VLTI 2.0: Imaging the Universe at the Milliarcsecond Scale

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Abstract

We propose an extension of the Very Large Telescope Interferometer through the addition of four 8 m-class Unit Telescopes. This upgrade would provide a dense and homogeneous *uv* coverage with baselines up to 200 m, enabling true imaging at milliarcsecond angular resolution. The resulting gain in sensitivity and imaging fidelity would open a broad range of science cases, from Solar System objects to distant active galactic nuclei, and secure the long-term scientific leadership of Paranal in high-angular-resolution astronomy.

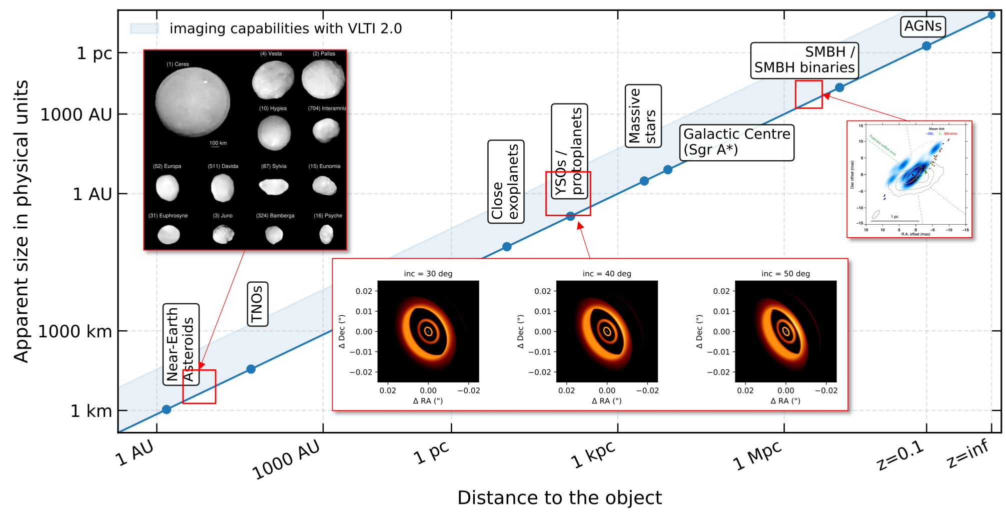

Figure 1: Physical spatial resolution of VLTI 2.0 as a function of distance. Boxes indicate the approximate distance regimes relevant for key science cases, spanning Solar System objects (near-Earth asteroids and trans-Neptunian objects), nearby and Galactic targets (exoplanets, young stellar objects, massive stars, and the Galactic Centre), and extragalactic sources (supermassive black holes, binary SMBHs, and active galactic nuclei). Inserted are 3 science cases: small bodies (Vernazza et al. 2021), AGN imaging(GRAVITY Collaboration et al. 2020), and an illustration of a protoplanetary disk. These images are based on radiative-transfer simulations performed with the MCFOST code (Pinte et al. 2006, 2009). The disk exhibits multiple concentric rings located at radial distances of approximately 0.3–0.5 au, 0.8–1.0 au, and 2–3 au, representative of sub-au to few-au scale structures associated with planet formation processes. Such spatial scales are directly accessible with milliarcsecond-resolution interferometric imaging, highlighting the potential to image planet–disk interactions in nearby star-forming regions.

The Plateau de Bure Observatory began as a three-antenna radio interferometer. With its transformation into NOEMA (NOrthern Extended Millimeter Array), it reached its full scientific potential following the inauguration of its seventh antenna in September 2014. The transition from an array primarily suited to model fitting to a true imaging instrument is, of course, not abrupt. Nevertheless, experience shows that the regime of seven to eight elements represents a critical threshold: prior to NOEMA, Plateau de Bure largely served as a technical and scientific pathfinder for ALMA; afterwards, it became a highly productive imaging observatory in its own right.

We argue that the VLTI is now at a similar turning point. With the advent of GRAVITY (Gravity Collaboration et al. 2017), the VLTI has reached technological maturity and demonstrated its unique scientific power. However, to fully deliver on its potential for the community, the VLTI requires additional telescopes. Robust imaging capabilities are essential to move beyond highly parameterised models and to access physical regimes that cannot be constrained with sparse interferometric data alone.

With the proposed upgrade (Fig. 2), the VLTI would achieve a dense and homogeneous *uv* coverage, providing baselines of up to 200 m. This configuration would deliver angular resolutions of order 1 mas over a field of view of approximately 50 mas. Such enhanced *uv* coverage would enable true snapshot imaging, opening the door to time-resolved studies of transient and dynamic phenomena, from accreting young stars to stars orbiting supermassive black holes.

A key strength of the proposed facility lies in the diversity of scientific cases it can address, as well as in the wide range of physical scales it can probe, from Solar System bodies to objects at extreme redshifts. Probing this wide range of spatial scales requires high sensitivity, which is a key driver of the proposed concept. Surface brightness sensitivity is particularly critical, from faint Solar System objects such as trans-Neptunian objects to distant active galactic nuclei. Observing these low surface brightness objects demands a large collective collecting area, which can only be provided by 8 m-class telescopes. In this

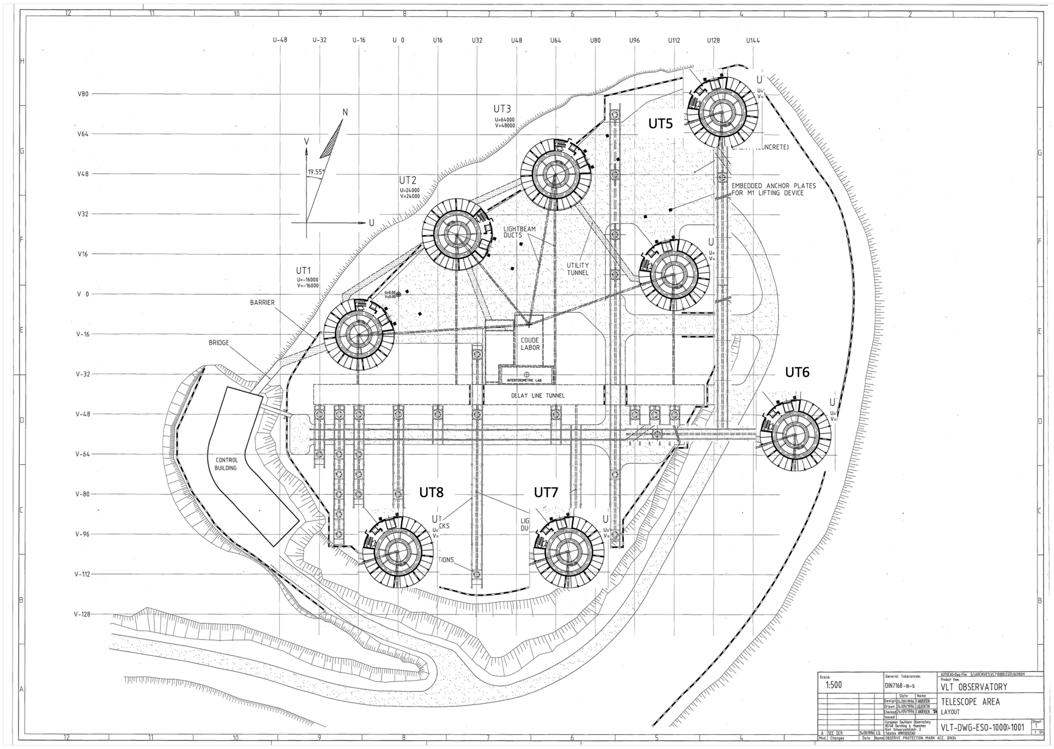

Figure 2: Conceptual layout of the Paranal Observatory illustrating the proposed addition of four new 8 m Unit Telescopes (UT5–UT8). When combined with the existing UTs, the extended array provides up to 22 additional interferometric baselines, including four long baselines of up to ~200 m oriented toward the north-west. The proposed locations are compatible with the existing delay-line tunnels, coudé laboratory, and observatory infrastructure.

context, the development of the Extremely Large Telescope (ELT) programme offers a unique opportunity: the use of primary mirrors of similar size and a common segmented-mirror technology would allow significant technological synergy, reducing development risks and overall costs through shared design, manufacturing, coating, and operational experience. Beyond its scientific impact, this project would provide a long-term perspective for the Paranal Observatory, ensuring its continued role as a forefront facility for high-angular-resolution astronomy in the era of the ELT.

Figure 1 provides an overview of the spatial scales accessible with milliarcsecond angular resolution. Below, we present a non-exhaustive list of representative scientific cases (from `https://horizons-olbin.sciencesconf.org/`).

- **Near-Earth Asteroids (NEAs):** Milliarcsecond-resolution imaging enables direct reconstruction of asteroid shapes, surface structures, and binarity. Such images constrain internal structure, rotational state, and surface heterogeneity, which are critical for understanding asteroid evolution and impact-risk mitigation (Vernazza et al. 2021).
- **Trans-Neptunian Objects (TNOs):** Direct imaging resolves the largest TNOs and binary systems, allowing measurements of shapes, sizes, and albedo variations. These observations provide key constraints on bulk density, composition, and the collisional history of the outer Solar System (Braga-Ribas et al. 2014).
- **Small-body activity (comets and active asteroids):** High-resolution imaging of the inner coma and jets reveals the spatial distribution of dust and gas close to the nucleus. This directly probes outgassing mechanisms and the physical processes driving activity in small bodies.
- **Close Exoplanets:** Interferometric imaging spatially separates close-in exoplanets from their host stars at sub-AU scales for nearby systems. Direct images enable measurements of orbital geometry, phase-dependent brightness, and rings.
- **Exomoons:** High-contrast imaging offers a pathway to detecting and characterising large exomoons around nearby exoplanets. Spatially resolved planet–moon systems constrain satellite formation scenarios and orbital dynamics.
- **Young Stellar Objects:** Imaging at milliarcsecond resolution probes the inner AU-scale regions of protoplanetary disks. Direct images of gaps, spirals, and circumplanetary material reveal planet–disk interactions and constrain planet formation mechanisms and timescales (Monnier et al. 2018)
- **Protoplanets and Circumplanetary disks:** Direct imaging of circumplanetary disks provides unique constraints on

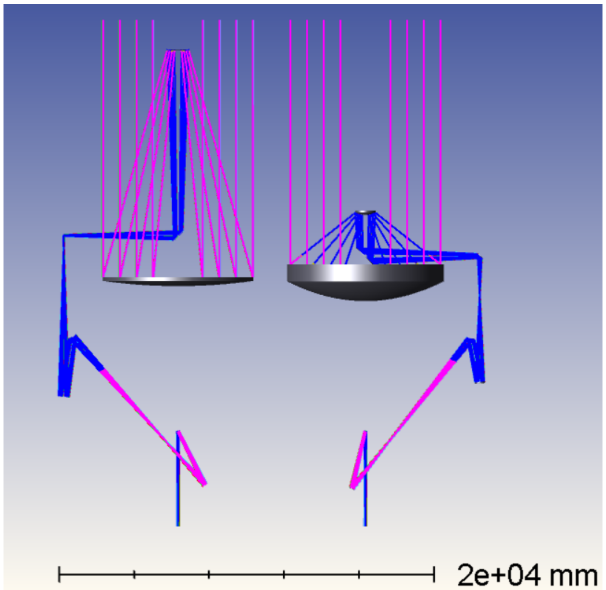

Figure 3: Comparison between the current optical layout of an 8 m Unit Telescope (UT) at Paranal (left) and an extreme compact UT concept with faster optics (right). The proposed design preserves the same coudé interface as the current UT for GLAO operation, with an effective focal ratio of F/50.28 at the coudé focus, a 30 arcsec field of view, and an exit pupil located on the M8 deformable mirror at the same distance from the focal plane as in the current design (5540.2 mm). The optical layout uses purely conic mirrors, with a segmented primary mirror composed of 37 segments. The M1 vertex is located at the same altitude as for the existing UTs on the Paranal platform, resulting in a coudé focus located 13 044 mm below the M1 vertex.

mass accretion and satellite formation around young giant planets. These observations will provide direct clues on planet formation (Wang et al. 2021).

- **Evolved Stars:** Interferometric imaging resolves stellar photospheres, convection cells, and dust-formation regions in the immediate circumstellar environment. These images directly constrain mass-loss processes and the shaping of planetary nebulae (Montargès et al. 2021).
- **Stellar surface imaging:** Direct imaging of stellar surfaces reveals spots, plages, and large-scale magnetic structures. Time-resolved images constrain stellar dynamos and magnetic activity cycles beyond the Solar analog.
- **Stellar multiplicity and hierarchical systems:** Milliarcsecond imaging resolves close multiple systems across the full stellar mass range. These observations constrain formation pathways, orbital evolution, and dynamical interactions in young and evolved systems (Sana et al. 2012).
- **Massive Stars:** High-angular-resolution imaging resolves stellar surfaces, winds, and close environments of massive stars. Direct images reveal rotational distortion, wind clumping, and interacting binaries, providing critical input for models of massive-star evolution.
- **Stellar-mass black holes:** High-angular-resolution interferometric imaging of gravitational microlensing events enables a direct constraint on the mass distribution of stellar-mass black holes. That would provide key constraints on black hole formation channels (Mróz et al. 2025).
- **Galactic Centre:** Interferometric imaging resolves the immediate environment of the Galactic Centre black hole. Time-resolved images of stars orbiting close to the black hole horizon allows tests of the general relativity and constrains the properties of Sgr A*.
- **Resolved stellar populations in nearby galaxies:** Milliarcsecond imaging separates individual stars in dense regions of nearby galaxies. This enables studies of star-formation histories, stellar evolution, and metallicity gradients.
- **Supermassive black holes and binary SMBHs:** High-resolution imaging enables the spatial separation of dual and binary SMBHs in nearby galaxies. Direct measurements of separations and orientations constrain black hole merger scenarios and gravitational-wave progenitors.
- **Active Galactic Nuclei (AGNs):** Interferometric imaging resolves the central parsec of AGNs, separating the dusty torus, broad-line region, and jet base. These images provide direct tests of AGN unification models and accretion–feedback coupling (GRAVITY Collaboration et al. 2020).
- **Time-domain and transient phenomena:** Time-resolved imaging of transients such as tidal disruption events, supernovae, and variable AGN structures probes the dynamical evolution of compact astrophysical systems.
- **Measurement of the Hubble constant (H_0):** High-angular-resolution imaging of geometric distance indicators, such as Cepheids, eclipsing binaries, and maser disks, enables precise and model-light distance measurements. In combination with reverberation mapping of active galactic nuclei, interferometric imaging provides direct constraints on the size and geometry of the broad-line region, anchoring luminosity distances at $z \approx 1$ and enabling an independent determination of the Hubble constant with reduced systematic uncertainties (Abdalla et al. 2022).

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