400 Years of the Telescope:
Special Feature on History and Development of ESO Telescopes and Instrumentation

The International Year of Astronomy 2009 celebrates the 400th anniversary of Galileo Galilei's construction of a telescope and the cascade of discoveries that have resulted since he first pointed it to the sky.

This special feature celebrates that anniversary with some reminiscences of developments in ESO telescopes and instrumentation.

This feature is produced in conjunction with a special issue of GeminiFocus that celebrates the history of the Gemini telescopes and the people who shaped them.

The Editor

ESO's Telescopes
In memoriam Daniel Enard

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The contributions of ESO to the art of telescope-making have come a long way since the early years, placing it, by the turn of the millennium, among the acknowledged leaders in the field. In this article I will give a brief history of what are, in my view, the highlights among these developments, from the 3.6-metre telescope through the NTT and VLT/I to the E-ELT.

Bridging the gap

In the years after the Second World War it became evident that astronomy and particle physics in Europe had fallen behind the US. In both cases, intergovernmental cooperation was identified as a solution. The European Organization for Nuclear Research (CERN) was conceived in 1949 and created in 1954, followed by ESO, conceived in 1954 and created in 1962. Since then, both organisations have grown to become significant players and even leaders in their field.

ESO's beginnings were not very spectacular. The design of the 3-metre telescope, a goal explicitly set out in the ESO convention, suffered from lack of expertise, especially concerning the mechanics. Patterned originally on the 3-metre Lick telescope, its diameter was increased to 3.5 m to accommodate a more spacious prime focus cage (much to the delight of the rotunder astronomers!). The final diameter of 3.6 m was reached because the blank size allowed it.

The design was a modified Ritchey–Chrétien with exchangeable secondary mirrors and envisaged three foci, as recommended by the Instrumentation Committee: an F/3 prime, an F/8 Cassegrain and an F/30 Coudé. The mirror cell was designed to compensate passively for the deformations of the primary that, even with a thickness of 50 cm, was not stiff enough to avoid flexure due to the changing gravity load during observations: it included thirty independent concentric axial supports (astatic levers) with three pads and a system of air cushions providing the lateral support. Polishing of the mirror and manufacturing of the cell were carried out by the same company, allowing the mirror and cell to be tested as a single unit.

Meanwhile, the pre-design of the mechanics, an interesting mix of horseshoe and fork mountings, resembling the Lassell mount of a century earlier, was progressing fairly slowly, due mostly to the rather understaffed design team. This led to a number of options being considered, including outsourcing the design to some large firms (which was discarded as no firms with the appropriate experience existed) and collaboration with other scientific organisations with experience in managing large projects. Contacts were made with CERN and the European Space Research Organisation (ESRO), and in late 1969 a proposal to collaborate with CERN was submitted to Council. In June 1970, the ESO Council endorsed the creation of a Telescope Development Group, an increase in staff, and the start of the collaboration with CERN. The latter was approved by the CERN Council a week later, and in September a formal agreement was signed. In October the newly named Telescope Project Division moved to Geneva. The collaboration proved extremely positive for the project, and by the end of 1972 the first contracts for the construction of the 3.6-metre telescope were awarded to industry. Four years later, on 7 November 1976, the telescope achieved first light at La Silla (see an example image in Figure 1). The gap with the "competition" had begun to close, although it took until the end of the 1990s to align the telescope properly, and the arrival of a new secondary mirror unit in 2004 to achieve its intrinsic image quality.

An active development

Léon Foucault, he of the famed pendulum, not only invented the modern reflecting telescope around 1857 (using metallised glass mirrors, which he polished hyperbolic so as to compensate for the aberrations of the eyepiece), but also introduced a rudimentary pneumatic support of the primary mirror using support vessels that could be inflated or deflated to allow the mirror to reach its optimal figure. His 80-cm telescope is on display at the Observatoire de Marseille, France.

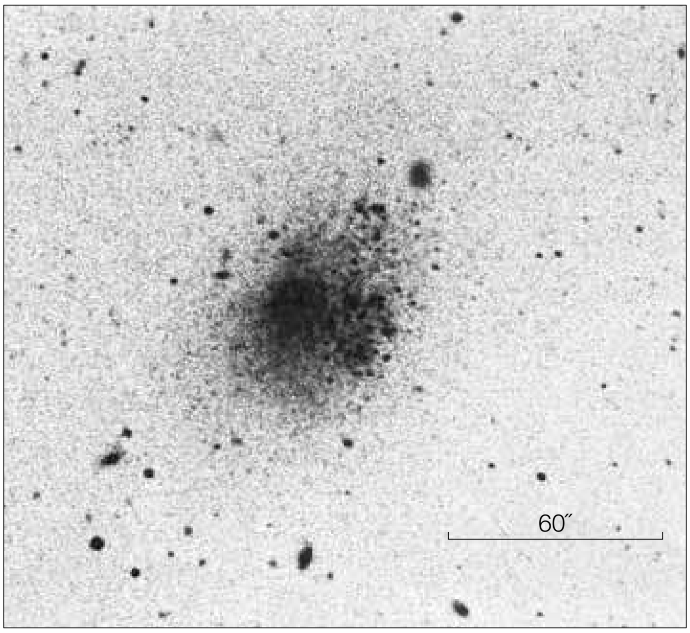

Figure 1. One of the first images obtained at the ESO 3.6-metre telescope prime focus: the Sculptor dwarf galaxy (120-minute exposure on IIIa-J emulsion and taken on 11 November 1976).

It took another 120 years for this concept to mature into one of the most important ESO contributions to the development of the telescope: active optics. The brainchild of Ray Wilson, active optics allows the telescope to monitor its own image quality, correcting automatically for any errors introduced by thermal or gravity deformations. Equally importantly, the technique also allows some of the tolerances of the mirror production to be relaxed without impairing its performance, which in turn allows diameters beyond the 4–5-metre class to be seriously contemplated. The principle of active optics is based on an image analyser that measures the aberrations introduced by any deformations, and then applying compensating forces to the back of the mirror via a series of computer-controlled actuators so that the mirror returns to its optical prescription (while the focus and collimation are corrected by moving the secondary mirror). This happens continuously during an observation without disturbing it. Corrections are applied every few minutes in closed loop. This technique was certified with a 1-metre prototype, and the New Technology Telescope (NTT) mirror has proved to be one of the best ever built (on a par, if not superior, to the Hubble Space Telescope (HST) primary, although both suffered from spherical aberration, but that is much easier to correct with active optics!).

Conceived as a test bed to explore solutions for a future very large telescope (and to ease the demand on the 3.6-metre telescope), the initial specifications for the 3.5-metre NTT were defined in 1980, the year ESO moved from Geneva to Garching (losing many of its technical staff in the process). Following the entry of Switzerland (1981) and Italy (1982) into ESO, the NTT became a "real" project, with a budget about one third that of the 3.6-metre. Its main characteristics were compact design and low weight, to be achieved through a thin, fast F/2.2 primary (40% of the thickness of the 3.6-metre primary) controlled by active optics; altazimuth mounting; a single focus (F/11 Nasmyth, at two locations); and a compact co-rotating building without a classical dome. It also included modular ("maintenance-friendly") electronics. The optical design is of the Ritchey- Chrétien type. Many of these characteristics were later included in the design of the Very Large Telescope (VLT).

The experience gained from the design and construction of the 3.6-metre telescope (as well as a number of smaller ones, e.g. the MPG/ESO 2.2-metre telescope, where remote observing was tested in 1986) reinforced by an increase in technical staff, enabled the project to progress more smoothly, first under the direction of Ray Wilson and later, from 1984, of Massimo Tarenghi. The NTT telescope was fully assembled and functionally tested in Europe before being shipped to La Silla in the spring of 1988. Erection of the enclosure was already advanced by then, the telescope was integrated and testing started later that year. The NTT achieved first light on 22 March 1989, with an image quality of only 0.33 arcseconds.

That the NTT image quality was indeed outstanding I learned from personal experience. In December 1989 I was at La Silla to search for the suspected ring around SN 1987A using the 2.2-metre telescope with an instrument developed at the Space Telescope Science Institute, where I was working at the time. The instrument had a photon counting array that provided the position and time of arrival of each photon, and the idea was to try to reconstruct a high spatial resolution image from this information (a sort of *post facto* speckle imaging). The night before my run I was invited by Massimo Tarenghi to visit the NTT control room during a commissioning run. A short observation of SN 1987A was taken "in my honour", and to my great astonishment as the image appeared on the screen, the ring was clearly visible in the 0.4 arcsecond picture (see Figure 2). My observing programme became obsolete then and there, but this was more than compensated for by the spectacular confirmation of the existence of the ring!

The NTT was not a milestone towards the realisation of the VLT in technical terms only. In 1993, on the advice of an *ad hoc* committee, it was decided to upgrade it to achieve its full potential. In what was called the "NTT Big Bang", an activity led initially by Dietrich Baade and then by Jason Spyromilio, the upgrade included replacing the old control system by the VLT one. This allowed the VLT control system to be brought up to full functional status well before the start of VLT commissioning, which represented an enormous advantage both in terms of the understanding and experience that were gained, and of time.

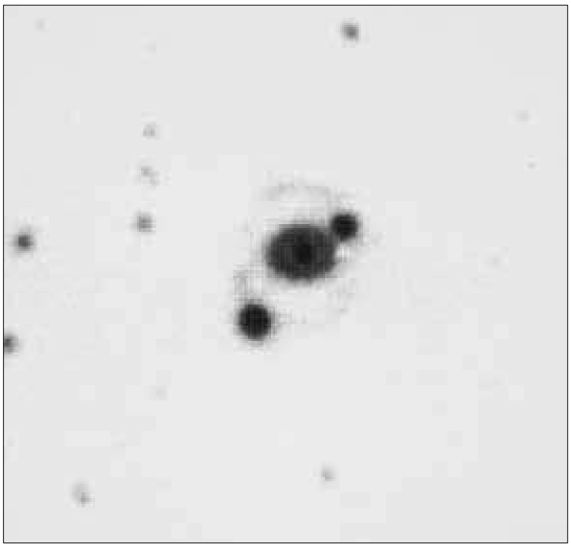

Figure 2. One of the images of SN 1987A taken at the NTT with EFOSC2 on 18 December 1989 (see Wampler et al., 1990).

The science machine

As early as 1978, well before the NTT had even been conceived, ESO started thinking about a Very Large Telescope. The solutions contemplated by the working group, chaired by Wolfgang Richter, included a single 16-metre telescope and arrays of four 8-metre and sixteen 4-metre telescopes. A second working group, chaired first by Ray Wilson and later by Jean-Pierre Swings when Ray took over the NTT project, was appointed in 1981. Its work concluded with the Cargèse workshop in 1983 where the preferred option (among the three proposed by the first working group, plus that of a multi-mirror (MMT-like) telescope) was presented: an array of four 8-metre telescopes. This had been the favourite since mid-1982 (and indeed the reference for the decision of proposing the NTT as a prototype for active optics) on the basis of its scientific advantages, including the potential for inteferometric combination (albeit dependent on the as-yet not well-established use of adaptive optics). The workshop endorsed the choice, and a project group was set up at ESO under the leadership of Daniel Enard. An external committee chaired by Jean-Pierre Swings provided supervision.

The project group started by looking at the same options again, but now from an engineering point of view. Although both the segmented single telescope and the MMT options were considered attractive, the 8-metre array design proved superior to both because it built on the experience ESO was developing in active optics and because it was more flexible (construction could be timed to reflect the current resources, each telescope could be offered to the community as it was completed, and the interferometric combination could be implemented when the appropriate technology became available). Interaction with industry and the community quickly determined that an 8-metre monolithic, thin (hence active) mirror was feasible and that a low cost enclosure concept and an efficient beam combination could be developed. This led to the "linear array" concept that became the baseline for the VLT (see Enard, 1987).

Setting the example currently being followed in the European Extremely Large Telescope (E-ELT) Phase B, a number of competitive design/feasibility contracts were placed with industry (with others carried out in-house). This allowed different solutions to be explored and accurate cost estimates to be obtained, advancing the project considerably. In 1986 it was presented at a dedicated conference in Venice, achieving a large consensus. By early 1987 a proposal for construction had been prepared and distributed to the ESO governing bodies.

On 8 December 1987 the ESO Council gave the green light to the start of the project. The Council decision was courageous, displaying both forward-looking vision and trust in the executive (the NTT was still more than one year from first light at that time!).

Thus began the great adventure of the construction of the VLT. Each Unit Telescope is a Ritchey–Chrétien with an F/1.8 primary and equipped with four foci (F/13.4 Cassegrain, two F/15 Nasmyth and F/47.3 Coudé). Each primary takes full advantage of active optics, and, with a thickness of 175 mm, is some 40 times more flexible than the NTT mirror (which was conservatively sized so as also to be able to function in passive mode). In particular, this flexibility allows the focus to be switched between Cassegrain and Nasmyth by changing the conic constant of the primary. The secondary is a lightweight beryllium mirror with five degrees of freedom and is used for many functions: to focus and collimate the telescope as part of the active optics control loop; to maintain the pointing of the telescope; to field stabilise the focal plane, thus rejecting vibrations induced by wind and motors; as well as to chop and nod when observing in the infrared.

Contracts began to be placed with industry for the long-lead items (e.g., the primaries) while options were still being explored for other subsystems (e.g., the dome, whose design was selected in 1991, the year the top of Paranal was flattened to create the necessary area). Some technical problems occurred with some of the contracts (e.g., the secondary mirror), but the project, from 1987 under the leadership of Massimo Tarenghi, with a brief tenure by Joachim Becker in 1991, progressed at a healthy pace. The interferometric infrastructure was being redefined, increasing the number of delay lines and auxiliary telescopes to allow phase closure, thanks also to special contributions by France and Germany (later supplemented by Belgium, Italy and Switzerland for the production of a fourth Auxiliary Telescope). The final location of the Unit Telescopes (UTs) on the Paranal "platform" was defined so that when used as an interferometer the best coverage of the uv plane could be achieved (within the constraint of mutual vignetting by the domes). Civil works, lead by Joerg Eshway, progressed steadily on the mountain, notwithstanding the "La Torre family incident" in 1994.

Figure 3. VLT FORS image of the spiral galaxy NGC 1232 taken during commissioning on 21 September 1998. This image was voted amongst the ten most inspiring images of the century (Sky and Telescope, January 2000).

By 1996 all primary mirror blanks had been delivered, and the Observatory was beginning to take shape: the erection of the main structure of UT1 had started at Paranal, while a complete UT had been installed and tested functionally in Europe. The first secondary mirror blank had been completed, and the first enclosure was nearly complete.

First light of UT1 was achieved on 25 May 1998, after the heroic efforts of the Acceptance, Integration and Verification (AIV) team lead by Peter Gray had succeeded in fully integrating the telescope. Commissioning of the telescope under the leadership of Jason Spyromilio came next, while I started defining the science operations scenario for the Observatory: in this capacity I was privileged to witness first light, and to share in the excitement of that memorable event (see Tarenghi et al., 1998). By April 1999 the telescope and its two first instruments FORS1 and ISAAC had been commissioned, and operations of UT1 started. The following years saw the completion of the other telescopes and of the interferometer infrastructure. By September 2000 all telescopes had seen first light, and in March 2001 the first fringes had been detected by the interferometer combining the light from two small siderostats.

The VLT represents the crowning achievement of ESO in the field of telescope-making. Thousand of man-years of effort by ESO and its contractors were invested in this success, and today the Paranal observatory — with its four 8-metre telescopes, four 1.8-metre ATs, the almost complete VLT Interferometer (VLTI) and the VLT Survey Telescope (VST) and the VLT Infrared Survey Telescope for Astronomy (VISTA) telescopes soon to enter service — is the leading astronomical facility in the world, serving more than 4500 astronomers and producing an average of two refereed papers per day, the highest scientific output of any observatory anywhere.

This success is due, in my opinion, to a number of factors, among which I would like to emphasise the tight collaboration with industry, the professional management methods, the professionalism and enthusiasm of the staff and the integrated system design that includes an end-to-end scientific approach for its operations. The VLT was designed to be a proper interferometer, and new results will start appearing after the current commissioning of the PRIMA facility concludes. With its low technical downtime and high scientific efficiency, the VLT can truly be considered a science machine!

The future

In 1998 ESO began analysing the concept of an extremely large telescope, a 100-metre behemoth called OWL (for the eponymous bird's keen night vision and for being OverWhelmingly Large, a marvellous name coined by the project manager of the OWL studies, Philippe Dierickx). The OWL was based on a spherical primary that allowed the advantages of mass production to contain costs, but at the expense of a complex optical design to correct for the enormous spherical aberration introduced by the primary. The OWL had a Phase A review by an international panel in November 2005. The review panel judged the project feasible, but identified some technical risks that might affect the schedule and the budget and recommended that the project proceed to Phase B, but that a smaller size be considered to mitigate the risks and to contain the budget.

What followed was the definition of a European Extremely Large Telescope that involved extensive community consultation through five panels established by the ESO Director General in late December

2005 on the topics of science, site, adaptive optics, instrumentation and telescope. The conclusions of the ELT Science and Engineering Working Group (composed of chairs and co-chairs of the panels and chaired by Daniel Enard) was a toolbox to be used as a guide for the ESO ELT Project Office (created 1 June 2006) for the definition of a basic reference design that could be presented to the community and the committees of ESO. The premise underlying these activities was the December 2004 strategic resolution of the ESO Council that requires that the organisation develop a facility that will address the exciting science awaiting us in the coming decade and will be competitive in timescale and performance with similar facilities planned elsewhere.

The work by the ESE panels and the Working Group represents a remarkable success of the community. This, not only for having been able to produce the toolbox (consisting of several hundred pages of reports) in just a few months, but above all for demonstrating the ability to converge to a unified set of requirements and to a unified concept. The specific goals to be addressed in the design were that the E-ELT should have a primary mirror of 42 m in diameter (considered a good compromise between ambition and timeliness), the primary should preferably not be spherical, the telescope should have adaptive optics built into it, and should deliver a science field of view of at least five arcminutes in diameter with a strong preference for larger fields. Furthermore the telescope was to provide multiple stable observing platforms and have a focal ratio favourable to instrumentation.

Additional inputs to the design of the telescope came from the conclusions of the OWL review. The panel had recommended that certain high risk items present in the OWL design should be avoided in the next iteration of the design. Double segmentation (on OWL the primary and secondary were both segmented) and the high complexity of the adaptive mirror (in OWL the 6th mirror combined field stabilisation and adaptive corrections in a single unit) were considered risks that would delay or jeopardise the project. The fast focal ratio of the telescope (F/6), the absence of gravity invariant focal stations, and the concept

Figure 4. Simulated E-ELT image (bottom) compared with the same view by HST (top) and by an 8-metre diffraction-limited telescope (centre).

of open-air operation were also on the list of things to be avoided in the redesign.

On the advice of the ESE working group, during 2006 the ELT project office at ESO analysed two designs of a fully adaptive telescope — a Gregorian and a novel five-mirror design proposed by Bernard Delabre (an on-axis three mirror anastigmat with two additional flat mirrors conveniently located to serve as adaptive optics and field stabilisation mirrors). The anastigmat design provides excellent image quality (diffraction limited over the full 10-arcminute field of view), is almost free of field curvature, has the exit pupil concentric with the focal plane, can adapt its focal length to the different foci in a way similar to the VLT's, and introduces minimal aberrations in the wavefront from laser guide stars.

Eventually, the notion of an adaptive telescope may one day be seen as a natural evolution of telescope design. As size increases, so does the potential resolution, and atmospheric turbulence becomes just one more error source (admittedly a major one) the telescope must deal with. Indeed, with the E-ELT the boundary between adaptive and active optics becomes blurred, if there at all.

A detailed trade-off between the two designs was performed and presented to the ESO committees and to the European community at the Marseille conference in December 2006 (Hook, 2007; Monnet, 2007; Cuby 2007). On the basis of the industrial studies it appeared that the complexity, cost and schedule risk of a 4.8-metre Gregorian deformable secondary mirror would seriously endanger the project. While the 2.6-metre deformable mirror of the five-mirror design is anything but straightforward, the industrial proposals for its construction placed it far from the critical path with a number of alternative solutions. The 3-metre field stabilisation mirror (M5) is also far from simple. Another major challenge for the five-mirror design is the 5.7-metre secondary mirror. Polishing such a convex mirror (actually it is the testing rather than the polishing) requires some innovative approaches, but industrial suppliers have confirmed that it can be achieved.

The advantages of the E-ELT five-mirror design in separating the field stabilisation function from the adaptive mirror, providing an instrument-friendly focal plane and being laser-friendly, make it a very attractive design. The two additional reflections of the five-mirror design are not expected to contribute dramatically to the total mirror count before the photons arrive at the instrumentation detectors. The Project Office is looking into novel coatings that are currently under development and can further mitigate the effect of more reflections. Another significant advantage of the E-ELT design is that, the telescope is well configured to take advantage of future enhancements in the technology of deformable mirrors. The cost of an upgrade to a higher density of actuators, when this becomes feasible, would be comparable to that of a novel instrument and could be deployed in a similar or even shorter timescale. In the Gregorian case the cost and schedule of such an upgrade could be prohibitive.

The ESO committees and the community unanimously supported the choice of the five-mirror design, and of the 42-metre size, and recommended the start of the detailed design phase.

In December 2006 the ESO Council resolved that ESO should proceed into Phase B with the aim of having a proposal for construction ready to be submitted to the ESO Council in late 2009 or early 2010. The resources allocated to Phase B are 57.2 M€ including manpower costs.

During Phase B, contracts have been placed with industry for the advancement to preliminary design status for all major subsystems. Contracts are in place for the development of the main structure, the dome, the adaptive mirrors, the tip-tilt unit and the primary mirror support. Several prototype mirror segments are being procured and polished to the specifications of the project. Integrated modelling, development of concepts for the control system, the mirror cells and the adaptor rotators (now called pre-focal stations) are ongoing, as is the design of the secondary unit. For critical subsystems where more than one technology exists or where more than one approach is possible, multiple contracts have been placed. At the present time, more than 90% of the Phase B budget has been committed. See Spyromilio et al. (2008) for details.

Phase B is supported by the EC-sponsored (Framework Programme 6) ELT-Design Study (DS) work that started in 2005 as a pan-European design independent R&D activity, but was aligned to the E-ELT design at the end of 2006. Many of the ELT-DS results have been folded into the Phase B activity. Further supporting activities are being carried out under an FP7-sponsored “preparation for construction” activity.

Supervision for the project is provided by the E-ELT Science and Engineering subcommittee of the Scientific Technical Committee (STC) chaired by Tom Herbst, by the STC itself, and by the ESO Council's ELT Standing Review Committee chaired by Roger Davies. A Site Selection Advisory Committee will advise the Director General about the site choice, to be made within a year.

Phase B has just passed its mid-term review after a number of internal reviews consolidated the baseline reference design, and is on track for submitting a construction proposal to the ESO committees and Council by autumn 2010 after a construction review that will take place in September 2010.

Acknowledgements

During the past 40 years ESO has regained a competitive level for European ground-based observational astronomy, has pioneered new technologies and new operational solutions, and is poised to take the lead in the design and construction of an extremely large telescope. This has been made possible by the combined efforts of its staff members. Acknowledging all who have contributed would require the whole ESO organigram during the past 40 years to be reproduced!

Daniel Enard, who contributed so much to the development of the VLT and to helping us set the course for the E-ELT, passed away on 2 August 2008. He is sorely missed. An obituary can be found in Messenger 134 (Cullum, 2008).

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