Highly sensitive telescope designs for higher contrast observations

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Off-axis telescopes have better emissivities, throughputs, diffraction-limited energy concentrations, and higher dynamic ranges than traditional concentric instruments.

The effectiveness of telescope systems with conventional obstructed on-axis concentric designs are limited by scattered light and emissivity caused by their auxiliary mirrors (see Figure 1A).1 Over field angles that range from a few arcseconds to several arcminutes, the importance of edge (aperture) diffraction, relative to the scattered surface brightness, increases with wavelength and dominates telescope point spread functions (PSF), which is the response of an imaging system to a point source (see Figure 1B and C).2,3 These light scattering characteristics limit the performance of telescopes when they are used to make measurements requiring a very high photometric dynamic range. Such measurements include astronomical observations of faint objects that are close to bright sources (e.g., extra-solar planets).

To improve the scientific capabilities and performance of telescopes, light scattering needs to be controlled and minimized. Optical technologies now exist that enable telescope PSF core energies to be maximized while simultaneously minimizing the side scattered light flux.4 An example of this new breed of optical instruments is the Advanced Technology Solar Telescope. This is a 4.2m off-axis high-dynamic range telescope, and it is currently being constructed on Haleakala in Maui.5

Our novel instrument design (see Figure 2) for the High Dynamic Range Telescope (HDRT) provides high sensitivity for observing faint astronomical objects that are located in the environment of bright sources. This specification also provides a wide-field observation mode. Our work on HDRT demonstrates how mirror segments in large optical or infrared astronomical telescopes can be arranged so that maximum image clarity and the best adaptive optics (AO) systems, which remove the effects of atmospheric distortion, can be achieved.6 We encountered some particular difficulties in the design process. These included the mirror edges, which are difficult to polish accurately, and the

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pupil element. The relatively large angle-diffracted energy from a point source increases with the perimeter-to-area ratio of the pupil element. Straight-line edges in the pupil also tend to localize diffracted light to larger angles than those achieved with curved segments. We use large circular-segment unobstructed pupils to overcome this limitation. This approach minimizes light scattering and the number of edge supports required to actively control each mirror surface and provides unrivaled clarity. We conducted a study which showed that a hexagonal pattern of circular mirrors with a spacing of 4% larger than the diameter of each mirror can almost reproduce the resolution and performance of a single large mirror of equal diameter. We employ this specific ratio in the placement of the 8m mirrors in the HDRT pupil plane.

Figure 2 shows the HDRT concept layout that we proposed in 2000. By using a $6 \times 6.5m$ off-axis mirror segment, this design achieved an effective light collecting area that is equal to that of an unobstructed 15.9m diameter telescope. Although 8m mirror segments are optimal, we chose the 6.5m off-axis segments due to polishing cost concerns for larger mirrors. It is now known that off-axis segments have a diameter limit of 8.4m. Our HDRT optical configuration is unique in its ability to operate in a wide-field mode while serving also as a narrow-field mode imaging and a full AO compensated coronagraphic telescope. Since the mirrors do not touch, it is possible to design an efficient mechanical system that supports both the mirrors and the instruments, and secondary optics can be added. The 25m Giant Magellan Telescope is based on seven 8.4m segments and has partly adopted the HDRT concept design, whereby the secondary mirror is segmented to match the primary one. The small, agile secondary segments perform the fine alignment for each primary mirror. In addition, the secondary mirrors are deformable and enable AO, phasing, and the coherent combination of the sub-apertures.

We have proposed a novel wide-field infrared survey off-axis telescope concept for Antarctica (2.5@C) that is based on our HDRT design. This system (see Figure 3) will use the unique properties of the atmosphere above the Antarctic Plateau. The sky opacity, particularly in the infrared, is considerably lower than average and the thermal infrared sky background radiation is 10–20 times lower in the 2–3μm range. A medium or large aperture telescope, such as this, on the Antarctic Plateau has the potential to accomplish tasks that were previously thought to be possible only in space, such as the imaging and spectroscopy of Earth-sized extra-solar planets.

Using the HDRT design, we are able to develop a concept that consists of 60 independent off-axis 8m pupils (see Figure 4). A preliminary PSF calculation shows that this telescope-interferometric model can achieve a 74m effective resolution that is better than 1 milliarcsecond and a raw-contrast of about $10^{-5}$. This visualization could be used as the basis for a highly capable system if used on the Antarctic Plateau.

We believe that many areas in modern astrophysics are dynamic-range limited rather than flux-limited. The collection of more photons cannot solve these problems. Better (i.e.,
Figure 4. A concept developed from the High Dynamic Range Telescope (HDRT) design. This achieves a 74m effective resolution with its 60 independent off-axis 8m pupils. PSF: point spread function.

off-axis) telescopes used at specialized sites, rather than bigger ones, are required. The technology involved is now sufficiently mature to make off-axis telescopes feasible. We are now focusing on how to arrange mirror segments in large optical or infrared astronomical telescopes to maximize their dynamic range. Although the future telescopes we propose do not have circular symmetry, they will significantly improve large-angle scattered light performances and out-of-field rejection properties, reduce telescope emissivities, and provide better core PSF fidelity from AO systems.

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Gil Moretto’s research interests are off-axis telescopes and astronomical instrumentation, including adaptive optics to achieve high contrasts and resolutions.

References