Looking Beyond 30m-class Telescopes: The Colossus Project

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ABSTRACT

The exponential growth in exoplanet studies is a powerful reason for developing very large optical systems optimized for narrow-field science. Concepts which cross the boundary between fixed aperture telescopes and interferometers, combined with technologies that decrease the system moving mass, can violate the cost and mass scaling laws that make conventional large-aperture telescopes relatively expensive. Here we describe a concept which breaks this scaling relation in a large optical/IR system called “Colossus”.

Keywords: large telescopes, thin mirrors, redundant-baseline interferometry, phased array telescope, exoplanets

1. HIGH CONTRAST NARROW-FIELD SCIENCE

The world astronomy community is now far-along in planning, or building, at least three telescopes that could become the next “World’s Largest Telescope” (WLT). Each of these projects has the backing of hundreds of astronomers and the support of national government organizations. They will serve a large and diverse scientific community and are necessarily designed with broad optical performance requirements. It is perhaps not surprising that none of them is optimized for its scattered light, or dynamic range performance.

Exoplanetary science, in particular, could be well-served by a different type of astronomical telescope. There are compelling questions that benefit from the “volume effect,” of a larger aperture instrument. This is a case where the scientific output increases with the effective cosmic volume sampled by the telescope and its detectors. For many survey and discovery problems this is a $D^3$ effect where $D$ is the effective diameter of the telescope. We describe here some science that depends critically on telescope aperture and scattered light properties. It is possible that this optical system could be built using developing technologies for not much more than the next generation of WLTs.

1.1 Exoplanets, Life and Civilization

In a spatially correlated universe it is productive to look near bright optical sources. The science of stars and planetary environments is growing exponentially, at least as measured by the rate of detection of new exoplanets over the last decade. Misquoting Einstein we might even conclude that here is a case where “looking for lost keys under the lamppost in a dark night” makes great sense.

Focusing on the problem of measuring the light from exoplanets where liquid water is possible (“Habitable Zone” – HZ exoplanets), requires extraordinary telescopic scattered light rejection from the central star. The problem rapidly improves though with larger diameter exoplanets and when the host star has a cooler effective temperature. Figure 1 shows the reflected and emitted planetary-light-to-stellar-light contrast ratio in the visible and at thermal radiation wavelengths of 5 and 10 $\mu$m.

The prospect of seeing exoplanet atmospheres to learn about extraterrestrial life or even “exo-civilizations” improves if we can devise “biomarkers” or “civilization markers” into the infrared. Of course Figure 1 also shows that we must have a very good coronagraph that is capable of background light suppression at levels greater than $10^6$. 

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Figure 1. Flux contrast for a planet in the habitable zone versus star temperature in scattered stellar light (blue), in emission at a wavelength of 5μm (green) and in emission at 10μm (red). Solid lines show contrast of Earth-radius planets and dashed lines correspond to 5 Earth-radius planets.

We’ve pointed out\(^5\) that an Earth-like or slightly more advanced civilization on a rotating exoplanet emits a thermal “civilization biomarker” signal that might be detected with a sufficiently large coronagraph and IR-sensitive telescope. This biomarker allows the possibility of conducting a census for advanced Earth-like civilizations near the Sun, using large aperture telescopes, and motivates the Colossus study described here. Regardless of the uncertain odds of a civilization surviving beyond Earth-like conditions, the spectroscopic and spectropolarimetric measurements of exoplanet atmospheres and more general life-biomarkers\(^7\) from such a telescope will provide an enormous step in our understanding of life on HZ exoplanets.

1.2 The importance of aperture

At a fixed angle from a bright star the diffracted light suppression improves with smaller wavelength and larger telescope diameter. Since we require contrast sensitivity into the IR (see Figure 1), coronagraphic light suppression needs large aperture telescopes. The telescope angular resolution tends to determine the minimum angular separation of a detectable exoplanet from its host star, so that the possibility of detecting bio- or civilization-markers out to cosmic distances, \(d\), must be generally proportional to the telescope aperture. Based on the performance of current coronagraph systems, we have estimated the number of stars where an advanced Earth-like civilization biomarker is detectable as a function of the telescope aperture, planet diameter and coronagraph. Figure 2 shows the number of possible civilization detections for a GMT, TMT, EELT, or something larger. The vertical arrow plotted shows how the sample size of a potential census grows if the assumed exoplanet radii are increased from Earth-size to twice the Earth-radius, and the symbols show how these estimates change with different coronagraph assumptions.

The thermal heat signature of advanced Earth-like civilizations is an almost unavoidable civilization biomarker, but it will require an optical system that has large aperture, excellent coronagraph properties, and minimal infrared background. These properties are achievable with current technologies. Our modeling\(^5\) in Figure 2 suggests that as many as 100 HZ exoplanets could harbor detectable exo-civilizations for a telescope with an aperture of at least 75m. Unfortunately, detecting exo-civilizations with the three currently planned WLTs is unlikely because of their scattered light properties and their smaller apertures.
2. GIANT TELESCOPE CONCEPTS

2.1 Issues to overcome

A mechanical imaging structure generally requires sufficient stiffness to yield a stable mirror support shape with sub-micron stability over the length scale of the primary mirror. Such stiffness must be achieved from the supporting structure mass and, perhaps, by dynamically enhancing the stiffness electromechanically. Since the cost of mechanically similar systems typically scales with the total “moving mass” of the optical support structure, there is added cost to increase the stiffness with mass. Major resources have been invested in the detailed designs of the WLT concepts and the even larger 100m OWL . Naturally these large telescope primary mirrors are segmented and can be described by three nested mechanical components: 1) there is the glass and light reflecting surface of each subaperture, 2) a backing mechanical mirror support structure for each subaperture, and 3) the global optical support structure that defines the overall segmented primary mirror shape. The total mass of the three components effectively determines the system moving mass.

Figure 3 is based on the published design information for four WLT’s (and the as built Keck telescope) moving mass versus the telescope aperture. It is surprising to see how precisely these points fall along a line. Evidently the moving mass is accurately proportional to the primary mirror area for comparable modern telescope designs. Since the line in Figure 3 includes the Keck telescope, we could conclude that the WLT designers have rather precisely extended the Keck mirror concept. The fact that the overall WLT mass is not increasing faster than the mirror area reflects designer confidence that the larger optical support structures can achieve the required mechanical stiffness without additional (i.e. nonscaling) mass using active control systems. For comparison the Hobby-Eberly telescope, HET , is also plotted on this figure. It falls notably below the scaling law because it is a fixed gravity telescope with relaxed stiffness requirements, unlike any of the other proposed or built WLTs. We note also that the cost (as built or estimated) for each of these telescopes generally increases with its moving mass. For many telescopes this proportionality can be about $1M per ton.

An active mirror support system can decrease the mass of the first (glass) mass component, but, for position-servoed electromechanical control, requires a stiff and thus more massive subaperture backing structure. The alternative of force controlling the glass mirror surface using occasional optical wavefront information allows the total glass and backing
structure mass to be reduced. If the overall M1 support stiffness requirement of the global optical support structure component can be relaxed then the total mass decreases further. The HET is such an example, where the fixed gravity vector allows a lighter optical support structure. Current WLTs have areal mass densities in the 1st and 2nd components of the M1 mirror that are about 500 kg/m² but the Colossus group is exploring active structures that could decrease this mass component to 100 kg/m² or less.

![Figure 3](image_url)

Figure 3. WLT moving mass for build (Keck) and designed telescope systems including the proposed OWL	extsuperscript{a}. The HET	extsuperscript{b} is also plotted and departs from this mass-diameter correlation because it is a fixed gravity (and therefore less massive) instrument.

2.2 Optical concept

Following Fig. 3, it appears that a telescope with an aperture approaching 100m, as current WLTs are designed, will cost at least $10B. Reducing the cost requires reducing the mass (and stiffness requirement) of the telescope support structure. Colossus allows primary mirror subaperture elements to “float” mechanically by a few microns. Its design also uses mirror segments with an areal mass density of about 100kg/m². To minimize light diffraction and “complexity cost” the Colossus M1 is also composed from large subaperture units with a diameter of at least 8m. This also reduces the diffraeted light scatter by reducing the edge-to-area ratio of the full mirror system. Cost and complexity are reduced because the optical configuration is “scalable” in that each subaperture segment illuminates its own secondary. Additional complexity comes from the new need for interferometric beam compensators to correct for the atmosphere and “floppy” telescope structure-induced phase errors.

The Colossus optical design is composed from a moderate number (N≈60) of off-axis parabolic 8m telescopes with a common Gregorian focus near the vertex of the large parent parabola. These telescopes move on a common mount and over a total diameter of many 10’s of meters each diffraction-limited subaperture wavefront requires tip-tilt and piston phase adjustment to yield a common high-resolution focus. To achieve a small secondary mirror structure implies a field-of-view for the telescope which is small – something like 5-10 arcseconds. Also, to phase the subapertures without a stiff mechanical structure (and without mechanical mirror edge sensors), will require a bright source in the Colossus field-of-view. While these requirements may seem severe, they are well matched to stellar and exoplanet science requirements (and other near-Earth remote sensing problems).

Each subaperture must deliver a high-Strehl wavefront to a beam combiner at the common Gregorian focus. This is attained with duplicate natural guide star adaptive optic subsystems, operating on each 8m subaperture. An optical configuration is illustrated in Figure 4. This is a hexagonal grid of 60x8m telescope subapertures from a parent Gregorian geometry. The subaperture grid is spaced to allow top-end mechanical support of the secondary optics tower without obstructing any primary optics. Each subaperture secondary mirror is about 38cm in diameter. The diffraction-limited FOV of the optics is about 8 arcseconds and the principle aberration is coma which increases linearly with angle from the field-center. In this configuration the diameter of the parent primary is about 75m with 380m focal length and the 3.6m diameter secondary structure is 20m above the parent primary vertex. Each 38cm adaptive secondary segment provides wavefront tilt, piston, and high order adaptive wavefront correction to deliver 60 diffraction limited beams to the common focus. Under these conditions the diffraction limited Colossus PSF is illustrated in Figure 5.
2.3 Subaperture configuration

A key design feature is the array geometry of off-axis subapertures. The optical performance, achievable contrast sensitivity, and mechanical stiffness and mass are a function of the mirror lay-out. In general, the stiffness, mass, and imaging photometric signal-to-noise push the geometric configuration toward a “close-packed”, or nearly filled-aperture geometry\textsuperscript{10}. Allowing space for the M2 truss structure, so it doesn’t shadow the optics, opens up the M1 design slightly. The hexagonal configuration achieves an area fill factor of more than 70\% of the circumscribed parent aperture area. The resulting MTF has no zeros at scales smaller than the M1 parent radius. This preserves image information at angular scales near the diffraction limit of the full aperture. This geometry also minimizes the mass of the third M1 structural component. A mechanical design of the Colossus enclosure done by Dynamic Structures Ltd. indicates that the optical opening in the “dome” could also drive mass and costs of this essential wind protection structure. For such large telescopes there is mechanical advantage in matching the primary mirror geometry to the enclosure opening. Thus we have also considered M1 optical footprints with a rectangular envelope shaped like the telescope enclosure opening shown in Figure 6.
2.4 Mirror phasing and coronagraphy

There are other issues that affect the subaperture geometry. We’ll determine the relative wavefront phases and tilts of each subaperture from a least-squares phase-diversity solution obtained from speckle images of the bright on-axis stellar source. An iterative solution for the phases and tilts has been demonstrated\textsuperscript{11}. Physical phasing of the elements can be achieved by controlling the 3N subaperture adaptive tip/tilt/piston secondary mirror control elements. This must be done within each atmospheric seeing evolution timescale. Finding mirror phases from the completely dephased starting configuration of the optics has also been demonstrated. For example, a non-iterative solution for mirror phases can be obtained from multi-wavelength monochromatic speckle images. The total phase path errors due to the atmosphere and the mechanical structure should be about 10\textmu m and these can also be obtained using a phase-diversity least-squares solution. Figure 7 illustrates how the telescope initially “boots-up” with a non-iterative phase algorithm that works to bring the mirror phases into a linear iterative solution regime for the mirror phases and tip/tilts.

The Colossus is a phased-array telescope that can also be operated as a nulling interferometer in order to generate a dark spot in the image-plane diffractive PSF. By adjusting mirror phases, such a dark spot can be scanned through the circumstellar image to find faint off-axis exoplanet light. Recently a powerful technique has been discussed for non-redundant baseline phased telescopes\textsuperscript{12}. Alternatively a post-focus coronagraph can be effective with the segmented Colossus pupil design, for example, by beam remapping as described in ref. 13. An on-going effort will compare the nulling versus remapped pupil coronagraph concepts in order to maximize the spectral bandpass and contrast sensitivity. These considerations may also affect the optimal subaperture geometry.

![Figure 6. The non-redundant Colossus configuration and optimal enclosure design.](image)

2.5 Light-weight mirrors

Reducing a mirrors’ area mass density is an old and fundamental problem for telescope builders and any new solution must depend on novel material properties or control solutions. We adopt an approach that uses electromechanical force-actuators, weighing less than the eliminated substrate glass, that control shape and provide stiffness. Unlike most telescopes, the Colossus subapertures each continuously observe a star, so it is possible to obtain slow (with expected update rates less than 1 Hz) information on the mirror shape from wavefront measurements. The control system need only maintain the mirror shape between optical wavefront updates. Mirror alignment is obtained from the common Gregorian focus and the phasing algorithm. As long as the gravity deformation and surface roughness of the mirror on length scales shorter than the distance between actuator support points is small enough, a control system may provide and maintain the necessary optical surface.
The gravity surface deformation, $z$, between glass mirror support points separated a distance $a$, for a material of density $\rho$, and Young’s Modulus $E$ scales as $z \propto a^4/\rho a^4 t^2$. Numerical finite element modeling of thin plates gives a useful normalization of this equation, and for glass with thickness between 0.5 and 10cm we obtain $z_{pp} = 10 \rho a^4 t^2$ with $z_{pp}$ the peak-peak gravity deformation between actuators, $E$ measured in Pa, masses in grams, and lengths measured in cm. A 5cm thick glass substrate with 20cm actuator spacing ($E=6\times10^{10}$, $\rho=2.3$) gives $z_{pp}=25$nm which corresponds to an rms wavefront error of about 10nm. If actuators have mass $m$, then the minimum total mirror mass density occurs with a thickness $t^2 = m\sqrt{10\rho/E}$ in these units. With actuators weighing $m=100g$ the minimal area density mirror could be as thin as 1cm. Note also that $t$ has only a weak dependence on the specified rms wavefront error and material properties. The necessary actuator spacing varies as $a = (zE/10\rho)^{1/4} \sqrt{t}$, which for the minimal configuration is about 10cm. Thus each 8m mirror subaperture would need approximately 5000 actuators. If such a mirror used a reaction mass comparable to the glass mirror substrate then it would have an area density of about 60 kg/m$^2$ or almost an order of magnitude less than conventional mirrors. Each actuator supports less than 300g of glass but they must also be able to control the transverse and longitudinal mirror weight components. They operate within individual force-servo control loops and the entire control system operates through a local area network controller that has access to occasional optical wavefront information.

On length scales up to 20cm, fire-polished commercial plate glass can be very smooth – smooth enough that thousands of actuators on an 8m glass plate, which is approximating a parabola, may create an optical quality surface -- potentially without requiring abrasive grinding. On short scales a fire-polished flat glass mirror can be much smoother than conventionally polished mirrors. The Colossus group has “deterministically slumped” 0.5m diameter, 6mm thick, flat plates into parabolic shapes with less than 100$\mu$m shape errors. Such slumped parabolic or off-axis parabolic plate-glass surfaces can then be manipulated to optical quality (50nm rms wavefront errors) using dynamic force actuation.

The Colossus mirrors are unlike normal optics as they are never separated from their electromechanical backing structure after manufacturing. They depend on a highly parallel network control system and must have optical wavefront control information for fixing the mirror shape. The trade-off is that these “live mirrors” have significantly less mass than conventional large telescope mirror optics and can potentially be created without conventional grinding using smooth flat glass substrates that are slumped to off-axis parabolic shape.

**Image domain mirror phase recovery**

![Image domain mirror phase recovery](image)

Figure 7. A non-iterative direct mirror phase solution for $N=59$ in a non-redundant configuration. The left panel shows the intensity speckle pattern for random mirror phases. The right panel shows the intensity after direct least-square minimization. The lower graphs show the input, reconstructed, and residual phase errors for 59 mirrors.
3. CONCLUSIONS AND STATUS

Future telescopes larger than 40m diameter may be built as nearly close-packed co-moving phased-arrays. To decrease the total system mass the subaperture mirror elements will use force-servoed active mirror control with 1000’s of closed-loop actuators. Small adaptive secondary mirrors and image speckle information from bright on-axis sources will provide fast and slow-adaptive wavefront control at the common Gregorian focus of the optical system. The most natural optical configuration will use off-axis parabolic segments with mirrors that could weigh as little as 60kg/m². The Colossus group has prototyped these new technologies that will enable lightweight mirror controls, and has developed an optical design for a 75m diameter telescope that has sufficient aperture and scattered light suppression to allow detection of exoplanet biomarkers and perhaps even civilization biomarkers within 60 light years of the Sun. This work was supported by the Harlingten Center for Innovative Optics, the Institute for Astronomy, UH, and the Kiepenheuer Instititte for Sonnnenphysik. We’re grateful to Ian Cunnyngham who helped to model the non-iterative phase solutions, Joe Ritter for help to demonstrate thin mirror prototypes, and Chris Packham for important comments on the manuscript.

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