ground-based telescopes has to consider the uniqueness of the UV imaging from space and the fact that, since the HST Point Spread Function departs considerably from a gaussian-like profile, spatial resolutions cannot be compared just by using the FWHM as a parameter. Moreover, the two HST spectrographs are less affected than the cameras and most of the scientific programs should still be feasible, albeit with an increase in the exposure times.

Currently, a Scientific Assessment Team has been formed at the ST Science Institute with the task of preparing an observing programme (to be carried out in August-September) which will allow a better evaluation of the actual performance of the scientific instruments. The relevant data will be made available to interested scientists shortly after the observation. Concurrently the Guarantied Time Observers and General Observers' proposals are being reviewed for feasibility and modification. More about this exercise will be published in the ST Newsletters, in the electronic Bulletin Board and communicated directly to the HST Principal Investigators.

On the front of correcting the problem, NASA intends to speed up the construction of the second generation instruments, in particular of the WF/PC II, which will include appropriate modifications in the optical design to compensate for the spherical aberration of the telescope. The situation of the ESA Faint Object Camera in the light of the HST performance will be reviewed in the coming weeks.

Considerable effort is also being invested in evaluating the applicability of different image restoration methods. ECF staff, in collaboration with ESO colleagues, is experimenting with different algorithms on simulated images which make use of the actual, aberrated, HST psf. The results will be presented to a specific workshop on the subject which has been organized by the ST Science Institute on August 21–22. Meanwhile the ECF continues to maintain contact with the European PIs who are involved in Cycle 1 observations offering assistance in the review and possible modification of their programmes.

P. BENVENUTI, ST-ECF

"Matching Error" (Spherical Aberration) in the Hubble Space Telescope (HST): Some Technical Comments

R. N. WILSON, ESO

Much consternation has been caused in the astronomical community because of the revelations since the last week of June that the Hubble Space Telescope (HST) has a systematic error giving an image with about 70 % of the geometrical light energy within about 1.5 arcsec diameter instead of less than the 0.1 arcsec predicted from its specification of "diffraction limited performance" for visible light (wavelength 500 nm). The error has been identified as mainly spherical aberration due to "matching error". The above quality figure has been quoted in a number of reports, but may include other errors (including residual focus error) of unknown amount. From more specific information on the amount of spherical aberration, I have calculated below that the spherical aberration error *alone* would give an image at best focus with 100 % of the geometrical light energy within about 1.5 arcsec diameter.

Before considering further the origins of this error, let us look at the meaning of the term "spherical aberration". Elementary text books on optics usually explain it as a "longitudinal aberration" as shown in Figure 1. Rays coming from the central part of the optical system (near its axis) focus at the point O on the axis, whereas those from the outer circumference focus at A. The sign of the aberration as shown above with A to the left of O is what a simple convex lens would generate, whereas in the HST it is probably the opposite. The distance AO is called the longitudinal spherical aberration and is about 40 mm in the HST. If the focus for the detector is chosen to be at O (the so-called paraxial or Gaussian focus), then the total transverse spread of the light has the diameter BC. It can be shown that, for the basic (so-called "third order") spherical aberration, the optimum focus reducing the diameter of the light patch to a minimum is at D, one quarter of the distance from A to O. This minimum diameter is called the "disk of least confusion" EF which is obviously one quarter of BC. Taking AO as about 40 mm in the HST, an exit beam of f/24, the diameter BC containing 100 % of the energy at the Gaussian focus is 6.0 arcsec; at the best focus it is 1.5 arcsec. These figures, expressing angular aberration, can easily be converted into the so-called "wavefront aberration" which gives the maximum phase error of the image forming light. This is 4.34 μm for the above figures and an aperture of 2.4 m for the HST. This wavefront aberration is the best physical measure of the error and is, in fact, exactly twice the maximum error on the mirror surface involved, referred to the Gaussian focus, which is therefore 2.17 μm. Frequently, the rms (root mean square) error on the surface has been quoted which is about one sixth of the above, or 0.36 μm, or somewhat more than half a wavelength of laser light of 0.632 μm. The above figures reveal how essential it is to define exactly what definition is being used, otherwise serious confusion results.

Let us now return to the probable origin of this spherical aberration error in the HST.

In the technical domain of the produc-

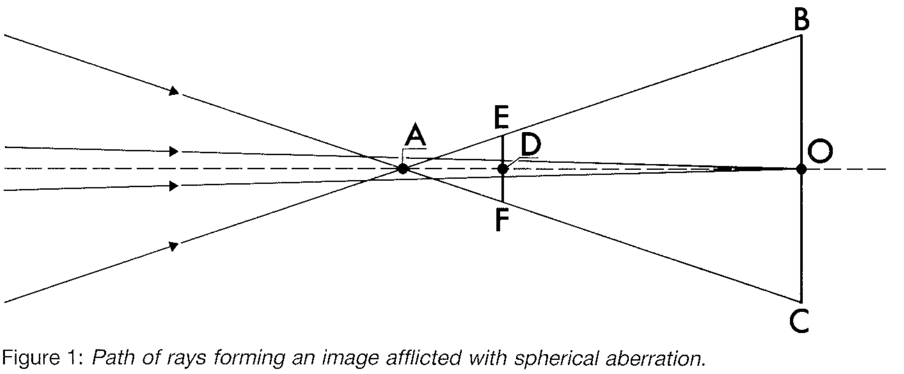

Figure 1: *Path of rays forming an image afflicted with spherical aberration.*

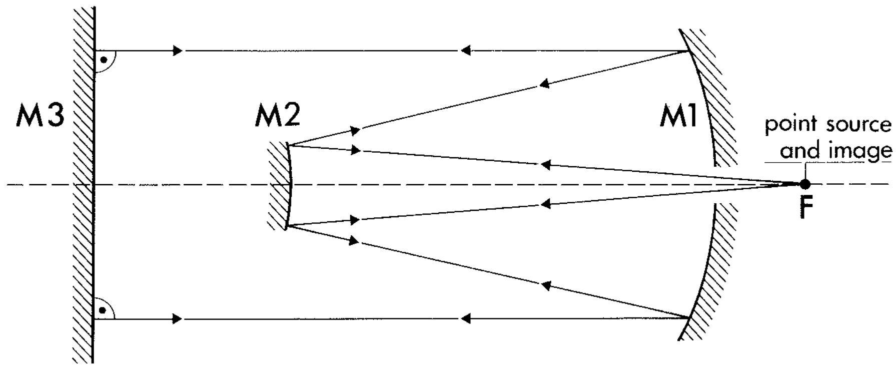

Figure 2: *Autocollimation test of a Cassegrain telescope in functional geometry against a plane mirror. A point source at the nominal focus F sends a light beam backwards through the telescope which is reflected back in the same path by the plane mirror M3. The image formed at F contains the errors of M 1 and M2 doubled by the double pass. Any errors of M3 are also imprinted on the image. In practice, a plane mirror M3 of adequate quality is prohibitively expensive and difficult to produce for diameters above 1 m. The errors in the image at F are measured by an image analyser, usually an interferometer or a Shack-Hartmann device.*

tion of large precision optics, the danger of such "matching error" is well known. A complete functional test of a combined Cassegrain system (see Fig. 2) cannot be performed for apertures above about 1 m since a plane mirror of the excellent quality required does not exist for larger apertures – even a 1-m diameter flat is a rare and very expensive element. However, there are other possibilities for testing for "matching error" in a functional way, as shown below.

In practice, the primary mirrors of modern large telescopes are tested in autocollimation at their centres of curvature, the errors being determined by interferometric or Hartmann type analysis of the image. Since modern, short primaries are strongly aspheric (slightly hyperbolic for Ritchey-Chrétien type telescopes) the autocollimation image is strongly aberrated. This aberration is normally compensated by a so-called "compensation" or "null" system, so that the errors can be referred to a corrected image. This key technology was first proposed by the English amateur Horace Dall in 1947 [1] and is the basis of most modern mirror testing. The "null system" must be correct to very high precision, in its design, manufacture *and in its positioning in the test set-up* – otherwise a systematic error arises which is spherical aberration in its classic form.

Cassegrain secondaries are more difficult to test because they are convex and cannot deliver a real image without an ancillary system. Testing of convex secondaries is a whole technological area in its own right [2]. However, the test methods will all have tolerances (more or less severe, depending on the method) which will lead to a similar systematic spherical aberration error if they are not rigorously respected. But there is one test of secondaries which effectively ensures that such "matching error" cannot occur. This is the so-called "Pentaprism Test". In fact, the Pentaprism Test is only a test of the spherical aberration, i. e. a test to ensure that the basic form of the two mirrors will, in combination, give an image free from spherical aberration at the nominal Cassegrain focus. For other errors over the surface such as astigmatism or high spatial frequency errors, some other test of the whole surface is required and various possibilities exist [2].

The Pentaprism Test (see Fig. 3) was probably first invented by Wetthauer and Brodhun in 1920 [3] and has been systematically used by a number of manufacturers, for example REOSC in Paris [4], who have applied it routinely with great success for 25 years or more, or Korhonen in the successful manufacture of the optics of the recently completed 2.5-m Nordic Optical Telescope. It was also used already in 1939 in the United States by Hendrix and Christie [5] in connection with Schmidt systems, and described by Hochgraf [6] in 1969. It seems surprising that this test, which is simple and cheap to set up (with the system axis either horizontal or vertical), was not applied to the HST, since it would certainly have revealed the error. However, its use is by no means general in the manufacture of ground-based telescopes which explains why "matching

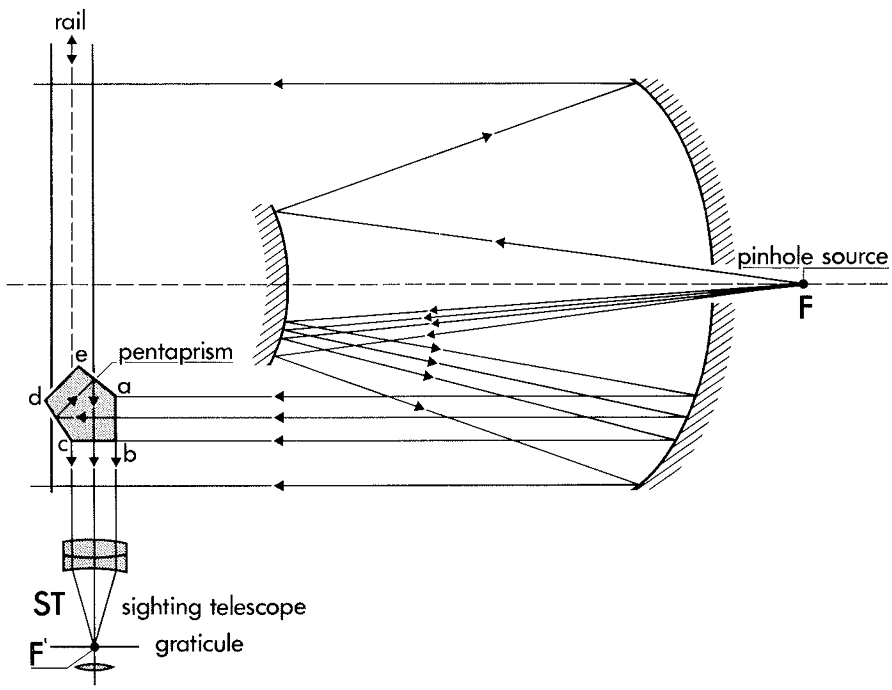

Figure 3: *The Pentaprism Test: As in Figure 2, a pinhole source at the nominal focus sends a beam of light backwards through the telescope. Instead of being reflected back by a large plane mirror, a small part of the parallel beam enters the face ab of a pentaprism which can be moved along a rail across the diameter of the telescope. After reflections at faces cd and ea of the pentaprism, the selected beam emerges via face cd deflected about 90 °. A fixed sighting telescope ST, firmly mounted, measures the direction of the beam by observing the image F' of F on a graticule. The basis of the test is that, in the section shown in the diagram,* the deflection of a pentaprism is unaltered by small rotations of the pentaprism about an axis perpendicular to the plane of the paper. *Such small rotations of the pentaprism are unavoidable in moving it across the diameter, but have no effect on the angles measured in the plane of measurement. Thus one can measure directly the differences of angle of the small beams as the pentaprism is moved over the telescope diameter. This measures directly the angular spherical aberration, from which integration gives the wavefront aberration. Other errors, such as defocus and coma, can be eliminated as they have a different dependence on distance from the axis.*

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.

Literature

1. H.E. Dall, 1947, *J. Brit. Astron. Ass.,* **57** (5) also 1953, *Amateur Telescope Making, Book 3,* Scientific American Inc., **149.**
2. R.N. Wilson, 1974, *ESO Technical Report* No. **3,** July 1974.
3. Wetthauer and Brodhun, 1920, *Zeitschrift f. Instrumentenkunde* **40,** 96.
4. J. Espiard and B. Favre, 1970, *Nouvelle Rev. d'Optique appliquée,* **1** (6), 395.
5. D.O. Hendrix and W.H. Christie, 1939, *Scientific American,* August 1939.
6. Hochgraf, 1969, *Opt. Sci. Center Newsletter,* Jan.-March 1969, 41.
7. R.N. Wilson, F. Franza, L. Noethe and G. Andreoni, 1990, ESO Technical Preprint No. 24, May 1990.

HST Images: What Can Image Processing Do?

D. BAADE and L. B. LUCY, ESO

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