error", often very large, has been a common technical error. One telescope where this happened was the Canada-France-Hawaii-Telescope (CFHT), for which the spherical aberration was afterwards successfully corrected by bending the secondary (a case of dc-fixed-active correction at the secondary).

The NTT also had a matching error, provoked by a systematic error in positioning of the compensation systems used in testing the primary. Although this error was small (1.8 mm in a test distance of about 15.4 m) the spherical aberration error introduced had a coefficient (i.e. peak-to-valley wavefront aberration) of about 3000 nm. This corresponds to an image diameter, for this effect alone, containing 100 % of the geometrical light energy, of 0.71 arcsec at optimum focus. Although this was outside the so-called "passive" specification, *we were able to correct it completely by the first (fixed) level of the active optics system of the NTT,* as has been reported in our recent paper "Active optics IV" [7].

It is interesting to consider the decisions taken with respect to a possible matching error at the time of the contractual discussions for the optics of the NTT. At that time, the author proposed to the manufacturer, Carl Zeiss, that a pentaprism test be done to ensure that matching error would be negligible. However, the active optics concept allows relaxed tolerances precisely for such errors as spherical aberration (this is one of its two principal aims) and a relaxation up to a coefficient of the order of 2000 nm was proposed. Furthermore, the test procedures for primary and secondary comprised not only tests at the normal visible wavelength (632 nm) but also a test with an independent IR system working at a wavelength of 10 μm. Although the resolution of the IR system was about 16 times lower than that of the visible one, it was considered by Carl Zeiss that an error exceeding the tolerance would be detected by the comparison between the two systems. (In fact, the matching error made *was* detected in this way, but was believed to be still just within the measuring noise – all other errors showed excellent agreement between the two test systems). Because of the tight time schedule, ESO and Carl Zeiss agreed to drop the pentaprism test in view of the above cross-check security of the tests and the considerable dynamic range of correction of the active optics system. This decision was subsequently validated by our ability to achieve complete correction actively of the matching error as well as all other actively controllable errors in the system, giving the spectacular image quality results of the NTT [7]. The essential feature of the figuring work by Carl Zeiss was the excellent quality regarding the more rapidly varying (higher frequency) defects on the surfaces such as zones or local hills and hollows, for which they were well inside the very hard specification. Thus the excellent work of Carl Zeiss and the NTT active optics system were both essential and complementary to each other for the success of the final optical system.

The HST, by contrast, has a very stiff, lightweighted, egg-crate type of primary. From its nature, the dynamic range available with the 24 actuators operating on the primary must be far too small to permit correction of a matching error significantly larger than that of the NTT in terms of wavefront aberration. Probably only a retouch of astigmatism would be possible with them. So the HST is effectively a passive telescope so far as bending (correcting) the primary is concerned. For this situation, the pentaprism test would have been the best guarantee against matching error. It is reliable, simple and cheap.

Statements have been made that the current performance of the HST is as good as the best ground-based telescopes. This is certainly not true. Apart from the NTT which – because of its active optics, very "smooth" mirrors and building concept – routinely produces total images at the excellent La Silla site with a d_{70} (i.e. diameter containing 70 % of the geometrical light energy) of less than 0.5 arcsec, there are a number of excellent "passive" telescopes in operation (including the William Herschel Telescope) capable under favourable seeing conditions of producing total images with a d_{70} well under 1 arcsec. In contrast, the HST has a d_{70} from given data of about 1 arcsec from the spherical aberration alone.

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HST Images: What Can Image Processing Do?

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In these first days after the actual image quality of the Hubble Space Telescope has become known, two lines of effort to achieve improvements are being mentioned most often: optical correctors in the second generation instruments and numerical image processing – i.e., deconvolution. The first measure will undoubtedly be more effective but its realization will take at least 2½ years. Deconvolution, on the other hand, can be applied already to data achievable with the present instrumental configuration.

Previous Work

Originally, image restoration algorithms were thought to be desirable for HST data because most of the imaging modes would undersample the anticipated point spread function (PSF). We therefore developed and implemented one such technique (Lucy and Baade, 1989), which combines deconvolution with a simultaneous resampling to a smaller pixel size. In that particular implementation, an iterative deconvolution method (Lucy, 1974) was used, but our technique of simultaneous resampling can in principle be mated with other image restoration algorithms, e.g., the maximum entropy method. Indeed, such tests as have been carried out (Heasley, 1984) indicate that the maximum entropy method will yield results

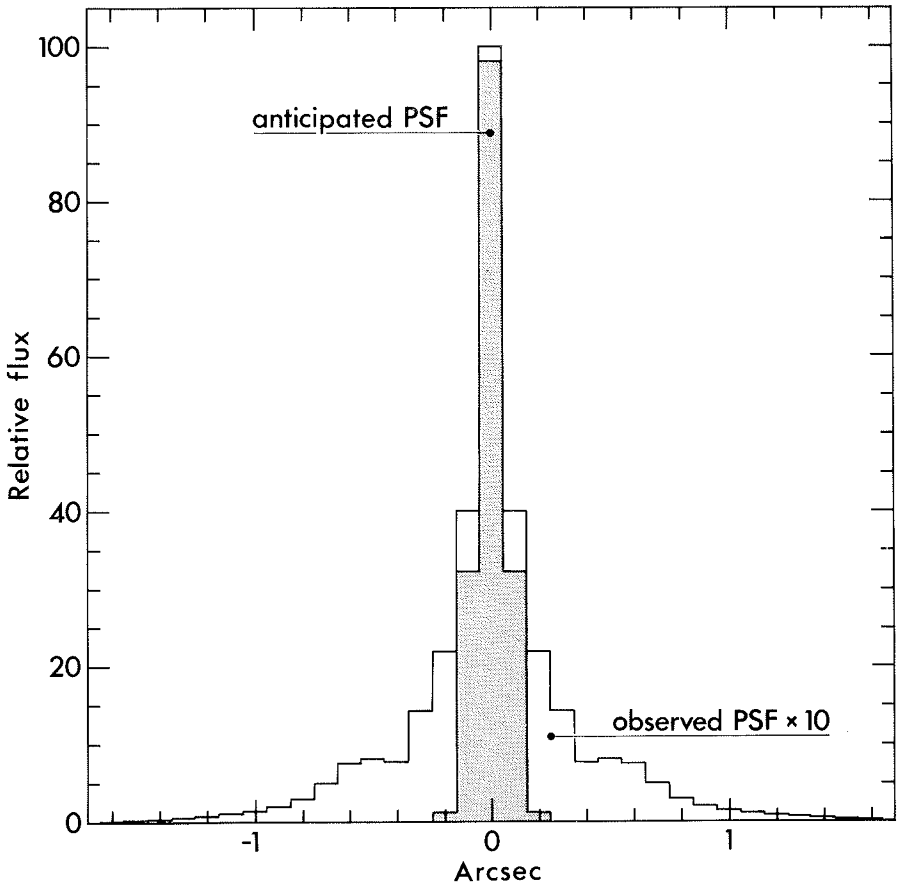

Figure 1: *Central cuts through the adopted and the originally specified (shaded) point spread functions of HST sampled with 0.1 arcsec pixels. Both PSF's are normalized to the same total flux but the adopted PSF is plotted on a 10 times expanded flux scale.*

closely comparable to those presented herein.

Readers of the *Messenger* have already seen examples of the performance of the deconvolution method in No. **56,** p. 3 and p. 35, where it was applied to the first NTT images and to 3.6-m telescope observations of the nebulosities around SN 1987 A, respectively.

Numerical Experiments

In a note dated June 29 and posted on the electronic bulletin board of the Space Telescope-European Coordination Facility, H. E. Bond and H. S. Stockman (Space Telescope Science Institute, Baltimore) provided the fractional encircled energy at radii 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 1.0, and 1.5 arcsec as measured with the Planetary Camera on board HST during June 10–24. Under the assumption of circular symmetry, we have used this information to construct the PSF plotted in Figure 1. This adopted PSF has a full width at half maximum (FWHM) of 0.2 arcsec (or two pixels). However, the comparison (Fig. 1) with the original specifications for the PSF shows how dramatic the loss in contrast actually is (or, conversely, how big the gain over conventional ground-based observations could have been). Note that the non-monotonic decline of the adopted, schematic PSF is in agreement with actual HST stellar images, which consist of a core and a ring-like outer halo. Since, in the absence of a real focus position, the definition of "the" PSF is in fact somewhat blurred, our approximation should be good enough to test the viability of deconvolution techniques for HST images. This is the purpose of our present exercise.

Our simulations assume a pixel size of 0.1 arcsec and therefore correspond to the case of the Wide Field Camera. Figure 2 illustrates the effects of deconvolution on a single noise-free point source with perfectly compensated (i.e., black) background. As can be seen, by going from 10 to 20 iterations – as would be appropriate for very high S/N data – the gain achieved is still worth the effort. The comparison with the two PSF's of Figure 1 shows that although the shortfall with respect to the original specifications is still large, the improvement over the raw data is even larger. In these deconvolutions, the resampling option was turned off.

As can partly be seen in Figure 1, the PSF has a very narrow core which, in some observations, has been found to be as narrow as 0.07 arcsec FWHM but to contain only about 15 % of the total flux. This shows that, in spite of the broad wings, there is still genuine high-frequency information in HST images and that this is only sparsely sampled. In order, therefore, to test the ability of our technique to recover some of this high-frequency information, we have simulated observations of a double-star in the following way: Star A, of total flux 3000 units, is located at fractional coordinates (0.7, 0.4) pixels. Star B is 2.5 times (i.e., 1 mag) brighter and is shifted with respect to Star A by (−4.1, −1.3) pixels, which corresponds to a separation of 0.43 arcsec or just over 2 times the FWHM of the PSF. Neither stellar profile includes noise, but a background with an average flux of 50 units per pixel and Poissonian noise has been added. The raw image as well as the results of 10 and 20 iterations of the deconvolution algorithm with simultaneous resampling by a factor of 3 in both dimensions are shown in Figure 3.

From other experiments with our method, we have found that, with a Gaussian PSF, a necessary condition for it to be able to separate two point sources is that along the line connecting the centres of the two sources a local minimum occurs. (For example, two stars of equal brightness usually need to be separated by more than one FWHM.) This makes sense because without further information it is otherwise impossible to distinguish between two point sources and a truly elongated, single object. Our double star just satisfies this condition. Generally, the ability to separate two closely spaced point sources depends on their relative distance and their brightness ratio. Because of the narrow core of the adopted PSF, the corresponding two-parameter space for the nominal performance of HST appears relatively little affected with respect to separation, whereas the constraint on the maximum allowable brightness ratio at a given scale is strongly compromised. In other words, the ability of HST to resolve fine structures is not too severely affected so long as their contrast difference is small.

In some sense, our input assumptions represent a worst-case situation: The relative noise in the background is high, the separation is small, and the sampling is the coarsest of all HST imaging modes. We therefore infer that cameras on board HST with imaging modes that sample the reported 0.07 arcsec core of the telescope's PSF better than in our crude simulation of the Wide Field Cam-

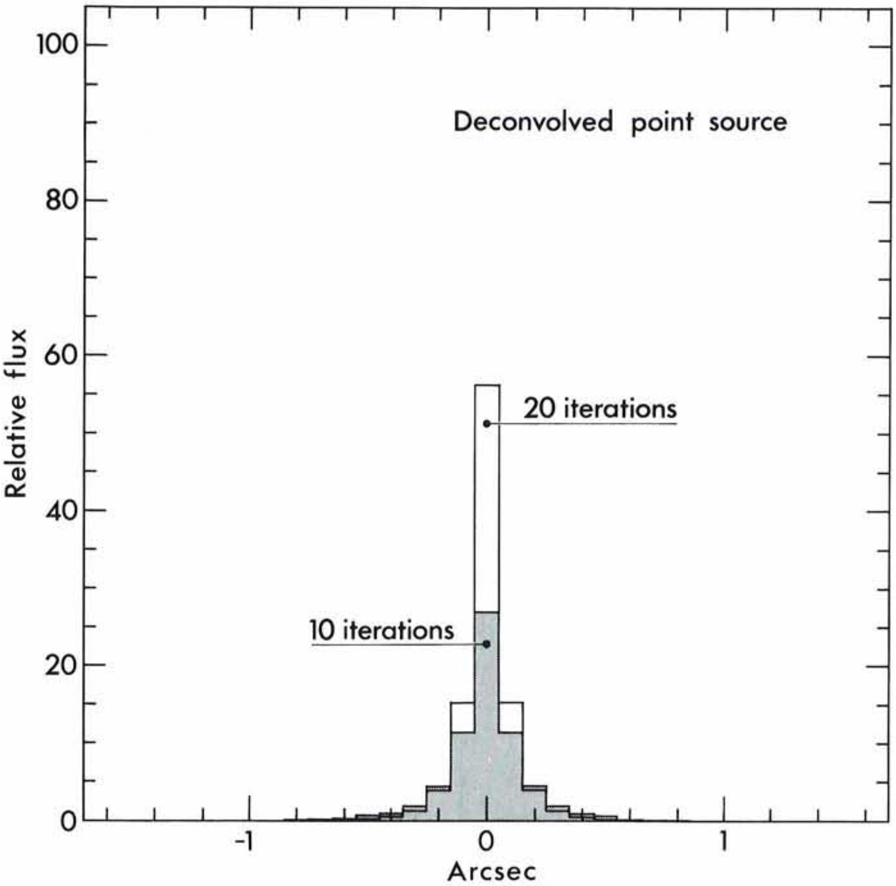

Figure 2: *The adopted PSF after 10 (shaded) and 20 deconvolution iterations, respectively. Flux scales and total fluxes are the same as in Figure 1 for the specified PSF.*

era will yield data from which image structure can be restored at spatial frequencies that are presently still inaccessible to routine direct imaging from ground-based observatories.

Even on an array processor and after vectorization of the code, the amount of computer time required for the deconvolution of a full 1600 × 1600 pixel WFPC image will still be very considerable, especially with the resampling option. However, given the other expenses of the HST project – or even only the costs of replacing some of HST's instruments – this point is of relatively minor importance. Nevertheless, if the assumption of point sources is justified or other additional information is available about the nature of a given structure, PSF fitting and similar, source-model techniques are much more effective than an assumption-free deconvolution. However, even then, a previously applied, mild deconvolution could still be advantageous, as it provides a PSF-neutral smoothing, especially if the simultaneous resampling option is chosen. It may also help to recover part of the loss in limiting magnitude incurred because of the image spread.

Existing Options

We conclude this brief report by pointing out that the tools we have been using here have, since the 1989 November release of ESO's MIDAS image processing system, been made generally available (command REBIN/DECONVOLVE, context PHOTOM) so that anyone interested can repeat our experiments but tailor them more specifically for the needs of a particular observing programme. Indeed, such experiments could determine whether the scientific goals of an approved imaging proposal can still be at least partly achieved. Note that the MIDAS implementation can accept any numerical representation of the PSF and does not require axial symmetry. Thus, already available is the option of carrying out deconvolutions using the highly structured, two-dimensional observed PSF, which shows numerous spikes and rings.

With respect to the resampling option, it should perhaps be stressed that this is implemented (Lucy and Baade, 1989) without any degradation of the observational data. In contrast, this is not true for the experiments reported by Evans et al. (1989) since their shifting and adding procedure for introducing sub-pixels represents a convolution applied to the observed data.

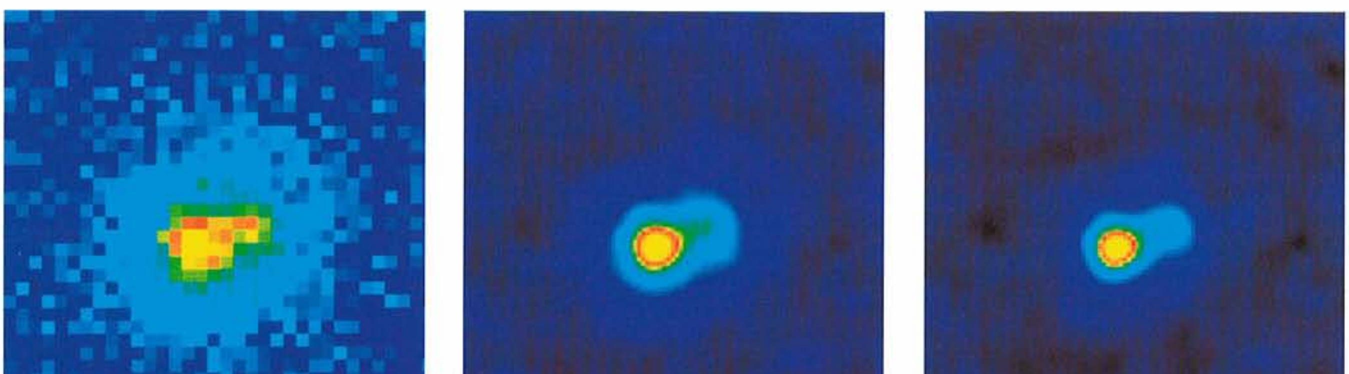

Figure 3: *The simulated binary star image described in the text. From left to right are shown the raw data (the false colour scale ranges from 30 to 220 flux units), and the results of 10 (high cut set to 530 units) and 20 (high cut 760 units) iterations of the deconvolution algorithm. In the raw data, the coarse 0.1 × 0.1 arcsec pixels are clearly seen. The deconvolved images are smoother partly because of the simultaneous resampling to a pixel size of 1/30 arcsec and partly because of the deconvolution algorithm's reluctance to introduce structure on a finer scale than the PSF allows.*

Potential Options

If required, the programme could be extended to take account of the variation of the PSF with position in the focal plane.

At present, the code assumes a spatially invariant PSF but, in contrast to, e.g., Fourier transform techniques, this assumption is not fundamentally demanded by the iterative deconvolution algorithm.

A further possibility is to develop a code that simultaneously deconvolves several images of the same field, each of which is displaced by a fraction of a pixel.

This possibility, which has been investigated theoretically by Adorf (1989), introduces an element of image reconstruction by tomography and might well be useful for certain objects with structure on the scale of the narrow core of the observed PSF.

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ESO'S EARLY HISTORY, 1953–1975

VIII. The 3.6-m Telescope Project; From Concept to the Late 1960's*

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"Le programme initial de l'Organisation comporte la construction, l'installation et le fonctionnement d'un observatoire dans l'hémisphère austral, comprenant: a) un télescope d'environ 3 mètres d'ouverture; – – –"
From the ESO Convention, Art. II.2.

Introduction

This article reviews work towards the realization of the 3.6-m telescope from the early beginnings of ESO up to the moment, at the end of 1969, when Council drastically changed course. These early years saw an Instrumentation Committee, a Directorate and an engineering bureau devoted to the creation of an instrument of dimensions and costs, an order of magnitude larger than anything achieved so far in optical astronomy in Europe. Unfortunately, lack of experience proved to be a serious drawback, and this unavoidably puts its stamp on the present, somewhat cheerless, account. The new approach adopted by Council late 1969, will be described in the next article.

Basic Concepts

A telescope project like the one for the ESO 3.6-m telescope, starts by specifying the dimension of the main mirror as this determines the light gathering power of the instrument, and by choosing the desired focal ratios for the different modes in which the instrument is to be used; the Prime focus, the Cassegrain focus and the Coudé focus. These focal ratios determine the dimensions of the telescope tube. The design of all other components of the project follows from these. It has been mentioned before (article IV) that the example ESO had in mind in the very beginning was the 3-m telescope of Lick Observatory, however the ESO design soon deviated from this.

Naturally, the designs of the various components of the project are interrelated, but once a certain stage has been reached, the further development and construction of the various parts tends to proceed largely independently. For our project this was particularly so for, on the one hand, the housing of the telescope, i.e. building and dome, and on the other hand the ensemble of tube, optics and mounting. Within the latter again a subdivision can be made: the combination tube/optics, and the mounting plus drive. The account on the progress in the project can be subdivided accordingly. Up to the early 1970's, the progress of the project as a whole was determined almost entirely by the (lack of progress in the) design of the mechanical parts of telescope tube and mounting. Contrary to what seemed to have been a tradition in earlier generations of large-telescope building, progress for the ESO 3.6-m telescope was not determined by the completion of the optics.

Early Conferences and Texts

The early years of ESO's project coincided with a general, international broadening of interest in large-telescope building and the publication of significant documentation. In the year 1960 appeared the compendium "Telescopes", Volume I of the series Stars and Stellar Systems edited by Gerard P. Kuiper and Barbara Middlehurst. It contained chapters by leading experts, among which descriptions of the two recently completed largest instruments: of the 200-inch Hale Telescope by Ira S. Bowen, and of the Lick 120-inch by W.W. Baustian; and furthermore chapters on Design of Reflecting Telescopes by Aden B. Meinel; and on Schmidt Camera's, again by Bowen. This Volume became a basic reference text for the next decades.

Another important event was IAU Symposium No. 27, "The Construction of Large Telescopes" held from 5 to 12 April 1965 at Tucson, Arizona, and at Pasadena and Mt. Hamilton (Lick Observatory) in California. The proceedings, edited by David L. Crawford and published in 1966, contained much basic information and instructive discussion reports. Among the participants from ESO countries were Baranne, Bahner, Courtès, Elsässer, Fehrenbach, Heckmann, Ramberg and the engineer who worked for ESO, W. Strewinski. In the present context mentioning should be made also of K. Bahner's Chapter "Teleskope" in Handbuch der Physik, Vol. 29, 1967, and Bahner's article "Large and Very Large Telescopes; Projects and Considerations" in ESO Bulletin No. 5 of December 1968, which includes a summary of large telescope projects under design or construction in December 1967.

Finally, as a quite useful – and readable! – review of the main elements in large-telescope construction and the status of the principal projects, let me mention B.V. Barlow's monograph "The Astronomical Telescope" of 1975 [1].

* Previous articles in this series appeared in the *Messenger* Nos. 54 to 60.