GRAVITY : Probing Space-Time and Faint Objects in the Infrared

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Introduction

We introduce a new infrared adaptive optics assisted multiple-beam instrument for the VLTI infrastructure.

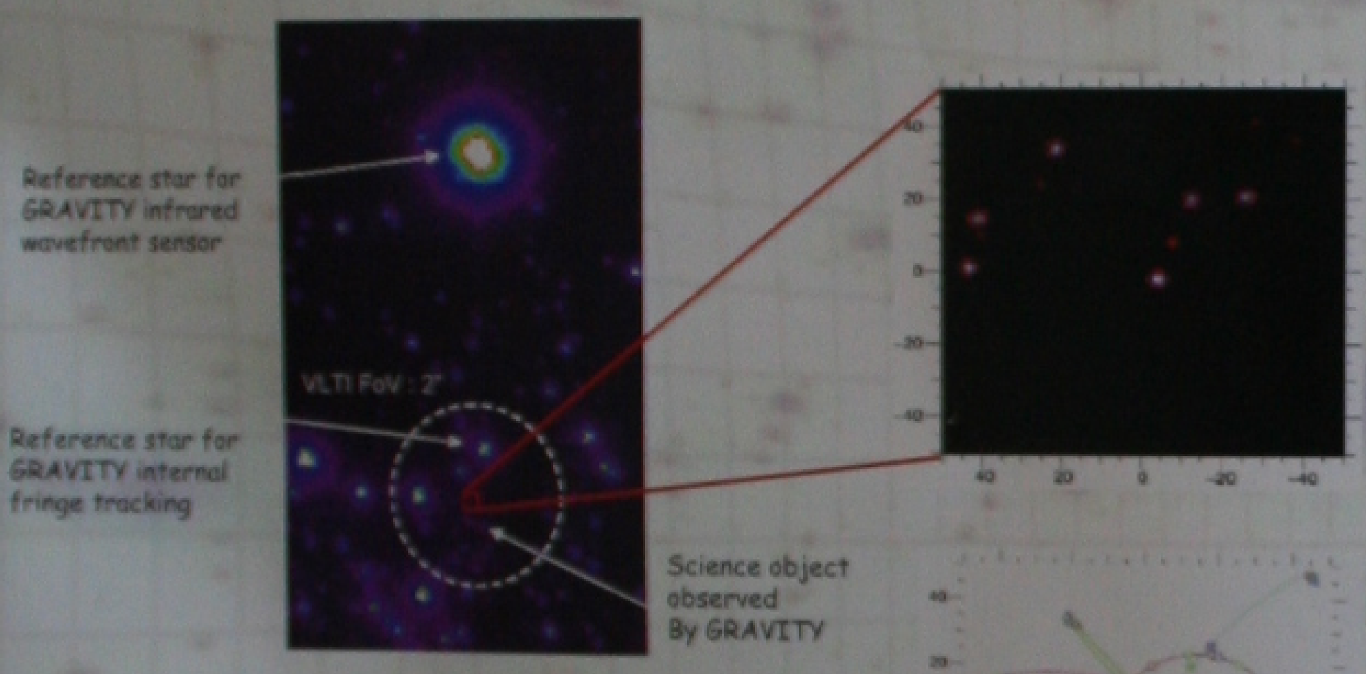
GRAVITY (standing for General Relativity Analysis via VLT InterferometrY) will allow simultaneous observations of two objects by phase-referenced interferometric imaging and narrow angle astrometry with a high sensitivity. At the heart of a consortium between the MPE, MPIA, LESIA and the University of Cologne, GRAVITY is a versatile instrument and is able to tackle a wide range of open questions. It will be a very powerful tool e.g. for studying gas motions and stellar orbits around supermassive black holes (BH) and active galactic nuclei (AGN), for exploring the existence and mass of intermediate mass black holes in star clusters, for studying stellar masses at both ends of the mass function, for investigating circumstellar disks and jets around young stars, for dynamically detecting and measuring the masses of extrasolar planets.

The Center of the Milky Way

The Galactic Center is the closest galactic nucleus, and harbors the currently best (supermassive) black hole candidate. Given its mass, its equivalent zero-spin event horizon radius (Schwarzschild radius) is RS ~ 9 µas. The main goal for GRAVITY is to probe the space-time around Sgr A* down to a few RS thanks to its astrometric accuracy of 10 µas.

Sgr A* exhibits outbursts of infrared, X-ray, and submillimeter emission typically a few times a day. These "flare" events last for about 1 h, and their light-curves show significant variations on a typical timescale of 15 - 20 min in the IR. Therefore, measuring the 2D astrometry of flares will not only allow the determination of the location of the flares with respect to the BH, but also their proper motions. This will enable understanding their nature and constraining the processes at work in other galactic nuclei.

Particularly, one of the major scientific objectives of GRAVITY is the precise determination of the location and motions of hot gas clouds ("flares") just outside the event horizon of the Galactic Center black hole candidate Sgr A* through narrow angle astrometry, as well as the determination of orbits of stars very close to Sgr A* through image synthesis. The current best estimates of the mass of Sgr A* and the distance to the Galactic Center are obtained through orbit fitting of stars in the central arcsecond of the Galaxy, the so-called S-stars. The repeated interferometric imaging of these stars will allow testing of relativistic effects, in particular the prograde periastron shift (see Figure 1).



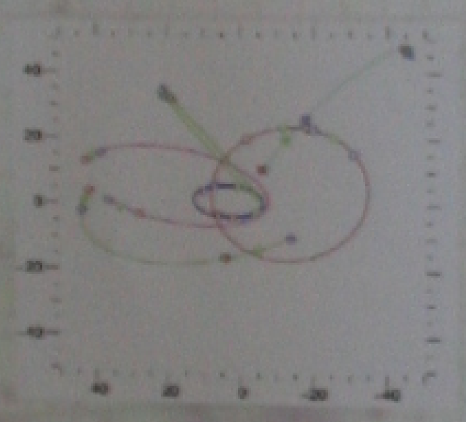


Figure 1 : The right panel illustrates the principle of a typical observation of GRAVITY.
The upper right panel shows a simulation of a 4 mas resolution interferometric imaging of the Galactic center in a field of 100 mas. The lower panel represents the results of a 15 months 10 µas accuracy astrometry. Several stars have completed at least one orbit, and the relativistic periastron shift is already significant for at least one star (axes are in mas). Paumard et al., 2005.

Making science with GRAVITY

Active galactic nuclei

The astrometric technique proposed for the Galactic Center could be complementary to direct imaging for AGNs (Figure 2). With up to 1 arcminute distant reference sources an astrometric accuracy of 100 µas will be reach for GRAVITY on AGNs, allowing monitoring of dynamic changes on scales of 0.05 pc for sources as distant as 100 Mpc.

Figure 2 : Artist view of an AGN. For the few sources at 10 Mpc, the astrometric accuracy translates into 0.005 pc and may give access to the outer edge of the accretion disk, a significant improvement over observations with more classical interferometric instruments.

Substellar objects

GRAVITY would be able to detect Jupiter from 1 kpc away in one Jupiter period (12 yr). The wobble of a Sun due to a hot Jupiter could be determined at distances up to 10 pc in a few days. GRAVITY offers the possibility to search for exoplanets at kpc distances even with the Auxiliary Telescopes (AT) thanks to its optimized throughput.

Masses of the most massive stars

With a nominal resolution of 4 mas at a wavelength of 2 µm, GRAVITY could resolve some of the longer period spectroscopic binaries, and monitor the astrometric motion of the photo-center for the shorter period, closer binaries with a precision of 10 µas. Astrometric orbits for these deeply embedded binary stars will hence directly yield dynamical mass estimates. See Figure 3.

Figure 3 : color H- and K-band image of the Arches starburst cluster in the Galactic Center region with a resolution of approx. 60 mas, i.e. about 500 AU (Stolte et al. 2005). GRAVITY will resolve binaries with separations of less than 40 AU, and monitor the photo-center movements of still closer binaries, resulting in dynamical mass estimates for the most massive stars.

GRAVITY, a unique instrument

Adaptive optics system

The GRAVITY adaptive optics system will be made of four individual adaptive optics systems to correct the atmospheric turbulence of every UT. Hence the GRAVITY AO system will be the first to control simultaneously four individual AO systems. Moreover, it will take advantage of what is already available on the VLTI :

- in its baseline design, the MACAO 60-actuator bimorph deformable mirrors can be used to compensate atmospheric turbulence and tunnel seeing for observations with the UTs;
- in order to sense the tunnel seeing as well as static optical aberrations, the wavefront sensors will be placed in the VLTI lab close to the GRAVITY beam combiner.

Deep interferometric imaging

GRAVITY measures visibilities and phases for up to four telescopes (four UT's, or the full four-telescope AT array) corresponding to six baselines. It also measures referenced phases (see the frame on phase referencing) - in addition to the usual closure phase - using its internal phase referencing system, when a reference source closer than 2" is available, or using the PRIMA facility (Phase-Referenced Imaging and Micro-arcsecond Astrometry, Delplancke et al., 2000) , when a reference source is available at 2 arcsec to 1 arcmin.

Using phase referencing (6 phases for a 4 telescope configuration) instead of closure phases (3 closure phases for a 4 telescope configuration) will significantly improve the quality of the image reconstruction because it is a major advantage in terms of model-independence of reliable interferometric maps.

The key-performances of GRAVITY are summarized in Table 1.

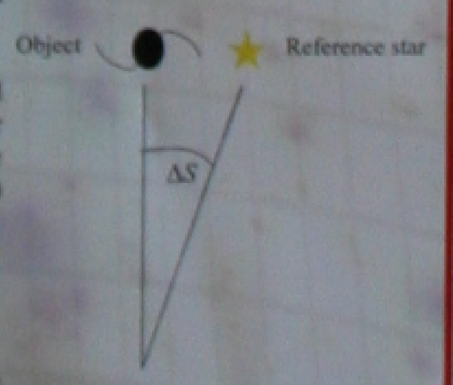
Phase Referencing

We observe fringes both on the source and on the reference star at the same time.

If the phase of the reference star is null and if the error due to the piston is the same for the 2 objects (object located in the anisoplanetism field of the reference star) we have :

$$\Delta\varphi_{obs} = \varphi_{object} + 2\pi B \Delta S/\lambda$$

The reconstructed image has the reference star for zero point in phase so that we don't lose any phase information.



Infrared wavefront sensor	**Limiting magnitude**	**Number of sub-apertures**
	$m_K > 10$ (comparable to NAOS)	≈ 60 (matching MACAO DMs, Strehl ratio ≈ 50 % @ 2.2 µm)
Fringe tracking	**Limiting magnitude**	**Maximum distance from science object**
	$m_K > 10$	2 arcsec (VLTI FoV)
Narrow-angle astrometry	**Accuracy**	**Maximum separation**
	≈ 10 µas (for UTs factor 10 better than PRIMA)	2 arcsec (VLTI FoV)
Interferometric imaging	**Limiting magnitude**	**Accuracy**
	When fringe tracking $m_K > 19.5$ in 1 hour	< 1% in visibility < 1° in phase
	In short exposure mode $m_K > 12$	

Table 1 : Main instrumental features of GRAVITY

GRAVITY in brief

GRAVITY will be installed on Paranal in 2012.

With an accuracy of 10 µas, GRAVITY will be able to study motions to within a few times the event horizon size of the Galactic Center massive black hole and potentially test General Relativity in its strong field limit. It will also be able to detect intermediate mass black holes throughout the Galaxy by their gravitational action on surrounding stars.

Through its high performance infrared wavefront sensing system, GRAVITY will open up deep interferometric imaging studies of stellar and gas components in dusty, obscured regions, such as obscured active galactic nuclei, dust-embedded star forming regions, and protoplanetary disks.

By significantly extending the astrometric capability and sensitivity of the VLTI, GRAVITY will bring the tool of precision interferometry to a large community of users.