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Review Article

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Highly sensitive telescope designs for higher contrast observations

Abstract: Off-axis telescope concepts that use unobstructed pupils have better emissivity, throughput, diffraction-limited energy concentrations, and higher dynamic range than traditional concentric instruments. The coronagraphic performance of off-axis telescopes will enable instruments, which are starved for higher dynamic range, for example, those devoted to faint companion detection, circumstellar and solar atmosphere studies.

Keywords: higher dynamic range; low emissivity; low scattered light; off-axis telescope.

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1 Introduction

The effectiveness of telescope systems with conventional obstructed on-axis concentric designs are limited by scattered light and emissivity caused by their auxiliary mirrors. Over field angles that range from a few arc-seconds to several arc-minutes, the importance of edge (aperture) diffraction, relative to the scattered surface brightness, increases with wavelength and dominates telescope point spread functions (PSF). 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 such telescopes, light scattering needs to be controlled and minimized. How? – off-axis telescopes.

We review here, off-axis telescopes already built and proposed concepts, and address some misconceptions about their feasibility [1]. Novel telescopes like Scatter-free Observatory for Limb Active Regions and Coronae (SOLARC) and New Solar Telescope (NST) are pathfinders for future off-axis telescope projects that help to overcome the technical and engineering challenges specific to this kind of design.

The polishing of the first 8.4 m parabolic off-axis section mirror by the SOML (The University of Arizona, Steward Observatory Mirror Lab, Tucson, AZ, USA) is also a fundamental milestone for which the NST was a pathfinder toward technology maturity. The SOML is not alone; European fabricator (REOSC/France) (REOSC is a subsidiary of Safran/Sagem high tech group, France) and industrial and university collaboration initiatives (UNAM/Mexico & Innovative Optics/Canada) are routinely polishing off-axis optics.

2 Advantages of off-axis telescopes

It has been shown that telescopes systems making use of a conventional obstructed on-axis concentric design are limited by the scattered light and emissivity caused by the auxiliary mirrors. Figure 1 shows a representative image of a bright star obtained with a conventional 4-m aperture astronomical telescope. Most of the diffuse structure in the image is the result of spurious scattered and diffracted light from the material obstruction of the pupil associated with the secondary mirror. The scattering from the primary and secondary mirrors causes the faint radial flares near the center of the image, while much of the scattered light haze in the image core is due to atmospheric scatter. The various scattered light source contributions for a conventional on-axis telescope has been analyzed and described by Kuhn and Hawley [2] and Moretto and Kuhn [3].

Each PSF contribution for a 6.5-m aperture telescope at a wavelength of 1 μm is shown in Figure 2A. Figure 2B and C show how the relative importance of edge (aperture)

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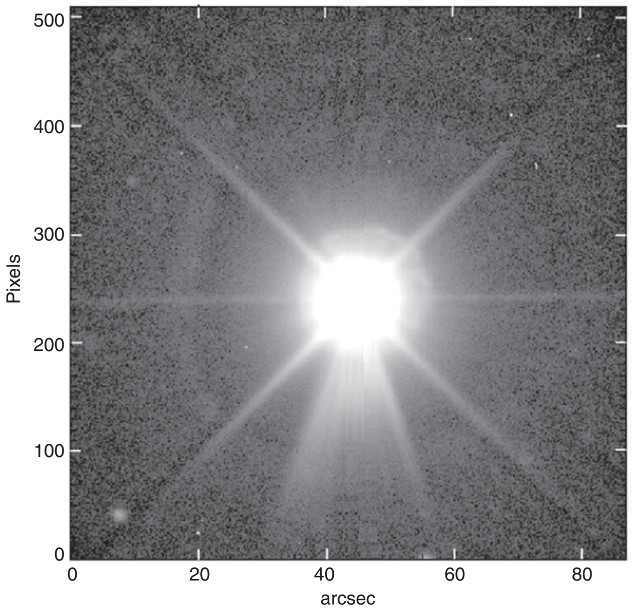

Figure 1 A representative bright star image obtained with a conventional 4-m aperture obscured astronomical telescope (CTIO Blanco 4 m). Part of the sky is hidden from our point of view by scattered light. The display range shows 3 orders of magnitude and is logarithmic [3].

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 [2]. The effectiveness of an unobstructed pupil is still more relevant for thermal infrared optimized telescopes reducing the sources of self-thermal emissivity. Figure 3 shows the image of the Gran Telescopio Canarias (GTC) telescope pupil showing some of the warm components of the telescope emission. In light gray color, we can see the emission from the interspace between M1 segments (1) and from the M2 support structure spider (2). Such advantages will be a must for space-based telescopes [4].

Another advantage inherent to off-axis telescopes is the absence of 'holes' in a convex pupil where wavefront information would otherwise require interpolation. This has advantages for interferometry and adaptive optics where beams must be combined, or the rotating time dependent PSF of the telescope (for example, from an alt-az mount) can introduce wavefront errors.

3 Some pathfinder telescopes

Two optical/IR off-axis solar telescopes have been built: SOLARC and NST. Such projects have served as pathfinder prototypes to larger telescopes now underway.

SOLARC – Scatter-free Observatory for Limb Active Regions and Coronae is a 0.5-m off-axis coronagraphic reflecting telescope located on Haleakala (Hawaii) adjacent to Mees Solar Observatory. Construction was started in October 1998 and first light (Figure 4) was achieved in August 2001. The scientific goals are to (i) provide more accurate coronal measurements, which have not been realized, even from space, in order to explain and better understand many solar phenomena; (ii) support several long-term coronal observing platforms, which extend intermittent coronal space observations. SOLARC has acted as a 'prototype off-axis telescope' in order to provide a model environment for the others projects – such as 1.6 m NST, 1.9 m PLANETS, and 4.2 m ATST – and to enable more thorough understanding of how to overcame the technical and engineering challenges specific to this kind of telescope design: alignment, heat dissipation, and guiding off of asymmetrical phenomena. The pioneer SOLAR-C has addressed some of the off-axis telescope misconceptions: aberrations are not worse than conventional telescopes; off-axis telescopes can be aligned, and large off-axis mirrors are polishable.

NST – New Solar Telescope is so far the largest aperture and highest resolution solar off-axis telescope. The 1.6-m off-axis primary mirror is housed at the Big Bear Solar Observatory (BBSO) in California. NST is a collaboration of BBSO/NJIT with the University of Hawaii and the Korea Astronomy and Space Science Institute. The NST used and employed the SOLARC 'savoir-faire' for its realization (see Goode and Cao [5]).

BBSO has installed NST, and first light (2010) with adaptive optics has been attained in the Coudé Lab at the Nasmyth focus. A first light image of granulation is shown in Figure 5E. The new telescope offers a significant improvement in ground-based high angular resolution capabilities and will substantially enhance our efforts to understand our dynamic star. NST is fully operational, and it also acts as a pathfinder for future off-axis telescope projects to improve the maturity of evolving technologies (Figure 5). Its larger aperture and larger primary mirror off-axis distance than SOLARC mark a successful trend. In particular, the 1.6-m off-axis primary mirror (Figure 5C) was polished by SOML and used as a prototype (proof-of-concept) for the 6×8.4-m parabolic off-axis mirrors for the GMT (as discussed later). The NST M1 was figured to a final residual error of 16 nm RMS.

4 Off-axis telescopes underway

Following the SOLARC and NST, two projects have been proposed, funded, and are underway: ATST and PLANETS.

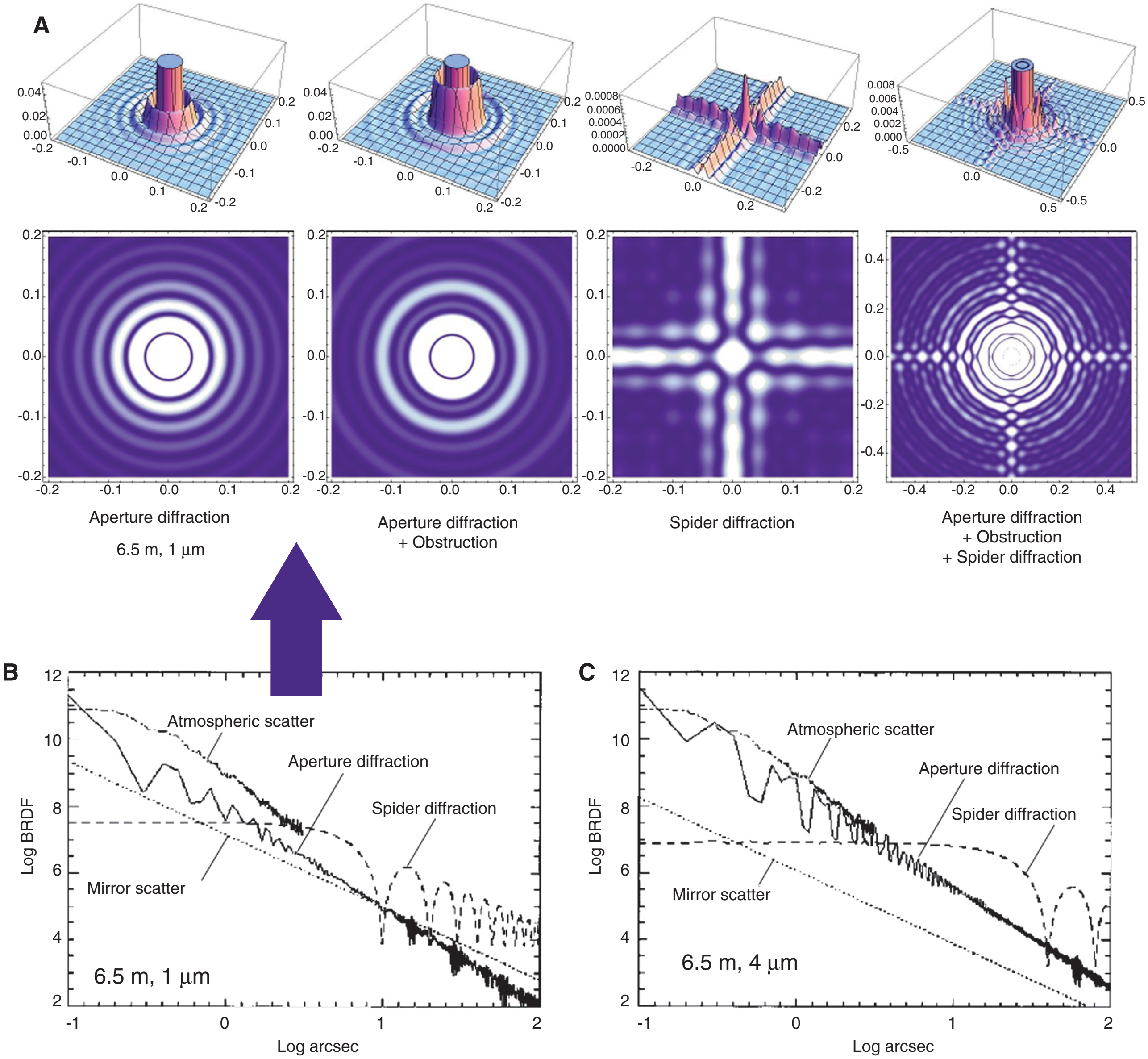

Figure 2 (A) The diffraction patterns (λ=1 µm) along the orthogonal θx- or θy-directions; (up) the 3D and (down) the density profiles for the 6.5-m unobscured aperture (edge) diffraction, aperture diffraction with obscuration (ε=0.250), spider diffraction along the orthogonal legs (four legs 50 mm×3250 mm), and finally all PSF diffraction contributions. (B) and (C) are the scattered light PSF contributions for a conventional 6.5-m telescope at 1 µm and 4 µm. 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 2-cm-wide secondary mirror support spider, and the dash-dotted line shows the atmospheric BRDF for an atmosphere characterized by a 15-cm Fried parameter [1].

ATST – The Advanced Technology Solar Telescope [recently renamed the 'Daniel K. Innouye Solar Telescope' (DKIST)] is a project of the National Solar Observatory operated by the Association of Universities for Research in Astronomy (AURA), under a cooperative agreement with the US National Science Foundation (NSF). ATST represents a collaboration of 22 institutions, reflecting a broad segment of the solar physics community. The construction phase of the project, to build the next-generation ground-based solar telescope, is underway now Figure 6 (see McMullin et al. [6]).

The telescope is an off-axis Gregorian configuration based on an altitude-azimuth mount with independently rotating Coudé platform. Its optical performance is optimized across a 3-arc-min FOV producing seeing limited observations under excellent atmospheric conditions (0.15-arcsec images). With its integrated AO system, it will yield diffraction-limited solar images with a Strehl ratio

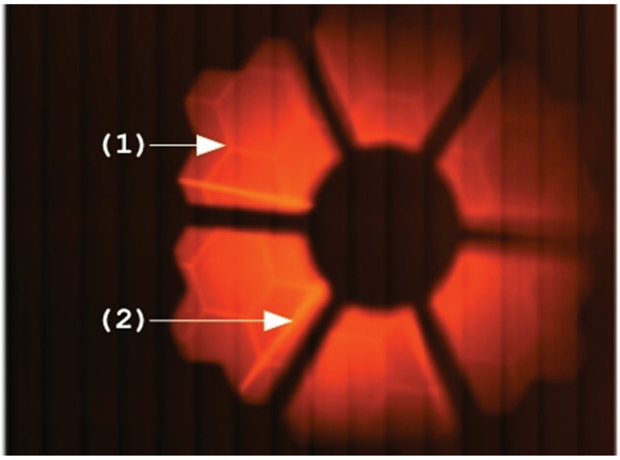

Figure 3 Image of the Gran Telescopio Canarias (GTC) telescope pupil (at 10 μm) showing some of the warm components of telescope emission; (1) emission from the interspaces between M1 segments and (2) from the spider support structure. The 'Rose Petal' Lyot mask within CanariCam was used, and coronography plate scale is 0.08 arcsec/pixel. (http://www.gtc.iac.es/instruments/canaricam/MIR.php) [1].

better than 0.3 at a wavelength of 500 nm. Scattered light performance goal is <2.5×10^{-6} of solar disk brightness at 1/10th solar radii from limb at λ=1000 nm. Its fractional polarization accuracy will exceed 5×10^{-4}. DKIST will, by far, be the world's largest coronagraph optimized for high dynamic range observations over the full visible and IR spectrum.

The 4.2-m off-axis telescope DKIST project is the latest in a sequence of mature smaller off-axis telescopes like SOLAR-C and NST. It will define a new state-of-the-art in terms of off-axis telescope and adaptive optics technologies in order to deliver unprecedented abilities to view details and to advance our understanding of the Sun.

PLANETS – This off-axis telescope represents the interests of many institutions and research groups across the globe: Tokoku University (Japan); Institute for Astronomy, University of Hawaii (HI, USA); Kiepenheuer Institute for Solar Physics (Germany); The National University of Mexico (Mexico); Laboratory for Atmospheric and Space Physics, University of Colorado (CO, USA).

The PLANETS 1.9-m off-axis telescope (Figure 7A) expands the trend from the 1.6-m NST, but as a nighttime telescope. This telescope will be ideal for coronagraphy and other techniques requiring stable optical path, as it will be seeing limited with very low instrumental scattered light. By combining expertise from various

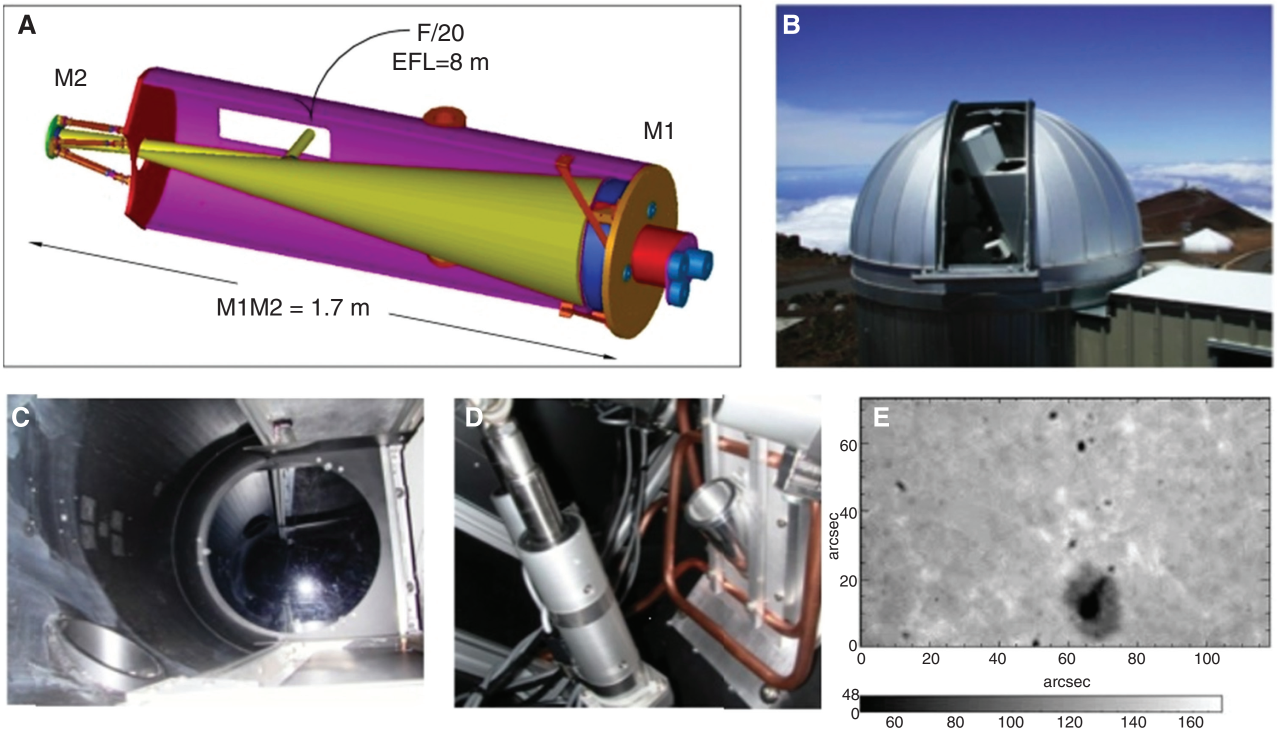

Figure 4 SOLARC.
(A) The off-axis Gregorian system with a 0.45-m diameter primary mirror. The prime focus plate scale is 120 arcsec/mm with a focal ratio of f/3.8. The system is a F/20 diffraction-limited over an 18 arcmin field at 1 μm. (B) SOLARC Dome above looking west southwest. A look at the construction of SOLARC showing in (C) the 0.5-m off-axis primary mirror and in (D) the field stop cooling system. The first light was achieved in 2001, when the telescope captured this sunspot image (E). (http://www.ifa.hawaii.edu/haleakalanew/solarc.shtml) [1].

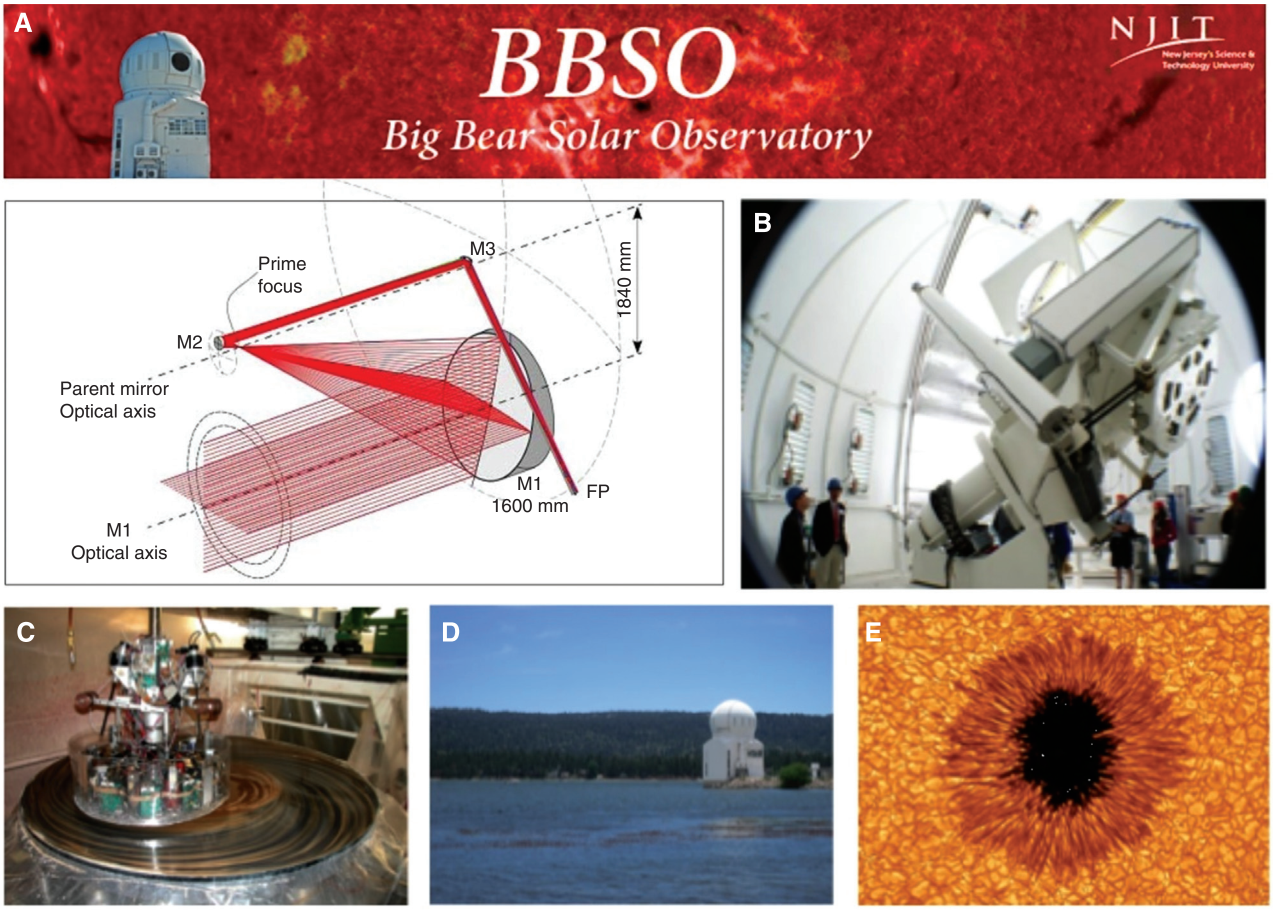

Figure 5 NST.
(A) The off-axis Gregorian system with a 1.7-m diameter F/2.4 primary mirror. The Gregorian focus is a F/52 (EFL=83.2 m) with a plate scale 2.48 arc-s/mm. (B) The NST open telescope structure with an equatorial mount. The primary mirror is supported by 36 actuators that can blend out low-order aberrations, such as those due to the gravity and/or thermal effects. M1 cell is clearly visible beneath the telescope structure. (C) The M1 being polished with 30 cm stressed lap at SOML. (D) The telescope is located in the lake, which provides a natural inversion that minimizes the image blurring caused by atmospheric turbulence. (E) First Light with AO: Sunspot observed in TiO 706 nm on July 2, 2010. A small sunspot (dark) in this approximately 25×40 arcsec image is surrounded by its penumbra (elongated fibrils). The penumbra is then surrounded by the Sun's ubiquitous granular field. The individual granules are the bright cells that can be as large as California. This picture was selected in 2010 as the most precise picture of the Sun [Ciel et Espace Magazine (France)] (http://www.bbso.njit.edu/) [1].

fields – coronagraphy and high-contrast imaging from solar physics, polishing, polarimetry, and adaptive optics from astronomical communities and the experience of each institutional partner, this telescope will make significant advances in several fields. The telescope will be constructed on Haleakala, a 3000-m (10 000 ft) volcano on the island of Maui, HI, with excellent weather and seeing.

The telescope uses several new technologies to minimize the telescope mass at given stiffness, while significant effort will go into minimizing the diffuse scatter from mirror roughness – a major source of scattering at large angles. UNAM/IA (Universidad Nacional Autónoma de México, Instituto de Astronomía) has developed a new tool Hydro-dynamic Radial Polishing Tool (HyDra) (Figure 7B) to rapidly and deterministically polish smooth surfaces. The group has recently demonstrated 1/100th of wavelength optical polish quality (Figure 7C). Figure 7D shows an 84-cm diameter mirror making use of HyDra. This polish will further reduce the diffuse scattered light component from the telescope increasing the dynamic range of the telescope. Hydra is now a trademark and has been commercialized by IO (Innovative Optics Ltd., http:/hciolivemirror.com/vision.html) and DSL (Dynamic Structures Ltd., http://www.empireds.com). Currently, the PLANETS CLEARCERAM®-Z (Ohara, Inc. glass-ceramic with an Ultra-Low Thermal Expansion Coefficient. http://www.ohara-inc.co.jp/en/product/electronics/clearceram.html) blank has been

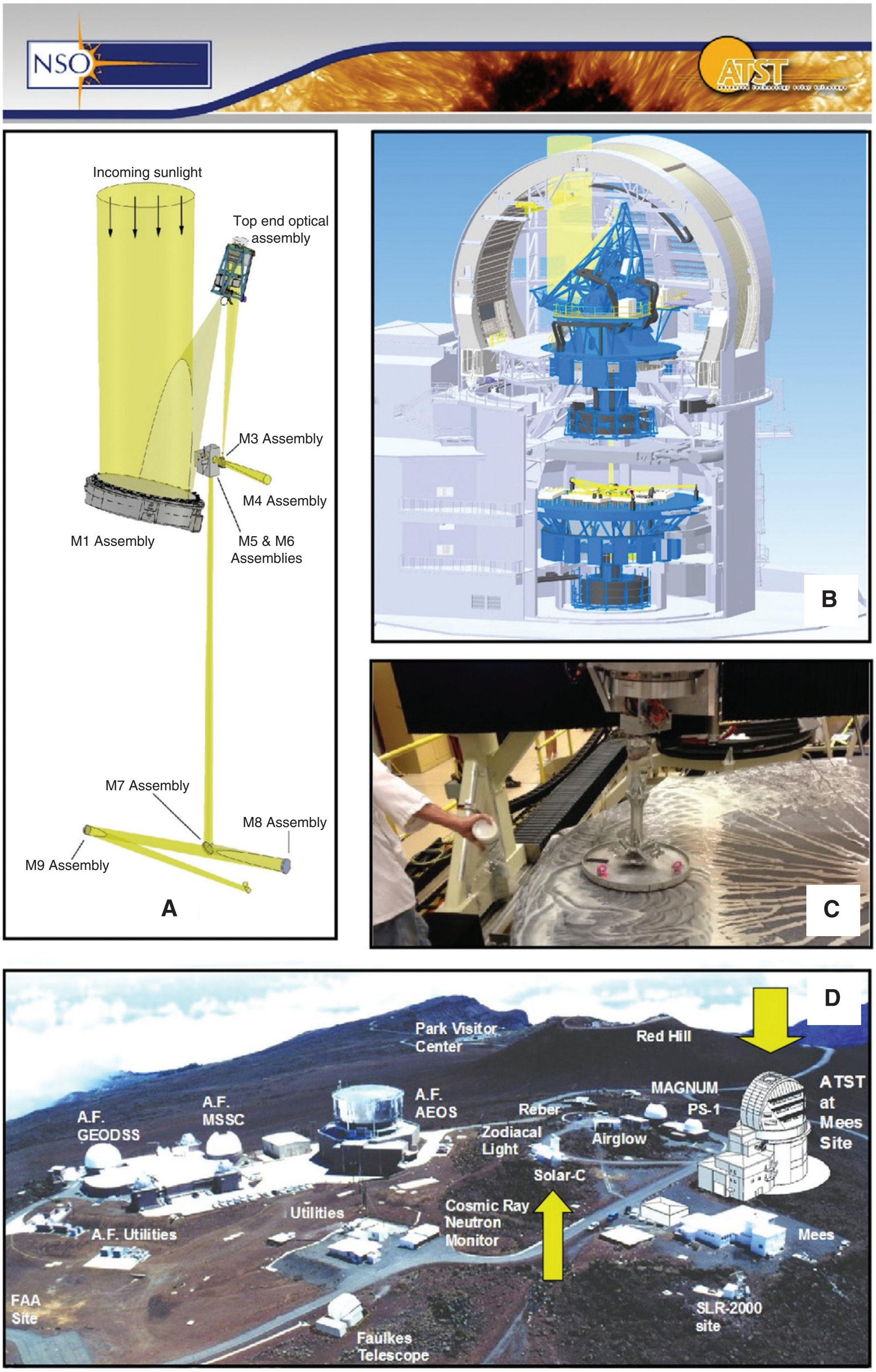

Figure 6 The ATST project.
(A) Schematic telescope mount assembly showing the independently rotating two-story Coudé platform. (B) The optical core of off-axis Gregorian concept up to Coudé lab. (C) Grinding activities on the Commissioning Blank at the Optics Shop at the College of Optical Sciences, University of Arizona (Oct. 2013). (D) Render of proposed ATST facility on Haleakalā. More information: http://atst.nso.edu/.

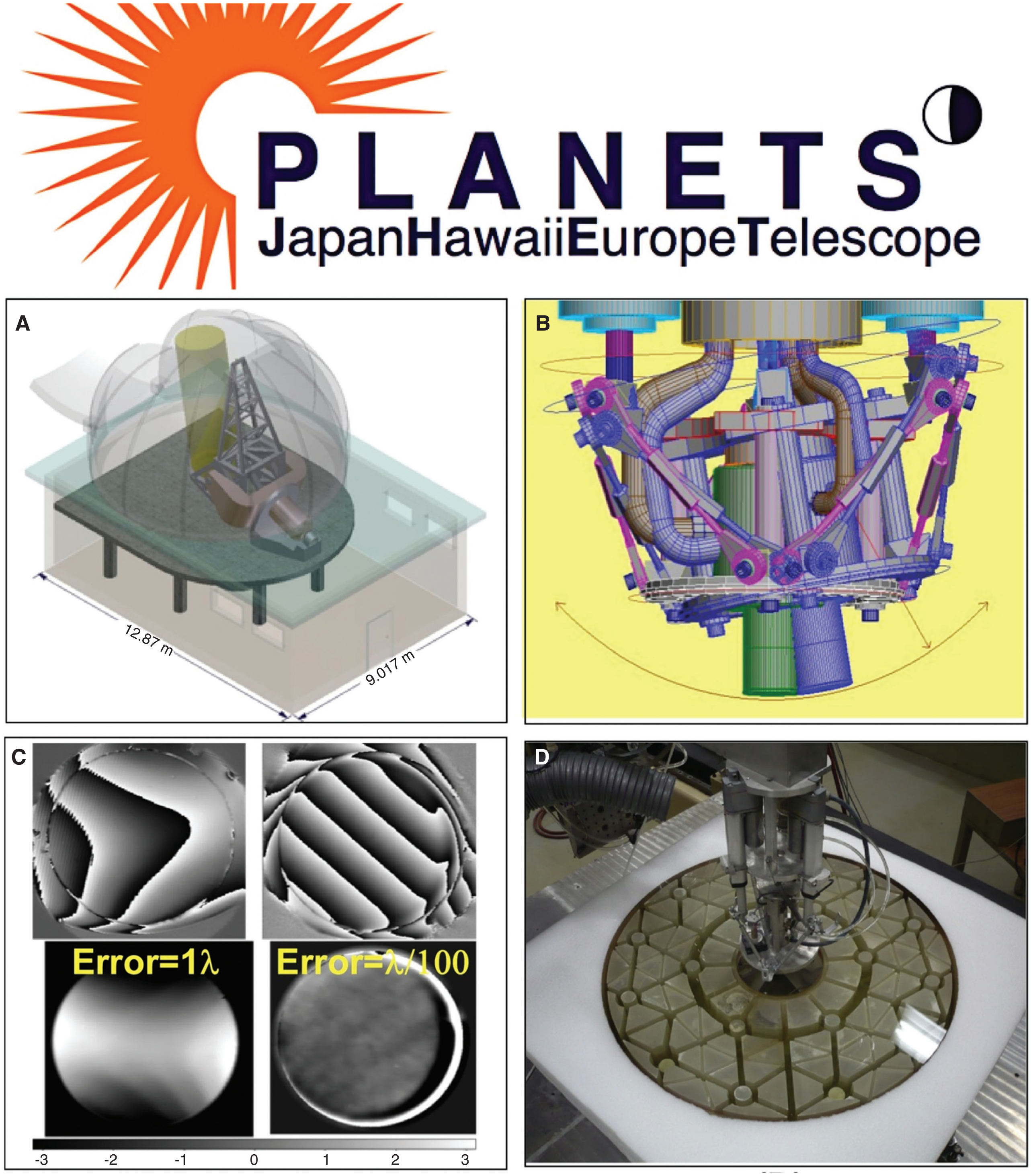

Figure 7 The 1.9-m PLANETS telescope.
(A) An off-axis telescope design optimized to deliver high-dynamic range imaging, imaging polarimetry, aperture polarimetry, spectropolarimetry, and coronagraphy assisted by adaptive optics. Telescope mirrors will be highly polished making use of Innovative Optics HyDra™ (hydrodynamic radial polishing tool) technique. (B) The Hydra mounted on a hexapod with load cell zero-force operation. (D) Hydra polishing an 84-cm diameter mirror, and (C) it was demonstrated as λ/100 polishing quality. (http://www.ifa.hawaii.edu/haleakalanew/planets/) [1].

pre-polished and awaits final polishing in Vancouver. The PLANETS will make use of adaptive optics, which can be used to suppress atmospheric wavefront error and scattering. By combining adaptive optics with other techniques, greater contrast enhancement and dynamic range are possible.

5 New concepts for off-axis telescopes

Lessons from this review have shown that optical technologies now exist that enable PSF core energies to be maximized while simultaneously minimizing the side-scattered light flux. These are the key requirements for achieving high angular and photometric dynamic range that had contributed heavily to the concept of the novel instrument design for the High Dynamic Range Telescope (HDRT). Such a concept provides high sensitivity for observing faint astronomical objects that are located in the environment of bright sources and also provides a wide-field observation mode (see Kuhn et al. [7]).

The HDRT design study demonstrates how mirror segments in large optical or infrared astronomical telescopes can be arranged so that there is maximum image clarity by allowing for the best possible adaptive optics system. A fundamental concern arises from the mirror segment edges. Mirror edges are difficult to polish accurately, and the relative 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. 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 8-m mirrors in the HDRT pupil plane. As its building blocks are now (2014) ‘conventional’ 8-m mirrors, it is straightforward to design an adaptive optics system. *This technology solves one of the leading problems facing large telescopes: how to make an AO system work on a large telescope*.

Figure 8 shows the HDRT concept layout as it was proposed (in 2000) as a replacement for the Canada-France-Hawaii Telescope (CFHT) on Mauna Kea. By using a 6×6.5-m off-axis mirror segment, this design achieved an effective light-collecting area that is equal to that of an unobstructed 15.9-m diameter telescope. Although 8-m mirror segments are optimal, we chose the 6.5-m off-axis segments due (in 2000) to polishing cost concerns for larger mirrors. It is now known that off-axis segments have a diameter limit of 8.4 m [8]. The 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 (Figure 9). As the mirrors do not touch, it is possible to design an efficient mechanical system that supports both the mirrors and the instruments and allows for great flexibility in adding secondary optics.

The HDRT concept was based on a new concept – the New Planetary Telescope (NPT) – of an off-axis design for a single 6.5-m telescope optimized for high angular resolution, high sensitivity in the optical and thermal infrared, and high photometric dynamic range [9]. The concept with the same primary mirror allows several modes of observation: (A) a narrow-field mode optimized across a 2×2-arcmin FOV, and (B) a wide-field mode, optimized across a 2° FOV. The NPT was devised in 1999 as a replacement for the NASA Infrared Telescope Facility [3, 9].

The 25-m Giant Magellan Telescope (GMT home page: http://www.gmto.org), which is based on seven 8.4-m segments has partly adopted the HDRT concept design Figure 10, whereby the secondary mirror is segmented to match the primary one. As the HDRT concept, the GMT’s small, agile secondary segments perform the fine alignment for each primary mirror. They will be deformable and enable adaptive optics, phasing, and the coherent combination of the subapertures.

SOML has successfully finished the polishing of the first GMT 8.4-m off-axis segment (2012), and the second segment is on the way. The third primary mirror segment came out of SOML’s custom-built spinning furnace on December 2013 and is in line for a 3-year polishing process. The center mirror segment is scheduled to be cast in early 2015. The four mirror segments will be used for the GMT early science phase. Figure 11 shows the stressed-lap polishing technique, which was developed for the highly aspheric 8.4-m optical surface and make use of technology gained from the 1.7-m off-axis primary mirror for the NST Figure 5C, which is a single one-fifth scale version of the GMT. For the GMT, a new test tower and the principal optical test setup make use of advances in laser metrology and computer-generated holograms [10].

SAGEM-Reosc (France) was awarded a contract by the European Southern Observatory (ESO) for manufacturing and testing seven prototype segments to the European-Extremely Large Telescope (E-ELT) primary mirror in 2008. The manufacturing of the prototype segments is now completed, and they have been delivered. Reosc has achieved an overall surface error of 23 nm RMS and 6 nm RMS after removal of the allowed amount of focus, astigmatism, and trefoil. The ability to produce aspherical off-axis hexagonal segments with very little edge effect and very high-quality wavefront error has been demonstrated and plans

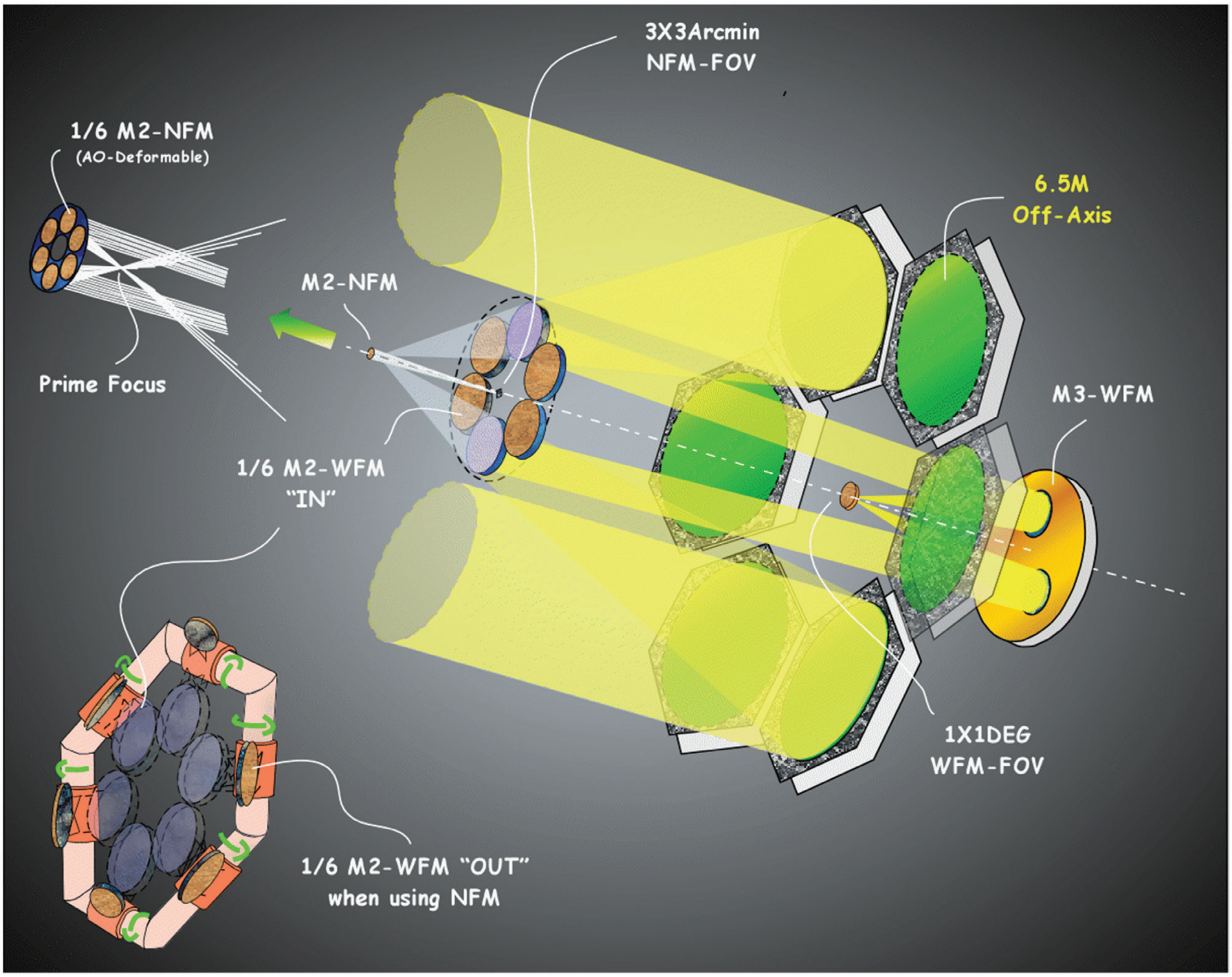

Figure 8 The full HDRT optical layout is shown here.
At the bottom-left corner of the figure, M2-WFM is composed of six subaperture mirrors, and they can be separately folded up or down – like petals on a flower – out of the way of the NFM light path. At the top-left of the figure, we see the six narrow-field subaperture mirrors that are 140 mm in diameter and the unobstructed prime focus. Another fundamental advantage of the HDRT is the versatility of its 'open' design. As its mirrors do not actually touch each other, it is possible to design an efficient mechanical system that both supports the mirrors and instruments and which allows great flexibility in adding secondary optics [7].

for the production of the 931 segments that are needed for the primary mirror, and spares are underway [11].

New technologies that allow larger asphericities to be readily ('inexpensively') measured and manufactured are also encouraging trends toward manufacturable off-axis optical systems [12].

6 Off-axis telescope new concept for Antarctica

The properties of the atmosphere above the Antarctic Plateau are known to be unique. Atmospheric turbulence is concentrated in a thin layer of a few tens of meters, the sky opacity, particularly in the infrared, is considerably reduced, and the thermal infrared sky background radiation is lower by a factor of 10 to 20 in the 2- to 3-µm windows. These are advantages that offer exceptional atmospheric and environmental conditions for astronomical observations over a wide range of wavelengths and are *particularly favorable to infrared astronomy*. Exceptional low sky brightness throughout the near- and mid-infrared and a telescope facility complying with the highest possible dynamic range for photometry, angular resolution, and the wide field leads to the possibility of a modest-sized 2- to 4-m off-axis telescope for achieving comparable sensitivity to that of a larger ground-based 8- to 10-m class telescope or a same-sized space-based ones.

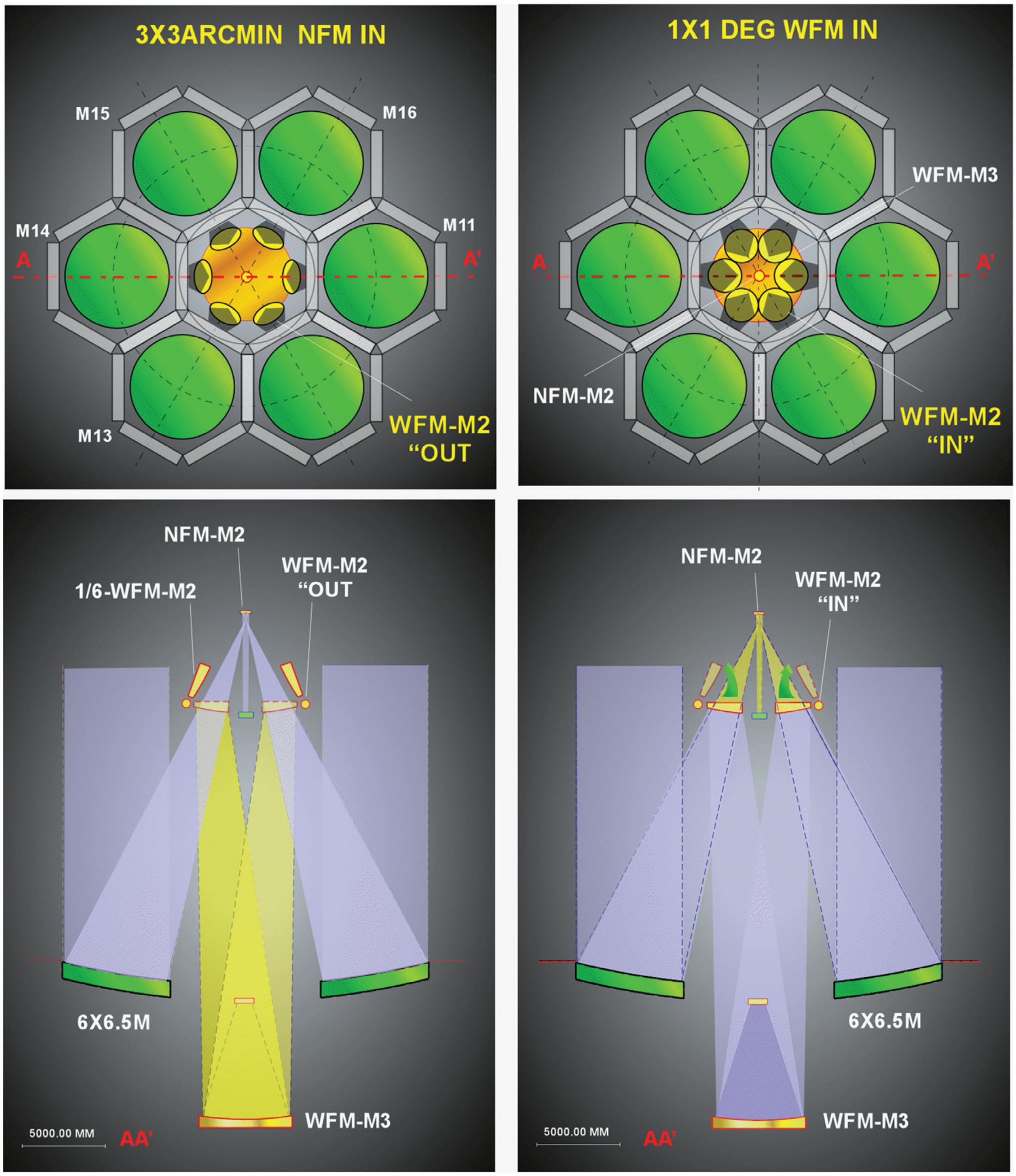

Figure 9 The permanently mounted HDRT optical configuration allows three distinct optical operating modes from the same facility: (left) a narrow field mode (NFM) allowing a full AO compensated coronagraphic telescope with a diffraction limited FOV at least 10 arcsec and a moderate mode optimized across a 3×3 arcmin FOV with the same single small secondary mirror (NFM-M2); (right) a wide-field mode (WFM) optimized across a 1×1° FOV, making use of a set of secondary mirrors (WFM-M2) and a tertiary single mirror (WFM-M3) [7].

The Antarctic Plateau is thus likely to become, in the coming decades, a major new platform for advanced astronomical observations. In the short/medium term, it is expected that synoptic infrared imaging and spectro-imaging surveys exploring the temporal dimension from Antarctica could play an essential role in the context of the future large ground-based and space projects such as E-ELT, JWST, LSST, EUCLID, GAIA. Taking advantage of these unique properties, we have proposed [13] a novel wide-field infrared survey off-axis telescope concept for Antarctica, which relies on a 2.5-m unobstructed aperture telescope configuration, which should produce an F/8 system optimized over a 1×1° field-of-view as shown in Figure 12.

A medium/large aperture telescope on the Antarctic Plateau will have the potential to undertake tasks previously thought to be possible only in space, for example, the imaging and crude spectroscopy of Earth-size extrasolar planets [14].

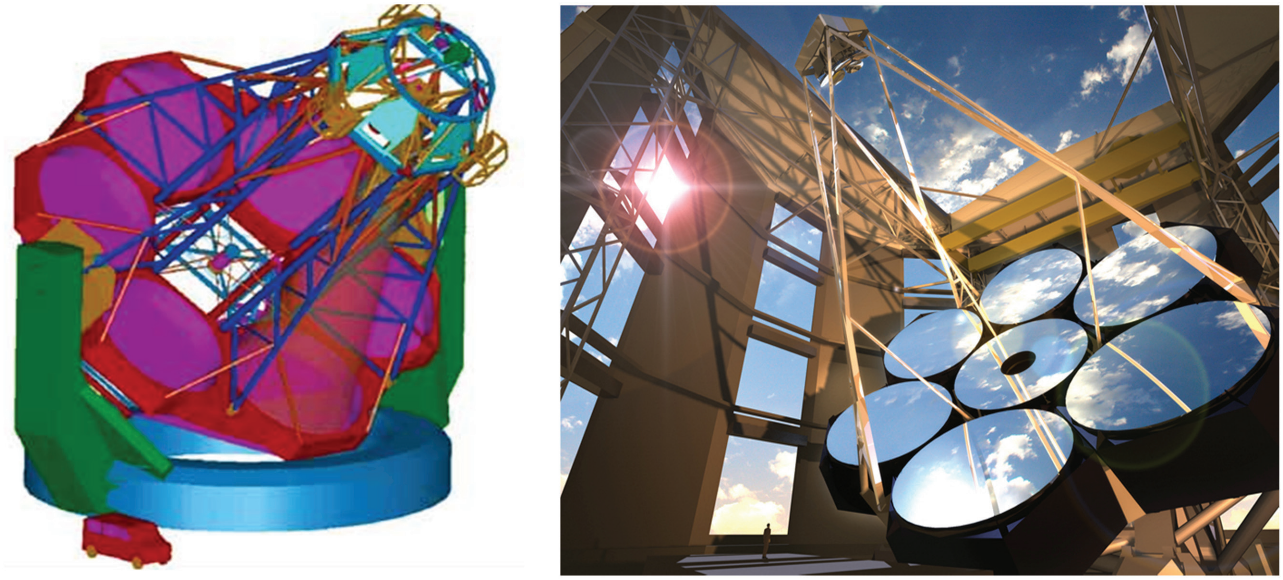

Figure 10 At the left part of the figure, the full HDRT and at the right side, the GMT optical support systems for comparison. Note at the top-right corner of the HDRT, the figure is the M2-WFM support structure composed of six subaperture mirrors, and they can be separately folded up or down out of the way of the NFM light path [1].

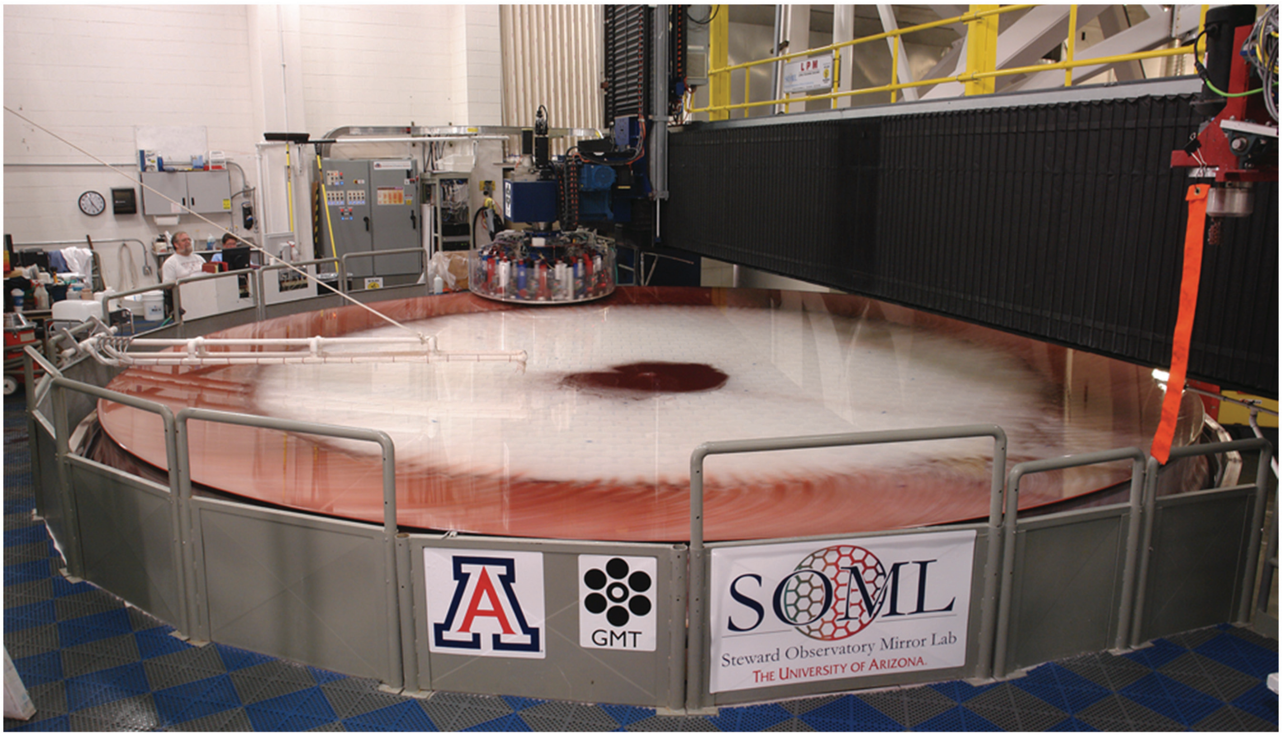

Figure 11 The GMT's first 8.4-m off-axis segment mirror polishing with stressed lap technique developed for high aspheric surfaces by SOML (2012) [1].

7 Conclusions

Many areas of modern astrophysics are not flux-limited but are rather dynamic-range limited. Simply collecting more photons will not solve the problem – for these topics, *we do not need bigger telescopes, we need better telescopes set up at exceptional sites* – we need off-axis telescopes. From this review, it is evident that with the maturity of technology, the feasibility of off-axis telescopes is a reality.

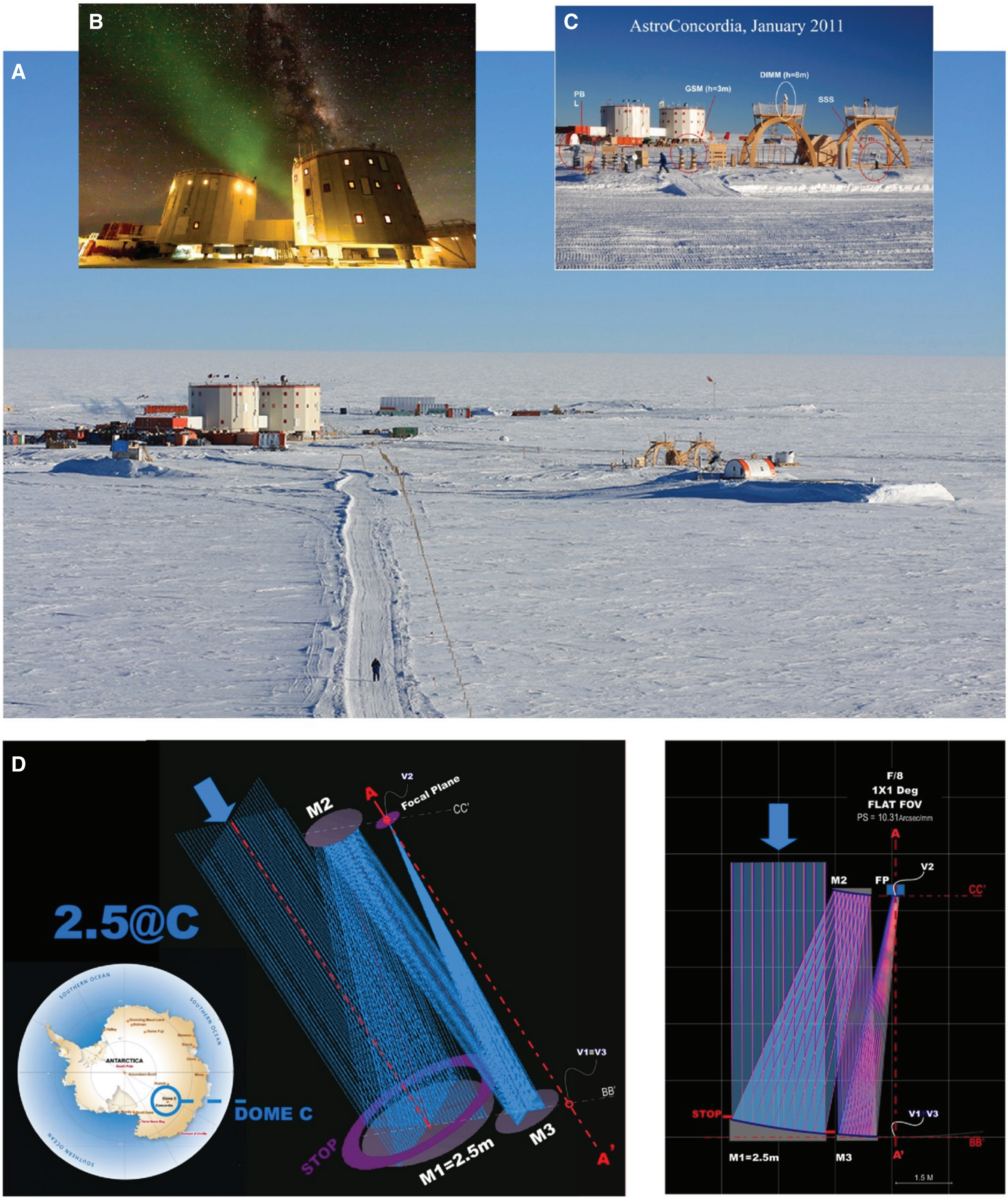

Figure 12 (A, B) The Concordia station research base jointly operated by France and Italy. It is located at Dome C, Antarctic Plateau at 75°06′06″S–123°23′43″E, at an elevation of 3233 m and around 1000 km inland. (C) It is a permanent, all-year research station with several small-sized telescopes. (D) The 2.5@C, an off-axis telescope for Dome C. A 2.5-m unobstructed aperture M1 yielding in a F/8 system optimized over a 1×1 Deg FOV. AA' is the parent mirrors M1, M2, and M3 optical axis. M1 and M3 vertexes V1 and V3 are coincident as well as for M2 (V2) and FP.

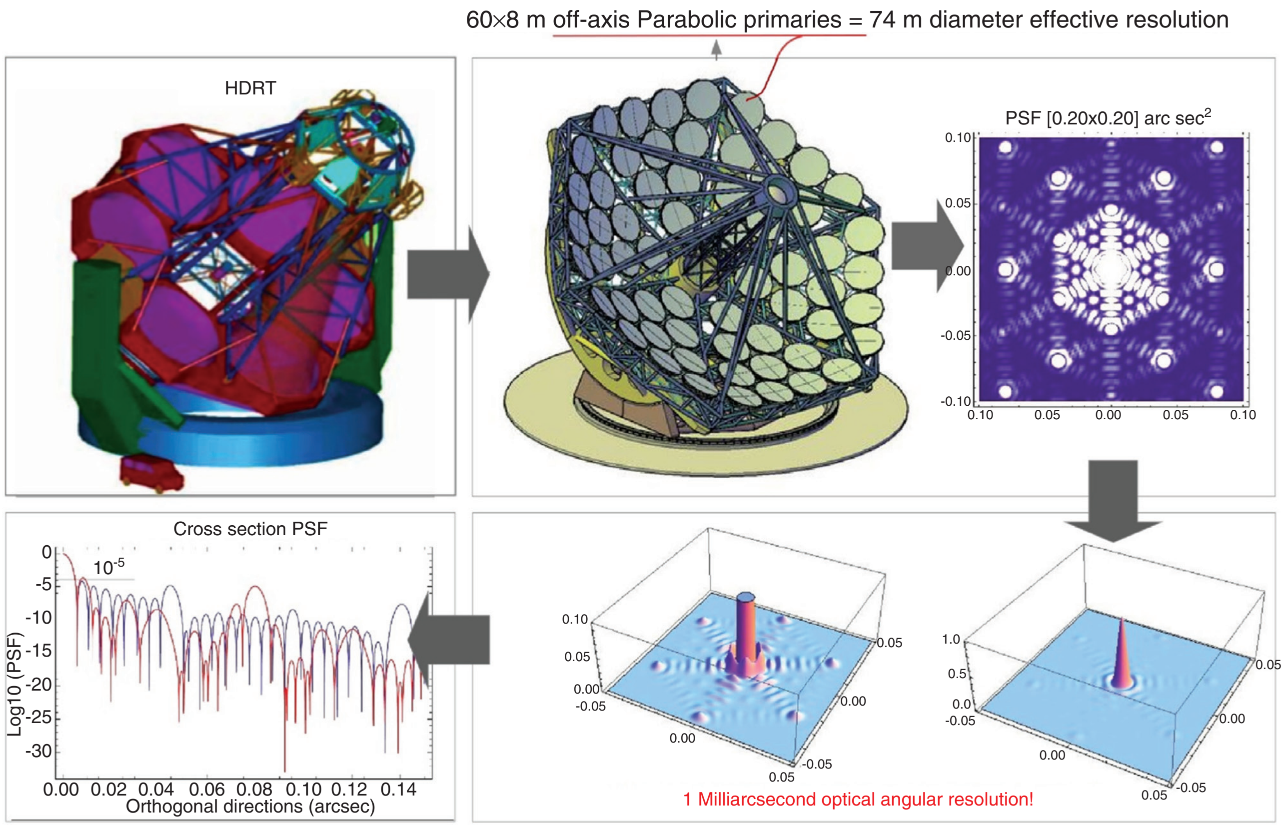

Figure 13 The full HDRT concept and a visualized concept of 60×8-m off-axis pupils and its exquisite performance.

Many areas of modern astrophysics are flux-limited. Optical technology dictates that single mirrors cannot be made large enough for the next generation of telescopes. How should mirror segments in a large optical/infrared astronomical telescope be arranged to maximize dynamic range?

We presented, here, the HDRT concept, which addresses all of these questions to obtain a very efficient and versatile large or extremely large telescope. Despite the loss in circular symmetry, future telescopes may realize significant advantages in large-angle scattered light performance, reduced telescope emissivity, better core PSF fidelity from AO systems, and improved out-of-field light rejection properties.

Extending the HDRT design, we have developed a concept that consists of 60 independent off-axis 8-m pupils (see Figure 13). A preliminary PSF calculation shows that this telescope interferometric model can achieve a 74-m effective resolution that is better than 1 marc-s and a raw contrast of about 10^{-5} – *The highest resolution optical and infrared telescope and the most sensitive telescope ever built for studying, via spectroscopy and polarimetry, the neighborhoods of bright stars in the galaxy.*

Common misconceptions that off-axis telescopes come with enormous cost and, e.g., alignment difficulties [10] are giving way (http//arxiv.org/abs/1008.1235) to readily manufacturable unobstructed designs implemented on powerful working telescope systems. We believe this trend is only just beginning.

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