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PREVIEW

Telescopes 2

ELT Control (partial)

INSIGHTS, STORIES AND EXPERIENCES

from ten years of reporting on science and engineering

MARKUS VOELTER

Introduction. Controlling 10,000 tons of steel and glass spread over a thousand mirrors, moved and positioned by 20,000 actuators, plus a total of 60,000 input/output data points, to micrometer precision at (in some places) up to a kilohertz is a seriously non-trivial task. Let's try to get a grasp of how to tackle this challenge. We will look at how to form a working telescope from all the optical components, and also at the bigger picture—the systems engineering of the control system.

The first order of business is to break the overall system down into subsystems that have some degree of autonomy in terms of how they are controlled: modularization is not just best practice in software, but also in systems engineering. The most complex subsystem is the optical path itself: there are several separate but closely synchronized control loops, with rates from 0.01 Hz to several kHz. Some of these loops have significant computational and bandwidth requirements. For example, the adaptive optics requires 700 Gflops of computing power and realtime data rates of up to 17 GB/s. Overall, this is a control task with many thousands of degrees of freedom.

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The MELT and the PDS. Let's look at the control of the optics in more detail. There are two main aspects: the alignment of the 798 segments of M1 to produce one 39-meter virtual mirror, and the control of the other four mirrors to form a precise optical path. A team of five engineers is currently developing the control strategy for both—which they have to do without an actual telescope. As a subsitute they have developed the Mini-ELT (aka MELT), an optical bench setup that has all the important components of the future ELT.

Central to the MELT is a 15-cm mirror built out of 61 hexagonal segments. It has been developed as part of ESO's Active Phasing Experiment, which was on sky as an "instrument" on the VLT. It also had various kinds of wavefront sensors, to evaluate their capability to detect the aberrations produced by a segmented mirror.

The MELT's optical path then has a hexapod-positionable lens that emulates M2, a deformable mirror for adaptive optics that corresponds to M4, as well as a fast tip/tilt mirror that simulates M5. M3 is omitted, because it does not play an important role in the control strategy. A movable light source that emits radiation in the relevant wavelength range through a turbulence generator emulates the ELT's main axes and the atmosphere. The MELT also has ways of introducing some of the aberrations that the ELT will exhibit naturally, such as beam instability due to pupil movement as the telescope moves across the sky.

The MELT serves three purposes. One is to understand the aberrations of the ELT's optical path and develop optical components to diagnose them. For example, the MELT has various kinds of wavefront sensors that work in different wavelength ranges and detect different kinds of aberrations, plus several cameras. Once understood, this will help with the design of the Phasing and Diagnostics Station (PDS), a simplified "instrument" that is inserted into the optical path to help calibrate the ELT. The PDS is small enough to be calibrated on the bench using lasers, sighting telescopes and other lab-size equipment; it then acts as a pre-calibrated reference during calibration of the full telescope. The second goal of the MELT is to define an approach to commissioning the telescope. What steps must be taken to get from a telescope that is initially aligned only to mechanical tolerances to one that has the necessarily precise optical path? What algorithms are necessary, and how will they exploit the PDS? The third goal is to validate the control strategies, a set of software algorithms that maintain the telescope's focus and pointing during an observation. The MELT has the same software interfaces as the future real telescope, which means that the control programs can be adapted with very little effort after they have proved their efficacy on the MELT.

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Phasing M1. Let's understand how to make sense of the main mirror. Initially, its 798 segments are installed to mechanical tolerances for piston, orientation and shape. Consequently, each segment will project its own separate image of a point source instead of one integrated, focused point (the purpose of a large mirror is of course to collect lots of light and project it all onto one bright image). And each projection will probably be a donut instead of a point, because the telescope will initially be out of focus. Based on calculations, the team expects that all these donuts will be distributed over a five arcminute area in the focus. Initially it will be unclear which mirror segment creates which donut, because of the random orientation of each segment. As the telescope follows the sky, each donut will move and warp in undefined ways, because there will not yet be a pointing model, no understanding of how gravity impacts the alignment and shape of each segment.

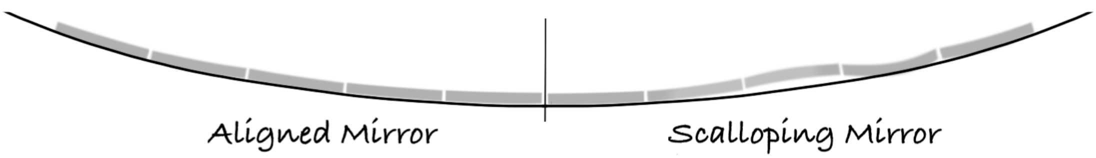
To "assemble" an integrated M1 from this disjointed collection of 798 separate 1.42-meter mirrors, the first step is moving M2 up and down to get the telescope into focus as much as possible—to get the donuts to better approximate points.

Step two is called "segment capture". The goal is to identify which segment produces which donut. As Thomas Pfrommer said in our interview, "We have to develop an efficient algorithm that wiggles each mirror and observe the changes in the image plane. Initially we cannot even use the PDS, because it can only see the central arcminute. We plan to put a 2 x 2-meter screen at the focus of the telescope and then use basically a better webcam to capture the image."

Once captured, the segments have to be stacked: the goal is to ensure that all 798 segments project their image exactly on top of each other. Assuming they all project to the central arcminute, stacking can be done with the PDS using its wavefront sensors and the algorithms developed in the MELT.

To understand the position and attitude of each segment relative to its neighborhood, each segment shares 12 contactless inductive edge sensors with its six neighbors. These sense differences in piston, gap and along-edge with picometer accuracy. They are glued to the segments, and one challenge is to make sure that the glue does not creep too much over the years. Statistical approaches are used to detect edge sensors that report unreliable data and cut them out of the control loop until they are repaired.

The next step is coherencing, which means that the segments are positioned so as to align their wavefronts to within one wavelength, around 700 nm. This mostly means moving the segments in piston and using the edge sensors to detect offset. For seeing-limited observations, where the atmosphere determines the resolution of the image, a coherent M1 is good enough. However, for diffraction-limited observations, where the telescope has to perform at the limit of its optical performance, the segments have to be aligned even more precisely such that even the phase of all segments is aligned. To achieve this level of precision, it is no longer enough for the segments to be aligned perfectly in piston and position; the shape of each segment has to fit with the ideal shape of the virtual 39-meter mirror. An error called "scalloping" describes the situation in which the edge sensors are all within limits but there are still low-order deformations over the whole surface.



Such deformations lead to errors in the wavefronts not unlike those produced by the atmosphere: the angle at which the light hits the sensor changes. Consequently, errors from deformed segments can also be detected in the same way, using wavefront sensors. The PDS has lots of them to help "phase" M1. The warping harness underneath each segment mirror is then used to adjust the shape of the glass of each M1 segment until the wavefront sensors are happy. You might wonder why the (probably not yet corrected) atmospheric distortions don't disrupt the phasing of M1. The reason is that the wavefront errors that result from the atmosphere are at different granularities than those produced by a scalloping M1. In addition, the atmosphere wobbles: the patterns change quickly over time. Errors from M1, however, change only very slowly as the telescope rotates.

Once the PDS has been used to diagnose the mirror, and the positions and shapes of all segements have been adjusted, the respective settings are stored in huge lookup tables. During observations an open-loop control system based on these tables keeps the mirror roughly "in shape"; a second-level finer-grained closed control loop relies on the wavefront sensors in the adapter probes mentioned earlier. The calibration has have to be performed for the different elevation angles, because of the varying direction of the gravity vector. Because of drifts in sensors and other accumulating errors, the team expects that it will be necessary to "rephase" the mirror every two weeks once the telescope is operational.

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Controlling M2 through M5. The approach for controlling the position of M2 also relies on the wavefront sensors: if the mirror is out of position it produces characteristic wavefront errors that are different than those produced by, for example, a non-phased M1. The PDS can detect these and instruct M2's position actuators to correct them. Once again the parameters are put into elevation-dependent lookup tables, and used by a relatively slow open-loop controller that keeps the position of M2 stable during an observation—because of its position roughly 40 meters above M1 it is especially sensitive to elevation-induced bending.

M3 is not expected to be actively controlled during regular operation. Because it sits near the bottom of the telescope, its mount is much stiffer, and no need for elevation-dependent correction is expected. It does have actuators through, because during commissioning, of course, its shape and position has to be determined and adjusted.

Just like the segments of M1, the six petals of the adaptive M4 have to be phased: M4 has its own control system to achieve this phasing, but the PDS can detect the resulting characteristic wavefront errors as well, for example, using pyramid wavefront sensors in the infrared band.

M5's main task is to reflect the light out to the Nasmyth platform that hosts the PFS and the instruments, but it also corrects the wind shake of the exposed M2 using a fast tip/tilt mechanism. The control strategy uses data from accelerometers in M2, but it also receives input from the wavefront sensors in the instrument or the PDS; specific patterns are characteristic of M2 wind shake. M5 is also involved in M4's adaptive optics. The voice-coil actuators in M4 have limited range; they are optimized for speed, not travel. So when the M4 actuators get close to their range limits, the tip/tilt mechanism in M5 is used to offset M4, effectively giving back travel to the voice coils.

As we have seen, errors in the alignment of each mirror in the optical path lead to characteristic patterns in the wavefront, which are detectable by the PDS. If it turns out that the differences are not distinctive enough, another means of disentangling the aberrations produced by the various mirrors is available. If you look at the optical path diagram shown previously, you can see that there is an intermediate focus between M2 and M3, more or less at the location of M4. There are provisions for placing an artificial light source at this location. This would allow the impact from M1 and M2 to be separated from the M3-M4-M5 train.

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