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MAVIS on the VLT: A Powerful, Synergistic ELT Complement in the Visible

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On 1 June 2021 ESO and a consortium of Australian, Italian and French institutions signed an agreement for the design and construction of the MCAO Assisted Visible Imager and Spectrograph (MAVIS). This Very Large Telescope (VLT) instrument will push the frontier of new astronomical instrument technologies to provide, for the first time, wide-field, diffraction-limited angular resolution at visible wavelengths. In combination with the VLT Adaptive Optics Facility, it will use multi-conjugate adaptive optics (MCAO) to feed a 4k × 4k imager covering 30 × 30 arcseconds, as well as an Integral Field Spectrograph (IFS). Angular resolution down to 18 milliarcseconds will be achieved at a wavelength of 550 nm (*V* band). The IFS will provide four spectral modes, with spectral resolutions from 4000 to over 15 000 between 370 and 950 nm. This will enable a wide variety of science cases, spanning themes that include the emergence of the Hubble sequence, resolving the contents of nearby galaxies, star clusters over cosmic time and the birth, life, and death of stars and their planets. Delivering visible images and integral-field spectroscopy at an angular resolution two to three times better than that of the Hubble Space Telescope will make MAVIS a powerful complement at visible wavelengths to future facilities like the James Webb Space Telescope and the 30–40-metre-class ground-based telescopes currently under construction, which are all optimised for science at infrared wavelengths.

About MAVIS

Pushing adaptive optics (AO) technologies to the visible region has been the holy grail of high angular resolution observations since the inception of AO. It is indeed a very challenging proposition: enabling compensation at shorter wavelengths means deformable mirrors with more actuators (proportional to $\lambda^{-2.4}$), faster systems ($\lambda^{-1.2}$) and a correction valid over smaller isoplanatic patches ($\lambda^{-2.4}$). As a result the overall complexity grows as λ^{-6}. Having more actuators also means smaller subapertures in the wavefront sensors (WFSs), which requires more powerful lasers. It all becomes more complicated — and more expensive. Some extreme AO systems have been working in the visible, generally focused on high-contrast applications, but these systems generally have very low sky coverage, with access to only a few hundred targets and small fields of view (MagAO at the Magellan Telescopes, the First Light Adaptive Optics [FLAO] system at the Large Binocular Telescope, and the Spectro-Polarimetric High-contrast Exoplanet REsearch [SPHERE] instrument at ESO's Very Large Telescope [VLT]).

AO has matured over the last decades, and recently it has become possible to consider building a wide-field, high-sky-coverage facility instrument to serve a large number of science cases in the visible (Esposito et al., 2016). This was made possible by a number of key developments.

– The maturation of key technologies, including: (a) large, high-actuator-density deformable mirrors and deformable secondary mirrors; (b) high-power commercial lasers to create sodium guide stars like the ones used in the VLT Adaptive Optics Facility (AOF); and (c) high-throughput, low-latency real-time computers, and in particular the variant based on a graphics processing unit, which has

seen major performance and functionality improvements in the past decade.
- New control techniques. AO control got stuck with linear integrator controllers for a long time, but the past decade has seen the emergence of many promising techniques, such as Minimum Mean Square Error, Learn and Apply and the various incarnations of predictive controllers such as Linear Quadratic Gaussian control, together with the emergence of tricks like superresolution.
- The success of on-sky demonstrators (for example, the Multi-conjugate Adaptive-optics Demonstrator [MAD] at ESO), or first-generation facility systems like GeMS, the MCAO system at the Gemini telescope, that could be considered as the precursor of MAVIS, with its five laser guide stars (LGSs) and three deformable mirrors. The consortium is also drawing from the experience of the AOF and more recently, the InfraRed Low Order Sensor (IRLOS) WFS upgrade for the Multi Unit Spectroscopic Explorer (MUSE).

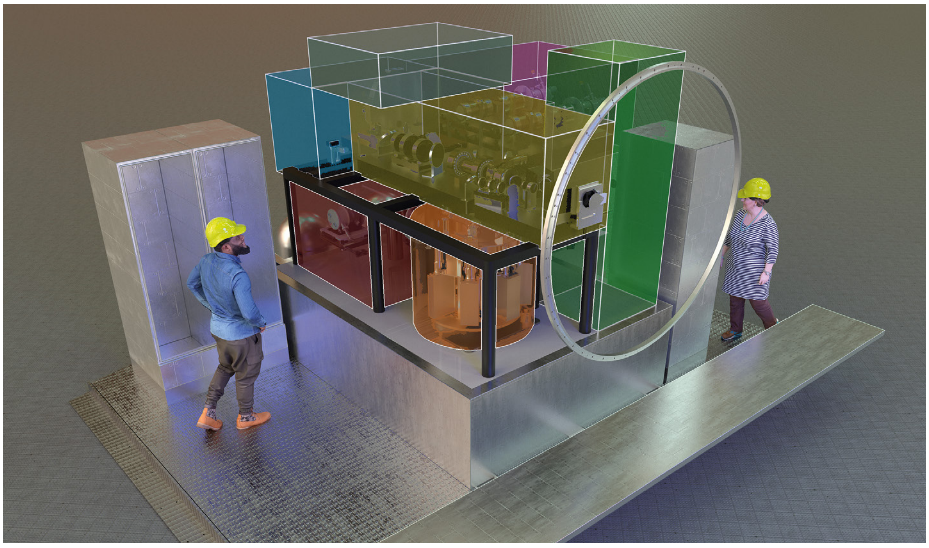


Figure 1. A rendering of MAVIS on the Nasmyth platform. The circle represents the rotator-adaptor interface (to which MAVIS is not attached). The various volumes are coloured as follows: yellow — adaptive optics module; orange — laser guide star wavefront sensor; red — natural guide star wavefront sensor; blue (behind) — imager; purple — spectrograph; green — calibration unit; grey — electronics cabinets. MAVIS will be fitted with a light-tight enclosure, but will rely on passive thermal management, with the possible exception of the spectrograph which might be actively temperature controlled (currently being studied).

MAVIS will go at the Nasmyth A focus of the VLT AOF (at Unit Telescope 4), opposite MUSE (see Figure 1). MAVIS is composed of four main modules (Rigaut et al., 2020): the AO module, that processes the light and compensates for most of the atmospheric-induced aberrations; a 4k × 4k imager equipped with a set of narrow- and broadband filters; an integral field spectrograph (IFS) with two modes, one with a field of view of 3.6 × 2.5 arcseconds and spaxels of 25 milliarcseconds, the other with a field of view of 7.2 × 5 arcseconds and spaxels of 50 milliarcseconds, and multiple spectral resolutions; and the calibration unit, which provides what is needed for the calibration of the AO module and the instruments. Both the imager and the spectrograph cover the wavelength range 370–950 nm in the baseline design, and have been informed by a comprehensive science case built in consultation with the ESO user community (McDermid et al., 2020).

The MAVIS consortium[1] is made up of ASTRALIS[2] (Australia, formerly the AAO Consortium), INAF (Italy), the Laboratoire d'Astrophysique de Marseille (LAM, France) and ESO. ASTRALIS (the AAO and ANU nodes) provides the Project Office, the imager and spectrograph, the LGS WFS, the Real-Time Controller, the detectors, and the calibration unit. INAF is responsible for the AO module, as well as the natural guide star (NGS) WFS, the performance simulations, and the Instrument Control System. LAM provides AO expertise and point spread function reconstruction. Finally, ESO is responsible for driving the deformable mirror development and procurement, the LGS Facility upgrade to split the four existing LGS beams into eight beacons, the interface with the VLT, and the commissioning. ESO will also provide nine smALl vIsible CamEra (ALICE) cameras and up to five Next Generation Controller II detector controllers. The COVID-19 pandemic posed a major challenge to the smooth operation of such a distributed consortium. In particular, the closure of Australia's borders (likely to stay in effect until sometime in 2022) has without a doubt impaired the efficiency of communication within the consortium.

Phase A of MAVIS began in February 2019 and the Phase A final review was passed with flying colours in May 2020. The ESO follow-up team organised the start of Phase B and coordinated the various approval steps (by the Scientific Technical Committee, the Finance Committee and Council) with the Paranal Instrumentation Programme. The agreement for Phases B to E was signed on 1 June 2021.

A period of slightly more than one year is planned for each of the preliminary design and final design. Preliminary Design Review is expected in July 2022 and Final Design Review in August 2023. The Preliminary Acceptance Europe milestone is scheduled for 2027 and could take place in Australia (to be decided). First light is currently scheduled for the second semester of 2027, in line with first light of ESO's Extremely Large Telescope (ELT).

Science drivers

By probing the frontiers of angular resolution and sensitivity across a large portion of the observable sky (~ 50% at the galactic pole) at visible wavelengths, MAVIS will enable progress on an array of scientific topics, from studies of the Solar System to planetary systems around other stars, and from the physics of star formation in the Milky Way to the first star clusters in the Universe.

The point-source imaging sensitivity of MAVIS will exceed that of the Hubble Space Telescope (HST), giving an order of magnitude greater depth, and with higher angular resolution. In 10 hours of integration, MAVIS will detect point sources and compact galaxies down to 30.4 *AB* in *I* band, about 1 magnitude deeper than the Hubble Ultra-Deep Field in *i775*, despite its integration time a factor of 10 longer (96 hrs). This will allow MAVIS to produce the deepest optical images ever obtained on a large field of view. This will open a new window onto the study of the structural properties of the first galaxies and of compact galaxies across cosmic time, as illustrated by Figure 2.

Spectroscopically, the combination of high spatial resolution, large wavelength coverage and high spectral resolution (R > 5000) will allow MAVIS to finally trace the evolution of the interstellar medium (ISM) during the critical galaxy transformation in the redshift range $0.2 < z < 0.8$, from the clumpy and turbulent discs observed at high redshift into the thin discs of local late-type galaxies, resolving the intrinsic velocity dispersion and the chemical and physical properties of the ISM.

The astrometric precision and magnitude limits of MAVIS will exceed those of the HST and will extend the ultra-precise local framework from the Gaia mission into the densest and most crowded fields, out to the furthest reaches of the Milky Way and into the Local Group. MAVIS will provide proper motion accuracies of 5–10 km s^{-1} out to distances of ~ 100 kpc over five-year timescales, approaching the radial velocity accuracy from MAVIS spectroscopy. The combined spectral and imaging capabilities will provide full 6D phase-space information of individual stars, giving a new precision to studies of intermediate mass black holes in globular clusters (Monty et al., 2021), and unique dynamical information to constrain the dark matter properties of local group dwarf galaxies.

MAVIS will enable access to the new regimes of faint sources and complex crowded fields that will become commonplace at longer wavelengths in the era of ELTs, but with the diagnostic power of optical wavelengths. This will be particularly important in the low-redshift Universe (z < 0.5), where the best-calibrated and understood physical diagnostics are found at wavelengths below 1 μm. In this way, MAVIS will be a crucial complement to the capabilities of ESO's ELT, delivering angular resolution in the optical comparable to that delivered by ELTs in the infrared. A key example of this synergy is in studying resolved stellar populations beyond the Local Group. Whilst ELTs will be able to detect individual stars in galaxies beyond several Mpc with modest integration times, infrared wavelengths probe mainly the Rayleigh-Jeans tail of the stellar black body spectrum, making infrared colours largely degenerate to key stellar population parameters such as age and metallicity. By contrast, the shallower depths accessible on an 8-metre telescope are fully compensated by the increased diagnostic power of optical colours, making MAVIS a crucial tool for capitalising on ELT science.

The unprecedented combination of sensitivity, angular resolution, blue coverage and moderately-high-resolution spectroscopy (R > 12 000) afforded by MAVIS and the AOF will allow, for the first time, the characterisation of the cores of globular clusters. It will be possible to explore abundances anomalies, multiple stellar populations, and core binary fractions: the missing link to understanding the formation scenario and subsequent dynamical and chemical evolution of these systems.

Finally, MAVIS will be transformational for our understanding of the life and death of stars and their planets, by revealing uncharted details of their close environment, such as protoplanetary discs, jets and companions. This includes our own Solar System, where MAVIS will provide spectroscopy and high-contrast imaging of planetary atmospheres, cometary activity and Kuiper Belt Objects.

Given this broad range of foreseen scientific applications, combined with a robust and flexible operational model, MAVIS will represent the general purpose facility instrument that will fill the gap for high-spatial-resolution optical capabilities in the post-HST era. Moreover, MAVIS operations will closely overlap with the new generation of giant telescopes optimised for near-IR observations, providing their fundamental complement in the optical regime.

Instrument design concept

Informed by a number of trade-off studies of the most crucial elements, the MAVIS

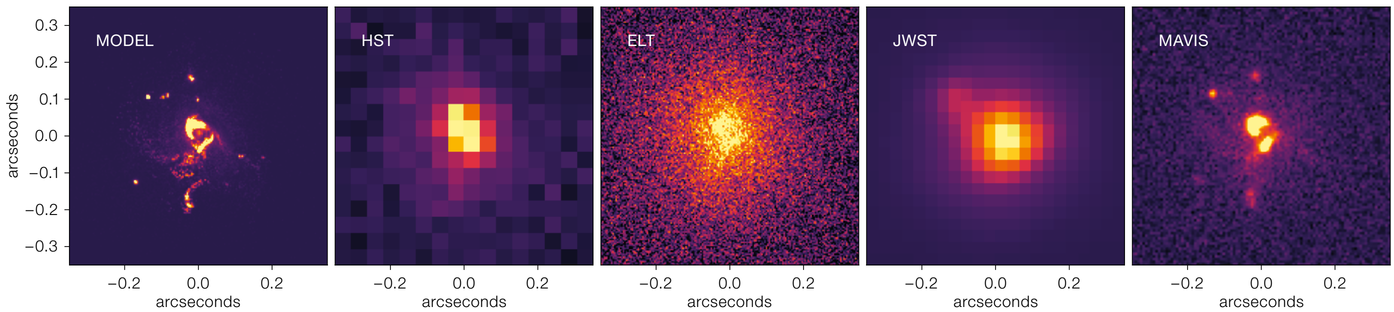


Figure 2. Example of a morphological study of a high-z galaxy as observed in the *I* band with the HST, the Multi-AO Imaging Camera for Deep Observations (MICADO) at ESO's ELT, NIRCam on the James Webb Space Telescope and MAVIS. Based on the $z = 5$ high-resolution simulated "Althaea" galaxy (Pallottini et al., 2017), shown in the first panel, the other panels show how the same target of 25 *AB* magnitude would appear in the *I* band if observed with different facilities for a fixed exposure time of 1 hour. In the VLT/MAVIS image, clumpy regions as faint as 29 *AB* magnitude are detected with a signal-to-noise ratio of five.

design went through several iterations during Phase A, to finally converge on the current baseline. The considerable expertise within the consortium in AO and post-focal instrumentation helped in converging on a healthy design, in particular the optical design, which maximises throughput and minimises optical aberrations and field distortion, whilst allowing easy alignment and modular integration (Viotto et al., 2020; Ellis et al., 2020).

The current MAVIS design can be summarised as follows:
- A largely transmissive design across the board (AO module, imager, spectrograph), using only on-axis optics. The intention is to minimise field distortions, as well as to make the optical alignment more tolerant.
- A gravity-invariant design, in which the science and NGS WFSs are commonly de-rotated optically and the LGS WFSs use mechanical de-rotation to track the LGS constellation.
- Three deformable mirrors: the AOF secondary (1170 actuators) and two post-focal deformable mirrors, optically conjugated to 6 and 13.5 kilometres, for a grand total of 5420 actuators.
- Eight laser guide stars created from splitting the four existing AOF lasers, feeding eight 40 × 40 Shack-Hartmann WFSs. The current concept makes use of diffraction gratings to split each laser and is minimally invasive to the LGS Facility, maintaining full compatibility with existing AOF operation modes.
- Three near-infrared NGS WFSs, providing tip-tilt and focus information (each has a selectable 1 × 1 or 2 × 2 lenslet array). These WFSs use SAPHIRA detectors over the *J* and *H* bands and NGCII controllers for maximum sensitivity, leading to a limiting magnitude of more than $V = 18.5$.
- An imager covering the 30 × 30 arcsecond field of view, better-than-Nyquist sampled in the *V* band (7.36 milliarcseconds pixel^{-1}, for images of 18 milliarcseconds full width at half maximum [FWHM] in good conditions). Note that for relatively obvious geometric reasons, the image quality performance is specified over the disc of radius 15 arcseconds, but we are looking for ways to also optimise the field corners.
- A very compact, high-throughput monolithic IFS, covering 370 to 950 nm (possibly to 1000 nm), with four spectral modes, providing spectral resolutions from 4000 through over 15 000 (see Figure 3) and two spaxel scales (approximately 25 and 50 milliarcseconds spaxel^{-1}), corresponding to fields of view of 3.6 × 2.5 arcseconds and 7.2 × 5 arcseconds. The current design uses a field of view offset from the optical axis by about 8 arcseconds (see Figure 4), which slightly improves the probability of finding NGSs. We are looking into the option of using the imager and the spectrograph simulta-

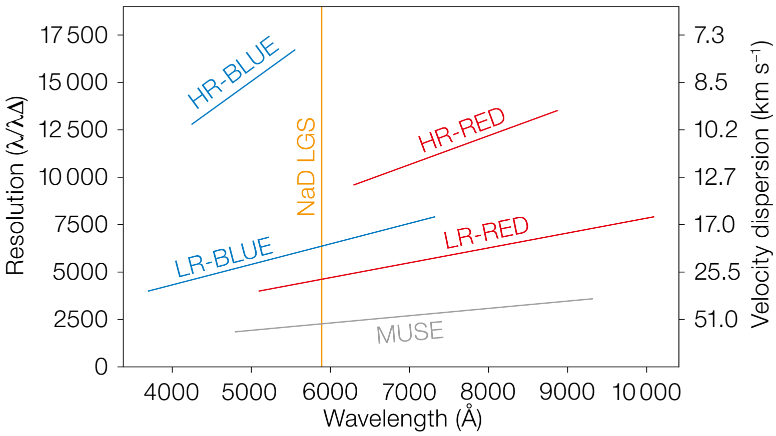
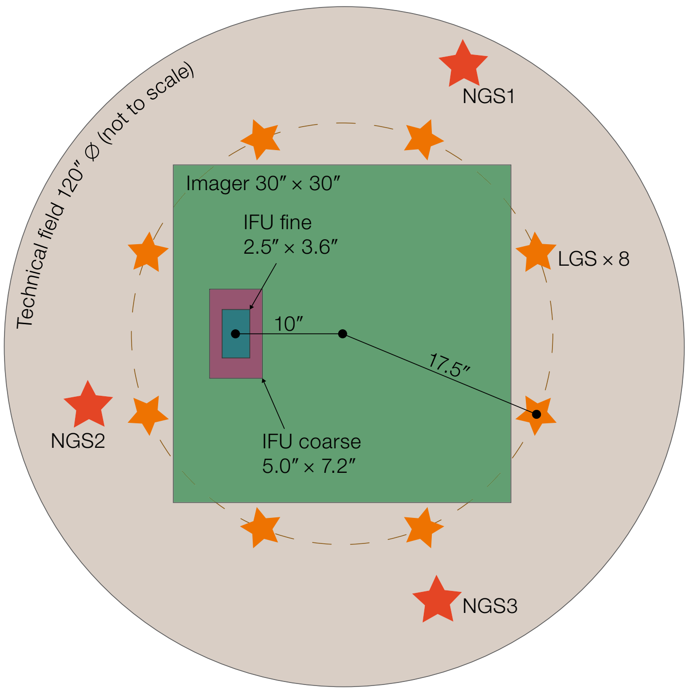


Figure 3. (Above) The four MAVIS IFS spectral resolution modes and corresponding dynamical scales, chosen to address key science areas. These include: the study of chemical abundances and radial velocities in crowded fields (HR-BLUE); exploring the evolution of ISM turbulence in galaxy discs and hunting intermediate-mass black holes (HR-RED); probing the extremes of mass and metallicity of young stars and untangling the complexity of ionised gas in galaxies (LR-BLUE); and resolving Lyman-alpha emitters at $z > 6.5$, and studying stellar dynamics in $z < 1$ galaxies (LR-RED). MUSE is shown in grey for comparison.

Figure 4. (Below) The MAVIS focal plane, with eight laser guide stars (orange) and three natural guide stars (red). The imager covers/defines the “science field” (green). The integral field spectrograph (IFS) field is in purple (coarse mode) and blue (fine mode). The exact shape and location of the IFS field of view are still being optimised. Having the IFS off-centred with respect to the technical field increases the capture range for natural guide stars, and thus the sky coverage.



neously, which will provide interesting opportunities to extract information from the IFS when in crowded fields.

Performance

The system performance requirements were specified for typical Paranal turbulence conditions, i.e., a seeing of 0.87 arcseconds at a zenith angle of 30 degrees. There has been a huge push during phase A and the start of phase B on numerical simulations (Agapito et al., 2020). These were instrumental in driving the instrument AO design: how many actuators were needed? how many deformable mirrors? how many laser guide stars and wavefront sensors? natural guide stars? All of these design parameters were optimised on the basis of the initial call for proposal requirements. Once the baseline design was settled, numerical simulations were then used to fine tune performance estimates. The consortium is still in this phase, and we have embarked on statistical performance estimates and sensitivity analyses, based on the recently released database of turbulence profiles for Paranal.

Because of the very tight wavefront error allowance — of the order of 110 nm — resulting from the fact that MAVIS targets correction at visible wavelengths, the MAVIS simulation and control group has had to make use of both proven (for example, Learn and Apply or Minimum Mean Square Error) and more novel control techniques. The latter include predictive control (Cranney et al., 2020) and "super-resolution", a technique to increase wavefront sensing diversity (or reduce redundancy) by shifting/rotating the WFSs with respect to each other.

Figure 5 presents the long-exposure Strehl ratio (well known to AO connoisseurs, the Strehl is a measure of how close the image is to the diffraction limit). These results include only atmospheric and AO error terms. The average Strehl over the disc of radius 15 arcseconds is 28.9%, which provides a very healthy margin over the specified 15% to accommodate other error sources such as optics, vibrations, etc. The absolute Strehl standard deviation over the same circular field is 1.3% (4.5% relative), indicating a very uniform image quality — a trademark of multi-conjugate AO. At this level of Strehl, the images appear essentially diffraction-limited, i.e., close to λ/D in FWHM. When including vibrations, and various detector effects, we are expecting image sizes of 18 milliarcseconds.

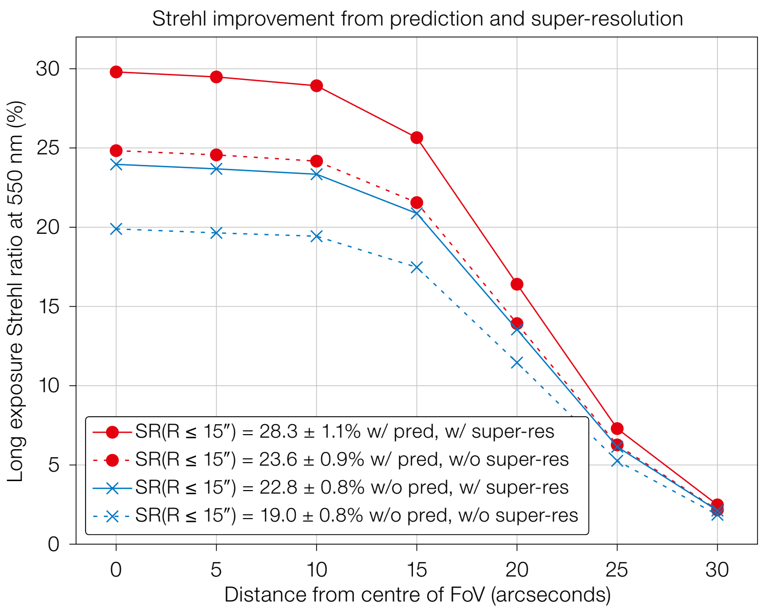


Figure 5. Strehl radial profile as a function of the off-axis distance, for various controllers (Minimum Mean Square Error or Learn and Apply, with or without predictive control and super-resolution). The Strehl performance specifications are defined over the disc of radius 15 arcseconds (not over the 30 × 30 arcsecond-square field). This set of simulations uses three bright natural guide stars on a triangle, at 20 arcsecond radius from the centre of the field.

The choice of near-infrared wavelengths for the NGS WFS provides a welcome boost to the sky coverage of MAVIS, where sources in the partially-corrected NGS patrol field are diffraction-limited at 1.6 µm, with moderate to high Strehl. Combined with the use of near-infrared avalanche photodiode arrays, this allows it to reach high sky coverage values; over 50% of the pointings at the galactic pole will provide images with better-than-HST angular resolution (< 50 milliarcseconds).

Finally, a preliminary exposure time calculator has been developed and is available on github[3]. MAVISIM[4], a tool to generate synthetic images, has also been developed. It employs a user-provided object model (currently only point sources) and a database of field-varying point spread functions from end-to-end numerical AO simulations. A future version will offer compatibility with extended objects. Both the exposure time calculator and MAVISIM are under active development, with updated versions expected throughout phase B.

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Links

1 The MAVIS consortium: mavis-ao.org/consortium
2 AUSTRALIS: https://astralis.org.au/
3 MAVIS exposure time calculator: https://github.com/jtmendel/mavisetc
4 MAVISIM image generation tool: https://github.com/smonty93/MAVISIM