OPTICAL FABRICATION IN THE LARGE

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Abstract

Extremely large telescope concepts, with pupil diameter of 25-m and beyond, have been proposed in the past two decades but, so far, never materialized. First, ground-base telescopes were handicapped by atmospheric turbulence, which sets angular resolution and limits the benefit of size to collecting power. Second, the limited number of suitable optical substrates, the inherently slow and difficult development required to enlarge their size, and the marginal demand and profits brought by astronomical applications, implied costs and risks which limited the pace of progress. Third, optical surfacing methods were poorly deterministic, thereby hindering the fabrication of the faster and more complex optical shapes required in extremely large telescopes. In brief, atmosphere limited scientific incentives, costs were too high and technology was not present, in part for market reasons, in part for real limitations. It is proposed that this situation has changed dramatically. First, adaptive optics promises to restore the full interest of larger size. In this paper, we elaborate on the second and third arguments, review current mirror concepts and associated technologies, and come to the conclusion that, as far as optical fabrication is concerned, the technologies required for fabrication extremely large aperture telescopes are readily available.

1. Introduction

Giant telescopes with apertures in the 25-m range have been proposed over more than 20 years[1,2]. Although the scope of the present paper is about optical fabrication for large to extremely large telescopes, it is instructive to reflect on the possible reasons, technological and others, why these early proposals did not yet materialize, and derive orientations for future developments.

A determinant factor might well have been that until quite recently, atmospheric turbulence prevented that increased diameter be rewarded by a proportional increase in resolution. Interferometers overcome this problem, however at the cost of comparably low efficiency and high technical and operational complexity.

Hence, science objectives for telescopes with diameters beyond that of the 8- to 10-m class generation may not have been sufficiently attractive in relation to their cost. By filling the *resolution gap* that let ground-based optical astronomy trailing far behind radio and space-based astronomy, adaptive optics has the potential to revert this situation. Assuming that adaptive optics will, in a near future, become mature as standard observing mode providing reasonable sky covergae, which is quite likely, the next question to assess is whether technology permits further extrapolation in telescope diameter.

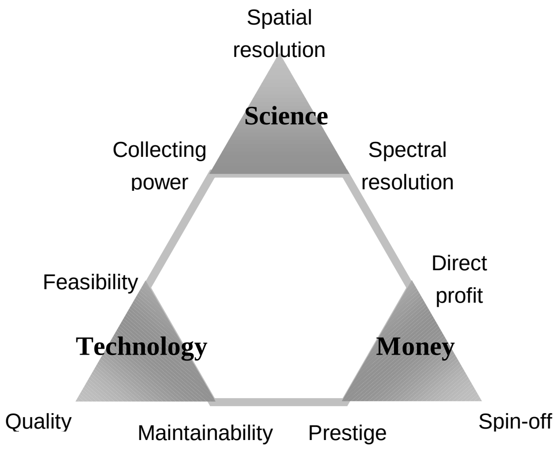

Figure 1

Answering such question on the basis of technological considerations only would probably be uncareful. Alike any large scientific project, extremely large telescopes must be conceived around three themes (Fig. 1): science objectives and capabilities, technology, and money. The current 8- and 10-m telescopes owe their very existence to substantial development and industrial efforts, and larger projects will only increase the demand on an industrial support which will be bound to measurable return –be it in the form of prestige, spin-off or direct profit.

In critical areas such as large optics, industrial support was probably motivated by prestige and spin-off (e.g. in the form of consumer applications of glass-ceramics materials or use of advanced polishing techniques for microlithography optics). This

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situation may not hold when it will come to extremely large telescopes, whose main optics will demand substantially larger budgets. Public funding will most likely be bound to higher industrial return, and emphasis may therefore have to shift towards solutions that imply low industrial risk and good predictability.

It could be argued, of course, that further development could provide elegant and effective solutions to the fabrication of extremely large mirrors, and that such development does not necessarily have to rely exclusively on industrial resources. A case in point is the stress polishing technique developed for the Keck project by Nelson et al[3] or the mirror technology by Angel et al[4]. Experience shows, however, that progress in optical fabrication is very slow. Computer-controlled polishing was successfully demonstrated[5,6] in the early 70s, but it took at least a decade to see it implemented in large-scale astronomical projects. A similar statement could be made about mirror materials, be it glass-ceramics or metal.

Size extrapolation should therefore be considered carefully. In spite of the appearances, this discussion, however, is not meant to prevent optimism. Two fundamental concepts have been proven in the last decade: segmentation and active optics. The beauty of the former is that it allows, in theory, any size extrapolation without a corresponding size extrapolation of fabrication processes. The latter, by relaxing fabrication tolerances and allowing automated control of optical quality[7], dramatically widens the acceptable range of materials and processes.

2. Evaluation of materials and processes

Evaluating materials and processes for the fabrication of large optical components is a rather complex task, which requires careful definition of the objectives and constraints, at system and subsystem levels, and in-depth understanding of design, fabrication and operation constraints (Table 1). There will most likely be overlap between the three, and evaluation may become highly iterative. Programmatic considerations are likely to play a crucial role as well, depending on budget, schedules, and allowable risks.

Design	Fabrication	Operation
Performance specifications Environmental specifications Lifetime Safety Transportability	Material properties Material fabrication Optical fabrication	Integration Maintainability

Table 1. Engineering considerations

A common pitfall in evaluating materials and processes is over-emphasis put on a single property or on the “elegance” of a determined solution to a specific problem. This may translate into confusion between objectives and solutions. Conflicting requirements are more common than concurring ones, and sound solutions are built on rational compromises and trade-offs.

Design considerations translate into an error budget (Fig. 2), which, at this stage, may be seen as representing the performance merit function associated with the subsystem. Specific materials and processes should evidently be scrutinized for their ability to meet requirements and for their influence on the error budget.

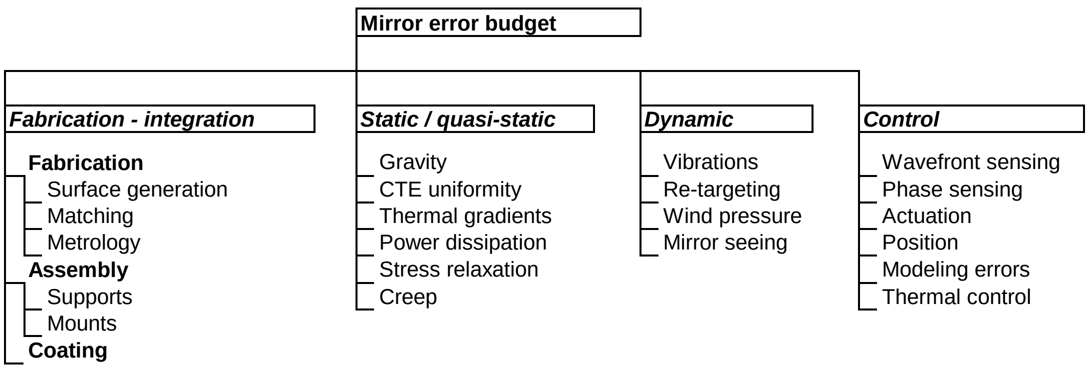

Figure 2. Design considerations, mirror error budget.

Material properties considerations, some of which specific to metal mirrors, are listed in Table 2 (adapted from Paquin[8], 1989). It should be noted that some of the properties listed in this table are temperature-dependent, a factor that must be duly taken into account. The list is certainly not exhaustive and should be prioritized on a case-by-case basis.

Depending on the type of application and objectives, material properties can be combined into specific merit functions. These functions will actually correlate to critical subsets of the error budget. A graphic example is shown in the diagram of Fig. 3, which compares a few mirror materials for their specific stiffness (ρ/E, where E is the Young's modulus and ρ the density) and steady state thermal distortion coefficients (CTE/k, where CTE is the Coefficient of Thermal Expansion and k the thermal conductivity). Those properties are frequently essential to astronomical applications, and have strong influence on system concept, opto-mechanical design, and error budget allocations. In this particular case, the merit function is relevant to the optical manufacturer as well, as the thermo-mechanical properties will be related to quilting under polishing pressure and dimensional stability with respect to friction-generated heat.

Mechanical	Physical	Optical	Structural	Fabrication	General
Young's modulus	CTE	Reflectivity	Crystal structure	Machinability	Availability
Strength	Density	Absorption	Phases	Polishability	Scalability
Microyield strength	Thermal conductivity	Refractive index	Voids and inclusions	Platability	Cost
Creep strength	Specific heat	Emissivitiy	Grain size	Optical	Lead-time
Hardness	Melting temperature		Transition temperature	replication	
Ductility	Electrical conductivity		Stress relief temperature	compatibility	
Fracture toughness	Vapor pressure		Heat treatable		
	Corrosion potential		Texture		
	Chemical properties		Porosity		

Table 2. Material selection.

In general, the requirements underlying large-scale, ground-based astronomical applications are fairly restricted and environmental constraints relatively benign. Not withstanding performance requirements, primary targets are usually low cost, low mass or inertia, availability in large sizes or scalability. Secondary selection criteria generally focus on homogeneity of thermo-mechanical properties, high specific stiffness, low residual stresses, long-term dimensional stability, and polishability.

It must be kept in mind that optical fabrication cannot be described in terms as simple as material properties. The end product is the result of a process, which may affect or be affected by the substrate properties. Process control is, indeed, an integral part of optical fabrication, and virtually every step, starting with the procurement of raw material and ending with the integration of the finished component, must be covered by suitable quality inspection methods.

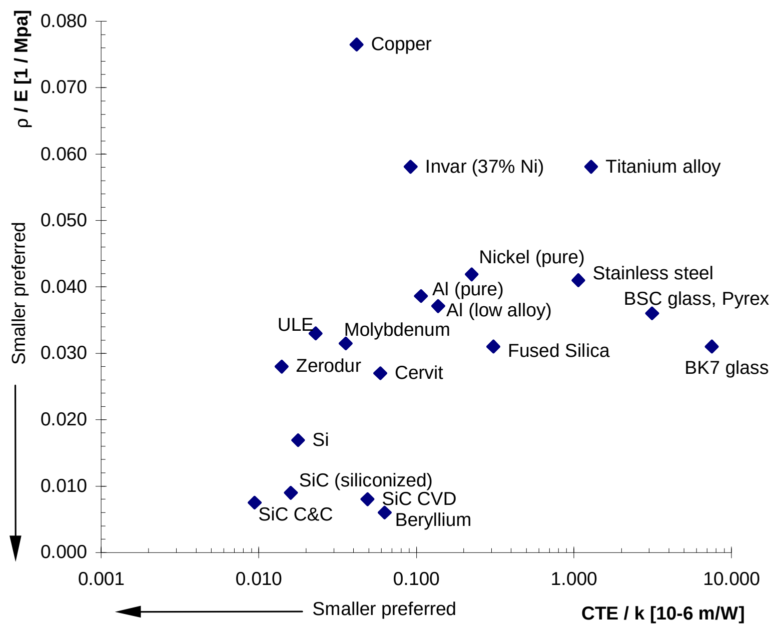

Figure 3. Thermo-mechanical figures of merit (steady state)

Of prime importance are the control of residual stresses while the substrate is being formed and the minimization of applied stresses thereafter. Substrates that appear robust to breakage, like metals, may have to be mounted and handled with no less care than brittle ones. To an optical component, stresses are, simply, unforgiving.

Finally, and as emphasized in the introduction, available materials and processes for such uncommon application as large or extremely large telescope optics may be severely limited by market constraints.

3. Active optics and segmentation

A review of optical fabrication in the large without consideration for active optics and segmentation would almost amount to anachronism. The two technologies have so profound impact that they do not only drive modern telescope design, they also drive optical fabrication in general.

The prime target of active optics[9] is essentially to increase and maintain performance. It also has definite advantages in terms of cost reduction, feasibility and scalability. Furthermore, it allows a healthy competition between traditional, thermally stable optical materials and cheaper or lighter ones. Relaxation of surface tolerances plays a major role in reducing costs and improving performances, since it allows the manufacturer to concentrate on the removal of high spatial frequency errors. Table 3 gives a brief and certainly incomplete overview of fabrication aspects potentially affected by active optics.

Materials & processes	Optical figuring
Non-zero CTE Relaxation of homogeneity requirements Relaxation of residual stresses requirements Relaxation of long-term dimensional stability requirements Spin-casting of thin substrate, very large monolithic substrates Bimetallic effect acceptable to some extent	Relaxation of figuring tolerances Relaxation of support tolerances Simple and reliable matching test Stressed polishing

Table 3. Active optics, influence on fabrication aspects.

It should be observed, however, that active optics by deformation of continuous surfaces is best adapted to ground-based applications because in such applications, wavefront slope is, to a large extent, more relevant than wavefront amplitude.

The main drawbacks are the added system complexity, both at operational and maintenance levels, and the sensitivity to loads at frequencies higher than that allowed by the control loop. Results obtained with the current generation of active telescopes show that these drawbacks can be handled fairly well, and that they are an acceptable price to pay for truly seeing-limited performance.

For ground-based astronomical applications, the lower limit for active systems is probably in the 2-m range, where conceptually simpler, cost-effective solutions exist (active alignment control may, however, still be attractive at lower scales). There is widespread consensus that the technology becomes mandatory above 4-m, if not below. The upper limit is probably not much higher than the 8-m range, essentially for fabrication, transport and handling reasons, rather than for conceptual or physical ones.

The situation is quite different with segmentation, which emphasizes cost reduction and scalability, at some limited but not negligible expense in terms of performance. The high slope error generated by surface discontinuities not being filtered by atmospheric turbulence, phase errors have to comply with stringent requirements, comparable to those normally applying to space-based systems. A possible weakness of segmentation, namely its reliance on position sensors for phasing, may eventually disappear if piston-sensitive wavefront sensors could be developed to close the phasing loop in real time on sky objects. Once this problem will be solved, it is quite likely that the performance gap with active systems will narrow down.

These drawbacks should be evaluated in relation to the immense potential of segmentation with respect to scalability. Regarding materials, virtually any acceptable solution for passive substrates in the 1- to 2-m range becomes scalable to any size, the limitation being essentially imposed by control complexity and segments mass production. A reservation must however be made for homogeneity of thermo-mechanical properties within and between segments, whose tight curvature tolerances must be kept within the entire range of environmental specifications. So far, this dramatically limited material and processes options[3].

The scalability potential also applies to optical figuring of spherical surfaces, which can be replicated or figured on planetary machines at low cost. The generation and testing of off-axis aspheric surfaces is substantially more difficult and, although this problem has been successfully solved, there is little doubt that segmentation is inherently better adapted to the production of all-identical, spherical surfaces.

An attempt at merging the two concepts, allowing some (limited) active shape control of individual segments, is currently made by Castro et al[10]. Segments being typically in the 2-m range and, so far, made of thermally stable materials, active shape control does not need to be pushed as far as with 4- to 8-m class mirrors, and serves mostly to relax tolerances on segments lowest order misfigure. If successful, this attempt may substantially widen options for segmented mirrors while at the same time alleviating some drawbacks of the technology.

With extremely large telescopes, both technologies are likely to play a key role, with giant segmented spherical mirrors and actively controlled monolithic aspheric corrective optics.

In conclusion, and with apologies for the strongly caricatural statement, it is proposed that active optics offers unlimited material options in a limited size range, while segmentation offers limited material options in an unlimited size range.

4. Mirror materials

An exhaustive discussion of possible optical materials and processes for reflective optics is impossible within the framework of a brief article. Extensive research driven by military and high energy applications took place in the last two decades, and is still progressing. The applications that are publicly known focus mainly on medium-size components, at least by the standard of today's astronomical optics.

Suitable materials for mirror fabrication in the large include a variety of glass, ceramics and metals. Table 4 gives a non-exhaustive list of potential candidates for astronomical applications. Substrates are formed by casting, fusion, welding, infiltration, rolling, forging, or machining of a solid block.

Material	Technology		Max. size	Remarks
Zerodur	Casting	solid blank	4-m	
	Spin-casting	thin meniscus	8.2-m	active optics mandatory
	Machined solid blank	Lightweight	2-m	
Silica, ULE	Fusion of boules	solid blank	4-m	
	Fusion of boules	thin meniscus	8.3-m	active optics mandatory
	Machined blank	lightweight	2-m	
	Structured blank	lightweight	2.5-m	
Borosilicate	Spin-casting	structured	8.4-m	active optics & thermal control mandatory
Al	EB welding	solid blank	1.8-m	active optics mandatory
	Build-up welding	solid blank	1.8-m	active optics mandatory
Be	HIP	lightweight	1.2-m	active optics mandatory
SiC	Infiltration	lightweight	~ 1-m	

Table 4. State-of-the art materials for large, ground-based astronomical applications.

With reference to the diagram shown in Fig. 3, the materials listed in table 4 could be split into three categories.

The first category would be that of "classical", thermally stable materials (steady state) which can be produced in large to very large dimensions: Zerodur, Astro-Sitall, Silica, ULE, and Aluminum. The latter set aside, these are the classical options, demonstrated and generally acceptable for passive systems up to the 4-m range and active up to 8.4-m.

Production of large Zerodur, Silica and ULE substrates has been extensively described in the literature[11-14] and will only be outlined here. Glass-ceramics (Zerodur, Astro-Sitall) are two-phase materials, whereby the balance between the crystalline phase (with negative coefficient of thermal expansion or CTE) and the amorphous phase (positive CTE) can be set to minimize the overall expansion coefficient in a given temperature range. The substrate is cast to glassy state, cooled to ambient temperature, pre-machined, and re-heated in a ceramization process to stimulate crystal growth. Once ceramized, it is machined to near-net shape, annealed, and finally machined to specifications (Fig. 4). To minimize residual stresses, thermal gradients must be controlled to high accuracy throughout the whole process. Meniscus geometry is, in this respect, an advantage up to 4-m, and probably a prerequisite above. Highest breakage risks occur during the cooling phase in the glassy state, when a crystalline layer is grown at the contact area with the refractory mold. This layer having a different expansion than the amorphous substrate, stresses build up during cooling and breakage may occur. The problem becomes critical with very large, thin substrates. For Zerodur at least, it has been solved by SCHOTT.

Large silica blanks are formed by sealing hexagons together at ~1500 ^{o}C, and sagging the flat blank onto a convex refractory mold. Contrarily to glass-ceramics, a substantial part of the cost is the raw material. Therefore, hexagons are made by stacking sets of three boules, the central one being high grade. Slicing the stack in two yields two hexagons, each with one side at face plate quality. Silica blanks tend to have a fairly high density of bubbles, located at the seals. Although a potential source of concern to the optical manufacturer, this has, so far, not been a major issue.

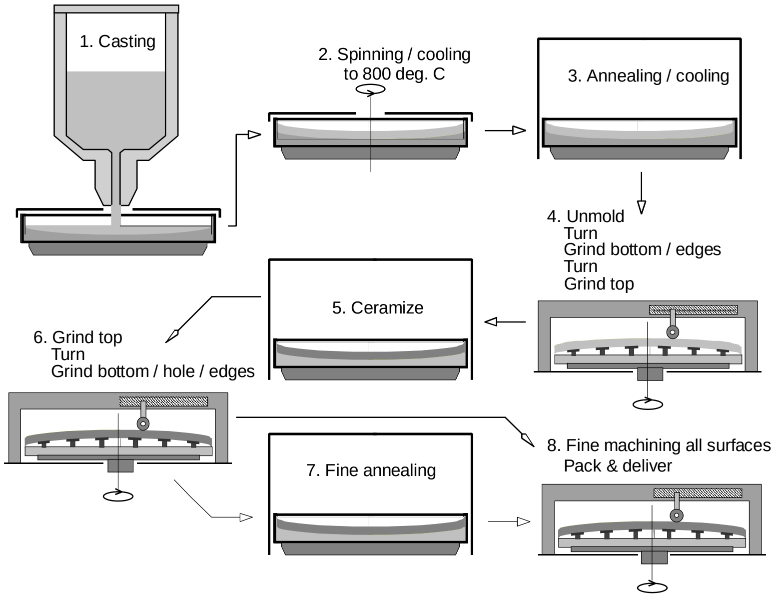

Figure 4. Spin-casting of large Zerodur blanks

Best internal quality has been so far attained with Zerodur, which shows the lowest residual stresses, bubbles and seeds content, and homogeneity. The casting process is however intrinsically more complex than fusion of silica boules, a process inherently more scalable. The Zerodur spin-casting process is schematically outlined in Fig. 4 and the fusion of silica boules in Fig. 5.

Aluminum substrates have to be actively controlled above the ~1.5-m range. Although there is strong confidence in the technology, it has not been demonstrated beyond 1.8-m. The option was seriously considered for the primary mirror for the ESO 3.5-m New Technology Telescope, and perfectly valid offers for forged or cast blanks were received[15], until it was dismissed for entirely organisational reasons.

Fairly good results have been obtained[16] with two aluminum technologies, build-up welding and electron-beam welding. Both have been tested by ESO in the late 80's on 1.8-m mirrors, under contract with industry (Linde, Telas, Reosc), with a view to providing a backup to Zerodur for the production of the VLT primary mirror blanks. Build-up welding consists in a continuous deposition of welding seams onto a rotating mandrel. The technology seems easily scalable, and has been shown to provide excellent substrate homogeneity. Particular attention must however be paid to alloy selection and to thermal stresses, as the process inevitably leads to strong thermal gradients between the location of the welding heads and the opposite section of the blank. Indeed, the first attempts made at producing a 1.8-m class blank resulted in dramatic failures (cracks). The contractor (Linde) eventually solved the problem by selecting a more resistant alloy and preventing the blank to cool upon its rotation.

The process of electron-beam welding consists in fusing seals between pre-assembled aluminum parts with a high-powered electron gun. The process requires a vacuum chamber of suitable dimensions or, since vacuum requirements are not particularly critical, a suitable system to ensure local vacuum in the area of the seals. Although the total energy transferred into the blank is fairly small, the severe thermal gradients upon welding requires careful design of the clamping devices used for pre-assembly. The required gun power is in the 100 kW range for a 300-mm thick blank. The ESO 1.8-m electron-beam welded mirror was assembled from four forged aluminum quarters. Casting of a single piece would have been possible, but this mirror was made as a demonstrator for upgrade to 8-m class, a dimension deemed too large for casting.

Both processes imply using alloys, as pure aluminum would lead to unacceptable porosity.

The two ESO 1.8-m test mirrors were manufactured to specifications, and thermally cycled to simulate aging. The deformations were found to be within one fringe, stable, free of high spatial frequency content and therefore fully acceptable with an active support system.

A serious drawback of aluminum mirrors is the need, for visible applications, of a nickel coating. Although the process is fairly well controlled for adherence, thickness, homogeneity and stresses, it is an inevitable source or risk (break-through of coating during polishing). It also leads to bimetallic effects, which should however be of no serious consequence in an active system.

The second category would include materials such as Borosilicate (BSC), with lower thermal performance requiring potentially complex thermal control. This material can be produced[4] in large to very large dimensions. Spin casting in a structured mold allows aerial density to be somewhat lower than with materials of the first category. Although very large, thick and structured BSC blanks can be made stiffer than their meniscus counterparts of the first category, they still imperatively require active supporting. The higher stiffness could however become an advantage with telescopes designed to operate in open air, where wind excitation may impair the performance of more flexible mirrors.

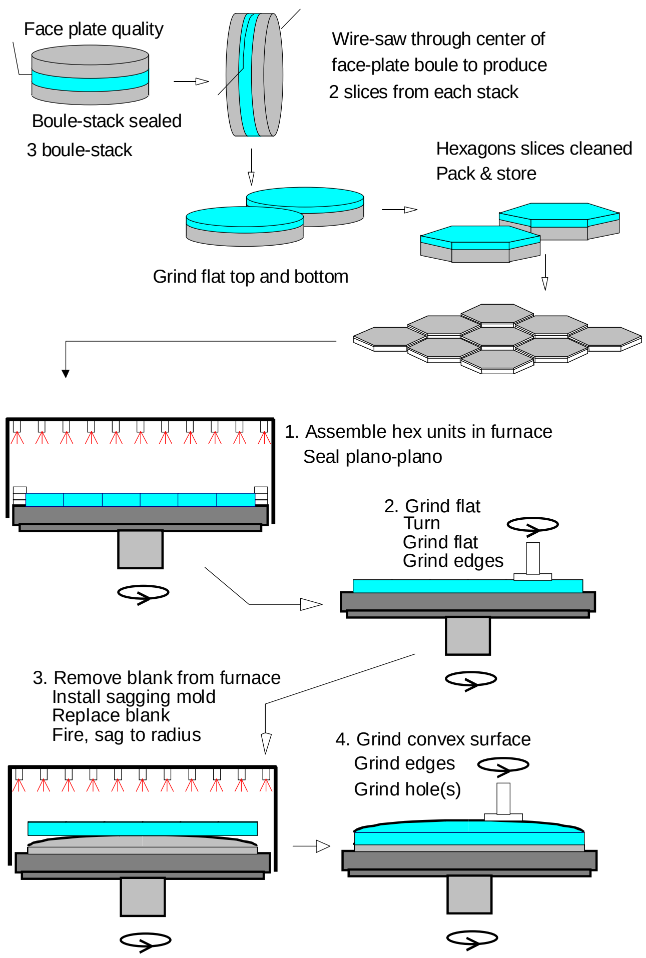

Figure 5. Production of large silica blanks.

Steel, although not mentioned in the list of table 4, could be put in the second category as well. This option has been briefly explored by ESO for the VLT primary mirrors in the late 80s, and several 500-mm blanks were successfully produced and tested. The program was discontinued in favor of aluminum.

It is tempting to call the third category (Beryllium and Silicon Carbide) "super-materials", because their very high specific stiffness allows spectacular mass-savings. These materials are best suited for low mass and inertia, fast steering secondary mirrors. 1-m class Beryllium mirrors with aerial density in the 40 kg/m^2 range have been produced to highest accuracy[17]. Best results so far were obtained with Hot Isostatic Pressed billets of high-grade, fine Be powder. Alike aluminum, Be blanks must be coated with a thin nickel layer to allow polishing to visible, optical specifications. Although the fabrication process is far from trivial and requires constant care with respect to stress relaxation, Reosc and Brush-Wellmann, under contract with Dornier and Eso for the procurement of the VLT secondary mirrors units, unequivocally demonstrated that 1-m class Be mirrors can be produced to highest standards. It cannot be guaranteed, of course, that the VLT secondary mirrors will have long-term dimensional stability comparable to that of glass-ceramics, but the risk of warping can be reasonably deemed very low and uncritical in view of the VLT active optics capability.

As for Silicon Carbide, there is very strong confidence that an aerial density in the range of 30 kg/m^2 could readily be supplied with mirrors in the 1-m range, and suppliers feel confident in bringing the figure down to ~10 kg/m^2 in a near future.

There are, essentially, two Silicon Carbide technologies: CVD and infiltrated SiC. While in theory the former would yield highest specific stiffness, in practice infiltration is preferred for lower if not negligible residual stresses. This technology was successfully developed by several manufacturers, United Technologies and Carborundum, to name a few, until production was discontinued and facilities shut down, most likely for market rather than technical reasons. European suppliers may take the challenge up, with Céramique & Composites on the French side and IABG on the German one. In fact, there is room for cautious optimism regarding the production of up to ~2.5-m SiC moderately to ultra-lightweight substrates at very competitive prices[18]. The problems that remain to be solved are essentially:

- Support stresses induced in the siliconization process. The green body that is heated up to ~1800 ^{o}C has a different coefficient of thermal expansion coefficient than that of the infiltrated blank and the support must be designed to accommodate the resulting dimensional change without introducing critical stresses in the blank.
- Polishability. Neither of the suppliers mentioned above can guarantee a surface polishable to optical standard, be it because of residual porosity or because of residual carbon grains which may impair surface cleanliness. However, several solutions, CVD- or PVD-deposited coatings to name a few, have been successfully explored.

Compared to Beryllium, raw material is fairly inexpensive and blank production faster. Hence, SiC may become a potential challenger to classical glass-ceramics materials when it will come to mass-production of segments for extremely large telescope projects.

Extrapolation of materials and processes to much larger sizes than those listed in table 4, if driven by astronomical applications only, is quite unlikely. Very strong scientific and technical arguments against segmentation would be required to justify the costs and risks underlying the development of extremely large monolithic mirrors much beyond the current range. Materials of the first and second categories could probably be extrapolated to the ~12-16-m range in a foreseeable future, the most favorable candidate being fused silica. Fabrication, transport, handling and maintenance complexity could however cancel, in part or in full, the gain in cost per unit area generally associated with active optics.

As for the third category, future development might go in two directions: ultra-lightweight substrates in the 2- to 4-m range, with aerial density in the 10 kg/m^2 range or even below, and cost-competitive lightweight materials with aerial density in the 30-50 kg/m^2. The former would be driven by space applications, the latter by extremely large ground-based telescopes.

5. Optical fabrication and testing

Until quite recently, optical fabrication was fairly limited in its options. Figuring an optical surface would normally start with grinding and smoothing with progressively finer abrasives, and finish with pitch polishing. Aspheric surfaces would be generated by progressive deviation from an initially spherical surface. Producing smooth surfaces required relatively stiff tools with dimensions comparable to that of the piece under figuring. Such conditions can evidently not be fulfilled with aspheric surfaces, where tool dimension and stiffness must be relaxed to allow matching of the shapes of the tool and of the optical substrate. Even though the process could be improved, for example with petal tools yielding non-uniform wear, departure from spherical surface was inevitably limited.

The issue of generating aspheric surfaces is not material removal per se, but removal at different rates over neighboring areas: what truly matters is not the deviation from best fitting sphere but the slope difference between the desired shape and the best fitting sphere. With conventional polishing techniques and conic surfaces it is convenient to define a difficulty criterion *dy* given by

$$dy = \frac{8N^3}{k},$$

where N is the focal ratio of the optical surface and k its conic constant. It can be shown that *dy* is inversely proportional to the slope difference between the desired conic surface and its best fitting sphere i.e. the smaller *dy*, the more difficult the asphеrization. The third power factor in f/D yields a rapid increase of difficulty towards small focal ratios, a factor that constrained the former generations of telescopes to relatively slow primaries.

As formulated by Preston[19] already in 1922, removal of material by lapping is a function of tool pressure, relative velocity between tool and substrate, and lapping time. Making any of these parameters variable with respect to tool position would theoretically allow to modulate tool wear and produce aspheric shapes in a controlled manner. Sufficient predictability not only requires appropriate control of the parameters mentioned above, but also suitable measurement methods allowing feedback to the polishing machine. Indeed, optical testing forms a fundamental and integral part of optical fabrication.

While computer-controlled polishing techniques were already demonstrated[5,6] in the early 70s, reliable, cost-effective test methods appeared somewhat later. Measurement of the surface of the ESO 3.6-m primary mirror, which was completed in the 70s, was done by photographic Hartmann test and implied lengthy preparation, acquisition and data reduction. The output of a measuring run represented a mere kilobyte of data, while today's high-sampling, high accuracy interferometric test methods allow acquisition of megabytes within a few hours at most.

Furthermore, and in view of the low predictability of the figuring process and to reduce risks, polishing runs were adjusted to remove misfigure in part only.

The technological revolution permitted by computer-controlled polishing techniques and modern testing methods is clearly illustrated in Fig. 6, which plots the achieved optical quality (wavefront RMS misfigure) as a function of *dy* for a series of aspheric mirrors produced over the last 30 years. As shown in this figure, mirrors produced before ~1985 with classical methods tended to follow a power law limiting the achievable quality. As unequivocally demonstrated by the quality of the Vatican 1.8-m mirror[20], the segments of the Keck telescope[21], the primary mirror of the 3.5 m Galileo telescope[22], or the VLT secondary mirrors[17], there is virtually no limitation in shape -provided, of course, that a suitable test set-up provides the necessary surface data.

In *Reflecting Telescope Optics II*, Wilson[15] makes an extensive review of modern, controlled figuring techniques. Those include lapping and ion-beam figuring. Diamond turning is not considered as it is quite limited in size, and requires post-polishing for visible applications. Lapping techniques can be categorized according to which parameter or which combinations of parameters of Preston's law (pressure, velocity, or time) they vary to figure the desired shape. In practice, these techniques are not exclusive and may be specifically adapted to different stages of the figuring process i.e., one technique may be suitable for final correction of zonal defects or high spatial frequency errors, for example, while another one will be more effective in generating the overall profile.

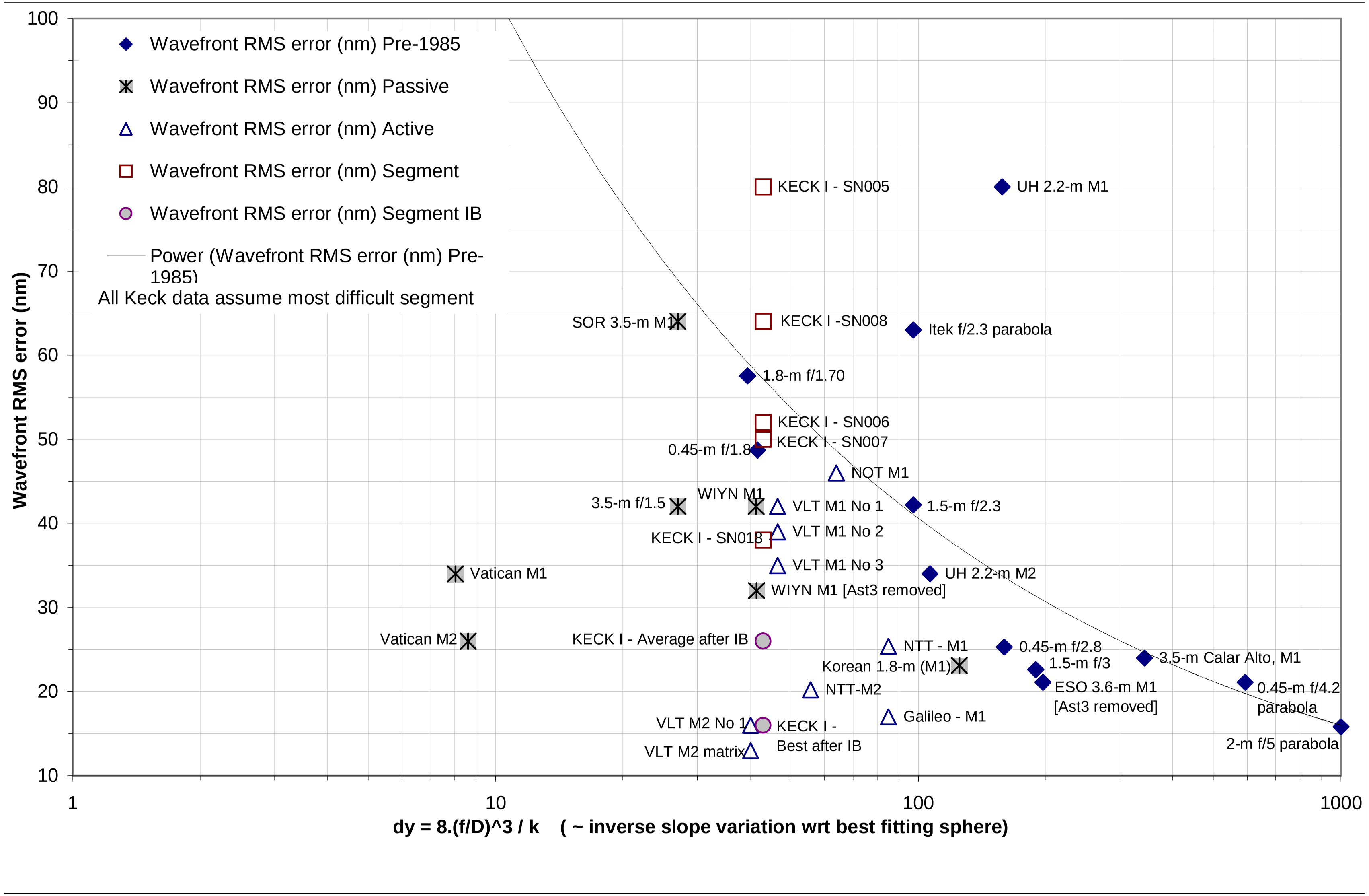

Figure 6. Optical quality obtained with aspheric mirrors over the last 30 years

All modern lapping techniques involve control of the relative motion of the tool and workpiece, most conveniently achieved by computerized motion of both. Lapping tools can be stiff or flexible, the latter being either passively flexible or actively controlled.

Large stiff tools, with dimensions comparable to that of the workpiece, are effective in producing smooth spherical surfaces and therefore, ideally suited at the grinding stage. Low aspherization, typically that of a parabola with a focal ratio not lower than ~4, is possible with large, stiff pattern tools, whereby the pattern of grinding tiles or polishing pitch is adjusted to provide a radially variable wear. Moderate aspherization requires combining stiff and flexible tools of decreasing sizes. Small or flexible tools tend, however, to generate high frequency ripple and zonal errors and it might be necessary to revert to relatively large tools for smoothing runs. Again, the pattern of tiles or pitch can be adjusted to the desired wear function. This is the technique applied successfully by Reosc to the production of the 8-m, f/1.8 primary mirrors of the Gemini and VLT telescopes (Fig. 7), with a final wavefront accuracy on the order of 30-40 nm RMS after active correction of lowest modes. The mirror is supported on a rotating table and the tools are moved by a robot arm, allowing precise control of the relative speed between tool and workpiece. Smallest tools are in the 1-m range. The progress of quality over the production of the five 8-m mirrors already completed is a clear indication that the technological limit of this process is not yet reached.

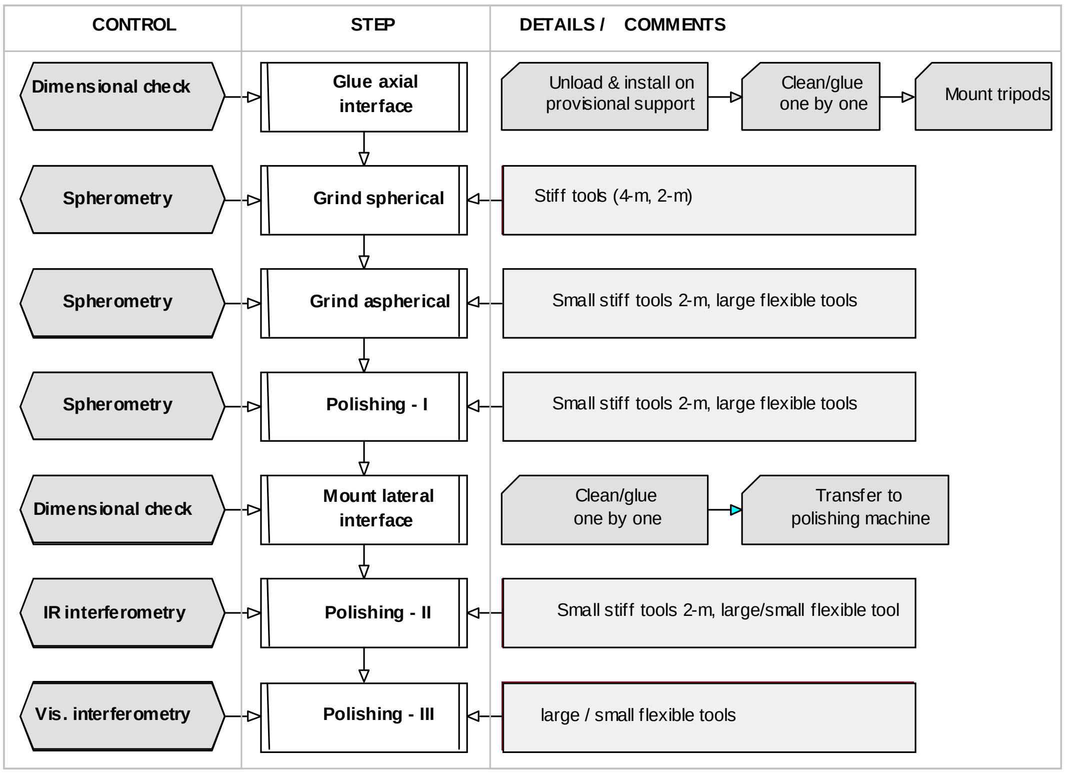

Figure 7. Optical fabrication of the VLT primary mirrors – outline.

Motion (relative speed), dwell time and pressure control have been successfully applied with very small stiff tools, having dimensions lower than 1/10th of the workpiece. Pioneering work was done at Perkin-Elmer in the early 70s, paving the way for spectacular achievements. One major drawback of the technology, namely the loss of rotational symmetry, is now fully compensated by suitable computer-controlled motion systems. The technology is very effective for finishing highly aspheric surfaces and production of off-axis aspheres, and substantially more deterministic than those relying on large tools. Processing time is inevitably longer, in view of the small area being worked at a given time. Some of the most spectacular results have been obtained by Reosc with the VLT secondary mirrors, which were produced to ~15 nm RMS wavefront (after removal of the lowest modes, as permitted by the telescope active concept) over a surface extending *up to 2 mm from the mirror physical edge.*

Active, flexible tools include membrane tools (Zeiss[24], Korhonen et al[25]), and stessed laps (Angel[26,27]). Membrane tools consist in rectangular flexible strips, which oscillate radially over the rotating workpiece. Actuators mounted onto the membrane allow adjusting the pressure as a function of radial and azimuthal location on the workpiece. The stiffness of the membrane and the actuator characteristics can be set to allow efficient smoothing of high spatial frequency errors, while guaranteeing appropriate matching of the tool shape with the desired aspheric profile, and effective control of non-axisymmetrical errors. The total area worked at any time being relatively large, the process is, in addition, as time-effective as "classical" large-tool figuring. In principle, the same tool could be used throughout the entire figuring process, from grinding to final polishing. The NTT and Galileo[21] 3.5-m class mirrors polished by Zeiss to 25 and 17 nm wavefront RMS (after removal of lowest modes), respectively, demonstrate the superb potential of this technology.

Stressed lap polishing has similar advantages and performances. In this arrangement, a large, possibly full-size lap, is continuously deformed by applying variable bending moments at the tool's edges. The moments applied, hence the tool shape, are adjusted according to tool position in order to ensure proper matching with the desired profile. Relative speed can be adjusted to allow non-uniform wear. The technology can deliver diffraction-limited quality with extremely steep aspheric mirrors[20] (f/1.0 parabola).

Contrarily to all the above options, stress polishing does, in principle, not imply any particular modification of the classical, large and stiff tool approach. Instead, it is the workpiece that is deformed, either by active support forces, bending moments or variable pressure, in a manner to allow its surface to be figured spherical (or flat). The constraints are predetermined in such a way that once relaxed, the workpiece takes the desired profile. This technique is quite effective in the production of Schmidt plates[28] and was the baseline solution selected for the fabrication of the off-axis hyperbolic segments of the Keck telescopes. Misfigure tolerances are tighter with reflective surfaces, however, and the uncontrolled warping which may occur upon relaxation of the constraints may exceed specifications. The most likely reason is that the grinding and polishing processes inevitably affect the distribution of residual stresses within the substrates, thereby making the process somewhat unpredictable at the level of optical tolerances. In addition, cutting of segments to hexagonal shape after figuring was, for similar reasons, a serious area of concerns. Hence, very tight requirements apply to residual stresses in the optical substrate. These problems required the Keck segments to be finished by ion-beam polishing.

The problems encountered upon figuring the Keck segments do not imply, however, that this approach is to be rejected. The uncontrolled warping mentioned before is very unlikely to include substantial high spatial frequency components and the technology could therefore be ideally suited for cost-effective production of highly aspheric active monolithic mirrors.

Ion-beam figuring constitutes an entirely different approach to optical figuring. In this process, material is removed by bombardment with Argon ions in a vacuum chamber. The workpiece is mounted optical surface down and suitable mechanisms provide the necessary degrees of freedom to "scan" the workpiece in a controlled manner. The process is deterministic to an unprecedented level, and therefore highly cost-effective. The only limitation seems to be the accuracy of the test data required to program the dwell time of the ion beam. Although heat generation is fairly low, local thermal gradients may have adverse effects with plated mirrors, e.g. Nickel-coated Beryllium or Aluminum mirrors. The process requires the workpiece to be already polished and does not introduce noticeable degradation of microroughness. It is, therefore, ideally suited for fine correction of residual errors in the ~1 micron range, be they structure print-through or polishing residuals. A striking demonstration of the technology was made with the finishing by Eastman Kodak of the Keck off-axis segments[21].

The discussion above, and the results shown in Fig. 6, not only indicate that several options exist for the fabrication of highly aspheric surfaces, but also shows that all options are basically similar in terms of final quality. However, and as mentioned before, all processes require accurate mapping of the misfigure to be polished out. Being part of the fabrication process, testing must be possible in a routine and time-efficient manner. Simultaneous acquisition of the entire optical surface is evidently preferable.

Progress in figuring and testing technologies went in parallel and probably stimulated each other. A review of all solutions is impossible within the framework of this article, but the current situation can be resumed in a single statement: it is today perfectly reasonable to expect data sampling of a few hundred points per surface diameter and a sensitivity in the range of a few nm. Substantial improvements have also been achieved with respect to influence of vibrations on interferometric test.

Direct interferometric measurement of aspheric surfaces is generally impossible as deviations from ideal spherical surfaces can easily exceed a few tenth of mm. Hence, the need for null systems (or null-lenses) to allow stigmatic or near-stigmatic test conditions. Concave mirrors are most conveniently tested at center of curvature through such lull-lens, while convex ones require compensators at least as large as the mirror itself (matrix or Hindle sphere). This is a strongly limiting factor when it comes to producing large convex mirrors.

In view of the strong spherical aberration these null systems must compensate, alignment is generally critical. Third order coma and focus terms are generally ignored as they can be cancelled in the telescope by refocusing and decenter of the secondary mirror. Aspheric segments do not allow such simplification. Other terms, including high orders, may however be significant and it is mandatory to perform final tests under different respective orientations of the null system and workpiece[29].

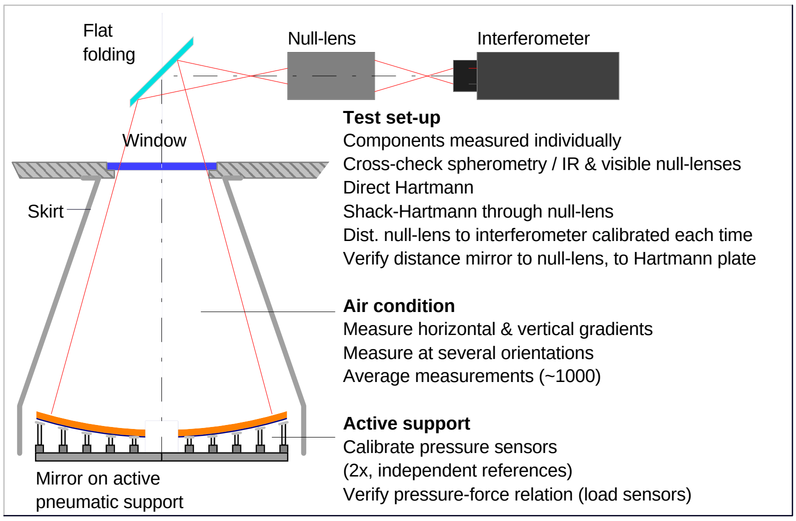

Figure 8 Metrology for the verification of optical quality of the VLT primary mirrors.

Null systems are sadly notorious for their capacity to introduce major flaws if built incorrectly, and need to be cross-checked. Fabricating two independent null systems might substantially reduce risks, but other solutions exist. An elegant solution demonstrated by Burge[30] is to crosscheck the null-lens against a *Computer-Generated Hologram* (CGH) simulating the aberration of the mirror to be tested. In a modified version, the CGH technology also allows to test convex mirrors against a spherical matrix[31].

With active mirrors, the strategy for final measurements is different and generally simpler than with passive mirrors. The general principle is to cross-check the highly accurate interferometric data in the simplest manner, priority being given to reliability. The objective is to ensure that, would an error have escaped detection, the active correction necessary to restore nominal performance will be well within the active force budget. In brief, highly accurate tests are complemented with highly reliable debugging tests. The solution applied to the VLT primary mirrors is to measure the aspheric profile with a simple photographic Hartmann test at center of curvature, without null system[29]. This test, however, forms only part of the overall crosscheck, since other factors may influence the conicity error: erroneous support forces, thermal gradients in the test tower. The complete set of tests applied to the VLT primary mirrors is schematically shown in Fig. 8.

While most of the technologies described so far are directly applicable to optical fabrication for up to ~10-m class telescopes, larger projects will inevitably shift attention towards cost-effective production of large segmented mirrors. The cost and complexity of fabricating off-axis aspherical segments and the limited field a giant Ritchey-Chrétien design would provide are strong arguments in favor of designs based on spherical primary-secondary mirrors[32]. Correction of spherical and field aberrations will have to be taken care of by strongly aspherical corrective optics, whose fabrication will most likely involve one or more of the solutions described above.

A promising approach to mass-production of spherical segments is that applied to the fabrication of the 97 segments of the Hobby-Eberly telescope[33] primary mirror. The segments, having a fairly large radius of curvature (26-m), could be polished on a modified, 4-m class planetary machine, down to approximately 2.5 fringes accuracy. Average polishing time per segment was on the order of 65 hours. Residual errors were removed in one or two runs by ion-beam finishing at Eastman Kodak. Reosc reports comparable if not better performance for the mass-production of amplifier plates of the *Mégajoule* experiment[34]. The largest planetary machines currently in operation have diameters on the order of 4-m. Mass-production of 2-m class segments would probably involve two or three 8-m class machines allowing production rates in the range of 1 segment per day.

Stressed polishing may permit a similar arrangement for mass-production of aspherical segments. The segments would be mounted into warping harnesses and polished spherical on planetary machines, the bending moment applied through the harness being set to provide the aspherical shape upon relaxation. Even with stringent material specifications (residual substrate stresses), the process is however very unlikely to be as deterministic as with simple, unstressed spherical segments, and more emphasis would have to be put on post-processing with computer controlled polishing or ion-beam finishing. Optical testing would be intrinsically more complex as well. These drawbacks, and the higher costs they imply, should however be evaluated in relation to the potential benefit of aspherical surfaces with respect to telescope design.

6. Conclusions

Advanced materials and processes, together with active optics and optical segmentation concepts, will undoubtedly shape the future of telescope design. Size extrapolation has been traditionally limited to about a factor two between successive generations, the limiting factor being the difficulty to fabricate and handle larger mirror substrates.

This limitation has been virtually eliminated by optical segmentation, and maximum telescope aperture may in the future be limited by maximum allowable control complexity or by the maximum allowable size of mechanical structures. Mass-production of segments at reasonable costs and fabrication of highly aspherical surfaces are fully within the reach of modern technology. Extremely large aperture dimensions, up to 100-m and possibly beyond, are now possible. Although rapid progress is occurring in the field, it remains to be demonstrated that adaptive optics will allow the *overwhelming* science objectives of such giants to be realized.

References

1. A. B. Meinel, *An overview of the Technological Possibilities of Future Telescopes*, 1978, ESO Conf. Proc. **23**, 13.
2. L. D. Barr, *Factors Influencing Selection of a Next Generation Telescope Concept*, 1979, Proc. SPIE Vol. **172**, 8.
3. J. E. Nelson, T. S. Mast, S. M. Faber, *The Design of the Keck Observatory and Telescope*, Keck Obs. Report **90**, 1985.
4. J. R. P. Angel, proc. ESO Conf. *Very Large Telescopes and their Instrumentation*, 1988, ESO, Garching, 281.
5. D. S. Brown, 1971, Proc. ESO/CERN Conference *Large Telescope Design*, ESO, Geneva, 273.
6. R. A. Jones, P. L. Kadakia, , 1968, Appl. Opt., **7**, 1477.
7. R. N. Wilson et al, *Towards Fully Automated Optimisation of Optical Quality in Telescopes*, in *Progress in Telescope and Instrumentation Technologies*, 1992, ESO, Garching.
8. R. A. Paquin, *Metal Optics*, SPIE, **T48**, Orlando, 1989.
9. R. N. Wilson, Reflecting Telescope Optics I, 3.6.15, Springer Verlag, 1996
10. L. Jochum, J. Castro, N. Devaney, *Gran Telescopio Canarias: current status of its optical design and opto-mechanical support system*, 1998, SPIE **3352**, 621.
11. R. Müller, H. Höness, proc. ESO Conf. *Very Large Telescopes and their Instrumentation*, 1988, ESO, Garching, 313.
12. H. Morian, R. Müller, proc. ESO Conf. *Progress in Telescope and Instrumentation Technologies*, 1992, ESO, Garching, 47.
13. N. van Dyke, proc. ESO Conf. *Very Large Telescopes and their Instrumentation*, 1988, ESO, Garching, 319.
14. N. Kaifu, proc. Lund/ESO/SPIE Conf. *Optical Telescopes of Today and Tomorrow*, 1996, Landskrona, SPIE **2871**, 24.
15. R. N. Wilson, Reflecting Telescope Optics II, 3.3, Springer Verlag, 1999.
16. P. Dierickx, *Optical Quality and Stability of 1.8-m Aluminum Mirrors*, in *Metal Mirrors*, University College London, 1992.
17. M. Cayrel, *VLT Beryllium Secondary Mirror No 1 – Performance Review*, 1998, SPIE **3352**, 721.
18. M. Deyerler, M. Cayrel, private communications.
19. F. W. Preston, Transc. Opt. Soc. London, 1922, 23.
20. S. C. West et al, *Progress at the Vatican Advanced Technology Telescope*, Proc. SPIE, **2871**, 1996.
21. L. N. Allen, *Results of ion polishing of Keck primary mirror segments*, 1992, OSA Optical Fabrication and Testing Worshop (Boston, MA)
22. E. D. Knohl, M. Schmidt, *Galileo Optic waiting for homing in*, 1994, Proc. SPIE Vol. **2199**, 1079.
23. R. A. Jones, 1978, Appl. Opt., **16**, 218.
24. K. Beckstette, E. Heynacher, Proc. ESO Conf. *Very Large Telescopes and their Instrumentation*, 1988, Vol. I, 341.
25. T. Korhonen, L. Lappalainen, SPIE Conf. *Advanced Technology Optical Telescopes IV*, 1990, SPIE Vol. **1236**, 691.
26. J. R. P. Angel, R. E. Parks, OSA Workshop *Optical Fabrication and Testing*, 1984, Monterey, Cal.
27. J. R. P. Angel, Proc. IAU No. **79** *Very Large Telescopes, their Instrumentation and Programs*, 1984, ESO, Garching, 11.
28. B. Schmidt, Mitt. Hamburger Sternw., 1932, **7**, 15.
29. P. Dierickx et al, *VLT primary mirrors: mirror production and measured performance*, 1996, SPIE Vol. **2871**, 385.
30. J. H. Burge, *Advanced Techniques for Measuring Primary Mirrors for Astronomical Telescopes*, 1993, Ph.D. dissertation.
31. J. H. Burge, *Measurement of large convex aspheres*, 1997, Proc. SPIE Vol. **2871**, 362.
32. P. Dierickx et al, *The Optics of the OWL 100-M Adaptive Telescope*, this conference.
33. F. Carbone, *Innovations make large-segment-mirror telescopes more affordable*, Laser Focus World, Aug. 1998, 229.
34. M. Cayrel, 1998, *private communication*.