*A Giant Step: from Milli- to Micro-arcsecond Astrometry*
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# GRAVITY: microarcsecond astrometry and deep interferometric imaging with the VLTI

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**Abstract.** We present the adaptive optics assisted, near-infrared VLTI instrument GRAVITY for precision narrow-angle astrometry and interferometric phase referenced imaging of faint objects. With its two fibers per telescope beam, its internal wavefront sensors and fringe tracker, and a novel metrology concept, GRAVITY will not only push the sensitivity far beyond what is offered today, but will also advance the astrometric accuracy for UTs to 10$\mu$as. GRAVITY is designed to work with four telescopes, thus providing phase referenced imaging and astrometry for 6 baselines simultaneously. Its unique capabilities and sensitivity will open a new window for the observation of a wide range of objects, and — amongst others — will allow the study of motion within a few times the event horizon size of the Galactic Center black hole.

**Keywords.** instrumentation: interferometers, instrumentation: adaptive optics, Galaxy: center

## 1. Fundamental measurements over a wide range of astrophysics

GRAVITY, an interferometric imager with 10$\mu$as astrometric capability, coupled with spectroscopic and polarization modes and optimized to exploit the exquisite sensitivity of the 4x4 VLTI system, will revolutionize dynamical measurements of celestial sources interacting through gravity. It will carry out the ultimate test of determining whether or not the Galactic Centre harbours a $4 \times 10^6$ $M_\odot$ black hole. It has the potential to directly measure the space-time metric around this black hole, and thus may be able to test General Relativity in the presently unexplored strong curvature limit. GRAVITY will also be able to unambiguously detect and measure the mass of black holes in massive star clusters throughout the Milky Way and in many AGN. It will make unique measurements on gas jets in YSOs and AGN. It will explore binary stars, exoplanet systems and young stellar disks. Because of its superb sensitivity GRAVITY will excel in milli-arcsecond phase-referenced imaging of faint objects of any kind. Because of its outstanding astrometric capabilities, it will detect motions throughout the local Universe and perhaps beyond.

Because of its spectroscopic and polarimetric capabilities it is capable of detecting gas motions and magnetic field structures on sub-milliarcsecond scales.

## 2. Instrument design and perfomance

The VLTI, with its four 8m telescopes and a collecting area of 200m$^2$, is the only interferometer to allow direct imaging at high sensitivity and image quality. GRAVITY will for the first time utilize the unique 2" field of view of the VLTI, providing simultaneous interferometry of two objects with four telescopes. This permits narrow angle astrometry with a precision of 10$\mu$as. The application of phase referenced imaging — instead of closure phases — is a major advantage in terms of model-independence and fiducial quality of interferometric maps with a sparse array such as the VLTI. The second major new element of GRAVITY is the use of infrared wavefront sensors to open a new window for interferometry. In addition to broad band (K) imaging and astrometry, GRAVITY also features modest resolution spectroscopy and polarization analysis capabilities. The following Table 1 gives an overview of the expected performance of GRAVITY.

**Table 1.** Expected performance of GRAVITY.

| | |
|---|---|
| Adaptive optics on K=7 star | 36 % Strehl |
| Fringe tracking on K=10 star | 270 nm rms OPD on science channel |
| Astrometry on K=10 primary and K=15 secondary star | 10 $\mu$as in 5 minutes |
| Interferometric imaging on K=16 in 100 s | S/N Visibility = 10 |
| Size and position measurements | K $\geqslant$ 19 in 6 hours |

The baseline for the infrared wavefront sensor is a Shack Hartmann system. It will be located in the VLTI laboratory, thus also correcting for tunnel seeing in the VLTI optical train. The wavefront correction will be applied to the MACAO deformable mirrors located at the UT Coude focus. The interferometric beam combiner is based on fiber-fed integrated optics. The instrument is equipped with polarization-control, differential delay lines, and fast tip/tilt and fringe tracking actuators. GRAVITY will have two beam combiners for two objects. The first is optimized for phase referencing/fringe tracking at a high frame rate. The second, the science beam combiner, is optimized for long integrations. Its spectrometer provides moderate spectral resolution (R $\approx$ 500), and a Wollaston prism for polarization analysis. GRAVITY will have all its components enclosed in a vacuum cryostat for optimum stability and background suppression. The GRAVITY metrology is optimized for astrometric accuracy. Laser light is back-propagated from the GRAVITY beam combiners up to the telescope secondary mirrors, producing fringe patterns, which carry the differential optical path information. These fringe patterns are observed in scattered light through cameras mounted on the telescopes. Other than classical laser metrologies, the GRAVITY metrology measures the full beam and covers the entire optics train except the primary mirror, therefore reducing all systematic errors from non-common optical paths to a minimum.

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