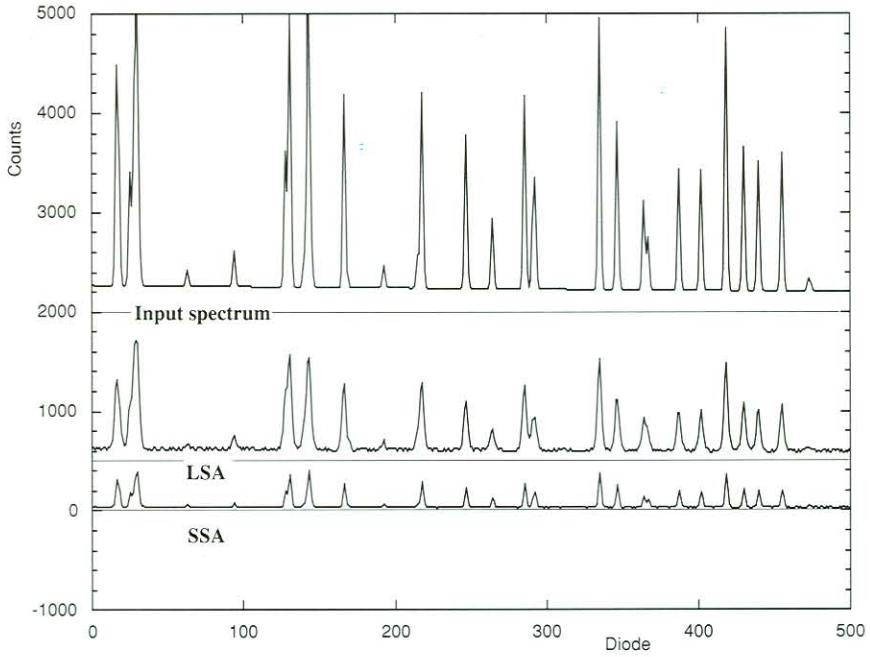


Figure 6: The result of the reduced throughput and degraded resolution produced by the GHRS large and small apertures illustrated by their response to the synthetic emission line spectrum shown at the top.

Table 1 shows the throughputs of the various FOS apertures measured for the same FOC 120nm PSF compared with the nominal values (see Figure 4.2–2 of the FOS Instrument Handbook).

The apertures with an occulting bar have not been considered as these are now of little use. The degradation in spectral resolution will be largest for the 1.0arcsec square aperture with a broad peak and extensive line wings; the best trade-off between resolution loss and throughput is for the 0.25x2.0 aperture, where the FWHM is increased by only ~10% over the nominal value (1 diode). The long axis of this aperture does, however, project to a length greater than that of the diodes.

Aperture	Throughput (%) measured PSF	nominal
0.3" circular	15	84
0.5" circular	21	94
1.0" circular	34	99
0.1x0.1" PAIR	5	60
0.25x0.25" PAIR	14	80
0.5x0.5" PAIR	23	94
1.0x1.0" PAIR	37	99
0.25x2.0"	23	89

Table 1: Throughput of FOS apertures at 120nm.

STScI NEWSLETTER

The Space Telescope Science Institute publishes a Newsletter at regular intervals (3–4 times per year). The STScI Newsletter contains information of interest to proposers, including updates on the status of the HST and its instruments. Subscriptions are available at no cost to all interested scientists; requests to be added to the mailing list should be sent (by regular or electronic mail) to the User Support Branch at the following address:

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A selection of SAO/ERO images

Here and on the front page, we give a small selection of the Science Assessment and Early Release images obtained recently with the WFPC and the FOC. Apart from the standard 'pipeline' processing, these have not been subjected to any kind of image restoration and are included simply to give an idea of the appearance of 'raw' data.

Front cover

SN1987a
FOC *f*/96, F501N
approx 2000s

NGC1850
WFC, F555W
1100s

Saturn
WFC, F439W
0.4s

This page

Pluto/Charon
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FOC *f*/96, F346M+F8ND
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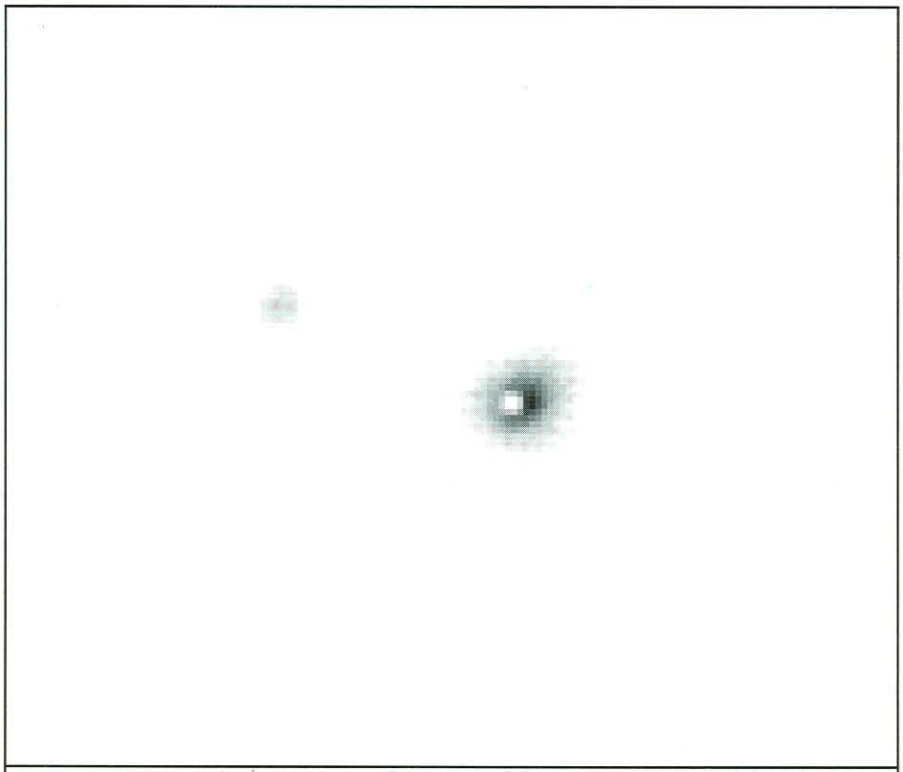
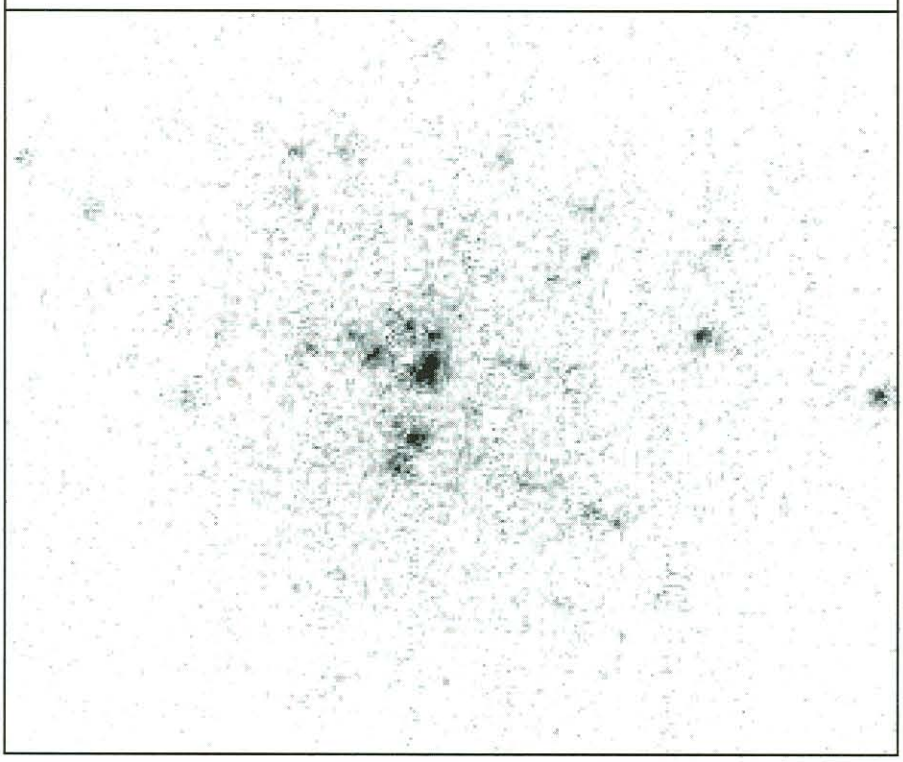




Restoring HST images— an ST–ECF perspective

For several years HST observations will suffer from a point spread function (PSF) which is severely degraded by spherical aberration. Sophisticated image restoration and statistical estimation methods will play an important rôle in HST data analysis. Issues to be addressed will include PSF determination, data pre-processing, statistical inference and error estimation, all in a high-speed computing environment.

Hans-Martin Adorf

The aberrated point spread function

The spherically aberrated PSF of the otherwise diffraction limited HST optics (see the companion article by di Serego Alighieri & Walsh 1990, Fosbury 1990) differs substantially from the near-Gaussian shaped PSFs encountered in ground-based optical imaging. The prospects of image restoration rely mainly on the existence of the sharp inner PSF core, but the tendrils and other small-scale details—distracting as they are to the unaided eye—also facilitate a proper two-dimensional reconstruction (given that the PSF can be determined well enough), since any fine structure provides power in the important high spatial frequencies. As opposed to radio synthesis data, the support of the two-dimensional Fourier-transform of the HST PSF fortunately does not show 'holes', i.e., largeish areas of zero power. Thus linear inverse and Wiener filtering can work on not too noisy HST data.

An outstanding feature of the degraded HST PSF is its peculiar power spectrum distribution (see Fig. 4 of di Serego Alighieri & Walsh 1990) with three distinct components: the 'head' (component 1), the 'neck' (component 2) and the 'shoulder' (component 3). Neck and shoulder are important for image restoration and are affected by noise in quite different ways (cf. Beletic 1990): As long as the level of noise, assumed to be white, stays well below the shoulder, high spatial frequencies can be exploited for image restoration or position estimates. Raising the noise floor above the shoulder leads to a sudden drop in spatial resolution, since all frequencies making up the shoulder are practically simultaneously lost for restoration. A further rise of the noise level entails only a gradual loss of the higher frequencies in the neck.

From an image restorers point of view two questions are of interest: Firstly, can the PSF be assumed to be known in all necessary detail and will it be stable in time? Secondly, is the PSF, seen as a linear operator acting on images via convolution, positive definite, i.e., does the PSF have only positive eigenvalues? Both questions are under investigation.

❶ Image restoration as an 'Inverse Problem'

Image restoration methods are not fundamentally different from other data analysis procedures: "The theme ... is inversion: determination of the properties of light from measurements of photoelectron-statistics" (Saleh 1978). The process of deriving properties of astronomical objects from recorded data (based on intercepted emitted or reflected light) in the presence of noise is an 'inverse problem' demanding the use of some form of 'statistical inference' (see e.g. Edwards 1972). What distinguishes image restoration from more conventional data analysis procedures (e.g. PSF fitting in a standard photometry package) is that—neglecting for the moment the non-negativity of the undistorted flux-distribution and, potentially, some further deterministic and stochastic assumptions of the data gathering process—restoration techniques are usually *unconstrained* or 'model-free' with respect to the content of the given image. It is this absence of constraints which substantially exacerbates the intrinsically difficult task to be accomplished.

The appreciation of statistical estimation as an appropriate tool for the analysis of noisy data calls for the conceptual transition from a *deterministic* viewpoint, which considers the required inference solely as a problem of matrix inversion or solution of an integral equation, to a fully-fledged *stochastic* perspective, which explicitly acknowledges the statistical properties of the signal and the recording process and considers the recorded data as a realization of a stochastic process. As a consequence the results of image processing also become stochastic quantities.

Statistical estimation methods (Melsa & Cohn 1978; Nunez & Llacer 1990) rely on the application of likelihood principles which require a description of the data gathering process in form of an explicit 'stochastic model', also called 'data formation model', 'forward transform' or 'likelihood function'. An indispensable tool for scientific inference is Bayes' equation $p(f|g)\ p(g) = p(g|f)\ p(f)$ relating the desired posterior conditional probability $p(f|g)$ to the computable likelihood $p(g|f)$. Here g denotes the recorded data and f the unknown signal to be restored.

Relevance of image restoration

When contemplating the application of restoration methods to HST images, the question naturally arises about which benefits to expect. For example, under which circumstances can the scattered light in the wings of source A be successfully removed from the core of source B? Will the light in the wings essentially always be lost and if not, when can it be exploited? It will presumably take some time before a comprehensive answer to these problems can be given.

Another question is whether one should perform measurements on restored images. The answer here depends on the kind of object of interest and also on the state of the analysis software.

For isolated point sources on a low background, all the light may be recollected by the standard analysis procedures without

the need for image restoration.

For point sources in more crowded fields the application of a general (sophisticated) restoration method followed by a (simple minded) photometry/astrometry procedure provides a good first attempt at the problem of measuring positions and fluxes, although there is general agreement that simultaneous PSF-fitting to the unrestored data is the preferred method—provided the analysis software is capable of dealing with the complexities of multiple HST PSFs. In any case, a restoration method can be used as a technical aide for locating point source candidates.

For extended objects, restoration methods will play a much more decisive rôle. When surface photometry on a pixel-by-pixel basis is the goal, image restoration is unavoidable, since any data analysis method which refrains from assumptions about the image content (and is capable of delivering the desired result) is, in effect, an image restoration technique. Another area for which restoration methods will be indispensable is exploratory data analysis, i.e. the discovery of the unknown.

Feasibility and success of image restoration depends critically on the characteristics of the PSF, the quality of the data—both of which are important ingredients of the stochastic model (see Box 1) for the data gathering process—and of course the quality of the algorithm employed.

Restoring real images

Instructive as it is to consider an idealised restoration problem first (see Box 2), one eventually has to face the facts of real HST data with noise, saturation, insufficient sampling, cosmic ray hits, cold columns, detector bleeding, read-out noise etc. (for the WFPC see Lauer 1989). The area of astronomical image restoration was comprehensively reviewed by Wells (1980, 1983) emphasising the importance of non-linear methods, and his main conclusions are still valid. Progress since then—as far as I am aware—has been mainly accomplished outside astronomy, e.g. in the area of *computer hardware*, which has become much faster and more common, and in *medical imaging*, where the Richardson-Lucy algorithm was studied extensively and generalized (Snyder 1990 and references therein).

Restoring HST images actually requires three separate steps: preparation of the required PSF(s), preparation of the data and application of the restoration method (inverse filtering, Wiener filtering, Richardson-Lucy-restoration, maximum entropy etc.). Once the algorithms are implemented, time and effort on the astronomer's part are spent mostly on data and PSF treatment.

PSF preparation. Knowledge of flawless PSFs without noise, holes (from reseaux marks of the FOC) or cosmic-ray hits (frequent on WFPC frames) is decisive for the image restoration process. A non-trivial question is how to determine such PSFs empirically from observations or theoretically from a model (see Box 3).

As long as these 'good' PSFs are unavailable, image restorers will have to resort to empirical PSFs derived from individual observations and suitably 'massaged' to meet the fairly high demands of image restoration algorithms. In principle, PSF preparation (Adorf 1990b) proceeds very much along the lines of data pre-processing (see below). Particular care is required for removing the background outside of the PSF-support, e.g. with a suitable circular apodizing mask.

Data pre-processing. Data pre-processing (Adorf 1990b) comprises all the usual calibration steps such as geometrical distortion correction (for the FOC), flat-fielding and background subtraction, plus some further steps required by the restoration process such as zero-level clipping in order to exploit the non-negativity constraint, removing bright frame borders by masking (for the FOC), embedding the data frame into a larger frame in order to avoid wrap-around effects of the Fourier transforms, apodizing the data, reconstructing missing parts of bright sources and resampling of the distorted data to a finer grid (mainly for the WFPC). Whether this last pre-processing step actually aids the restoration algorithm or introduces an additional 'dimensional instability' as reported by some authors, remains to be seen.

Choice and application of a suitable algorithm. Since the spherical aberration problem of HST became known, experience at the ST–ECF has been gained mainly on simulated data with two linear methods: inverse filtering and Wiener filtering, and two non-linear methods: the Richardson-Lucy iterative rectification scheme and maximum entropy (MaxEnt or MEM) restoration. Our initial conclusions can been summarized as follows (Adorf, Walsh & Hook 1990):

Restoration algorithms tend to separate into two classes with corresponding results. The *linear* restoration methods are cheap (in terms of CPU-cycles), fast, dirty and limited. They achieve high resolution at the expense of recognisable artifacts such as rings around point sources, negative values and a blotchy background; they are not doing too well on extended sources. The *non-linear* restoration methods on the other hand are expensive, slow, clean and generalizable. They deliver somewhat inferior resolution (unless driven to the extreme), but restore extended source structures quite reliably and, being iterative, they deliver a sequence of improving restorations. It can be anticipated that a cheap linear deconvolution will always be done as a first step and that, while one is contemplating the initial results, the computer will proceed to restore the data using a more expensive non-linear algorithm.

Preliminary attempts to quantify the errors of positional and flux measurements on the restored data show that the results of the various methods are fairly

❷ Restoring ideal data

Under certain circumstances, a *continuous* bipolar signal (i.e. a signal with positive and negative values) degraded by a non-ideal PSF can be completely restored with no information loss from a finitely sampled discrete data set. The following conditions must hold:

- ❒ The effective PSF, combining the degradations of the optics and the detector, must be known and its Fourier transform must show *no zeros*.
- ❒ The degraded continuous image before sampling must be *band-limited* in the spatial frequency domain.
- ❒ Sampling through the detector must be *sufficiently dense*.
- ❒ There must be *no noise*.

Some relaxations are possible in the presence of additional constraints such as non-negativity of the image to be restored.

A violation of the first condition means that plane wave portions of the signal corresponding to zero-power frequencies are completely extinguished. A violation of the second and third conditions leads to aliased frequencies. A violation of the fourth condition entails an irrecoverable loss of information. The extent to which the conditions above are violated determines the degree of difficulty (up to impossibility) of the restoration problem.

The method which accomplishes the ideal reconstruction task is the well-known inverse filtering followed by a sinc-function interpolation between the discrete data points, based on the classical sampling theorem.

consistent with each other (at least within the two algorithm classes).

Since the days of the STScI workshop some *real* HST data obtained within the Science Assessment Observation program have been restored. At the ST–ECF we have focussed on applying Wiener filtering and the Richardson-Lucy method to FOC f/96 images of SN1987A and R Aquarii. Also the most recent version of the commercial MEM-SYS3 quantified MaxEnt code (Skilling 1990) was installed and tested on real HST images. Some results will be presented at the forthcoming ESA/ESTEC HST workshop (Adorf & Lucy 1990).

Error estimation. During the recent restoration workshop at the STScI (see Adorf 1990a) it has repeatedly been stressed that the errors of the restoration results have to be *quantified*. For linear restoration methods an error estimate can easily be calculated (King 1990). For non-linear methods the problem of error estimation is partially unsolved although progress, e.g. on quantified MaxEnt, is being made (Skilling 1990). In any case, error estimates can be obtained by measuring variances on Monte Carlo simulations—if one has the appropriate stochastic model and the required immense computer power at one's disposal.

A possibility which has received relatively little attention so far is to use the Cramér-Rao or 'minimum variance bound' theorem (Slump & Ferwerda 1986; Adorf 1987; Pelat 1988) for establishing a method-independent lower bound to the errors of some estimated quantities. The Cramér-Rao-theorem again presupposes the existence of a stochastic model.

Representation of results. Anyone who has viewed a few restored images has noticed that they all look 'odd' in some sense and do not automatically convey a feeling of the errors involved, as opposed to normal observational data with their 'salt-and-pepper' noise. The question therefore has been raised of how to display restored data (e.g. in a publication) in such a way that the expectation and the variance are both easily grasped.

Two methods readily come to mind: (a) to add to the restored 'mean' image Poissonian noise corresponding to the local error estimate or (b) to display, alongside each restored image, a separate image with the error estimate. The first method is intuitively appealing and saves space, whereas the second preserves the (so painfully computed) information somewhat better but requires an intercomparison of two separate images by the viewer.

Another issue is that of displaying critically or insufficiently sampled data on a finer grid for reasons of easier visualization and æsthetic appeal (Lucy 1990). Methods which maintain a clear distinction between (observed) data and (restored) image space—such as the MaxEnt or the Richardson-Lucy algorithm, but not Jansson-van Cittert's—allow an arbitrary choice of the density of sampling points for the restored image as an integral part of the restoration process.

Impact on computing

Computationally, HST image restoration presents a big worry just because of the size of the datasets involved (up to 512x1024 pixels ≈ 2MB for a dezoomed FOC frame and 800x800 pixels ≈ 2.56MB for each WFPC-CCD frame). If resampling onto a finer grid is being considered, these sizes should be multiplied by a factor between 4 and 9. The size of the aberrated PSF, together with the wrap-around effects incurred with Fourier-based methods and the considerable problems of managing many data sets preclude the restoration of only small subframes containing the objects of interest.

Of particular concern is the restoration of images from the WFPC with its space-variant PSF. Restoration will presumably be done on overlapping 'tiles' with a PSF assumed to be constant within each tile. Depending on the amount of overlap, the initial dataset sizes are again increased by something between 4 and 9.

The more promising non-linear methods require typically about 40 iterations (i.e. 160 full-frame Fourier transforms for the Richardson-Lucy method) for satisfactory results. It is clear that the problem of restoring HST data will put optical astronomers into the domain of *real* number crunching. High-speed computing environments will almost certainly be needed in order to maintain the desirable interactivity in the data analysis process. Among the options, currently being scrutinised at the ST–ECF (Adorf 1990b), are vectorizing co-processor boards for workstations. These show some promise of being immediately available, affordable, easy-to-use and to deliver the required 'personal supercomputing' performance (i.e. a 512x512 single-precision Fourier transform in 0.25 sec).

Where do we go from here?

Considering the spherical aberration predominantly as a contrast and faint limit reducer rather than a resolution degrader, we can be moderately optimistic that image restoration works for HST. Careful data treatment similar to that in radio-astronomy (large PSFs), X-ray astronomy (noise statistics) and other fields will be much more important than it would have been with HST performing to specifications. The simulation tools such as the STScI's XCAL (Blades 1990) or the ST–ECF's instrument model software will increas-

❸ Derivation of 'good' PSFs

In order to arrive at a single desired 'good' *empirical* PSF, a collection of PSFs mutually displaced by random fractional pixels widths will have to be combined. Particularly for the WFPC with its severe undersampling problem (Adorf 1989a, b; Holtzman 1990) it would be advantageous if the PSFs could be represented on a finer grid or even in a continuous form ready for re-sampling on any desired grid. Estimating the underlying continuous PSF from the discrete noisy data in an optimum way will presumably require a version of the classical Whittaker-Ferrar-Nyquist-Whittaker-Kotel'nikov-Shannon sampling theorem—originally formulated for a one-dimensional deterministic continuous signal sampled on a regular grid—suitably generalized to two-dimensional stochastic data sampled on a semi-irregular grid (see e.g. Jerri 1977).

For several reasons one would prefer to ultimately use *theoretical* PSFs for image restoration and analysis. The results obtained so far (Burrows 1990; Thomson & Lasenby 1990) justify some optimism that the light path of the Optical Telescope Assembly and the instruments can eventually be modelled, although a lack of knowledge about the precise location of obscurations in the light path poses a problem at present. With a model at hand theoretical PSFs will be computable for any desired instrument mode, point within the field-of-view and wavelength, with the probable exception of the far ultraviolet. The establishment of a valid model requires the derivation of its free parameters from good observed PSFs and a continuous monitoring of the temporal stability of the optics.

Even with some anticipated streamlining of the existing code, the CPU-demands for PSF-computations will presumably be non-negligible. Calculating once a complete set of PSFs for all filters and a sufficient number of positions on each of the four Wide Field and Planetary Camera CCD-chips—the most demanding task—is forecast to require two CPU-years on a DEC VAX 8600 (Hanisch 1990).

❹ The Richardson-Lucy restoration method

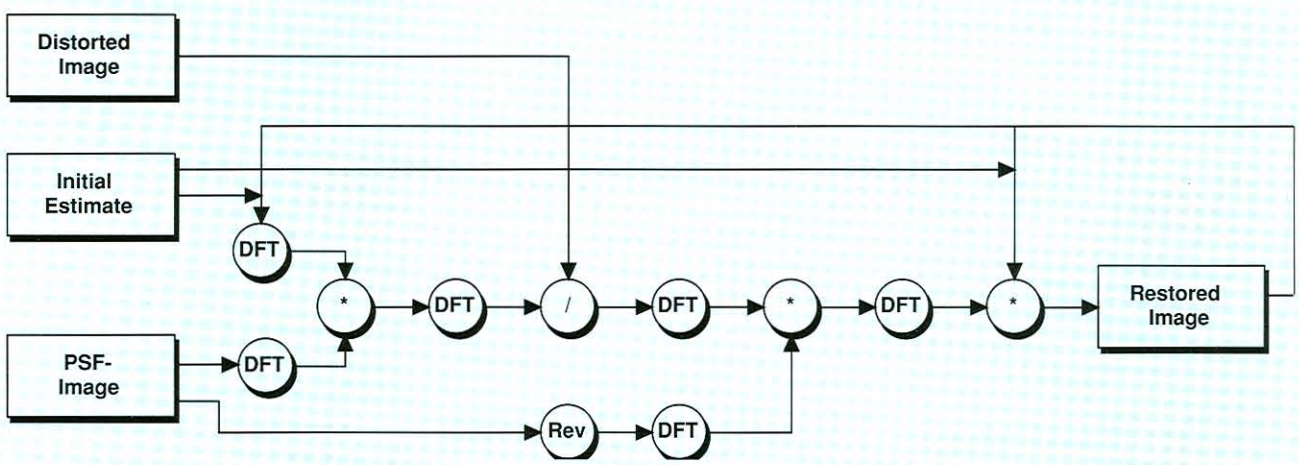
First devised in 1972 by William Hadley Richardson, this iterative inversion scheme was independently discovered for astronomical inverse problems by Leon Lucy in 1974. The derivation of the Richardson-Lucy method invokes Bayes' equation of conditional probabilities and solves the resulting Fredholm equation by a simple Picard fixed-point iteration. The method has been recommended for astronomical image restoration in general by Wells (1980) and specifically for HST restoration work by Baade & Lucy (1990). The algorithm is well known outside astronomy, e.g. in emission tomography (Snyder 1990) and is rapidly catching on within the HST restoration community.

The Richardson-Lucy algorithm is a non-linear iterative algorithm based on a linear data gathering model and aims at estimating for each pixel the prior probability of the image value (which is equated with the image value itself). The algorithm has several nice properties:

- ❒ It preserves image flux locally and hence also globally.
- ❒ It preserves non-negativity of the restored image, provided that the original image and the PSF are both non-negative. (Thus the algorithm cannot 'dig' into a zero-background as linear methods often do.)
- ❒ It is suited to astronomical data with quantum noise, since it is the expectation maximization (EM) algorithm for independent Poisson variables (Shepp & Vardi 1982).
- ❒ It seems to tolerate small errors in the PSF, since in the iteration scheme the PSF only appears convolved with the current estimate or convolved with the ratio of observed and 'predicted' data.
- ❒ Low spatial frequencies are immediately restored; higher frequencies are gently introduced later.
- ❒ Due to the iterative nature of the algorithm, intermediate restoration results can be monitored.
- ❒ The algorithm clearly distinguishes between image and data space. It is therefore possible to restore the image on a finer grid than the observed data.

For space-invariant PSFs the algorithm is simple to implement in any image processing system using solely operations on the image level embedded in a single loop. Each iteration consists of 4 fast Fourier transforms, three image multiplications and one division.

The algorithm is also easy to use because there are no free parameters besides the number of iterations. This is controllable by computing the reduced χ^2 between the observed data and the 'predicted data' obtained from the restored image via a PSF convolution.



ingly be used for proposal planning and feasibility tests.

Among the many tasks related to future HST data analysis, and at least to some extent addressable outside the STScI, I consider the following five to be of primary importance:

- ❑ to establish an optimised method for *PSF estimation* from observed data,
- ❑ to describe comprehensively the *stochastic models* for the various instruments (and potentially to revise the corresponding simulation software),
- ❑ to acquire or implement and optimise *restoration and estimation algorithms* and to quantitatively compare their results,
- ❑ to establish and implement *error estimators* and to derive the *Cramér-Rao-bounds* for the most interesting cases, and last, but not least
- ❑ to continue the evaluation of *high-speed computing options*.

Work has started on several of these issues at the ST–ECF. HST restoration work is being pursued elsewhere in Europe as well, e.g. by G. Weigelt *et al.* at the Max-Planck-Institut für Radioastronomie, Bonn, by J. Pfleiderer at the Astronomisches Institut, Universität Innsbruck and by J. Reiter at the Mathematisches Institut, Technische Universität München. All suggestions and contributions from the community are of course most welcome.

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Communications note

Richard Hook

In the last edition of the Newsletter, under Software News, there was a description of how to access the anonymous ftp account at STScI via the SPAN/Internet Gateway at Goddard. Unfortunately, the file used in the example (STEIS.DIR) has since been removed and the example command should now read:

```
$ type east"stsci.edu!anonymous
  name"::"README"
```

We apologise for any confusion this may have caused.

The Archive column

The data are coming...

Benoît Pirenne & Fabio Pasian

Data now flowing to ST–ECF

The flow of real spacecraft data into the Hubble Space Telescope archive at the ST–ECF has started. Although these first few months of operations have been devoted mainly to spacecraft verification and instrument assessment, the amount of data produced and received is already considerable.

Both the catalogue and the bulk of the data are arriving regularly: daily updates for the catalogue and bi-monthly shipments of optical disks from the STScI for the actual data files. This means that the catalogue of observations closely follows HST operations and that anyone using STARCAT can get a good idea of the most recent observations—targets, instruments, proposals etc. Since the data files themselves remain proprietary for a period of one year at least, the slightly longer wait for the data on optical disk is not a problem.

So far, more that 200,000 individual files have been archived. They consist of engineering files, calibration files, science mission schedules, on-board computer dumps, astrometry information, telemetry data and science files. For more information on the file content of a science observation set please refer to *ST–ECF Newsletter, No. 13*, p 5.

Distribution of SAO/ERO data

Due to the problem with the HST optics, Guaranteed Time and General Observers having HST time in forthcoming observing cycles need to reassess their observing programmes. The management of the HST project has therefore decided to distribute to the Principal Investigators some of the early data: a total of 38 images, obtained with WF/PC and FOC in the course of the so-called Early Release Observation (ERO) and Science Assessment Observation (SAO) programmes. As a part of this distribution effort, the ST–ECF recently shipped copies of the distribution tapes to 43 European scientists—within 2 days of the receipt of the data!

Catalogue data quality

The quality of the data stored in the early months of operations was often doubtful. For example, observation dates and exposure start and stop times were wrong. Most problems have now been cured but, pending a reprocessing of the data at the STScI, this information will remain absent from the catalogue for earlier observations. A few less important 'teething problems' have also been corrected in the meantime.

Accessing the HST catalogue

To obtain access to the catalogue—and in the future to obtain data files—users will have to use STARCAT. To connect to STARCAT at ESO/ST–ECF, we suggest that you login to the STESIS (28771) Vax as user *starcat* with password *catuser*. We suggest also that you first use the 'post-obs' screen of the HST catalogue, since it provides the most useful introductory information on executed HST exposures. To access this screen, type at the first prompt in STARCAT:

```
cat hst <return>          ! invoke hst catalogue
sel observer <return>     ! select observer screens
sel post-obs <return>     ! select the post-obs screen
<return>                  ! use menu mode
```

At this point, a set of available commands is displayed in a menu. They are grouped into 3 classes:

```
qualification    (center, qualify, mod_query, restart, unqualify),
retrieval        (findnext, backfind, scan)
miscellaneous    (help, doc, output-file, utilities, exit).
```

Please refer to the on-line help or to the *STARCAT Quick-Guide* for more information on the use of these functions.

Other astronomical catalogues

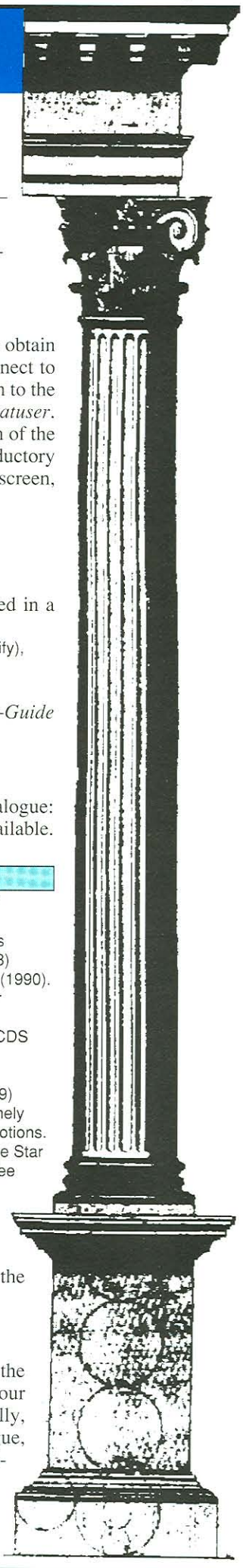
STARCAT not only provides access to the HST catalogue: more than 40 other astronomical catalogues are also available. Amongst the most recent inclusions, we note:

Name	Author(s)	Description
b2	Colla *et al.*	New version of this catalogue of radio sources
cadars	Fracassini *et al.*	Catalogue of apparent diameters and absolute radii of stars. (1988)
c87gb	Gregory & Condon	New catalogue of radio sources (1990).
ppm	Bastian & Röser	Positions and proper motions for 326,518 objects (1990)
ngc	CDS	compilation reconstructed from CDS data, not complete
pgc	Paturel *et al.*	Principal galaxies catalogue
zcat	Huchra	CfA galaxy radial velocities (1989)
fk5	Fricke *et al.*	1500 reference stars with extremely accurate positions and proper motions.
gsc	STScI	the 25 million entries of the Guide Star Catalogue are now available. (See next issue of this *Newsletter* for details of the STARCAT implementation)

All these catalogues have been incorporated into STARCAT as a collaboration between the ESO and the ST–ECF archive groups.

Conclusion

With the steady flow of data from the STScI, both for the catalogue and for the archive, we now consider that our archive has entered a routine phase which should, hopefully, last for more than 15 years. Also, with the HST catalogue, the astronomical catalogues and the Guide Star Catalogue, we now have more than a Gigabyte of astronomical information available on-line.



Restoration work at Cambridge

Two methods in which Cambridge astronomers have acknowledged expertise promise important applications to the HST. One of them, developed by a radio astonomer, allows the reconstruction of the mirror figure from in-orbit data. The other, Maximum Entropy deconvolution, is one of several techniques which are producing encouraging results on images.

Bob Thomson[†] *& Anthony Lasenby*[‡]

Immediately after NASA's announcement that the HST optics were flawed, astronomers at Cambridge as elsewhere became fluent in the terminology of aberrations and deconvolution. During the last three months, much work has been done by the STScI and other groups to determine the exact nature of the aberration and to investigate the effectiveness of image reconstruction techniques.

Chris Burrows (STScI) was able to determine the magnitude and sign of the defect by analysing out-of-focus WFPC/FOC data. This has since been corroborated by Lew Allen's team who have identified the cause and size of the defect from studies of the reflective null corrector used to test the primary mirror. One of us (AL) was able to improve this technique by globally fitting the mirror surface using several out-of-focus images simultaneously. This allows not only the gross defect to be modelled accurately, but gives a detailed residual map of the mirror surface, including small scale structure.

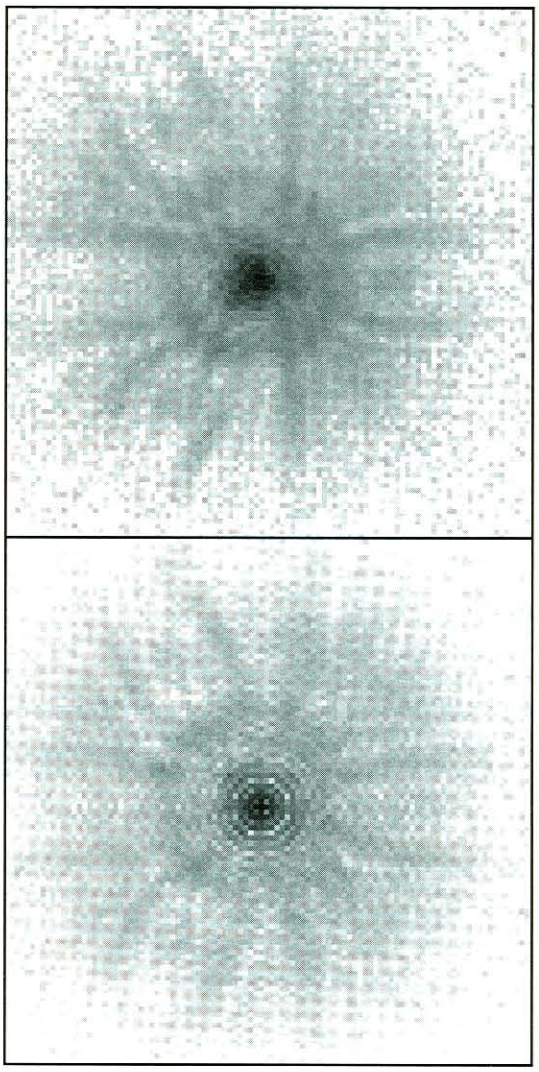
This technique, called phase reconstruction, was originally developed to configure the multi-plate dish of the sub-millimetre James Clerk Maxwell Telescope (JCMT) in Hawaii. The experience gained in configuring the JCMT surface was directly applicable to determining the true mirror surface of the HST. Preliminary data revealed a 2μm deviation from the prescribed surface at the edge of the mirror. The current estimate of the spherical aberration is 2.1 μm and the associated residual map shows an annular feature which could be related to the grinding of the mirror. A better estimate of the spherical aberration and the associated residual map will be obtained after the latest through-focus data have been taken and made available.

Once the mirror surface has been accurately determined, a noise-free PSF can be produced for a specified wavelength, focus setting and field position. This will enable more accurate restorations to be made of HST images. Already, the predicted PSFs closely resemble the 'squashed spider' produced by HST in both the WFPC and the FOC. The predicted PSFs can also be used to help determine the 'best' focus setting for the OTA. The figure shows a star image as seen by the PC together with the predicted PSF. The greater detail seen in the predicted PSF is mainly due to the assumption that the light is monochromatic while the star image was taken through a medium band filter (F550M).

Maximum entropy restoration is one of the most successful methods for image reconstruction and has been used by radio astronomers for many years. Two of the original proponents of maximum entropy methods, Steve Gull and John Skilling, are based at Cambridge and have been working on its application to HST data. Initially, working with simulated data and a FOC star image for the PSF, results were encouraging and more recent work has concentrated on restoring real HST data provided by the STScI and the FOC IDT. Undoubtedly other techniques (eg, CLEAN, Lucy's iterative method) are also being used and we look forward to comparing the results.

It is worth noting the impact of this work on HST data processing requirements. Apart from the inherent disk space requirements associated with image processing, restoration is a very CPU and memory intensive operation. Full maximum entropy restoration of a 512x512 image can take about 10 hours of CPU time on a VAXstation 3100 and requires upwards of 11Mb of memory. High performance computers with large memory capacities are required to do this work on a regular basis—restoring HST data routinely on an already overloaded MicroVAX won't work.

The HST is a fully functioning, albeit slightly wobbly, observatory in space with an extended but *stable* PSF. Once the mirror defect and associated PSF have been fully understood and described, modern restoration methods should significantly improve the image quality.



Observed (upper) and modelled (lower) Point Spread Functions. The Planetary Camera image is with a medium banwidth filter (F550M) while the model is for monochromatic light.

Further reading

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Meetings

Restoration of HST images and spectra

A report on the workshop held at the STScI, Baltimore on 21—22 August 1990

Hans-Martin Adorf

The Space Telescope Science Institute invited image processing specialists from within and outside astronomy to participate in a two-day workshop dedicated to the problems and prospects of applying restoration methods to degraded HST images and spectra. More than fifty external attendees and many STScI staff members followed over two dozen presentations interspersed with lively discussions. The workshop was designed to elucidate optimum methods of data gathering and to clarify which restoration techniques were available and suited to the HST point spread function (PSF), HST datasets and the special needs of astronomers.

After a review of the spherical aberration problem and its impact on imaging and spectroscopy with HST, the theory of image restoration methods and their limitations was reviewed. A variety of specific methods were presented; some well established such as the traditional linear inverse and Wiener filtering, Lucy's non-linear iterative scheme and, of course, the 'classic' maximum entropy method; some less well known such as the maximum information method, still have to prove their merits. Unfortunately nothing was said about the recently developed method of 'projections onto convex sets' (POCS). Several interesting contributions came from the field of medical imaging, particularly positron emission tomography, where Poisson noise is a dominant source of degradation and Lucy's iterative restoration method is well studied and established.

From several presentations it could be inferred that the non-negative property of astronomical images is indeed a powerful constraint which can be exploited usefully in a variety of ways at the cost of some added complexity in the restoration algorithms. Benefits can range from noise suppression to PSF-bootstrapping from observed frames and even to super-resolution which overcomes some of the aliasing occurring in undersampled datasets, eg, from the Wide Field and Planetary Camera.

Several convincing restorations were shown obtained from the simulated but realistic HST data which had been prepared and distributed by STScI staff before the meeting. These results supported a general feeling of moderate optimism that the HST PSF, solely degraded as it is by spherical aberration, belongs to a class of 'good' PSFs which allow restoration methods to work well. This is in distinct contrast with ground-based images which have a near-Gaussian PSF arising from atmospheric blurring.

From discussions in the hallways it became clear that linear, deterministic restoration methods, though useful as cheap and quick ways of obtaining first 'dirty' results, have to be complemented by more sophisticated non-linear statistical estimation methods which are alone capable of obeying the important non-negativity constraint and which can accommodate stochastic models of the data gathering process. While these models exist—they form the basis of the various HST instrument software simulators—they need to be reviewed and described in a coherent and authoritative form of concise mathematical equations, ready for incorporation into restoration and statistical estimation algorithms.

Questions were asked repeatedly about the reliability and stability of restoration results and how errors could be quantified. It has been pointed out that linear methods applied to Poisson-noise data immediately provide an error estimate. Perhaps more importantly the maximum entropy method, when suitably modified, was claimed to be able to quantify restoration errors and Lucy's iterative method also shows some prospects of meeting this requirement. Clearly, more attention and work will have to be devoted to this important topic.

To conclude, a panel of distinguished skeptics was supposed to discuss the question: "Why image processing won't work". This turned out to be not at all pessimistic about the recovery of at least some of the design performance of the telescope.

Subsequent work on real HST data has confirmed that the optimism about image restoration was justified but has somewhat shifted attention from restoration methods themselves to the question of careful data pre-processing and, even more importantly, to the necessity of good PSF construction. It is fairly safe to predict that HST data analysis, at least before any optical corrections are put in place, will see an enormously increased appetite for CPU-cycles, physical memory, disk space and large-format data-display capabilities. This will go along with an increased emphasis on statistical estimation methods based on likelihood and Bayesian principles.

The STScI plans rapid publication of the workshop proceedings.

HST Workshop

ESTEC, Noordwijk, The Netherlands, 31 Oct – 1 Nov, 1990

The European Space Agency and the Space Telescope – European Coordinating Facility invite European astronomers to participate in a two-day Workshop to be held at ESTEC.

The specific purpose of the Workshop is:

- *To inform the European community about the status of the HST Project and in particular about the first scientific results, the nature and the cause of the optical aberration affecting the telescope, the actual performance of the scientific instruments and of the Fine Guidance System, the short term measures adopted by the STScI and the ST–ECF to cope with the problem and the possible options for a correction of the HST optics in the longer term.*
- *To stimulate the discussion on the most effective way of exploiting the current HST performance and on the best strategies to restore, in full or in part, its design capabilities.*

For further information, contact: Ms Véronique Bourlon, Astrophysics Division, Space Science Department, ESTEC Postbus 299, NL–2200 AG Noordwijk. Tel: +31-1719-84754, Fax: +31-1719-84690, SPAN: ESTSA0::VBOURLON

Editorial

THE HST IS NOW AN OPERATING space observatory. The first scientific observations have already been made even though the planned orbital and scientific verification phases are not yet complete. Some General Observers should start receiving data during the first half of next year. The scientific instruments have, so far, come through their tests with pleasing and encouraging results, the two cameras being exercised frequently in support of various spacecraft verification activities.

The spherical aberration present in the images delivered to the focal plane by the 2.4m telescope is now well documented. Its cause has been discovered during a careful examination of the test equipment and procedures used during the figuring of the primary mirror. The effects of the resulting image degradation will be with us at least until the first refurbishment mission by a Shuttle takes place—no earlier than 1993.

The two issues which are occupying the minds of many astronomers and engineers are, fairly obviously: (1) how best to live with what we have until the observatory can be corrected and (2) how to perform this correction with the minimum risk to the spacecraft and the maximum long-term scientific gain.

On both counts, there is some cause for optimism although not so much that we can afford to relax in the quest for solutions. Doing the job properly will be difficult.

The images produced by the telescope now have a structure—a point spread function—which is radically different from the near-Gaussian profile familiar to ground-based optical observers. Although the wings are broad, there is a great deal of high spatial frequency information present with a significant flux remaining in the diffraction-limited core. Such a profile promises important gains from the application of a wide range of image restoration methods. When sufficient signal can be accumulated, the diffraction limited resolution of the telescope can largely be recovered. There are losses of course and these losses, of sensitivity and contrast, can be serious.

Many strategies for correcting the telescope and/or instrument optics will be proposed over the next few months. The final choice, or combination of choices, will have to depend on how well the pointing and tracking systems prove to work in practice. This question is under very intensive study at the moment. There have been, undeniably, problems and uncertainties some of which have been resolved. If significant ones remain, a solution which encompasses correction of the Fine Guidance Sensors may be forced upon us.

Astronomers who already have accepted programmes in the first cycle of General Observer time will have to make a reassessment of their feasibility. Those applying for time in Cycle 2 will have to design observations which exploit the many unique capabilities of the HST which remain. The ST–ECF staff will help them in any way that they can.

We should like this Newsletter to reach as wide an audience of European astronomers as possible. If you are not on the mailing list but would like to receive future issues, please write to the editor stating your affiliation.

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