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Active Optics: the NTT and the Future

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1. Background to the Development of Active Optics at ESO

At a press conference on 13 July at Carl Zeiss, Oberkochen, jointly organized by ESO and Carl Zeiss, the final results of the manufacture (figuring) of the NTT optics were announced. This included a functional test of the basic Active Optics correction of the telescope. The results were so good that they exceeded even the expectations of both Carl Zeiss and ESO in all respects. We consider this to be a milestone not only in the development of the NTT and the history of ESO, but also in the evolution of the astronomical reflecting telescope in general.

To understand the significance of the NTT optics and the quality achieved, we must first review the background of the development and the principles on which it is based.

It is not the purpose of this article to give a full scientific account of the ESO Active Optics system. This is fully documented in the publications "Active Optics I" and "Active Optics II" [1] [2]. Here we wish to give the reader a résumé of the essential features and advantages of the system, and the practical results with the NTT optics.

The first ideas on a general active control system for the optical quality of telescopes go back to the late sixties when the first author was in charge of optical design for astronomical instruments at Carl Zeiss. Here he became conscious of the extreme difficulty of

The finished NTT primary mirror at Carl Zeiss in July 1988. The mirror is mounted here on its final NTT support in its cell for testing in the same set-up as was used for manufacture.

respecting centring tolerances with conventional large telescopes, i.e. maintaining the primary and secondary mirror optical axes sufficiently colinear. Very few telescopes maintain in practical use the centring tolerances required for high image quality and this leads to an ugly, asymmetrical image error known technically as *decentring coma*. Since this is the commonest and most serious optical "illness" of Cassegrain telescopes (the standard modern form because it is effectively a powerful mirror telephoto system giving a tube length much shorter than its focal length), the first author called it "Cassegrainitis". In the early seventies he concluded that it was hopeless to expect to maintain such absolute tolerances in a *passive* system, and some sort of *active correction* was necessary. While still at Carl Zeiss, he also learned from a colleague, Gerhard Schwesinger, the basic principles of the design of mirror supports. These principles were an essential prerequisite for the later development of active optics at ESO.

We have introduced above two fundamental terms, *passive* and *active*, which must now be defined. A normal, conventional telescope is *passive* in the sense that it is set up by some adjustment procedure and can only be maintained or modified by a subsequent *off-line* maintenance operation. Between such operations, the adjustment will degrade and will anyway be influenced by the telescope attitude. A further problem is that off-line access to telescopes is always difficult and in conflict with the observing schedules. The consequence is that telescopes are, in practice, virtually never in an optimum state of optical performance: often they are shockingly bad and nowhere near the quality achieved by the optician.

ESO Places Contract For World's Largest Mirror Blanks

After a period of intense negotiation, the European Southern Observatory and Schott Glaswerke, Mainz (F.R. Germany), reached agreement about the delivery of four giant mirror blanks for the ESO Very Large Telescope (VLT). The blanks will be spin-cast of Zerodur, a ceramic material. Each will have a diameter of 8.2 metres, an area of ~ 53 square metres and a thickness of only 17.5 centimetres.

The contract was signed on September 12 at the ESO Headquarters in Garching bei München, by Professor Harry van der Laan (right), Director General of ESO, and Mr. Erich Schuster (left), Member of the Board of Directors of Schott Glaswerke.

During the set-up and alignment of the ESO 3.6-m telescope in 1976 [3], the basic scheme for an *active* telescope became clear to the first author, although it was quite impossible to realize it with that telescope. Such an *active* telescope would monitor its own image quality *on-line* and correct any errors (i.e. optimize itself) automatically. The first and most important aspect of an active telescope is therefore *automatic maintenance* of optimum optical quality. Later it became clear that there was a second aspect of active optics which is hardly less important than the first: the relaxation of certain manufacturing tolerances which, with subsequent active correction, leads to an optimum level of quality far surpassing anything achievable with passive telescopes.

To understand this, we must introduce the term *Intrinsic Quality* (the IQ of a telescope!) which was defined in connection with the set-up tests of the (passive) ESO 3.6-m telescope in 1976. Figure 1 shows the results of these (Hartmann) tests for the zenith position and for zenith distances from 45° to 60° at the four azimuths south, west, east, north. In each case, the left-hand point of the histograms gives the actual image quality of the telescope as measured in the conventional way (image diameter in arcsec containing 80 % of the geometrical energy of a star image). Note that there is a significant variation of quality with telescope attitude, the quality being worst in the south and best in the north. The principal reason for this is quite simple: a residual of decentring coma is increased in the south by tube flexure (Serrurier) error, whereas it is compensated in the north. The histograms show the improvement that *would be* achieved *if* the errors shown were removed. Although the histograms must all fall monotonically towards the last point 5 on the right, their form varies significantly. However, within the error of measurement, the right-hand point is a constant for this telescope, independent not only of telescope attitudes but also of time. This is what we call the

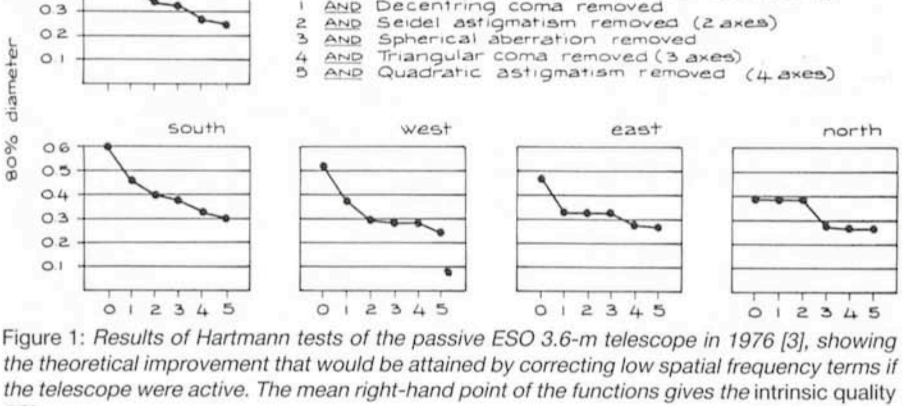

Figure 1: *Results of Hartmann tests of the passive ESO 3.6-m telescope in 1976 [3], showing the theoretical improvement that would be attained by correcting low spatial frequency terms if the telescope were active. The mean right-hand point of the functions gives the* intrinsic quality *(IQ).*

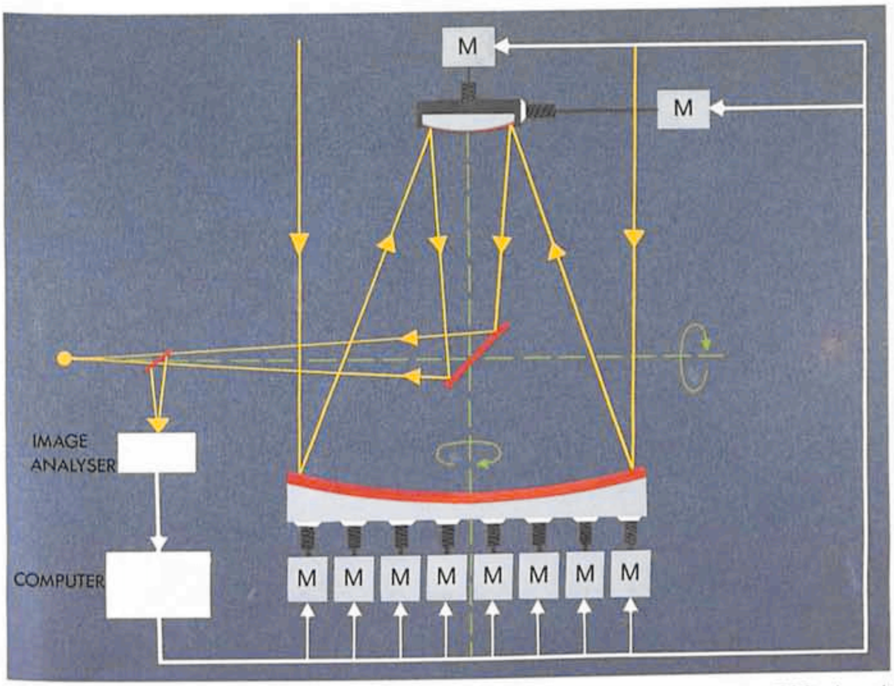

Figure 2: Active optics *for low frequency bandpass correction: principle of the ESO closed-loop control technique for optimizing image qualitiy.*

intrinsic quality of the telescope, the value for the 3.6-m being 80% geometrical energy in 0.27 arcsec.

It is important to realize that the process shown above for the 3.6-m telescope was a purely mathematical abstraction. In practice, this telescope has no physical means for systematically carrying out the process shown. The same is true of all conventional, passive telescopes. The best one can do is from time to time to try to correct one or more of these errors in a laborious off-line operation. In practice, the left-hand point of the histogram often has a far worse quality than that shown above, because of deterioration of the adjustment.

The difference with the NTT, an *active* telescope, is that the correction process shown in the histograms *can be performed at will on-line so that the IQ can be realized all the time.* The left-hand point of the histograms is then of no importance, so that relaxed manufacturing tolerances for the terms shown are possible. Hence we have the two advantages:

- Relaxation of low spatial frequency (long-wave) manufacturing tolerances.
- Automatic maintenance in respect of all errors which can vary through maladjustments, etc.

2. Practical Application to the NTT

How, then, is this process realized in the NTT? This is shown schematically in Figure 2. The offset guide star image is "borrowed" from time to time for the image analyses whose measurements are processed in the computer. Using prestored information and a simple algorithm, signals are sent to the secondary mirror and to the primary mirror. The secondary is then rotated slightly about its centre of curvature (to correct decentring coma) or shifted along its axis (to correct defocus). The signals to the primary mirror modify the axial support forces and thereby correct all the other errors which are to be controlled. It should be noted that the form of the primary mirror is *not* determined by direct position control since this would require an impossibly stiff supporting cell. The mirror is located by three fixed points and its form determined by the forces exerted by 75 astatic (i.e. floating) supports. Apart from the important difference that the forces can be modified in a controlled way, the support operates essentially in the same way as the astatic lever invented by the English engineer Lassell in 1842 and used in innumerable telescopes since then.

The algorithm for the correction process is based on three laws of physics:

- *The linearity law:* This is simply Hooke's law in elasticity theory which says that the strain (deformation) in a system is linearly proportional to the stress (force).
- *The convergence law:* This arises out of the principle of St. Venant in elasticity theory. The important consequence for active optics is that only relatively few low spatial frequency (i.e. "long-wave") terms need to be corrected to achieve the IQ.
- *The orthogonality law:* This results from the definition of the error terms and states that they can be corrected independently.

The image analyzer requires a minimum of 30 seconds, preferably 60 seconds, to obtain the basic data. This integration time is necessary in order to eliminate the effects of the atmosphere which would otherwise falsify the results. (Correction of disturbances due to the atmosphere requires a system with response to higher time frequencies. This is the field of *adaptive optics* which is enormously more difficult and still represents an unsolved problem at visible wavelengths.) A further 60 seconds is sufficient for the computer analysis and actual correction process. This whole process of detection, analysis and correction does not disturb the observation in any way: indeed, the astronomer will be unaware that it is taking place! The rhythm with which it is desirable to perform corrections will have to be decided by practical experiments but it is unlikely to be more than once per hour or once per change of object. The NTT is designed to track within 0.1 arcsec without guiding for at least 15 minutes, far longer than the 1-minute integration time.

3. Experimental Confirmation from the 1-m Experiment

Our active optics concept is an essentially simple and natural development out of normal passive support systems. Nevertheless, as with all new developments, it was desirable to test it in

Figure 3: *The 1-m test mirror (the thin rim shows the high aspect ratio of 56).*

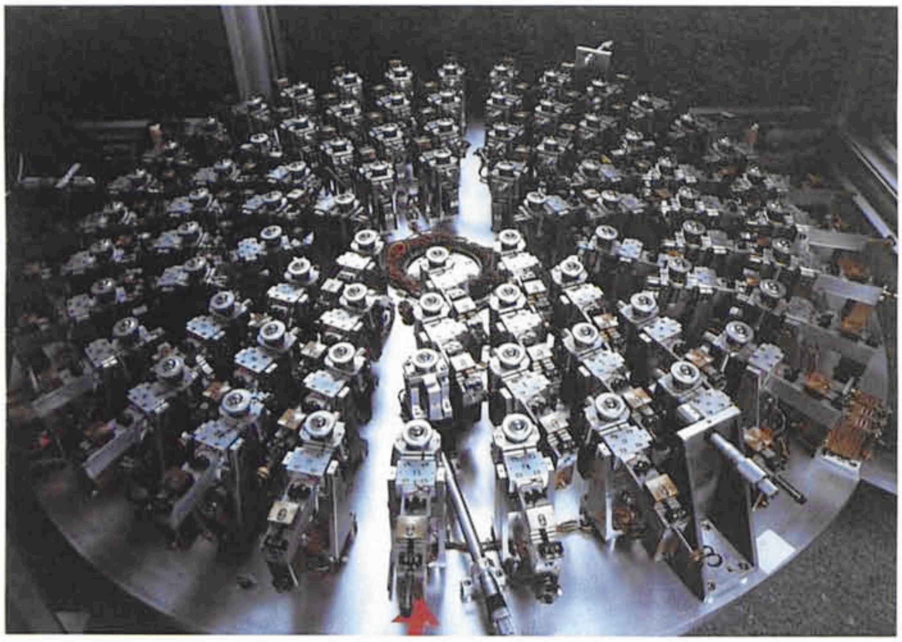

Figure 4: *Photo of the complete 1-m support. There are 78 individual supports of which 75 are active levers and 3 fixed points. The geometry of the support in the 4 rings is identical with that of the NTT primary mirror. Each support has a load cell to measure the force.*

practice before applying it to the NTT itself. This was the purpose of the 1-m test mirror, which had a diameter of 1,050 mm and a thickness of only 18.9 mm. These dimensions were obtained by scaling the NTT primary (diameter 3,580 mm, thickness 240 mm) according to the *gravity flexure law.* The geometry of the support can then be taken over and all forces scaled in the ratio of the weights of the two mirrors.

Figure 3 shows the 1-m mirror and Figure 4 its support. The four support rings are easily recognizable, but the supports themselves are simpler than in the NTT since the 1-m mirror is a fixed installation. Although the 1-m looks very thin – and *is* thin compared with a conventional mirror – it is not particularly so compared with more modern developments. The proposed VLT mirror would have a 1-m equivalent of only about 2½ mm, roughly like window glass! In fact, the thickness of the NTT primary was quite cautiously chosen to be about 40% of that of a conventional blank since an imposed requirement was that it should also work with normal quality in the purely passive mode.

The 1-m experiment had many purposes which are described in detail in ref. [2]. Here we will give only two results which illustrate clearly the power of active optics control.

As was indicated above, an essential feature of the method is modal control, i.e. the independent correction of certain errors or aberrations. The mode most easily generated in telescope mirrors is the *astigmatism mode.* To correct such a mode, we start with a theoretical *calibration* of a force variation pattern intended to generate such a mode in quite pure form. Figure 5 shows the generation of such a mode on the 1-m mirror using the ESO MIDAS image processing system. These colour patterns were produced off-line from data given on-line by the image analyzer. Starting with an arbitrary state of the mirror, a large amount of astigmatism was introduced. Then the same was done with reversed sign. Subtraction of the second result from the first should leave a large amount of pure astigmatism, about 7 wavelengths of *wavefront aberration.* This result is shown at the top left of Figure 5. The astigmatic effect is very obvious: one axis is more curved, the other less curved. The pattern at the top right of Figure 5 is a mathematical construction of the pure effect intended. At the bottom left, the difference of these is shown on the same colour scale and represents the error, or *cross-talk,* in the procedure. On this scale, hardly any error is detectable. At the bottom right, the colour scale has been magnified 24 times to show the residual error in detail. Clearly it is only random noise.

Our second example (Fig. 6) shows a MIDAS representation of the actual active correction of the 1-m mirror, as it was first performed. The top left-hand pattern shows a state of the mirror in which major aberrations left by the manufacturer were still to be corrected (since active correction was intended, quite generous tolerances were given to the manufacturer for the terms concerned). Clearly there is a major amount of astigmatism, as well as other errors. At the top right, a *manual* correction of the support has been performed to get the mirror into the dynamic range of

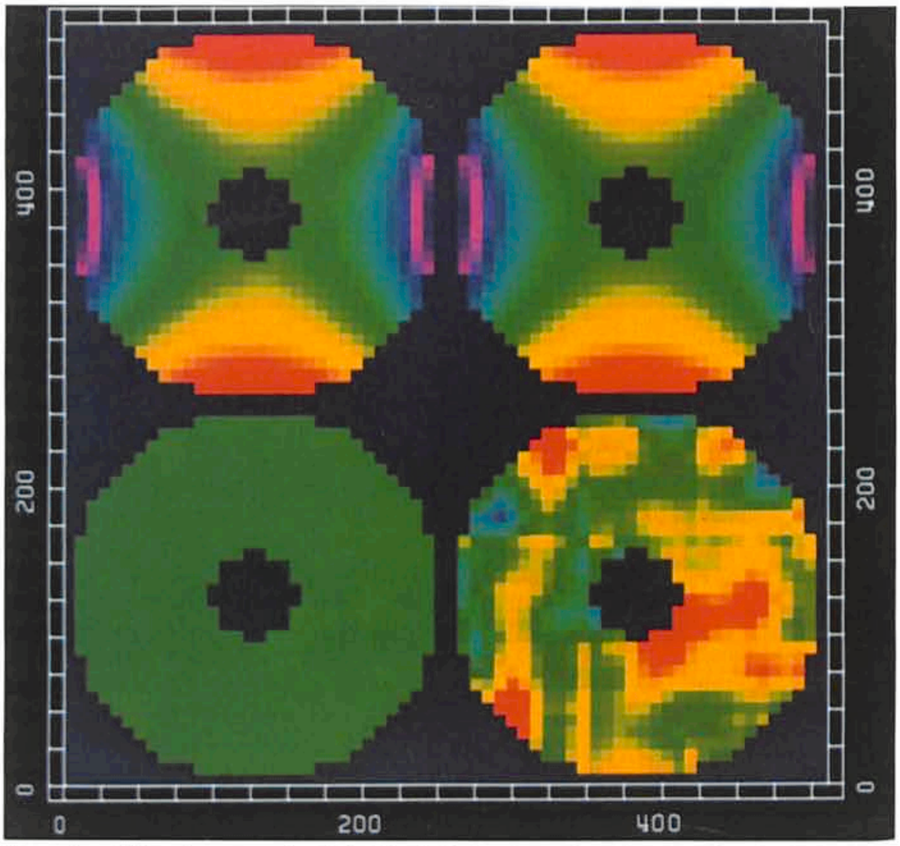

Figure 5: *Off-line demonstration (MIDAS) of third-order astigmatism (Ast3) variation (calibration) with the 1-m test mirror [2]. Colour scale 3650 nm except lower right which is 150 nm.*

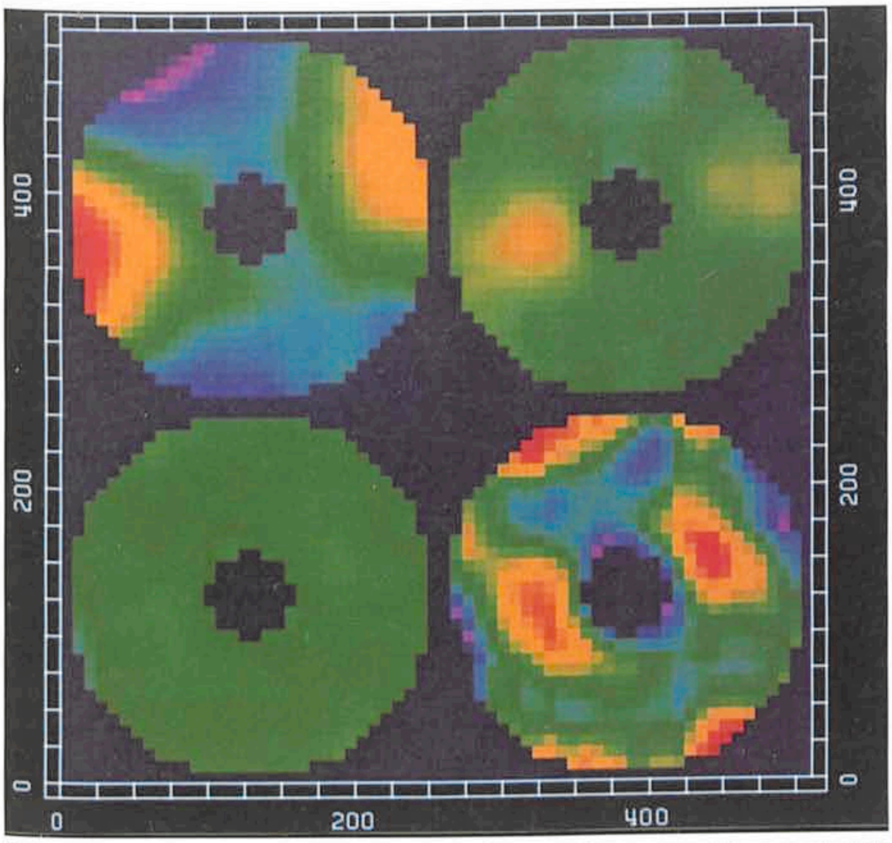

Figure 6: *Off-line demonstration (MIDAS) of the active correction process of the 1-m mirror [2]:*
Upper left: *Initial state. Colour scale 2340 nm.*
Upper right: *After hand correction. Colour scale 2340 nm.*
Lower left: *After automatic correction (1 iteration only). Colour scale 2340 nm.*
Lower right: *After automatic correction (1 iteration only). Colour scale 370 nm. The small residue of Ast5 was subsequently removed in a second iteration.*

automatic correction. At the lower left, the automatic correction has been carried out giving a hardly detectable error on this colour scale. At the bottom right, the colour scale has been increased by 6.3 times. We had expected a purely statistical result, as with Figure 5. But this pattern shows in fact a systematic residual error known technically as fifth-order astigmatism. We had considered controlling this term but expected it to be negligible. It appeared, in fact, as a small but readily detectable harmonic of the astigmatism we had permitted in the tolerance. A theoretical calibration was then performed and the term subsequently removed leaving purely statistical noise. This shows the flexibility of our active optics correction system. One estimates the terms necessary for correction to the quality desired. More terms can always be added if necessary, provided the dynamic range of the system is sufficient.

4. Tests of the Finished Optics of the NTT

We referred at the beginning of this paper to the press conference on 13 July announcing the results of the optical figuring at Carl Zeiss, Oberkochen. The background of these tests was given in the *Messenger* No. 52, which we reproduce here:

"To understand the manufacture of the NTT optics, we must look at its specification for the final Nasmyth image:

(a) 80 % geometrical energy within 0.40 arcsec.
(b) 80 % geometrical energy within 0.15 arcsec if 5 terms, to be controlled actively, are mathematically removed from the combined image forming wavefront (Intrinsic Quality).

The active control gives a relaxation of certain errors (such as astigmatism) which enables the manufacturer to concentrate above all on specification (b) which ensures very smooth surfaces without high frequency errors such as "ripple", zones or local bumps. In function, specification (b) should then operate all the time and will be the working specification of the telescope. This is quite near the "diffraction limit" for such a telescope.

The blank with aspect ratio 1 : 15 (2½× thinner than the blank of the ESO 3.6-m telescope) was delivered from Schott to Carl Zeiss in June 1986. The blank itself represents a great technical achievement by Schott in zero-expansion glass ceramic, Zerodur. Two years of intensive work at Carl Zeiss followed. The NTT specification (b) has required, and resulted in, a remarkable technological development at Carl Zeiss both in figuring techniques and in test technology. With the practical development of 'stabilized phase interferometry', Carl Zeiss is now in possession of an excellent and time-saving technology in the manufacture of large optics.

The results of the Carl Zeiss interferometric tests, established in a most rigorous way, are as follows for the whole optical train M1, M2, M3:

(a) 80 % geometrical energy within ca. 0.30 arcsec.
(b) 80 % geometrical energy within ca. 0.125 arcsec for the Intrinsic Quality.

Both values are thus well within the specification."

The above results were obtained on the original manufacturing support. The mirror cell, with the actual supports to be used in the telescope, was then mounted on the manufacturing table and the primary mirror (M1) lowered on to its support system and tested under the same conditions (see photograph on page 1). There was no detectable difference in the image quality according to specification (a) above between the Carl Zeiss and ESO supports: for M1 alone the value was 80 % in *0.25 arcsec,* already a remarkable technical achievement. However, specification (a) does not take account of the improvement achievable by active optics: specification (b) is what should be achieved in the telescope. Carl Zeiss had calculated the result according to the (b) specification for M1 alone as 80 % in *0.096 arcsec!* But this was a *mathematical* calculation and this quality had not been physically realized. So the last stage of the tests was to perform physically the active correction. This was achieved under calm air conditions at night, the controlled error being reduced to the detection level. In this state the mirror showed *physically* no difference from the *mathematically* produced form. Figure 7* (basic material kindly supplied by Mr. Knohl of Carl Zeiss) demonstrates these results. Figure 7 (i) shows the initial *passive* state, corresponding to 80 % in 0.25 arcsec, as an on-line, stabilized interferogram. It is clear that the principal low frequency error is as-

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* The wavefronts of Figure 7 show a quite sharp "ring" at about half radius. This ring has nothing to do with the real form of the mirror: it is an artifact introduced by reflexions in the so-called "Null" or "Compensation" system used by Carl Zeiss to remove the huge amount of aberration which would appear in the image due to the correct aspheric form when the primary is tested at its centre of curvature. For technical reasons, Carl Zeiss used the "Offner type" of Null system in which such reflexions cannot be avoided.

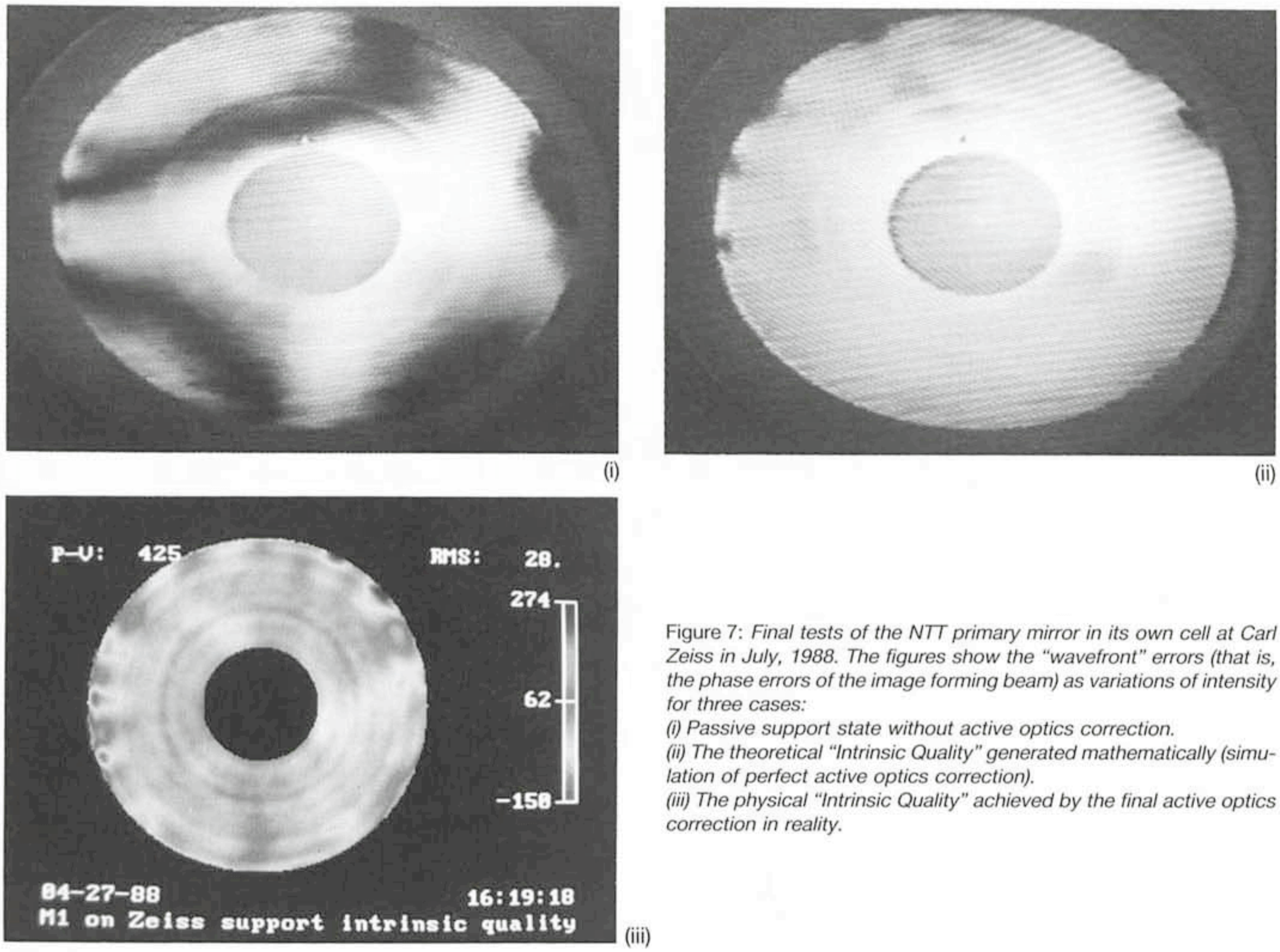

Figure 7: *Final tests of the NTT primary mirror in its own cell at Carl Zeiss in July, 1988. The figures show the "wavefront" errors (that is, the phase errors of the image forming beam) as variations of intensity for three cases:*
(i) Passive support state without active optics correction.
(ii) The theoretical "Intrinsic Quality" generated mathematically (simulation of perfect active optics correction).
(iii) The physical "Intrinsic Quality" achieved by the final active optics correction in reality.

tigmatism. The averaged rms error of such frames is 175 nm. The elliptical pupil form arose from transfer to a video-recording from which these on-line frames were photographed. Figure 7 (ii) shows the final state, corrected by active optics. This is also an on-line, stabilized interferogram produced under exactly the same conditions. Clearly, the low frequency errors have been corrected, and all that remains is some high frequency azimuthal error at the edge. Figure 7 (iii) shows an *artificial* representation after theoretically perfect correction of the low frequency terms: these terms were mathematically removed from the passive state (equivalent of Fig. 7 (i) above) and the residual errors are represented here as a variation of grey intensity (originally in a colour scale). This grey scale somewhat confuses the direction of the error compared with the colour original, but the high frequency residual errors at the edge are clearly identifiable with those of Figure 7 (ii), taking account of a slight azimuthal rotation. Figure 7 (iii) is averaged for a number of frames and has an rms error of 28 nm, *equivalent to the IQ of 80 % in 0.096 arcsec.* Comparison of Figure 7 (ii) and (iii) demonstrates clearly that this IQ has been physically realized.

With the possible exception of the primary of the Space Telescope (2.4 m), this quality for the NTT primary is easily the highest ever achieved in large telescope optics. With active optics the step from Figure 7 (i) to (ii) is a rapid and quite trivial operation. By contrast, it is the considered professional opinion of Carl Zeiss that this quality could not be achieved by conventional *passive* means, not even at ten times the price or more!

5. Final Installation of the NTT

In the autumn of this year, the optics of the NTT will be aligned following our standard procedures – essentially with reference to the altitude axis. After completion of the electronics and optimization of tracking and pointing, the active optics system will be fully tested and its fixed (dc) component installed – the equivalent of the correction just performed at Carl Zeiss. It is expected that this will be completed by March 1989.

We are confident that the NTT will then be working constantly at its Intrinsic Quality, i.e. 80 % geometrical energy within 0.125 arcsec. As the first active telescope, it will have easily the best optical quality of all ground-based telescopes. We believe the NTT building and site are well chosen to exploit this inherent quality. But the NTT will still be limited by the seeing. With advances in *adaptive optics* (atmospheric correction), it will be possible in the future to exploit even more fully the quality of the NTT.

6. The Future of Active Optics

We hope we have convinced the reader that the ESO NTT will be a milestone in telescope development. The VLT is based on the same principles but is defined from the start as only functioning in the active mode, since its primaries will be some 40 times more flexible than the NTT primary. The future of active optics with thin monoliths has been discussed in a paper [4] at the ESO conference in March 1988. Perhaps the most exciting possibility is the combination of stress polishing and active optics to avoid completely the aspherizing process for primary mirrors. The VLT blanks are already most of the way towards the necessary flexibility. However, a difficult overlap area, because of time frequencies entering the adaptive optics bandpass, is that of deformations of very thin primaries due to wind buffets. The possibilities and limitations of active optics in this area are still under investigation.

7. Acknowledgements

We wish to acknowledge the advice and help of Gerhard Schwesinger, not only for his invaluable contribution through the theoretical calibrations for the active control of the NTT primary and 1-m mirrors, but also in many other aspects; the firm of REOSC for excellent work on the manufacture of the 1-m mirror; Oberto Citterio and his colleagues in Milan for the design and manufacture of the 1-m supports which have functioned superbly; and, last chronologically but by no means least, the firms of Schott and Carl Zeiss and all their colleagues who contributed to the final excellent test results of the NTT optics and the active optics demonstration. We wish also to thank many ESO colleagues for their contribution.

References

[1] Wilson, R.N., Franza, F., Noethe, L., 1987, "Active Optics I", ESO Preprint No. 484 and *Journal of Modern Optics* **34** (4), 485.

[2] Noethe, L., Franza, F., Giordano, P., Wilson, R.N., Citterio, O., Conti, G., Mattaini, E., 1987, "Active Optics II", ESO Preprint No. 560, accepted for publication in *Journal of Modern Optics*.

[3] Franza, F., Le Luyer, M., Wilson, R.N., 1977, "3.6-m Telescope: The Adjustment and Test on the Sky of the PF Optics with the Gascoigne Plate Correctors", ESO Technical Report No. 8.

[4] Wilson, R.N., Noethe, L., 1988, "Mirrors and Supports", Proc. ESO Conf. on "Very Large Telescopes and their Instrumentation", Garching, March 1988, to appear shortly.

The 3rd ESO/CERN Symposium

G. SETTI, ESO

The 3rd ESO/CERN Symposium on "Astronomy, Cosmology and Fundamental Physics" was held in Bologna (16–20 May, 1988) at the invitation of the University of Bologna celebrating its 900-year anniversary. It was attended by approximately 250 participants, but on many occasions the audience was much larger due to the presence of local scientists and students.

The Symposium was focused on the various subjects important to cosmology and particle physics which were covered by a set of comprehensive review lectures, contributed papers and posters. The reviews included a critical discussion of the value of the Hubble constant (A. Dressler), the large scale distribution of galaxies (M. Geller), a discussion on the distribution and properties of classes of objects at high redshifts (R. Kron), the microwave background (B. Partridge) and the formation of structures in the Universe (N. Vittorio, A. Starobinsky), the evidence and particle constituents of dark matter (D. Lynden-Bell, M. Turner), the status of the standard model of particle physics (R. Peccei), the implications both for the inflationary model of the Universe and of particle physics of going well beyond the standard model (D. Nanopoulos), the fascinating results of ultrarelativistic nuclear collisions (M. Satz) and a review of the underground physics experiments (E. Bellotti). One afternoon was dedicated to the discussion of the Supernova 1987A, this extraordinary event which took place in the Large Magellanic Cloud and for which ESO has accumulated an impressive amount of observational material.

The introductory lecture was given by Prof. A. Salam, Nobel Prize for Physics, who, among other things, emphasized the fundamental importance of studying the Universe for the understanding of the basic laws of physics. As he put it, the extreme conditions to be found in the hot "big-bang" scenario would require man-made particle accelerators having sizes up to the distance to the nearby stars, which is obviously outside of any foreseeable technological development. The main results of the Symposium were beautifully summarized in the Closing Lecture by L. Van Hove.

According to many unsolicited comments the meeting was extremely successful, both scientifically and organizationally, and for this last point a special thanks should be addressed to the local organizers, the Departments of Astronomy and Physics of the University of Bologna. The organization of the meeting greatly benefitted from the generous support provided, among others, by the University of Bologna, the City Authorities of Bologna, the National Research Council of Italy (C.N.R.) and the National Institute of Nuclear Physics (I.N.F.N.).

The Proceedings will be published by Reidel towards the end of this year. Their availability will be announced in the *Messenger*.

At the end of the Symposium, in a ceremony that took place at 12 a.m. on May 20, the Rector of the University of Bologna presented Professor L. Van Hove, former Director General of CERN, and Professor L. Woltjer, former Director General of ESO, with a laurea "honoris causa" respectively in Astronomy and in Physics.

In parallel with the ESO/CERN Symposium, and on the same premises, the Departments of Physics and Astronomy of the Bologna University had organized an exhibition in astronomy and particle physics at which both ESO and CERN participated with their exhibition material. The exhibition was officially opened on May 7 by the Rector of the University and local authorities and was extremely successful, attracting about 30,000 visitors, including many organized school tours.

List of ESO Preprints

June–August 1988

592. P. Bouchet et al.: Infrared Photometry and Spectrophotometry of SN 1987A: March to October 1987 Observations. *Astronomy and Astrophysics*.
593. L. Milano et al.: Search for Contact Systems Among EB-Type Binaries. I: TT Herculis. *Astronomy and Astrophysics*.
594. R. Buonanno et al.: On the Ages of Globular Clusters and the Sandage Period-Shift Effect. *Astronomy and Astrophysics*.
595. J. Melnick et al.: The Galactic Giant H II Region NGC 3603. *Astronomy and Astrophysics*.
596. P.A. Shaver et al.: The Evolution of Structure. Paper presented at a meeting on "Large-Scale Structure and Motions in the Universe", Trieste, April 1988 (to be published by Reidel; eds. G. Giuricin et al.).