GRAVITY: Astrometry on the Galactic Center and beyond

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Abstract

We present the second-generation VLTI instrument GRAVITY, which currently is in the preliminary design phase. GRAVITY is specifically designed to observe highly relativistic motions of matter close to the event horizon of Sgr A*, the massive black hole at the center of the Milky Way. We have identified the key design features needed to achieve this goal and present the resulting instrument concept. It includes an integrated optics, four-telescope, dual feed beam combiner operated in a cryogenic vessel, near infrared wavefront sensing adaptive optics, fringe tracking on secondary sources within the field of view of the VLTI and a novel metrology concept. Simulations show that the planned design matches the scientific needs; in particular that 10μas astrometry is feasible for a source with a magnitude of $m_K = 15$ like Sgr A*, given the availability of suitable phase reference sources.

Key words:
Galactic Center, Sgr A*, black hole, interferometry, VLTI, near-infrared

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1. INTRODUCTION

The aim of GRAVITY is to offer to the observers an instrument that interferometrically combines near-infrared (NIR) light (see e.g. Shao & Colavita, 1992) collected by the four unit telescopes of ESO's Very Large Telescope. It will use adaptive optics at the telescope level and fringe tracking at the interferometer level. This instrument can be operated in an imaging mode, yielding an unprecedented resolution of ~ 3 mas in the NIR for objects that can be as faint as $m_K = 18$ when using a fringe tracking star of $m_K = 10$. 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. In its astrometric mode, GRAVITY will allow to measure distances between the fringe tracking star and a science object to an accuracy of 10μas. This will allow one to measure directly the on-sky motions of many objects in the field of view (2") in a relatively short amount of time. At 100 pc, a velocity of 10μas/yr corresponds to 5 m/s, at 1 Mpc to 50 km/s. Such high precision astrometry will thus give the astronomical community a tool at hand, which makes it possible to watch how objects move in the local universe. The use of infrared wavefront sensors enables one to observe highly obscured or dust embedded sources like the Galactic Center and young stellar objects at the highest sensitivity.

2. KEY SCIENCE CASES

*2.1. Stellar orbits around Sgr A**

The best case for the existence of an astrophysical black hole is the massive black hole (MBH) in the Galactic Center (GC). The combination of radio and NIR observations has proven beyond any reasonable doubt that at the dynamical center of the Milky Way a black hole of 4 million solar masses resides, coinciding with the radio source Sgr A*. The mass measurement became possible with the advent of high angular resolution techniques in the

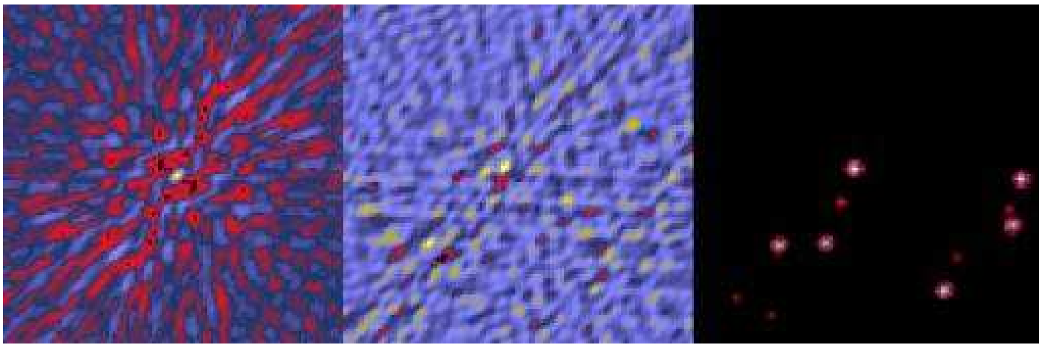

Figure 1: Simulated observation of a star field with 6 stars placed in orbit around Sgr A* in a 100 mas square field. Left panel: The PSF for one night of VLTI observations. Middle panel: The reconstructed image. Right panel: The recovered image from the middle panel, using a simple CLEAN algorithm (Paumard et al., 2005, 2008).

NIR. In particular, the combination of adaptive optics (AO) and large (8m-10m diameter) telescopes made it possible to observe a multitude of stellar orbits moving in the gravitational potential of the MBH (Schödel et al., 2002; Ghez et al., 2005; Eisenhauer et al., 2005). Up to now the system can be described perfectly by a single point mass and Newtonian gravity. Nevertheless, deviations from these simple assumptions are expected to exist: A cluster of dark objects with stellar masses (e.g. neutron stars or stellar mass black holes) might well be present around Sgr A* (Morris, 1993; Muno et al., 2005). Furthermore, the effects of general relativity will break the assumption of a Newtonian system. In order to detect such deviations, both high precision astrometry and spectroscopy of stars passing very close to the MBH can be used. Thus, this experiment naturally demands to go to the highest spatial resolution achievable in the NIR, namely interferometry.

We have examined the feasibility of detecting the Schwarzschild precession around Sgr A*. Given the density profile and luminosity function of the Galactic Center star cluster, we estimate that a few stars with $17 < m_K < 19$ at any point in time should reside in the central 60 mas, thus being essentially unresolved with current NIR instrumentation, but being accessible with the VLTI (Paumard et al., 2005). Figure 1 shows simulated observations using all 4 UTs for 9 hours of 6 stars placed in orbit around Sgr A* in a 100 mas square field. We were able to show that it is possible to recover the assumed star fields from the simulated data. Such stars will have orbital periods of ~ 1 year. Their orbits should show measurable (few degrees per

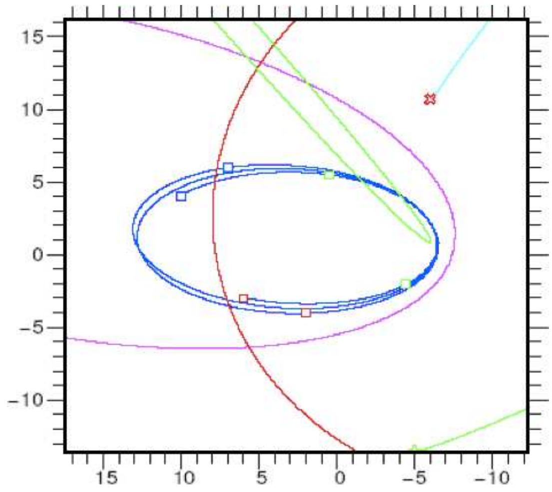

Figure 2: Simulated orbit figures for stars orbiting Sgr A* with semi major axis of $\sim$ 100 AU (axes in μas). The axes of the plot are in units of milliarcseconds. The strong precession due to the Schwarzschild metric is evident after even only two revolutions, each lasting no more than a year (Paumard et al., 2005, 2008).

revolution) prograde relativistic periastron shifts, resulting in rosetta shaped orbits. An extended stellar mass component (Trippe et al., 2008; Gillessen et al., 2009; Schödel et al., 2009) causes a retrograde periastron-shift (Rubilar & Eckart, 2001; Alexander, 2005; Weinberg et al., 2005). Figure 2 shows the reconstructed orbits of simulated stars orbiting Sgr A* with semi major axis of $\sim$ 100 AU. The strong precession due to the Schwarzschild metric is already evident after only two revolutions. In addition to measure the orbits of faint stars very near to Sgr A* with GRAVITY it will also be possible to measure accelerations for stars up to projected distances of several arcseconds. Together with a radial velocity measurement from spectroscopic observations one can determine the full (Kepler) orbit of the star. This will greatly increase the significance with which one can constrain the dynamics of the cluster of old stars in the Galactic center (e.g. Trippe et al., 2008) as well as the young and massive stars located in possibly warped disks (Bartko et al., 2009). Possible applications and the limitations of the upcoming two-telescope facilities PRIMA and ASTRA in the GC are discussed in (Bartko et al., 2008; Pott et al., 2008). First VLTI infrared spectro-interferometry on the star GC IRS 7, the brightest NIR object ($mK \sim 6.4$) within several arcseconds of Sgr A*, have been presented by Pott et al. (2008a).

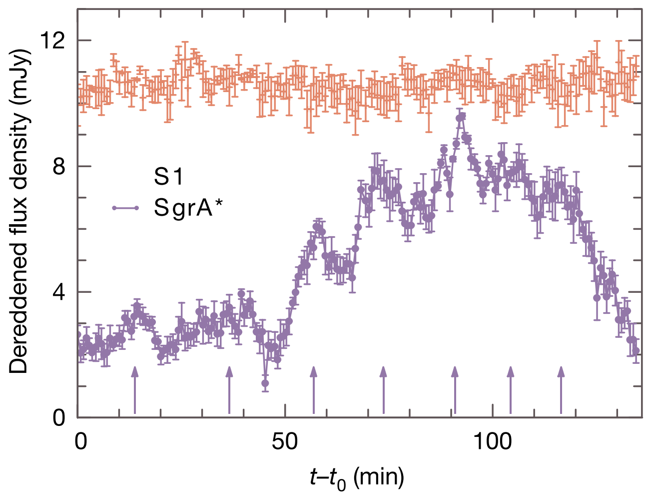

Figure 3: Light curve of a strong infrared flare, observed in K-band at the VLT on June 16, 2003. For comparison, the light curve of a star is shown. In the flare's light curve, substructure is present with a quasi-period of about 20 – 22 minutes. From (Genzel et al., 2003).

*2.2. Flares from Sgr A**

Genzel et al. (2003) observed for the first time sporadic NIR emission from Sgr A*. Figure 3 shows the light curve of the first observed infrared flare on June 16, 2003. Since then, many such flares occurring at a rate of 1/night and lasting each for ~ 2 hours have been observed. Most of the flares show quasiperiodic substructures with typical time scales of 20 minutes (Trippe et al., 2007; Dodds-Eden et al., 2009). The flare together with its quasi-periodicity can be understood in terms of an orbiting hot spot model, where a heated gas blob close to the innermost circular orbit revolves around the MBH, yielding the light curve modulations due to the orbiting motion (Hamaus et al., 2008). Given the apparent diameter of 10μas for a MBH of 4 million solar masses at a distance of 8 kpc, the motion might be detectable with NIR interferometric means. Do et al. (2009) rather attribute the flare structures to red noise and Meyer et al. (2009) link the emission properties of Sgr A* to the ones of stellar mass black holes.

Although the flares will not be resolved, the astrometric wobble of the centroid can be detected. While such an observation would already be extremely exciting, an even more rewarding goal would be to characterize the motion. The spin of the MBH and strong lensing effects will lead to characteristic deviations from a circular motion. Thus, the flares can be used as probes for the strongly curved space-time in which they move, ultimately testing the theory of gravity, general relativity (GR), in its strong field limit for an extremely heavy mass. This perspective coined the name GRAVITY for the instrument. We have simulated VLTI observations of flares from Sgr A*. Assuming reasonable parameters for the beam-combining instrument, we were able to show that already the observation of a single flare will allow us to detect the orbital motion. If ~ 10 flares can be coadded suitably (see Hamaus et al., 2008), the strong relativistic effects become visible. Neither the exact emission mechanism nor the exact motion are strong prerequisites.

It is well worth to compare that route of testing GR with other experiments:

- Classical solar system tests give access to the low curvature, low mass regime of GR (Psaltis, 2004).

- Earth-bound gravitational wave detectors such as LIGO, GEO, TAMA or VIRGO should be able to detect single supernova explosions, corresponding to the high curvature, low-mass regime of GR. The high-mass regime requires to go to lower frequencies which are not accessible from ground (Abramovici et al., 1992).

- Space-borne gravitational wave detectors (e.g. LISA) will extend the accessible frequency range to the regime in which the signal of merging MBHs is expected to occur, testing the high-curvature, high-mass regime of GR (Berti et al., 2006).

- A submm-VLBI array should be able to actually resolve Sgr A*, possibly showing its event horizon as a shadow (Falcke et al., 2000; Doleman et al., 2008).

The so-far untested strong field limit of GR is tested with the last three items only. Gravitational wave detectors have a different focus, since very dynamic events will be observed. Thus the structure of space-time is tested rather indirectly. Furthermore gravitational wave detectors are quite expansive devices, and only upper limits on the emission of gravitational waves have been obtained so far experimentally. The submm-VLBI observations are unlikely to yield a dynamic picture of Sgr A* since the estimates for the

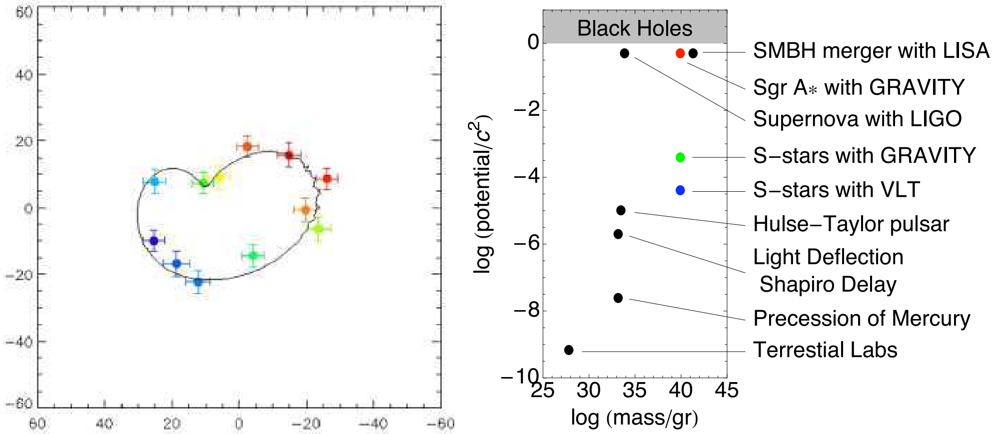

Figure 4: Left: model of the apparent trajectory of a flare event (solid line, axes in μas). The material is assumed to orbit the black hole (BH) at $3R_S$ with an inclination of 45°. The combination of lensing (including multiple images), relativistic beaming and Doppler effect result in a cardioid, which can be resolved by co-adding the time-resolved astrometric observations of a few flares to reduce the error bars (dots with error bars, resulting from 10 observations in this example), figure from Paumard et al. (2005, 2008). Right: Dynamical tests of general relativity as a function of the mass of the gravitating body and the curvature of space-time, adapted from Psaltis (2004).

exposure times needed are much longer than the orbital period, the characteristic time scale of the system. Hence, GRAVITY offers a quite promising route to severely test GR. In addition, the measurement of the precession of closed orbits with GRAVITY could yield an estimate of the spin of the MBH through the Lense-Thirring effect. Observations with GRAVITY can be considered as a test particle approach to the structure of space-time around a MBH, which at the same time has only a very moderate price, namely that of building a four-telescope interferometric beam combiner. At a rate of about one flare per night and a contingency of 50% for weather and technology the observation of 10 flares requires 15 nights with all four VLT UTs.

2.3. Active galactic nuclei

The standard unified model (Antonucci, 1993) postulates that all active galactic nuclei (AGNs) are accreting SMBHs surrounded by a geometrically thick, dusty interstellar cloud structure (the 'torus') whose orientation relative to the observer's line of sight determines the specific phenomena observed. Historically it has proven difficult to study AGN at the spatial scales on which these components exist. For seeing-limited observations, at a distance of 20 Mpc, 1" corresponds to 100 pc. Over the last few years, using AO for NIR observations, it has become possible to probe these objects at 100 mas scales. IR interferometry has now resolved the dusty torus for ~ 10 AGN and even more detailed views were possible for NGC 1068 (Jaffe et al., 2004; Wittkowski et al., 2004) and NGC 4151 (Swain et al., 2003). GRAVITY will continue that route to smaller angular sizes. In the closest AGN – those within 20 Mpc – one will be able to probe scales less than 0.5 pc. In Circinus and Cen A, the spatial resolution will be around 0.1 pc, a scale which is close to what was possible in the GC before the advent of AO.

Perhaps the most exciting advances for AGN science that will become possible with GRAVITY concern the Broad Line Region (BLR). This is a compact region lying between the AGN and the inner edge of the torus, in which the large width of optical/NIR emission lines arises from the high velocities of the clouds as they orbit the central black hole (BH). Currently, the size of the BLR can only be inferred indirectly from time variability studies ('reverberation mapping'), available for 35 AGN (Peterson, 2004). The BLR sizes are derived from the time delay between UV continuum and emission line variations. The BLR is always smaller than 0.1 mas across and hence too small to be resolved with VLTI direct broad-band imaging at infrared wavelengths. The excellent 10μas astrometric accuracy of GRAVITY will enable deriving a velocity gradient across it. First and foremost, this will provide a statistical estimate of the fraction of BLRs in which there is a significant component of ordered rotation. For these sources, it will become possible to make an estimate of the size of the BLR and also to directly determine the central BH mass. The way this can be done is by measuring the phase difference between the blue and red sides of the broad Brγ (or Paα) lines – analogous to comparing velocity channel maps. With GRAVITY's spectral resolution of $R > 500$ even a line with a FWHM of 1000 km/s (which includes all Narrow Line Seyfert 1 galaxies) can be spectrally resolved into two independent segments. In most cases the lines have much greater widths such that they can be resolved far better.

Another important aspect is nuclear star formation. There are observational and theoretical reasons to believe that the AGN and the surrounding star formation are influencing each other. This interaction can have an impact on different scales, from fuelling the AGN (because of the effect a nuclear starburst will have on gas inflow) to the evolution of the galaxy (via feedback from the AGN). GRAVITY's spectroscopic capabilities will allow to study this on the relevant physical size scales.

2.4. Intermediate mass black holes

The correlation between the mass of the spheroidal stellar component of a galaxy and the mass of the central MBH suggests that in dense star clusters intermediate mass black holes could reside. This is supported by theoretical simulations that imply that in sufficiently massive and dense star clusters (e.g. Portegies Zwart et al., 2004) the core collapses and collisionally a central object is built up. Recent searches in globular clusters suggest evidence for such IMBHs (e.g. Gebhardt et al., 2002; Baumgardt et al., 2003; McLaughlin et al., 2006). However, the sphere of influence of the postulated BHs is typically less than a few arcseconds, such that only a few stars are available for this type of statistical studies. GRAVITY will dramatically change this situation in a few suitable cases. With the high angular resolution accelerations may be determined for some stars, offering a precise tool for determining the gravitational potential. Figure 5 shows expected angular accelerations of orbiting stars as a function of the distance from the centers for several massive star clusters, assuming that these clusters contain IMBHs as estimated from recent observations.

2.5. Young stellar objects

GRAVITY will be ideal for investigations of YSOs, namely their circumstellar disks and outflows. Since the systems are embedded in dust clouds, GRAVITY's infrared wavefront-sensing capability is critical. The disk may for example show spiral structures, wakes and gaps expected as a result of the interaction between a forming planet and the disk. Such structures have indeed already been observed in a number of cases, e.g. GG Tau (Dutrey et al., 1994) and Fomalhaut (Kalas et al., 2005). The relative faintness of young giant planets compared to the high surface brightness of the typical circumstellar disk has thus far prevented direct detection in diffraction limited observations with 8m class telescopes in the NIR. GRAVITY's 4 mas resolution (compared to 60 mas resolution for one UT) drastically improves the contrast between a disk and its embedded planet. It should be possible to probe for young giant planets, which are almost 6 mag fainter than what is currently achievable. Additional but less direct evidence for the presence of such planets could be derived from the photocenter movement of the exoplanet host star around the common center of mass. Furthermore, the inner edge of the circumstellar disk indicates also the boundary of the possible

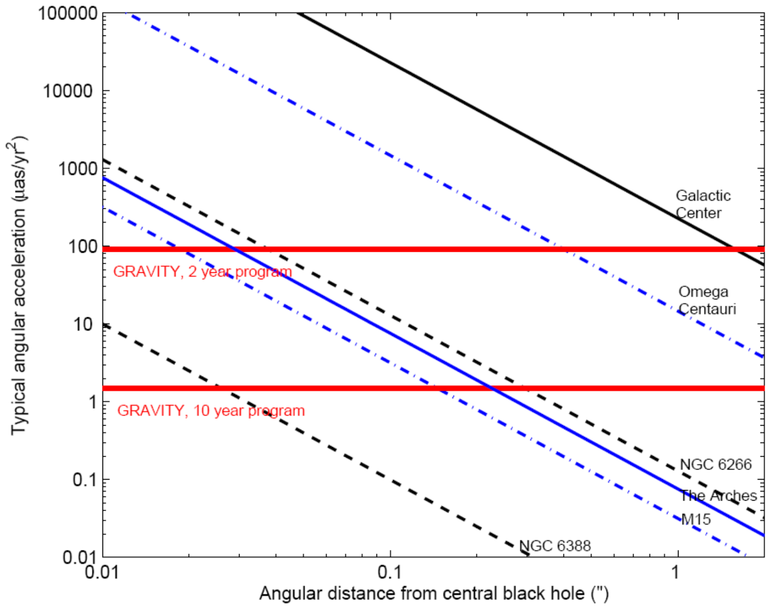

Figure 5: Angular acceleration of orbiting stars as a function of the distance from the centers for several massive star clusters, assuming that these clusters contain IMBHs as estimated from recent observations.

planet-forming region, so that the physical conditions there can also exert an important influence on the outcomes of planetary formation. GRAVITY could allow imaging this inner disk. For the goals and prospects of an astrometric planet search with PRIMA see Reffert et al. (2006).

The physics behind the formation of jets in YSOs, and in particular the launching mechanism, is still poorly understood. The important processes seem to take place within less than 0.5 AU from the star, which at typical distances to the nearest star forming regions of 150 pc translates into an angular size of less than 30 mas. At 4 mas resolution, GRAVITY will be able to resolve the central jet formation engine around young, nearby stars. Furthermore, at a distance of 150 pc, an astrometric precision of 10μas over a time span of 1 h corresponds to a transversal velocity accuracy of $\sim$ 60 km/s. Hence, high-velocity outflows and the formation and evolution of jets from T Tauri stars (Edwards et al., 1987) with typical velocities of 150 km/s can be resolved and the time evolution of jet formation at the base of the outflow can be directly traced with GRAVITY.

3. Top Level Requirements & Working Principle

3.1. Top level requirements

Given the key science cases we have derived the following top-level requirements:

- Operation in the K-band (2.2μm), offering a well-suited atmospheric window and being the scientifically most interesting waveband for all types of obscured objects.
- Interferometric combination of the light collected with all four 8m diameter UTs to collect as much light as possible for the interferograms to achieve the highest possible limiting magnitude.
- Simultaneous combination of the light of two sources for each of the six baselines between the four UTs in order to provide the maximum possible UV-coverage possible with four telescopes.
- Adaptive Optics at each telescope using a wavefront sensor operating in the NIR. The wavefront sensor, in the baseline design, will be located in the VLTI lab. A Strehl ratio of $\sim$ 40% should be reached for a magnitude of $m_K = 6.5$ assuming typical atmospheric conditions for the VLTI site, Paranal, and a distance of the guide star to the science field of 6". Wavefront sensing should be possible also on-source.
- Fringe Tracking, either on source or using a phase reference source within the 2" field of view of the VLTI, down to $m_K = 10$ assuming typical atmospheric conditions.
- Control of the relevant optical path differences at the level of 5 nm, corresponding to the desired accuracy of 10μas for a 100 m baseline.
- Spectral resolution up to at least 500 and active polarization control.

3.2. Working principle

The working principle of GRAVITY is illustrated in figure 6. Up to four celestial sources are used in GRAVITY: The science target (SCI), the AO guide star (NGS), the fringe tracking star (FS) and an additional guide star (AGS) for compensation of tip/tilt errors occurring between the NGS and the

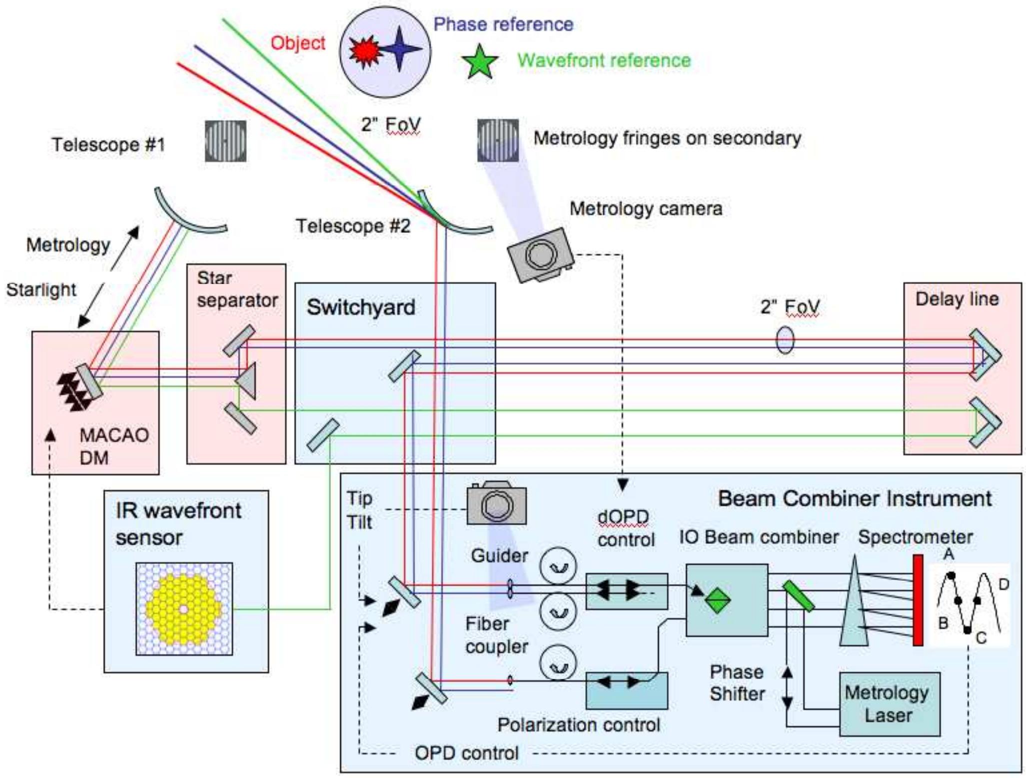

Figure 6: GRAVITY concept. For a description see the main text.

interferometer entrance. SCI, FS and AGS have to lie within the interferometric field of view of 2” of the VLTI. The NGS can be chosen in a field of 1’ around the science field. The light is sent from each telescope to the respective star separators (Delplancke et al., 2004), where the science field SCI and the field for the NGS are separated. Both fields are sent via the VLTI delay lines to a switchyard table located in the VLTI laboratory. At that point the path difference between the different telescopes has been compensated. The switchyard reflects the light of the NGS into the WFS modules in the VLTI lab, which in turn command the deformable mirrors of the telescopes, located just in front of the star separators. The light from the science field enters the beam combiner instrument. In an image plane the SCI and FS are picked up by two monomode fibers. An acquisition camera records the image plane. During acquisition it can be used to check the position of the fibers that have to be moved to the locations of SCI and FS. During the

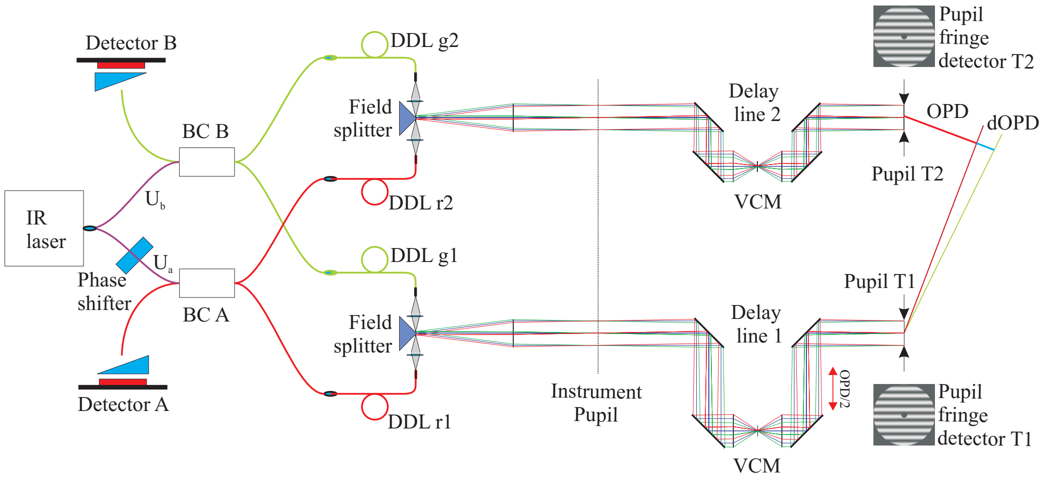

Figure 7: Metrology concept. For a description see the main text.

observation, the light of the AGS (or the artificial reference source) can be seen in the acquisition camera and thus provides the possibility to correct for differential motions as internal turbulences seem to be decorrelated between the two GRAVITY fields. For each telescope the light from SCI and FS travels through the two fibers, passing a polarization control unit as well as the differential delay lines. These are needed to compensate for the differential delay occurring between SCI and FS due to their slightly deviating positions in the sky. Finally, the four SCI fibers (corresponding to the four telescopes) and the four FS fibers are fed into the science beam combiner and the fringe tracking beam combiner, both planned as integrated optics beam combiners (Benisty et al., 2009). The output of each beam combiner consists of 24 beams, for each baseline simultaneously a full set of four phases (ABCD) is created. The beams are then imaged via a spectrometer onto the two detectors.

In order to control the internal path lengths to the required accuracy of 5 nm a metrology system is required. The current design foresees a novel concept for the metrology as illustrated in figure 7. A NIR laser with a wavelength slightly shorter than the K-band is launched before the integrated optics beam combiners such that its light travels the whole optical path of the VLTI back to the telescopes. For each telescope the same laser light is sent once via the science channel and once via the fringe-tracking channel towards the telescope. In one of the channels a phase shifter is acting on the beam before the light enters the VLTI optics, allowing one to actively apply phase shifts between the two beams traveling towards the telescope. Due to the fixed phase relation between the two laser beams, they will create an interference pattern in each pupil plane, in particular also on M2, the secondary mirror of telescope. The fringe spacing and orientation is a function of the distance and position angle of the two fibers and thus of the celestial positions of SCI and FS. By means of the phase shifter the fringes can be time-sampled ('phase shifting interferometry') and the relative phase of the two beams can be recovered (Rabien, 2008). If the relative optical path lengths towards one telescope change (e.g. due to the operation of the differential delay line) the fringe pattern will shift by the corresponding phase. Thus, by monitoring the fringe pattern one can detect changes in the optical paths. The fringe pattern occurs on a mirror; nevertheless it will be possible to detect it in scattered light, using a commercial NIR camera observing M2 from an off-axis position in a way that M2 simply acts as a scattering screen. Our preliminary tests conducted at the VLT have shown that this manner of detection indeed is feasible and that the required accuracy can be reached. We have simulated the interferometric performance of the instrument using realistic input data (Haubois, 2008). The main conclusion is that the anticipated accuracy and sensitivity can be reached. This means that the science cases as outlined above are feasible with the proposed design. The science products of the GRAVITY data reduction software will be phases and visibilities as these quantities can be determined source-model-independent. For more information about the preliminary design and prototyping see Eisenhauer et al. (2005, 2008); Gillessen et al. (2006).

4. Project Details

GRAVITY is a joint project by currently seven institions, including ESO. The PI-ship and project management are located at the Max-Planck-Institut für extraterrestrische Physik (Garching, Germany) that also is responsible for the beam combiner instrument cryostat, the fiber optics and the metrology. The Laboratoire d'AstrOphysique de Grenoble, France (LAOG) is in charge of the integrated optics beam combiner. The AO module and the switchyard are done jointly by the Max-Planck-Institut für Astronomie (Heidelberg, Germany) and the Observatoire de Paris, France (LESIA) and ONERA, France. ONERA and LESIA have formed a partnership called PHASE and are in charge of the fringe tracker and the beam combiner integration as well as the fiber optics functions (differential delay lines and polarization controllers) and the data reduction software. The spectrometer is the work package of the University of Cologne, Germany, and the acquisition camera will be build by . The project successfully concluded a feasibility study in mid-2007. Late 2007 the ESO Scientific and Technical Committee (STC) recommended to ESO to start the project. Currently, the partners work on the preliminary design and at the same time contracting with ESO is underway. Preliminary design review is foreseen for December 2009. Shipping to Paranal of GRAVITY is planned for 2012, and science operation could start in 2013.

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