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New Cophasing and AO strategies for an extremely large telescope dedicated to extremely high contrast: The Colossus Project**

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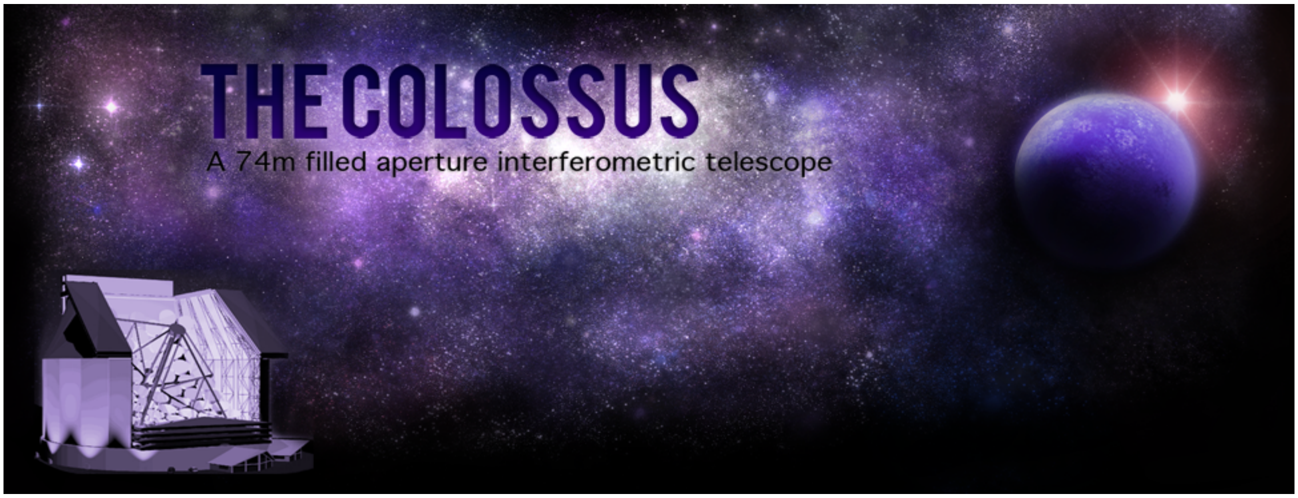

ABSTRACT - Detecting an exoplanetary life signal is extremely challenging with current technology because it requires a sensitive telescope and instrument that can measure the planet's reflected optical and infrared light, while distinguishing this from the star's scattered light and the terrestrial thermal noise background. This requires highly accurate adaptive optics, a coronagraph system, and **a specially designed and aligned giant telescope**. We present here new strategies for building such a telescope with large circular segments using adaptive optics correction 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.

1. HIGH RESOLUTION AND HIGH CONTRAST

Challenging science cases such as the detection of exoplanetary life signal 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 with as large as possible its diameter what impose a large number of segments and an optimized aperture configuration, which a mechanical structure would support. **Sensitivity** 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 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 guarantee of high sensitivity is guaranteed making use of off-axis segments to form the effective primary aperture. It has been shown the advantages of off-axis telescopes by Kuhn and Hawley (1999) and Moretto and Kuhn (2000). Figure 1A shows each PSF contribution for a 6.5-m aperture telescope at a wavelength of 1μm, where Figure 1B and C show how the relative importance of edge (aperture) diffraction to the scattered surface brightness increases with

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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 [2].

We present here the strategies concerning high resolution, high sensitivity and adaptive optics and cophasing for the designing and for building such dedicated to extremely high contrast new telescope – The Colossus Project.

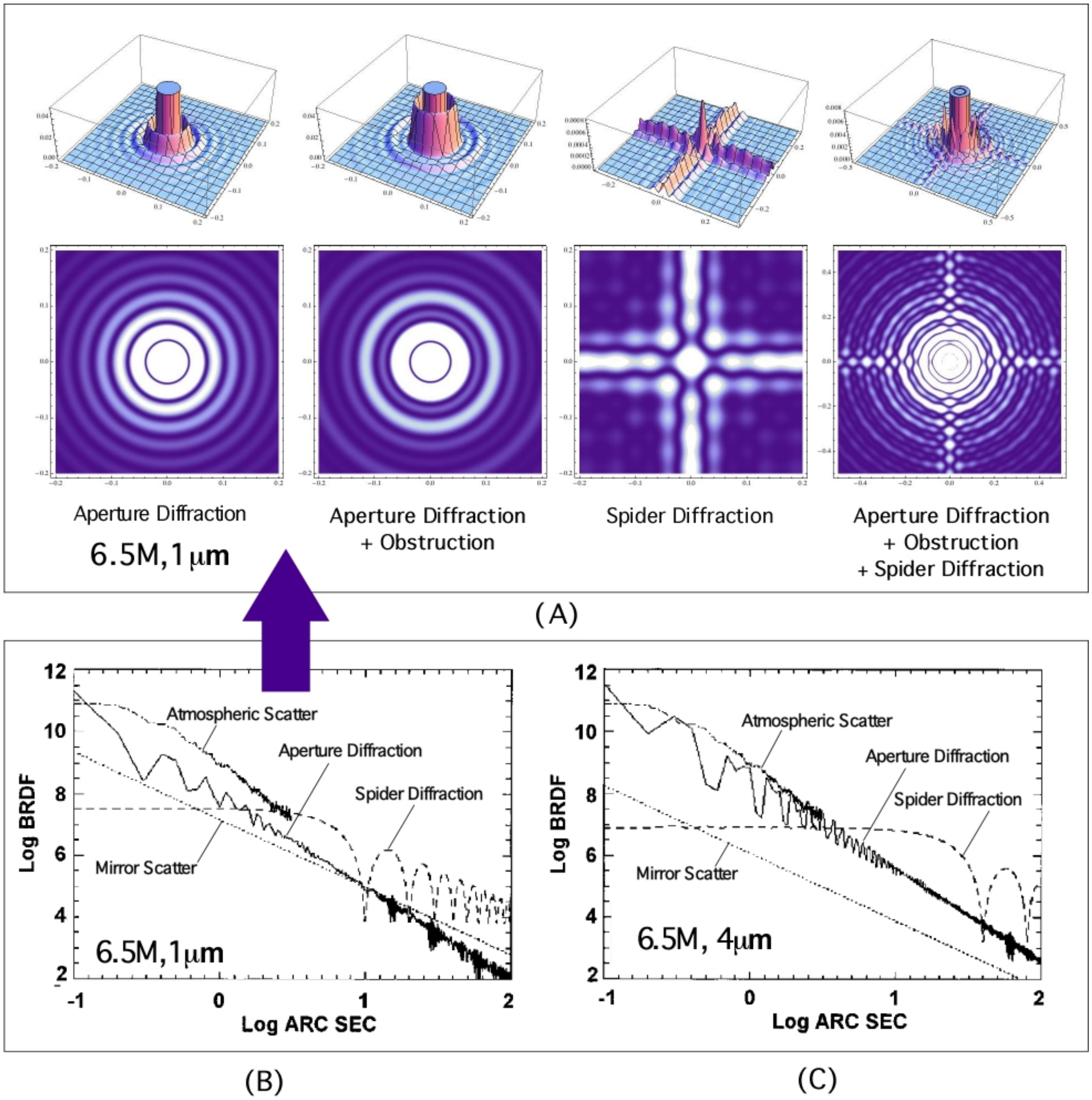


Figure 1 - **(A)** The diffraction patterns (λ=1μm) along the orthogonal θx- or θy-directions; **(up)** the 3D and **(down)** the density profiles for the 6.5m unobscured aperture (edge) diffraction, aperture diffraction with obscuration (ε = 0.250), spider diffraction along the orthogonal legs (4 legs 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 a 2cm wide secondary 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)

2. GIANT TELESCOPE CONCEPTS

The large telescope primary mirrors are segmented and can be modeled with three 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 parent primary mirror shape. The total mass of the three components of such a primary mirror system will determine the system moving mass. One solution for achieving aperture at lower cost is to reduce the mass (and stiffness requirement) for the telescope support structure. The Colossus achieves this by relying on an optical support structure that allows subaperture elements to be "loosely" aligned mechanically, and by decreasing the area mass density of the subaperture **(1)** and **(2)** mass components – thereby decreasing the total system moving mass. To minimize light diffraction and "complexity cost" the Colossus is also formed from the largest feasible subaperture units (currently about 8m diameter). This also minimizes the edge to area ratio of the full mirror system.

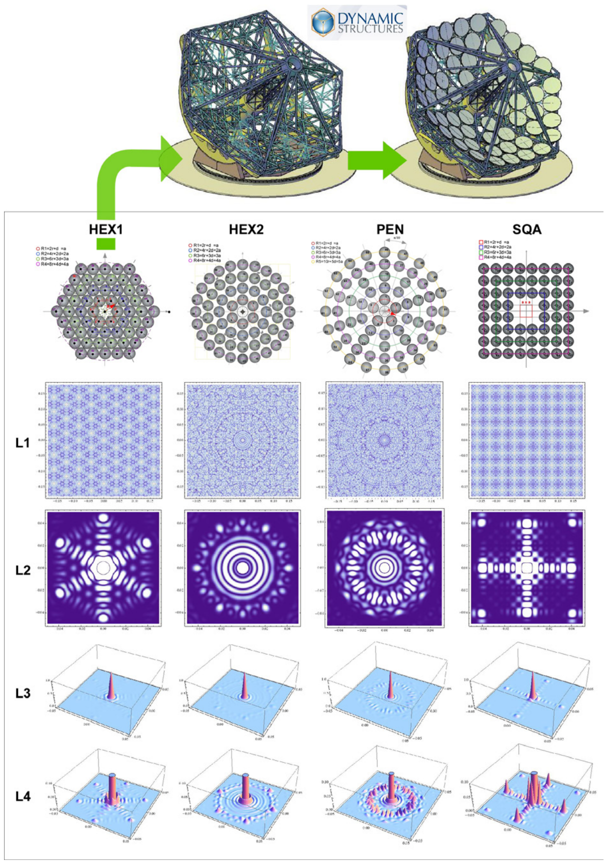


Figure 2 – The four pupil geometries HEX1, HEX2, PEN and SQA are shown in row 1. Row **L1** shows the distribution structure function for the 60 mirrors distribution for each pupil geometry for a region 0.18 x 0.18 arcsec^2 wide and separation distance d=200mm. Row **L2** shows for each pupil geometry the density plot for PSF intensity at a wavelength of 1600nm and for the region 0.05x0.05 Arcsec^2. The 3D plots of PSF intensity for the region 0.1x0.1arcsec^2 for the normalized intensity is shown in row **L3** and up to 10% PSF intensity with more details for the lobes in row **L4**. At the top a preliminary design for the telescope structure for the hexagonal distribution (HEX1).

Considering the three mechanical issues **(1)+(2)+(3)** the Colossus telescope optical configuration preliminarily adopted was the distribution of 60x8meters off-axis primary mirrors ($M1_i$) **–** But in which configuration? Figure 2 shows preliminary designs and PSF calculations done for four distributions: hexagonal (HEX1), circular-hexagonal (HEX2), pentagonal (PEN) and square (SQA). All the distribution has an adjacent separation between subapertures of d=200mm.

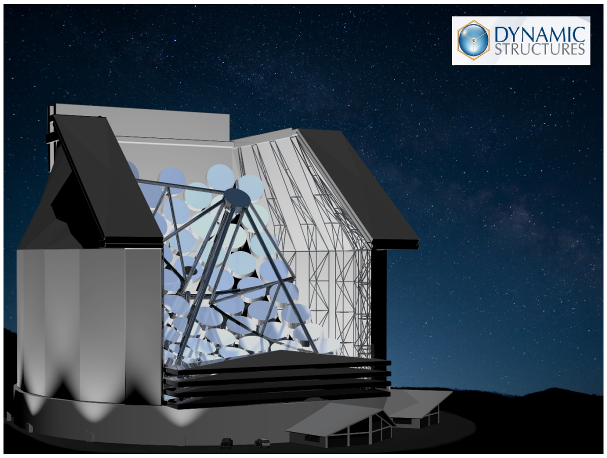


Figure 3 – The Colossus telescope preliminary enclosure as proposed by the Dynamic Structures Ltd (Canada).

Also the mechanical issues (1)+(2)+(3), the optimal Colossus subaperture mirror configuration should considers the fact that it will must operate with a structure which is not mechanically stiff and its enclosure must provide good wind isolation. To minimize the enclosure mass it is advantageous to match the enclosure opening (Figure 3) to the mirror footprint.

At the moment a rectangular mirror array has been considered. Figure 4 illustrates this configuration of 60 mirrors arranged on a relatively close-packed rectangular grid that matches the enclosure opening (Figure 3). Note this rectangular configuration outcome in a bidirectional resolution limit. What 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.

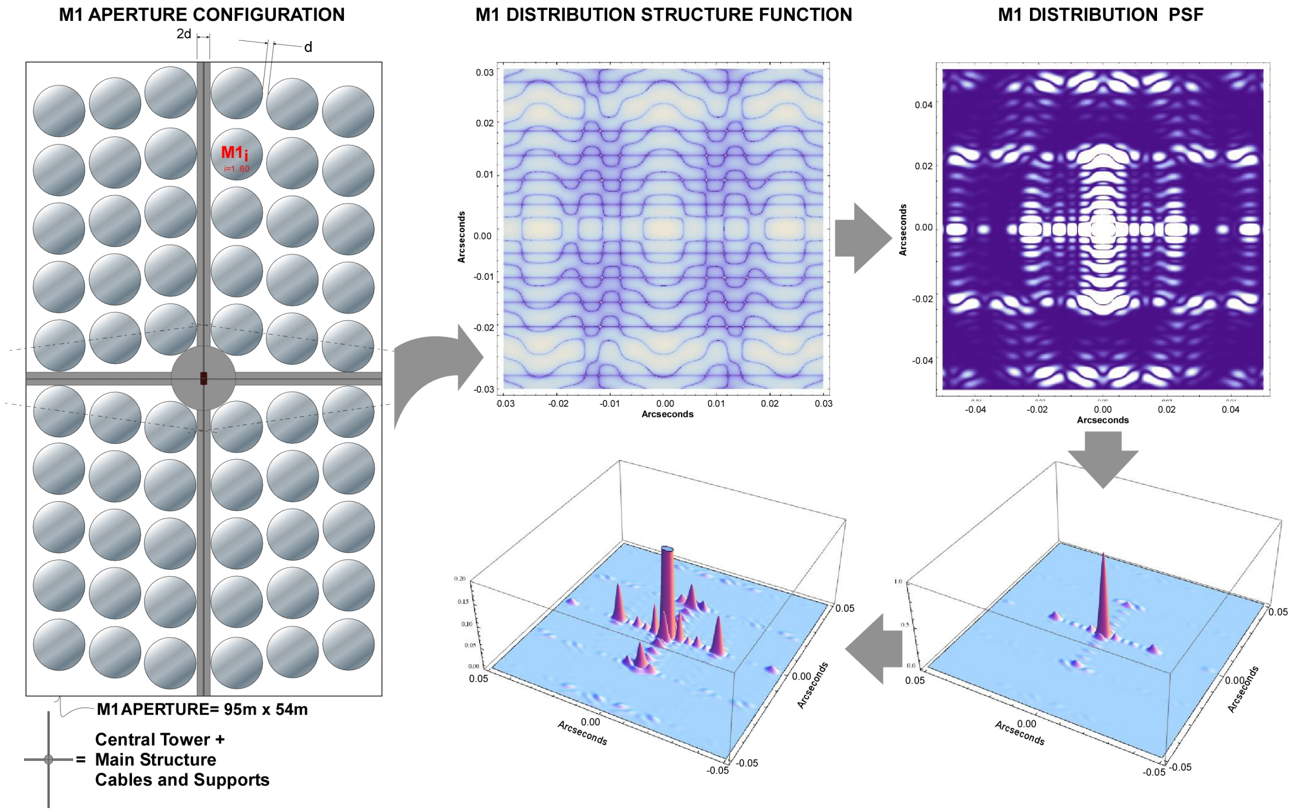


Figure 4 – The Colossus telescope optical configuration for the primary mirror and its distribution structure function and PSF. The "grey-cross" are the space reserved to the mechanical central tower and main structure cables and supports to hold the secondary mirror.

The Colossus system requires an optical configuration that is "scalable" in 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.

In order to achieve these optical 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 5. This is a rectangular grid of 60x8m telescope subapertures (Figure 5B) in a parent Gregorian geometry. The each secondary subaperture mirror has an elliptical conic (k=-0.94) and is only 180mm in diameter, (Figure 5C). 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).

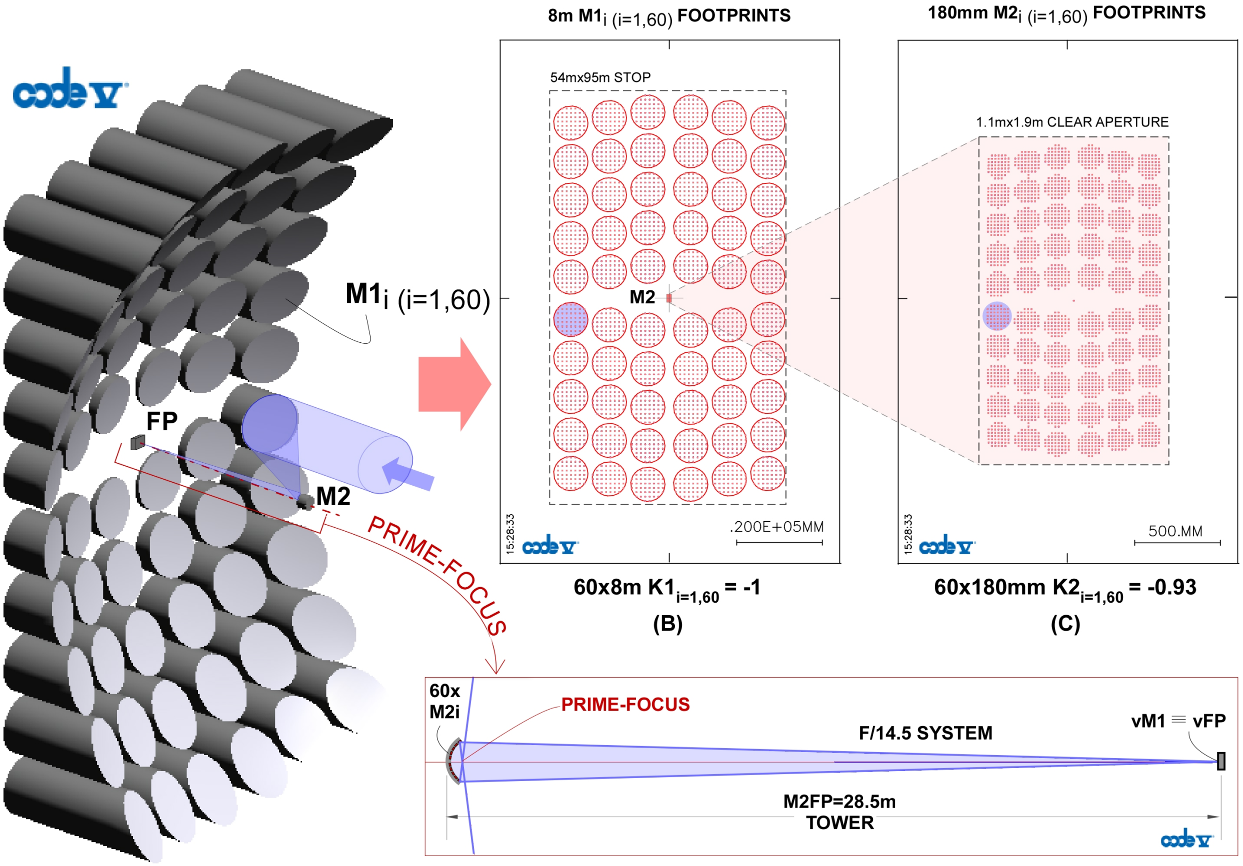
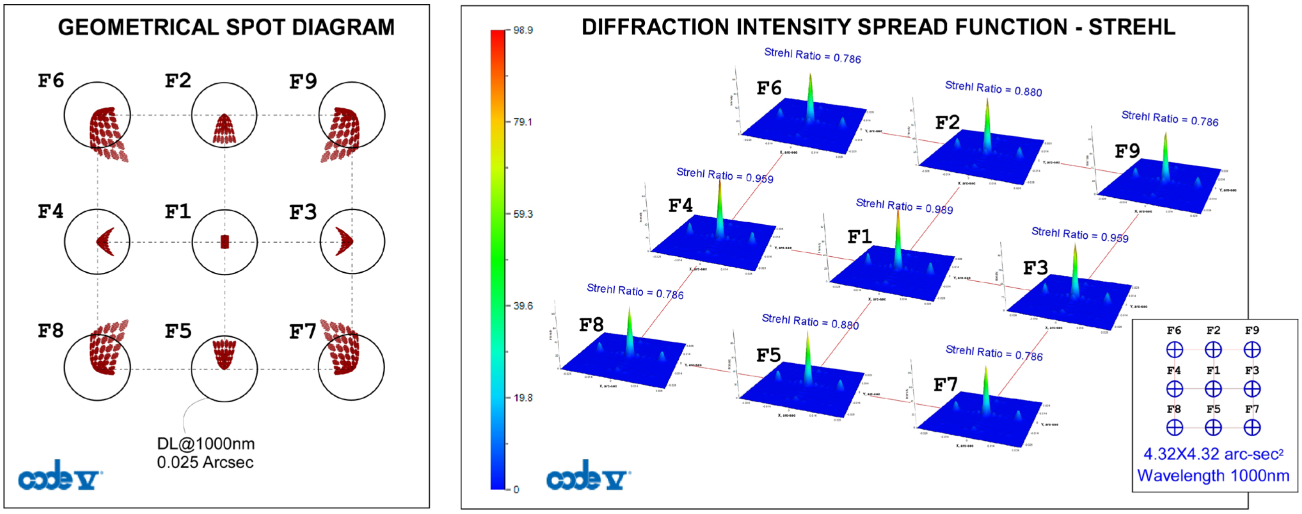


Figure 5 – The Colossus telescope optical interferometric configuration optimized for the rectangular distribution for the primary mirror. (B) The footprint for the 60x8m $M1_i$ resulting on a clear rectangular aperture of 54mx95m. (C) The footprint for the 60x180mm $M2_j$ producing a clear aperture for the parent M2 of 1.1mx1.9m.



(A) (B)

Figure 6 – The Colossus telescope optical performance: (A) Geometrical spot diagram and (B) Diffraction intensity PSFs, both across 19 Arcsec^2 and for WVL=1000nm.

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 supersede the parent optics. In such a way each subaperture delivers a high-Strehl wavefront to the beam combiner. Another deal to the adaptive optics for the telescope, which is composed from distinct AO systems working on each 8m M1$_i$ subaperture. Each of these will produce M2$_i$ subaperture small of 180mm diameter for a 19 arsec^2 field of view (FoV). This Gregorian design configuration produces an exit pupil on the M2 parent locus; a deformable M2$_i$ secondary mirrors with 36 actuators per diameter (for a 5mm pitch, yield in a 1060 actuators per 180mm diameter mirror) would be foresee considering the off-shelf technology presently available.

The optical performance across a 19 arcsec^2 is shown in Figure 6. 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 7.

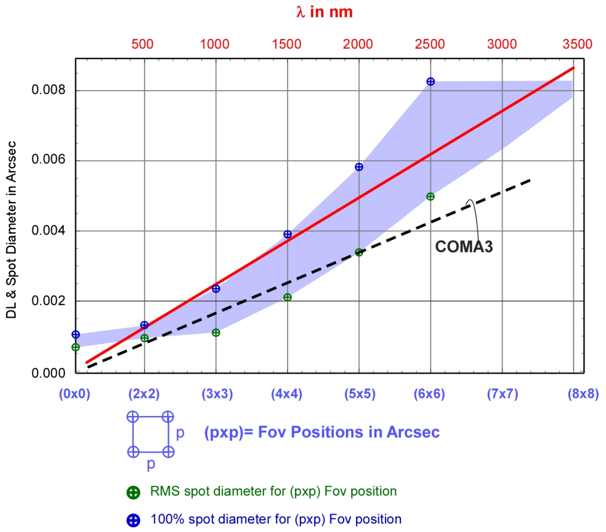


Figure 7 – The Colossus telescope optical performance across the fov size (pxp) is limited mostly by coma3 aberration increasing linearly (dashed line) from the field center. The red full line represents the diffraction limit (DL) for the circular primary parent M1 in function of wavelength (λ) in nanometers.

3. COPHASING VIA PHASE DIVERSITY

Cophasing a multi-aperture telescope is a critical and crucial issue to guarantee and assure the telescope performance without degradation by phase perturbations. We propose to exploit phase diversity (PD) approach to estimate the residual phase aberrations which are due to piston and tip-tilt errors for each M1$_{i(i=1,60)}$ segments.

Phase diversity is a focal plane technique proposed by Gonsalves (1982) to estimate the phase aberrations without ambiguities. It however requires to jointly estimate the object brightness distribution and, being highly non-linear, it relies on iterative (and hence slow) algorithms to find the solution. Blanc et al. (2003) showed that marginalization (that is, integrating the object out of the problem) yields better phase estimation. The phase estimated by Gonsalves (1982) and Blanc et al. (2003) corresponds to the maximum likelihood (ML). Rondeau et al. (2007) proposed a global optimization method for *a maximum a posteriori* (MAP) phase restoration from a single focal-plane image. However their method may be too slow for real-time applications and relies on phase priors to cancel the ambiguities and assumes the object shape is known. Meimon et al. (2008) considered using phase diversity to phase a segmented mirror and to compensate slowly variable aberrations of low order (piston and tip-tilt). They showed that an accurate correction ($\sim \lambda/100$) is reachable with integration times of a few seconds. For a point-like object and a noncentrosymmetric (nonredundant) pupil, Baron et al. (2008) demonstrated that a single focal plane image was sufficient for cophasing a multi-aperture telescope (Figure 8). This method can be extended for cases where the object is extended providing its shape is known. The constraint of having a noncentrosymmetric pupil is to avoid a sign ambiguity in the estimation of the even part of the phase. We however would rather not impose such constraints for the purpose of estimating the residual aberrations as the pupil configuration should be driven by coronographic considerations via co-design strategy (Figure 9). In the regime of small aberrations, it is possible to linearize the problem and thus derive an analytical solution to the co-phasing problem from phase-diversity images (Baron et al., 2008; Mocœur et al., 2009), yielding in a fast method suitable for real-time applications.

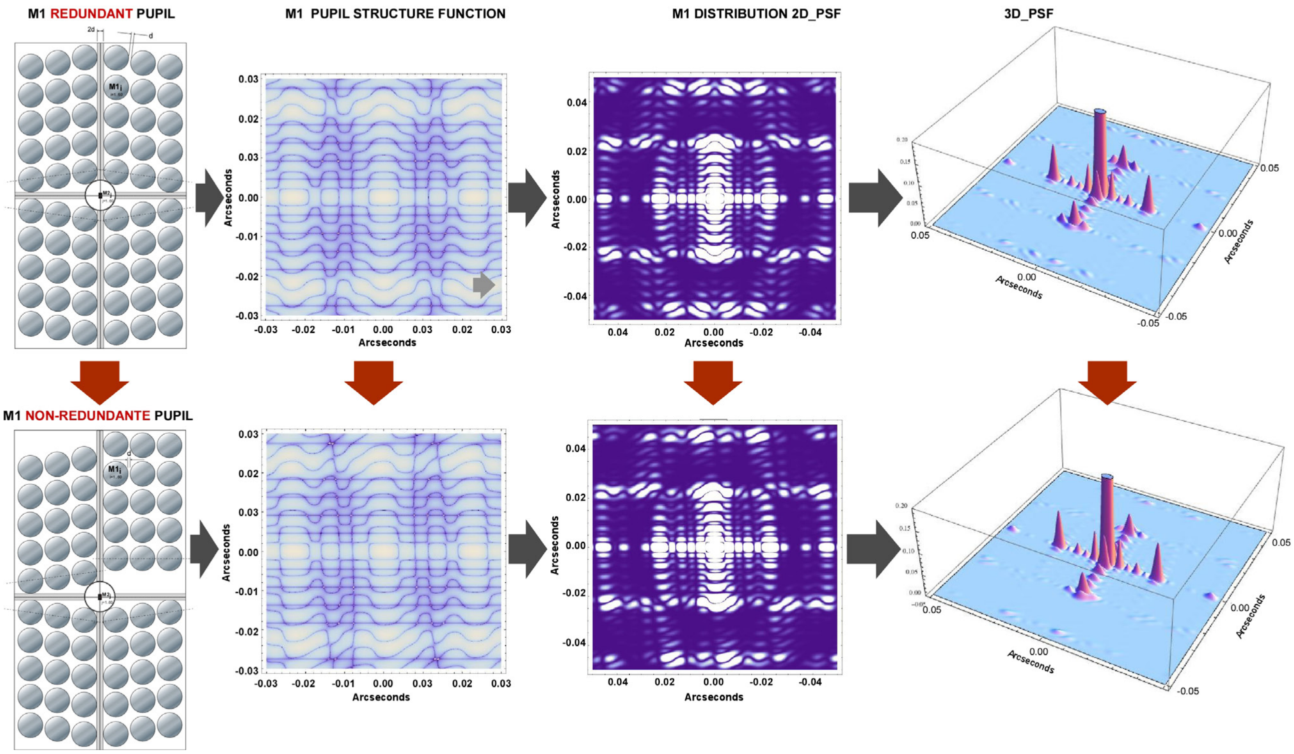


Figure 9 – A skewed pupil configuration produces a non-symmetrical structure function and PSF. The constraint of having a noncentrosymmetric pupil is to avoid a sign ambiguity in the estimation of the even part of the phase.

To meet our requirements for the cophasing of the segmented mirror of the Colossus telescope by means of phase diversity, a number of issues have to be solved:

1. **Solving for ambiguities.** To have the simplest setup, we would favor methods based on a single focal-plane image. This gives rise to several ambiguities related to the unknown shape of the object and to the insensitivity to the sign of the even part of the global phase aberration if the synthesized pupil is centrosymmetric (redundant pupil). Providing that the phase aberration have limited amplitudes (this is certainly true in closed-loop mode), it is possible to add a known even aberration so as to shift the even part of the phase aberrations toward positive (or negative) values and thus remove the ambiguity (Meimon, 2010).
2. **Estimating the shape of the object.** At the resolution of a 74m telescope, the observed object will be resolved and its shape must be known to estimate the phase from a single focal-plane image. Using a pair of images (with a different focalization) is the conventional mean to solve this issue. In our case, we expect to be able to derive a good approximation of the object brightness distribution from a sequence of images as the object remains steady while the aberrations, and hence the PSF, change. For instance, we can exploit a multi-frame blind deconvolution method (Schulz, 1993).
3. **Fast phase restoration.** The correction must be estimated and applied in real-time, this put strong constraints on the allowed computational burden for the algorithm in charge of the data processing. In the small aberrations regime (at least when the loop has been closed), the linearized version of the phase restoration algorithm (Baron et al., 2008; Mocœur et al., 2009) will match our needs. When the loop is not yet closed, we have to demonstrate whether a limited number of iterations of a non-linear method can substantially improve the phase estimation so as to quickly close the loop.
4. **Improving the precision.** Another consequence of the fast acquisition rate, is the limited amount of photons that will be available for the analysis. This can severely impact the precision of the estimated phase. In order to integrate the photons on a larger spectral bandwidth, we foresee to exploit polychromatic images acquired simultaneously. This would not only improve the accuracy of the estimated parameters but also help to avoid quasi-ambiguities in the phase restoration problem (Rondeau, 2007).
5. **Toward *co-design*: benchmarking the algorithms and the pupil configurations.** In the case of the estimation of the aberrations from focal-plane image(s), we have derived the formal expression of the Fréchet-Darmois-Cramér-

Rao bound. This gives us the best possible accuracy of any unbiased estimator and will be a very useful tool to compare different optical configurations (Figures 2 and 4) and assess the performances of the phase restoration algorithms (Figure 9).

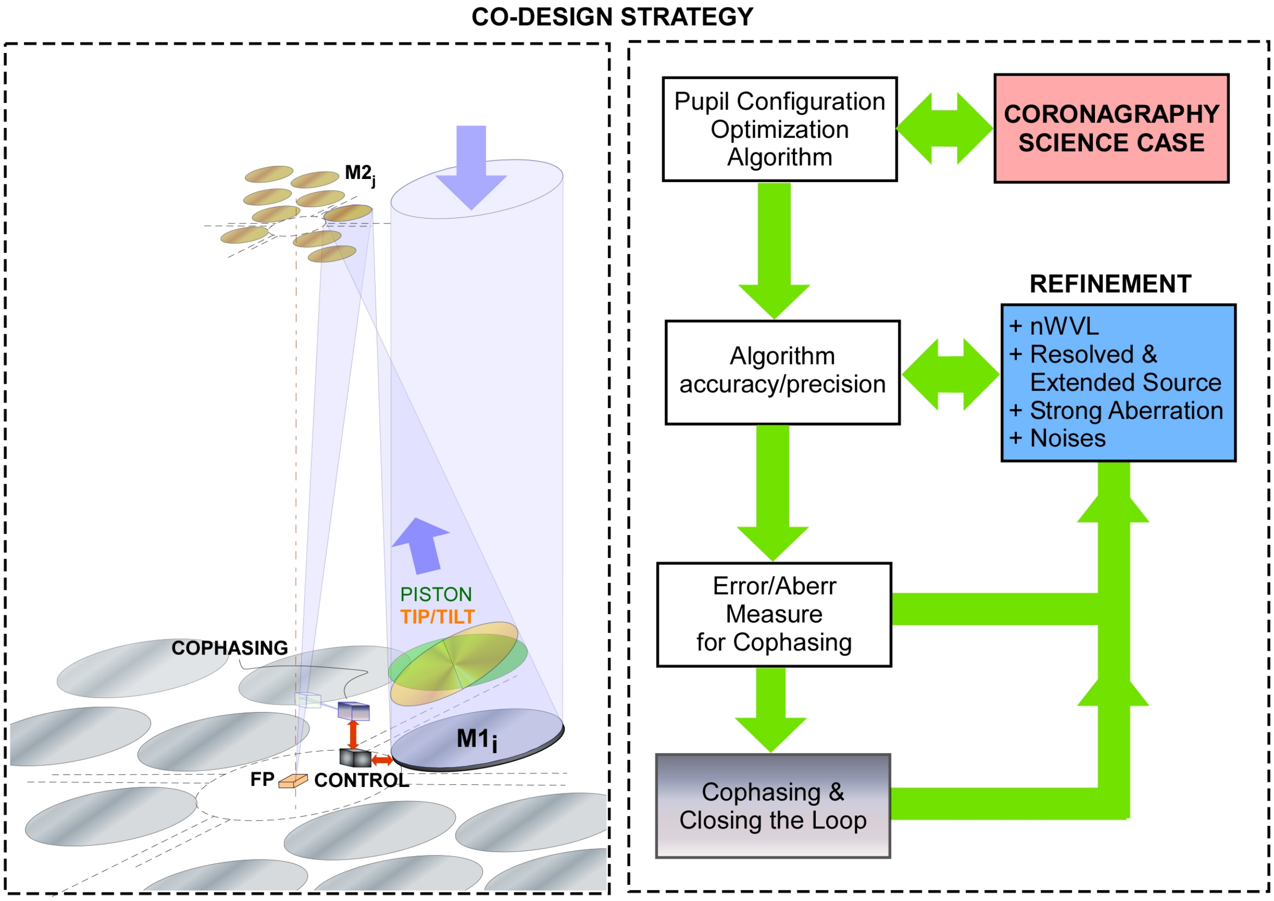


Figure 9– Cophasing via co-design a **benchmarking the algorithms and the pupil configurations.** A refinement procedure to look for the best possible accuracy of any unbiased estimator and will be a very useful tool to compare different optical configurations and assess the performances of the phase restoration algorithms.

How the telescope “boots up”: 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 (Baron et als, 2008). 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 10µm and these can also be obtained using a phase-diversity least-squares solution. Figure 10 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[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.

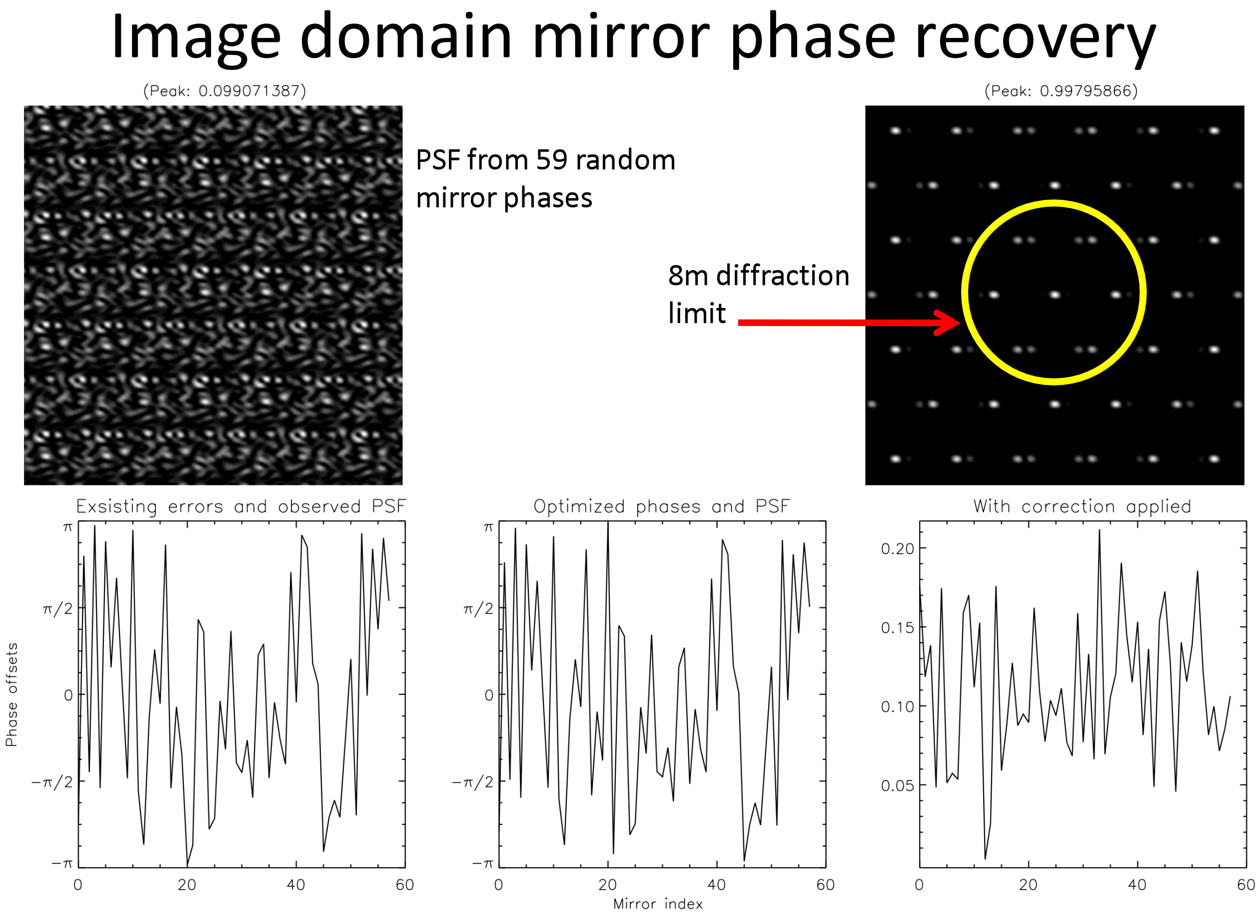


Figure 10 - A non-iterative direct mirror phase solution for N=59 in a non-redundant configuration. The left panel shows the intensity speckle pattern for random mirror phases. The right panel shows the intensity after direct least-square minimization. The lower graphs show the input, reconstructed, and residual phase errors for 59 mirrors.

4. CONCLUSIONS SO FAR AND NEXT

We propose a new ways to build and to make large telescopes. The Colossus telescope is optimized for its dynamic range and resolution performance. This is a narrow-field coronagraphic telescope dedicated to the studies of faint object near bright optical surfaces, for example exoplanetary science. New strategies for building such a telescope with large circular segments using adaptive optics correction independently for each of these segments prior to cophasing the segments have been proposed here. The decision on the pupil configuration for the primary mirror will be a compromise between opto-mechanical issues, science cases and cophasing strategies. The cophasing co-design strategy using focal plane images allows piston and tip/tilt measurements and correction between all the segments.

Next we intend to improve the co-design strategy to solve all the issues concerned to the implementation of phase-diversity procedure adapted to the Colossus Telescope. Also we intend to perform detailed simulations of this cophasing scheme including adaptive optics correction. At the end we would like to demonstrate that a natural star can be used successfully by a multiwavelength focal-plane image sensor to cophase in real time a telescope composed of sixty 8m circular segments and to reach very high contrast compatible with imaging of extrasolar planets and detecting an exoplanetary life signal. Also in the frame of this project, we'll continue to investigate the possibility of performing extreme adaptive optics correction quasi independently for each of the segments prior to cophasing the segments. Detailed numerical analysis of this multi-segmented extreme adaptive optics system and its possible trade-offs will be our next efforts.

Finally 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/m^2. The Colossus group has prototyped these new technologies that will enable lightweight mirror controls, and has developed an optical design for a 77m 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.

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