Development of breakthrough technology for building next generation ground based telescopes

SUMMARY

Mass production and control technology now exists to build telescope primary mirrors out of panels consisting of a large number of small agile segments that will correct directly for atmospheric turbulence, wind-shake and the effect of deformations in the telescope structure. Successful development of this technology will enable AO telescopes to be built that are light, compact, failure tolerant and deliver 100 nm class wavefront error at the focal plane without use of an adaptive secondary mirror. There is no obvious limitation to the size of telescope that can be built with this technology. A 25 meter version is estimated to cost $250M and could be built within the next decade. Initial investment at a level of $20M over 4 years is necessary to validate the technology.

Current State of the Art

The biggest telescopes in the world use either monolithic, lightweighted mirrors (LBT) or an array of 1.8-meter size segments phased using edge sensors (Keck Observatory). Designers of the next generation of telescopes have concentrated on scaling up these existing designs. However as the size of the telescope increases the effect of gravitational distorting forces and wind loading on the mirror becomes increasing severe; these problems drive up the price and technical risk to the project. The current cost of TMT and GMT together is $1.5B and they will require most of the current NSF budget in optical astronomy to operate. These telescopes are designed to operate from UV to Far IR and provide everything from wide field seeing limited observations to coronographic observations of exo-planets.

Astrophysics is moving to an era in which statistical surveys of large numbers of faint objects are required to distinguish between the increasing detailed theoretical models of the evolution of the universe and galaxies. These projects require high spatial resolution and almost certainly more time than will be available using TMT and GMT. We need to build not just bigger telescopes but <u>more</u> telescopes of large collecting areas, with reasonable, but perhaps not diffraction limited, correction of atmospheric turbulence over the widest possible areas, that are affordable to build, simple to maintain and available to the general community. More than ever, advances in observational capabilities are going to be driven access and cost and will require innovation to achieve breakthroughs in telescope technology. This is immensely challenging; the cost of a telescope is the sum of its parts and even dramatic reduction in the cost of one of the system component, such as the primary mirror, may not significantly impact the overall cost. Breakthroughs have to be made at the system level.

Is Breakthrough technology possible?

It has been argued that no alternative technology exists for building the next generation of telescopes and that to even seek alternatives is to divert effort and waste resources. However, over the last century or more every increase in telescope size by a factor of two has relied on using a new approach in technology, simply because it was too expensive to use existing technology. The current ELT designs are already near their limit in size and affordability. They attempt to produce a perfect primary mirror surface, (except possibly at the largest spatial scales), and then try to correct the effects of the atmospheric turbulence by deformable optics between the primary mirror and the instrument. The effect of wind and structural deformation then determines how large a telescope can be constructed and its ultimate performance.

In general, the overall weight of the telescope and size of dome are important factors in reducing cost. The weight of a telescope of given aperture is driven by the weight of the primary and secondary optics, while the size of the dome is driven by the F-ratio of the telescope and the level of wind loading that can be handled by the primary and the telescope structure. For a given support structure and mirror design, the mass per square meter of the primary mirror scales as d^2, where d is the segment size; the amount of material we must remove to correct for the astigmatism of an off-axis, spherical mirror scales as $d^2/(F^3 D)$ and as $d^3/(D^2F^3)$ for Coma and the alignment tolerance for skew of the segments on the backing structure are also reduced for smaller segments. The choice of segment size for TMT and ESO is 1.44 meters, each segment weighing about 120kg/m^2; GMT uses 7 x 8.4 m mirrors each weighing 16 tons (300 kg/m^2). Each servo controlled actuator supporting the glass has to move about 40 -100 kg, depending on the telescope design. Reducing the size of segments by a factor of two does not appear to bring much benefit if conventional manufacturing techniques are used and the actuators still need considerable forces to move the segments.

However, as the segment size is reduced to ≈ 0.3 meter, new methods of fabrication and testing and support are possible and the use of small, agile segments impacts almost every aspect of telescope design. The high bandwidth of the segment controls system ($\approx 10^2$ Hz) means that the control system not only automatically corrects for gravitational and wind deflections but also for atmospheric turbulence and essentially decouples dependence of the primary mirror shape on the stability of the backing structure. Smaller segments allow construction of a lighter telescope using high damping composite materials, dome size can be minimized because the effect of wind on delivered image quality is less, we do not have to build an additional AO system , the number of elements in the optical train is minimized. At these sizes we can also literally mass produce light weighted segments and support structures, only needing to take out astigmatism by stressed lapping, and can support the segments astatically using low cost, highly reliable voice coils. These segments can then be assembled to form panels of convient size (typically 10 m^2) for installation on the telescope. This is not just then a means of making lower cost primary mirrors but effects all aspects of the telescope design and cost; it is a truly breakthrough technology and it is how the next generation of telescopes will be built. An example of a telescope design for a 25-meter telescope using this technology is given in the appendix.

ELTs in Antarctica

Most of the best sites on earth have similar characteristics but, for certain sites in Antarctica, the diffraction limited field of view for an infinitely large telescope equipped with adaptive optics is 10 times larger in area than at Mauna Kea (the best low latitude site) and the Fried parameter may be twice as large (good). The average wind speed is much lower than at low latitude sites, which translates to low bandwidths for the adaptive optics system (< 20Hz @ 0.7 μm wavelength) and low windshake in the telescope structure. Because of the low temperature of the site, the sky background at wavelengths from 2.2 to 10 micron region is at least an order of magnitude smaller than all lower latitude sites. These factors together mean that a 10-meter telescope at such a site would collect data <u>at least</u> ten times faster at infrared wavelengths than a 30-meter telescope located at the best low latitude site despite the great different in size. At these sites, the sky is clear for 75% of the time with 24hour/day observation during the winter.

Building a telescope in Antarctica raises difficult engineering and logistic issues: the site is remote and cold; construction can only be carried out for a few months/year. The University of Chicago has been involved in building and operating telescopes at the South Pole for nearly 20 years and it is this background of experience that suggests that large telescopes can be built on in Antarctica, provided the telescopes are suitability designed. John Carlstrom has already has already deployed a 10 meter Far-IR telescope at the South Pole whose surface is maintained to an accuracy of microns without the use of active control and is of similar weight to the proposed telescope. The highly modular nature of this telescope design will spend up on-site construction and overcome the big problem of frosting, which iscaused by the high positive thermal gradient (order 0.2-0.4 degree/m) existing near the surface of the ice sheet. Any surface colder than ambient temperature gets covered in frost. A large isothermal mirror therefore suffers either from mirror seeing, frosting or both. The size and low thermal time constant of small segments is the only technology capable of producing diffraction limited imaging under these conditions without frosting.

Funding and Investment levels

All new breakthrough technologies require high-risk funding to determine the viable and full potential of the concept. The key issues to be solved are:

(1) Can we design and build a segment with the required control bandwidth and freedom from deleterious resonances internal to the segments themselves?

(2) Can we figure and trim a segment so that the optical quality of the surface is maintained to 1mm of the edge of the segment?

(3) Can we operate a number of segments together on a compliant backing structure at interesting bandwidths? How does the system performance compare with theory?

(4) Can we design and bread board a wavefront sensing system that will be able to provide adequate control signals to the segment controllers?

(5) Can we build a control system that is sufficiently robust to detect and correct for bad measurements and pupil obscuration by the secondary support structure

(6) Can we fabricate segments at an adequate rate?

Major thrusts in developing the technology

(1) Simulation the operation of a large telescope by demonstrating in a laboratory setting the real-time control of a number of segments in a panel and a large number of rafts on a compliant optical support and compare the experimental results with a theoretical simulation. The work requires integration of a number of diverse skills, including the mechanical design of the segments; the specification of the segment position; the wavefront sensing; the adaptive optics control of the test bed; the development of verification techniques; and the development of the innovative theory needed to solve the multidimensional, coupled, control problem. In the end, we will produce a credible estimate of the expected telescope system wavefront error and estimate how it depends on the key system design parameters.

(2) Design a wavefront sensing system that can provide the signals used to control the actuators. This requires us to design an AO control system that uses tip/tilt and edge sensing data together to form a minimum variance model of the wavefront error and can cope with bad data or actuators and obscuration of parts of the primary mirror by the secondary support structure. We will present a conceptual design of this system, together with a plan to validate the concept, in the proposal.

(3) Build a full-scale panel made up of of order 36 segments and demonstrate its performance

Budget

A full cost breakdown with appropriate management information will be given in our proposal. We summarize the estimated funding profile below.

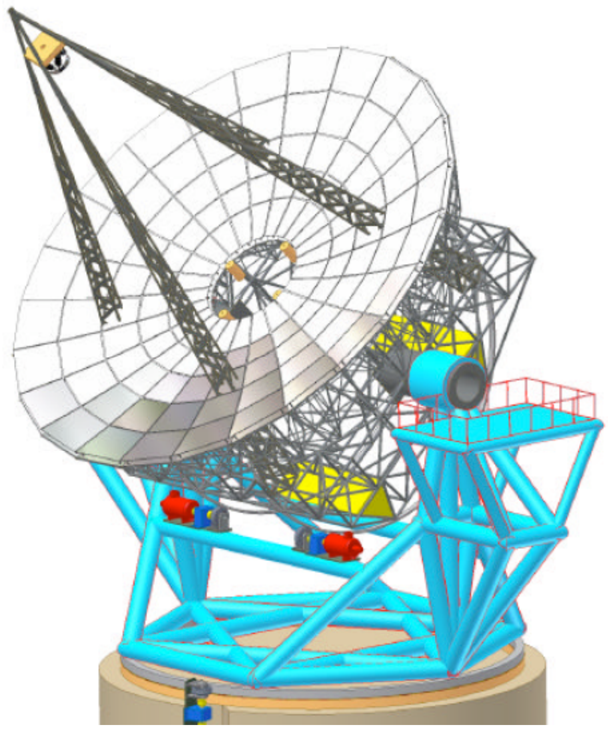
Funding Profile (Thousands of dollars)

Function	Year 1	Year 2	Year 3	Year 4	Total
Core Design Team	500	1100	1200	1200	4000
Workshops	200	200	150	150	700
External Studies	450	800	900	700	2850
Breadboard Construction	200	1200	4200	3000	8600
Contingency	150	500	750	650	2050
TOTAL	1500	3800	7200	5700	18200

This requires a 4 year program at a cost of $18.2M to develop the technology to a level where we can build and test a panel.

The parts of the program with highest risk are in the segment fabrication and control. These are also relatively low cost. We estimate that $2M would be able to determine how well we can fabricate and control single segments and measure their shape as a function temperature.

APPENDIX: ATLAS (Adaptive Telescope using a Large Array of Segments) reference design summary.



ATLAS is designed as an adaptive primary mirror telescope, providing a 400 nm wavefront error over a 1 arcminute field using a single laser beacon and a 120 nm error over smaller fields when used with a laser constellation. Correction over wider fields will be possible with additional conjugate correction surfaces. ATLAS has a circular entrance pupil 25 meters in diameter with a central obscuration of 5 meters and primary mirror focal length of 20 meters. The primary mirror consists of 84 panels arranged in a radial configuration. Each panel will support between 38 and 72 segments each about 0.3 m square. The primary mirror therefore consists of 4944 segments, each controlled in tip, tilt and piston to provide ~10^4 degrees of freedom. Each panel will weigh about the same as a single segment of the Keck telescope (400 kg) and will be about 6 m^2 in area.

ATLAS Specifications

Telescope aperture	25 m
Primary F/ratio	0.8
Secondary F/ratio	16
Aplanatic Gregorian field of view	20 arc minutes
Number of panels	84
Typical segment size	0.3125 x 0.3125m
Typical segment mass	2 kg
Number of segments	4944
Computing Requirement (total, distributed)	900 Gops/sec
Delivered wavefront distortion (0.6 " seeing)	120 nm

SUMMARY OF REFERENCE DESIGN

Segment design

The reference design uses light-weighted segments approximately 0.3 m square and 0.05 m thick made from borosilicate glass and supported on six points by three wiffle trees. Each segment weighs 2 kg and the support + drive system another 2 kg. The drive is astatic and dissipates only 100 mw/segment under no-load conditions, which is significantly less than the heat output of the segment as it cools during the night. Because the support system is astatic, motion of the backing structure is only weakly transmitted to the segment; the backing structure's function is to maintain the approximate position of the segments and to dissipate the energy. This characteristic enables the significant savings in weight and cost of the support system and moving elements of the telescope but can potentially introduce coupling between the segments. If one segment position is changed in a step displacement, its control system applies forces to the segment and reaction forces are transmitted to the backing structure and thence to its neighbors. This effect, however, is small, as is illustrated in Figure 1, which shows the closed-loop response of one segment to a step displacement and the corresponding motions of the 5 nearest neighbors. Backing structures with high damping are desirable for this application and ATLAS will use a carbon-fiber backing structure to support the segments.

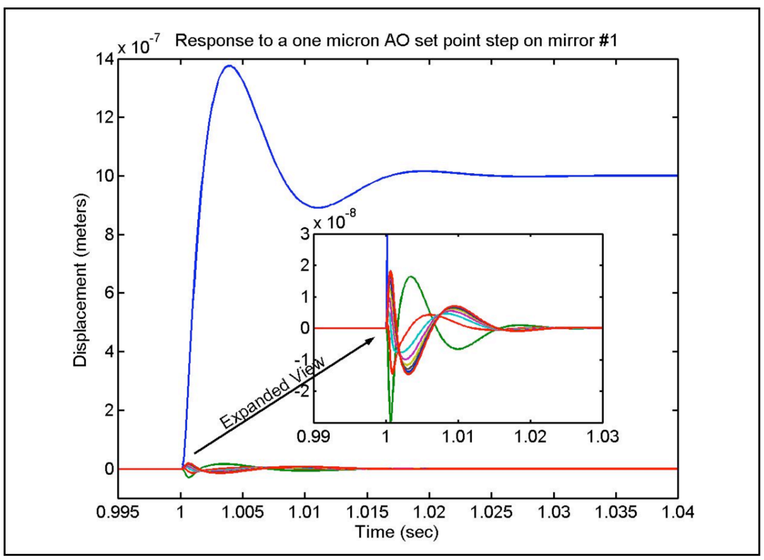


Figure 1: A 1-micron step displacement produces displacements of nearby segmentsye45 10 nm that are damped out in a few milliseconds. More realistic simulations, in which the segments are directly exposed to 5 m/s winds for a von Karman turbulent power spectrum with a break frequency of 0.3 Hz show rms segment motions of less than 15 nm. This wind speed corresponds to a force of a few N/m^2 and is considerably higher than the forces needed to correct for atmospheric turbulence.

Thermal Issues

The reference design will use borosilicate glass to make segments for reasons of cost and ease of fabricating lightweight mirrors. The thermal time constant for the faceplate of ATLAS segments is 20 minutes with wind speeds of 2 m/sec. The mirror will be within 0.2 ^{0}C of ambient air temperature if the temperature changes by 0.5^{0}C/hr, so the effect of "mirror seeing", will be negligible for ATLAS. Temperature gradients within the structure scale as (wall thickness)^2. For a typical heat transfer of 5 watts/^{0}C/m^2 into the environment, the internal temperature will stay within 0.04 ^{0}C of the wall temperature.

Optical Fabrication

A number of new polishing technologies have been proposed in recent years aimed at high volume production of light-weighted mirror blanks. The most conservative option, and the one chosen for the base plan, is to use the Nelson bend and polish technique to polish the segment on a spherical planetary lapping machine. For our segments, the direction of astigmatism always lies along a radius vector, so it can be introduced easily and accurately by applying a bending moment along opposite sides of the segments prior to polishing. FEA analysis of this design gives a fit of better than 100 nm to the ideal aspheric surface for all segments types. We plan to make the faceplate of the segment slightly oversized and cut it to the appropriate shape after polishing using a water jet. Residual aberrations will then be corrected by Ion polishing or similar technique. Nelson has reported that a single Ion polishing station with a 0.025 m diameter beam can remove 5 x10^{11} μm^3/day, so that in principle we can process 600 m^2 with an initial surface error of 200 nm in less than 6 months. Segment production for ATLAS is planned to take two years with 20% spare segments.

Optical Testing

Optical testing is a large part of the cost of fabricating mirrors. ATLAS has two important advantages compared to other approaches. The segments are small and the number of different segments is low. ATLAS uses only 32 different segment shapes to make up the 25-m primary and the profile of each segment shape will be measured against a master using a Fizeau interferometer during fabrication. Each master will be measured by the project team against a small number of reference spheres and sub-masters, and we have designed a testing procedure that will make surface measurements with an absolute accuracy better than 20 nm. This approach will allow the project to provide the optical fabrication vendor with known reference surfaces, greatly improving the certainty that the optics are generated to the optical prescription and allowing multiple vendors to fabricate the optics. Once the segments have been fabricated they will be instrumented with edge sensors, mounted on the wiffle trees, assembled into panels, aligned, and tested as a unit using a large vertical flat as an autocollimator.

Segment control

Segment control is a major issue since there are 16,000 actuators in the primary mirror, about the same number of degrees of freedom in a high order AO system. High volume production of both inductive and capacitive devices results in high reliability sensing estimated at $400/segment with positional accuracy of 50 nm and a bandwidth of a few Hz. High accuracy and high bandwidth control of the mirror surface will be made using laser guide stars. The segment geometry lend itself to a convenient wavefront sensor using pulse tracking to reduce spot elongation problems and a viable laser has been designed for this application. The telescope will use robust reconstruction techniques that produce accurate reconstruction even when some sensors and actuators are faulty and will identify the faults as they occur.

Laser Beacons

The reference design will use a short-pulse laser to produce a beacon in the sodium layer, using slab-laser technology already developed by Chicago for the Palomar sum-frequency laser. At the zenith, the laser will generate three 800 watt top-hat pulses 5 microseconds in length separated by 100 microseconds and this pulse train will be repeated every 1200 microseconds. All pulse and timing durations will scale as sec Z. When this laser is used with the wavefront sensor described below we will obtain a wavefront error due to photon noise/beacon equal to 65 nm at a sodium abundance of 3x10^13 sodium atoms/m^2 and in seeing of 0.6 arcsecond.

Wavefront Sensor

The position of a short laser pulse appears to move across the wavefront sensor as the pulse moves through the sodium layer. We have designed for ATLAS a suitable wavefront sensor using existing CCDs which makes use of the radial arrangement of the sectors and reduces the radial elongation of any spot in the pupil to less than 0.6 arcsecond.

AO performance

The telescope will operate in a number of different AO modes using only the primary mirror to correct the wavefront. We expect a wavefront error of 120 nm in this mode with multiple guide stars. A potentially powerful operating mode will use only a single laser beam for survey work. In this mode, the performance of the AO system is dominated by the cone effect, which, for a sodium laser and a 25-m telescope, amounts to 400 nm in 0.7 arcsecond seeing. The cone effect the on-axis Strehl ratio but increases the isoplanatic angle, causing the telescope to act like a high-performance ground-layer AO system over significant field angles. Although the on-axis Strehl ratio is only 10% @ 1.65 µm with this degree of correction, the intensity of the diffraction-limited core of the image is about two orders of magnitude greater than that of the natural-seeing image over an arcminute field, and ~40% of the light is concentrated within a 0.2 arcsecond diameter aperture over a 1 $arcmin^2$ FOV.

Telescope Structure

The segments are supported on a backing structure that contains the electronics, cooling, and communication needed to drive the segments, together, they form a modular panel. The panels are carried by the primary mirror support truss, a 10-ton carbon-fiber structure attached to the box frame. The approximate weight and cost of each part of the telescope is given in Table 2.

Table 2: Weight and estimated cost of telescope components.

ITEM	**TOTAL WEIGHT (tons)**	**Approximate Cost**
Segments	10.3	$24M
Wiffle Tree+ lateral support	9.7	$9M
Panel Structure	9.5	$3M
Control Electronics	4.0	$1.5M
Panel backing structure	11.5	$3.5M
Optical Support Structure	10	$3M
Secondary Support Structure	8	$2.4M
Lightweight Secondary	0.3	$13M
Alt-Az Mount and drive	154	$18M
TOTAL TELESCOPE	**217.3**	**$77.4M**

No costings are available for dome and site work.

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