Partially filled aperture interferometric telescopes: achieving large aperture and coronagraphic performance

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ABSTRACT

The exponential growth in exoplanet studies and science cases requiring high contrast observations 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 concepts of large, filled-aperture (Colossus) and partially filled aperture (ParFAIT) interferometric optical/IR telescope systems which break this scaling relation. These systems are dedicated to high dynamic range science such as detecting life and even civilizations on Earth-like planets.

Keywords: large telescopes, thin mirrors, redundantbaseline 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 projects13 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 D3 effect, where D is the effective diameter of the telescope. We describe here an optical system1 significantly larger than the currently planned WLTs and some science cases which depend critically on the 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 (0.5µm) and at thermal radiation wavelengths of 5µm and 10µm1,3.
The Earth-like atmosphere is best detectable between 0.6µm and 10µm, where oxygen, water vapor, methane and carbon dioxide absorb the stellar light and the planetary own radiation. A multitude of photosynthetic biopigments in the terrestrial life have evolved to absorb between 0.4µm and 0.7µm where the stellar flux is maximal and the atmosphere absorption is minimal. As Figure 1 shows, the prospect of seeing exoplanet atmospheres, extraterrestrial life and even “exo-civilizations” improves if we can devise “biomarkers” and “technomarkers” for the infrared. It also shows that we must have a very good coronagraph that is capable of background light suppression at levels greater than 10^6. Employing differential techniques enhancing the contrast, such as spectro-polarimetry, increases our chances to detect exo-life.

It was pointed out that an Earth-like or slightly more advanced civilization on a rotating exoplanet emits a thermal “civilization technomarker” signal that might be detected with a sufficiently large coronagraph and IR-sensitive telescope. This technomarker allows the possibility of conducting a census for advanced Earth-like civilizations near the Sun, independently on their communication intentions. It requires large aperture telescopes and motivates the Colossus study described here. Regardless of the uncertain odds of a civilization surviving beyond Earth-like conditions, spectroscopic and spectropolarimetric measurements of exoplanet atmospheres and a search for photosynthetic biomarkers using 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 Fig. 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 technomarker is detectable as a function of the telescope aperture, planet diameter and coronagraph. Figure 2 shows the number of possible civilization detections with GMT, TMT, EELT, or a larger telescope (XXT). 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 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.

![Figure 1](image1.png)

**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. Adapted from Kuhn & Berdyugina (2015), Ref. [6].

![Figure 2](image2.png)

**Figure 2.** Maximum number of detectable Earth-size HZ planets versus telescope size (assuming one planet per star and full utilization of stellar light encountered by the planet). ‘Star’ symbols show number of detectable planets at 5µm due to thermal emission assuming 5x10^-8 contrast sensitivity at an angle of 2.5/D from the host star and at 500 nm with five times smaller contrast at 20/D. ‘Diamond’ symbols show the number with corresponding IR contrast at 2x10^-6, and ‘plus’ symbols show the number detectible with contrast sensitivity of 10^-8. Up arrow shows the increase in detection numbers if HZ planets have a radius twice the Earth’s.
2. HIGH RESOLUTION AND HIGH CONTRAST TELESCOPE

Challenging science cases such as the detection of exoplanetary life signals requires also a demanding new concept of telescope. The main issues concerned here are (i) resolution, (ii) sensitivity and (iii) adaptive optics prior to cophasing the whole system. Resolution would be guaranteed by an as large as possible diameter, which imposes a large number of segments, an optimized aperture configuration, and a mechanical structure to support it. Sensitivity is driving to a concept which minimizes the light scattering: off-axis segments. The way to guarantee high resolution and high contrast is to optimize the adaptive optics and cophasing implementations. Adaptive optics is optimized by considering large circular segments using wavefront corrections independently for each of these segments prior to cophasing the segments. The foreseen cophasing technique uses focal plane images that allow piston measurements and correction between all the segments. In this context we propose to derive the segment phase error using the inverse approach knowing the segment positions and the single aperture Airy function. The high sensitivity is guaranteed by off-axis segments forming the effective primary aperture which has significant demonstrated advantages. In Figure 3 panels A show each PSF contribution for a 6.5-m aperture telescope at a wavelength of 1µm, and panels B and C show how the relative importance of edge (aperture) diffraction to the scattered surface brightness increases with wavelength and dominates the telescope PSF at wavelengths of a few microns over field angles ranging from a few arc-seconds to several arc-minutes. Improving the telescope mirror optical ‘microroughness’ and quality also minimizes mirror scatter contribution.

Figure 3 - (A) The diffraction patterns (λ=1µm) along the orthogonal θx- or θy-directions; (up) the 3D and (down) the density profiles for the 6.5m unobscured aperture (edge) diffraction, aperture diffraction with obscuration (ε=0.250), spider diffraction along the orthogonal legs (4 legs 50mm x 3250mm), and finally all PSF diffraction contributions. (B) and (C) are the scattered light PSF contributions for a conventional 6.5m telescope at 1micron and 4micron. The solid line shows the unobscured aperture (edge) diffraction. The dotted line shows the BRDF from mirror roughness scattering assuming a mirror as smooth as the Hubble Space Telescope primary. The dashed line shows the BRDF from mirror support spider and the dash-dotted line shows the atmospheric BRDF for an atmosphere characterized by a 15cm Fried parameter. Adapted from Moretto and Kuhn (2000), Ref. [9].
3. GIANT HIGH DYNAMIC TELESCOPE CONCEPTS

3.1 Issues to Overcome

A mechanical structure of an imaging system 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\textsuperscript{11} (now EELT\textsuperscript{3}). These are “Keck-era” telescopes using the same design principles as the Keck segmented primary mirrors. 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 4 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 4 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\textsuperscript{12} 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.

3.2 A Giant Optical Concept

Following Figure 4, 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. The Colossus\textsuperscript{4} concept 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/m\textsuperscript{2}. 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 diffracted light scatter by reducing the edge-to-area ratio of the full mirror system. The cost and complexity are reduced because the optical configuration is “scalable” in that each subaperture segment illuminates its own secondary. However, a new requirement arises for interferometric beam compensators to correct for the atmosphere and “floppy” telescope structure-induced phase errors.

![Figure 4. WLT moving mass for build (Keck) and designed telescope systems including the proposed OWL\textsuperscript{7}. The HET\textsuperscript{10} is also plotted and departs from this mass-diameter correlation because it is a fixed gravity (and therefore less massive) instrument. An active mirror support system can decrease the mass of the first (glass) mass component, but for position-servoed electromechanical control it 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 1\textsuperscript{st} and 2\textsuperscript{nd} components of the M1 mirror that are about 500 kg/m\textsuperscript{2} but the Colossus\textsuperscript{4} group is exploring active structures that could decrease this mass component to 100 kg/m\textsuperscript{2} or less.](image-url)
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 individual sub-telescopes are assembled and move on a common mount. Such an assembly over a total diameter of many 10’s of meters requires that each diffraction-limited subaperture wavefront is tip-tilt and piston phase adjusted to yield a common high-resolution focus. Achieving a small secondary mirror structure imposes a small field-of-view for the telescope – something like 5-10 arcseconds. Also, phasing 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).

Thus, a key design feature of the Colossus is the array geometry of off-axis subapertures. Furthermore, the optical performance, achievable contrast sensitivity, and mechanical stiffness and mass all depend on the mirror lay-out. In general, the stiffness, mass, and imaging photometric signal-to-noise push the geometric configuration toward a “closely-packed”, or nearly filled-aperture geometry. Allowing space for the M2 truss structure, so it doesn’t shadow the optics, opens up the M1 design slightly. Optimally, each possible configuration should achieve an area filling factor of more than 70% of the circumscribed parent aperture area, resulting in an MTF with 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. Also, this geometry minimizes the mass of the third M1 structural component.

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. Considering the mechanical issues, the preliminarily adopted Colossus telescope optical configuration was a central-symmetric distribution of 60x8m off-axis primary mirrors (M1). Figure 5 shows four such preliminary designs and corresponding PSFs: hexagonal (HEX1), circular-hexagonal (HEX2), pentagonal (PEN) and square (SQA). All the distributions have an adjacent separation between subapertures d=200mm.

An optimal Colossus subaperture mirror configuration should consider the fact that it must operate with a structure which is not mechanically stiff and that its enclosure must provide good wind isolation. To minimize the enclosure mass, it is advantageous to match the enclosure opening to the mirror footprint. A mechanical design of the Colossus enclosure done by Dynamic Structures Ltd. indicates that the optical opening in the “dome” could drive mass and costs of this essential wind protection structure. All these drive issues lead us to consider M1 optical footprints with a rectangular envelope shaped like the telescope enclosure opening shown in Figure 6. It also illustrates the configuration of 60 mirrors arranged on a relatively close-packed rectangular grid that matches the enclosure opening. One can point out that this rectangular configuration outcome in a bidirectional resolution limit. It is not a problem considering the telescope structure will be an alt-az mount and such behavior will add a coronagraphic advantage to the telescope.

Another design driver issue is that the Colossus system requires an optical configuration that is “scalable” that each subaperture primary segment illuminates its own secondary in a fashion that allows interferometric beam combination to compensate for the largescale atmosphere and (“floppy”) telescope structure induced phase errors. Thus the optical configuration is composed from a moderate number of off-axis parabolic 8m telescopes with a common Gregorian focus.
near the vertex of the large diameter parent parabolic optic (M1). Over a diameter of many 10’s of meters each diffraction-limited subaperture wavefront requires tip-tilt and piston phase adjustment to achieve a common high-resolution focus. In order to achieve high dynamic range the geometric configuration of 8m telescopes is driven toward a “close-packed”, nearly filled aperture geometry. This yields an optical MTF that is not too sparse.

**Figure 6.** The Colossus telescope optical configuration for the primary mirror and its distribution structure function and PSF. The “grey-cross” are the space reserved to the mechanical central tower and main structure cables and supports to hold the secondary mirror. Following a preliminary telescope enclosure as proposed by the Dynamic Structures Ltd (Canada).

**Figure 7.** The Colossus telescope optical interferometric configuration optimized for the rectangular distribution for the primary mirror. (B) The footprint for the 60x8m M1, resulting on a clear rectangular aperture of 54mx95m. (C) The footprint for the 60x180mm M2, producing a clear aperture for the parent M2 of 1.1mx1.9m. In order to achieve these opto-mechanical requirements with the smallest possible secondary mirror structure implies a field-of-view for the telescope which is small – something like 4x4 to 10x10 arcseconds. Also, to phase the subapertures
without a stiff mechanical structure (and, for example mirror edge sensors) will require a “point-like object” in the Colossus field-of-view. One optical configuration we’ve explored for Colossus is presented in Figure 7. This is a rectangular grid of 60x8m telescope subapertures (Figure 7B) in a parent Gregorian geometry. The each secondary subaperture mirror has an elliptical conic (k=−0.94) and is only 180mm in diameter, (Figure 7C). The constraints for the optical optimization were (i) the shorter possible central tower (M2FP = vM2 – vFP; v=vertex) and (ii) the same location for the vertexes of parent primary mirror (vM1) and the focal plane (vFP).

Optically this configuration is a decentered system preserving its bilateral symmetry. Preserving also many of the optical performances, tolerances and sensitivities characteristics of the parent concentric system – a deal for system optical alignment. Since only a small section of the parent optical system is illuminated, some geometrical performance characteristics of the daughter system supersed the parent optics. In such a way each subaperture delivers a high-Strehl wavefront to the beam combiner. The diffraction-limited FoV of the optics is about 8x8 arcsec$^2$ and mostly coma aberration, which increase linearly from the field center as shown in Figure 8.

![Figure 8](image)

**Figure 8.** The Colossus telescope optical performance across the FOV size (pxp) is limited mostly by coma aberration increasing linearly (dashed line) from the field center. The red full line represents the diffraction limit (DL) for the circular primary parent M1 in function of wavelength ($\lambda$) in nanometers.

### 3.3 Mirror Phasing Strategy

Cophasing a multi-aperture telescope is a critical and crucial issue to guarantee and to assure the telescope performance without degradation by phase perturbations, and it is also another issue that affect the choice of the subaperture geometry. The strategy used for cophasing is to 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\(^{14}\). 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. 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 10µm and these can also be obtained using a phase-diversity least-squares solution. Figure 9 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.

![Figure 9](image)

**Figure 9.** 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.
3.4 Very Fast 60 Extreme Adaptive Optics Strategy

Each of telescope subaperture delivers a high-Strehl wavefront to the beam combiner (Fig. 6B) that is essential for the adaptive optics (AO) of the telescope which we advocate here to be composed from distinct very fast and highly accurate AO systems working on each 8m M1 subaperture. Each of 60 independent extreme (X-AO) systems will be running in parallel and make use of the small 60xM2 subapertures, of only 180mm in diameter for a 19 arcsec² field of view.

The Colossus telescope Gregorian design configuration produces an exit pupil on the M2 parent locus, where a deformable M2 secondary mirrors with 36 actuators per diameter (for a 5mm pitch, yield in a 1060 actuators per 180mm diameter mirror) (Figure 8) would be foresee considering the off-shelf technology presently available. Note that the off-axis configuration design generates an unobstructed sub-aperture what guarantee no wavefront discontinuities for each distinct X-AO system. We have used FrIM2 code developed by M. Tallon for the preliminary AO simulations. Figure 11 shows the gains on the resolution and contrast making use of the 60x8m rectangular configuration for Colossus in comparison of a single off-axis 8m aperture. Those are the preliminaries numerical simulations and a more accurate and with more AO scenarios is under realization to obtain more details information on our model and strategy.

3.5 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 are developing a new and interdisciplinary technology for creating extremely light-weight diffraction-limited metamaterial-based optical surfaces with spectacularly lower cost and production time – Live-MetaOptics™ (patent pending). The key milestone for this technology which is outside the bounds of the conventional optical manufacturing is the proof of a scalable technology for large diameter, but low areal mass density mirrors through either (i) proof of a new material design for thin, low mass, mirror solutions, and (ii) proof of a economical, large diameter, thin substrate polishing solution, or (iii) proof of a low mass scalable additive optical surface manufacturing technology, e.g. based on manufactured active 3D metamaterials that do not require subtractive polishing (patent pending) (see Fig. 12).

Figure 10. Each of M2j (j=1…60) will generate a locus for an independent deformable mirror M2j of 180mm in diameter for a 19 arcsec² field of view and 36 actuators per diameter for a 5mm pitch, yielding in 1060 actuators per M2j.

Figure 12. Live-MetaOptics™ (patent pending) proof of a scalable technology for large diameter, but low areal mass density mirrors. Right picture prived communication by Leigh S. (2015).
Figure 11 – The Colossus 60x8M preliminary simulations making use of FrIM2. The initial parameters are 20cm 40x40 sub-apertures on a single off-axis 8m aperture; \( r_0 = 0.17m \), \( L_0 = 25m \), measurement noise is of 10 nm RMS; using the best re-constructor (MAP, generators, optimal pre-conditioner); it is assumed that \( r_0 \) and \( L_0 \) are perfectly known from the re-constructor; the level of modeled noise is optimized and so far it is not very sensitive; the simulations are on 10 cm sampling with some aliasing; it is assumed reconstructions at the corners of the sub-apertures; it is assumed actuators with bilinear shapes, and DM pitch is 20 cm with Fried geometry. The evaluations are on the same sampling as the simulation, i.e. 10 cm.
The Live-MetaOptics™ development will provide large optical quality mirrors made from fire-polished glass without abrasive polishing using additive technologies. We will replace conventional mirror substrate mass, that would normally be necessary for mechanical stiffness, with active 3-D printed sensors and actuators on accurately shaped paraboloidal glass substrates. With such hybrid structures, the net areal mass density can be an order of magnitude less than a conventional light-weight mirror with a diffraction-limited optical surface. These low-mass mirrors enable large optical surfaces to be economically created to approximate a parent paraboloid. The mass of the underlying multi-mirror support structure can be further reduced with a relatively “soft” global support structure.

ParFAIT’s optical configuration, such as the Colossus (Fig. 7), combines off-axis paraboloid segments with an ensemble of small elliptical secondary mirrors such that all optical beams share a common focus. Each elliptical secondary mirror is illuminated by one primary mirror segment, and becomes its steering and phasing element. In this way each beam is combined coherently at the Gregorian focus of the larger, two-axis tracking, primary parent optics without interferometer delay-lines. This optical system achieves the full angular resolution of the parent while efficiently matching the “softness” of the mechanical structure to the atmospheric piston phase fluctuations. ParFAIT has good optical Modulation Transfer Function (MTF) properties, and approaches the photometric dynamic range sensitivity of a filled-aperture 100m-class optical system. The ParFAIT optical concept is derived from the Colossus nearly-filled aperture interferometric telescope. A square off-axis parabola sections will be configured within a 70 x 70 x 30m volume into a sparsely sampled parent parabola optic. Figure 13A illustrates the primary and secondary mirror optics of the sparse ParFAIT mirror geometry. The secondary mirror segments are only about 25cm across and each one provides piston phase and tip-tilt wavefront control for one of the 39x(5x5)m parabola primary mirror segments. The secondary segments are adaptive so each 5x5m sub-optic delivers a diffraction limited wavefront to the common Gregorian focus. We believe a 100m ParFAIT can be constructed for about $150M with 39 5mx5m hybrid mirror segments in a “cross” configuration (Figure 13A). We note that ParFAIT has a field-of-view that is limited to a few arcsec by its primary optical system. Depending on seeing conditions, ParFAIT operates with a 13 magnitude or brighter source within its field-of-view, although artificial optical sources could mitigate this limitation.

As the Colossus, the ParFAIT 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 additional techniques have been discussed for non-redundant baseline phased telescopes (although the designs we favor for high dynamic range have pupil segment baselines that are highly redundant). Alternatively a post-focus coronagraph can be effective with the segmented Colossus or ParFAIT pupil designs, for example, by beam remapping as described in Ref. [16]. In the case of ParFAIT pupil is sampled along the diagonals of a 70m x 70m square. This makes it well-suited for detecting low-contrast and barely resolved objects in the presence of a bright on-axis source. Under many circumstances it has high dynamic range with the spatial resolution of the 100m parent aperture. The necessary global mirror phase information for each suboptic is reconstructed from final composite speckle image. Figure 13 (B) show a 0.1 x 0.1 arcsecond simulated noiseless ParFAIT image of a bright central point source. The intensity scale is logarithmic over 10 magnitudes in this display. The ParFAIT PSF resolution for imaging faint objects is effectively the full 100m aperture except in the x-y directions of the optical cross.

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.

5. 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 filled-aperture and 100m partially filled-aperture telescopes which have sufficient aperture and scattered light suppression to allow detection of exoplanet biomarkers and perhaps even civilization technomarkers within 60 light years of the Sun.
Figure 13. ParFAIT: (A) Square 39 5x5m off-axis paraboloid segments illuminate separate elliptical secondary segments to create a common Gregorian focus (C) near the vertex of the parabolic parent optic. The total length of each cross is 100m with 25x25cm secondary segments. (B) Upper (B1,3) shows how adjusting the phase on just one segment by 180 degrees inserts “dark-lines” in the 0.1 x 0.1 arcsec PSF (B1). A more complex phase solution on 8 segments (B3) creates a “dark hole” in the PSF diffraction pattern that can be moved within the field-of-view (B2,4). In (B2) the dark hole is periodic and to the lower left of the on-axis source. The intensity scale is logarithmic over 10 magnitudes in this display. The ParFAIT PSF resolution for imaging faint objects is effectively the full 100m aperture except in the x-y directions of the optical cross.

ACKNOWLEDGEMENTS

This work was supported by the Institute for Astronomy, University of Hawaii, and the European research Council (ERC) Advanced Grant HotMol (http://www.htmol.edu), ERC-2011-AdG 291659 at the Kiepenheuer Institut für Sonnenphysik. Dynamic Structures Ltd. designed the mechanical structure and enclosure of the Colossus and ParFAIT. We’re grateful to Ian Cunyngham 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, and to Simon Leight (University of Warwick, UK) and to Todd Williams (Printed Electronics Ltd., UK) for discussions on 3D printing additive manufacturing issues.
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